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Advanced Fiber-Optic Devices for Harsh Environments Based on High-Power Wireless Energy Transfer and Novel Interferometric Architectures

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Resumo

À medida que a humanidade progride e explora novos domínios, surge a necessidade de soluções que permitam a operação em ambientes extremos. O presente estudo tem como objetivo o desenvolvimento de sistemas óticos para a transmissão de energia sem fios por meio de feixes laser, com o intuito de viabilizar o abastecimento de sistemas localizados em zonas remotas, bem como de sensores em fibra ótica baseados no efeito de Vernier, com o objetivo de aumentar a sensibilidade. A técnica de interferometria de luz branca (WLI) é também utilizada com o propósito de elevar a frequência de amostragem sem que o alcance fique limitado a 2π .

O estudo inicia-se com uma visão geral sobre lasers, com ênfase nos lasers de fibra ótica. Esta comunicação tem como finalidade descrever o modo de operação dos lasers, os seus principais componentes, e os lasers de alta potência atualmente disponíveis, baseados em fibras dopadas com itérbio, érbio e túlio. No que respeita à propagação atmosférica, são analisados os fenómenos de absorção, dispersão e turbulência, concluindo-se que o comprimento de onda de $1,55\text{ }\mu\text{m}$ é o mais adequado, o que motiva a implementação de lasers com meio ativo dopado com érbio. Adicionalmente, aborda-se a divergência natural do feixe de luz, sendo modelado e construído um telescópio com arquitetura de expensor de feixe de zoom, de forma a controlar o diâmetro do feixe laser. O presente estudo inclui também a montagem e caracterização de um laser de fibra ótica com tripla bainha dopada com érbio. Adicionalmente, são delineadas configurações de conversores optoelectrónicos e descritas experiências que validam a transferência de energia sem fios.

Relativamente aos sensores interferométricos em fibra ótica, é apresentado um modelo teórico que descreve sensores individuais, o efeito de Vernier e a técnica WLI (ou interferometria de baixa coerência, LCI). A partir deste modelo, procede-se ao estudo da sensibilidade dos extremos do espectro e do intervalo espectral livre (*FSR*). A metodologia aplicada envolve a avaliação do desempenho do efeito de Vernier nas variantes Reduzida, Tradicional e

Aprimorada, bem como nos estados Fundamental e Harmónicos. Constatou-se que a envolvente da variante Aprimorada apresenta o dobro da sensibilidade da envolvente da variante Tradicional. Quanto aos estados, verifica-se que, quando os harmónicos são gerados através do aumento da cavidade de referência, ocorre uma amplificação por um factor $m + 1$. No entanto, este fenómeno não se verifica quando os harmónicos são gerados pelo aumento da cavidade sensora. Propõe-se uma reformulação do fator de magnificação (M) e uma nova figura de mérito ($FoM_{Vernier}$), a qual permite distinguir os casos com ou sem amplificação. A modelação teórica é finalizada com a análise dos sinais de saída na técnica WLI, estudando-se a dependência do sinal relativamente à fonte ótica utilizada.

Posteriormente, descrevem-se vários sensores baseados no efeito de Vernier que validam o modelo teórico proposto. Esta comunicação tem ainda como objetivo apresentar duas novas implementações de sensores. A primeira consiste num espelho em laço de fibra (FML) com dois circuladores óticos, permitindo a medição simultânea de deformação e torção. A segunda implementação baseia-se numa cavidade interna funcionalizada como sensor de temperatura, a qual gera uma função de erro que compensa variações térmicas sem necessidade de sensor externo.

No contexto das aplicações práticas da técnica WLI, destaca-se a produção de cinco interrogadores, o alcance de uma banda de interrogação superior a 150 μm e uma frequência de amostragem próxima de 1 kHz. Adicionalmente, é apresentado um algoritmo de filtragem e linearização de fase, capaz de processar sinais em tempo real a uma taxa de 1 kHz. Por fim, a cavidade interna de um circulador ótico é funcionalizada como referência, reduzindo o número de canais de leitura e aumentando a robustez do sistema de aquisição e processamento ótico.

Este trabalho aborda o desenvolvimento de sistemas óticos, estabelecendo fundamentos sólidos nas áreas de transmissão de energia sem fios por meio de lasers e de sensores interferométricos, com ênfase no efeito de Vernier e na técnica WLI, para aplicação em ambientes extremos, como o espaço.

Palavras chave: Laser em fibra ótica, propagação atmosférica, fibra ótica de tripla bainha dopada com erbio, sensores interferométricos, sensores em fibra ótica, efeito de Vernier, método de "push-pull", interferometria de luz branca (WLI).

Abstract

As humanity progresses and explores new domains, the need arises for solutions that enable operation in extreme environments. This study aims to develop optical systems for wireless power transmission via laser beams, with the purpose of enabling power supply to systems located in remote areas, as well as developing optical fibre sensors based on the Vernier effect, with the goal of increasing sensitivity. The white light interferometry (WLI) technique is also employed to raise the sampling frequency without restricting the measurement range to 2π .

The study begins with an overview of lasers, with a focus on optical fibre lasers. This communication aims to describe the operating principles of lasers, their main components, and the current high-power lasers based on fibres doped with ytterbium, erbium, and thulium. Regarding atmospheric propagation, phenomena such as absorption, scattering, and turbulence are analysed, leading to the conclusion that the wavelength of $1.55\text{ }\mu\text{m}$ is the most suitable. Consequently, lasers with erbium-doped active media are implemented. Additionally, the natural divergence of the light beam is addressed, and a zoom-type beam expander telescope is modelled and constructed to control the laser beam diameter. This study also covers the assembly and characterisation of an erbium-doped triple-clad fibre laser. Furthermore, configurations of optoelectronic converters are outlined, and experiments validating wireless energy transfer are described.

With respect to interferometric fibre optic sensors, a theoretical model is presented that describes individual sensors, the Vernier effect, and the WLI technique (also known as low-coherence interferometry, LCI). Based on this model, the sensitivity at the spectral extremes and the free spectral range (*FSR*) are analysed. The methodology involves evaluating the performance of the Vernier effect across three variants: Reduced, Traditional, and Enhanced, as well as across the Fundamental and Harmonic states. It was found that the envelope

of Enhanced variant exhibits twice the sensitivity of the envelope of Traditional variant. Regarding the states, when harmonics are generated by increasing the reference cavity, an amplification by a factor of $m + 1$ is observed. However, this amplification does not occur when harmonics are generated by increasing the sensing cavity. A reformulation of the magnification factor (M) is proposed, along with a new figure of merit ($FoM_{Vernier}$), which allows distinguishing between cases with and without amplification. The theoretical modelling concludes with the analysis of output signals in the WLI technique, studying the dependence of the output signal on the optical source used.

Subsequently, various sensors based on the Vernier effect are described, validating the proposed theoretical model. This communication also presents two new sensor implementations. The first consists of a fibre loop mirror (FML) with two optical circulators, enabling simultaneous measurement of strain and torsion. The second implementation is an internally functionalised cavity that operates as a temperature sensor, generating an error function to compensate for thermal variations without requiring an external sensor. In terms of practical applications of WLI, the production of five interrogators is highlighted, achieving an interrogation bandwidth greater than $150\text{ }\mu\text{m}$ and a sampling frequency close to 1 kHz . Additionally, a phase linearisation and filtering algorithm is presented, capable of real-time processing at 1 kHz . Finally, the cavity of an optical circulator is functionalised as a reference, reducing the number of readout channels and increasing the robustness of the optical acquisition and processing system.

This work addresses the development of optical systems, establishing a robust foundation in the fields of wireless energy transfer via lasers and interferometric sensors, with a specific focus on the Vernier effect and WLI technique, for application in extreme environments such as space.

Keywords: Fibre optic laser, atmospheric propagation, erbium-doped triple-cladding fibre, interferometric sensors, fibre optic sensors, Vernier effect, push-pull method, white light interferometry (WLI).

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*"The wealth is the slave of a wise man,
and the master of a foolish man"*

Lucius Annaeus Seneca

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Abbreviations

AO	Adaptive Optics
ASE	Amplified Spontaneous Emission
CLS	Cladding Light Stripping
CPU	Central Processing Unit
CW	Continuous-Wave
DARPA	Defense Advanced Research Projects Agency
FBG	Fibre Bragg Gratings
FLM	Fibre Loop Mirrors
FPI	Fabry-Pérot Interferometer
FPU	Fast Processing Unit
FSO	Free-Space Optical
FSR	Free Spectral Range
GEOS-II	Geodetic Earth Orbiting Satellite-II
GOLD	Ground/Orbital Lasercom Demonstration
GRIN	Gradient Index
GT-Wave	Gain-Topped Wave
Hi-Bi	High-Birefringence
HPCF	Hybrid Photonic Crystal Fibres
IR	Infrared
LCI	Low Coherence Interferometry
LIGO	Laser Interferometer Gravitational-Wave Observatory

LMA	Large-Mode-Area
MPE	Maximum Permissible Exposure
MZ	Mach-Zehnder
MZI	Mach-Zehnder Interferometer
NA	Numerical Aperture
NRL	Naval Research Laboratory
OCL	Optical Coherence Lattices
OD	Optical Density
OPD	Optical Path Difference
OPL	Optical Path Length
OSA	Optical Spectrum Analyser
PCF	Photonic Crystal Fibres
PLA	Polylactic Acid
PTROL	Power Transmitted Over Laser
PZT	Piezoelectric Transducer
RH	Relative Humidity
SMF	Single-Mode Fiber
SNR	Signal-to-Noise Ratio
SBS	Stimulated Brillouin Scattering
SRS	Stimulated Raman Scattering
SWELL	Space Wireless Energy Laser Link
TGG	Terbium Gallium Garnet
UAV	Unmanned Aerial Vehicle
UV	Ultra-Violet
WLI	White Light Interferometry

Chapter 1

Introduction

The need to explore extreme environments, such as space and the deep ocean, as well as the need to predict certain events, has increased the importance of optical systems in the current development of science and technology [1, 2, 3]. The earliest source of illumination for humankind was the sun, and fire subsequently emerged as the first light source. Moreover, the first optical sensor was the human eye. The study of phenomena such as reflection, refraction, and diffraction, which began in the 17th century, enabled the development of optical instruments such as telescopes and microscopes. The three fundamental advances that enabled the exponential growth of optical systems occurred in the 1960s. These advances were the first laser in 1960 [4], the development of the first optical fibre laser in 1964 [5], and the fabrication of the first low attenuation optical fibre in 1966 [6]. The development of these technologies, in turn, paved the way for advancements in optical communications [7], optical sensing [8, 9], and optical processing [10].

Presently, wireless energy transfer utilising high-power lasers is one of the domains demonstrating the most significant development [11]. These systems enable the establishment of power supply lines to systems located in remote areas and over long distances, with light being converted into electricity through photovoltaic or thermoelectric panels. The development of this technology has been focused on applications in energy supply for drones in full flight, satellites, and remote sensors, thereby reducing the necessity to carry large batteries.

Another important scientific area is fibre optic interferometric sensors. These sensors, also known as interferometric cavity sensors, have as their main method of operation the overlapping of at least two different optical paths, generating an interference pattern. These sensors are widely used in structural monitoring [12], gravitational wave detection (as the LIGO project) [13], precision metrology [14], and navigation systems [15]. Features such as high sensitivity, wide dynamic range and immunity to electromagnetic noise have made interferometric sensors an outstanding tool for the development of scientific, industrial, and commercial systems.

This Chapter presents a comprehensive overview of the motivation and objectives underlying the current PhD research. It is followed by a detailed description of the structure and organization of the dissertation. Furthermore, the chapter highlights the main contributions of the work to the field and includes a complete list of publications that have emerged from the research conducted during this doctoral programme.

1.1 Motivation and objectives

The continuous growth of the human population and the increasing need to predict and address future challenges have driven the demand for innovative solutions capable of operating in extreme environments, such as outer space. In this particular context, the central focus of the research activities presented in this dissertation has been on these novel solutions based on optical systems. The present work addresses two principal domains: wireless optical energy transfer using high-power lasers in remote areas and harsh environments; and the development of sensing technologies for challenging environments focused on enhancing sensitivity and advancing interrogation systems capable of high-precision measurements, employing techniques such as White Light Interferometry (WLI). Another significant motivation for this research has been the opportunity to test original ideas and contribute personally to advancing the

application and relevance of optical systems in devising solutions for emerging scientific and technological challenges. The main objectives of the activity carried out within the scope of this dissertation are as follows:

- To model, fabricate, and characterize a high-power optical fiber laser as well as the output beam management system, for implementation into a wireless optical energy transfer system.
- To investigate the Vernier effect with the aim of developing a detailed theoretical model and implementing it in interferometric sensors, in order to increase sensitivity in scenarios involving high optical path differences.
- To design, fabricate, and characterize interrogators for white light interferometry, and to develop an efficient algorithm for real-time signal analysis.

1.2 Disertation overview

The dissertation is organised in eight chapters, which are summarised below.

Chapter 1 delineates the motivation, objectives, and structure of this dissertation, in addition to the primary contributions and publications that have emerged from it.

Chapter 2 provides a comprehensive overview of the state of the art in laser technology, addressing the fundamental components of laser systems enabling the development of a high-power continuous wave (CW) laser. Additionally, it encompasses the latest advancements in atmospheric propagation of laser beams, including discussions on attenuation, dispersion, and turbulence.

Chapter 3 presents the development of an optical wireless power transfer system, covering laser beam atmospheric propagation, telescope design, optical and thermal component characterization, and the fabrication of a prototype tested in both laboratory and outdoor environments.

Chapter 4 focuses on the theoretical modeling of interferometric sensors, followed by the Vernier effect. A novel concept of the figure of merit is presented, derived from a new perspective of the magnification factor, thereby enabling the distinction between implementations, whether the amplification occurs or not. This chapter ends with the mathematical description of the white light interferometry (WLI) technique.

Chapter 5 validates experimentally the theoretical concepts addressed in Chapter 4. First, it explores fibre optic sensing configurations enhanced by the Vernier effect. It includes three-wave interferometry using fibre tip micro-structures, and the application of the Push-Pull method in Fabry-Perot interferometers. Also, distinct fiber loop mirror (FLM) setups are presented to improve sensitivity and measurement resolution.

Chapter 6 presents two novel approaches for interferometric sensing. Namely, a new fiber loop mirror (FLM) design using only single-mode fibres, capable of replicating the spectral response of a Hi-Bi fibre FLM. Additionally, a novel method is proposed to reduce the thermal sensitivity of a magneto-optical sensor employed in electric current measurements.

Chapter 7 focuses on the implementation of the WLI technique, detailing the development of five prototype interrogators, signal processing algorithms for phase filtering and linearization, and the use of the internal cavity of an optical circulator as reference.

Chapter 8 summarizes the main results of the dissertation and outlines future research challenges and opportunities.

1.3 Main contributions

The research conducted as part of this dissertation has yielded the following scientific contributions:

- Production of an erbium-doped triple photonic crystal cladding (HPCF) laser with a CW output of 20 W;

- Development of a theoretical model describing the Vernier effect;
- Reformulation of the magnification factor and presentation of a new figure of merit that allows distinguishing different implementations of the Vernier effect in terms of their sensitivity amplification factor;
- Development of a giant sensitivity sensing system based on the Vernier effect and the push-pull method;
- Functionalisation of internal cavities as sensors and references, commonly known as parasitic cavities;
- Development of WLI interrogators with an interrogation bandwidth higher than 100 μm and with an oscillation frequency close to or higher than 1 kHz;
- Participation in the conception of the patent entitled: "Thermoplasmonic device, respective wireless energy transfer system and respective operation method" with the number EP4339659 and submitted in 2024.

1.4 Main publications

The research conducted within the scope of this doctoral work resulted in 10 scientific journal publications, 5 conference presentations, and 4 conference posters. Notably, the jury prize for Best Poster was awarded during participation in the 2021 OPSP.

1.4.1 Scientific Journal Publications

1. **P. Robalinho**, A. Gomes and O. Frazão, "High Enhancement Strain Sensor Based on Vernier Effect Using 2-Fiber Loop Mirrors," in *IEEE Photonics Technology Letters*, vol. 32, no. 18, pp. 1139-1142, 2020, doi: 10.1109/LPT.2020.3014695"
2. **P. Robalinho**, A. Gomes, and O. Frazão, "Colossal Enhancement of Strain Sensitivity Using the Push-Pull Deformation Method," in *IEEE*

- Sensors Journal, vol. 21, no. 4, pp. 4623-4627, 15 Feb.15, 2021, doi: 10.1109/JSEN.2020.3033581;
3. **P. Robalinho** and O. Frazão, "Nano-Displacement Measurement Using an Optical Drop-Shaped Structure," in IEEE Photonics Technology Letters, vol. 33, no. 2, pp. 65-68, 15 Jan.15, 2021, doi: 10.1109/LPT.2020.3044118;
 4. **P. Robalinho**, O. Frazão, "Giant Displacement Sensitivity Using Push-Pull Method in Interferometry", Photonics, vol. 8, iss. 1, no. 23, 2021 doi: 10.3390/photonics8010023;
 5. **P. Robalinho**, M. Melo, O. Frazão and A. B. L. Ribeiro, "Temperature-Monitored Fibre Optic Current Sensor Using Channelled-Spectrum Analysis," in IEEE Photonics Technology Letters, vol. 34, no. 23, pp. 1308-1310, 1 Dec.1, 2022, doi: 10.1109/LPT.2022.3214105;
 6. **P. Robalinho**, B. Soares, A. Lobo, S. Silva, O. Frazão, "Fiber Loop Mirror Based on Optical Fiber Circulator for Sensing" Applications. Sensors, vol. 23, no. 618, 2023, doi: 10.3390/s23020618
 7. **P. Robalinho**, A. Rodrigues, S. Novais, A. L. Ribeiro, S. Silva, and O. Frazão, "Novel digital signal processing method for data acquired from Low Coherence Interferometry," in IEEE Sensors Journal, vol. 24, no. 24, pp. 40896-40903, 2024, doi: 10.1109/JSEN.2024.3483433.
 8. **P. Robalinho**, V. Piaia, L. Soares, S. Novais, A. L. Ribeiro, S. Silva, O. Frazão, "Phase-Shifted Fiber Bragg Grating by Selective Pitch Slicing", Sensors, vol. 24, no. 6898, 2024, doi: 10.3390/s24216898
 9. **P. Robalinho**, V. Piaia, A. Lobo-Ribeiro, S. Silva, and O. Frazão, "Virtual Vernier Effect Harmonics for Enhanced Fabry-Perot Interferometer Sensing," in IEEE Photonics Technology Letters, vol. 38, no. 1, pp. 41-44, 2026, doi: 10.1109/LPT.2025.3616517

10. **P. Robalinho**, V. Piaia, A. L. Ribeiro, S. Silva, and O. Frazão, "Optical Harmonic Vernier Effect: Conditions Required for Effective Sensitivity Amplification", accepted in the IEEE Lightwave journal, doi: 10.1109/JLT.2025.3634488

1.4.2 Conferences

1. **P. Robalinho**, O. Frazão, A. B. Lobo Ribeiro, "Intrinsic temperature-compensated fibre optic current sensor using wavelength multiplexing", 5^a Conferencia Internacional de Aplicações de Ótica e Fotónica, AOP 2022, Guimarães, Portugal.
2. **P. Robalinho**, R. Costa, M. M. Maia, M. Rocha, A. L. Pires, C. Furtado, A. Califórnia, S. Bogas, C. Ferreira, J. Silva, L. Sousa, J. Machado, B. Leconte, P. Roy, J.-L. Auguste, R. Jamier, F. Navarro-Medina, F. Aguado-Agelet, U. Garcia-Luis, C. Ulloa, P. Orgeira-Crespo, A. Camanzo-Mariño, V. Dragos-Darau, A. Gomez-San-Juan, R. Comesaña, O. Frazão and A. Pereira, "Wireless Power Supplier Next Generation: Optical Fiber CW Laser", DCE 2023, (Porto, Portugal, Jun.15-16, 2023)
3. **P. Robalinho**, A. Rodrigues, S. Novais, A. B. Lobo Ribeiro, S. Silva and O. Frazão, "Low Noise White Light Interferometry With Broad Cavity Interrogation Band and Fast Sampling ", in Proc. of 6th Int. Conf. on Applications of Optics and Photonics, AOP 2024 (Aveiro, Portugal, July 16-19, 2024)
4. **P. Robalinho**, A Rodrigues, S Novais, AB Lobo Ribeiro, S Silva, O Frazão, "Low Coherence Interferometry Measurement: An Algorithm for fast processing with low noise and phase linearization", 12^o European Optical Society Annual Meeting, EOSAM, EOSAM 2024, Naples, Italia, doi: 10.1051/epjconf/202430910022

5. **P. Robalinho**, A. Rodrigues, S. Novais, A. B. Lobo Ribeiro, S. Silva and O. Frazão, "Harnessing Parasitic Cavity as Reference for Low Coherence Systems," 2024 IEEE Photonics Conference (IPC), Rome, Italy, 2024, pp. 1-2, doi: 10.1109/IPC60965.2024.10799531
6. **P. Robalinho**, O. Frazão, "New combination of Push-Pull Method and Vernier Effect for Colossal Strain Sensitivities", OPSP 2021; This poster was awarded the jury's prize for best poster;
7. **P. Robalinho**, O. Frazão, "Compact Optical Fiber Sensor with Vernier Effect for Giant Displacement Sensitivity", DCE 2021 (Porto, Portugal, Jun.28-29, 2021);
8. **P. Robalinho**, A. Rodrigues, S. Novais, A. B. Lobo Ribeiro, S. Silva and O. Frazão, "White Light Interferometry: Absolute and High Precision Measurement for Long-Cavity Fibre Fabry-Perot Sensors", 11^o European Optical Society Annual Meeting, EOSAM, EOSAM 2023, Paris, França, doi: 10.1051/epjconf/202328709039
9. **P. Robalinho**, V. Piaia, A. L. Ribeiro, S. Silva, O. Frazão, "A New Perspective on the Optical Vernier Effect and Its Apparent Sensitivity Enhancement", OFS29, Proceedings Volume 13639, 1363930, 405-408, Porto, Portugal, May 25-30, 2025, doi: 10.1117/12.3062045

1.5 Other publications

The research conducted in this PhD dissertation resulted in other 3 publication scientific publications, 2 conference presentations, and 7 conference posters.

Scientific Journal Publications

1. B. Soares, **P. Robalinho**, A. Guerreiro, O. Frazão, "Resilience to Passive Attacks of a Secure Key Distribution System Based on an Ultra-Long Fiber

- Laser Using a Bi-Directional EDFA". *Photonics*, vol. 9, no. 825, 2022, doi: 10.3390/photonics9110825
2. M. Maia, A. Pires, M. Rocha, S. F.-Teixeira, **P. Robalinho**, O. Frazão, C. Furtado, A. Califórnia, V. Machado, S. Bogas, C. Ferreira, J. Machado, L. Sousa, U.G. Luis, A. M. G. S.-Juan, P. O. Crespo, F. N. Medina, C. U. Sande, A. C. Marino, G. R. González, A. T. Pereira, F. A. Agelet, R. Jamier, P. Roy, B. Leconte, J.-L. Auguste, A. M. Pereira, "A Photo-Thermoelectric Twist to Wireless Energy Transfer: Radial Flexible Thermoelectric Device Powered by a High-Power Laser Beam", *Adv. Mater. Technol.* 2023, 8, 2202104, doi: 10.1002/admt.202202104
 3. V. Piaia, **P. Robalinho**, A. Rodrigues, A. Lobo Ribeiro, S. Silva, and O. Frazão, "Displacement Sensing Based on Parasitic Cavity Referencing in Optical Circulators," in *IEEE Photonics Technology Letters*, vol. 37, no. 22, pp. 1293-1296, 2025, doi: 10.1109/LPT.2025.3597250"

Conferences

1. A. Rodrigues, **P. Robalinho**, S. M. O. Tavares, Orlando Frazão, "White light interferometric sensing system for measurement of fiber optic interferometric sensors", DCE 2023, (Porto, Portugal, Jun.15-16, 2023)
2. O. Frazão, **P. Robalinho**, A. Vaz, L. Soares, B. Soares, C. Monteiro, S. Novais, S. Silva, "How to Use Fiber Optic Sensors for Accurate Absolute Measurements-INVITED", 11° European Optical Society Annual Meeting, EOSAM, EOSAM 2023, Paris, França, doi: 10.1051/epjconf/202328709008
3. F. Maia, **P. Robalinho**, O. Frazão, "Simulations of atmospheric propagation under turbulent conditions and high power fiber laser", OPSP 2021;
4. F. Maia, **P. Robalinho** and O. Frazão, "Simulating the propagation of a laser through turbulent atmosphere", DCE 2021 (Porto, Portugal, Jun.28-29, 2021);

5. J. Reis, A. Rodrigues, **P. Robalinho**, S. Novais, J. Maia, P. Marques, D. Roma, J. Salvans, M. Canal, J. Ramos, V. Gualani, S. Sisteré, V. Martín, M. Nofrarias, S. Silva, O. Frazão, "The effect of frequency modulation on the FSR of a Fabry-Perot cavity using an Optical Spectrum Analyser", EPJ Web of Conferences 266, 13027, 2022, doi: 10.1051/epjconf/202226613027
6. A. Pires, M. Maia, M. Rocha, **P. Robalinho**, C. Furtado, O. Frazão, A. Pereira Pires, "Boosting Thermoelectric Power GenerationCoupling NIR Absorbers for Wireless Power Transfer", 18th European Conference on Thermoelectrics (ECT 2022), 2022.
7. A. Pires, M. Almeida, M. Maia, M. Rocha, **P. Robalinho**, C. Furtado, O. Frazão, A. Pereira, "The Play Role of Absorbers/Collectors in the Efficiency of Pioneering Radial Flexible Photo-Thermoelectric Optical Sensors", European Materials Research Society 2023 Spring Meeting, 2023.
8. A. Rodrigues, **P. Robalinho**, S. Silva, S. Tavares, O. Frazão, "High-precision fabrication method for Fabry-Perot cavities using white light interferometry", OFS29, Proceedings Volume 13639, 136392F, 321-324, Porto, Portugal, May 25-30, 2025, doi: 10.1117/12.3061101
9. V. Piaia, **P. Robalinho**, L. Soares, S. Novais, A. L. Ribeiro, O. Frazão, S. Silva, "Intensity-based refractive index sensor using sliced fiber Bragg grating", OFS29, Proceedings Volume 13639, 1363989, 55, Porto, Portugal, May 25-30, 2025, doi: 10.1117/12.3060327

1.6 Patent

The present dissertation comprises participation in the conception of the patent resulting from the work carried out in Wiptherm, a European project:

1. A. Pereira, A. Pires, M. Maia, J. A. Silva, J. Silva, A. Marques, O. Frazão, P. Robalinho, R. Jamier, B. Leconte, P. Roy, J.-L. Auguste, Jean-Louis, F. Agelet,

U. Luís, A. Juan, P. Crespo, V. Darau, "Thermoplasmonic device, respective wireless energy transfer system and respective operation method" with the number EP4339659 and WO2024057282, submitted in 2024.

Chapter 2

High-power fiber lasers and its atmospheric propagation

2.1 Introduction

Humanity's first light source was the sun, which, along with the discovery of fire and the development of candles and oil lamps, enabled the earliest optical experiments. The 19th century marked the beginning of the great major development of light sources, highlighting the appearance of the incandescent and fluorescent lamp. The history of lasers started at the beginning of the 20th century with the advances made by Max Planck and Albert Einstein, which introduced the concept of stimulated emission. Thus, after the appearance of the first maser in 1954, in 1960 the first solid state laser [4], based on a ruby crystal, and the first gas laser [16], He-Ne laser, appeared. Just four years later, the first optical fibre laser was produced [5].

There are three main types of laser: gas laser [17, 18, 19], solid-state laser [20, 21], and optical fibre laser [22, 23]. Gas lasers are further classified into three categories: neutral atom gas lasers, ion lasers, and molecular lasers. The light beam evidences narrow lines, being useful in areas such as holography, metrology, and laser material processing. However, their low efficiency, the complex architecture, and the low gain medium density make gas lasers less

suitable for high power laser applications. Recently, with the emergence of PCF fibre, gas-filled hollow-core fibre lasers have been tested. The greatest benefit has been the possibility of obtaining new wavelengths in optical fibre lasers. Nevertheless, due to significant losses in the guiding modes and the low efficiency of gaseous media, the output power typically remains around 1 W in continuous-wave (CW) operation. For many applications, optical fibre lasers are the preferred choice over solid-state lasers (Tab. 2.1). They have excellent thermal dissipation due to the area that is exposed to the air in opposite with solid-state laser, although the good thermal conductivity, the thermal dissipation is low because the surface in contact with air is low. This allows fibre lasers to achieve higher output powers, reaching the kW class in CW operation. The gain of the optical fibre laser is higher than the solid-state laser, presenting as well high absorption and emission cross-sections of rare-earth ions, allowing the tuning of the wavelength signal. Furthermore, the optical fiber laser has an excellent beam spatial quality thanks to the good light guiding mechanisms. Also, the system is simpler, more compact, and easier to integrate than the solid-state laser, considering that no alignment is required. However, the solid-state laser, namely the bulk crystal, has a higher damage threshold in pulsed operation than the optical fibre laser, where non-linear effects also occur and lead to pulse distortion.

This Chapter focuses on high-power optical fibre lasers operating in CW mode, following the considerations regarding the propagation of atmospheric light beams. It includes an overview of their working principles and discusses the main challenges associated with implementing high-power fibre laser systems, and a comparison of the three main types of fibre lasers is also presented. Lastly, a description of the propagation features of a light beam in the atmosphere are discussed, including phenomena such as attenuation, scattering, and turbulence. Furthermore, this study constitutes an analysis of the predominant issues that emerge in the context of beam propagation in the atmosphere. Within this section, telescopes based on the zoom beam expander scheme, a methodology employed for the purpose of regulating the diameter of the illuminated area, are

Table 2.1: Comparative analysis between solid state lasers and fibre optic lasers.

Features	<i>Solid-State</i>	<i>Optical Fiber</i>
<i>Laser Gain</i>	Low tolerance to internal losses.	High tolerance for internal losses.
<i>Spectroscopy</i>	Absorption and emission cross-sections are narrow.	Absorption and emission cross-sections are wide, allowing selection of the emission length.
<i>Thermal Dissipation</i>	Despite good thermal conductivity, thermal dissipation is low due to the contact area ratio.	Although thermal conductivity is lower, thermal dissipation is high due to the contact area ratio.
<i>Beam Quality</i>	Sensitive to misalignment and thermal degradation.	Good beam guiding mechanisms in the fiber core.
<i>Assembly and Calibration</i>	Not very compact and not very flexible, more sensitive to external disturbances.	Compact and flexible.
<i>Pulsed mode</i>	High damage threshold.	Non-linear effects and low damage threshold.
<i>CW mode</i>	High power strongly limited by thermal load.	Multi-kW due to good dissipation.

also described.

2.2 Laser operation mode

The laser operation consists in the population inversion that depends on the interaction of light with material media. The three interactions of interest are absorption, spontaneous emission, and stimulated emission. The laser operation begins with the photon absorption by an electron that transits to higher energy levels. Finally, one or more decays occur, which can be radiative and non-radiative. Radiative decays give rise to emission that can be stimulated, where all photons are in phase, contributing to signal amplification, or spontaneous, important in laser start-up. Non-radiative decays have a strong

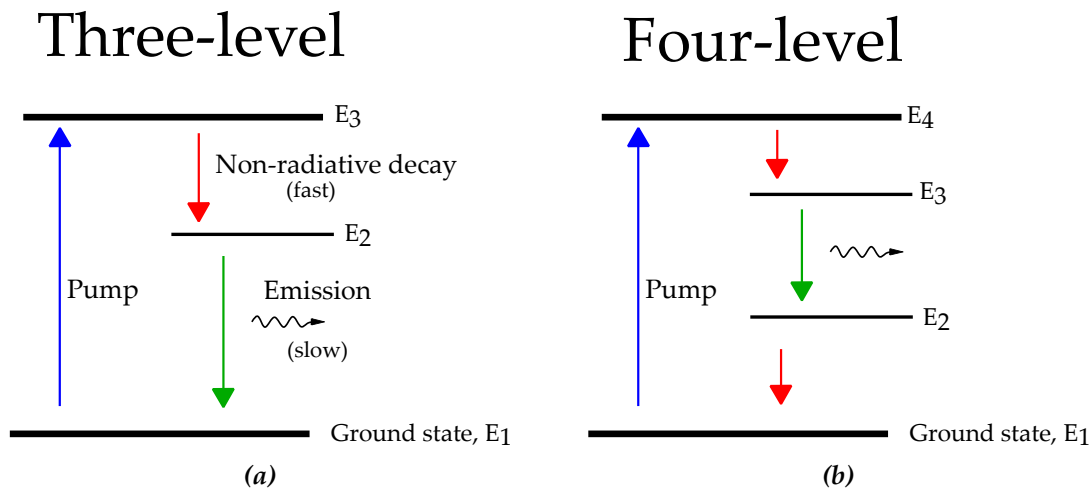


Figure 2.1: Schematic level representation for: (a) three-level system, and (b) four-level system.

impact in reducing the laser efficiency. This efficiency can be evaluated based on the quantum defect, and it can be described as follows [24]:

$$q = h\nu_{pump} - h\nu_{laser} = h\nu_{pump} \left(1 - \frac{\lambda_{pump}}{\lambda_{laser}} \right) \quad (2.1)$$

where h is the Planck constant, ν_{pump} and λ_{pump} are the frequency and wavelength of the pump, respectively, ν_{laser} and λ_{laser} are the frequency and wavelength of the laser, respectively. An increase in the quantum defect implies an increase in the losses which are usually in the form of heat.

Lasers can be divided into two main groups [25, 26]: three-level, and four-level laser systems. The three-level system is composed of a ground state where excited electrons transit to the highest energy level (Fig. 2.1a). Then, a non-radiative decay to an intermediate level occurs, and finally, through stimulated or spontaneous emission, the electrons radiatively decay to the ground state. The Er^{3+} ion, when pumped at 980 nm, is an example of a 3-level system. When the pump wavelengths are close to the signal wavelengths, this is called in-band pumping (also named resonant pump). On the other hand, the four-level system is composed by two intermediate levels, and the only radiative decay occurs between the two intermediate levels (Fig. 2.1b). An example of a four-level system is the Nd^{3+} ion.

Note that intermediate states need to be considered, namely, in the quasi

two-level, quasi three-level, and quasi four-level systems, where the intermediate level approaches the highest and/or ground energy level, reducing the energy associated to the non-radiative decay.

2.3 Fibre laser configurations

Two relevant features of a doped optical fibre are the numerical aperture (NA) and M^2 [27]. The use of small NA values restricts pumping to single-mode optical sources, which typically provide lower power when compared to multimode optical sources. With the development of optical fibre designs, NA values as high as 0.9 have been achieved. However, operation in multimode regimes - despite enabling the use of higher-power sources - results in the propagation of modes other than the fundamental Gaussian mode. This leads to increased beam divergence. In this context, the M^2 factor becomes relevant, and for a perfect Gaussian beam, it equals 1. Thus, considering that for certain doped fibers the M^2 value can reach as high as 10 [28] - indicating an output beam that is up to ten times more divergent than an ideal Gaussian beam - it becomes necessary to use external optical components to compensate for the propagation mode mismatch between different optical fiber devices. Figure 2.2 presents two possible optical fibre laser schemes.

Pumping can be performed by a cascaded Raman laser [29], a laser diode [30] or even another optical fibre laser source (named tandem pumping) [31]. There are three types of pump configurations: forward-pumping (pump and signal are co-propagating), backward-pumping (pump and signal are counter-propagating), and bidirectional pumping [32, 33]. The forward configuration is used only for low-power lasers since, for higher power, the amplified spontaneous emission (ASE) noise has a strong impact on the output signal. The backward configuration allows obtaining a reduced ASE, even for high pumping power, in addition to providing higher amplification. However, this configuration is more complex than the forward configuration. In

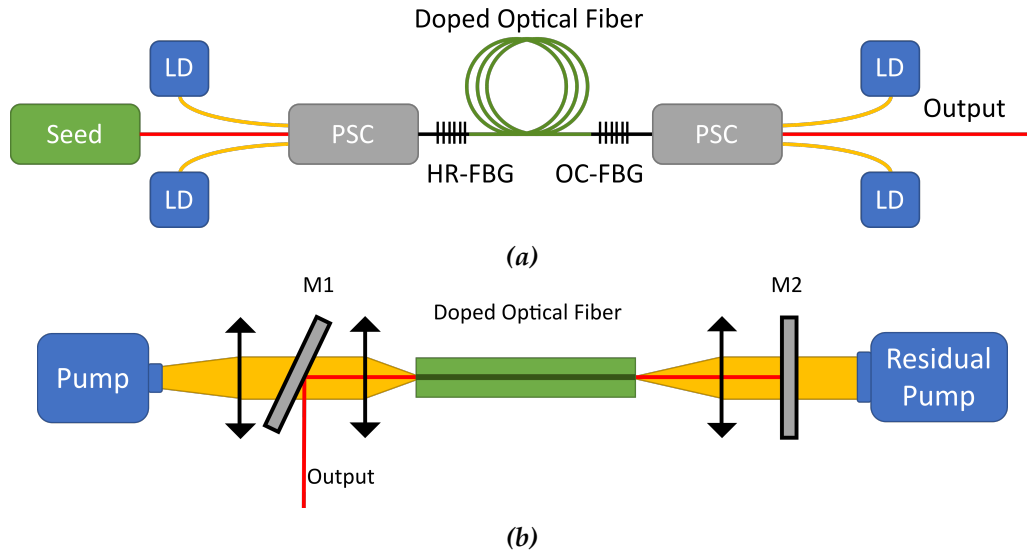


Figure 2.2: Examples of optical fiber laser schemes: (a) complete system is in optical fiber, and (b) only the active medium is in optical fiber. LD is pump diode laser, PSC is pump and signal combiners, HR-FBG and OC-FBG are high reflection and output coupler fiber Bragg gratings, and M is dichroic mirror.

high-power lasers, bidirectional pumping is used, which is the combination of the two previous configurations. For this type of lasers, usually doped optical fibres with large lengths are used, which means that the pumping is not constant along the fibre. Therefore, bidirectional pumping allows obtaining a constant gain along the entire doped optical fibre.

2.4 Fibre Bragg grating mirrors

The role of dichroic mirrors is particularly noteworthy; in the all-fibre configuration, this function is performed by Fibre Bragg Gratings (FBGs). An FBG consists of a periodic modulation in the refractive index along the fibre core, thereby enabling the generation of multiple reflections [34]. In the instance of these reflections being superimposed, it is to be noted that they selectively reflect a given wavelength - Bragg wavelength - which is given by the following equation:

$$\lambda_B = 2n_{eff}\Lambda, \quad (2.2)$$

where n_{eff} is the effective refractive index and Λ is the period of the network.

The performance of FBGs is contingent on the profiles and positions of the perturbation in relation to the light propagation axis. For high-power lasers, two configurations are of particular interest, as depicted in Figure 2.3 [35]. The uniform structure is characterised by all perturbations induced in the optical fibre having the same positive refractive index variation and dimension, as well as being perpendicular to the propagation axis (Fig. 2.3a). The apodised structure is characterised by an uniform FBG to which a second, long modulation is added to the refractive index of the perturbation. The modulation is typically characterised by a Gaussian or cosine-sine profile, thereby reducing the difference in the indices of the perturbation at the ends of the structure (Fig. 2.3b) [36]. The second modulation under consideration has been demonstrated to have the capacity to suppress side lobes and increase the SNR of the output signal, leading to suppression of beam emission at wavelengths that are close to the target wavelength and which are deemed to be unwanted.

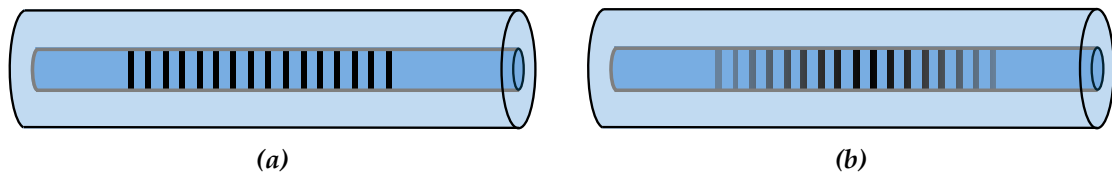


Figure 2.3: Schematics of FBG structures: (a) uniform, and (b) apodised. Images from [37].

The implementation of FBGs in high-power lasers must consider the temperature gradient, which can be minimised by absorption, scattering, and light coupling losses to the cladding. This requires the fabrication of homogeneous perturbations along the entire cross-section of the optical fibre core [34, 38]. The fabrication of FBGs typically involves the utilisation of phase masks and ultraviolet (UV) laser sources. In order to implement UV sources, it is necessary for the optical fibres to be photosensitive and doped with germanium (Ge) or/and boron (B). Furthermore, Ge-doped fibre must be previously exposed to a hydrogen-rich atmosphere and undergo thermal annealing subsequent to the inscription of the FBG. In addition to being an extended process, the residual

hydrogen in the optical fibre, when exposed to thermal annealing, will serve to increase the temperature gradient. In addition to being an extended process, the presence of residual hydrogen in the optical fibre, when exposed to thermal annealing, contributes to an increased temperature gradient. Furthermore, the use of UV lasers prevents the possibility of achieving a uniform cross-section of the various perturbations. In order to enhance manufacturing quality, UV lasers are being succeeded by femtosecond lasers (fs-lasers), which represent the most prevalent technology for producing gratings in the present day. In this instance, the employment of photosensitive optical fibres, as well as hydrogen-loading and thermal annealing treatments, is no longer a requirement. This approach has been demonstrated to reduce manufacturing costs whilst simultaneously enhancing the quality of the cross-sectional profile of the perturbation and reducing the temperature slope. One of the manufacturing methods under consideration is scanning, which consists of implementing cylindrical lenses and optical fibre mounted on translation stages. In order to inscribe the FBG, it is necessary to move the translation stages perpendicular to the axis of the fibre, requiring translation stages of a highly precise nature. In order to circumvent the financial implications of translation stage implementation, novel methodologies have been put forward. One such approach entails the galvanometer-based scanning strategy, which utilises the vibration of a galvanometer to facilitate the inscription of large-mode-area (LMA) FBGs characterised by homogeneous cross-sectional profiles (Fig. 2.4). FBGs can also be inscribed using direct writing. Despite the capacity for multiple FBGs to be inscribed in a versatile manner, the quality of the transverse profile of the perturbations is found to be inferior when compared to the implementation of the phase mask [39].

2.5 Insertion of optical pumps and combiner design

The first doped optical fibers for lasers were based in the standard core and cladding configuration. Despite the developments made in the last few years,

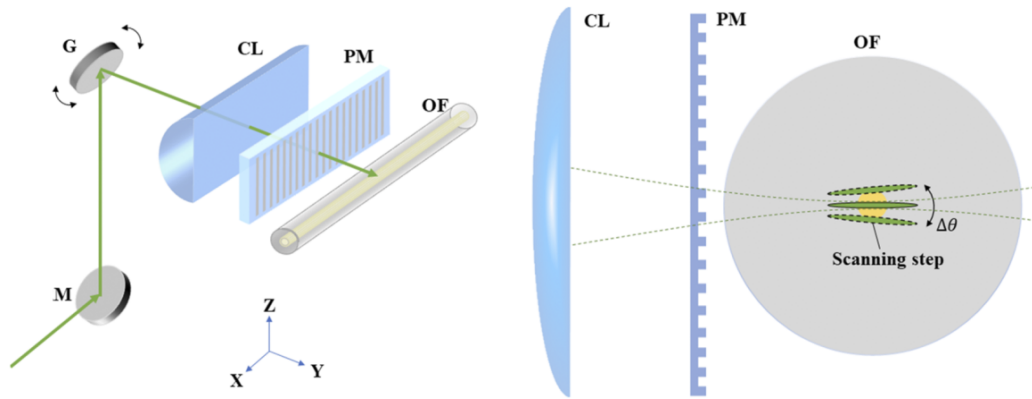


Figure 2.4: FBG inscription scheme in optical fibres using phase mask technique. M - mirror, G - galvanometer, PM - phase mask, OF - optical fibre. Image from [26].

this geometry only allowed the emission of a few watts. The main problem was the fact that both the pump and the signal propagate through the fiber core. This led to the following problem: achieving single transverse mode laser emission required a small fiber core, which in turn resulted in a low numerical aperture, thus requiring the use of single transverse mode pumping lasers. This limitation was solved with the development of the double-clad fiber (Maurer's original idea in 1974 [40] and implemented by Sntizer et al. [41]). The operation consists of pumping propagation through the inner cladding while the generated or amplified signal is confined on the core and has a single-mode propagation (Fig. 2.5a). The refractive index of the core is the highest, while the refractive index of the inner cladding is slightly lower but still close to that of the core. In addition, the diameter of the inner cladding is usually hundreds of micrometers, allowing a numerical aperture between 0.2 and 0.9 (depending on the outer cladding material, which is usually of low refractive index). Therefore, the double-clad optical fiber allows an increase in efficiency of light coupling from high-power multimode pumping diodes, making it possible to achieve kilowatt pumping power. More recently, a triple-clad index-guiding fibre structure appeared. The advantages are bend insensitivity and high suppression of higher order modes [42, 43, 44]. These features result in an output beam with M^2 below 1.3, an increased pump absorption, and higher insensitivity to ambient conditions. This

fibre geometry integrates the end-pumping group. There is another group named side-pumping, which includes the Gain-Topped Wave (GT-Wave) configuration [45, 46]. See Figure 2.5b. This configuration is an association of multiple fibres in parallel, where the doped optical fibre is in the central region. The fibres around the doped optical fibre are responsible for guiding the pumping that is coupled to the internal fibre. Also, the GT-Wave configuration allows for a smoother pumping, originating an output beam with a better value of M^2 . Furthermore, the light beam generated in the fiber is not interrupted during the combiner manufacturing process, which is beneficial for reducing insertion loss. This architecture exhibits excellent backward pump isolation, an important feature for backward-pumping or bi-directional pumping schemes.

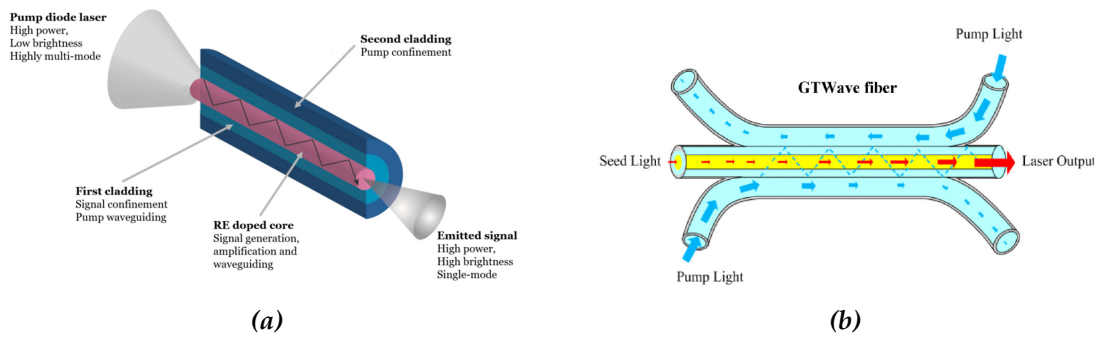


Figure 2.5: Schematic representation of: (a) double-clad fiber laser, and (b) GT-Wave fiber laser. Image (a) from [26] and image (b) from [46].

Presently, optical power output is typically in the order of kW, imposing the deployment of multiple pumping lasers, which are generally laser diodes. This configuration facilitates enhanced management of dissipated power and mitigates the risk of system failure due to the failure of a pumping laser [47]. The structures responsible for the management of pumping are known as combiners, and they facilitate the implementation of end-pumping and side-pumping of multiple pumps that are not in phase. These structures have the capacity to operate in either reflection or transmission mode.

Reflective structures generally enable end-pumping, whereby insertion is achieved through a curved surface. The surface in question facilitates the generation of a focused beam, with the focus situated at the entrance to the core

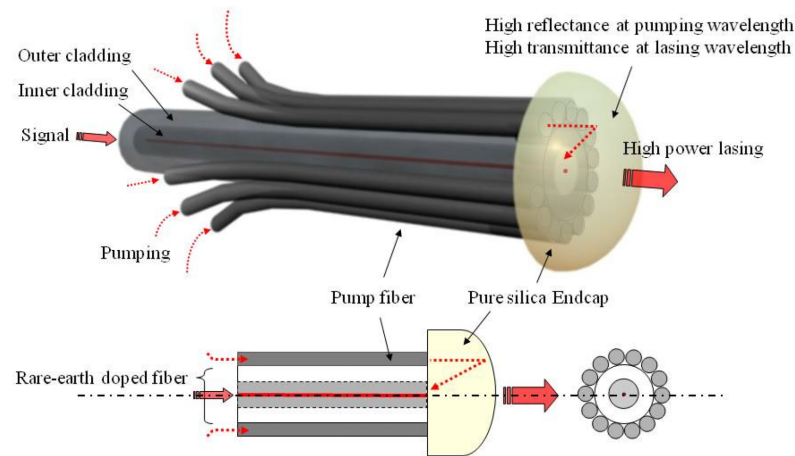


Figure 2.6: Scheme of a combiner in reflection operation. Image from [48].

of the doped optical fibre. Additionally, it is coated with a dichromatic layer that enables reflection at the wavelength of the pumps, and transmission of the output wavelength (Fig. 2.6). Nevertheless, the most prevalent and efficient architectures are those that function in transmission.

Architectures that operate in transmission allow the implementation of both side-pumping and end-pumping. In the process of implementing side-pumping, two structures are of particular significance [49, 50]. The conventional side-coupling structure consists of D-geometry fibres that are fused to the doped fibre, with the pump beams inserted diagonally (see Fig. 2.7a). The distributed side coupling structure consists of coiling the optical fibre of the pumps around the doped optical fibre. The coupling of the latter is achieved by fusion, allowing the three pumping configurations (Fig. 2.7b).

Regarding to the implementation of end-pumping, the most elementary configuration involves the use of a pumping fibre bundle and is comprised by three sections, as shown in Figure 2.8 [51]. The initial segment comprises a fibre bundle, the quantity of which is equivalent to the number of pumping lasers to be utilised. It is evident that the fibre bundles have a significantly larger diameter than the output fibre, and consequently, they undergo narrowing through the utilisation of the taper production technique. The bundle of optical fibres is connected to a multimode fibre, the core diameter of which exceeds

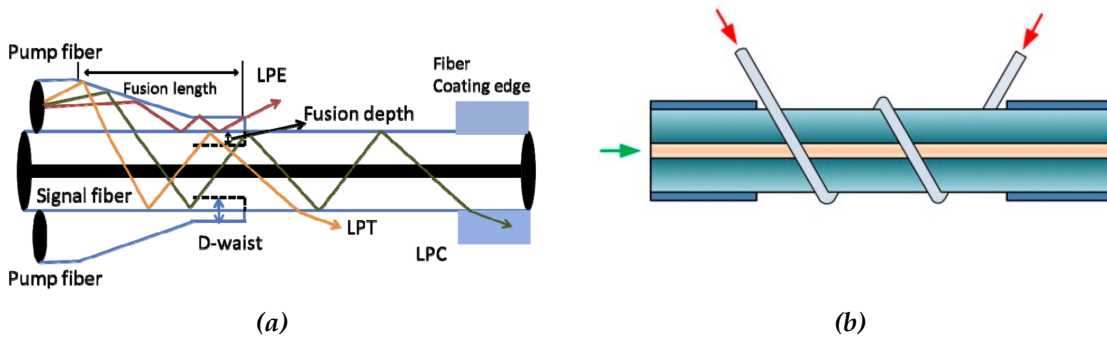


Figure 2.7: Two combiner schemes that operate in reflection and implement side-pumping: (a) conventional side-coupling, and (b) distributed side coupling. Image (a) from [49], and image (b) from [50].

that of the bundle. In the region proximate to the connection on the outgoing multimode fibre, with a length of approximately 1.5 cm, the surface is roughened to facilitate the design of cladding light stripping (CLS) by means of light scattering. The importance of this section is that it allows the light travelling through the cladding to be eliminated, thereby preventing thermal damage. The implementation of this architectural design is confined to regions within the laser system devoid of signal propagation, such as forward-pumping.

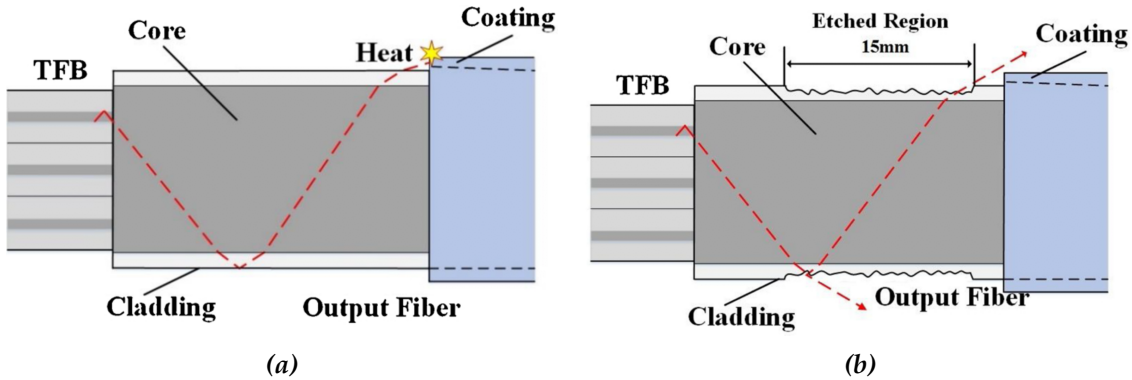


Figure 2.8: Combiner scheme that operates in transmission and implements end-pumping: (a) without CLS, and (b) with CLS. Image from [51].

In order to implement backward-pumping and bidirectional pumping, it is necessary to add an optical fibre to the centre of the fibre bundle, the function of which will be to guide the propagation of the output signal. In the field of architectural research, two structures have been identified that merit particular attention. The first of these is the end-pumping through a fused fibre bundle and

tapered bridging fiber, as illustrated in Figure 2.9a [50]. This structure involves the contraction of the bundle diameters through the use of a conical transition region. The second structure is the end-pumping through a conventional fused fibre bundle, as demonstrated in Figure 2.9b [50]. In this structure, the contraction of the bundles is achieved by narrowing all optical fibres. Due to the narrowing of the medium in which the light propagates, insertion losses are usually higher in this configuration compared to side-pumping architecture. Furthermore, if the light beam generated is single-mode, it requires higher complexity to maintain this state.

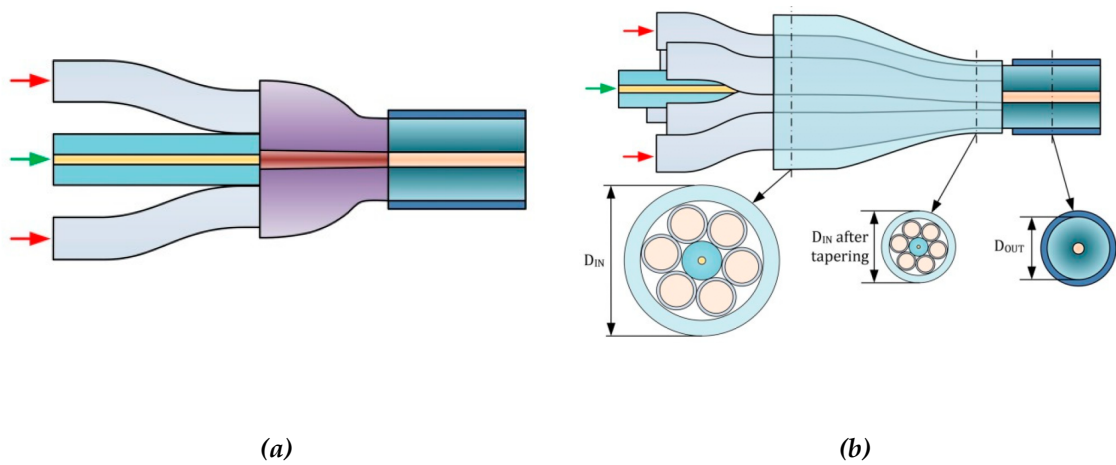


Figure 2.9: Combiner scheme that operates in transmission and implements end-pumping, enabling backward and bidirectional pumping: (a) fused fibre bundle with tapered bridging fiber, and (b) conventional fused fibre bundle. Images from [50].

2.6 Overview of high-power fiber lasers

After the increase of the emission power and with the development of pulsed lasers in optical fibre, a new problem appeared, namely, non-linear effects, highlighting Stimulated Brillouin Scattering (SBS) or Stimulated Raman Scattering (SRS). These effects cause changes in the propagation wavelength, distortion of the propagation signal, and increase in the temperature of the optical fibre. They result from the interaction of photons with the phonons of the medium in which the beam propagates. Since non-linear phenomena depend on

intensity (power per unit area) then the solution is to increase the dimensions of the optical fibre core, and the Large Mode Area (LMA) fibres appear [52]. However, the signal emitted by the laser becomes multimode. To avoid the excitation of modes higher than the fundamental, some techniques have been developed such as applying a curvature in the active fibre [53], gain filtering [54], selective signal launching [55], tapered fibres [56], Photonic Crystal Fibres (PCF) [57] and depressed-index optical fibre core [58] allowing to obtain the emission of a transverse singlemode signal.

This first optical fibre laser consisted of a Neodymium doped silica fibre cladding pumped by flashtube, resulting in an emission spectrum centred at 1.06 μm . Then, other rare earths were tested, which revealed different emission spectra. Ytterbium doped fibres exhibit a spectrum cantered at 1 μm [59] and they allow the development of the most powerful lasers with the highest efficiency due to the lowest quantum defect. Erbium doped fibres [60], with an emission spectrum at 1.55 μm , revolutionized optical communications due to lower transmission losses as well as a large gain bandwidth (~ 100 nm), allowing high data transmission rates over long distances and with low distortions [61]. In addition, Thulium doped fibres have emission spectra at 2 μm [62], Dysprosium at 3 μm [63], Holmium at 2.1 μm [64], and Praseodymium at 491 and 635 nm [65].

A laser with growing interest is the thulium-doped optical fibre laser. This exhibits an emission band between 1.7 μm and 2.1 μm and an absorption band centred at 790 nm [66] (Fig. 2.10). Typically, efficiencies of 40 % are obtained, but this can rise to 75 % when other dopants such as Al^{3+} are added [67]. Furthermore, the use of a pump at 1570 nm in fibre only doped with Thulium shows an efficiency of 50 % and an output beam with a narrow spectrum centred at 1950 nm [68]. Although a maximum emission power of 1 kW has been achieved and has a spectrum bandwidth of 200 nm [69], the lack of technological development in fibre components with operation at 2 μm makes them unattractive and more expensive than the ytterbium and erbium lasers.

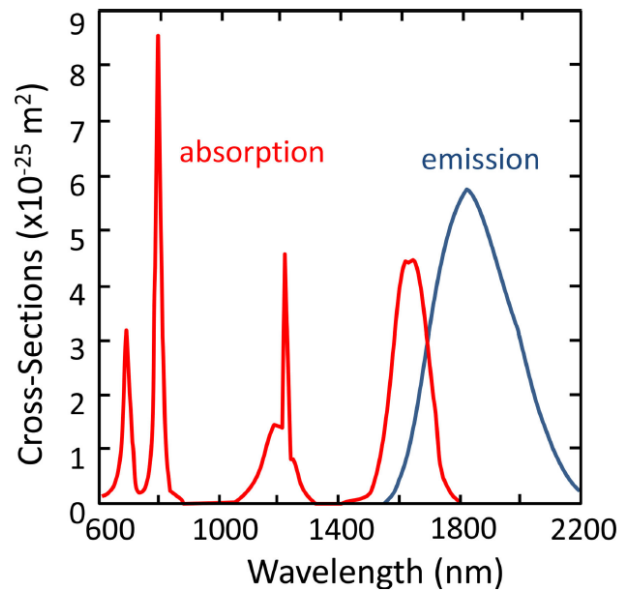


Figure 2.10: Typical absorption and emission spectra of Thulium ions. Image from [70].

Ytterbium-doped silica fibre lasers have an emission cross-section between 980 nm and 1100 nm and absorption cross-sections between 915 and 976 nm (Fig. 2.11), operating in a quasi-three-level scheme [71]. Thus, the quantum defect is low, which implies an efficiency of 90 % or higher [72]. Moreover, since the lifetime of the metastable energy level is close to 1 ms and the possibility of using large concentrations of the ytterbium ion (allowing high pump absorption) [73], ytterbium-doped fibre lasers are currently the most powerful lasers, belonging to the kW laser class [74]. Nowadays, the most powerful laser has been developed for commercial and industrial applications, emitting a signal with a power of 100 kW [75]. However, the efficiency is only 35 % and it is multimode, which implies that the output light beam is strongly divergent. For a maximum average power of 10 kW, IPG provides active fibre with transverse single-mode operation.

Erbium-doped optical fibre lasers have a typical emission spectrum between 1500 nm and 1600 nm, which, depending on the configuration, can be extended to a range of 1450 nm up to 1700 nm (Fig. 3.2). Emission in this wavelength band is important for optical communications, leading to a massive development of commercial devices for optical fibre at 1.5 μm . These lasers can be pumped

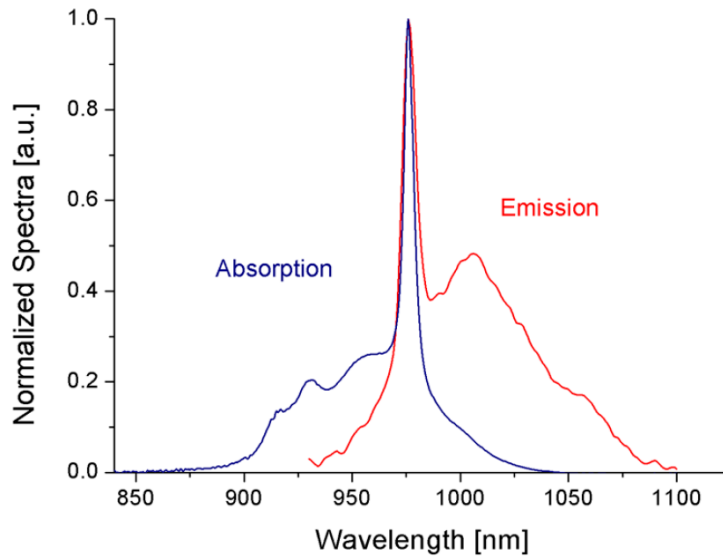


Figure 2.11: Typical absorption and emission spectra of Ytterbium ions. Image from [26].

at 1480 nm, but the best results occur with pumping centred at 980 nm [76], although the absorption cross-section is lower and requires a longer fibre length. The main issue is the impossibility of using high concentrations of the erbium ion due to the pair-induced quenching phenomenon (resulting in a nonradiative energy transfer between the erbium ions). This phenomenon leads to increased signal losses, decreasing the efficiency of the process [77]. Another problem is the quantum defect that allows an efficiency of 40 % for power higher than 70 W [78]. To overcome this problem, ytterbium ions are used simultaneously, forming the Er:Yb doped fibre lasers. This source allows to increase the lifetime of the metastable level due to the increased absorption of the pump at 976 nm and the energy transfer from the ytterbium ions to the erbium ions [79]. Up to pumping power of 200 W, the efficiency is around 40 % [80]. However, given the presence of ytterbium and with increasing pumping power, ASE located between 1030 nm and 1080 nm appears. Furthermore, for a pumping power higher than 200 W, the efficiency for the 1570 nm wavelength reduces up to 19 % (corresponding to 1 kW pumping power) and the efficiency for the 1070 nm wavelength is 42 % [81]. One way to reduce the impact of ASE is to propagate a seed at 1064 nm in the active medium [82, 83]. Another solution is the resonant pumping (or in-band

pumping), which in this case involves pumping at wavelengths between 1480 nm and 1530 nm, resulting in a maximum efficiency of 75 % for an emission at 1580 nm and a low working temperature [84]. Although the Er:Yb doped fibre lasers are most used for high power sources at 1.5 μm , a ytterbium-free erbium doped fibre laser with a maximum power of 656 W and an efficiency of 35 % appeared in 2018 [28]. However, since M^2 is close to 10.5. This implies that the emitted beam is 10.5 times more divergent than a Gaussian beam. Only the active medium is in optical fibre, requiring the insertion of a pump that propagates in air to improve the phase matching between the different propagation modes.

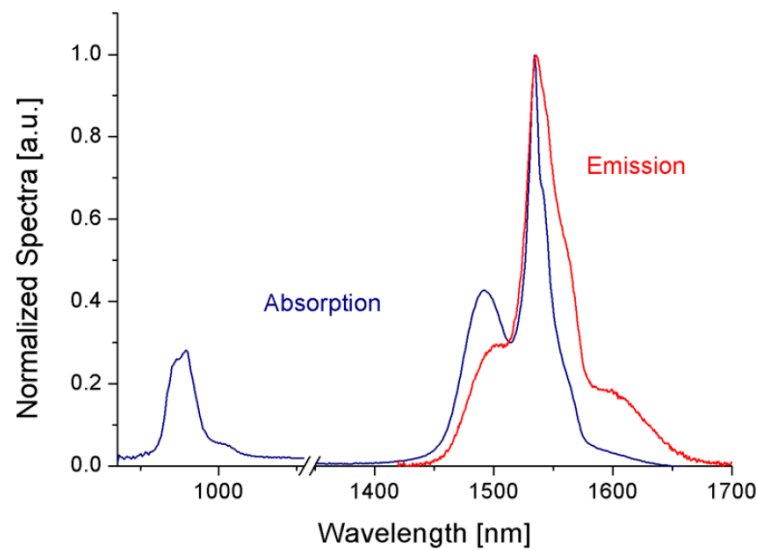


Figure 2.12: Typical absorption and emission spectra of Erbium ions. Image from [26].

2.7 Atmospheric light propagation

Despite the predominance of research focused on optical fibres for signal propagation - owing to their low attenuation, high bandwidth, and immunity to electromagnetic interference - an increasing number of studies have also addressed the propagation of light beams through the atmosphere. This alternative transmission medium is particularly relevant for free-space optical (FSO) communication systems, remote sensing, and directed energy applications, where the use of physical fibre links is either impractical or impossible [85, 86, 87].

The problems that occur in a heterogeneous medium can be divided in two types: phenomena that depend mainly on the wavelength [88] - attenuation and scattering - and phenomena that depend mainly on the beam size [89] - turbulence. The development of atmospheric propagation technology arises from the developments in optical communications to space. However, more recently, due to the evolution of laser technology, the energy supply of a given system based on a laser beam began to be explored [90]. Although these two themes involve the beam propagation in the atmosphere, the main considerations are different. In optical communications, the main objective is the propagation of information. To achieve this, adaptive optics (AO) is used to change the wavefront and compensate the aberrations induced by the atmosphere, reducing receiver errors and increasing the information transfer rate. For power delivery, the main objective is to minimise the beam power losses. Thus, it is necessary to consider the losses induced by adaptive optics. The theoretical study allowed the formulation of several atmospheric models where the Kolmogorov model [91] and the modified von Karman model [92] have special relevance. The Kolmogorov model is the simplest, and the atmosphere is considered a locally homogeneous medium. The modified von Karman model describes the atmosphere as a heterogeneous medium. This model is also named the non-Kolmogorov model and is one of the most widely used models today.

With the appearance of lasers in the 60's, many possible applications arose. One of them was the optical energy transfer, whose first studies were conducted by Fried in 1967 [93]. In 1972, the first application appeared where uplink data transmission with geodetic Earth orbiting satellite-II (GEOS-II) was established using a CW argon laser [85]. After theoretical studies of the light beam propagation in the atmosphere as well as the development of lasers, in 1995, the first bidirectional optical communication in ground/orbital lasercom demonstration (GOLD) [86] and a bidirectional Earth-Moon link [87] was established. Despite developments in optical energy transmission systems for the atmosphere and space [90], microwave systems [94] are the most widely

used. However, microwave energy propagation has several limitations. The fact that the beam is wide implies large divergence and a large area is exposed, requiring spectrum management and licensing. However, these problems can be solved with the use of beam lasers.

One advantage of using lasers with emission wavelengths in the infrared or below, is the possibility of implementing beams with smaller diameters than the microwave beam and with lower divergence, allowing propagation over a greater distance (considering equal emission powers). Thus, directionality is improved, and spectrum licensing is no longer required. In addition, optical systems have a lower power consumption and exhibit a higher power density, allowing the implementation of more compact systems than microwave systems. Although laser energy transfer began in the end of the 20th century [95], the low power emitted by lasers made microwave systems the most widely used system. However, with the great advances in lasers that occurred due to optical communications and space technologies [96], the first applications of lasers for power systems began to emerge.

In 2002, F. Steinsiek et al. successfully implemented a GaInP laser photovoltaic cell panel in a rover and illuminated it with an Nd:YAG laser that emitted a 5 W beam at 532 nm at a maximum distance of 300 m [97]. Following a series of trials, the team were ultimately able to generate a voltage of 6 V, thereby achieving an efficiency of 20 %. This successful outcome permitted the rover to operate as intended. Subsequently, in 2007, N. Kawashima et al. succeeded in achieving the flight of a helicopter kite for a duration exceeding 60 minutes [98]. In order to accomplish this objective, a total of 30 small GaAs solar cells were installed and illuminated by two 200 W laser diodes emitting at 808 nm, which were coupled to a multimode optical fibre. The final outcome of the experiment was a power output of 42 W when the helicopter kite was illuminated by a 300 W beam. In 2014, H. Tao et al. generated an electrical power of 9.4 W when illuminated by a 24 W laser at 793 nm and at a distance of 100 m, achieving an electrical-to-electrical efficiency of 11.6 % [99]. In 2019, the U.S. Naval Laboratory implemented a

prototype for the transmission of power between Earths, as part of the Power Transmitted Over Laser (PTROL) project. This prototype utilised a 2 kW infrared (IR) laser, capable of generating an electrical power of 400 W at a distance of 325 m [100]. In 2022, the U.S. Defense Advanced Research Projects Agency (DARPA) initiated research into the feasibility of refuelling Unmanned Aerial Vehicles (UAVs) by laser in mid-flight, a concept referred to as the "airborne energy wells" system [101]. In 2023, the U.S. Naval Research Laboratory (NRL) successfully implemented a space-to-space energy transfer system for the first time. This work was part of the Space Wireless Energy Laser Link (SWELL) project, and the distance between the transmitter and the receiver was 1.45 m. A final electrical power of 1.5 W was obtained [102]. The development of this technology is divided into two distinct implementation domains: the military and space sectors, where lasers with a power output of over 1 kW have been deployed and involve propagation distances that exceed 1 km; and the domestic sector, where communication companies and academic institutions are involved and whose systems consist of lasers with a power output of a few tens of watts and communication distances of approximately 200 m.

2.7.1 Atmospheric attenuation and dispersion

When a beam propagates in the atmosphere, it is subjected to losses and distortions resulting from phenomena such as attenuation and scattering [88]. Considering wavelengths in the IR domain, absorption results from ozone, carbon dioxide, and mainly water molecules (Fig. 2.13). Although the attenuation of water molecules has a strong absorption in the IR wavelength band, there are some bands, such as the 1.5 μm and 2 μm , in which the attenuation is low and allows the use of available laser technology. Visibility is also dependent on weather conditions [103]. For clear weather, the attenuation is about 0.01 dB/km. For poor visibility, the attenuation can be a few dB/km for haze or a few tens of dB/km for fog and rain. In addition, visibility is also affected by pollution, with rural and hilly areas showing higher visibility values.

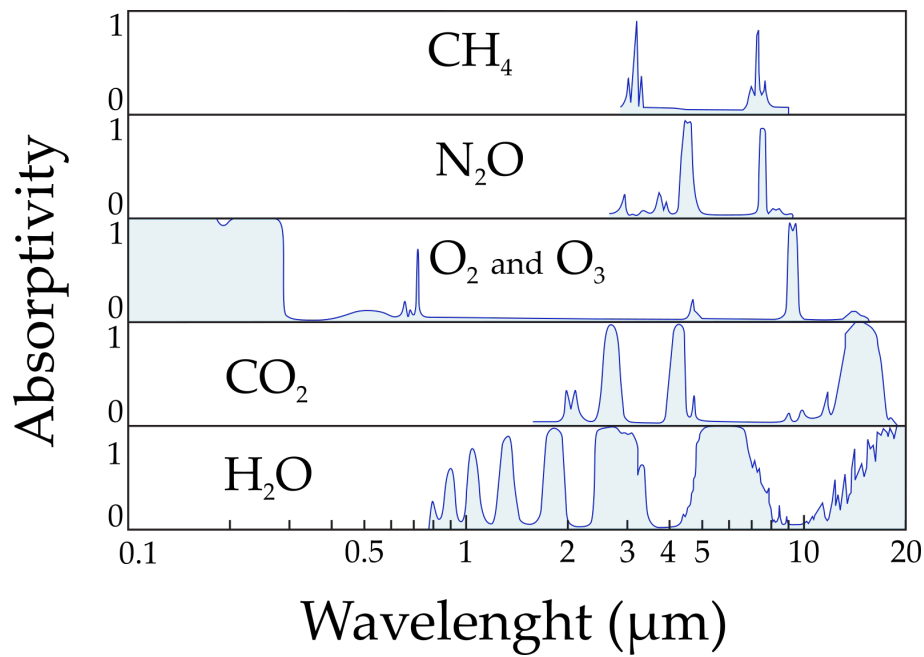


Figure 2.13: Atmospheric gas absorption spectra. Image from [104].

To analyse the atmospheric attenuation, the propagation of sunlight through the atmosphere can be examined. Assuming that the sun is a black body, then its spectral radiance can be determined through temperature. After analysis of sunlight on the earth surface, it was possible to obtain the atmospheric transmittance as a function of wavelength (Fig. 2.14) [105]. Wavelengths shorter than 1 μm are not ideal due to their low transmittance, and wavelengths longer than 3 μm , despite their low attenuation, the lack of technological development means that they are not the best choice at the moment. Thus, the wavelength band where the highest energy transmission is obtained is between 1.5 μm and 2.5 μm , corresponding to the rare earths: erbium and thulium.

Another problem is scattering [106, 107], which is divided into three types. Chromatic scattering occurs when the light beam interacts with particles larger than the wavelength of the beam, i.e., due to rain, snow, or hail. This effect can be described based on the optical geometric approximation. Rayleigh scattering occurs when the particles have a dimension smaller than the beam wavelength. This effect has the highest impact for beam wavelengths shorter than 1 μm and occurs mainly due to air molecules and haze. Mie scattering, also called

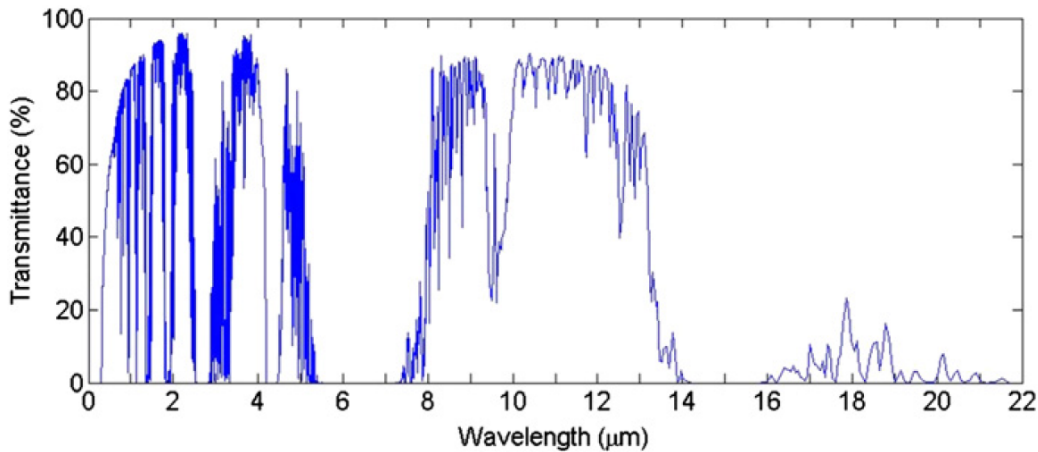


Figure 2.14: Atmospheric transmittance as a function of wavelength, obtained by Modtran5, path between sea level and space and based on a 1976 US Standard Atmosphere model. Image from [105].

non-molecular scattering, results from the interaction of the light beam with a particle of dimensions close to the light wavelength. This scattering is dominant and, for the IR spectrum, occurs due to aerosol particles and fog.

Besides the two phenomena mentioned above, atmospheric turbulence is also an important factor. Turbulence occurs due to the existence of pressure and temperature gradients, which are features of a heterogeneous medium [89, 108, 109], resulting in three effects. Beam scintillation is responsible for modifying the energy spatial distribution and occurs when the turbulence eddies' size is close to the beam size [110]. When the size of the eddies is smaller than the beam size, it causes diffraction and scattering, resulting in beam spreading [111]. Finally, beam wandering occurs when the eddies' size is larger than the beam size, introducing a random deflection [112]. Atmospheric turbulence is most intense near the ground. Thus, uplinks have higher losses and distortions than downlinks, and horizontal links show more turbulence impact than vertical links.

Attenuation is also caused by the alignment between the emitter and the receiver [113, 114, 115]. Given the high directivity of laser beams, precise alignment is required. In addition, if the systems change their positions, it is necessary to implement a system to follow the movement [116]. These systems

also mitigate the impact of beam deflection caused by atmospheric turbulence.

Beam scattering and scintillation are one of the biggest problems for optical communications in space [117]. To mitigate them, high altitude locations are chosen where the air density is lower and avoid passing the beam through areas of high atmospheric turbulence. In addition, lasers are coupled with optical systems, also called adaptive optics. This system is composed of lenses, mirrors, phase filters, and amplitude filters and allows changing the geometry of the wavefront in order to compensate for the aberrations that the beam will be exposed during propagation. In 2014, the properties of optical coherence lattices (OCL) were studied for the first time [118]. These are composed of periodic shape intensity distributions and are based on the complex Gaussian representation of statistical pulses [119]. Fig. 2.15 shows some frames of a propagation simulation of a given OCL. Initially, the periodicity is maintained, however, after some distance, the periodicity ceases to exist, and OCL turns into a Gaussian. Their use in optical communications allows for the beam scintillation reduction [120, 121, 122]. This system allows obtaining a divergence lower than mrad [123]. Another important factor is that the beam diameter increases with propagation, so the receivers are usually larger than the emitters [124].

2.7.2 Atmospheric models for turbulence and simulation

With the development of optical communications, atmospheric propagation models have been developed that take turbulence into account.

An important element for the implementation of these models is the refractive index structure parameter (C_n^2), which allows quantifying the atmospheric turbulence [125]. This parameter can be described as follows [126]:

$$C_n^2 = a^2 L^{4/3} M^2 \quad (2.3)$$

$$M = -79 \times 10^{-6} \frac{P}{T^2} \left(\frac{dT}{dz} + \gamma \right) \quad (2.4)$$

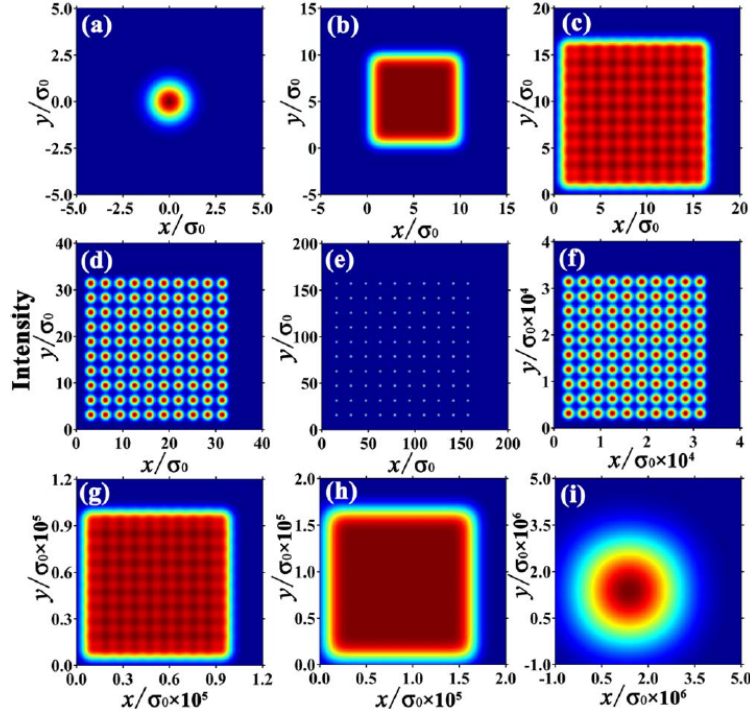


Figure 2.15: Propagation of an OCL with the lattice constant $a = 0.001$, the number of lattice lobes $N = 10$ in turbulent atmosphere with $C_n^2 = 10^{-15} \text{ m}^{-2/3}$ for the following distances: (a) 0, (b) $Z/z_r = 0.0005$, (c) $Z/z_r = 0.001$, (d) $Z/z_r = 0.005$, (e) $Z/z_r = 0.05$, (f) $Z/z_r = 1$, (g) $Z/z_r = 3$, (h) $Z/z_r = 5$, and (i) $Z/z_r = 80$. Image from [121].

where a^2 typically has a value of 2.8, L is the turbulence outer scale and is obtained based on the approach of the Thorpe scale, M is the refractive index gradient, and γ is the dry adiabatic lapse rate (9.8 K/km). Considering the ideal gas equation [127], the relationship between pressure and air density can be expressed as follows:

$$P = \rho R_{\text{specific}} T \quad (2.5)$$

where ρ is the air density, and R_{specific} is the specific gas constant. Thus, the equation 2.6 can be rewritten as follow:

$$M = -79 \times 10^{-6} \frac{\rho R_{\text{specific}}}{T} \left(\frac{dT}{dz} + \gamma \right) \quad (2.6)$$

Normally, C_n^2 values higher than $10^{-14} \text{ m}^{-2/3}$ is considered strong turbulence, for values lower than $10^{-17} \text{ m}^{-2/3}$ weak turbulence and the intermediate values

medium turbulence. From equations 2.3 and 2.6, C_n^2 is dependent on pressure and temperature, factors in the atmosphere that vary with altitude. Based on Figure 2.16a, the temperature takes on values above 180 K. Also, air density is maximum at the Earth's surface - Figure 2.16b - has an exponential decrease as altitude increases. Furthermore, for altitudes above 15 km (Tropopause), the air density is less than 0.2 kg/m^3 . Thus, the highest impact of turbulence occurs in the Troposphere, and for the upper layers, turbulence is practically null.

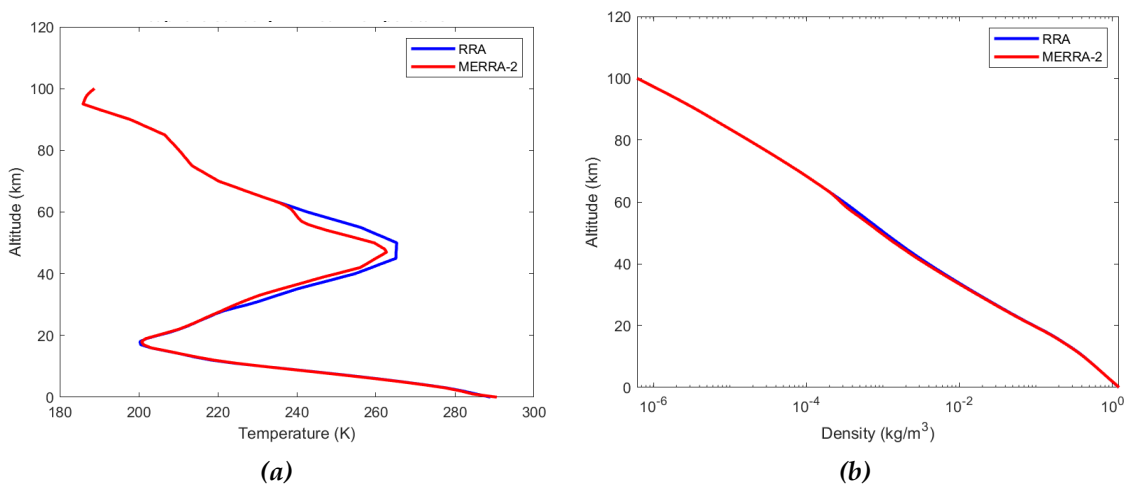


Figure 2.16: Physical parameters variation as a function of geometric altitude: (a) Temperature, and (b) Pressure and Density. Image from Earth Global Reference Atmospheric Model (Earth-GRAM) 2024, NASA.

Figure 2.17 is an example of measuring C_n^2 . On land, the C_n^2 is typically of the order $10^{-14} \text{ m}^{-2/3}$ (strong turbulence). As altitude increases, C_n^2 decreases, and for altitudes above 15 km, it has values typically below $10^{-17} \text{ m}^{-2/3}$ (weak turbulence). Another important factor is the air convection currents that cause an increase in turbulence.

Given the dynamism and random nature of atmospheric phenomena, considerations of fluid dynamics and statistics are necessary to establish a model for atmospheric turbulence [129]. In 1941, Kolmogorov presented a model for isotropic turbulence where he defines two parameters: l_0 , inner scale (smallest eddies size), and L_0 , outer scale (largest eddies size) [91]. In this model, the spectral power of the refractive index fluctuations is given by:

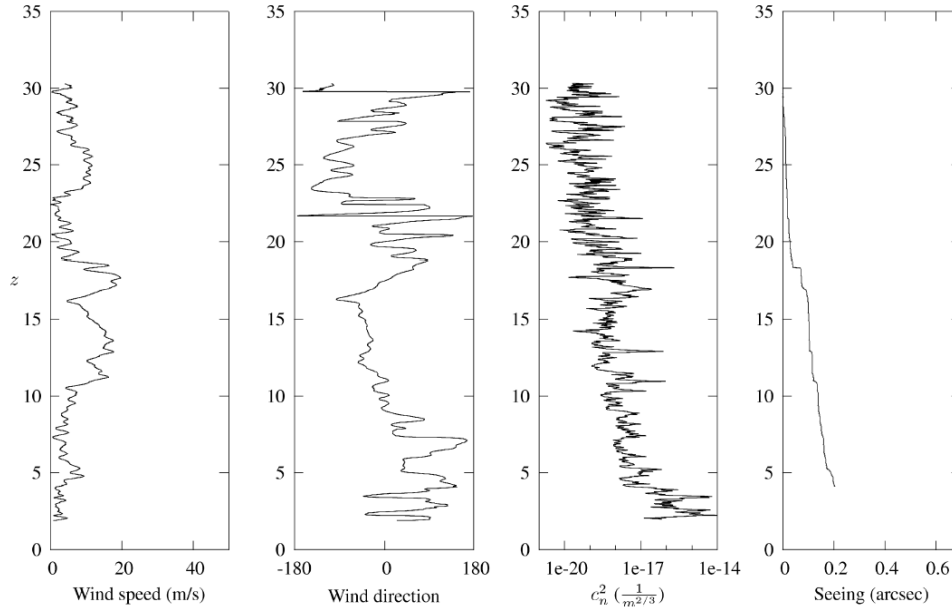


Figure 2.17: Example of measuring wind, C_n^2 and Seeing at Mauna Kea on the island of Hawaii in 2002. Image from [128].

$$\Phi_n = 0.033C_n^2K^{-11/3}, \quad 1/L_0 \ll K \ll 1/l_0 \quad (2.7)$$

where $K = 2\pi/L$, where L is the turbulence size. However, Kolmogorov's model is unable to describe turbulence for wavenumbers smaller than $1/L_0$ and higher than $1/l_0$, i.e. a heterogeneous atmosphere. After 20 years, Tatarski presented a modification of Kolmogorov's model resulting in the following spectrum [130]:

$$\Phi_n = 0.033C_n^2K^{-11/3}e^{-K^2/K_m^2}, \quad K \gg 1/L_0 \quad (2.8)$$

where K_m is $5.92/l_0$. Nevertheless, this model did not solve the problem for wave numbers smaller than $1/l_0$. Moreover, the spectra of the Kolmogorov model and the Tatarski model are undefined for $K = 0$. In the 70's appears the modified von Karman model that solves the two problems of Tatarski's model, and the power spectrum is given by [92]:

$$\Phi_n = 0.033C_n^2K^{-11/3}e^{-K^2/K_m^2}(K^2 + K_0^2)^{11/6}, \quad 0 \leq K \leq \infty \quad (2.9)$$

where K_m is $5.92/l_0$ and $K_0 = 1/L_0$. The modified von Karman model is still

used today to study signal propagation through the atmosphere, where it is also named the non-Kolmogorov model [131].

One of the simulation methods is the Split-Step Beam Propagation Method [132] and consists of dividing the distance into very small segments and applying the linear and non-linear steps separately. The linear part, the free propagation, can be implemented based on Fresnel-Kirchhoff diffraction. The implementation of turbulence involves the use of random phase screen, and the simulation step is given by [133]:

$$U_{out}(x, y) = U_{in}(x, y) e^{j\varphi(x, y)} \quad (2.10)$$

where $U_{in}(x, y)$ and $U_{out}(x, y)$ are field amplitude before and after random phase screen ($\varphi(x, y)$), respectively. This random phase screen can be generated as follows [133]:

$$\varphi(x, y) = TF^{-1} \left[(a + ib) \sqrt{\Phi_p \Delta k_x \Delta k_y} \right] \quad (2.11)$$

where TF^{-1} is the inverse Fourier transform, a and b are random numbers that allow implementing the noise randomness, and Φ_p is equal to the spectral power of the refractive index fluctuations (Φ_n) of the previously mentioned models with the replacement of C_n^2 by Fried's parameter (r_0) which is given by [134]:

$$r_0 = \begin{cases} (0.423k^2 \int_{Paht} C_n^2(z') dz')^{-3/5} & (\text{plane wave}) \\ (8/3)^{3/5} (0.423k^2 \int_{Paht} C_n^2(z') dz')^{-3/5} & (\text{spherical wave}) \end{cases} \quad (2.12)$$

where $k = \frac{2\pi}{\lambda}$.

2.8 Conclusions

In this Chapter, the operational methodology of a laser was delineated, including the assembly configurations, the types of pump sources, and the

roles of FBGs and optical combiners. These elements form the theoretical foundations for the practical implementation of this work. Furthermore, the state of the art of current high-power lasers was described, and it was determined that both Ytterbium-doped, Erbium-doped, and Thulium-doped fibre-optic lasers would be suitable candidates for the configuration to be described in the following Chapter. The propagation characteristics of a light beam through the atmosphere have also been studied. In this context, wavelengths operating in the IR domain are particularly well-suited due to their minimal atmospheric attenuation. These wavelengths currently support the most powerful laser sources, despite exhibiting increased dispersion compared to visible light. Considering contemporary laser technologies, the erbium laser is regarded as a leading contender. Although erbium lasers are among the most powerful available, they experience higher atmospheric attenuation. Furthermore, although atmospheric attenuation for wavelengths around 2 μm is minimal, there remains a lack of large-scale manufacturing and distribution of technology capable of operating at this wavelength. Consequently, the erbium laser is considered the optimal choice, despite its relatively lower power and the atmospheric attenuation it faces. Nevertheless, the advanced technological developments in optical communications have facilitated various commercial and industrial applications.

Chapter 3

Optical wireless energy transfer

The emerging need for systems applications in extreme conditions, such as in space, has led to the exploration of new approaches in the field of optics [135]. In addition to sensing, the need for energy supply in remote locations where energy is difficult to achieve has led to challenges in the implementation of monitoring and exploration systems [136]. One solution is the utilisation of lasers, which facilitate the delivery of high power over extended distances, obviating the need for connecting cables. In order to optimise the system, it is necessary to take into account the characteristics of the beam, such as the wavelength and beam profile to be used.

Propagation through the atmosphere is known to result in significant attenuation of wavelengths within the visible range when compared to those within the infrared range [137]. The wavelength that combines low attenuation with low implementation costs is 1.5 μm , given the great development of erbium-doped optical fibre lasers in the field of optical communications. Furthermore, turbulence phenomena have been shown to affect the effectiveness of laser energy supply [138]. The three phenomena of beam widening, scintillation, and random beam deflection must be considered. The latter is the predominant factor and can be mitigated by implementing a large beam diameter.

This Chapter delineates the practical implementation of a long-distance energy transfer system that is based on a high-power laser and supported by

the Wiptherm European project. The is to develop a laser system capable of illuminating the face of a CubeSat 100x100x100 mm (1U) and a CubeSat 300x100x100 mm (3U) at a distance of 1 km. The Chapter begins with the propagation of a light beam in the atmosphere, studying the implementation of telescopes based on the zoom beam expander scheme for the purpose of regulating the diameter of the illuminated area, and studying the impact of atmospheric turbulence on the beam propagation. Furthermore, it provides detailed information on the fabrication, the considerations regarding the safety and cooling of the laser system, and characterisation of a laser based on an erbium fibre emitting at 1.55 μm , with a maximum output power of 30 ± 0.1 W, M_x^2 of 1.08 and M_y^2 of 1.06. Moreover, this Chapter provides the description and a characterisation of a telescope, two lens arrays, and two possible geometries of thermoelectric converters. Two two-dimensional configurations require a beam to be focused, and two three-dimensional ones allow the number of conversion units to be increased, as well as increasing the dynamic range of the beam diameters. The Chapter ends with the presentation of experimental tests that validate the efficacy of the concept of long-distance energy delivery by the developed high-power laser.

3.1 Atmospheric propagation analysis

The following section presents the propagation analysis of the beam through the atmosphere, evaluates the diameter of the laser beam, and describes its control using a telescope. Furthermore, it evaluates the impact of turbulence on the transverse profile of the laser beam.

3.1.1 Natural divergence of a Gaussian beam

An electromagnetic wave can be described as follows [24]:

$$E(x,y,z,t) = \tilde{E}(x,y,z,t) e^{j\omega t} \quad (3.1)$$

where the complex field amplitude is given by:

$$(\nabla^2 + k^2) \tilde{E}(x, y, z, t) = 0 \quad (3.2)$$

The most common class of electric field solutions are known as Gaussian beams. Assuming the fundamental Gaussian mode and that the beam is initially collimated, the radius of curvature is set to ∞ , the radius of the beam (dimension defined by the intensity decay of $1/e^2$) at a given distance from the initial position is given by:

$$w^2(z) = w_0^2 + \left(\frac{z\lambda}{\pi w_0} \right)^2 \quad (3.3)$$

where z is the distance travelled by the beam, w_0 is the initial radius and λ is the wavelength. Figure 3.1 depicts the numerical analysis of the propagation of a collimated beam over 1 km, considering initial beams with distinct w_0 .

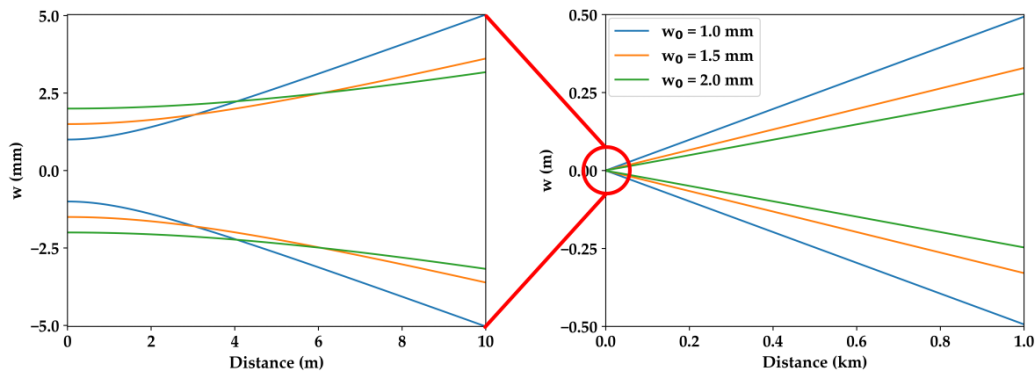


Figure 3.1: Propagation of a collimated beam over 1 km, considering three different initial beams with distinct radius w_0 .

The objective is to achieve a beam propagation distance of 1 km. In consideration of the diameter of the laser's output beam, which is approximately a few millimetres, as illustrated in Figure 3.1, the final illuminated area will have a diameter of more than 0.3 m, which is higher than the desired dimensions. The implementation of a telescope is necessary, and its design will be analysed in the following section. Based on Figure 3.2, it is possible to evaluate the final radius (w) as a function of the initial radius (w_0).

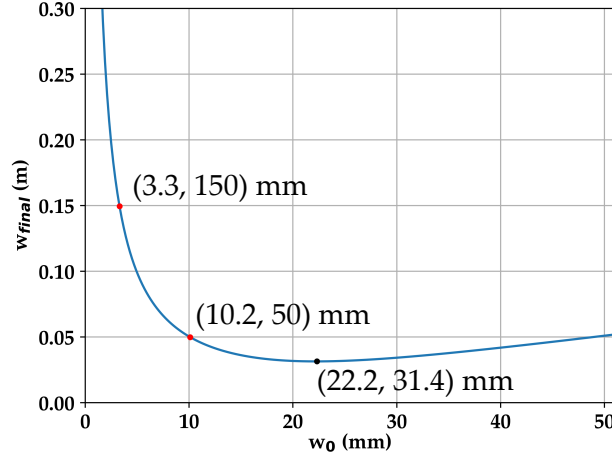


Figure 3.2: Final beam radius as a function of the initial beam radius and representation of the minimum and two points of interest.

At 1 km, the minimum radius is 31.4 mm, obtained with an initial radius of 22.2 mm. For the CubSat, the final dimensions of interest are 50 mm and 150 mm, which implies initial radius (w_0) of 10.1 mm and 3.3 mm, respectively.

An important parameter is the Rayleigh length z_R , which is given by:

$$z_R = \pi w_0^2 / \lambda. \quad (3.4)$$

This parameter enables the evaluation of the divergence of the beam, and when the light beam travels a distance equal to z_R , it implies that the diameter of the beam is:

$$w(z_R) = \sqrt{2} w_0. \quad (3.5)$$

When $z \rightarrow \infty$, the beam diameter increases almost linearly with distance, allowing to obtain a divergence angle that is given by:

$$\theta_d = \frac{\lambda}{\pi w_0}. \quad (3.6)$$

Another aspect to take into account is the focused beams. In this case, the characteristics of interest are the size of the focus and the distance at which it occurs. Thus, the effective focal length is given by:

$$z_m = f / \left[1 + (f/z_{R1})^2 \right], \quad (3.7)$$

where $z_{R1} = \pi w_1^2 / \lambda$ and w_1 is the radius of the beam in the lens. The minimum beam radius (w_{02}) is the following:

$$w_{02} = \frac{\lambda f}{\pi w_{01}} \left[1 + \left(\frac{f}{z_{R1}} \right)^2 \right]^{1/2}, \quad (3.8)$$

where, for $z_{R1} \gg f$, it implies that:

$$w_{02} \approx \frac{\lambda f}{\pi w_{01}}. \quad (3.9)$$

Another issue is that the light beam is not the fundamental Gaussian mode. In this case, the parameter M^2 (quality factor) arises, which for the fundamental Gaussian mode $M^2 = 1$, and for the other Gaussian modes (TEM_{nm}), the quality factor is given by:

$$M_x^2 = (2m + 1); M_y^2 = (2n + 1). \quad (3.10)$$

where m and n are the order of the modes along the x -axis and y -axis, respectively. Thus, the diameter of the beam is given by:

$$w^2(z) = w_0^2 + M^4 \left(\frac{z\lambda}{\pi w_0} \right)^2. \quad (3.11)$$

The numerical simulation of the preceding equation is represented by Figure 3.3. Figure 3.3a is the simulation of the final radius considering an initial radius of 10.2 mm for the four most probable values of M^2 . Fig. 3.3.b is the determination of the initial radius value required to achieve the desired final radius value for a given value of M^2 , leading to the conclusion that a final radius of 50 mm can only be achieved for M^2 equal to or less than 2.5.

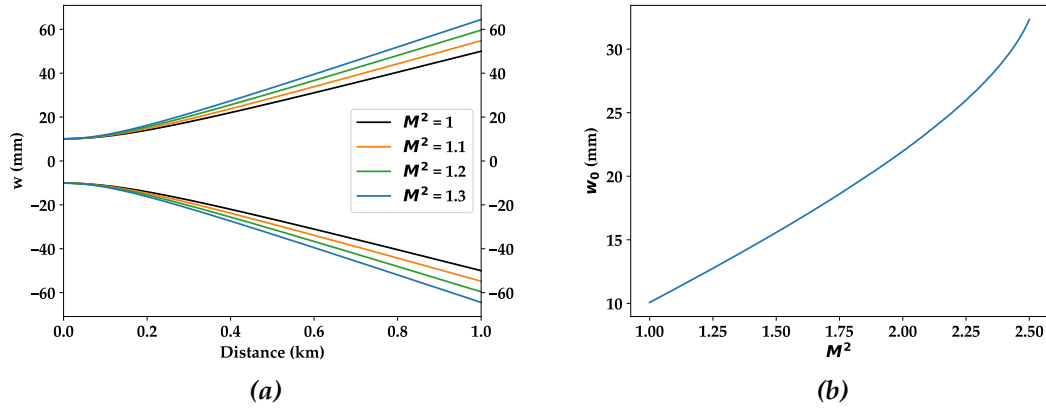


Figure 3.3: Impact of the M^2 factor on the propagation of a beam over 1 km: (a) representation of the propagation for four values of M^2 , and (b) initial radius (w_0) as a function of M^2 for a final radius (w) of 50 mm.

3.1.2 Telescope design

The basic principle of a telescope is the operation of a lens. This can be described as follows [139, 140]:

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}, \quad (3.12)$$

where s_o is the distance from the object to the lens, s_i is the distance from the image to the lens and f is the focal length of the lens. Although this equation facilitates the derivation of the general equation for a given lens system, the simulation of the lens system is obtained using a matrix described as follows [24]:

$$\begin{bmatrix} r_1 \\ r'_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} r_0 \\ r'_0 \end{bmatrix}, \quad (3.13)$$

where r_0 and r_1 are the radial distance and r'_1 and r'_0 are the angle of the ray in relation to the normal of the lens (index 0 refers to the initial characteristics and index 1 refers to the final characteristics). In the context of a multiple lens system, the description of the object using an equation is derived by considering the image of the previous lens as the object of the current lens. The matrix description

is obtained by multiplying the ABCD matrices of each lens. The most important matrices, in this case, are:

$$\text{Free Propagation} \quad \begin{bmatrix} 1 & \frac{L}{n} \\ 0 & 1 \end{bmatrix},$$

$$\text{Thin Lenses} \quad \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix},$$

$$\text{Spherical Mirrors} \quad \begin{bmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{bmatrix}.$$

In the context of this work, it is imperative to minimise beam attenuation during the light beam of processing and propagation. This approach entails the utilisation of the minimum number of lenses necessary to achieve the desired outcome. A salient feature of the system is the utilisation of a laser, that is, a quasi-monochromatic beam, a property that ensures the absence of chromatic aberrations. The most elementary telescope is constituted by the utilisation of two lenses, with the modulus of the focal length of the second lens being greater than the modulus of the focal length of the first lens (Fig. 3.4). The telescope considered in this work is afocal in order to avoid high-intensity focussing and consequently causing some damage to a given system. In order to achieve this objective, it is necessary that the first lens in the system be divergent, whilst the second must be convergent. Whilst this system is straightforward to implement, it permits a predetermined expansion only, a limitation that hinders the capacity to regulate the beam diameter in CubSat. It is also conceivable to regulate the beam diameter by modifying the distance between the two lenses. This indicates that the output beam is either convergent or divergent. However, given the 1 km distance to be covered by the demonstration, it is anticipated that controlling the focal length of the system will be a considerable challenge, particularly given the use of lenses with focal lengths in the range of tens or hundreds of millimetres, in addition to the necessity for lenses with a larger diameter. It is of the utmost importance that a variable magnification telescope is implemented in order to ensure control of the final diameter.

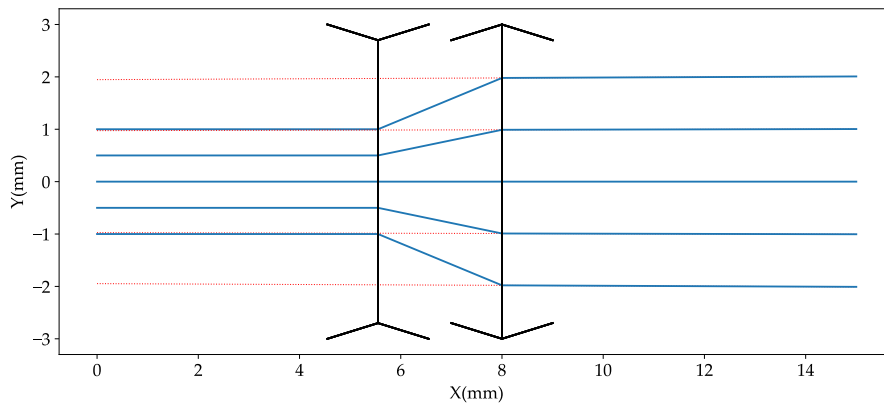


Figure 3.4: Two-lens telescope.

The simplest variable magnification telescope, also known as a zoom beam expander, can be assembled using three lenses (Fig. 3.5). The first and third lenses are converging (positive), and the second is diverging (negative).

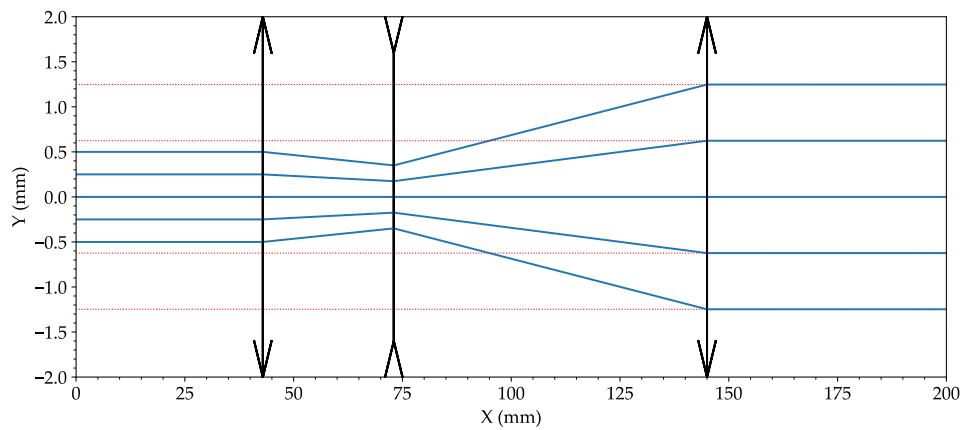


Figure 3.5: Schematic of the zoom beam expander system.

The variation in magnification is achieved, based on the movement of the first two lenses. In the event of the diverging lens varying linearly, the first lens will initially move in the opposite direction to that of the second lens, subsequently moving in the same direction. The focal lengths of the positive lenses are equal to or higher than twice the modulus of the negative lens. The focal length of the first two lenses can thus be calculated as follows:

$$\frac{1}{F} + \frac{1}{f_1} = \frac{1}{f_2}, \quad (3.14)$$

where f_1 is the focal length of the converging lens and f_2 is the focal length of the diverging lens. In this situation, F is negative. Note that the objective of this system is to generate a collimated output beam and, consequently, another predominant characteristic of the system under consideration is the distance between the two positive lenses, which is given by the following equation:

$$d = F + f_1. \quad (3.15)$$

Thus, the general equation for the system's operation is:

$$\frac{1}{f_2} = \frac{1}{F - z} - \frac{1}{f_1 - h}, \quad (3.16)$$

where z is the variation in the position of the diverging lens and h is the variation in the position of the first lens. Thus, the position of the first lens is given by:

$$h = z - f_1 + \frac{(F - z)f_2}{f_2 - F + z}. \quad (3.17)$$

The matrix results from the numerical simulation are shown in Figure 3.6, where $f_1 = f_3 = 100\text{mm}$ and $f_2 = -20\text{mm}$.

It can be seen that this system not only makes it possible to expand, but also to reduce the diameter of the beam. The magnification range is between 0.25x and 4x. Considering that the diameter of the light beam at the entrance is in the order of 1 mm and that the diameter at the exit of the telescope must be in the order of 10.1 mm, it is necessary to make changes to this system. There are two possibilities: changing the focal length of the last converging lens and/or implementing a fixed telescope at the beginning of the system.

The Figure 3.7 illustrates the matrix simulation for the situation where a longer focal length lens is implemented in the third position. In this case, identical values as the preceding simulation are used, with the exception of the final lens, for which it has a focus length of 300 mm. It is evident that increasing the

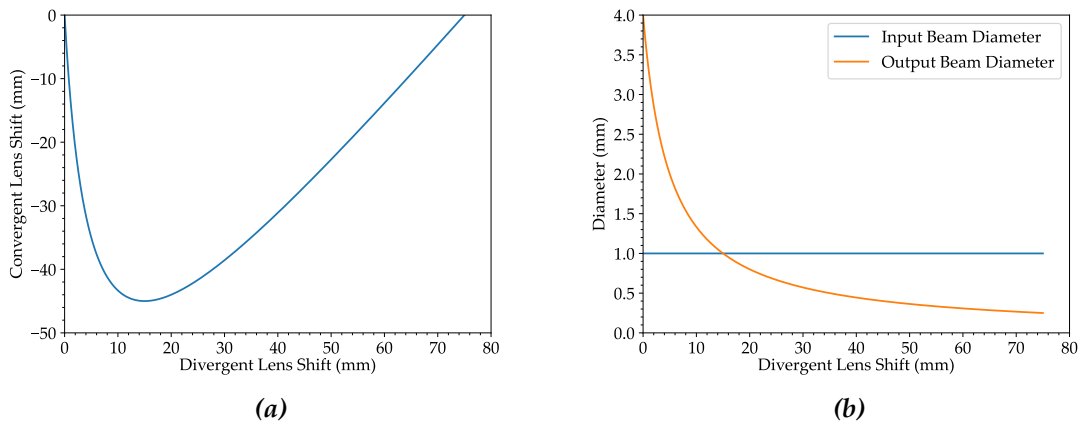


Figure 3.6: Zoom beam expander system: (a) displacement of the first lens as a function of the displacement of the diverging lens, and (b) final beam diameter as a function of the displacement of the diverging lens.

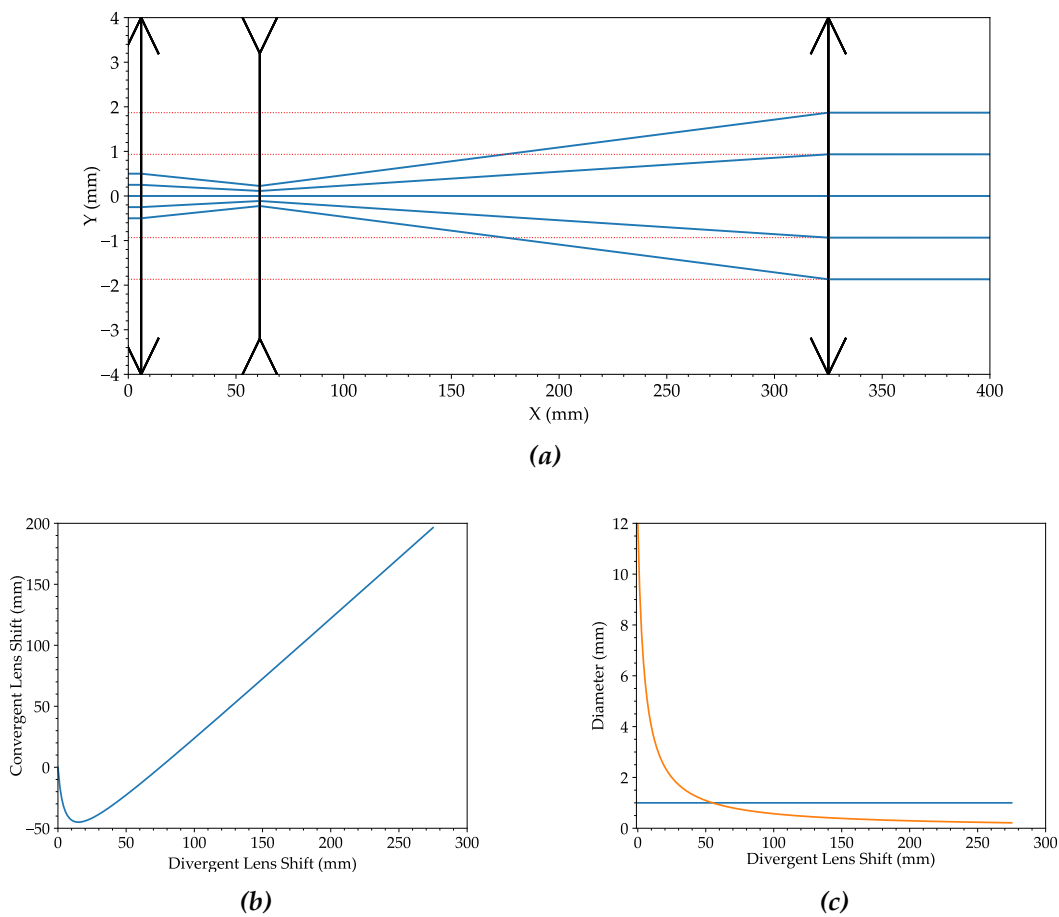


Figure 3.7: Zoom beam expander telescope with an increase in the focal length of the last lens: (a) telescope system scheme, (b) displacement of the first lens as a function of the displacement of the diverging lens, and (c) final beam diameter as a function of the displacement of the diverging lens.

focal length of the final lens results in an expansion of the magnification range, while there are still positions where the beam diameter contracts. This system has a magnification range between 0.21x and 12x, as well as increasing the set of positions in which the movement of the first lens is almost linear with the movement of the diverging lens.

Figure 3.8 illustrates the matrix simulation for the situation in which a fixed telescope is implemented before the zoom beam expander telescope. In this case, as the output lens of the first telescope can occupy the position of the input lens of the second telescope, the two lenses can be replaced by just one lens without changing the final diameter. In this system, the focal length of the first lens is set at -15 mm, the second at 50 mm, the third at -20 mm, and the last lens at 100 mm. This system has a magnification range between 1.6x and 26.6x, considering only beam expansion.

Finally, Figure 3.9 illustrates a simulation of a telescope that combines the two previous situations. The focal length of the first lens is -25 mm, the second lens 100 mm, the third lens -50 mm, and the last lens 250 mm. This system has a magnification range between 5x and 40x, and this system has a maximum length of 476 mm.

In order to illuminate a 3U CubeSat, it is necessary to implement a zoom beam expander telescope with a cylindrical lens in front of the previous system. This will contract one of the axes of the circular geometry, forming an ellipse.

Furthermore, the impact of turbulence on beam propagation in the atmosphere over a distance of 1 km was simulated, and two scenarios were analysed (see Appendix A): low turbulence ($C_n = 10^{-17}$) and medium turbulence ($C = 5 \times 10^{-16}$). In the context of low turbulence, the transmission level was found to be 95%, accompanied by minimal signal distortion. In the medium turbulence case, a transmission of 66%, and a wavefront distortion that renders the system unfeasible were achieved. Furthermore, the impact of beam deviation was investigated for the low attenuation case, yielding an average deviation of 2.5 ± 0.1 cm.

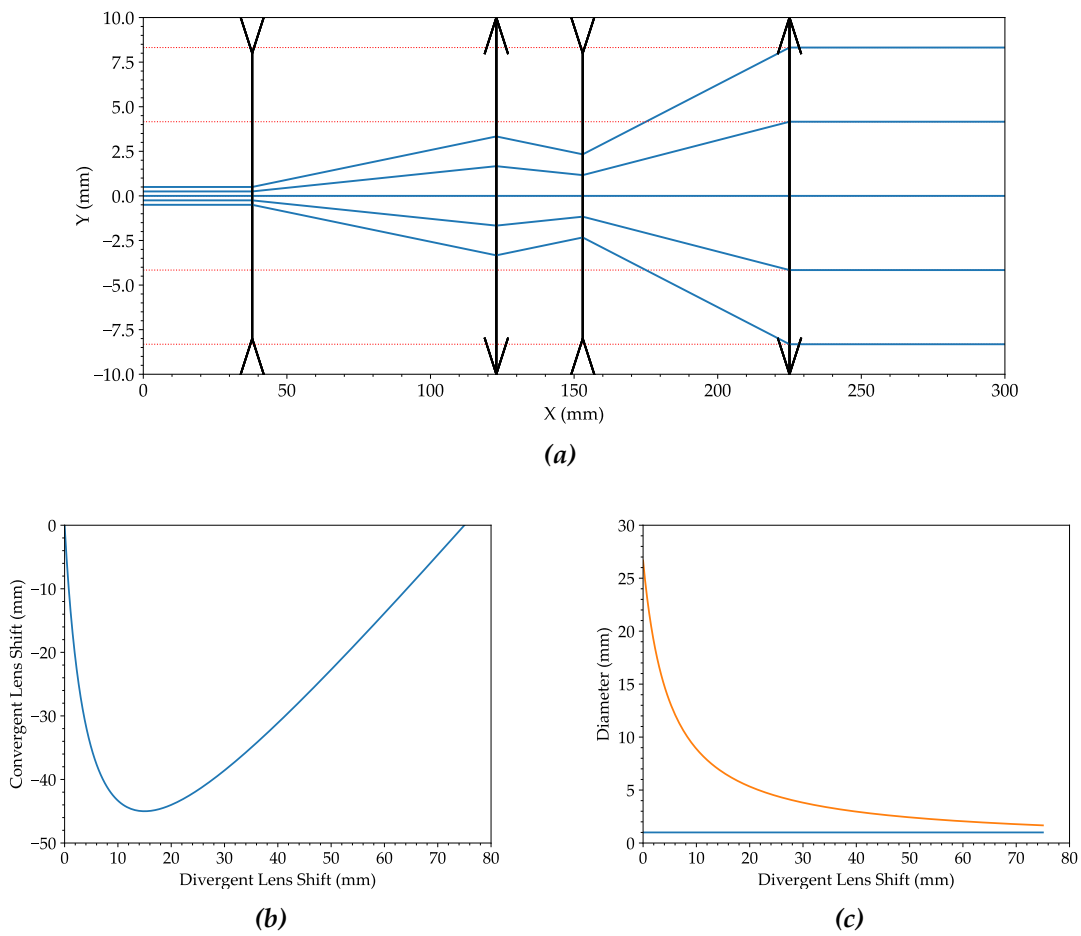


Figure 3.8: Combination of a fixed telescope with a zoom beam expander telescope: (a) telescope system scheme, (b) displacement of the first lens as a function of the displacement of the diverging lens, and (c) final beam diameter as a function of the displacement of the diverging lens.

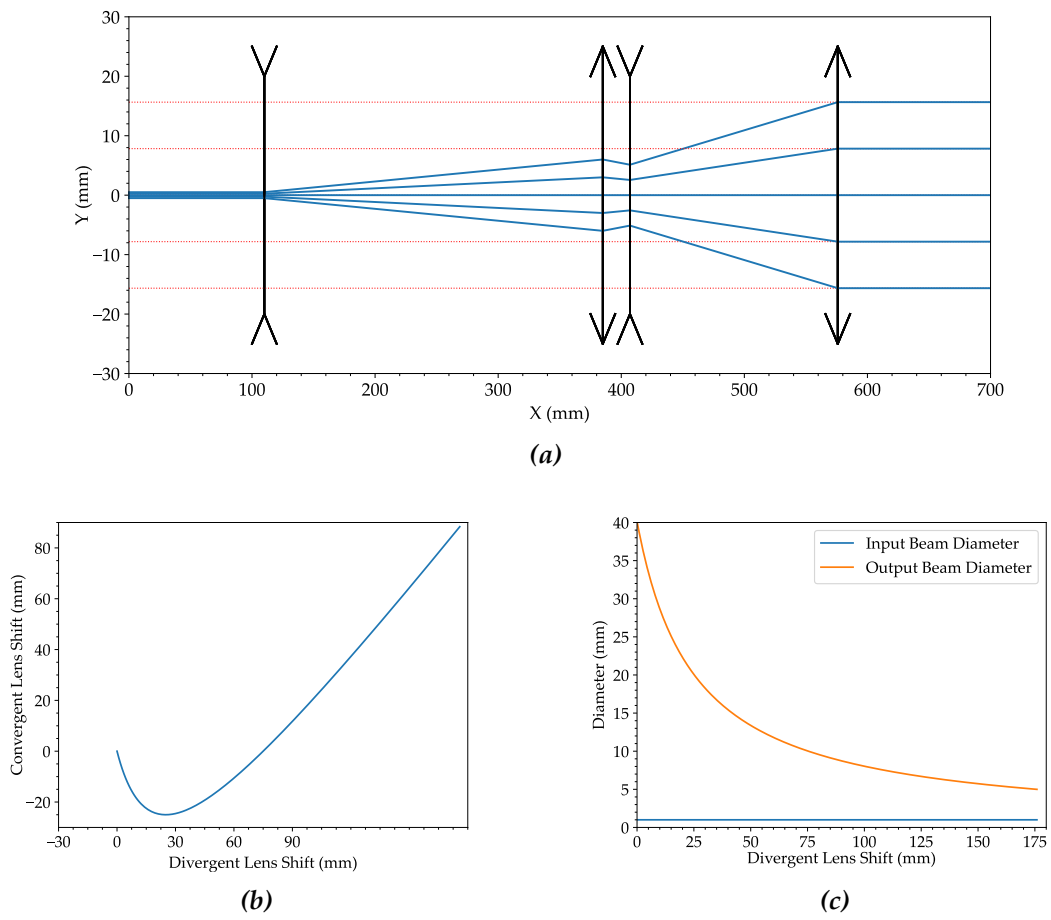


Figure 3.9: Zoom beam expander telescope combined with the increased focal length of the last lens and a fixed telescope: (a) telescope system scheme, (b) displacement of the first lens as a function of the displacement of the diverging lens, and (c) final beam diameter as a function of the displacement of the diverging lens.

3.2 Laser fabrication and characterisation

In accordance with the considerations in Chapters 2, an erbium-doped optical fibre was chosen because the emission length should be at $1.55\text{ }\mu\text{m}$, a wavelength that combines low attenuation in atmospheric propagation with low implementation costs. The implementation of this optical fibre necessitates the pumping of a light beam with wavelengths in proximity to 980 nm . The doped fibre utilised is distinguished by a triple photonic crystal cladding (HPCF), comprising an erbium-doped core with a diameter of $25\text{ }\mu\text{m}$ and a first cladding with a diameter of $110\text{ }\mu\text{m}$ (Fig. 3.10). The cladding contains areas doped with fluorine, which promote absorption of the pump beam. The second cladding has a diameter of $160\text{ }\mu\text{m}$, and the third cladding has a diameter of $180\text{ }\mu\text{m}$. The latter is a hollow structure that increases the confinement of the pumping light beam, thereby increasing the numerical aperture of the optical fibre and, consequently, the implementation of strongly multimode and higher power pumping. The total diameter of the fibre is $360\text{ }\mu\text{m}$.

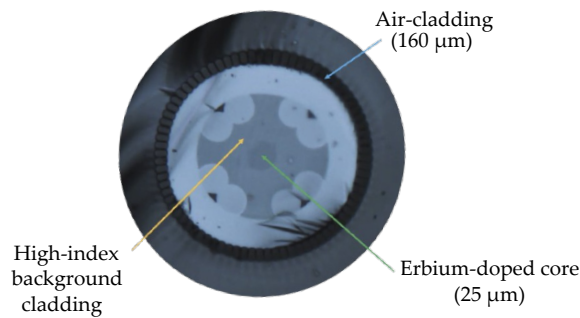
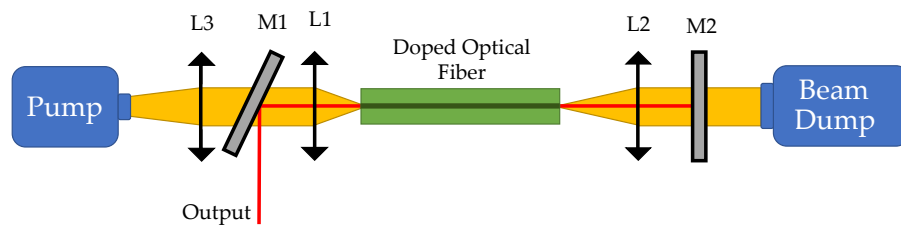
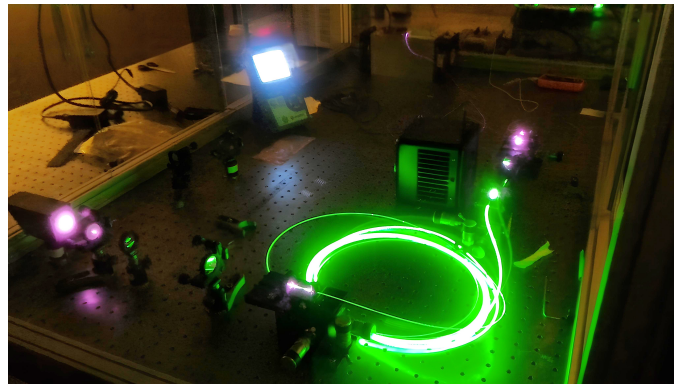


Figure 3.10: Profile of the doped optical fibre.

The implementation of the doped fibre follows the assembly of the diagram in Figure 3.11a. This system consists of three lenses (L1, L2, and L3) responsible for inserting the pumping beam and collimating the output beam, a dichroic mirror responsible for separating the pumping beam and the output signal (M1), and a high-reflectivity mirror that ends the laser cavity (M2). The doped optical fibre utilised in this experiment has a length of 6 m . The operation of the laser is characterised by a double pass. The light beam from the pumps is inserted



(a)



(b)

Figure 3.11: Laser system: (a) assembly diagram and (b) picture of the system.

into the optical fibre through the L3 lens and is absorbed as it propagates along the fibre. As no beam at $1.55\ \mu\text{m}$ is launched, the process starts with laser action, where spontaneous emission of photons at $1.55\ \mu\text{m}$ wavelength occurs at the beginning of the first pass, followed by signal amplification (stimulated emission). At the end of the first pass, both the $1.55\ \mu\text{m}$ beam and the residual 980nm beam are first collimated by lens L2, reflected by mirror M2, and re-injected into the doped fibre by lens L2 to start the second pass. In the second pass, the signal is amplified again, and finally, both beams are collimated via L1 and through the dichroic mirror, the output signal at $1.55\ \mu\text{m}$ is separated from the pumping beam. During laser operation, due to the low efficiency of erbium-doped fibres, the development of high power leads to the absorption of two photons simultaneously, resulting in the emission of a photon with a wavelength of $540\ \text{nm}$. See Figure 3.11b. While this phenomenon is not a desired outcome and cannot be addressed by current technological capabilities, it can be utilised as an indirect metric to evaluate the total power emitted. A notable

advantage of this configuration is that it enables the acquisition of high-power output signals with reduced fibre lengths.

The following equipment was utilised in the assembly of the laser: a laser diode emitting at 976 nm and a maximum power of 140 W (BWT Wavelength-Stabilised); laser drive GEN30-25 (Genesys); three 3-axis positioning carriages (Thorlabs MBT616D/M); two Thorlabs aspheric lenses (A240TM-C) with a focal length of 8 mm for the insertion and collimation of light from the doped optical fibre (L1 and L2); one lens (Thorlabs A240TM-B) with a focal length of 8 mm for the collimation of the pumping beam (L3), a dichroic mirror (Thorlabs DMSP1180), M1, and one aluminium mirror (Thorlabs PF10-03-G01), M2. The achievement of all cleavages of the doped optical fibre was achieved by the utilisation of a Ruby Fiber Scribe (Thorlabs S90R). A study was conducted on the basis of the previously mentioned components, with the objective of investigating the characteristics of the safety equipment and the characteristics of the cooling system (see Appendix B). Regarding safety equipment, the maximum permissible exposure (MPE) for both the skin and the eyes was taken into consideration. It was deduced that the optical density (OD) for the eyes should be 7 and for the skin it should be 4, for both wavelengths. As for the cooling system, the option of air cooling was selected, with the requirement of a minimum air flow of $15.2 \text{ m}^3/\text{min}$ and a maximum ambient temperature of 18°C .

In the initial laser characterisation (see Figure 3.12a), an efficiency of $25 \pm 0.5\%$ was achieved. Following the enhancement of the manual cleaving protocols (see Fig. 3.12b) and the laser calibration protocol, an efficiency of $29.7 \pm 0.5\%$ was obtained, which is equivalent to the maximum efficiency of 30% announced by the manufacturer. Furthermore, a maximum power emission of $30 \pm 0.1 \text{ W}$ was recorded. Subsequently, the propagation mode profile was measured (Fig. 3.12c), achieving M_x^2 of 1.08 and M_y^2 of 1.06, confirming the single-mode nature of the beam.

Once the laboratory prototype had been assembled and calibrated, the final laser configuration was designed for the experiments abroad. An important

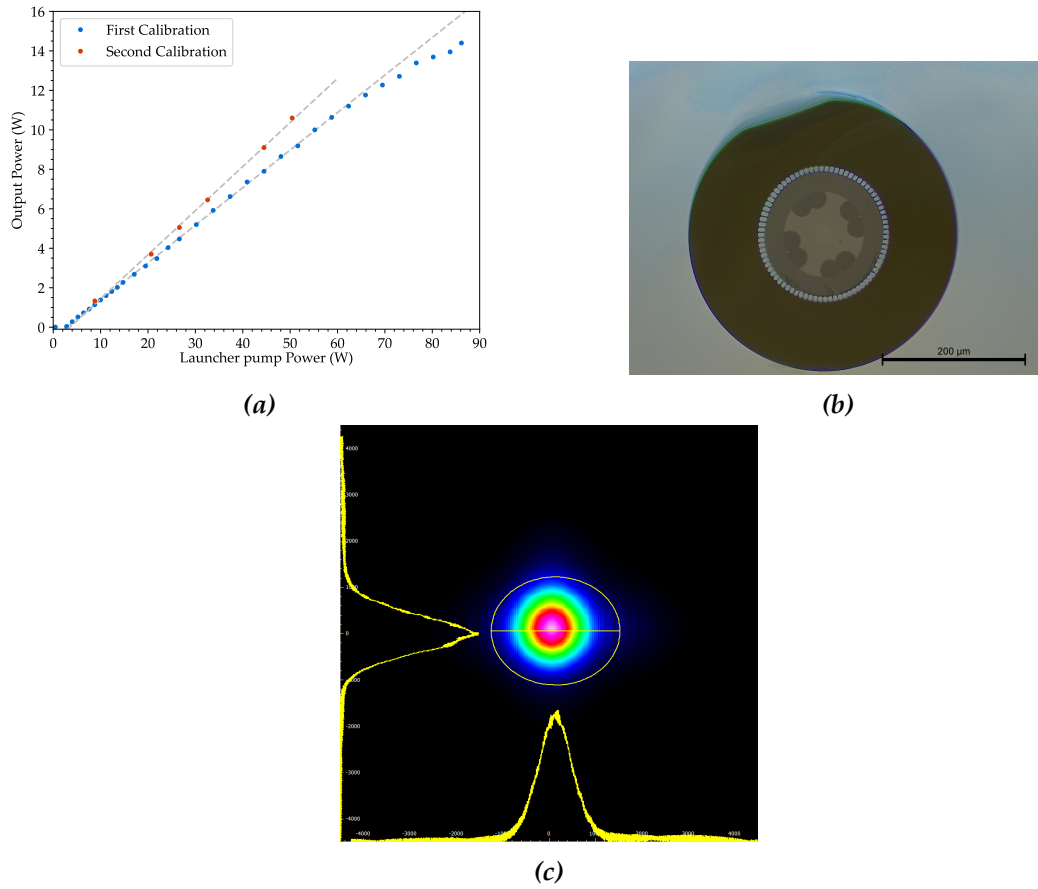


Figure 3.12: Laser system: (a) power characterisation, (b) cross-section of the doped optical fibre after manual cleaving, and (c) cross-sectional profile of the output beam.

consideration in the design of the system was the necessity for robustness; consequently, the new laser layout incorporates all fibre optic components, utilising FBGs and a combiner. The FBGs utilised in this configuration were manufactured by TeraXion, produced in Double Cladding Fiber UN-25/125-10, and are mounted on heat sinks, with the primary function of forming the laser cavity. The combiner utilised is (2+1)x1 Lightel, comprising two fibres with dimensions of 105/125 to be connected to the pumps, a Double Cladding Fiber UN-25/125-10 to be connected to the doped optical fibre, and a GDF-1550 single-mode fibre for emitting the signal at 1.55 µm. The latter performs the functions of inserting the pump beam into the doped fibre and separating the output beams. Given that the diameters of the outer cladding of the optical fibres of the different laser components are not uniform, all the splices between

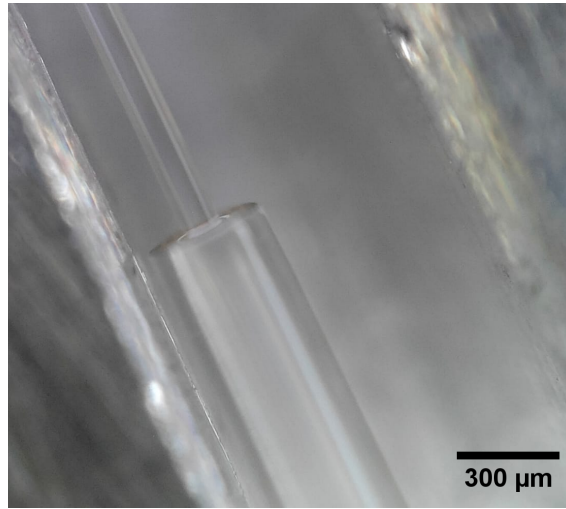


Figure 3.13: Picture of the splice region between the doped optical fibre and the FBG fibre.

the components were obtained using a splice machine, Fujikura FSM100P+ (Fig. 3.13). Furthermore, in order to mitigate potential fusions resulting from high point heats in the splice region, the different optical fibres were secured to aluminium plates using Kapton.

The following values were obtained from the characterisation of the FBGs: for the high reflectivity FBG (Fig. 3.14a) the peak occurs at 1564.50 ± 0.01 nm and has a 3 dB bandwidth of 0.04 ± 0.01 nm; for the output FBG (Fig. 3.14b) the peak occurs at 1564.55 ± 0.01 nm and has 3 dB bandwidth of 0.21 ± 0.01 nm, as specified by the manufacturer. The combiner was characterised and revealed a multimode output beam, with M_x^2 of 14.70 and M_y^2 of 13.39 (Fig. 3.14c), thus failing to comply with the request. In order to achieve the lowest possible beam divergence, it was necessary to use a single-mode beam, and the start date for the outdoor experiments was approaching. It was, therefore, necessary to reformulate the laser system assembly diagram. This resulted in the scheme shown in Fig. 3.14d, a hybrid version of the two schemes used previously. This new scheme employs two lenses to insert the pumping beam into the doped optical fibre, the high reflectivity FBG, and the dichroic mirror to separate the output signal from the pumping beam. The maximum output power achieved was 28.1 ± 0.1 W, corresponding to an efficiency of 25.9 ± 0.5 %. The observed decrease in efficiency is attributable to the conversion of the propagation modes of the doped fibre

with the FBG fibre. The configuration under discussion has been demonstrated to enhance the system's robustness and reduce the complexity of calibration for applications in outdoor environments.

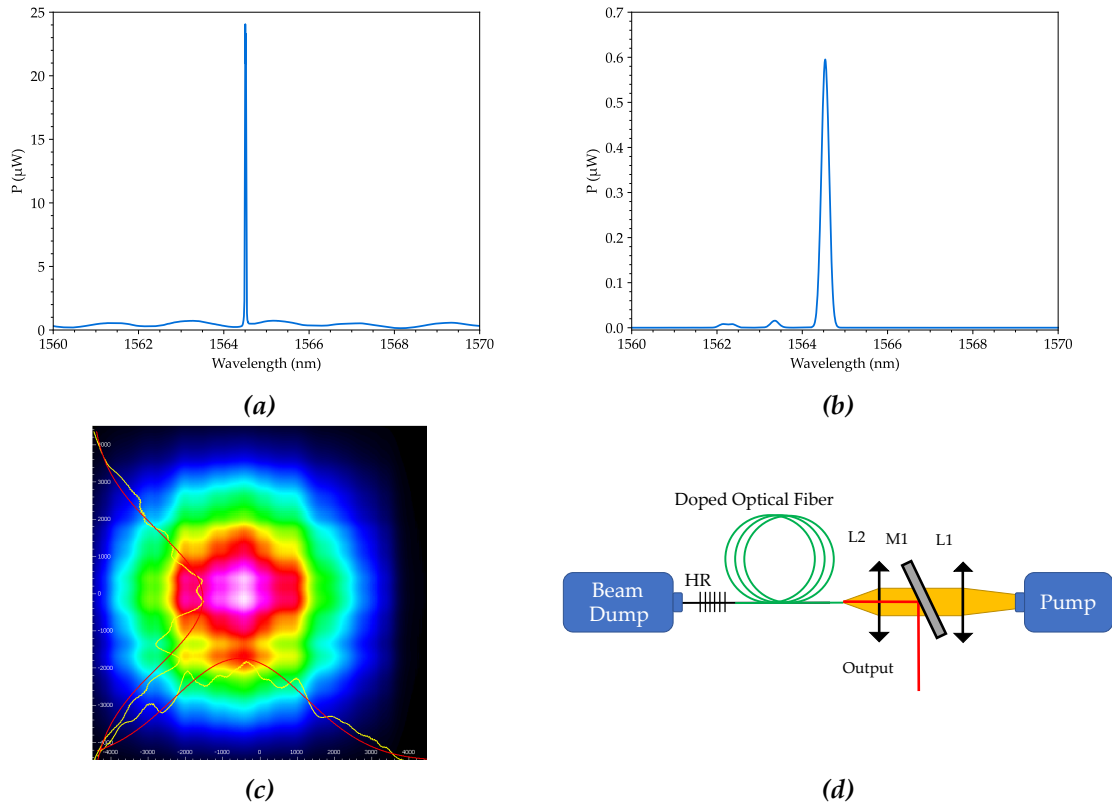


Figure 3.14: Characterisation of the optical components: (a) spectrum of the high reflectivity FBG, (b) spectrum of the output FBG, (c) cross-sectional profile of the combiner output beam, and (d) assembly diagram of the final laser system.

3.3 Manufacture and characterisation of the telescope and lens array

In order to manage the diameter of the output beam and optimise the beam diameter when illuminating the optical-electrical energy converters, a telescope was constructed. This comprised the lenses described in Table 3.1 and the schematic representation of which is shown in Figure 3.15.a. This system follows the scheme of a zoom beam expander which, by changing the position of lens 1,

which is convergent, and lens 2, which is divergent, makes it possible to vary the diameter of the output beam without losing the collimated state. The telescope's maximum operating size with this lens arrangement is 700mm, allowing the output beam diameter to be varied by a multiplicative factor between 0.2 and 10 in relation to the input beam diameter (Fig. 3.15.b). Ensuring the correct operation of the system necessitates the repositioning of lens 1, as the diverging lens approaches the third lens. This repositioning is guided by the movement delineated in Figure 3.15.c in order to maintain the collimated state of the output beam.

Table 3.1: Lens features

Lens	Focus length (mm)	Diameter (mm)	AR Coating
1	300	25.4	1550 nm
2	-50	25.4	1550 nm
3	600	25.4	1550 nm

The utilisation of spherical and cylindrical lens arrays combined with converter arrays was also investigated with a view to enhancing the energy output of the conversion system by increasing the number of converters. The configuration of the spherical lens array comprises 27 lenses, which are divided into three groups, with each group consisting of nine lenses. The centres of these groups are spaced 115 mm apart horizontally. Within each group, the spacing between each lens is 5 mm (Fig. 3.16). The cylindrical lens array, on the other hand, consists of 15 cylindrical lenses with a horizontal separation of 17.5 mm and a vertical separation of 9 mm (Fig. 3.16). However, the implementation of this lens array resulted in a loss of 7 dB. This is attributable to the necessity for a frame surrounding each lens to ensure correct fixation for applications subject to vibration. However, this option is only viable if the power of the laser beam is higher than the power the converters can handle to avoid their damage. Furthermore, it is important to implement this option with a limited number of lenses, preferably made from a single piece of glass, thereby minimising the blockage caused by the matrix structure.

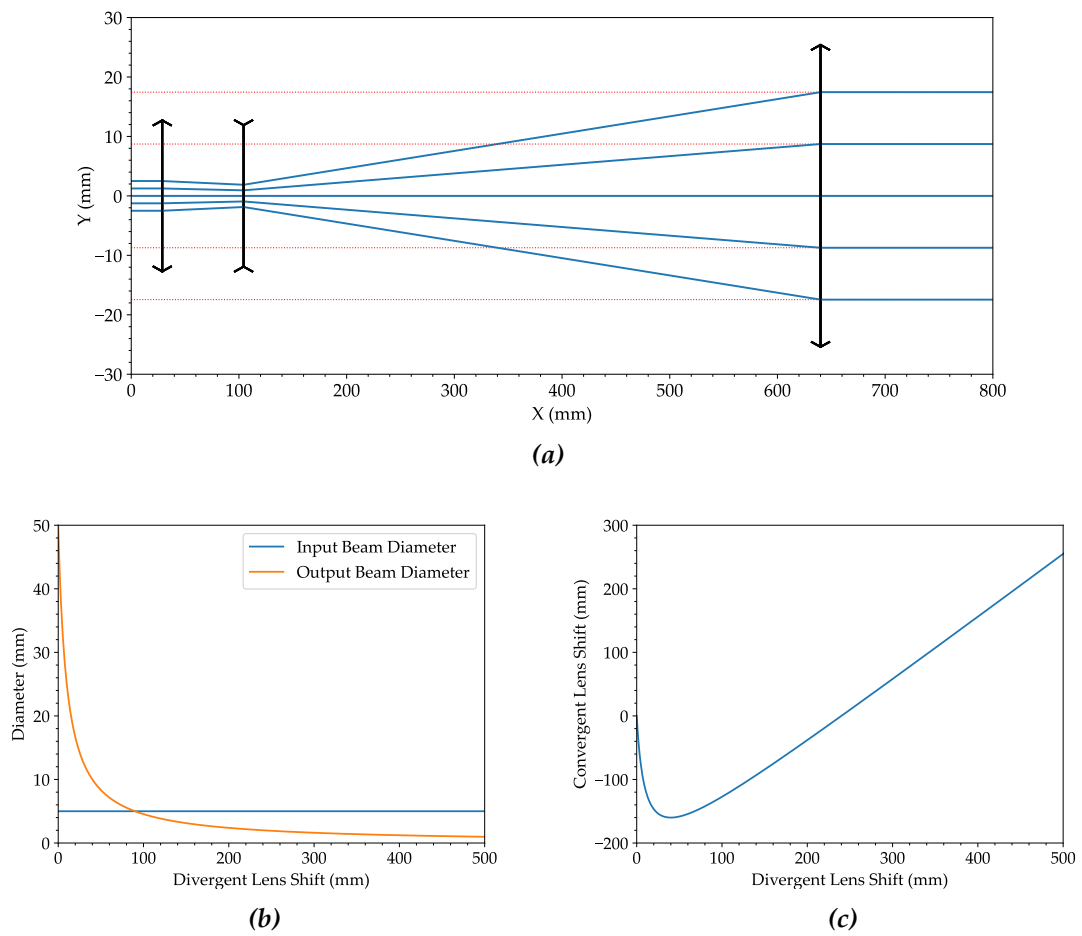


Figure 3.15: Telescope: (a) schematic representation, (b) variation of the diameter of the telescope's output beam with variation of the position of the diverging lens, and (c) variation in the position of the converging lens as a function of the position of the diverging lens.

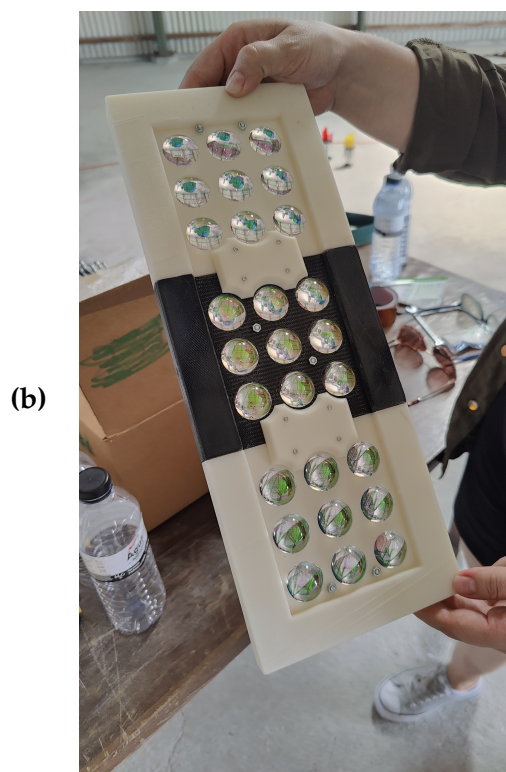
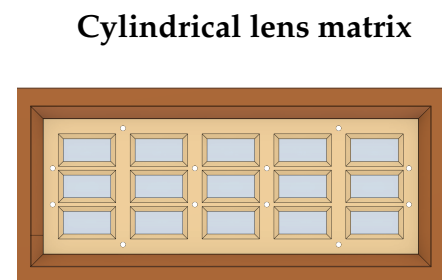
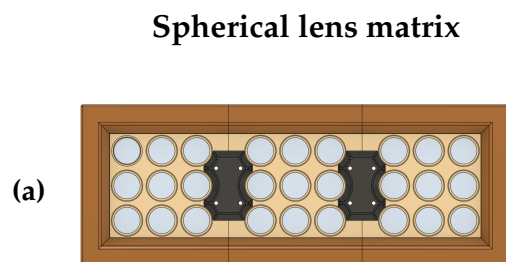


Figure 3.16: (a) Schematic drawing, and (b) picture of the spherical and cylindrical lens matrices.

3.4 Thermoelectric converter geometry considerations

In the design of the converters' geometry, one needs to consider their thermoelectric nature, which entails the generation of electrical voltage when the thermoelectric material is subjected to a thermal gradient. In this work, the architecture is based on the implementation of strips of thermoelectric material connected in series and the existence of a light beam absorption zone, the heating zone. Given that the temperature developed by the incidence of a light beam is higher the higher the intensity of that beam, the implementation of light beams focussed on the converter was initially selected.

The initial converter configuration was of a radial geometry, whereby the focused beam is directed towards the centre of the sensor, leading to the heating of the central region of the sensor and, consequently, the establishment of a radial gradient (Fig. 3.17a). A notable disadvantage of this configuration pertains to the distance between the heating zone and the strips, a limitation that arises from the manufacturing method available. Furthermore, the adoption of a triangular strip geometry would necessitate a redesign, resulting in an increase in internal resistance and, consequently, a decline in the generated current.

In order to overcome these limitations, a new geometry was developed, hereby defined as linear geometry (Fig. 3.17b). In this case, a focus with an elliptical geometry must be used, which can be achieved by implementing cylindrical lenses. Despite the reduction in the intensity of the light beam, given that one of the focus axes is larger than in the previous geometry, the increase in the number of strips for the same converter dimension, as well as the possibility of bringing the strips closer to the hot region of the converter, allows for an increase in conversion efficiency.

However, the utilisation of a small beam over long distances necessitates the incorporation of substantial lenses or curved mirrors at the output of the laser. This augmentation in complexity renders the manufacturing, assembly,

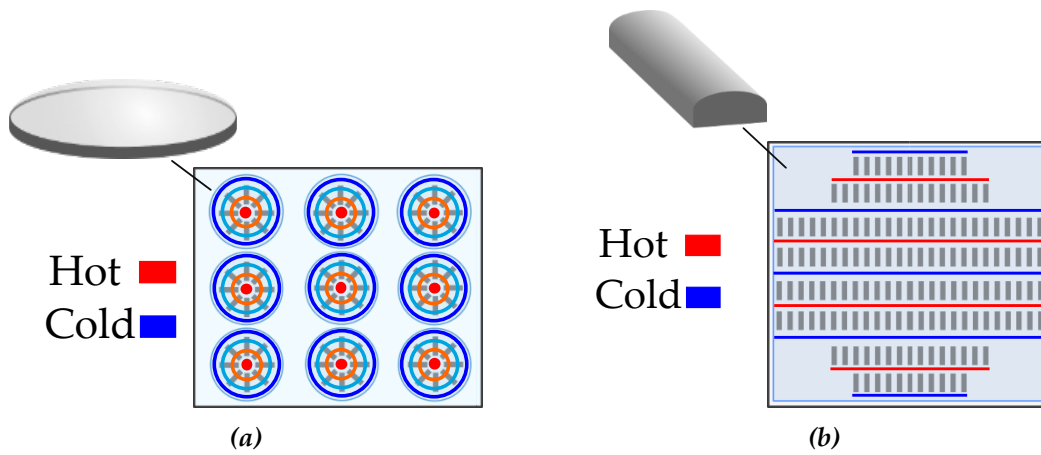


Figure 3.17: Two-dimensional converter configurations: (a) circular geometry and (b) linear geometry.

and calibration of the system more arduous. Alternatively, it is necessary to implement lenses or mirrors of comparable dimensions at the inlet of the converter, which results in a substantially heavier and less flexible system.

3.5 Laboratory prototype and outdoor applications

In the course of the experimental procedure, thermoelectric converters were utilised. To ensure the operational readiness of the electrical energy for utilisation in standard devices, the sensors were connected to a DC-DC converter, the output voltage of which was stabilised at 3.3 V.

In the laboratory demonstration, the sensor was placed inside a cryostat to create an environment similar to the space environment, with a pressure of 10^{-5} Torr (Fig. 3.18a). With the circular geometry, an output voltage of 440 mV was achieved, and with the linear geometry, a thermoelectric sensor output voltage of 600 mV was attained. In both cases, a laser beam with a power of 6W was used. Taking into account these results, the linear configuration was therefore selected. The thermoelectric device was then connected to the DC-DC converter, and the optical power required to activate the DC-DC converter, 3.4 W, was determined. This successfully concluded the demonstration of the use of lasers to supply energy to a given system at the laboratory level.

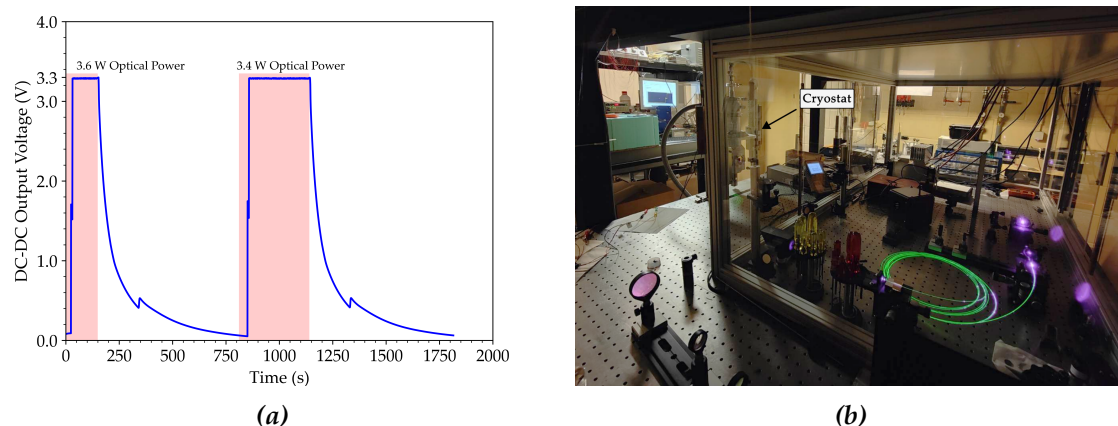


Figure 3.18: Laboratory prototype: (a) DC-DC converter output voltage and (b) picture of the experimental setup.

The system has undergone two outdoor tests. The first was conducted in the subterranean complex of the Faculty of Sciences at the University of Porto (Fig. 3.19a). The distance between the laser and the sensors was 70 metres, and it was possible to achieve voltage values at the output of the thermoelectric sensors of 950 mV for an optical power of 8 W. The second test was carried out at the S. Jacinto military base in Aveiro, where it was possible to test the entire system at a distance of 200 metres (Fig. 3.19b). For this test, a mirror (Thorlabs BB2-E04) was mounted after the telescope with a reflection angle of 90°. The mirror employed was actuated by two Thorlabs PIAK10 actuators and Thorlabs KIM101 drive. This configuration facilitated the precise positioning of the beam over extended distances. In order to achieve a propagation distance of 200 metres, it was necessary to install a mirror 100 metres away from the laser. This was due to the requirement for the transmitter and receiver to be in the same location. In the experiment, a sensor output voltage of 80 mV was achieved for an optical power of 20 W. This was due to the limited number of days available for testing (only two) and the fact that these days were marked by strong sunshine, which made it difficult to align the system. Additionally, the dimensions of the thermoelectric device proved to be a constraining factor, as it was incompatible with the beam diameter required for propagation over a distance of 200 metres. The data presented in Table 3.2 comprises the output

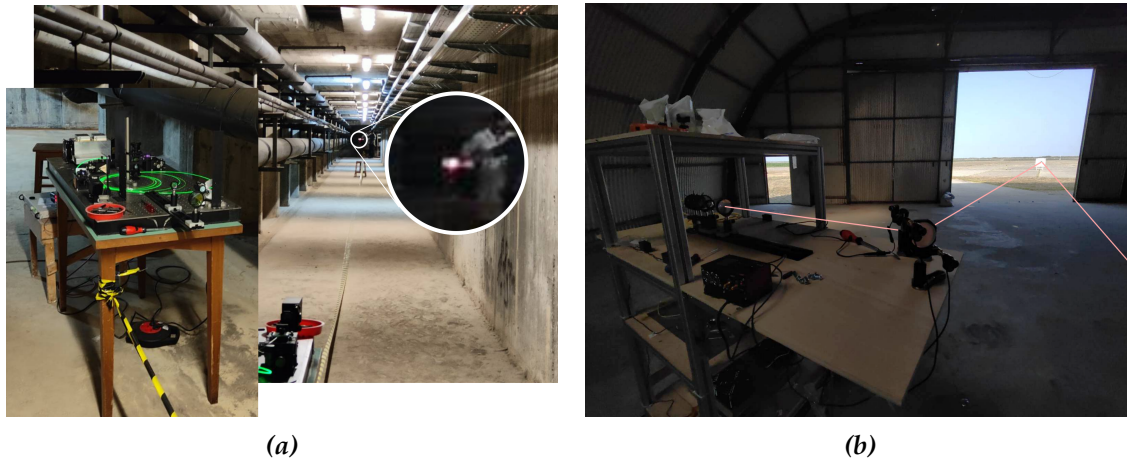


Figure 3.19: Experiences abroad: a) photography in the catacombs of the Faculty of Science of the University of Porto and b) photography of the laser system at the S. Jacinto military base.

voltage values of the thermoelectric converters obtained in the three experiments, in addition to the laser power utilised and the distance between the laser and the converters.

Table 3.2: Table with data on laser power, distance and voltage obtained from the converters for the three experiments: laboratory demonstration, subterranean complex of the Faculty of Science at the University of Porto, and S. Jacinto military base.

Test	Laser power (W)	Distance (m)	Converter output voltage (mV)
Laboratory	6	1	600
Subterranean	8	70	800
S. Jacinto	20	200	80

3.6 Conclusions

This Chapter delineated the natural divergence of the beam and demonstrated how the implementation of a telescope based on the zoom beam expander scheme enables the control of the diameter of the light beam at the receiver, based on the diameter of the beam emitted by the transmitter. In the second section, an erbium-doped triple hollow-cladding fibre laser with emission at $1.55 \mu\text{m}$, a maximum emission power of $30.0 \pm 0.1 \text{ W}$, an efficiency of $29.7 \pm 0.5 \%$ and M_x^2 of 1.08 and M_y^2 of 1.06 has been fabricated and characterised. Furthermore, it was determined that the safety equipment must be equipped

with an OD 7 for eye case and an OD 4 for skin case. The air cooling method was selected and considering the laser system, the required minimum air flow was $15.2 \text{ m}^3/\text{min}$, also crucial to ensure that the ambient temperature did not exceed 18°C . To control the diameter of the beam arriving at the opto-electrical converters, a telescope was developed to control the diameter of the laser system's output beam, allowing the output diameter to vary between 0.2 and 10 times the diameter of the input beam. Furthermore, the efficacy of lens arrays in facilitating the implementation of multiple converters was investigated. It was demonstrated that this solution necessitates the utilisation of all lenses composed of a single piece of glass, and is only viable in scenarios where the laser power exceeds the capacity of the converters to manage it. In this study, four converter configurations were proposed, with the two two-dimensional configurations being tested. The linear configuration exhibited an output voltage 36% higher than the circular configuration. The efficacy of the system was demonstrated through laboratory and outdoor testing, validating the practicality of utilising a laser beam for energy distribution over extended distances.

Chapter 4

Interferometric optical fiber sensors

Fibre optic interferometry has found widespread application in sensing and interrogation system contexts. The operation of an interferometer is achieved by the superimposition of at least two light beams of differing phases, thereby yielding an interference pattern. The application of this technique in the domain of sensors involves the modification of this interference pattern in accordance with the physical characteristics under investigation. The existing literature encompasses two-wave interferometers, including Mach-Zehnder [141] and Michelson [142] interferometers, and multi-wave interferometers, such as Fabry-Perot sensors [143]. Moreover, the utilisation of multiple waves enables the implementation of the Vernier effect. This effect involves the generation of a beat between two interference patterns, resulting in an envelope and a carrier.

Interferometers can be used to make two types of measurement: either in intensity or in phase. Intensity measurements are based on the y -axis, for example, changes in the absorption of a given medium [144]. Phase measurements are based on the x -axis, such as variations in the position of interferometric fringes [145]. Low Coherence Interferometry (LCI), alternatively referred to as White Light Interferometry (WLI), combines both intensity and phase approaches [146]. In this method, the output signal is determined by the fringe position, with its distribution modelled by an envelope.

The present Chapter provides a detailed description of fibre optic

interferometers and is divided into three sections. The first section focuses on interferometric sensors, analysing a theoretical model and the characteristics of the sensitivity curve. The second section explores the Vernier effect, discussing its variants and states, evaluating the sensitivity curve, and how different values can be implemented. The third section describes the LCI system, analysing its operation and the impact of different optical spectrum profiles.

4.1 Optical interferometric concept

Optical interferometry is based on the superposition of two or more electromagnetic waves, referred to here as light beams. When these waves have different phases, their superposition results in an interference pattern marked by fringes. To describe this phenomenon mathematically, it is first necessary to define the individual light beams. The electromagnetic wave propagating through the optical fibre can be represented as a plane wave, as shown in the following equation [140].

$$E_{out} = E_{in}e^{j(\omega t + \beta L)}, \quad (4.1)$$

where ω is the angular wave frequency, t is the time, β is the propagation constant and is given by $\beta = nk$, n is the refractive index, k is the angular wave number and $k = 2\pi/\lambda$, λ is the wavelength and L is the length travelled by the light. The equation 4.1 denotes two terms: the temporal term, ωt , and the spatial term, βL . In interferometry, the spatial term is subject to variation, thereby giving rise to the concept of optical path length (OPL). The OPL is determined by the multiplication of two variables: the length propagated by the beam and the refractive index (see equation 4.2). This enables the comparison of optical paths in different media.

$$OPL = nL \quad (4.2)$$

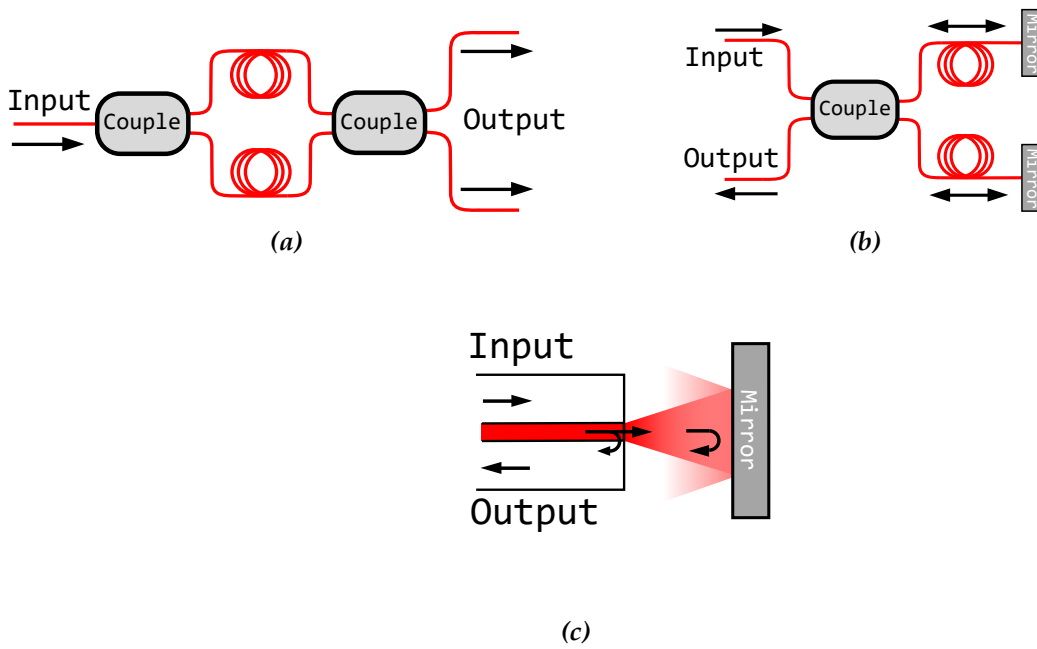


Figure 4.1: Interferometer operating diagrams: (a) MZI, (b) Michelson interferometer, and (c) FPI.

In an interferometric system, the operation begins with the division of a beam into two or more beams, each propagating through media with distinct properties. These light beams are then superimposed upon one another (Fig. 4.1). Interferometers can be classified into two main categories: transmission and reflection. In transmission interferometers, the light beam passes through the detection section once, resulting in a propagation distance equal to the cavity length. An example of a transmission interferometer is the Mach-Zehnder interferometer (MZI) (Fig. 4.1a). In reflection interferometers, the light beam travels through the sensing section twice, meaning the total propagation distance is twice the cavity length. An example of a reflection interferometer is the Michelson interferometer (Fig. 4.1b). It is important to note that the Fabry-Pérot interferometer (FPI) also follows the reflection scheme, with the distinction that the first optical path is reflected at the point where the beam is initially split (Fig. 4.1c).

In the case of an interferometer based on optical fibre that follows a two-wave interferometric architecture - which may also apply to low-finesse interferometers, such as FPIs with low reflectivity - the transfer function can be

defined by the following equation:

$$E_{out} = E_{in} e^{j(\omega t + \beta_1 L_1)} \left[A + B e^{j(\beta_2 \Delta L)} \right], \quad (4.3)$$

where A and B represent the amplitude of the light beam in each optical path and satisfy the condition $A + B = 1$ in a lossless situation. The term ΔL is defined as the difference in distance propagated by the two beams. This gives rise to the concept of optical path difference (OPD) as follows:

$$OPD = n_1 L_1 - n_2 L_2, \quad (4.4)$$

where indices 1 and 2 are used to distinguish between different optical paths. Equation 4.3 can be simplified as:

$$E_{out} = (A - B) E_{in} e^{j(\omega t + \beta_1 L_1)} + 2B E_{in} e^{j(\omega t + \beta_1 L_1)} e^{j(\beta_2 \Delta L)/2} \cos(\beta_2 \Delta L/2). \quad (4.5)$$

In practice, the intensity or power of the beam is measured and expressed as a function of wavelength using an optical spectrum analyser (OSA) or a spectrometer. The intensity profile can be described by Equation 4.6.

$$\frac{I_{out}}{I_{in}} = 4AB \cos^2(\beta_2 \Delta L/2) + (A - B)^2 \quad (4.6)$$

Figure 4.2 demonstrates the graphical representation of Equation 4.6, where the output signal spectrum consists of oscillations, commonly referred to as fringes. An important characteristic of these fringes is their free spectral range (FSR), defined as the wavelength interval between two consecutive maxima or minima. The FSR can be calculated using the following equation:

$$FSR = \frac{\lambda^2}{nL}. \quad (4.7)$$

As demonstrated in Equation 4.7, the FSR increases with increasing wavelength.

The use of these systems as sensors involves the measurement of fringe shift

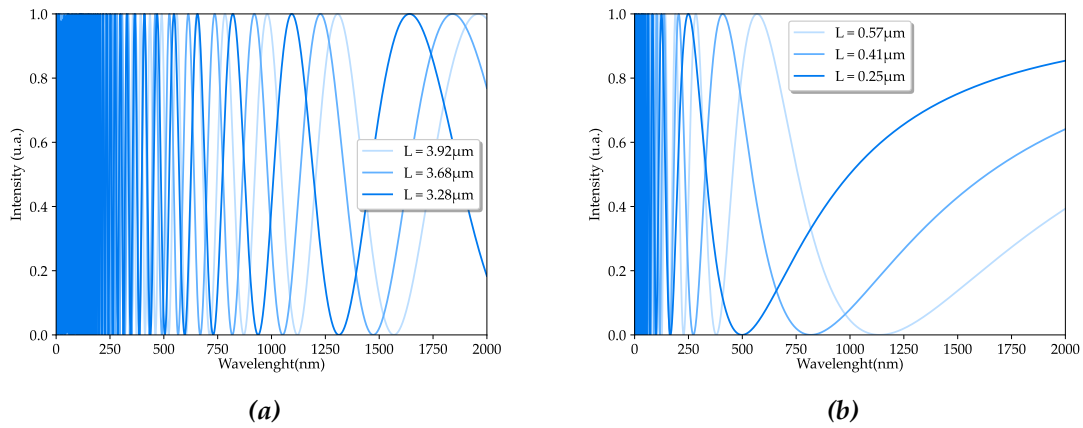


Figure 4.2: Optical spectrum of the output signal from an interferometer: (a) three cavities larger than the wavelengths under study, and (b) three cavities smaller than the wavelengths.

resulting from phase variation with the physical quantity, typically achieved by observing the shift of spectral extremes. In the case of cavities larger than the wavelengths under investigation, the spectrum consists of multiple oscillations (Fig. 4.2a). As the cavity decreases, the fringes shift to shorter wavelengths, and within a given optical band, the fringes become wider. When the cavity is on the order of, or smaller than, the wavelengths under study, the final fringe appears, followed by a plateau over the wavelength range where the interferometric phenomenon no longer has an effect (Fig. 4.2b). As the cavity becomes smaller, the fringes shift more rapidly, indicating that higher sensitivity is achieved with smaller cavities.

The study of fringe sensitivity as a function of cavity variation is shown in Figure 4.3. These figures demonstrate that the variation of the spectral extremes is linear with the variation of the cavity length, as the argument of the cosine function is linear with the OPD. However, the relationship between sensitivity and cavity length follows a hyperbolic trend.

Optimisation of sensitivity is achieved by using extrema associated with cavities whose dimensions are smaller than the maximum wavelength of the optical band in use. The point of maximum sensitivity is located at the minimum of the spectrum corresponding to order zero. The wavelengths at which the spectral minima occur can be determined using the following equation:

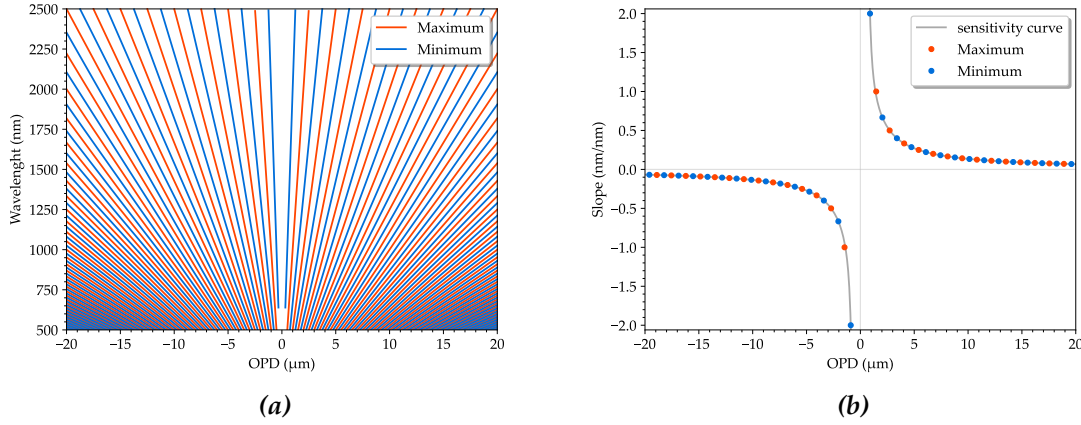


Figure 4.3: Sensitivity characterisation of different spectra: (a) displacement of extremes, and (b) sensitivity associated with each extreme.

$$\lambda_{\text{minimum}} = \frac{2n\Delta L}{2p+1}, \quad (4.8)$$

where p is the order of the minimum. The highest sensitivity is observed at the minimum of order zero, as demonstrated by the equation: $\lambda_{\text{extreme}} = 2n\Delta L$. This result is consistent with the sensitivity values shown in Figure 4.3b. An important feature is the maximum sensitivity value of 2 nm/nm. The value achieved in practice is significantly lower, typically between 10^{-3} and 10^{-2} nm/nm. This discrepancy is due to the use of cavities with typical dimensions in the tens of micrometres, and, in practice, the physical quantity is not perfectly transmitted to the sensor. Other important characteristics include the dynamic range of the system and its robustness (the latter being more related to system construction). Increased sensor sensitivity inevitably leads to a reduction in dynamic range. Therefore, a balance must be maintained between sensitivity and dynamic range.

4.2 Vernier effect concept

The Vernier effect is a significant phenomenon in the field of interferometry, first reported in 2011 [147]. This effect has enabled interferometric systems to achieve much higher sensitivity than previously possible, with demonstrated increases exceeding 200-fold [148]. The principle behind this enhancement is analogous to the use of Vernier scales, where two overlapping scales improve measurement accuracy. In interferometry, the Vernier effect involves the use of two cavities, with the optical signals from each cavity being superimposed to produce a beat. This phenomenon can be realised by combining three or four optical paths.

The Vernier effect can be categorised into variants and states. The variants are defined by the movement of the cavities and include:

- Traditional, where one cavity acts as the sensor and the other as the reference [149];
- Reduced, where both cavities are sensors and move in parallel directions [150];
- Enhanced, where both cavities are sensors and move in anti-parallel directions [151].

The states are classified as either fundamental or harmonic. The fundamental state is characterised by the similarity between the two cavities, while the harmonic state occurs when one cavity is an integer multiple of the other.

This section describes the implementation of the Vernier effect using three-wave and four-wave interferometers.

4.2.1 Configuration based on 3-wave interferometry

The implementation of three-wave interferometry can be achieved by modifying a two-wave interferometer, as illustrated in Figure 4.4. This figure shows a diagram of a three-wave FPI. The system can be described as follows:

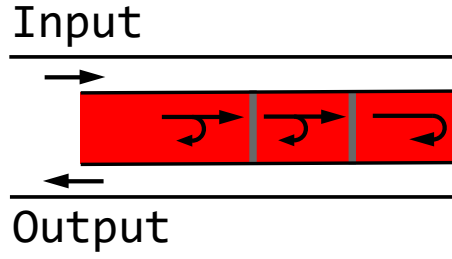


Figure 4.4: Schematic diagram illustrating the operation of a three-wave FPI.

$$E_{out} = E_{in} e^{j(\omega t + \beta_0 L_0)} \left[A + B e^{j(\beta_1 \Delta L_1)} + C e^{j(\beta_2 \Delta L_2)} \right], \quad (4.9)$$

where A , B , and C represent the amplitudes of the light beams in each optical path, and in a lossless system, they satisfy the condition $A + B + C = 1$ in a lossless situation. The indices 1 and 2 are used to distinguish between the different optical paths. This equation can be simplified by grouping the optical paths into two pairs, followed by a derivation analogous to that of Equation 4.5:

$$\begin{aligned} E_{Vernier} = & (A - B - C) E_{in} e^{j(\omega t + \beta_0 L_0)} + \\ & + 2B E_{in} e^{j(\omega t + \beta_0 L_0)} e^{j(\beta_1 \Delta L_1)/2} \cos(\beta_1 \Delta L_1/2) + \\ & + 2C E_{in} e^{j(\omega t + \beta_0 L_0)} e^{j(\beta_2 \Delta L_2)/2} \cos(\beta_2 \Delta L_2/2). \end{aligned} \quad (4.10)$$

Consequently, the intensity is given by:

$$\begin{aligned} I_{Vernier} = & (A - B - C)^2 + \\ & + 4B(1 + A - B - C) \cos^2(\beta_1 \Delta L_1/2) + \\ & + 4C(1 + A - B - C) \cos^2(\beta_2 \Delta L_2/2) + \\ & + 8BC \cos(\beta_1 \Delta L_1/2) \cos(\beta_2 \Delta L_2/2) \cos(\beta_1 \Delta L_1/2 - \beta_2 \Delta L_2/2). \end{aligned} \quad (4.11)$$

Considering the optimised case, where $A = 1/2$, $B = 1/4$, and $C = 1/4$, the resulting equation is as follows:

$$I_{\text{Vernier}} = 1 + \cos(\beta_1 \Delta L_1 / 2 - \beta_2 \Delta L_2 / 2) \left[\frac{1}{4} \cos(\beta_1 \Delta L_1 / 2 - \beta_2 \Delta L_2 / 2) + \frac{5}{4} \cos(\beta_1 \Delta L_1 / 2 + \beta_2 \Delta L_2 / 2) \right]. \quad (4.12)$$

The graphical representation of equation 4.12 for three optical paths is shown in Figure 4.5. The second and third paths differ from the first path by 220 μm and 225 μm , respectively.

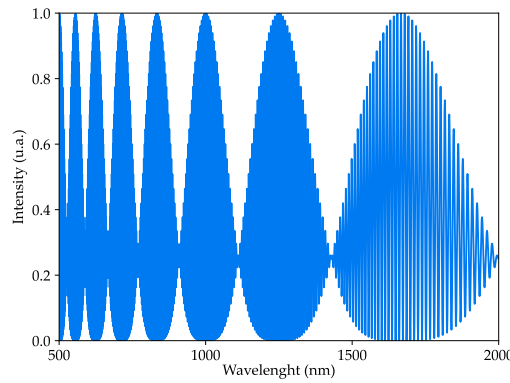


Figure 4.5: Simulation of the output signal spectrum of three optical paths, where the second and third optical paths differ by 220 μm and 225 μm , respectively, from the first optical path.

4.2.2 Configuration based on 4-wave interferometry

The implementation of the Vernier effect is typically achieved by interconnecting two independent interferometers, allowing the mixing of four optical waves. The electric field corresponding to the Vernier effect is obtained by taking the product of the transfer functions of each interferometer, leading to Equation 4.13.

$$E_{\text{Vernier}} = [4A_1B_1\cos^2(\beta_1\Delta L_1/2) + (A_1 - B_1)^2] \cdot [4A_2B_2\cos^2(\beta_2\Delta L_2/2) + (A_2 - B_2)^2] \quad (4.13)$$

Thus, the intensity is given by:

$$\begin{aligned}
I_{Vernier} = & 16A_1B_1A_2B_2\cos^2(\beta_1\Delta L_1/2)\cos^2(\beta_2\Delta L_2/2) + \\
& + 4A_2B_2(A_1 - B_1)^2\cos^2(\beta_2\Delta L_2/2) + \\
& + (A_2 - B_2)^24A_1B_1\cos^2(\beta_1\Delta L_1/2) + \\
& + (A_1 - B_1)^2(A_2 - B_2)^2. \quad (4.14)
\end{aligned}$$

The equation can also be expressed as follows:

$$\begin{aligned}
I_{Vernier} = & 16A_1B_1A_2B_2[\cos(\beta_1\Delta L_1/2 - \beta_2\Delta L_2/2) + \cos(\beta_1\Delta L_1/2 + \beta_2\Delta L_2/2)]^2 + \\
& + 4A_2B_2(A_1 - B_1)^2\cos^2(\beta_2\Delta L_2/2) + \\
& + (A_2 - B_2)^24A_1B_1\cos^2(\beta_1\Delta L_1/2) + \\
& + (A_1 - B_1)^2(A_2 - B_2)^2. \quad (4.15)
\end{aligned}$$

Considering the optimised case - where $A_1 = B_1 = 1/2$ and $A_2 = B_2 = 1/2$ - and assuming that the wavelength is identical for both B_1 and B_2 , the previous equation can be rewritten as follows:

$$I_{Vernier} = [\cos(k/2(n_1\Delta L_1 - n_2\Delta L_2)) + \cos(k/2(n_1\Delta L_1 + n_2\Delta L_2))]^2. \quad (4.16)$$

The graphical representation of Equation 4.16 for two cavities is shown in Figure 4.6. One cavity has a length of 220 μm , while the other measures 225 μm . Additionally, it is possible to connect both sensors in parallel, which yields the following equation:

$$\begin{aligned}
E_{Vernier} = & \left[\frac{E_{in}}{2} e^{j(\omega t + \beta L)} \right] \left[(A_1 - B_1) + 2B_1 e^{j(\beta\Delta L_1)/2} \cos(\beta\Delta L_1/2) \right. \\
& \left. (A_2 - B_2) + 2B_2 e^{j(\beta\Delta L_2)/2} \cos(\beta\Delta L_2/2) \right] \quad (4.17)
\end{aligned}$$

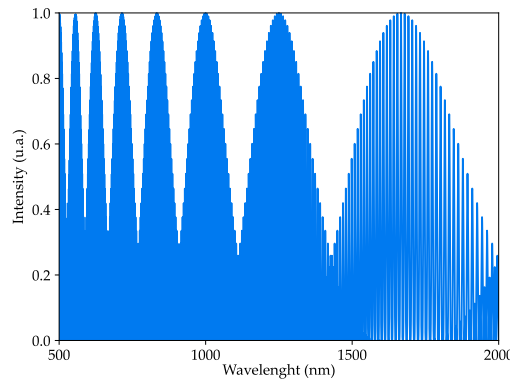


Figure 4.6: Simulation of the output signal spectrum of two cavities in series, one of 220 μm and the other of 225 μm

From equation 4.17, the normalised intensity is given by:

$$I_{\text{Vernier}} = G^2 + 4B_1(G+1)\cos^2(\beta_1\Delta L_1/2) + 4B_2(G+1)\cos^2(\beta_2\Delta L_2/2) + 8B_1B_2\cos(\beta_1\Delta L_1/2)\cos(\beta_2\Delta L_2/2)\cos(\beta_1\Delta L_1/2 - \beta_2\Delta L_2/2), \quad (4.18)$$

where $G = A_1 - B_1 + A_2 - B_2$. Considering an optimised system, where $A_1 = B_1 = A_2 = B_2 = 1/2$ and $k_1 = k_2$, the following equation is achieved:

$$I_{\text{Vernier}} = 1 + \cos(k/2(n_1\Delta L_1 - n_2\Delta L_2)) \cdot \left[\frac{1}{4}\cos(k/2(n_1\Delta L_1 - n_2\Delta L_2)) + \frac{5}{4}\cos(k/2(n_1\Delta L_1 + n_2\Delta L_2)) \right]. \quad (4.19)$$

The graphical representation of equation 4.19 for two cavities - one measuring 220 μm and the other 225 μm - is shown in Fig. 4.7. As expected, this result is equivalent to that obtained through three-wave interferometry.

4.2.3 Vernier effect implementation

In the Vernier effect, the spectra of the output signals display distinct geometries, depending on the nature of each interferometer and the configuration of their

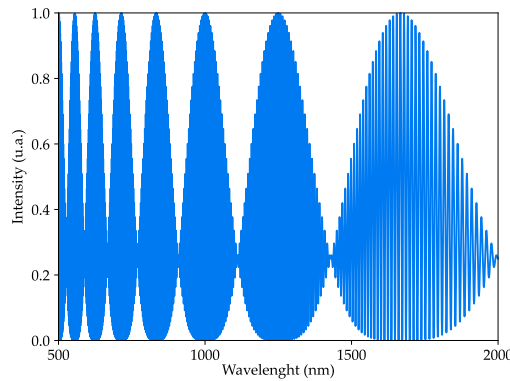


Figure 4.7: Simulation of the output signal spectrum of two cavities in parallel, with one cavity measuring $220\ \mu\text{m}$ and the other $225\ \mu\text{m}$.

interconnection. Regardless of the configuration, the optical spectrum consists of an envelope and a carrier. The envelope arises from the cosine term with the argument $n_1\Delta L_1 - n_2\Delta L_2$, while the carrier is associated with the cosine term $n_1\Delta L_1 + n_2\Delta L_2$. Therefore, the envelope exhibits features similar to the interference fringes produced by a small cavity, thus achieving a sensitivity greater than that of each individual sensor. Consequently, Vernier-effect-based sensors are designed to track the behaviour of the envelope.

The practical implementation of this phenomenon in interferometers has led to two distinct approaches: variants, which refer to the direction of sensitivity of the interferometers, and states, commonly referred to as harmonics.

4.2.3.1 Vernier effect classification

The Vernier effect can be classified into three distinct variants: Reduced, Traditional, and Enhanced, as presented in Figure 4.8.

The Traditional Vernier effect was the first variant to be investigated, involving the modulation of a single sensor while the second cavity functions as a reference. It should be noted that the results obtained using the equations discussed earlier are consistent for both series and parallel configurations (Fig. 4.9a). The dynamic range and maximum sensitivity - notably reaching $2\ \text{nm}/\text{nm}$ - are equivalent to those observed in a single cavity (Fig. 4.9c). However, a

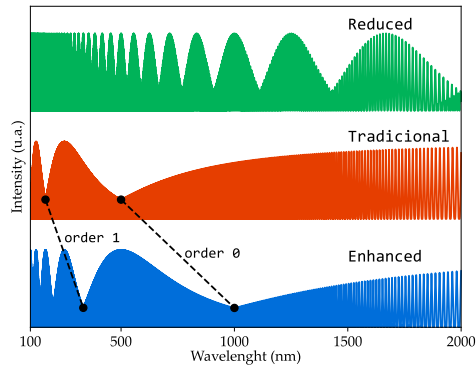


Figure 4.8: Representation of Vernier effect variants.

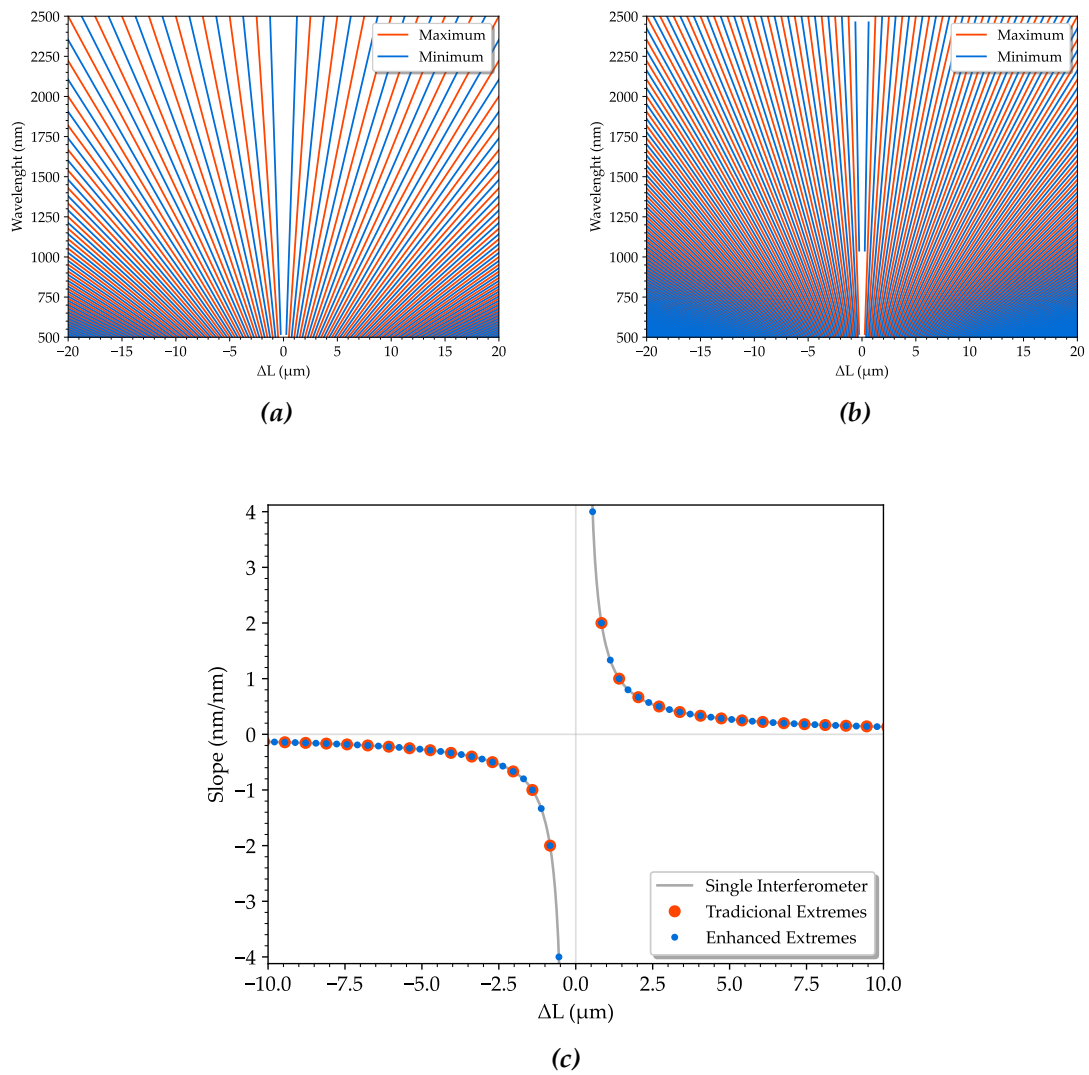


Figure 4.9: Sensitivity characterisation of different spectrum extremes: (a) displacement of extremes for the Traditional Vernier effect, (b) displacement of extremes for the Enhanced Vernier effect, and (c) sensitivity associated with each extreme for Traditional and Enhanced variants.

significant advantage of the Traditional variant lies in its ability to reach this maximum sensitivity at a cavity length of 200 μm . This underscores the key benefit of the Traditional configuration: its capacity to shift the sensitivity peak to a cavity dimension that is more practical and easier to fabricate, thus enabling enhanced sensitivity.

Beyond this, two additional configurations have been described: the Reduced and Enhanced variants. In the Reduced variant, both sensors move in the same direction, thus, the difference in OPDs remains constant, while the sum of the OPDs varies by a factor of two compared to the Traditional variant. Conversely, in the Enhanced variant, the sensors move symmetrically in opposite (antiparallel) directions. As a result, the difference in OPDs varies by a factor of two, while the sum remains constant compared to the Traditional case.

As illustrated in Figure 4.9b, the Enhanced variant exhibits twice the number of spectral extrema compared to the Traditional variant. This configuration is also reduced by half the dynamic range, while doubling the sensitivity for the same fringe order. Despite these differences, the sensitivity curve itself remains similar in shape to that of the Traditional variant (Fig. 4.9c). Although the mechanical displacement in the Enhanced configuration is doubled, it is balanced by the achievement of twice the cavity difference.

In summary, the *FSR* and sensitivity associated with the envelope fringes in the Enhanced variant are each half those of the Traditional configuration. The extrema corresponding to the same spectral order appear closer to the balance point ($\Delta L = 0$), resulting in a higher sensitivity - specifically, twice that of the Traditional variant.

Similarly to the single interferometer, the minima of the envelope are the extrema that exhibit the highest sensitivity. For the Traditional variant, their wavelength positions are defined by equation 4.8. In the case of the Enhanced Vernier effect, these positions are determined by equation 4.8 multiplied by a factor of 2, that is:

$$\lambda_{minimum} = \frac{4n\Delta L}{2p+1} . \quad (4.20)$$

In the Enhanced variant, carrier variation can occur even when the system is correctly calibrated, due to external disturbances. In other words, unlike the physical quantity under study - where the sensor cavities vary in opposite directions - external factors such as temperature cause both OPDs to expand or contract simultaneously. As a result, this variant also supports the behaviour of the Reduced variant in response to external disturbances, thereby enabling the simultaneous measurement of two physical quantities.

4.2.3.2 The state of the Vernier effect

The Vernier effect can be described as the superposition of optical cavities with OPDs of similar size; however, it can also occur when the OPDs are integer multiples of one another. The fundamental state corresponds to the initial case, or order 0, where the OPDs are nearly equal. The remaining configurations are referred to as harmonics, defined by the condition $OPD_1 \sim (m+1) \times OPD_2$, where m denotes the harmonic order and is an integer greater than zero (Fig. 4.10).

The effect of harmonics can be categorised into two scenarios [152]:

1. When the smaller cavity acts as the sensor and the larger cavity serves as the reference, in other words, the harmonics are generated by increasing the reference cavity, the system behaves as shown in Figure 4.10a. These results demonstrate that as the harmonic order m increases, the envelope's FSR decreases proportionally by a factor of $(m+1)$ when compared to the fundamental state. This behaviour resembles that of the Enhanced variant.
2. When variation is applied to the larger cavity (sensor) and the smaller cavity remains static (reference), in other words, the harmonics are generated by increasing the sensor cavity, no change in the envelope's FSR is observed (Fig. 4.10b).

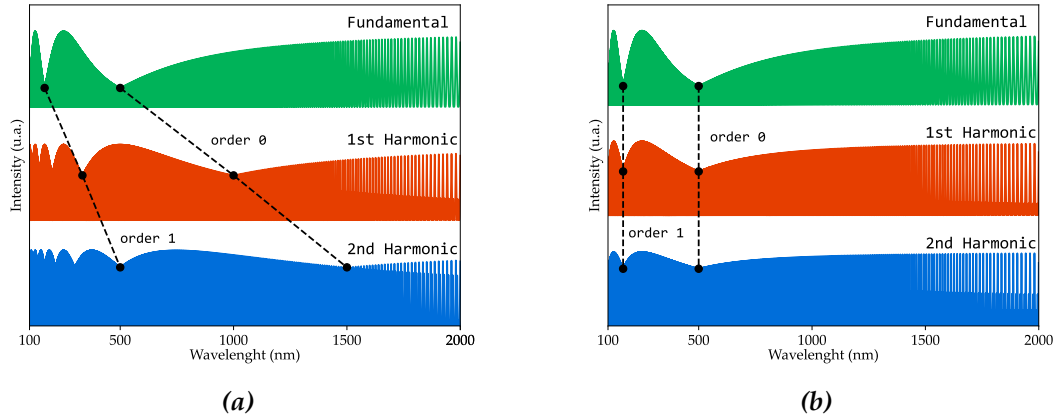


Figure 4.10: Fundamental and harmonic states for two cavities: (a) $L_1 = 200.25 \mu\text{m}$ and $L_2 = (m + 1) 200 \mu\text{m}$, and (b) $L_1 = 200 \mu\text{m}$ and $L_2 = (m + 1) 200 + 0.25 \mu\text{m}$.

When a variation occurs in the smaller cavity, and considering spectral extrema of the same order, the sensitivity of the harmonic states is equal to the sensitivity of the fundamental state multiplied by a factor of $(m + 1)$. As illustrated in Figure 4.11, although the sensitivity curves are identical across different harmonic orders, the envelope's *FSR* is reduced by a factor of $(m + 1)$. As a result, extrema of the same order appear closer to the balanced state ($\Delta L = 0$) and thus exhibit greater sensitivity (Fig. 4.11a). This behaviour is analogous to what is observed in the Enhanced Vernier variant.

In contrast, when the larger cavity is varied, the sensitivity of the harmonic states remains equal to that of the fundamental state, regardless of the harmonic order. This sensitivity also matches that achieved in the fundamental state with smaller cavity variation and is equivalent to the sensitivity observed in a single interferometer (Fig. 4.11b).

Despite the increase in sensitivity observed by higher-order harmonics, the signal geometry becomes more complex, requiring the use of more elaborate envelope analysis techniques as the harmonic order increases.

Finally, the wavelength positions of the spectral minima are given by:

$$\lambda_{\text{minimum}} = \frac{2(m+1)n\Delta L}{2p+1}, \quad (4.21)$$

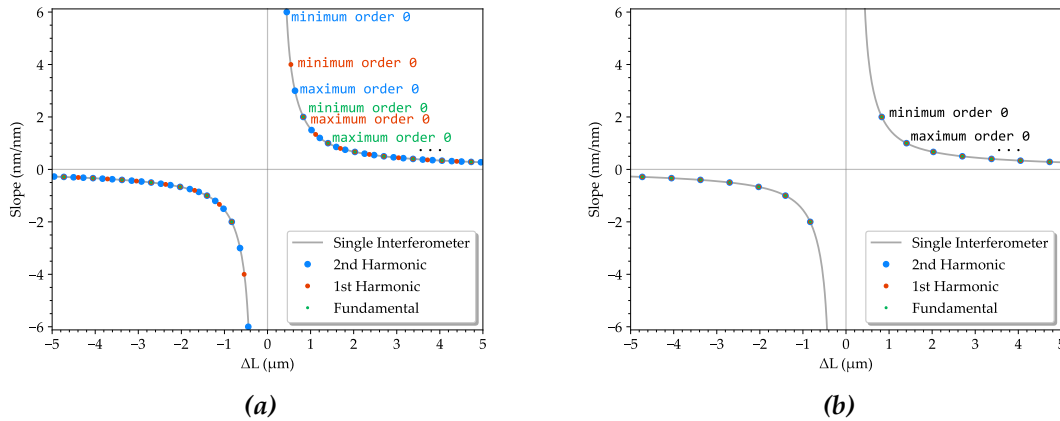


Figure 4.11: Sensitivity characterisation of different spectrum extremes for the fundamental and the harmonics of Vernier effect: (a) the sensor cavity is the smaller, and (b) the sensor cavity is the larger one.

where p is the order of the extreme.

4.2.4 Magnification factor

The performance of the Vernier effect is evaluated through the use of the magnification factor (M). This factor is typically defined in terms of the FSR and is expressed as follows [153, 154]:

$$M = FSR_{\text{envelope}} / FSR_{\text{sensor}} , \quad (4.22)$$

where FSR_{envelope} and FSR_{sensor} correspond to the FSR of the overall envelope and the FSR of a single sensor, respectively. An alternative method for defining the magnification factor is based on sensitivity. In this case, M is given by the ratio between the sensitivity of the envelope and that of an individual sensor [154]:

$$M = \text{sens}_{\text{envelope}} / \text{sens}_{\text{sensor}} , \quad (4.23)$$

where $\text{sens}_{\text{envelope}}$ and $\text{sens}_{\text{sensor}}$ are the sensitivities of the envelope and the individual sensor, respectively. However, it should be noted that both definitions of M are limited to evaluating the performance of a Vernier configuration relative to a single sensor. In particular, this magnification factor tends to increase with

cavity length, since sensor sensitivity typically decreases as the cavity increases. Therefore, this description does not provide an adequate comparison of the performance analysis across different Vernier effect implementations.

To overcome these limitations, additional factors have been proposed to facilitate the differentiation between various configurations [155]. Among them, two key parameters are the *FSR* magnification factor (M_{FSR}) and the sensitivity magnification factor (M_{Sens}), which are defined as follows:

$$M_{FSR} = FSR_{env} / FSR_{carr} , \quad (4.24)$$

$$M_{Sens} = Sens_{env} / Sens_{carr} , \quad (4.25)$$

where FSR_{carr} and $Sens_{carr}$ are the *FSR* and sensitivity of the carrier, respectively. The third factor is the Vernier magnification, which is given by:

$$M_V = M_{sens} / M_{FSR} , \quad (4.26)$$

where $M_V = 1$ for the Traditional case, $M_V < 1$ for the Reduced variant, and $M_V > 1$ for the Enhanced variant. It is evident that the proposed approach enables the distinction between different variants; however, it cannot differentiate between harmonics. This limitation motivated the development of a novel figure of merit, allowing a more robust and comprehensive comparison of performance across various Vernier effect configurations. The proposed methodology begins by establishing the relationship between sensitivity and *FSR*, expressed as:

$$M = Sens_{env} / FSR_{env} . \quad (4.27)$$

The figure of merit ($FoM_{Vernier}$) is defined as the ratio between the magnification factor of the measured state (M_m) and the magnification factor of the fundamental state - in the case of harmonics - or the Traditional variant - in the case of the variants (M_0):

$$FoM_{Vernier} = M_m/M_0 . \quad (4.28)$$

In the harmonic context, $FoM_{Vernier}$ assumes a value of $(m + 1)$ when the sensor cavity is at its smallest, and a value of 1 when the sensor cavity is at its largest, where m denotes the harmonic order. In the context of variants, $FoM_{Vernier}$ assumes the following values: 0 for the Reduced variant, 1 for the Traditional variant, and 2 for the Enhanced variant. Moreover, when a particular implementation combines the Enhanced variant and a harmonic, the resulting $FoM_{Vernier}$ assumes a value of $(m + 2)$

4.3 White Light Interferometer

The WLI is a measurement technique involving two optical cavities, typically arranged in tandem. One of these cavities acts as an interrogator cavity, with one of its arms being controlled by an actuator, and the other as a sensor or a reference cavity. These cavities are illuminated by a broadband spectrum source, and the signal is detected through a photodetector, an element that integrates all the spectral power of the optical signal. The measurement achieved by this technique can thus be described as the spectral power integral of the Vernier effect between the interrogator and the sensor cavity. In order to mathematically describe the phenomenon, it is necessary to consider the following aspects: the spectrum profile of the source (I_{SLD}), the interferometric fringes of both the interrogator and the sensor cavity (I_I and I_{Sensor} respectively) and the spectrum integration of the output signal, resulting in the following equation:

$$I_{PD}(\Delta L) = G \int_0^{+\infty} I_{SLD}(k) \cdot I_I(k, \Lambda_I) \cdot I_{Sensor}(k, \Lambda_S) dk , \quad (4.29)$$

where G is the normalisation constant, and Λ_I and Λ_S are the optical path differences between the interrogator and sensor, respectively.

The most common optical sources employed in the implementation of this effect are the flat and the Gaussian sources. Concerning the flat spectrum source, the following equation is achieved:

$$\begin{aligned}
 I_{PD}(\Lambda_I, \Lambda_S, G, k_1, k_2) = & G \frac{A^2 B^2}{8} [k_2 \text{sinc}(k_2(\Lambda_I + \Lambda_S)) - k_1 \text{sinc}(k_1(\Lambda_I + \Lambda_S)) + \\
 & + k_2 \text{sinc}(k_2(\Lambda_I - \Lambda_S)) - k_1 \text{sinc}(k_1(\Lambda_I - \Lambda_S)) + \\
 & + 2k_2 \text{sinc}(k_2\Lambda_I) - 2k_1 \text{sinc}(k_1\Lambda_I) + \\
 & + 2k_2 \text{sinc}(k_2\Lambda_S) - 2k_1 \text{sinc}(k_1\Lambda_S) + \\
 & + 2(k_2 - k_1)] , \quad (4.30)
 \end{aligned}$$

where A and B are the optical waves' amplitudes; k_1 and k_2 are the angular wave numbers associated with the extreme wavelength values of the optical band; Figure 4.12a shows its graphical representation. Considering the Gaussian spectrum source,

$$\begin{aligned}
 I_{PD}(\Lambda_I, \Lambda_S, G, \sigma_k, k_c) = & \frac{G}{16} \left[e^{-\frac{(\sigma_k(\Lambda_I - \Lambda_S))^2}{2}} \cos[k_c(\Lambda_I - \Lambda_S)] + \right. \\
 & + e^{-\frac{(\sigma_k(\Lambda_I + \Lambda_S))^2}{2}} \cos[k_c(\Lambda_I + \Lambda_S)] + \\
 & + 2e^{-\frac{(\sigma_k(\Lambda_I))^2}{2}} \cos(k_c\Lambda_I) + \\
 & + 2e^{-\frac{(\sigma_k(\Lambda_S))^2}{2}} \cos(k_c\Lambda_S) + \\
 & \left. + \frac{\sqrt{2\pi}}{8} \sigma_k \right] , \quad (4.31)
 \end{aligned}$$

where σ_k is the width at $1/e^2$ of the Gaussian spectrum, k_c is the central angular wave number of the Gaussian spectrum, and Figure 4.12b shows its graphical representation.

In both situations, the dominant terms are dependent on the difference and sum of the optical paths. Furthermore, the maximum of the signal occurs when the interrogator and the sensor cavities are identical. In these signals, the envelope is described by the term involving the subtraction of the OPDs, and the carrier is described by the term involving the sum of the OPDs. It is further

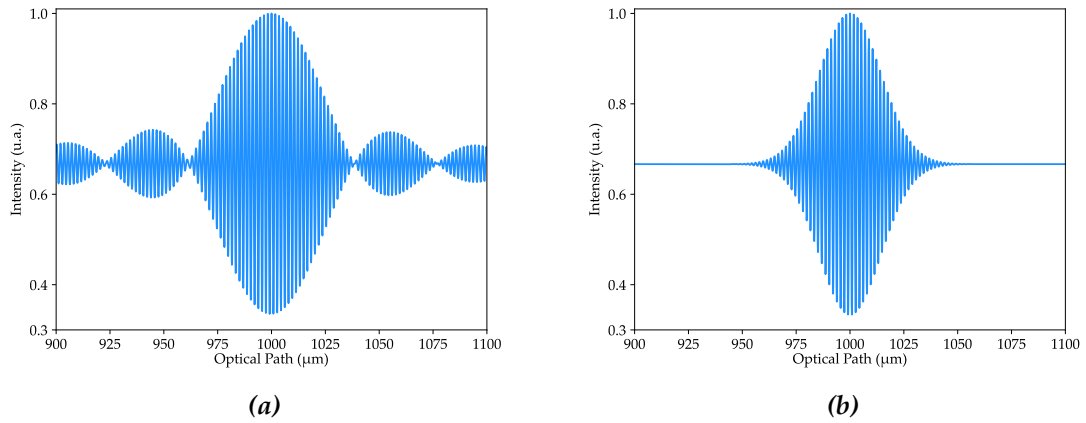


Figure 4.12: Graphical representation of the photodetector signal when implementing an optical source: (a) Flat and (b) Gaussian.

observed that a constant component emerges in the signal due to the presence of a minimum number of interferometric fringes along the interrogation (Fig. 4.12). The optical source also plays a crucial role in controlling the geometry of the side lobes - as observed in Figure 4.12a - where the signal obtained from a Gaussian spectrum source is characterised by the absence of side lobes (Fig. 4.12b). Furthermore, an increase in the optical bandwidth (Fig. 4.13a) and a decrease in signal wavelength (Fig. 4.13b) have been shown to result in a reduction of the envelope width.

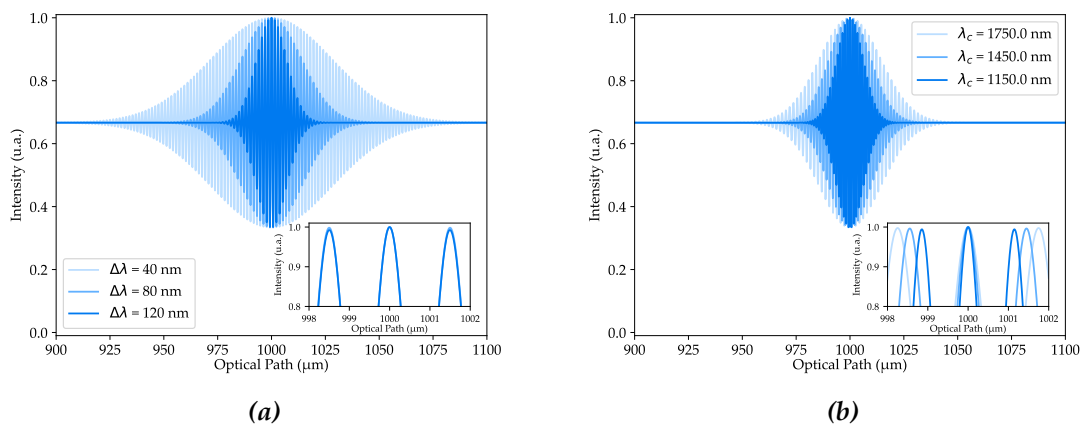


Figure 4.13: Variations of the photodetector signal depending on the characteristics of the optical source: (a) variation of the width of the optical source and (b) variation of centre wavelength of the optical band.

Another characteristic is the carrier frequency, which is determined by the wavelength of the optical source (Fig. 4.13.b). It is important to note that the frequency is lower the shorter the wavelength at which the optical band is located. Consequently, when multiple optical sources overlap, a beat occurs between the different carriers, thereby limiting the region of interest for the measurement (Fig. 4.14).

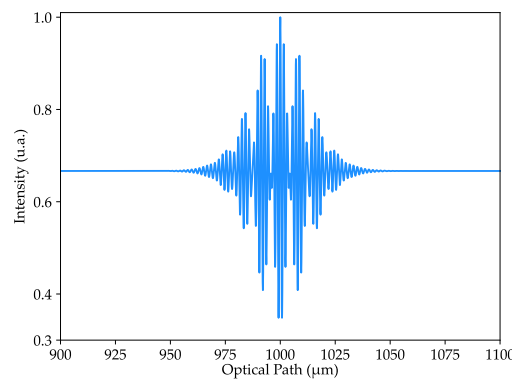


Figure 4.14: Photodetector signal when two Gaussian optical sources are implemented: one centred at 1750 nm and 80 nm-width, and the other centred at 1650 nm and 80 nm-width.

It should be noted that the system can also be illuminated using a laser, although this is no longer considered a WLI (as observed in Fig. 4.15). Due to the narrow-spectrum source, the envelope exhibits a flat geometry, and measurements are limited to the carrier. Although the measurements are confined to a 2π sensor variation, it is possible to obtain an oscillating function

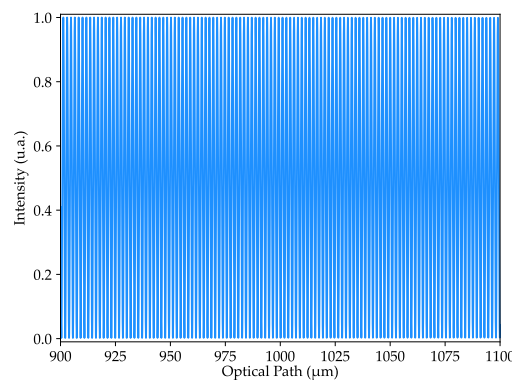


Figure 4.15: Photodetector signal when implementing a laser.

across the entire measurement range of the interrogator. This feature enables the generation of an error function to correct for the non-linear displacement of the actuator, based on the measurement of the signal's instantaneous frequency.

4.4 Conclusions

This Chapter focused on the operation of an interferometric sensor, the Vernier effect, and low-coherence interferometry (LCI), also known as white-light interferometry (WLI). The theoretical model of 2-wave interferometers and a study of the sensitivity curve were presented. In the development of the model, a range of spectral extremes were analysed, demonstrating that sensitivity increases with increasing FSR and both increase with decreasing OPD. The maximum possible sensitivity, 2 nm/nm, was also ascertained.

Moreover, a comprehensive investigation was conducted on the 3-wave and 4-wave interferometer, with particular emphasis on the Vernier effect. The theoretical model demonstrates that the geometry of the spectrum for the 4-wave interferometer of parallel cavities is equivalent to the geometry of the spectrum for the 3-wave interferometer. It was also demonstrated that this effect enables the sensitivity curve to be shifted, thereby locating the region of maximum sensitivity in the reference cavity. Furthermore, it was shown that the implementation of the Enhanced variant doubles the sensitivity for extremes of the same order when compared to the Traditional variant. The implementation of the states, when the different harmonics are achieved by increasing the reference cavity, allows extremes of the same order to be obtained with increased sensitivity (amplification factor of $m + 1$), since the FSR of the envelope decreases and allows the extremes to be brought closer to the balanced state ($\Delta L = 0$), where sensitivity is higher. Conversely, when the distinct harmonics are achieved through an increase in the sensing cavity, the sensitivity of the extremes of the same order is analogous to that of the 2-wave interferometer. However, it is important to note that the sensitivity curve associated with the Vernier effect remains the

same as that of a 2-wave interferometer, regardless of the implementation of the Vernier effect. This conclusion indicates that the amplification is apparent. Furthermore, a novel figure of merit (FoM) has been introduced, which facilitates a comparative analysis of different implementations of the Vernier effect. When the three variants were considered, it was found that FoM took the values 0, 1, and 2 for the Reduced, Traditional, and Enhanced variants, respectively. In the case of the different states, and for the case in which the harmonics were generated by increasing the reference cavity, $FoM_{Vernier}$ took values of $m + 1$. Conversely, when the harmonics were attained via the sensor cavity, $FoM_{Vernier}$ assumed the value of 1, independent of the order of the harmonic.

Finally, a descriptive model of white light interferometry, also known as low-coherence interferometry, was presented. These descriptions emphasised the implementation of the flat and Gaussian spectrum sources, with the Gaussian source allowing side lobes to be cancelled out. It was also concluded that reducing the width of the envelope could be achieved either by increasing the width of the optical source or by implementing shorter wavelengths. With regard to the variation in carrier frequency, this increased as the wavelength of the optical source decreased.

Thus, the present Chapter delineated the theoretical foundation supporting Chapters 5, 6, and 7.

Chapter 5

Fibre optic sensor configurations based on the Vernier effect

The Vernier effect arises from the superposition of fringes generated by two interferometers, producing a characteristic beat pattern. This beat comprises two components: the envelope and the carrier [156, 157, 158]. The envelope exhibits fringes with an equivalent optical cavity corresponding to the difference between the two interferometric cavities, thereby enhancing sensitivity. In contrast, the carrier presents fringes whose equivalent optical cavity corresponds to the sum of the two interferometric cavities.

In the context of its application, the Vernier effect can be categorised into different variants and states. The variants are divided into three categories: reduced, traditional, and enhanced, with the latter being the most sensitive (see Section 4.2.3.1). Furthermore, the Vernier effect has been observed to manifest itself in various states: Fundamental or Harmonics, whose occurrence derives from the relationship between the two cavities, $\Delta L_1 \sim (m + 1) \Delta L_2$, where ΔL_1 and ΔL_2 are the lengths of the two cavities and m represents the order of the state (see Section 4.2.3.2).

This Chapter presents the practical implementation of the theoretical Vernier effect model described in Chapter 4 and explores different optical fibre configurations that use this effect. The study begins with a description of a

drop-shaped structure constructed at the fibre tip, enabling the development of three-wave interferometry, where the Fundamental state, as well as the first and second Harmonics are studied. An implementation of the Enhanced Vernier effect using the push-pull method is also described, which is applied to two Fabry-Perot interferometers (FPI). In this section, the figure of merit is experimentally determined. Furthermore, the study focuses on the enhanced Vernier effect in both the Fundamental and the first Harmonic state using two fibre loop mirrors (FLM). Finally, it is explored the use of high-birefringence (Hi-Bi) optical fibres with symmetrical responses, the application of the push-pull method to examine the region where the Vernier effect exhibits maximum sensitivity.

5.1 Three-wave interferometry based on fibre tip sensing structure

The study is focused on the development of an optical displacement sensor. This sensor is based on a drop-shaped microstructure, which is spliced onto the cladding of the optical fibre tip. The practical implementation of the fundamental state, as well as the first and second harmonics of the traditional Vernier effect, are thereby explored (fig.5.2) [159].

The sensor fabrication process employed a conventional splice machine (Sumitomo Electric Type-72C, Osaka, Japan) and SMF28e optical fibre (see Fig. 5.1). The fabrication began with the application of an electric arc discharge (100 a.u. and 10 seconds) to two cleaved fibre tips, with simultaneous strain applied to both fibres (Fig. 5.1a). This process enabled the formation of two tapered tips (Fig. 5.1b). Subsequently, a tapered tip was manually spliced to a cleaved tip. During this step, an electric arc discharge with a power of 100 a.u. and a duration of 4 seconds was applied to the tapered tip, which was deliberately misaligned from the joint region (Fig. 5.1c). The application of an arc discharge at the end of the tapered section (Fig. 5.1c) resulted in the detachment of the tapered structure from the remaining optical fibre. Consequently, a drop-shaped microstructure

was formed at the fibre tip (Fig. 5.1d), measuring $193\ \mu\text{m}$ in length and $88\ \mu\text{m}$ in width, and the junction region, where the microstructure connects to the optical fibre, has a diameter of $20\ \mu\text{m}$.

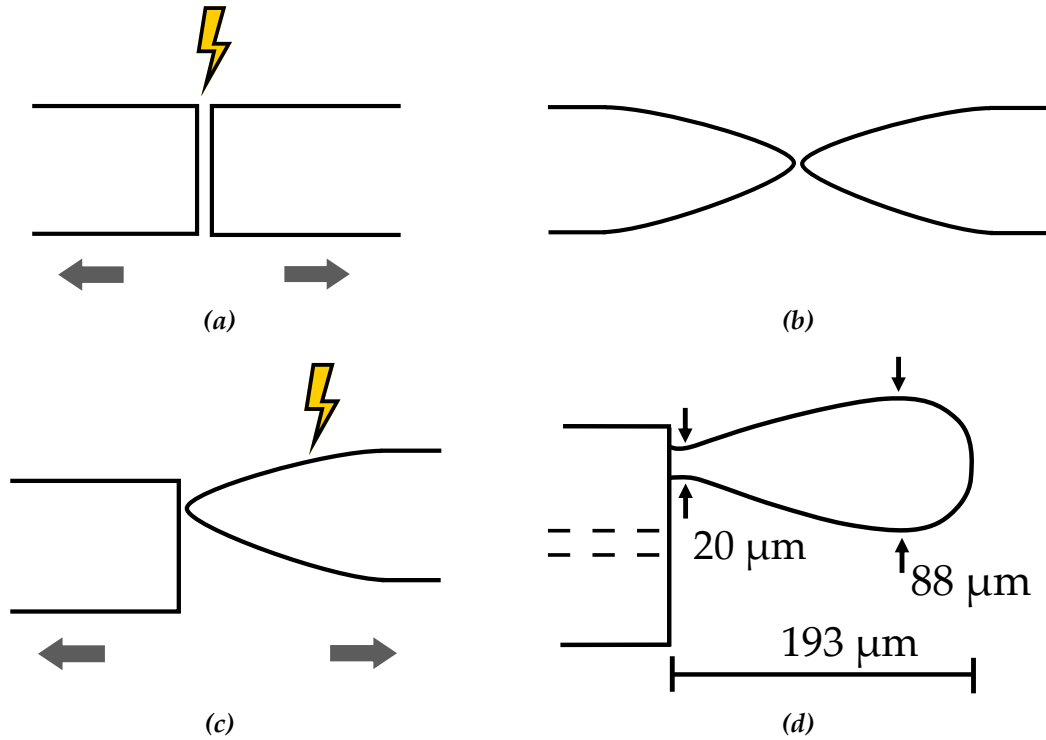


Figure 5.1: Fabrication process of the drop-shaped optical microstructure at the fibre tip: (a) Arc discharge applied to two cleaved fibre tips under strain; (b) formation of two tapered tips; (c) misaligned tapered tip manually spliced to a cleaved fibre tip; (d) detachment of the tapered structure from the remaining optical fibre, resulting in the formation of a drop-shaped microstructure.

The three-wave interferometry is enabled by the implementation of a drop-shaped microstructure (see optical paths A, B and C in Fig. 5.2b). Upon reaching the fibre's extremity, the light is reflected and transmitted. The reflection process generates optical path A, while the transmitted light generates two additional optical paths (B and C). The recoupling of light into the optical fibre is facilitated by the drop-shaped microstructure, resulting in the formation of optical path B. The application of a mirror in front of the system also enables the recoupling of light into the optical fibre, thereby creating optical path C. The reference optical cavity is formed by the overlap of optical paths A and B, since the drop-microstructure is insensitive to the displacement. The sensing optical

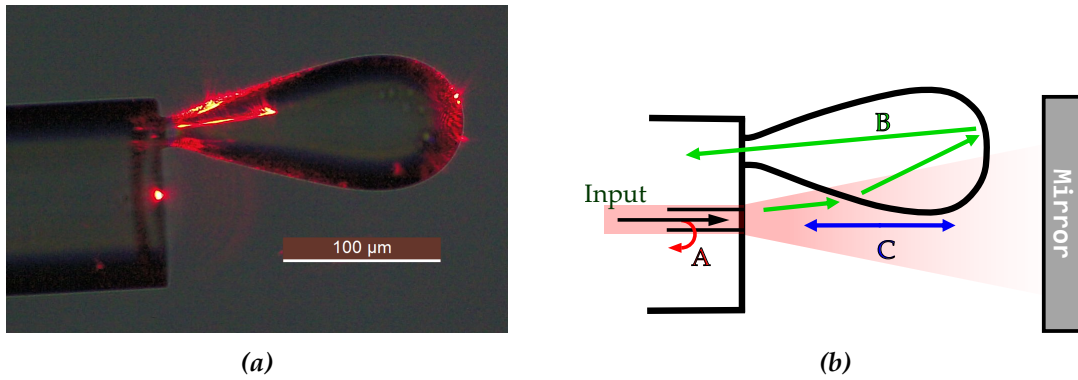


Figure 5.2: Operating principle of the drop-shaped microstructure: (a) image of the structure illuminated by a helium-neon laser through the optical fibre core and (b) schematic representation of the sensor.

cavity is formed by overlapping optical paths A and C, since the position of the mirror will be changed by a PZT during characterisation, simulating a particular object to be tracked. The interaction of these three optical paths gives rise to the traditional Vernier effect.

The characterisation scheme, illustrated in Figure 5.3, utilised a broadband source centred at 1560 nm, with a bandwidth of 100 nm at 3 dB. The setup also included an optical fibre circulator, an optical spectrum analyser (Advantest Q8384) with a resolution of 0.02 nm, and an SMF-28e optical fibre. Additionally, an aluminium-coated flat mirror was coupled to a PZT with a displacement of 32.8 ± 0.2 nm/V. The optical fibre was mounted on a micrometric translation stage, allowing for the fine tuning of different harmonics of the Vernier effect.

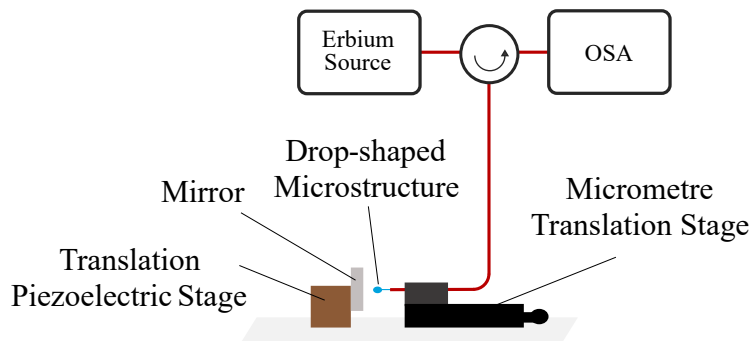


Figure 5.3: Set-up diagram for sensor characterisation

The initial step involved analysing the output spectrum of the developed sensor in the absence of a mirror, allowing for the evaluation of the reference

cavity (Fig. 5.4). The output spectrum comprises interferometric fringes associated with an free-spectral range (FSR) of 4.2 ± 0.1 nm, corresponding to a reference cavity length of 267.9 ± 0.5 μm - a value that was confirmed through microscope imaging (Fig. 5.2a).

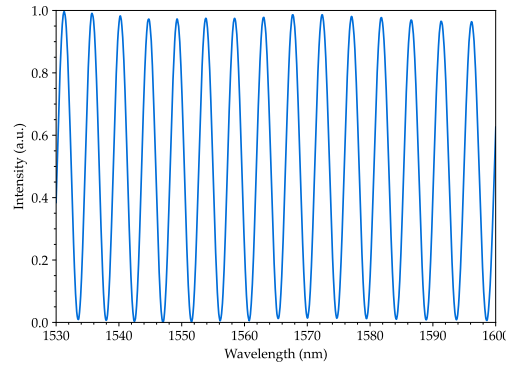


Figure 5.4: Output spectrum of the reference cavity

Subsequently, the Fundamental state and the first Harmonic were characterised (Fig. 5.5), with the sensor cavities (recall Figure 5.2) following the relationship described in Equation 5.1.

$$\Delta L_{\text{sensor}} = (m + 1) \Delta L_{\text{reference}} + dL, \quad (5.1)$$

where ΔL_{sensor} and $\Delta L_{\text{reference}}$ are the sensor cavity and the reference cavity lengths, respectively, m is the order of the Harmonic and dL is the detuning length. The tuning of the sensor cavity to produce the two states was achieved by the micrometric translation stage.

By analysing the output spectrum associated with the Fundamental state (Fig. 5.5a), it is possible to determine the difference between the sensor cavity and the reference cavity based on the FSR of the envelope. Given that the FSR of the envelope is 40.2 ± 0.1 nm, the corresponding detuning length is 29.9 ± 0.1 μm .

Since an increase in the sensor cavity length shifts the fringes toward longer wavelengths, the sensor cavity length is calculated to be 297.8 ± 0.6 μm . For the first Harmonic, the FSR of the envelope is 63.1 ± 0.5 nm, leading to a detuning length of 19 ± 1 μm (Fig. 5.5b). As the fringes shift toward longer

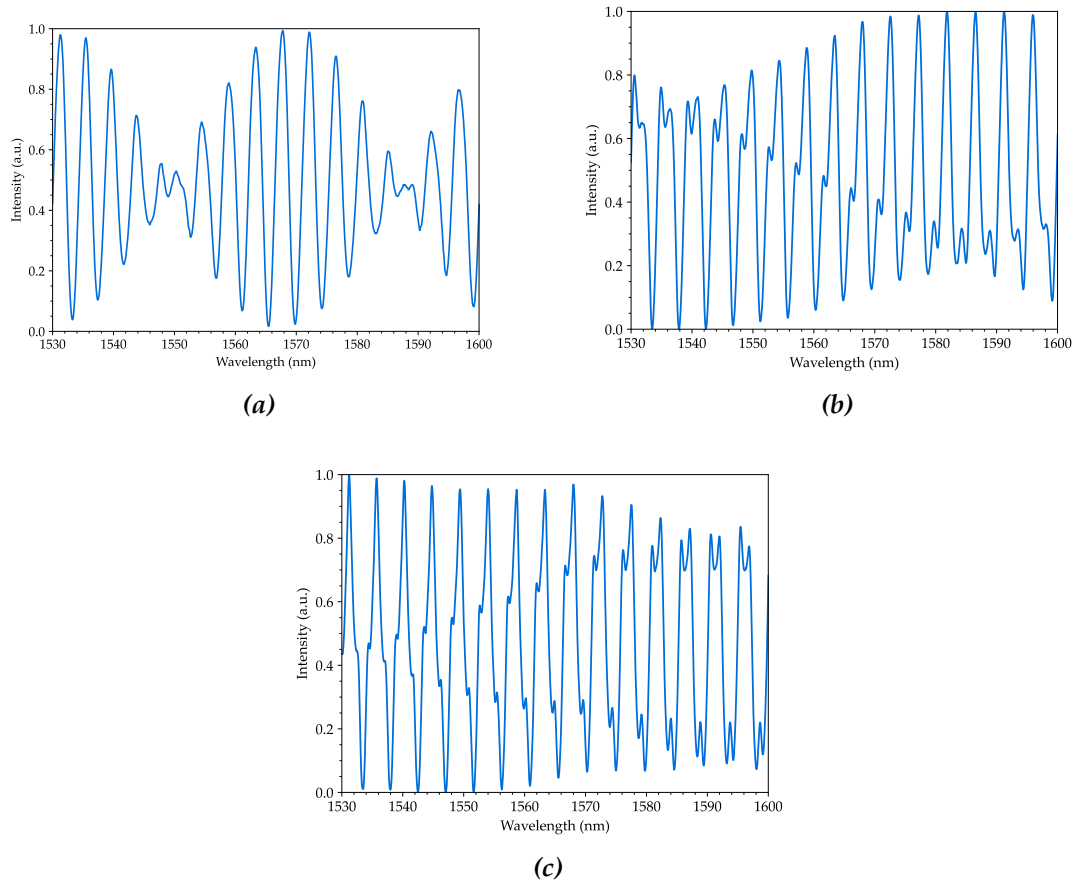


Figure 5.5: Optical spectrum of: (a) Fundamental state, (b) first Harmonic, and (c) second Harmonic

wavelengths, the sensor cavity length is determined to be $555 \pm 1 \mu\text{m}$. For the second Harmonic, the FSR of the envelope is $73 \pm 1 \text{ nm}$, resulting in a detuning length of $16 \pm 1 \mu\text{m}$ (Fig. 5.5c). In this case, since the fringes shift toward shorter wavelengths, the sensor cavity length is $787 \pm 1 \mu\text{m}$.

The corresponding sensitivities achieved for the Fundamental state, first and second Harmonics, are presented in Figure 5.6 and summarised in Table 5.1. Additionally, the sensitivity values exhibit a coefficient of determination (r^2) greater than 0.996, indicating a strong correlation. Table 5.1 also provides the FSR , magnification factor ($M = Sens_{env}/FSR_{env}$) and figure of merit ($FoM_{Vernier} = M_m/M_0$) for each case (see section 4.2.4).

The figure of merit achieved is 1 for all three cases. Given that the sensor cavity is larger, this sensor serves as a practical demonstration of the

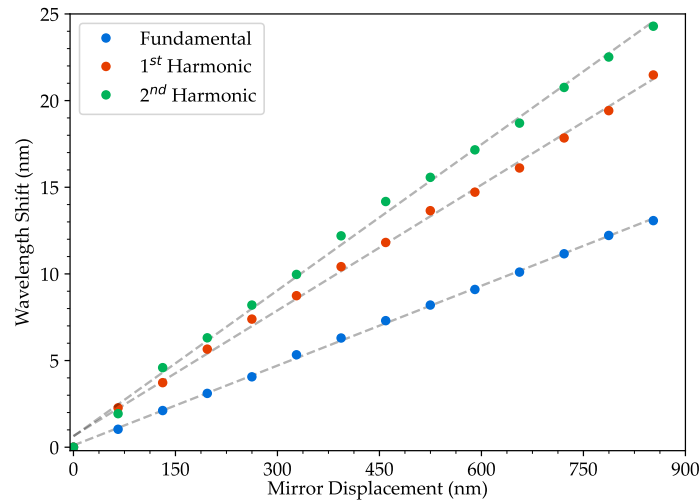


Figure 5.6: Sensitivity results for the Fundamental state, first Harmonic, and second Harmonic

theoretical framework described in Chapter 4 concerning the Harmonics of the Vernier effect. Additionally, the results highlight the system's potential as a micrometre-scale displacement sensor, achieving a resolution of 0.7 nm. A particularly noteworthy feature of this system is its capability for non-contact measurement, which enhances its applicability in various sensing environments.

5.2 Push-pull method in Fabry-Perot interferometers

This Section focuses on the application of the enhanced Vernier effect through the push-pull method, utilising two FPIs. This method is based on a sensor structure that symmetrises the response of both interferometers to the same variation in the physical quantity under investigation [160]. To achieve this, the measurement point is shared by both interferometers, which are aligned in parallel but oriented in opposite directions.

The developed system consists of two FPIs, implemented using two cleaved fibre tips and a double-sided reflecting mirror (Fig. 5.7). Both FPIs were connected in parallel via a 3 dB optical fibre coupler, which performed two primary functions: (i) splitting the input signal and (ii) superimposing the output signals from both interferometers. The system was illuminated by an

Table 5.1: Sensitivity values, FSR, M-factor and figure of merit for the Fundamental state, first and second Harmonic.

	Sensitivity (nm/ μm)	FSR (nm)	M (10^{-3}nm)	FoM_{Vernier}
Fundamental	15.1 ± 0.1	40.2 ± 0.1	0.38 ± 0.005	1.00 ± 0.01
1st Harmonic	24.7 ± 0.3	63.1 ± 0.5	0.39 ± 0.01	1.02 ± 0.03
2nd Harmonic	28.3 ± 0.3	73 ± 1	0.39 ± 0.01	1.02 ± 0.03

erbium-doped fibre source, with a central wavelength of 1565 nm and a 90 nm spectral bandwidth. The output signal was analysed using an optical spectrum analyser (OSA) (YOKOGAWA AQ5370C) with a resolution of 0.02 nm.

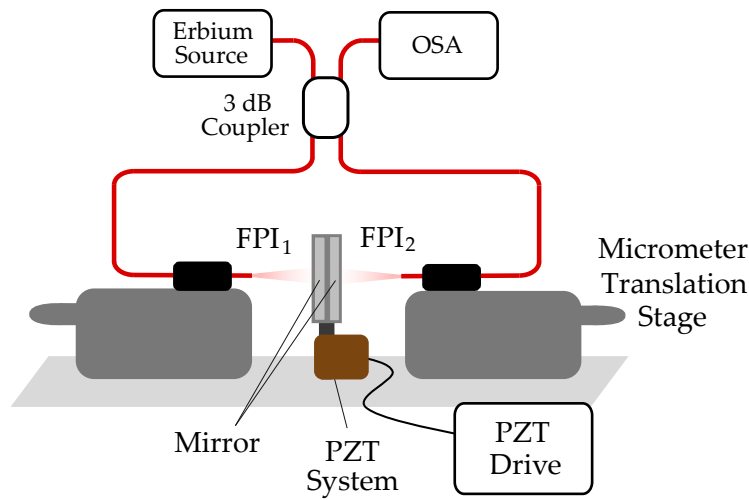


Figure 5.7: Set-up diagram for sensor characterisation

The characterisation process involved a double-sided mirror coupled to a PZT, with a displacement sensitivity of 180 ± 0.2 nm/V. Fibre optic splices were made using a conventional fusion splicing machine (Sumitomo Electric Type-72C, Osaka, Japan), while fibre cleaving was performed using the Fiber Cleaver FC-6RS.

The system operates by dynamically adjusting the mirror position, ensuring that as the cavity length of one interferometer (FPI_1) increases and the cavity length of the other (FPI_2) decreases proportionally. A key objective of this study is to compare the performance of a single FPI (FPI_1) with that of the enhanced Vernier effect, achieved using two FPIs (FPI_1 and FPI_2). Accordingly, the first step involved characterising an individual FPI (FPI_1 , see Figure 5.7).

Figure 5.8 presents the spectra for FPIs studied. Concerning FPI₁, an FSR_1 of 16.5 ± 0.1 nm was obtained, corresponding to a cavity length of 73 ± 1 μ m (Fig. 5.8a). By varying the mirror's position, a sensitivity of 29.2 ± 0.2 nm/ μ m was determined, with a coefficient of determination (r^2) of 0.9995. These values serve as the reference for evaluating the performance of the enhanced Vernier effect (Enhanced variant with two FPIs).

Next, the cavity length was increased to achieve a higher carrier spectral frequency, thereby increasing the number of extremes and improving the precision of envelope determination. As a result, an FSR_1 of 0.079 ± 0.001 nm was obtained (Fig. 5.8b), corresponding to a cavity length of 15.2 ± 0.3 mm, and with an associated sensitivity of 0.95 ± 0.05 nm/ μ m.

Following this, a second FPI (FPI₂) was introduced and calibrated to achieve an envelope FSR similar to that of the reference case. This setup resulted in an envelope FSR_2 of 18.0 ± 0.1 nm (Fig. 5.8c), corresponding to a cavity length difference of 66.7 ± 0.4 μ m, and a sensitivity of 60 ± 1 nm/ μ m. This sensitivity is twice that of an individual FPI (FPI₁) with a nearly identical FSR , demonstrating the magnification effect of the enhanced Vernier configuration (Enhanced variant).

Finally, the cavity length difference was further reduced to maximise sensitivity while considering the spectral bandwidth limitations of the optical source (Fig. 5.8d). This was achieved using a cavity length of 6.1 ± 0.2 nm in each FPI, resulting in an FSR of 75.1 ± 0.1 nm, a cavity length difference of 15.99 ± 0.02 μ m, and an enhanced sensitivity of 254 ± 6 nm/ μ m (maximised enhanced variant).

The sensitivity values obtained from the characterisation of FPI₁ alone and the implementation of the enhanced Vernier effect (both FPI₁ and FPI₂), are depicted in Figure 5.9 and summarised in Table 5.2. Additionally, Table 5.2 presents the FSR , magnification factor (M), and figure of merit ($FoM_{Vernier}$), for each case.

As described in Chapter 4, the figure of merit is determined using the magnification factor of an individual FPI as a reference (M_0), since its performance

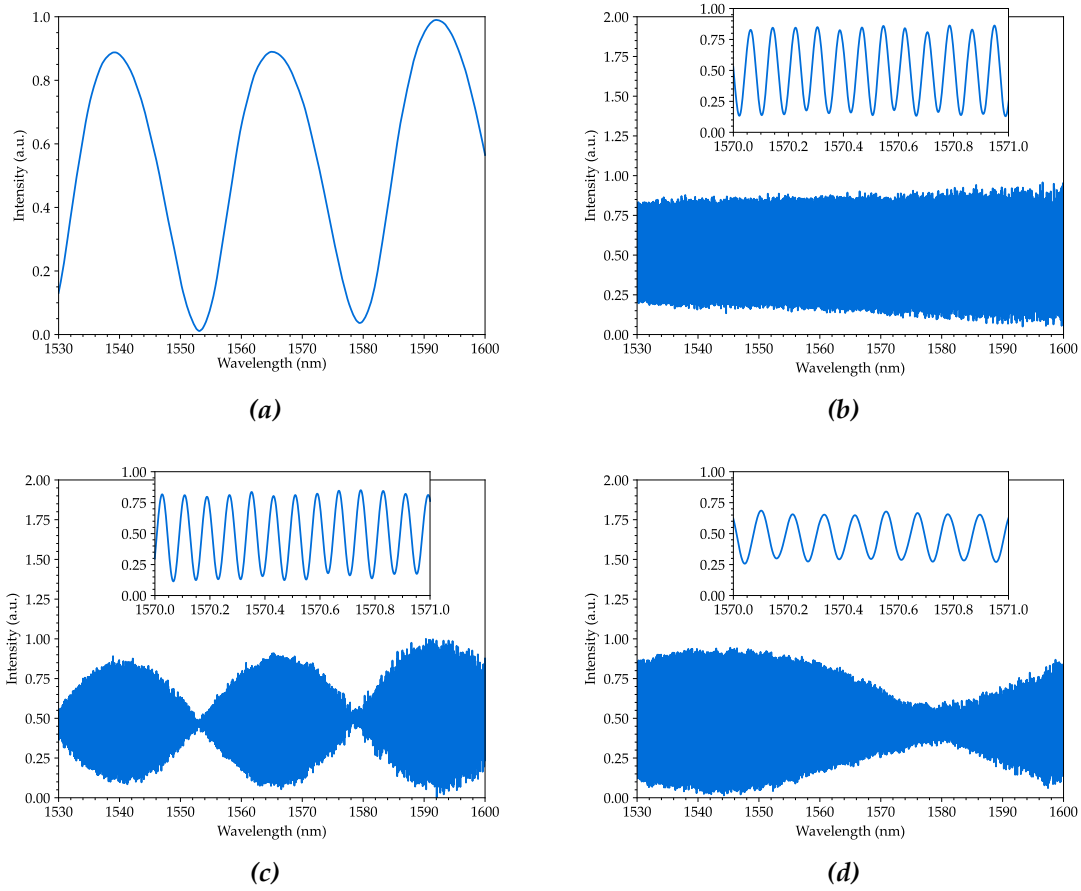


Figure 5.8: Output signal of: (a) 73 μm -long FPI_1 , (b) 15.2 mm-long FPI_1 , (c) enhanced Vernier variant ($\text{FPI}_1 + \text{FPI}_2$, cavity length difference of 66.7 μm), and (d) maximised enhanced Vernier variant ($\text{FPI}_1 + \text{FPI}_2$, cavity length difference of 15.99 μm).

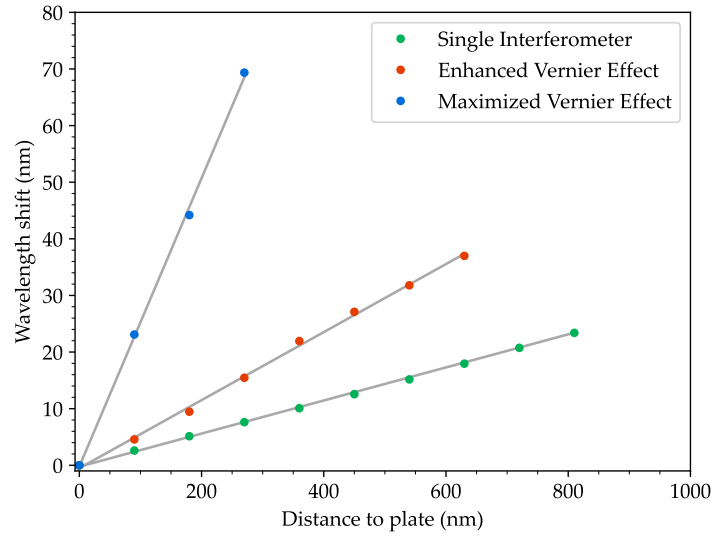


Figure 5.9: Sensitivity results for a single interferometer (73 μm -long FPI1), enhanced Vernier variant (FPI₁ + FPI₂, cavity length difference of 66.7 μm), and maximised enhanced Vernier variant (FPI₁ + FPI₂, cavity length difference of 15.99 μm)

is equivalent to that of the traditional Vernier effect variant. Consequently, for the implementation of the enhanced Vernier effect, the figure of merit is 2.1 ± 0.2 . The increase in sensitivity of the second implementation of the enhanced Vernier effect in the Fundamental state is achieved by reducing the detuning length. Furthermore, the results confirm that higher sensitivity is directly associated with an increase in the *FSR*.

5.3 Fiber Loop Mirror configurations

The FLM sensor consists of a coupler connected to a Hi-Bi fibre in a closed-loop configuration. Its operation relies on tuning the polarisation state of the input light beam using a polarisation controller to excite two orthogonally polarised propagation modes within the Hi-Bi fibre, thereby generating two distinct optical paths [161]. The path difference arises from the refractive index difference associated with each propagation mode. These optical paths are then recombined by the coupler, producing an interference pattern. FLM sensors are widely used

Table 5.2: Sensitivity values, FSR, M-factor and figure of merit for the single FPI, enhanced Vernier effect and its sensitivity maximisation.

	Sensitivity (nm/ μm)	FSR (nm)	M (μm^{-1})	FoM _{Vernier}
FPI individual	29.2 ± 0.2	26.5 ± 0.1	1.10 ± 0.02	1.00 ± 0.01
Enhanced variant	60 ± 1	26.0 ± 0.1	2.23 ± 0.2	2.1 ± 0.2
Maximised Enhanced variant	254 ± 6	75.1 ± 0.1	3.4 ± 0.2	3.1 ± 0.2

for measuring physical parameters such as strain and temperature [162]. This configuration is also referred to as a Sagnac interferometer.

In this study, a strain sensor based on an enhanced variant of the Vernier effect in the fundamental, first, and second harmonic states will be presented. The sensor will use two FLM Hi-Bi optical fibres with antiparallel strain responses. Furthermore, the present study investigates the potential of the push-pull method, which employs an FLM with two segments of Hi-Bi fibres, in enhancing the Vernier effect.

5.3.1 Fiber loop mirror in tandem configuration

The enhanced Vernier effect requires two cavities that move in opposite directions. To achieve this, two FLMs were connected in series, each incorporating birefringent fibres with antiparallel strain responses [155]. In this section, the study of the enhanced Vernier effect in the Fundamental and first Harmonic states.

The schematic diagram in Figure 5.10 illustrates the sensor characterisation setup. It consists of two FLMs illuminated by an erbium-doped fibre source, centred at 1560 nm with a 100 nm spectral bandwidth. The output signal was analysed using an optical spectrum analyser (OSA) (YOKOGAWA AQ5370C) with a 0.02 nm resolution. Each FLM comprises a 3 dB optical fibre coupler, a polarisation controller (Thorlabs FPC560), and a Hi-Bi fibre arranged in a closed loop. To establish interferometric cavities with opposite strain responses, FLM₁ incorporates a fibre section with Internal Elliptical Cladding (IEC), characterised by a birefringence parameter $\beta = 5.1 \times 10^{-4}$, while FLM₂ employs an e-core fibre section with $\beta = 3.85 \times 10^{-4}$. The strain is applied to two fibres concurrently via

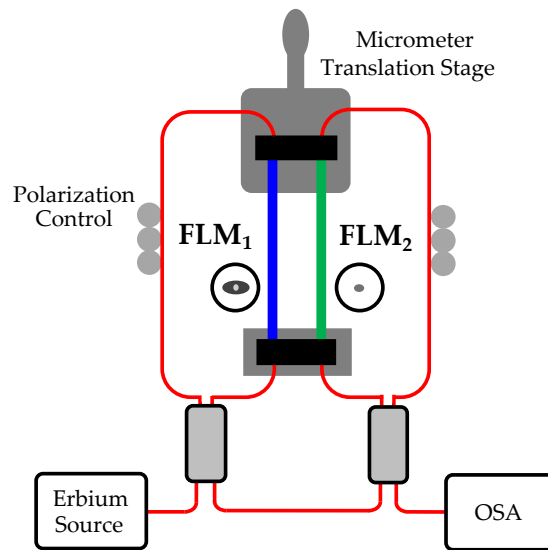


Figure 5.10: Set-up diagram for sensor characterisation

a micro-metric translation stage at the point they are coupled. The assembly of the two FLMs was performed using a Sumitomo Electric Type-72C fusion splicer (Osaka, Japan) and SMF28e fibre.

The optical characterisation process began with an individual analysis of each FLM spectrum, as depicted in Figure 5.11. For the FLM₁, an FSR_1 of 4.52 ± 0.01 nm was obtained, corresponding to a fibre length of 0.976 ± 0.002 m, with a strain sensitivity of 15.46 ± 0.02 pm/ $\mu\epsilon$. In the case of FLM₂, the measured FSR_2 was 5.95 ± 0.01 nm, corresponding to a fibre length of 0.982 ± 0.002 m, and a strain sensitivity of -2.41 ± 0.01 pm/ $\mu\epsilon$. Both sensitivity measurements exhibited a determination coefficient (r^2) greater than 0.9997 (see Figure 5.13).

By connecting the two FLMs in series, the Vernier effect was implemented (recall Figure 5.10). Given the similar optical path differences between the FLMs, the Fundamental state emerged, as observed in Figure 5.12a. Under these conditions, an FSR of 22.5 ± 0.1 nm and a strain sensitivity of 80.0 ± 0.3 pm/ $\mu\epsilon$ were achieved.

Next, the e -core section fibre was halved, enabling the first Harmonic generation (Figure 5.12b). In this case, an FSR of 31 ± 1 nm and a sensitivity of 120 ± 1 pm/ $\mu\epsilon$ were achieved. Both sensitivity measurements exhibited a coefficient of determination (r^2) greater than 0.9990 (see Figure 5.13).

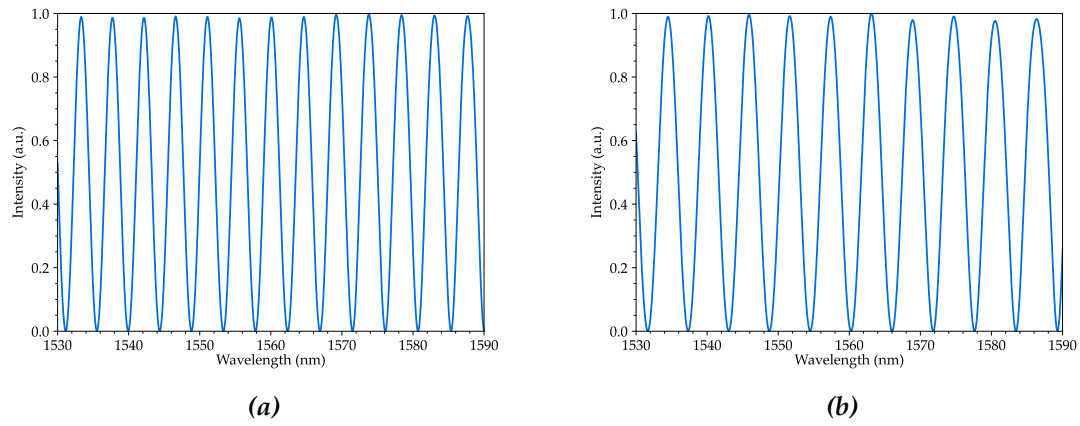


Figure 5.11: Optical spectrum of: (a) FLM1 (Internal Elliptical Cladding), and (b) FLM2 (e-core fiber).

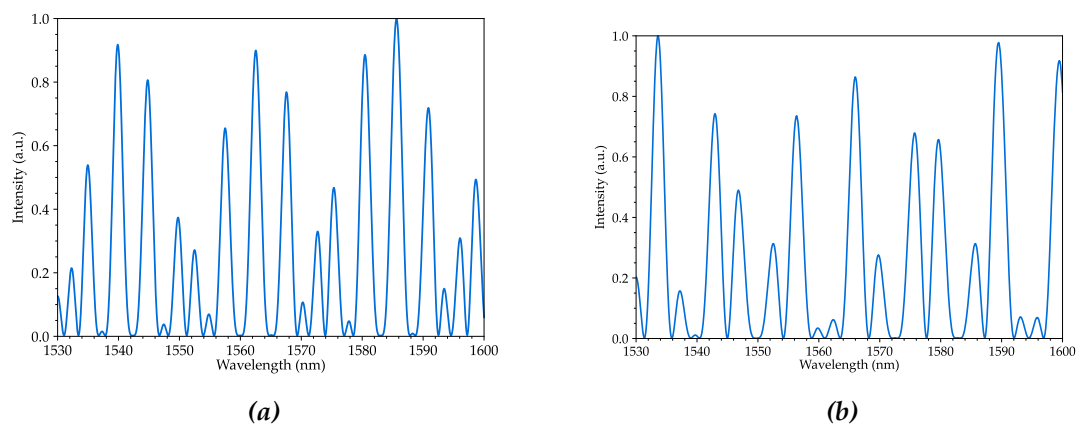


Figure 5.12: Optical spectrum of: (a) Fundamental state and (b) first Harmonic.

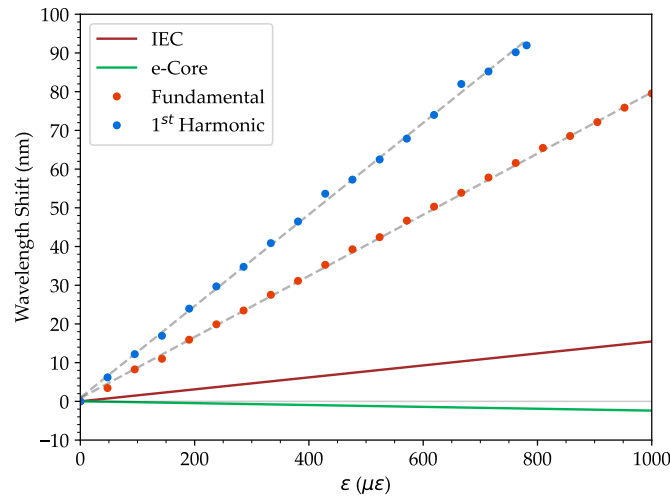


Figure 5.13: Sensitivity results for FLM₁ (IEC), FLM₂ (e-core), Fundamental state, and first Harmonic.

Figure 5.13 illustrates the sensitivity results obtained for FLM₁, FLM₂, the Fundamental state, and the first Harmonic. Table 5.3 summarises the sensitivity values, FSR , magnification factor (M), and figure of merit ($FoM_{Vernier}$) for each case.

Table 5.3: Sensitivity values, FSR , M and figure of merit for the enhanced Vernier effect Fundamental state and first Harmonic of the enhanced Vernier effect.

	Sensitivity (pm/ $\mu\epsilon$)	FSR (nm)	M ($10^{-3}\mu\epsilon^{-1}$)	$FoM_{Vernier}$
Fundamental	80.0 ± 0.3	22.5 ± 0.1	3.55 ± 0.02	1.00 ± 0.01
First Harmónico	120 ± 1	31 ± 0.5	3.9 ± 0.1	1.10 ± 0.04

Since the $M_{Vernier}$ of the first Harmonic is greater than 1 (considering the uncertainties in the experimental results), the use of Hi-Bi fibre with opposite strain responses enables the practical implementation of high-sensitivity measurements. However, the achieved value remains close to 1, as the sensitivity of the e-core section fibre accounts for only 15.6% of that of the IEC section fibre.

5.3.2 Push-Pull method in a single FLM

The push-pull method is applied to interferometric sensors by incorporating a mechanical structure that enables the two cavities to undergo symmetrical

actuation with the same variation in magnitude but in an antiparallel direction. This approach allows the application of a consistent sensor structure [148]. In the previously described system, the opposite directional response was an intrinsic property of the Hi-Bi fibres. However, in this case, since the antiparallel movement is extrinsic to the Hi-Bi fibre, it is possible to use two sensors fabricated from the same type of Hi-Bi fibre. This method maximises the performance of the enhanced Vernier effect.

Figure 5.14 illustrates the experimental setup, which comprises two non-balanced Mach-Zehnder interferometers (MZIs) arranged in series within an FLM. The MZIs are implemented using two identical bow-tie optical fibres, each measuring 1.25 ± 0.01 m, with a birefringence parameter of $\beta = 4.35 \times 10^{-4}$. These fibres are coupled to a micrometric translation stage at the connection zone, which serves as the measurement point of the system. Additionally, two polarisation controllers are positioned at the ends of the MZI set. The system is illuminated by an erbium-doped fibre source, centred at 1560 nm with a 100 nm spectral bandwidth, and the output signal is analysed using an optical spectrum analyser (OSA) (YOKOGAWA AQ5370C) with a resolution of 0.02 nm. A 3 dB optical fiber coupler is also integrated into the setup.

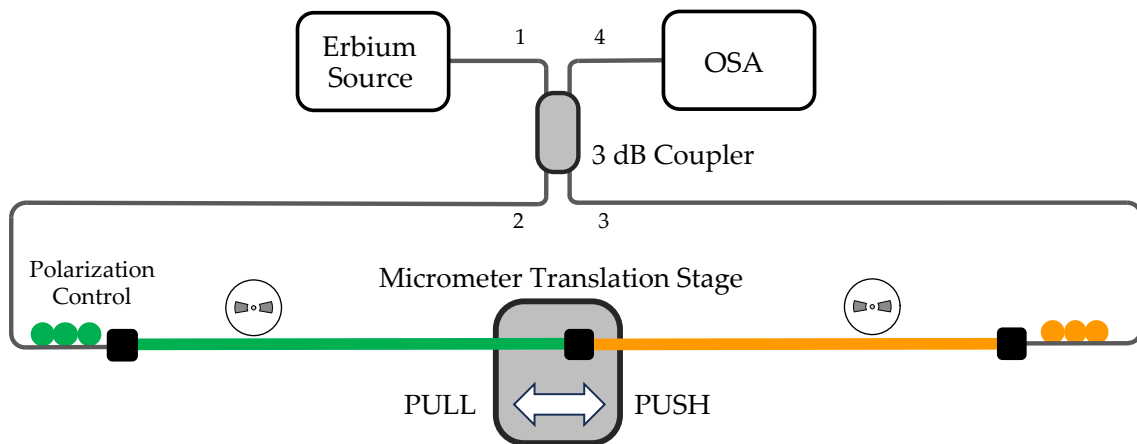


Figure 5.14: Experimental setup of the push-pull method.

A pre-strain is applied to the Hi-Bi fibres to ensure proper system operation, as an increase in strain in one fibre results in a corresponding reduction in the other. This pre-strain also serves in equalising the optical path difference, achieving a

balanced state (Figure 5.15a). When strain is applied using the push-pull method, an antiparallel variation occurs, causing the system to become unbalanced and leading to the emergence of an interference envelope (Figure 5.15b).

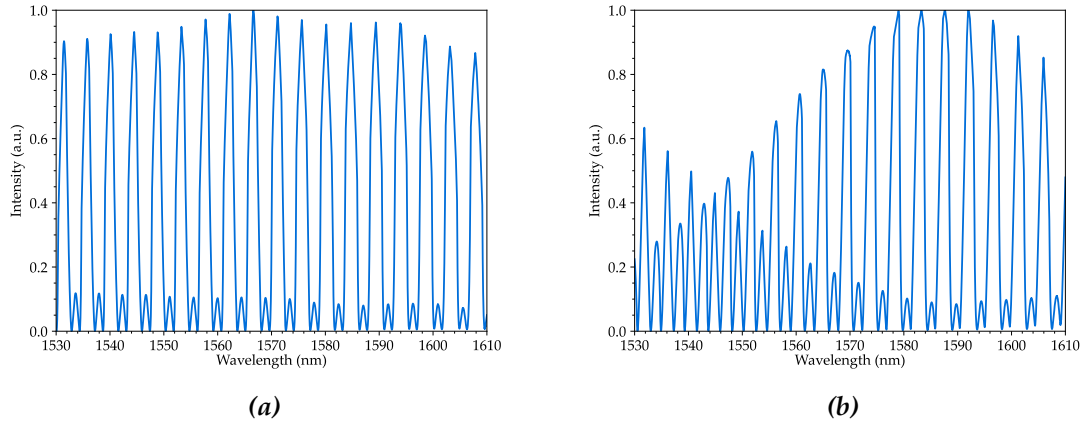


Figure 5.15: Push-pull method implementation: spectrum of the (a) balanced state, and (b) unbalanced state.

The experimental characterisation started with the individual testing of the Hi-Bi fibre utilising a micro-metric translation stage with step increments of $8 \mu\epsilon$. The system demonstrated a sensitivity of $29.31 \pm 0.01 \text{ pm}/\mu\epsilon$. Subsequently, the two Hi-Bi fibre sections were connected in series (Fig. 5.14). The push-pull method was applied with step increments of $8 \mu\epsilon$. Figure 5.16a presents the slope associated with each envelope fringe, while Figure 5.16b shows a two-dimensional plot depicting envelope variations as a function of strain. The red lines in Figure 5.16a represent the theoretical sensitivities as described in Chapter 4.

The sensor demonstrates higher sensitivity in regions close to the balanced state ($\Delta\epsilon = 0$). Considering the optical spectral bandwidth of the light source, the system achieves a maximum sensitivity of $10100 \pm 100 \text{ pm}/\mu\epsilon$, corresponding to a dynamic range of $8 \mu\epsilon$. As the unbalance between the interferometers increases, sensitivity decreases, with a minimum sensitivity of $1160 \pm 30 \text{ pm}/\mu\epsilon$, associated with a dynamic range of $80 \mu\epsilon$.

An analysis of the carrier fringes reveals a total variation of -0.36 nm throughout the measurement process. To accurately interpret this result, it

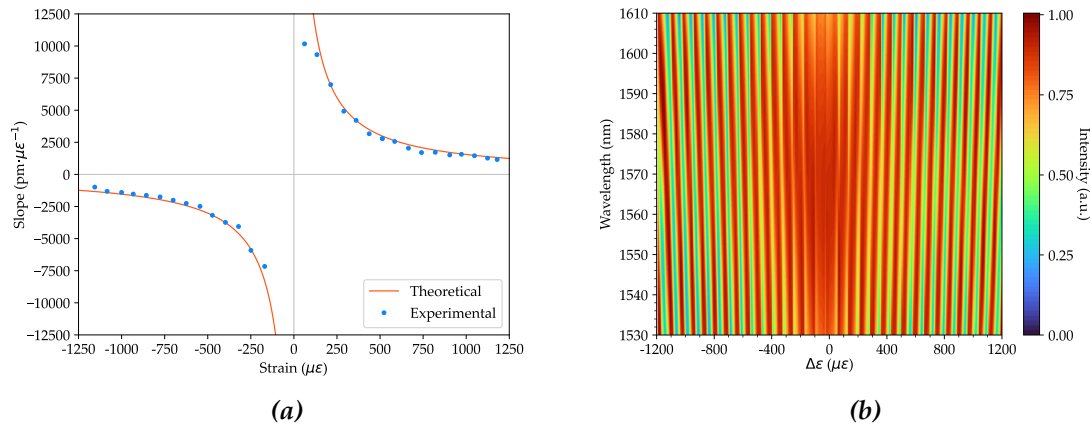


Figure 5.16: Sensitivity characterisation of the system: (a) slope associated with each envelope fringe and respective theoretical curve (red lines), and (b) two-dimensional graph depicting envelope variations as a function of strain.

is essential to consider not only the physical quantity being analysed but also external factors such as environmental temperature fluctuations. Since strain variation induces a symmetrical response in the interferometers, the measurements are derived from variations in the envelope state. In contrast, temperature fluctuations lead to an equal variation in both interferometers, allowing these variations to be measured via the carrier signal. Given that the temperature sensitivity of bow-tie fibres is $-1.23 \text{ nm}/^\circ\text{C}$ [162], the observed temperature variation of the Hi-Bi fibres during the measurement acquisition was 0.15°C .

This study demonstrates that maximising the performance of the enhanced Vernier effect can be achieved using the push-pull method. This approach ensures that the two interferometers respond antiparallely to the same physical quantity variation. Additionally, this method allows for precise system calibration, optimising operation within the region where the Vernier effect sensitivity curve reaches its maximum sensitivity. A sensitivity of $10100 \pm 100 \text{ pm}/\mu\epsilon$ was achieved, corresponding to a minimum measurement resolution of $2 \text{ n}\epsilon$, considering the OSA resolution of 0.02 nm . In addition, the carrier signal is susceptible to external factors, including temperature, which influence both interferometers proportionally.

5.4 Conclusions

In this Chapter, various optical fibre configurations that employ the optical Vernier effect were studied. The feasibility of employing a drop-shaped microstructure at the fibre tip to implement a 3-wave interferometer was demonstrated. Despite the varying sensitivities obtained – fundamental: $15.1 \pm 0.1 \text{ nm}/\mu\text{m}$, first harmonic: $24.7 \pm 0.3 \text{ nm}/\mu\text{m}$, and second harmonic: $28.3 \pm 0.3 \text{ nm}/\mu\text{m}$ – the figure of merit remained 1, as the sensing cavity corresponded to the larger cavity. Consequently, the sensitivity increase was attributed solely to the smaller detuning length rather than an intrinsic enhancement of the system's performance.

Following, the enhanced Vernier effect was implemented by using two FPIs with cavity lengths exceeding 10 mm, arranged in parallel. Based on the obtained results – a sensitivity of $29.2 \pm 0.2 \text{ nm}/\mu\text{m}$ and an FSR of $26.5 \pm 0.1 \mu\text{m}$ for the individual FPI, and a sensitivity of $60 \pm 1 \text{ nm}/\mu\text{m}$ with an FSR of $26.0 \pm 0.1 \mu\text{m}$ for the enhanced Vernier effect – the figure of merit was determined to be 2.1 ± 0.2 , aligning with the theoretical predictions outlined in Chapter 4. Furthermore, by optimising the system based on the optical source used, a maximum sensitivity of $254 \pm 6 \text{ nm}/\mu\text{m}$ was achieved.

The potential of the Vernier effect based on FMLs was also explored. Firstly, the enhanced variant combined with the fundamental and the first harmonic allowed achieving sensitivities of $80.0 \pm 0.3 \text{ pm}/\mu\epsilon$ and $120 \pm 1 \text{ pm}/\mu\epsilon$, respectively. The system's figure of merit was determined to be 1.10 ± 0.04 . This enhancement in sensitivity can be attributed to the implementation of the first Harmonic. Secondly, the capabilities of the push-pull method by implementing the Vernier effect were investigated. It was demonstrated that this method enables an antiparallel variation of the interferometers, allowing the implementation of equal interferometers. Furthermore, it facilitates the exploration of cavity differences where the Vernier effect exhibits the highest sensitivity. The system achieved a maximum sensitivity of $10100 \pm 100 \text{ pm}/\mu\epsilon$. Furthermore, the carrier signal is sensitive to external factors such as temperature,

as these factors influence both interferometers proportionally.

Concluding, the work presented in this Chapter was a practical demonstration of the theoretical modeling descriptions set out in Chapter 4. Also, it was demonstrated that the implementation of harmonics, in specific configurations, and the enhanced variant, facilitates an increase in sensitivity within a practical application. It was demonstrated that, while the sensitivity curve remains constant for a single interferometer as for the Vernier effect for the same detuning length, the reduction of the *FSR* allows the mitigation of the optical spectral bandwidth limitation of the optical source since spectral extremes appear closer to the condition of balanced interferometers.

Chapter 6

New concepts of interferometric configurations

The operation of interferometric sensors is achieved by monitoring the interferometric pattern resulting from the superposition of two or more optical paths. This superposition gives rise to a phase difference, which is determined by the optical path difference using a length difference between the arms of the interferometer [163]. Examples of such interferometers include the Michelson and Mach-Zehnder interferometers (MZIs) [164]. Alternatively, the use of fibre birefringence can be employed [165]. In this scenario, the utilisation of a fibre with high birefringence facilitates the construction of a polarimetric sensor [166] or an interferometric sensor [167]. The latter is achieved by incorporating a Hi-Bi fibre section into a fibre loop mirror [168]. Alternatively, the use of media, such as magneto-optical crystals, whose characteristics can be altered by external factors is a viable solution [169].

This chapter presents two new configurations. The initial section introduces a novel fibre loop mirror sensor configuration, utilising two optical circulators and single-mode fibre. This configuration corresponds to a Mach-Zehnder (MZ) configuration that is not balanced, in which a difference in optical path is generated by the sections of the fibre-optic cable within the two circulators. This configuration enables the simultaneous measurement of strain and torsion. The

second section presents a magneto-optical sensor that incorporates an internal cavity, in contrast to standard configurations that rely on an external sensor to monitor temperature. This innovation simplifies manufacturing and enhances the accuracy of temperature measurements within the magneto-optical crystal.

6.1 New fiber loop mirror configuration

One of the key characteristics of using Hi-Bi fibre as a sensor element is the requirement for long fibre lengths. The necessary length depends on the birefringence value, where higher birefringence allows for shorter fibre lengths to achieve equivalent performance. An alternative approach involves the implementation of a fiber loop mirror (FLM) using two optical circulators. This configuration facilitates the development of FLMs where single-mode fibres are employed, instead of birefringent fibres, thereby allowing the exploitation of refractive index differences that are of the order of 10^{-2} [170].

Figure 6.1 illustrates the schematic diagram of the sensing system developed in this study. The setup comprises two optical circulators, a 3 dB coupler, a polarisation controller, and SMF28e optical fibre. The system is illuminated by an erbium-doped fibre source, centred at 1565 nm with a 70 nm bandwidth, and the output signal is analysed using an optical spectrum analyser (OSA) (YOKOGAWA AQ5370C) with a resolution of 0.02 nm. Fibre splicing was performed using a Sumitomo Electric Type-72C fusion splicer (Osaka, Japan). Additionally, a rotation stage and a micrometre translation stage were added to perform torsion and strain measurements.

The system operates by splitting the input light beam via the 3 dB coupler, similar to conventional FLMs, generating two beams: clockwise (CW) and counterclockwise (CCW) – see Figure 6.1. Due to the interconnection between the two circulators, the CW beam propagates through the outer ring (SMF₁), while the CCW beam travels through the inner ring (SMF₂), forming two interferometric arms. The interference pattern of the system can arise from

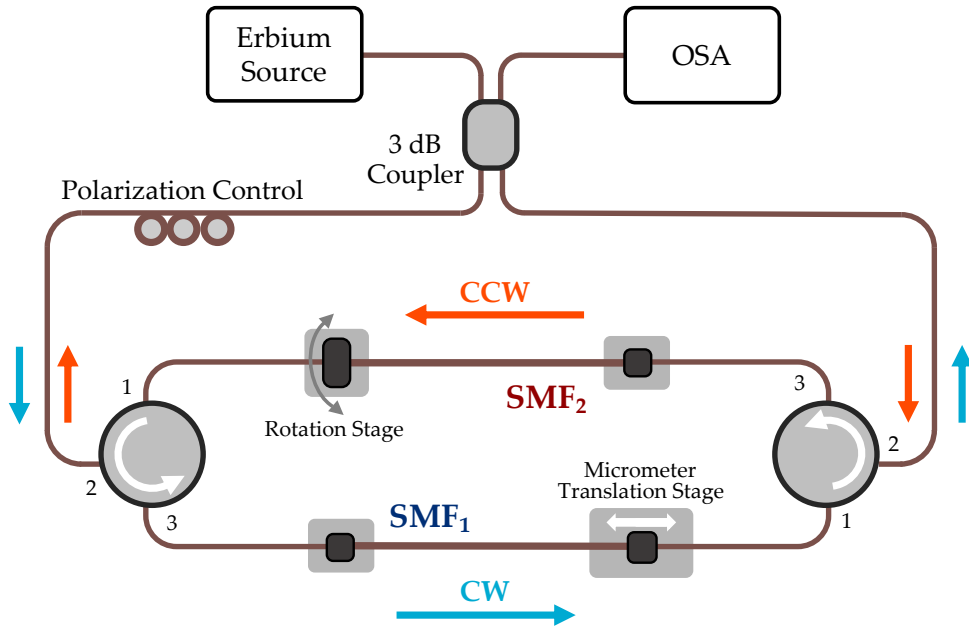


Figure 6.1: Setup diagram for sensor characterisation

differences in optical fibre length between the two rings or from using fibres with different effective refractive indices. The system allows the simultaneous measurement of distinct physical parameters applied to the two interferometric arms, namely, torsion and strain.

Figure 6.2a presents the optical spectrum of the generated interference pattern, while Figure 6.2b shows the corresponding Fast Fourier Transform (FFT). The free spectral range (FSR) of the interference pattern is 0.075 ± 0.02 nm, corresponding to an optical fibre length difference of 22 ± 1 nm. Additionally, since both interferometric arms are composed of SMF28e optical fibre, the effective refractive index difference is approximately zero ($\Delta n \approx 0$).

Following, torsion and strain were measured with the developed setup. Torsion variation induces a rotation of the polarisation state in one arm, resulting in changes in interferometric fringe visibility, whereas strain variation leads to an optical path difference, causing a shift in the interferometric fringe frequency. In both situations, the variation in the amplitude of the fringes (ΔA) and the frequency associated with the interferometric fringes (Δf) were analysed.

For strain characterisation, a micrometre translation stage was used by applying $50 \mu\text{m}$ displacement steps to a fibre section of 430 ± 1 mm. In this

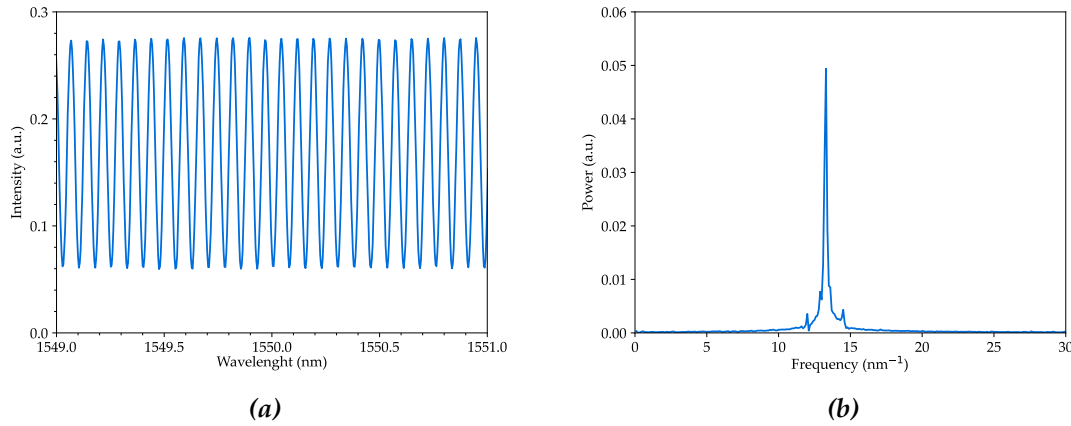


Figure 6.2: Output signal: (a) optical spectrum and (b) its Fourier transform

case, an amplitude variation of $(4.9 \pm 0.3) \times 10^{-7} \mu\epsilon^{-1}$ and a spectral frequency variation of $(-2.1 \pm 0.3) \times 10^{-4} \text{nm}^{-1} \mu\epsilon^{-1}$ were achieved (Figure 6.3a and b).

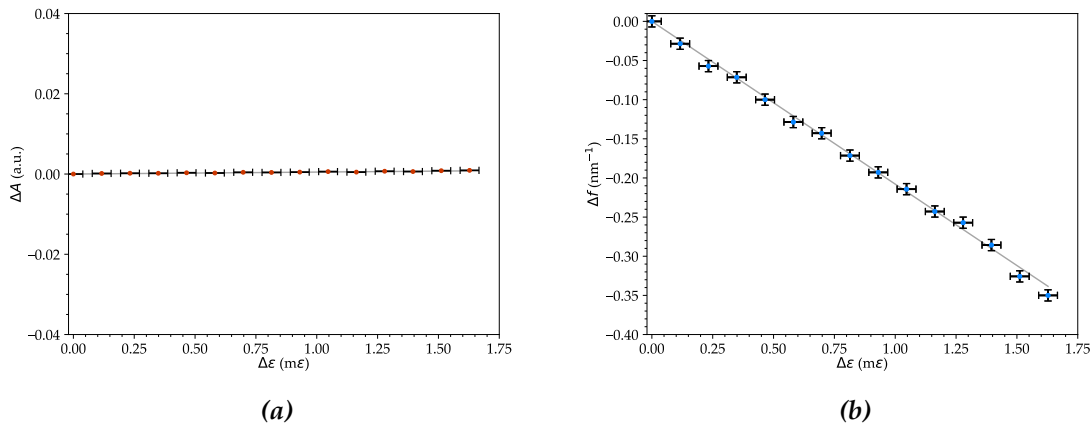


Figure 6.3: Sensor characterisation: a) Variation of a) amplitude and b) frequency as a function of strain

For torsion characterisation, a rotation stage was used to apply 5° step increments to a fibre section measuring 50 ± 1 mm. A linear amplitude variation of $(-1.02 \pm 0.06) \times 10^{-3}/^\circ$ was observed for a maximum torsion variation of 45° , along with a spectral frequency variation of $(-2.177 \pm 0.002) \times 10^{-12} \text{nm}^{-1}/^\circ$ (Figure 6.4a and b). Additionally, for a torsion variation of 180° , the amplitude variation follows a cosinusoidal behavior.

Thus, torsion is measured based on the amplitude variation of the interferometric fringes, as its variation due to torsion is 33 dB higher than that

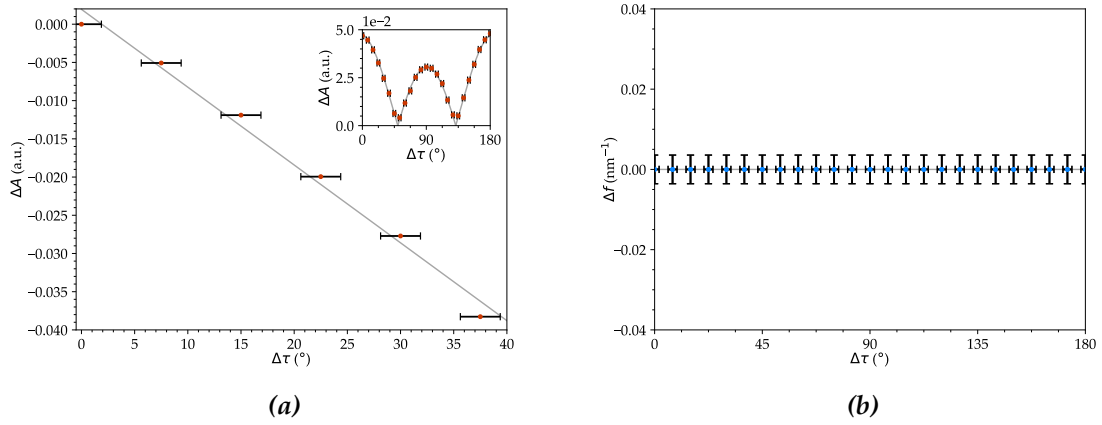


Figure 6.4: Sensor characterisation: variation of (a) amplitude and (b) frequency as a function of torsion.

caused by strain. Conversely, strain is measured through spectral frequency variation, since its effect on spectral frequency variation is 100 dB higher than that of torsion.

To enable simultaneous measurement of strain and torsion, the matrix method was applied, using amplitude and frequency variations. Systems capable of measuring two physical quantities simultaneously can be represented by the following matrix equation [171]:

$$\begin{bmatrix} \Delta \varepsilon \\ \Delta \tau \end{bmatrix} = \frac{1}{K_{\varepsilon,f}K_{\tau,A} - K_{\tau,f}K_{\varepsilon,A}} \begin{bmatrix} K_{\tau,A} & -K_{\tau,f} \\ -K_{\varepsilon,A} & K_{\varepsilon,f} \end{bmatrix} \begin{bmatrix} \Delta f \\ \Delta A \end{bmatrix} \quad (6.1)$$

where $K_{i,j}$ ($i = \varepsilon, \tau$ and $j = f, A$) are the slopes of the linear variations. In this study, the mathematical equation enabling the distinction between simultaneous torsion and strain measurements is expressed as:

$$\begin{bmatrix} \Delta \varepsilon \\ \Delta \tau \end{bmatrix} = \frac{1}{2.142 \times 10^{-7}} \begin{bmatrix} -1.02 \times 10^{-3} & 2.177 \times 10^{-12} \\ -4.9 \times 10^{-7} & -2.1 \times 10^{-4} \end{bmatrix} \begin{bmatrix} \Delta f \\ \Delta A \end{bmatrix} \quad (6.2)$$

Finally, an analysis of interferometric fringe variations for both parameters revealed sensitivities of $0.576 \pm 0.009 \text{ pm}/\mu\text{m}\varepsilon^{-1}$ and $2.09 \pm 0.06 \text{ pm}/^\circ$ for strain and torsion, respectively (Fig. 6.5). Table 6.1 summarises the achieved sensitivities

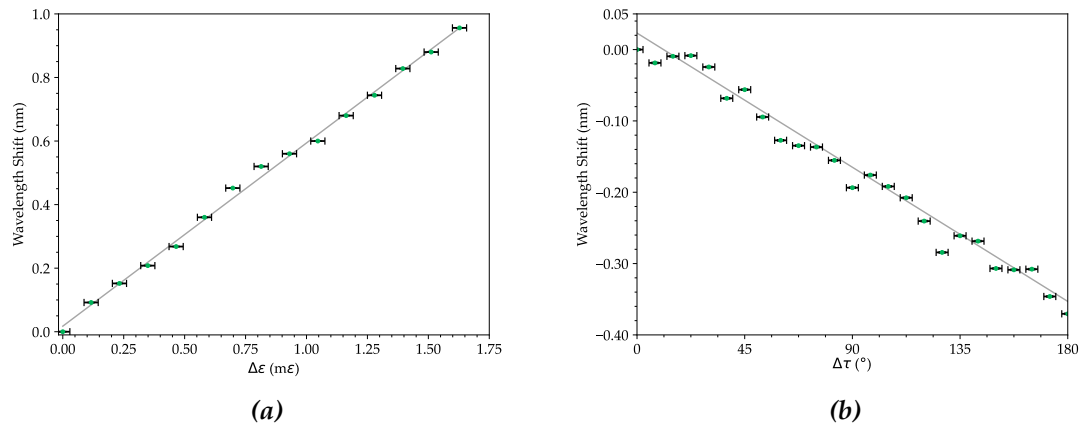


Figure 6.5: Wavelength shift for (a) strain variation and (b) torsion variation

for the physical parameters under study, including measurements based on amplitude, spatial frequency, and wavelength shift, obtained using the developed interferometric sensor.

Table 6.1: Sensitivity values for amplitude, spatial frequency, and wavelength shift, as a function of strain and torsion.

Strain		Torsion	
Figure	Sensitivity	Figure	Sensitivity
6.3.a	Amplitude (ΔA) $(4.9 \pm 0.3) \times 10^{-7} \mu\epsilon^{-1}$	6.4.a	Amplitude (ΔA) $(1.02 \pm 0.06) \times 10^{-3} / ^\circ$
6.3.b	Spatial Frequency Shift (Δf) $(-2.1 \pm 0.3) \times 10^{-4} \text{ nm}^{-1} \mu\epsilon^{-1}$	6.4.b	Spatial Frequency Shift (Δf) $(-2.177 \pm 0.002) \times 10^{-12} \text{ nm}^{-1} / ^\circ$
6.5.a	Spectrum Extreme Shift $0.576 \pm 0.009 \text{ pm } \mu\epsilon^{-1}$	6.5.b	Spectrum Extreme Shift $2.09 \pm 0.06 \text{ pm} / ^\circ$

Finally, the system was characterised with two fibre sections exhibiting different refractive indices. In the first measurement, the optical fibre sections of the two interferometric arms were identical (SMF28e optical fibre) implying $\Delta n \approx 0$. The system achieved an *FSR* of $15.5 \pm 0.1 \text{ nm}$ at 1531.4 nm , corresponding to a path length difference of $68.3 \pm 0.5 \text{ nm}$. To unbalance the system, a 120 mm

section of one interferometric arm was replaced with boron-doped photosensitive fibre (PS1250/1500), which implies $\Delta n \approx 4 \times 10^{-3}$. The spectral measurement indicated that this modification resulted in an FSR of 4.5 nm at 1539.9 nm, implying a refractive index variation of $(4.2 \pm 0.5) \times 10^{-3}$.

This study demonstrates that the developed system enables the implementation of interferometric arms with a nonzero refractive index difference. The observed refractive index difference can exceed the birefringence of Hi-Bi optical fibres, facilitating the design of more compact sensing regions. Furthermore, the system enables the simultaneous measurement of torsion and strain, achieved by analysing the amplitude and spectral frequency variations of the interferometric fringes.

6.2 Internal interferometer in magneto-optic sensor

In the domain of magneto-optic materials, Faraday rotation is observed in magneto-optic crystals when exposed to a magnetic field, leading to the rotation of polarisation [172]. This phenomenon exhibits a linear response to the applied magnetic field, with its magnitude influenced by the field intensity, system geometry, and the optical properties of the material used in the sensor. This effect is widely utilised in magneto-optical sensors for measuring magnetic fields and electric currents in conductors, where the polarisation rotation is precisely monitored [173, 174]. The governing equation for this phenomenon is as follows:

$$\theta_B = V(\lambda, T)BL, \quad (6.3)$$

where θ_B is the polarisation rotation angle, $V(\lambda, T)$ is the Verdet constant of the magneto-optical material, being dependent on wavelength and temperature, B the external magnetic induction applied to the material, and L is the magneto-optical crystal rod length.

The magneto-optical crystals are mounted between two polarisers, which enables the measurement of the rotation of the polarisation through the variation

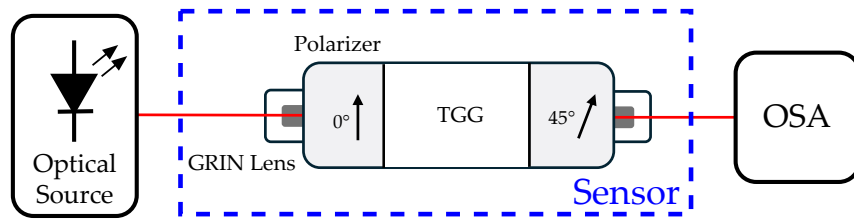


Figure 6.6: Magneto-optical sensor design.

in intensity (see Figure 6.6). It is important to note that the magnetic field of an electrical conductor is described by

$$B = \frac{\mu_0 i}{(2\pi r)}, \quad (6.4)$$

where μ_0 is the vacuum permittivity, i is the current flowing through the conductor and r is the radius of the conductor. Thus, for small rotations

$$\frac{\Delta I}{\Delta i} = \frac{\mu_0 L V}{(2\pi r)}, \quad (6.5)$$

where ΔI and Δi are the variation in optical intensity and electric current, respectively.

In the context of magnetic field measurements performed with magneto-optical crystals, it is imperative to acknowledge the temperature-dependent nature of these measurements. In order to overcome this dependence, it is standard practice to use a temperature sensor, which can be either external or directly coupled to the magneto-optical material.

In this investigation, the implementation of an internal cavity as a sensor cavity in a terbium gallium garnet (TGG) crystal-based sensor is explored, thereby eliminating the need for a second sensor. The sensor comprises two GRIN collimating lenses and two micro-optical linear polarisers, with 1 mm-thickness, working at wavelengths centred at 800 nm (Fig. 6.6). The polariser's main axis of the second polariser is rotated by 45° relative to the main axis of the first polariser. Between the polarisers, it is mounted a cylindrical TGG magneto-optical crystal with a length of 20.5 mm and a Verdet constant of -13.8 rad/T-m at 1550 nm. The sensor was characterised by illuminating it with an erbium source centred

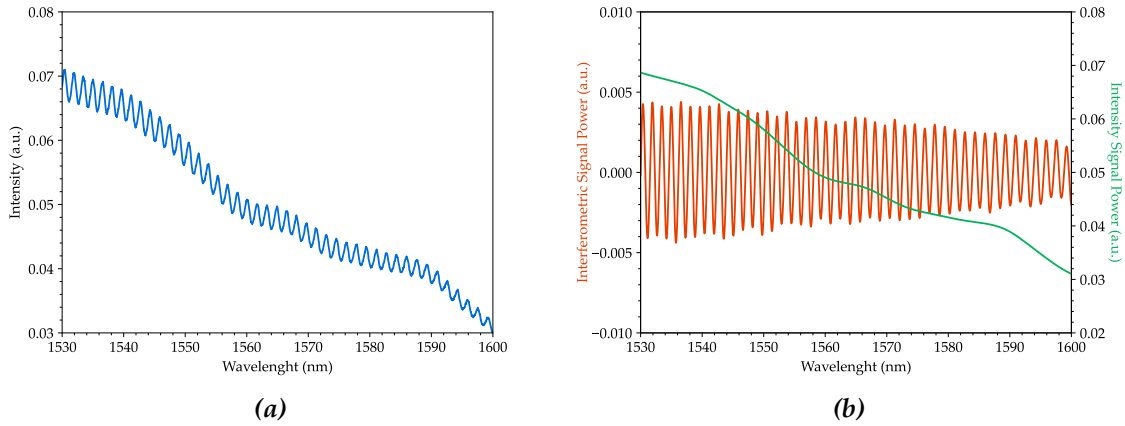


Figure 6.7: Output signal of the magneto-optic sensor: (a) spectrum and (b) two signals of interest resulting from the decomposition of the spectrum of the input signal.

at 1560 nm, and a bandwidth of 90 nm. The output signal was monitored using an optical spectrometer (OSA) ('YOKOGAWA AQ5370C') with a resolution of 0.02 nm. The magnetic field induced in the sensor was generated by a solenoid, to which electrical currents ranging from 0 to 2 A were applied. This enabled the recreation of a situation equivalent to a conductor in which the sensor was perpendicular, at a distance of 10 mm, and an electrical current ranging from 0 to 1700 A was applied. Figure 6.7a shows the output spectrum, and it was separated into two signals (Fig. 6.7b): the intensity signal, which resulted in the electric current measurements, and the interferometric signal, which generated the temperature measurements. The interferometric fringes exhibited a FSR of 1.6 ± 0.1 nm, which corresponds to a cavity with dimensions analogous to the polarisers' length.

The characterisation of the sensor in relation to the electric current is illustrated in Figure 6.8. In the study of the intensity signal (Fig. 6.8a), a sensitivity of $(5.2 \pm 0.1) \times 10^{-6} \text{ A}^{-1}$ was achieved. The theoretical value derived from Equation 6.5 is $5.6 \times 10^{-6} \text{ A}^{-1}$, then the experimental value is associated with an error of 7%. In the study of the interferometric signal (Fig. 6.8b), a sensitivity of $(-3.1 \pm 0.6) \times 10^{-3} \text{ pm/A}$ was obtained.

The characterisation as a function of temperature is presented for three current values in Figure 6.9. In the study of the interferometric signal (Fig. 6.9a), the

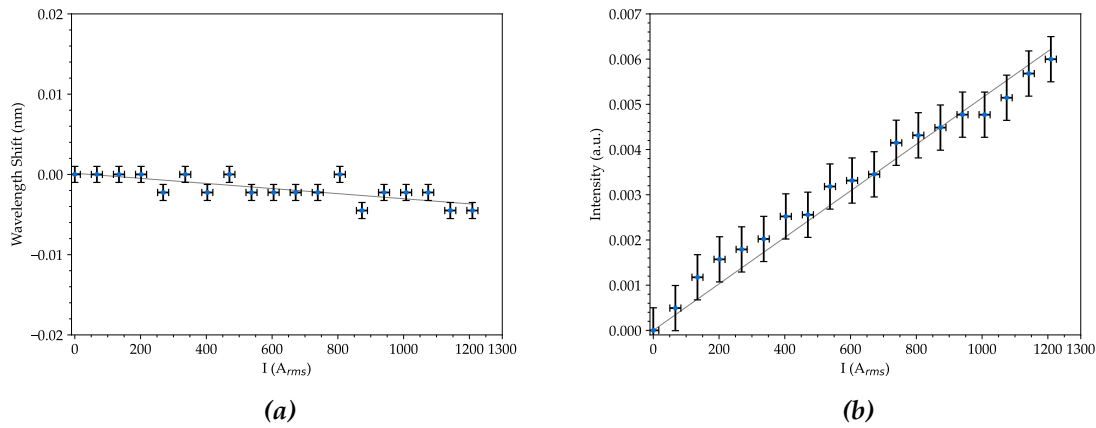


Figure 6.8: Characterisation of the sensor as a function of the current in the conductor: (a) wavelength shift and (b) intensity variation.

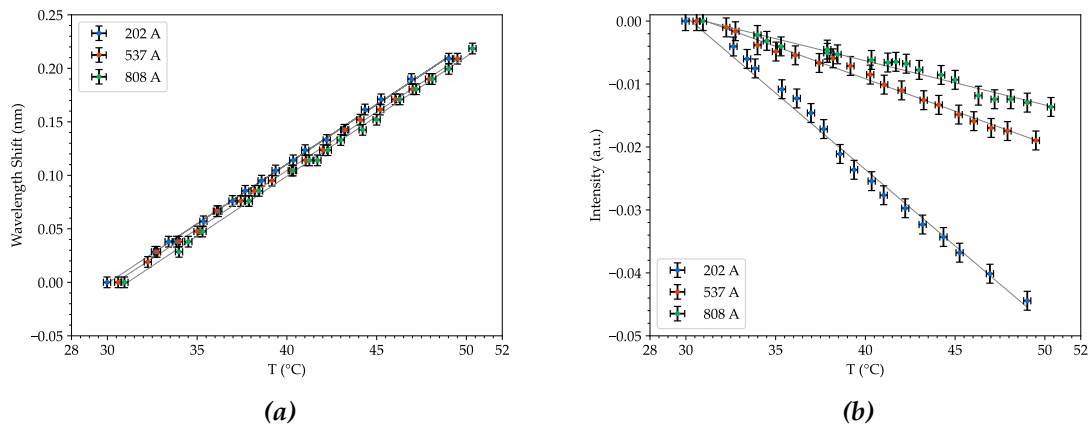


Figure 6.9: Sensor characterisation as a function of temperature: (a) wavelength shift and (b) intensity variation for three different conductor currents.

displacement of the fringes with temperature is 11.2 ± 0.2 pm/ $^{\circ}C$ for all current values. Consequently, the displacement of the interferometric fringes in response to temperature variations is 35 dB greater than that observed for variations in the conductor current. Thus, the internal cavity resulting from the polarisers can be designated as a sensor cavity. A study of the variation in signal intensity was also carried out, where the following sensitivities were determined (Fig. 6.9b): -2.43 ± 0.05 pm/ $^{\circ}C$ for 202 A, -1.03 ± 0.03 pm/ $^{\circ}C$ for 537 A, and -0.70 ± 0.03 pm/ $^{\circ}C$ at 808 A. These values indicate a decrease in temperature dependence with increasing current.

6.3 Conclusions

This chapter presented two novel optical sensing approaches. First, an interferometric configuration based on two interconnected circulators and single-mode fibre was presented. The developed system demonstrated the ability to obtain an FML without a birefringent fibre whose refractive index difference between the two propagation modes is based on the difference of effective refractive index of the single-mode fibre. It was also demonstrated that the system allows for the simultaneous measurement strain and torsion between the arms of the interferometer. Concerning strain characterisation, an amplitude variation of $(4.9 \pm 0.3) \times 10^{-7} \mu\epsilon^{-1}$ and a frequency variation of $(-2.1 \pm 0.3) \times 10^{-4} \text{nm}^{-1} \mu\epsilon^{-1}$ were obtained. Whereas the characterisation of torsion, an amplitude variation of $(-1.02 \pm 0.06) \times 10^{-3}/^\circ$ and a frequency variation of $(-2.177 \pm 0.002) \times 10^{-12} \text{nm}^{-1}/^\circ$ were obtained. It can be concluded that the strain measurement was obtained by varying the fringes' frequency since the frequency variation due to strain is 100 dB greater than the variation obtained by torsion. The torsion measurement was obtained by varying the amplitude of the fringes since the amplitude variation by torsion was 33 dB greater than the variation obtained by strain.

Following, an internal cavity of a magneto-optical sensor was functionalised as a thermal sensor, thus eliminating the standard use of external sensors. For the characterisation of the current variation of the conductor, the power signal demonstrates a sensitivity of $(5.2 \pm 0.1) \times 10^{-6} \text{A}^{-1}$, which is associated with an error of 7% in relation to the theoretical value. The sensitivity associated with interferometric fringes is $(-3.1 \pm 0.6) \times 10^{-3} \text{pm/A}$. Also, the characterisation of the temperature variation was performed, and the sensitivity of the interferometric fringes was $11.2 \pm 0.2 \text{pm}/^\circ\text{C}$, which was 35 dB higher than the sensitivity obtained by the current variation of the conductor. Concerning intensity variation, the following sensitivities were obtained: $-2.43 \pm 0.05 ^\circ\text{C}^{-1}$ for 202 A, $-1.03 \pm 0.03 ^\circ\text{C}^{-1}$ for 537 A, and $-0.70 \pm 0.03 ^\circ\text{C}^{-1}$ at 808 A, i.e. a reduction in temperature dependence with the increase of the conductor current.

Chapter 7

Interrogation system for white light interferometry

The white light interferometry (WLI) technique was first documented in 1976 [175] and involves the implementation of at least two cavities, typically in tandem, one acting as an interrogator and the others as sensor or reference cavities. The interrogator is a cavity in which an actuator is mounted on at least one of its arms, allowing the control of the optical path difference (OPD) value and the scan of a specific range of OPDs [176, 177, 178]. The output signal is composed of the overlapping spectrum of the two cavities, giving rise to the Vernier effect, with the resulting output signal's spectral power being integrated through a photodetector [179]. When the interrogator actuator is modelled temporally, the output signal is formed of two waves: the carrier and the envelope. The carrier wave is a periodic wave, with maxima occurring when the OPD is a multiple of the centre wavelength of the optical source spectrum. The envelope wave is a non-periodic wave, with the maximum occurring when the OPD of the interrogator is equal to the OPD of the sensor or reference cavity. The stability of the interrogator's operation is affected when it is exposed to variations in external factors, such as temperature and humidity, which cause changes in the interrogation band's width and position. Minimising such variations is of the utmost importance for a successful implementation.

This Chapter describes the manufacture and practical implementation of a WLI interrogation system. The study begins with a detailed discussion of the fabrication and characterisation of the interrogator prototypes based on the Mach-Zehnder interferometer (MZI). Subsequently, an analysis algorithm is presented and evaluated that incorporates convolution and cross-correlation operations as filtering elements and a linearisation function that enables real-time analysis at a frequency of 1 kHz. Finally, the functionalisation of internal cavities is explored: one as a reference and the other as a sensor.

7.1 The actuator implementation

The WLI technique involves the interrogator implementation, which is defined as an interferometer with phase variation achieved through an actuator mounted on one of its arms. The two most common actuator types are mechanical, such as piezoelectric transducers (PZTs), in which phase variation is achieved by changing the arm length, and electro-optical, such as electro-optic crystals, in which phase variation is achieved by changing the refractive index of the propagation medium.

The objective of this study is to develop a thermal sensing system for utilisation in a space exploration system. In order to achieve this objective, the following requirements must be met: an Fabry-Pérot interferometer (FPI) cavity interrogation bands greater than 100 μm and centred between 500 μm and 1000 μm , a sampling frequency between 500 Hz and 1000 Hz, and the ability to operate at temperatures between 0 °C and 50 °C.

A Mach-Zehnder interferometer (MZI) was chosen as the interrogator, incorporating a cylindrical PZT as the actuator. This MZI was constructed using two couplers and SMF-28e single-mode fibre (Figure 7.1).

The objective of this study is to analyse the FPI cavity; therefore, the corresponding MZI cavity required to achieve the same OPD as the FPI is given by:

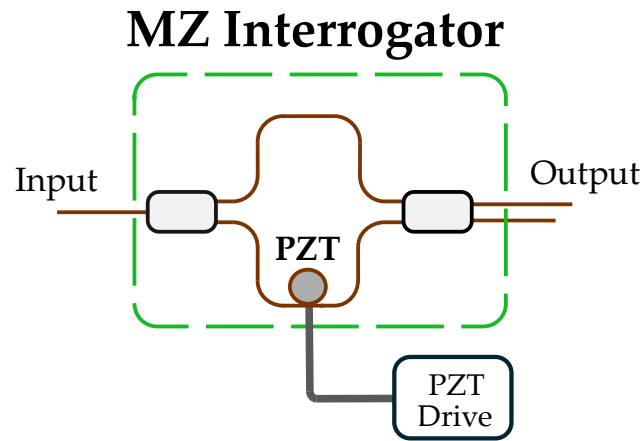


Figure 7.1: Interrogation interferometer schematic

$$\Delta L_{MZI} = \frac{2}{n_{eff}} \Delta L_{FPI} \quad (7.1)$$

where ΔL_{MZI} and ΔL_{FPI} are the cavity lengths of the MZI and FPI, respectively, and n_{eff} is the effective refractive index of the SMF-28e optical fibre. Note that, to properly interrogate the FPI cavity, the MZI needs to attain an interrogation bandwidth of at least 100 μm ; thus, a cavity variation of at least 140 μm is required.

The initial approach involved the implementation of a PZT (PI PT140.70 model) with a height of 40 mm, an inner diameter of 38 mm and an outer diameter of 40 mm, and a capacitance of 70 nF. Also, it exhibits a height variation of 15 μm and a diameter variation of 12 μm , for a voltage variation between 0 V and 1000 V. The PZT is controlled by a signal generator (Stanford Research Systems Model DS345) and an amplifier based on the Apex Microtechnology PA91 chip, according to the traditional configuration (see appendix C.1).

The actuator system is implemented by coiling the optical fibre around the PZT with 16 turns (see Fig. 7.2a). The PZT was modulated by a triangular electrical signal with an amplitude of 400 V. The interrogator was characterized, and an interrogation bandwidth of more than 100 μm was achieved for frequencies above 500 Hz. Also, a bandwidth of 104 μm for a frequency of 1 kHz was attained. When the PZT oscillates at a frequency of

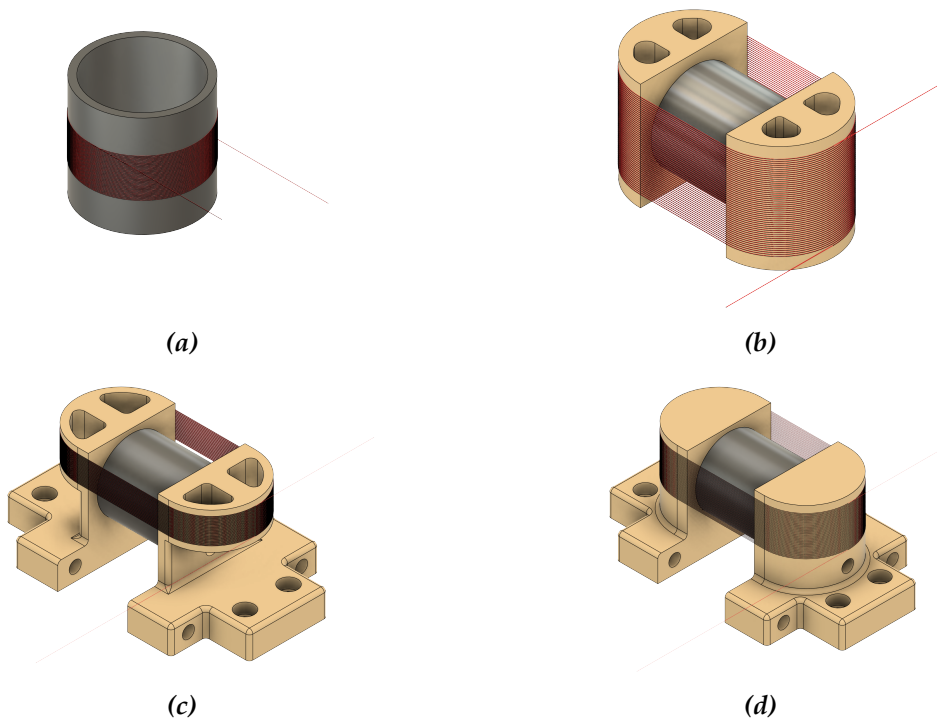


Figure 7.2: Actuator implementation configurations: (a) traditional configuration, and (b) first, (c) second, and (d) third prototype D-configurations.

1 kHz, it reaches a temperature of 50 °C, at an ambient temperature of 20 °C. Furthermore, when a triangular signal is applied at 1 kHz, the output signal exhibits non-linearities. This is a consequence of the non-linear movement of the PZT, which is caused by the PZT's spectral response, due to its resonance and anti-resonance. Furthermore, when a sinusoidal signal is applied, the monitor signal reveals a distorted sinusoidal wave, indicating that the amplifier has reached its limit. Consequently, there was the need to develop a new interrogator configuration that would reduce the power consumption due to the PZT and the non-linearities of the PZT's movement.

In order to enhance the interrogator's features, a D-configuration was developed (see appendix C.2). This configuration exploits the PZT's height variation, where the optical fibre is coupled to it by two structures (see Fig. 7.2b). The simplest geometry for this type of structure is to split a cylinder vertically in half. These supports were 3D-printed with polylactic acid (PLA), and glass lamellas were incorporated into the interface with the PZT. This served to enable

thermal insulation and mitigate pressure applied to the structure by the PZT, as it increases the force in the application area. The initial prototype comprises 56 turns of optical fibre, and a 200 V sinusoidal signal was applied. Characterisation revealed anti-resonance at 450 Hz and resonance at 525 Hz. The interrogation bandwidth achieved with the resonance is 135 μm .

The second prototype was built to increase the bandwidth and shift the resonance frequency to a higher value (see appendix C.3). The development of said structure consists of four parts (Fig. 7.2c): fibre support, stem, calibration, and fixation. The fibre support region follows the geometry shown previously. The stem consists of a thin volume that gives the structure more flexibility, thus reducing the load on the PZT. The calibration area consists of two screws that allow the load on the PZT to be calibrated and the resonance frequency to be tuned. The fixation area allows one of the structures to be fixed to the base of the interferometer. The interrogation band was characterised by applying a sinusoidal signal with an amplitude of 50 V. This interrogator has two resonances: one at a frequency of 4 kHz and an amplitude of 275 μm , and the other at a frequency of 2.6 kHz and an amplitude of 130 μm . However, at a frequency of 1 kHz, it only shows an amplitude of 25 μm .

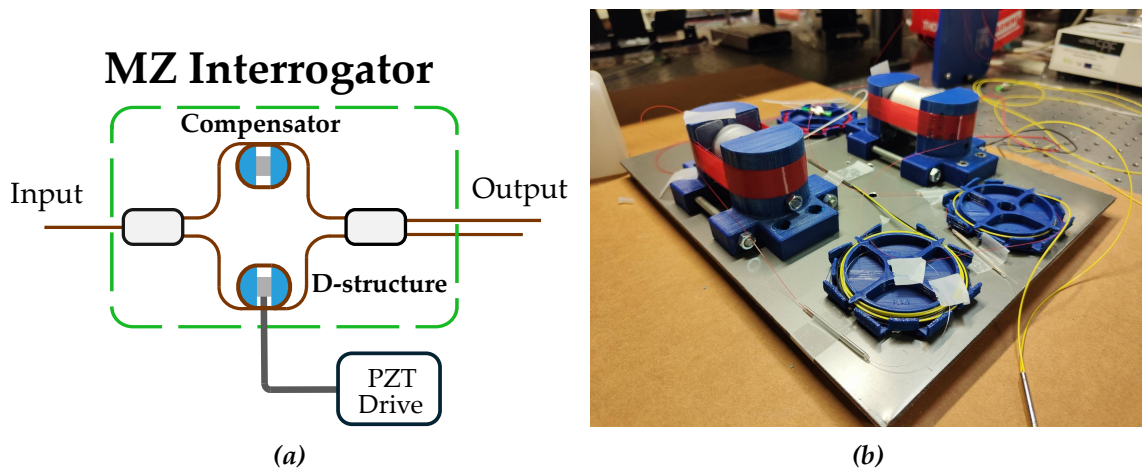


Figure 7.3: Third interrogator prototype: a) assembling scheme and b) photo

In the third prototype, the supports were redesigned to shift the resonant frequency to 1 kHz, a reduction in resonance frequency that was achieved by

removing the hollow areas and the thin connecting region between the fibre supports and the fixing region (Fig. 7.2d). Additionally, 73 turns of optical fibre were coiled to compensate for the increased load on the PZT. However, the location of the interrogation band was found to have a dependence of $600 \pm 30 \mu\text{m}/^\circ\text{C}$ during the interrogator's characterisation, rendering it unsuitable for practical application. This variation is attributable to the thermal expansion of PLA. Low thermal expansion materials such as glass can mitigate this issue, but fully eliminating it remains impractical, as the interferometer arms are not actuated identically. This problem can be solved by introducing a compensator in the unactuated arm (Fig. 7.3). This structure is analogous to the D configuration, where the PZT is substituted by a 38 mm long aluminium tube, thereby replicating the thermal expansion of the PZT. This compensation is passive and fulfils the requirement of using only one actuator. The position variation of the interrogation band with temperature is reduced to $110 \pm 10 \mu\text{m}/^\circ\text{C}$, thus decreasing 5.45 times the value achieved without the compensator.

The characterisation of the interrogation band in terms of the oscillation frequency of the PZT is shown in Figure 7.4, where a sinusoidal signal with voltages between 0 and 50 V was applied to the PZT. The centre of the interrogation band shifts from 980 μm to 950 μm as the frequency varies from 0 Hz to 1 kHz, and from 950 μm to 1070 μm as the frequency varies from 1 kHz to 4.5 kHz. The interrogation bandwidth has four resonances, which stand out at 1.83 kHz, with an amplitude of 140 μm , and 1.02 kHz, with an amplitude of 75 μm .

This system also exhibits a reduction of the actuator's non-linear movements (Fig. 7.5). This is achieved by ensuring that the signal fundamental frequency applied to the PZT coincides with the system's resonance frequency. Furthermore, the operating temperature of the PZT is equal to the temperature of the environment.

The fourth prototype is similar to the third one, having the following differences: the PZT was changed to a different model, and marine plywood

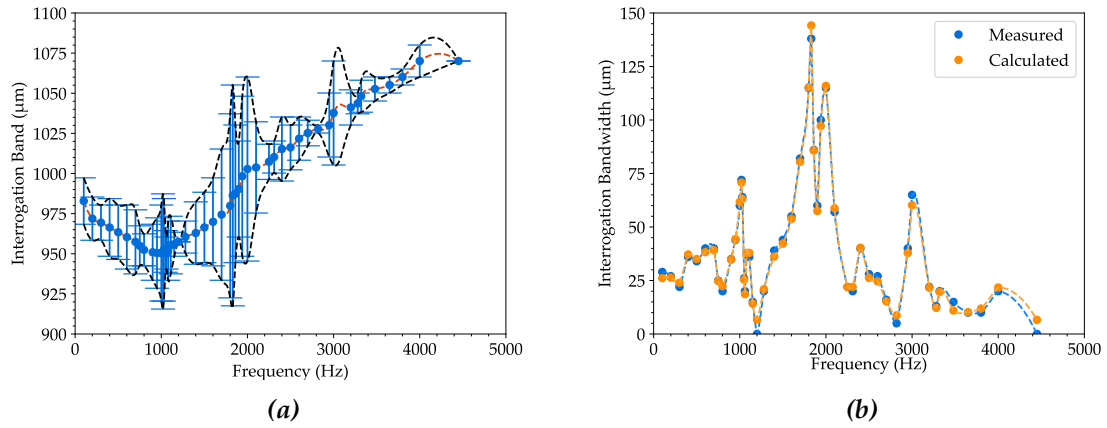


Figure 7.4: Characterisation of the third interrogator prototype: (a) maximum, minimum, and centre of the interrogation band as a function of the PZT oscillation frequency and (b) interrogation bandwidth as a function of the PZT oscillation frequency.

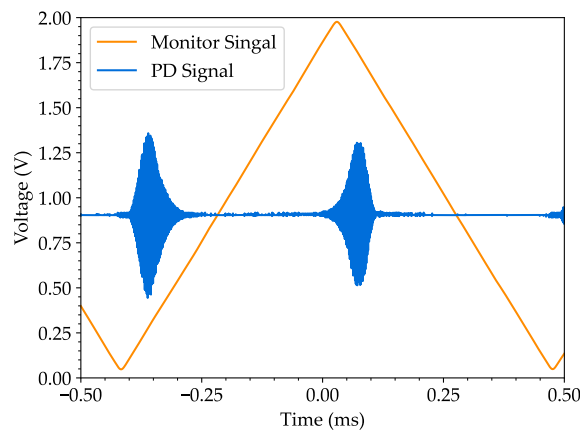


Figure 7.5: A measurement frame when a 100 V triangular electrical signal is applied to the PZT of the third prototype.

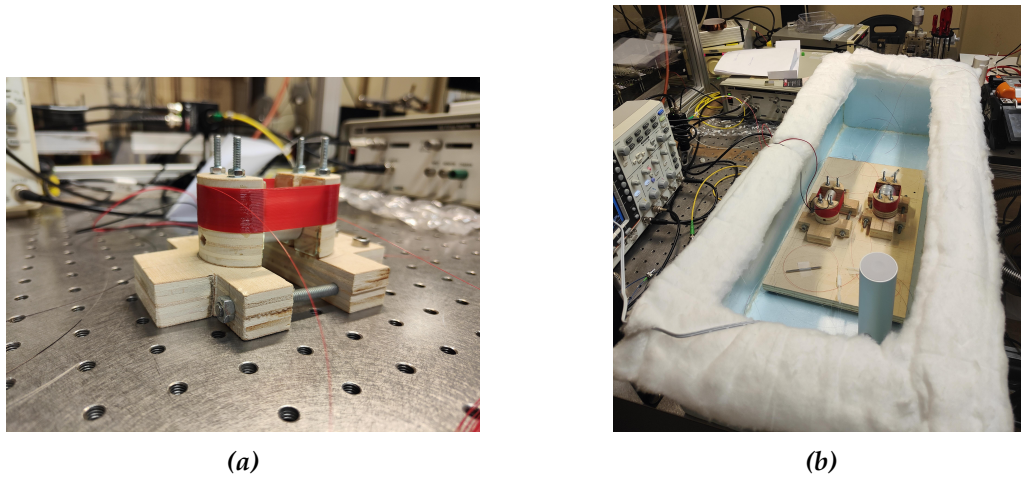


Figure 7.6: Pictures of the fourth prototype: (a) picture of the structure holding the PZT and (b) photo of the interrogator inside the polystyrene box.

supports was used to built the supports (see Fig. 7.6a). The PZT (PI PT130.50 model) has a capacitance of 35 nF, a height of 30 mm, an inner diameter of 20 mm, and an outer diameter of 18 mm. Also, it exhibits a height variation of $9\text{ }\mu\text{m}$ at a voltage of 1000 V. In this prototype, $22.0 \pm 0.1\text{ m}$ of optical fibre was coiled around the PZT, corresponding to 73 turns.

The characterisation of the interrogator, conducted in the absence of the compensator, resulted in a variation of $95\text{ }\mu\text{m}/^{\circ}\text{C}$ in the interrogation band position, representing a 6.3-fold reduction compared to the third prototype. Furthermore, a humidity dependence of $70\text{ }\mu\text{m}/\%\text{RH}$ was attained. To mitigate these effects, in addition to assembling a compensator, the supports and coiled optical fibre were coated with acrylic to protect them from humidity. This approach reduced the temperature and humidity variation to $25\text{ }\mu\text{m}/^{\circ}\text{C}$ and $7\text{ }\mu\text{m}/\%\text{RH}$, respectively. Moreover, the interrogator was placed inside a polystyrene box, whose opening was sealed with cotton wool and acrylic coating, to minimise fluctuations in temperature and humidity around the system (Fig. 7.6b).

As demonstrated in Figure 7.7, the characterisation of the interrogation band as a function of the PZT oscillation frequency was performed. In this experiment, a sinusoidal signal was applied to the PZT with voltages ranging from 0 to 100 V. It was observed that the centre of the interrogation band shifted from 1040

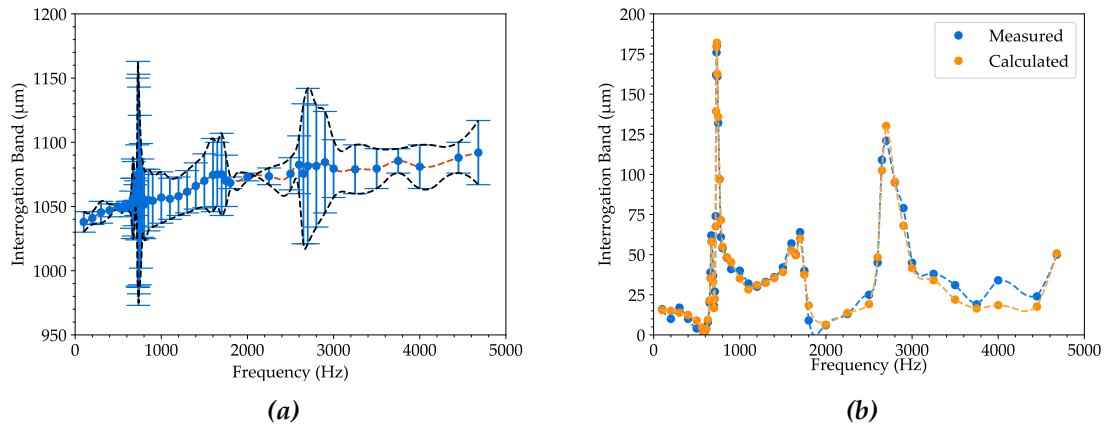


Figure 7.7: Characterisation of the fourth interrogator prototype: (a) maximum, minimum, and centre of the interrogation band as a function of the PZT oscillation frequency and (b) interrogation bandwidth as a function of the PZT oscillation frequency.

μm to 1070 μm as the frequency varied from 0 Hz to 4.5 kHz. The interrogation bandwidth exhibits two resonances: 750 Hz, with an amplitude of 180 μm, and 2.70 kHz, with an amplitude of 125 μm.

Table 7.1 summarises the main characteristics of the developed interrogators. The results obtained from the optimised prototype indicate that it successfully meets all established criteria. Furthermore, the adoption of the D configuration has led to significant improvements, including an enhancement in the interrogation bandwidth, a reduction in the voltage applied to the PZT, and a decrease in the non-linearities related to the PZT's movement compared to conventional configurations.

Table 7.1: Main features of the interrogators based on the traditional approach and the four prototypes based on the D-configuration.

Prototype	PZT	# Turns	Frequency (Hz)	Dynamic Range (μm)	Delta V (V)
Traditional	PI PT140.70	16	1000	104	400
1	PI PT140.70	56	525	135	200
2	PI PT140.70	56	2600 / 4000	130 / 275	50
3	PI PT140.70	73	1020 / 1830	75 / 140	50
4	PI PT130.50	73	750 / 2700	180 / 125	100

7.2 Output signal processing method

In a practical implementation, variations in factors such as temperature, both in the environment and within the system itself, will affect the stability of the OPD and the linearity of the actuator's sweep, resulting in three effects: (a) a variation in the interrogation bandwidth, resulting in a reduction in measurement sensitivity; (b) deviation of the interrogation band position; (c) change in the resonant frequency of the PZT actuator, leading to non-linearities in the PZT motion. These effects result in noise and distortion, leading to an inaccurate determination of the maximum position associated with each cavity. Mathematical operations of convolution and cross-correlation can be implemented to minimise noise, thereby enabling the signal to be reconstructed from a sample [180]. The impact of actuator non-linearities can be reduced using a linearisation function; however, this type of signal processing is typically slow. This Section presents a signal processing algorithm that enables these two processes, filtering and linearisation, to be performed at sampling frequencies of at least 1 kHz.

7.2.1 Digital filtering employing convolution and cross-correlation operation

The present algorithm has been developed for signal reconstruction, where the signal in question is composed of multiple frequencies and has a known intensity profile. For certain filters, phase shifts and attenuation vary with frequency, and therefore, convolution and cross-correlation operations are used.

These operations enable the intensity profile at a given point to be reconstructed using neighbouring points and the desired profile. However, each operation introduces a shift in the output signal relative to the input. Comparing the shift introduced by the two operations shows that they are symmetrical. Therefore, the alternating application of the two operations compensates for this shift, and this approach is referred to as a filter layer (Fig. 7.8).

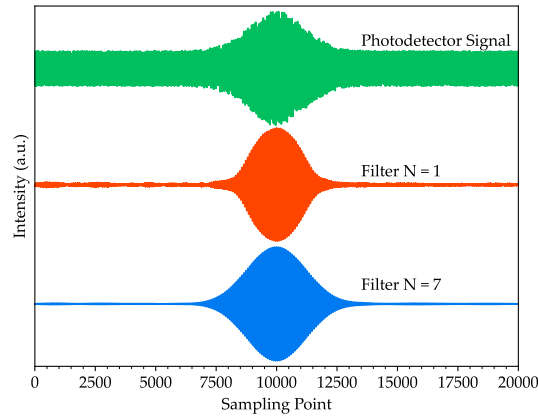


Figure 7.8: Simulation of the output signal with noise and corresponding filtering based on convolution and correlation operations for orders 1 and 7.

Operations can be calculated in two ways: (1) between the input signal and a theoretical signal, or (2) an experimental signal. The theoretical signal implementation allows faster processing, as it is generated before the commencement of processing. However, the use of an experimental signal enables an adaptive process. The position determination (or point in the sample) where the maximum occurs can be achieved by implementing a small sample that contains the intensity profile in the maximum region and minimises the unusable extreme edges of the signal (eq. 7.2).

$$Y = (((X \star sample) \otimes sample) \star \dots) \quad (7.2)$$

The convolution and the cross-correlation can be performed using the Fast Fourier Transform (FFT) algorithm or matrix multiplication. Achieving a low-noise signal implies the use of a high-order filter, which involves multiple filtering layers (Fig. 7.8). Consequently, the standard application of these operations using the FFT is slow due to the extensive computation required. Conversely, matrix filtering does not support adaptive filtering, as generating the cross-correlation and convolution matrices is slow. Therefore, an algorithm based on the Fourier transform is proposed, where the number of calculations is reduced by applying its properties (eq. 7.3).

$$Y = FT^{-1} [FT ((X \star sample) \otimes sample \dots)) \cdot \overline{FT(sample)} \cdot FT(sample) \cdot \overline{FT(sample)} \cdot FT(sample)] \quad (7.3)$$

Finally, the filtering process is summarised in three operations (eq. 7.4): firstly, the Fourier transform of the input signal is calculated; secondly, the signal is multiplied by a *SAMPLE*; and third, the inverse Fourier transform is calculated.

$$Y = FT^{-1} (FT(X) \cdot SAMPLE) \quad (7.4)$$

The '*SAMPLE*' is then defined by

$$SAMPLE = \left[\overline{FT(sample)} \cdot FT(sample) \right]^N, \quad (7.5)$$

where N represent the filter order (number of filter layers). Equations 7.4 and 7.5 allow the implementation of a filter whose processing time is independent of the filter order.

The efficacy of the filtering process is contingent upon the behaviour of the actuator, specifically, the presence of resonances and anti-resonances. Control signals comprising multiple spectral components, such as triangular and sawtooth waves, result in increased distortion due to the actuator's resonance and anti-resonance frequencies (Fig. 7.9). Consequently, linear-shaped waves should be substituted with sinusoidal waves to mitigate this effect. While this modification reduces noise by constraining the signal to a single spectral component, the actuator's movement remains nonlinear. To address this issue, the filtering algorithm must be modified.

The actuator's non-linear movement leads to a carrier with a non-constant instantaneous frequency across the interrogation band, resulting in an erroneous determination of the signal maximum position (Fig. 7.10a). As this information is contained within the envelope, a solution is to remove the carrier. This can be accomplished by computing the modulus of the analytic signal using

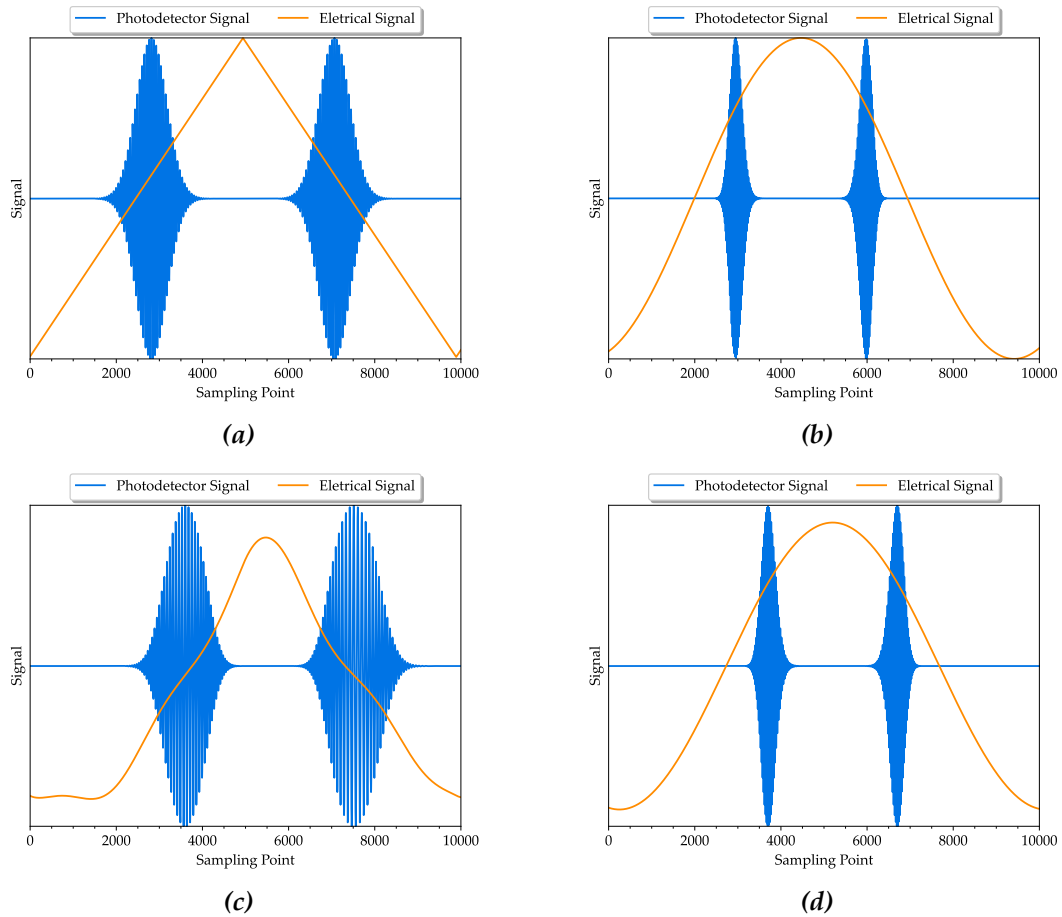


Figure 7.9: Simulation of the effect of the PZT response to the applied electrical signal on the output signal of the system: (a) application of a low-frequency triangular signal and (b) application of a triangular signal whose frequency is close to the resonance and anti-resonance frequency, (c) application of a low-frequency sinusoidal signal and (d) application of a sinusoidal signal whose frequency is close to the resonance and anti-resonance frequency.

the Hilbert-Huang transform (Fig. 7.10b). Although this approach provides high-quality results, it is computationally slow. To mitigate this issue, filtering can be performed using cross-correlation and convolution operations between the square of the oscillatory part of the signal and a sample containing only the envelope Section where the maximum is located (Fig. 7.10c). This method requires a higher-order filter than that used for the analytic signal. However, it should be noted that processing time remains unaffected by filter order. Furthermore, this approach enables a shorter processing time compared to analytic signal computation.

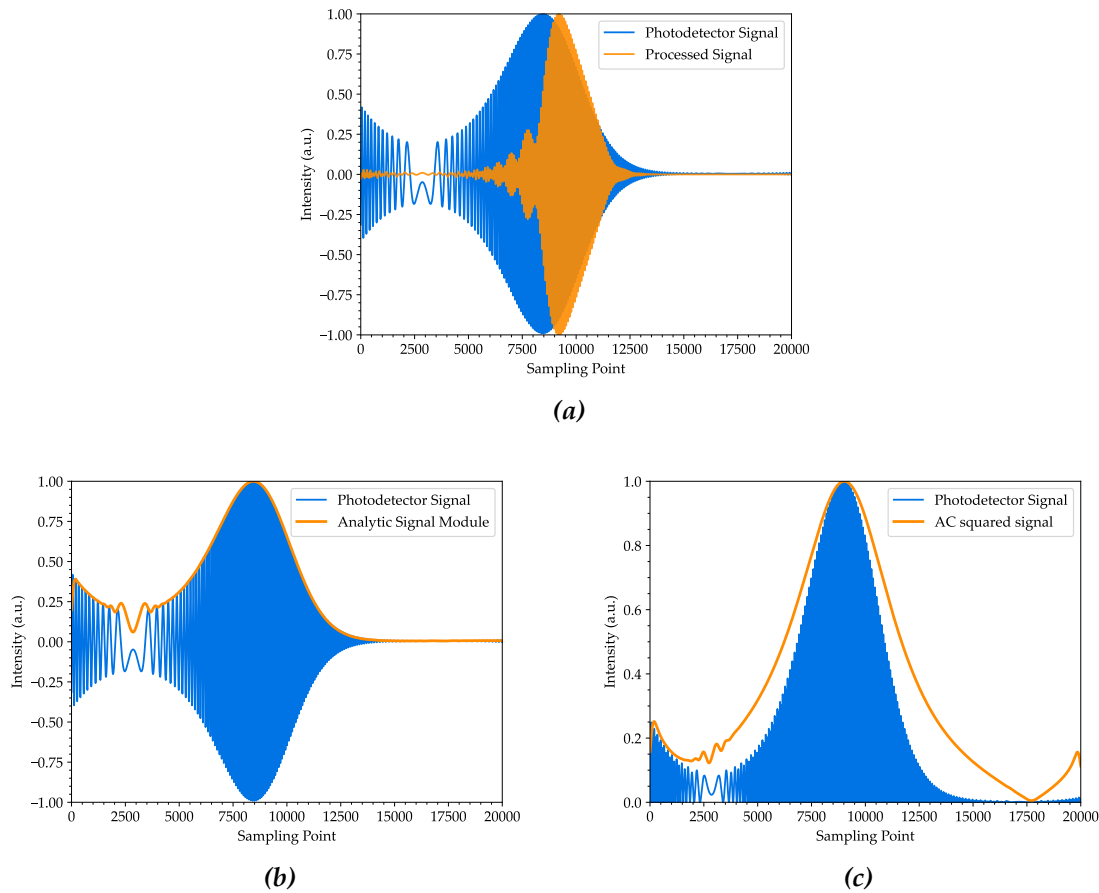


Figure 7.10: Simulation of the filtering process if the implemented sample is composed of: (a) envelope and carrier, (b) only envelope by analytical signal, and (c) only envelope through the square of the oscillating part of the signal.

7.2.2 Signal phase linearisation through the combination of a broadband source with a laser

The non-linear behaviour of the actuator leads to a carrier signal that does not have a constant instantaneous frequency. This has consequences, not only for filtering and determining the maximum position of the signal, but also for the measurement step associated with the interrogation band not being constant.

One solution to this problem is to determine a linearisation function that allows the maximum position to be corrected to the actual position if the actuator movement is linear. In a practical application, where the interrogator is exposed to external factors with high variability, it is necessary to update this function

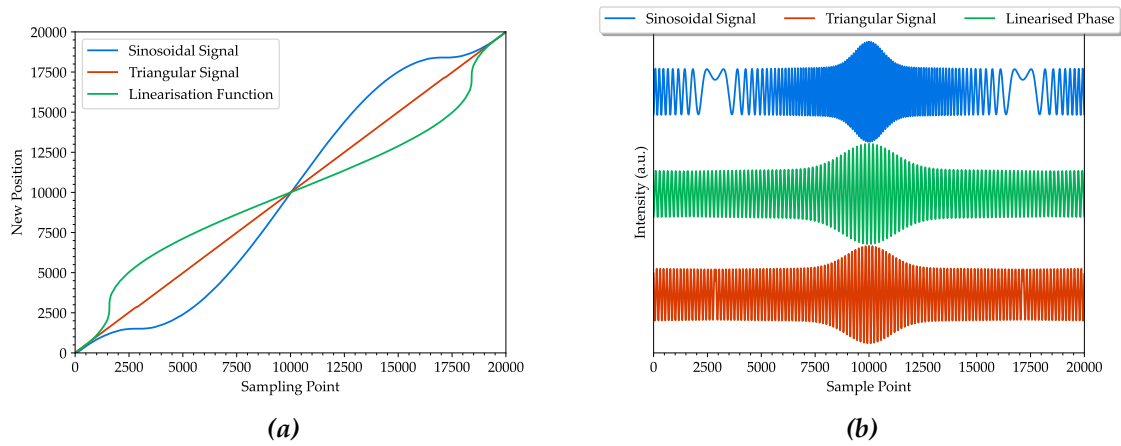


Figure 7.11: The signal phase linearisation: (a) the rescaled phase in number of points for the output signal when a sinusoidal and a triangular signal are applied to the PZT and the profile of the linearisation function, and (b) the output signal when a sinusoidal signal, a sinusoidal signal with phase rectified in post-processing and a triangular signal are applied to the PZT.

throughout the measurements. For this, a laser implementation generates a sine wave along the interrogation band, and a phase linearisation function can be generated by determining the phase of the analytic signal. Figure 7.11 shows the signal after applying the linearisation function, where the maxima of the carrier are equally spaced. Thus, this method allows the correction of non-linearities and achieves a result equivalent to what would be obtained if the PZT control signal was a low-frequency triangular wave. The main objective is to achieve low processing time, and to this end, correction should be applied only to the maximum positions.

7.2.3 Analysis algorithm structure

The developed algorithm has been designed to allow sampling frequencies of at least 1 kHz. However, since the full implementation of the filtering method and phase linearisation is slow, it is necessary to divide the process into two blocks (see Fig. 7.12). The first block is the central processing unit (CPU), which allows the generation and update of the filter sample and the linearisation function. The second block is the Fast Processing Unit (FPU), which performs the filtering and linearisation operations.

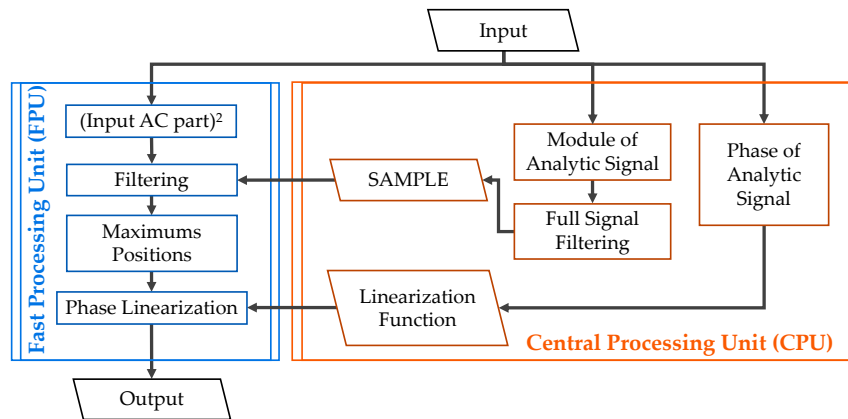


Figure 7.12: Diagram of the analysis process divided into two blocks: central processing unit (CPU) and fast processing unit (FPU).

Interrogator noise originates from gradually varying factors such as temperature and humidity. Consequently, the required CPU operating frequency is lower than the desired sampling frequency. Furthermore, it is possible to determine the effect of external factors on both the interrogation bandwidth and the resonance and anti-resonance frequency of the actuator by calculating the phase of the input signal. This can be used to minimise their impact by changing the control signal characteristics of the PZT.

Based on this processing scheme and considering an input signal of 50,000 points on an ordinary commercial laptop, the processing time for filtering is $900 \pm 20 \mu\text{s}$, squared signal oscillation processing is $10 \pm 1 \mu\text{s}$ and phase linearisation is $40 \pm 10 \mu\text{s}$, giving a total cumulative time of $950 \pm 31 \mu\text{s}$.

7.2.4 Practical implementation of the algorithm

The processing algorithm was tested using an LCI system, the schematic of which is shown in Fig. 7.13. The implementation of the algorithm in Python can be found in the appendix D. In order to execute this process, the optimised interrogator was employed, as outlined in the preceding Section. A broadband erbium ASE source centred at 1550 nm with 90 nm bandwidth, and a tunable laser centred at 1550 nm with a bandwidth of 0.17 nm were used.

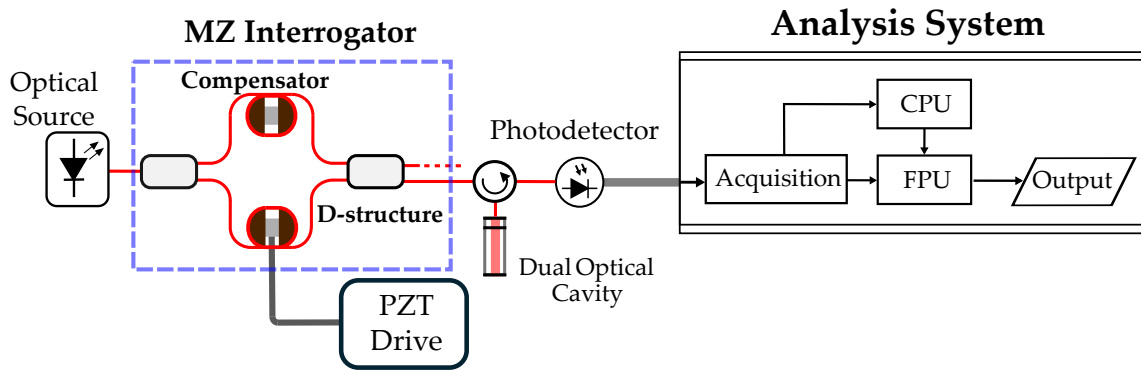


Figure 7.13: Experimental scheme for testing the algorithm.

The characterisation process involves two cavities in tandem configuration: one measuring $820 \pm 5 \mu\text{m}$ and the other $910 \pm 5 \mu\text{m}$. The presence of these two cavities enables the execution of differential measurements, which are imperative for minimising the impact of deviations in the interrogation band. As illustrated in Figure 7.14a, a measurement frame is presented, in which four maxima can be discerned. Only two correspond to the measured cavity, while the other two arise from the shape of the spectrum of the optical source (erbium ASE). Additionally, Fig. 7.14a displays both the input signal and the input signal after phase linearisation. In the latter, it is evident that correcting the signal phase results in a constant instantaneous frequency. Figure 7.14b illustrates the spectral density plots of the input signal, the phase-linearised input signal, and their respective envelopes obtained through the filtering algorithm. The input signal has an SNR of 10 dB and a bandwidth of $1.4 \times 10^{-3} \text{ Hz/Hz}$. Applying the linearisation algorithm corrects the maximum positions, reducing the bandwidth to 10^{-4} Hz/Hz (a reduction of 11.4 dB) and increasing the SNR to 30 dB (an improvement of 20 dB). Finally, by applying the filtering algorithm, the noise for normalised frequencies above $3 \times 10^{-3} \text{ Hz/Hz}$ is suppressed by 30 dB.

The impact of the algorithm on a long-term measurement is characterised in Figure 7.15. For this purpose, the interrogation band was considered to correspond to a temperature range of 50 °C. During the characterisation, the system was exposed to a temperature variation of 0.5 °C and a relative humidity variation of 3%. For frequencies below 1 mHz, a noise reduction of 11 dB was

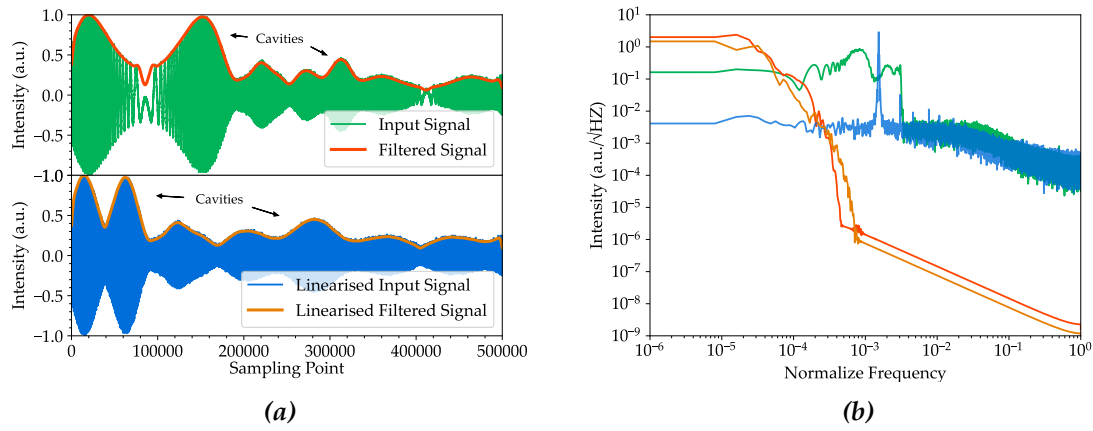


Figure 7.14: Characterisation of the WLI interrogator analysis algorithm: (a) a frame of the input signal and the input signal with phase linearisation and the respective signals resulting from applying the filtering method, and (b) the respective spectra.

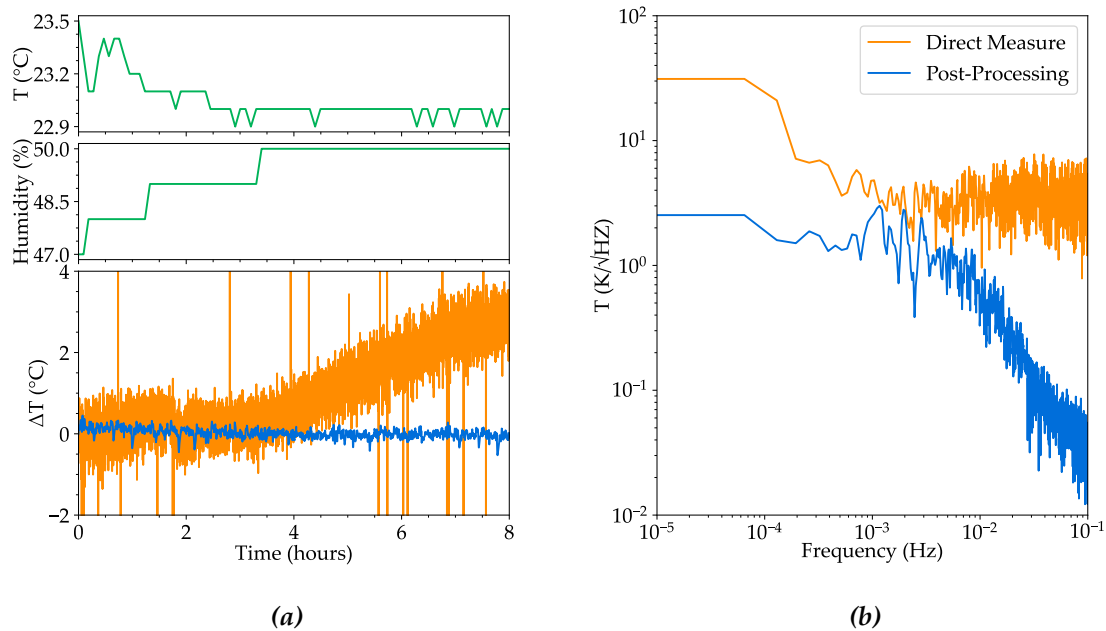


Figure 7.15: Characterisation of the WLI interrogator analysis algorithm in an 8-hour measurement: (a) temporal variation of environmental temperature and humidity and interrogator-induced temperature deviations with and without the algorithm application, and (b) the corresponding spectra.

achieved compared to the result obtained without the algorithm application. In overall, the implementation of the developed algorithm resulted in an SNR enhancement of 50 dB in each measurement frame, accompanied by a noise reduction of 11 dB for frequencies below 1 mHz in long-term measurements.

7.3 Functionalisation of internal cavities as reference cavities

The functionality of interrogation systems is invariably subject to the influences of various factors, including temperature, humidity, vibration, and others. Despite the potential for low-sensitivity materials utilisation, the disturbances are never zero. To mitigate the impact of these disturbances, reference cavities are incorporated. The conventional approach entails a structure design and manufacture that exhibits low sensitivity to the disturbing factor. These cavities are typically characterised by intricate architectures and the employment of unconventional materials, in addition to the need of being connected to the interrogator, reducing the number of channels associated with the sensing cavities.

In order to maximise the SNR of the system, anti-reflection coatings are applied to the various optical components, thereby minimising the amplitude of the optical signal associated with the internal cavities. This Section proposes a different approach, functionalising the internal cavities as a reference cavity, where the amplitude of the optical signal from this cavity is maximised by applying optical sources whose bandwidth is outside the working band of the optical components.

In the experimental research conducted with the WLI interrogator, an experiment was performed in which the system was illuminated with wavelengths outside the operational bandwidth of the system components, specifically the optical circulator. The results of this experiment revealed the presence of internal cavities in the output signal, which are typically classified as

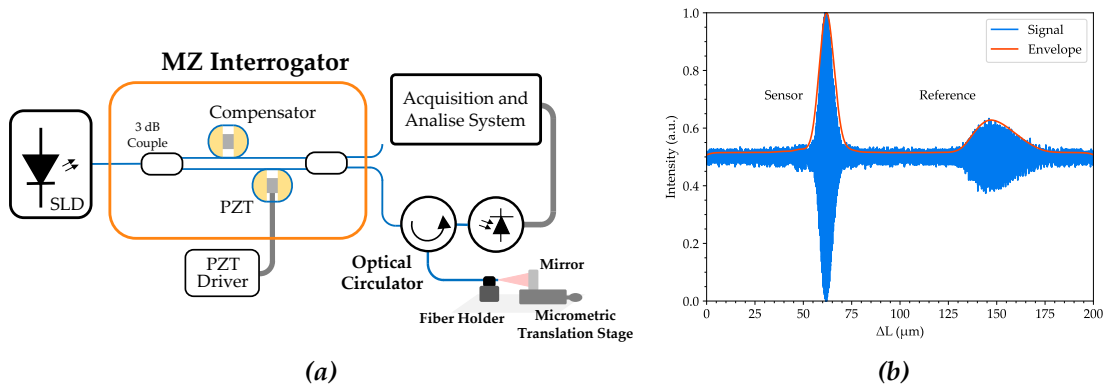


Figure 7.16: Practical implementation of the optical circulator's internal cavity as a reference cavity: a) a measurement frame where the sensor and reference signal are present, and b) experimental setup.

parasitic cavities. These cavities are mitigated by reducing internal reflectivity, which is commonly achieved by applying anti-reflective coatings to minimise internal losses. However, when the system is illuminated with wavelengths outside the operational range of the system components, specifically the optical circulator, the effectiveness of the anti-reflective coatings is significantly reduced, resulting in the emergence of internal cavities of the optical circulator (fig. 7.16b).

The internal cavity of the optical circulator (Thorlabs 6015-3-APC), with an operating band from 1525 nm to 1610 nm, was characterised by an SLD centred at 1300 nm and a bandwidth of 85 nm (Thorlabs S5FC1021S). A Mach-Zehnder interferometer (MZI) with a photodetector (Thorlabs PDA10CS-EC) was utilised as the WLI interrogator (Fig. 7.16b). The interrogator consists of two 3 dB couplers and a PZT (PI PT130.50) with an interrogation band of $800 \pm 2 \mu\text{m}$ to $1000 \pm 2 \mu\text{m}$. The PZT controller comprises an electrical signal generator (Stanford Research Systems model DS345) and a signal amplifier (Tegam model 2350), while the photodetector signal is acquired by a digital oscilloscope (Gwinstek CGS-2304A). In addition to the WLI system, an OSA (YOKOGAWA AQ5370C) with a resolution of 0.02 nm was used to study the interferometric fringes.

The spectral characterisation of the optical circulator is shown in Fig. 7.17a. To identify the internal cavities of the optical circulator, the signal was processed

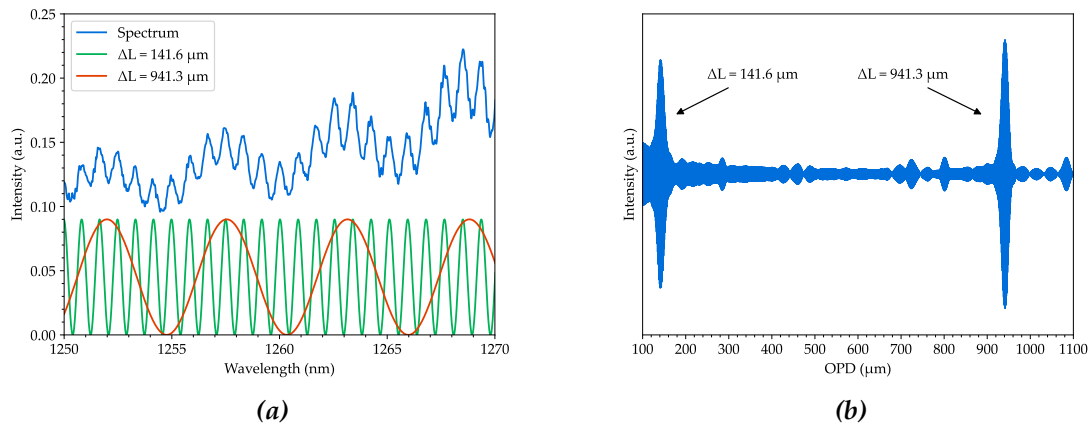


Figure 7.17: Characterization of the internal cavities: a) interferometric fringes, b) determination of the value of each cavity using the WLI technique.

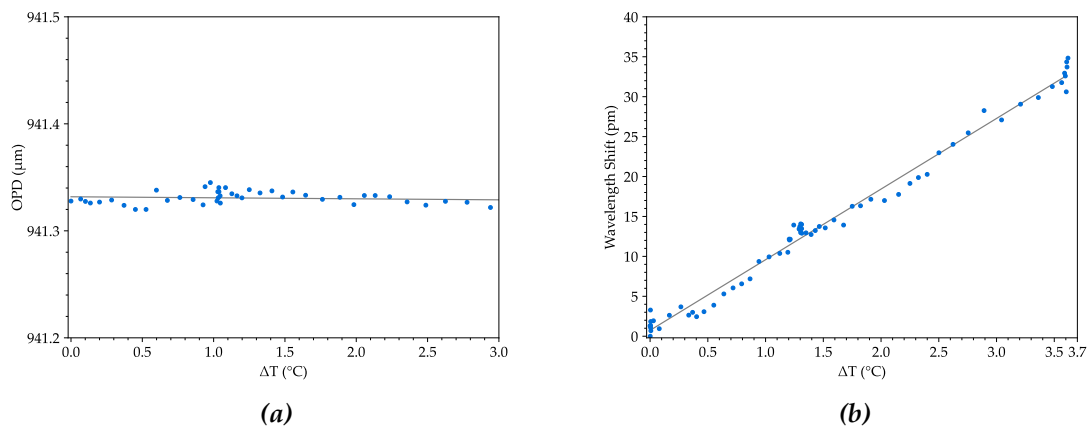


Figure 7.18: Characterisation of the internal cavity of the optical circulator in temperature: a) with the WLI interrogator and b) based on the shift of the interferometric fringes.

using the WLI technique (fig. 7.17b). The analysis identified two well-defined cavities: one with a length of $941.3 \pm 0.1 \mu\text{m}$ and the other with $141.6 \pm 0.1 \mu\text{m}$. Subsequently, the sensitivity of the optical circulator to external temperature variations was studied by analysing the cavity with a length of $941.3 \pm 0.1 \mu\text{m}$. This exhibits a translation of the interferometric fringes of $8.8 \pm 0.1 \text{ pm}/^\circ\text{C}$ (fig. 7.18a) and a length variation of $1 \pm 1 \text{ nm}/^\circ\text{C}$ (fig. 7.18b). Both values are associated with a coefficient of determination greater than 0.99 (r^2). The internal cavity demonstrates low-temperature sensitivity, a crucial attribute of a reference cavity.

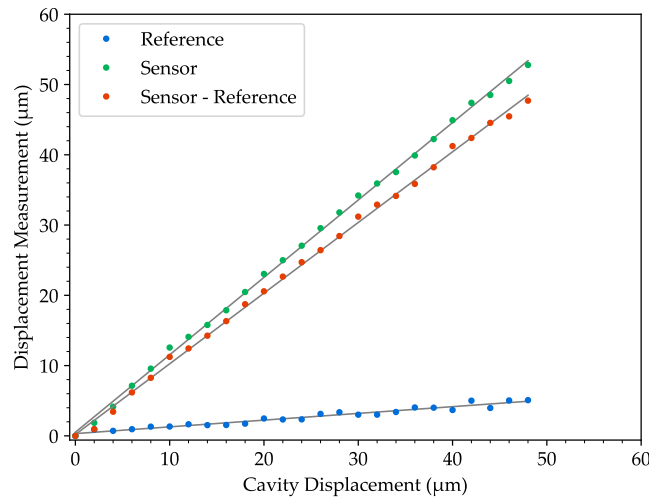


Figure 7.19: Characterization of the displacement of a displacement sensor implemented using an FPI: measured displacement as a function of real displacement, the variation associated with the reference cavity represents the difference between the two measurements.

The implementation of the internal cavity as a reference cavity in a WLI system for displacement measurement is illustrated in Figure 7.16a. Figure 7.19 shows the characterisation of the measured displacement as a function of the sensor displacement. The measurement of the variation in the sensor cavity exhibits a ratio of $1.10 \pm 0.1 \mu\text{m}/\mu\text{m}$, corresponding to a deviation of 10%. The implementation of the differential measurements between the sensor and the reference allowed to achieve $1.001 \pm 0.007 \mu\text{m}/\mu\text{m}$. Both values are associated with a coefficient of determination greater than 0.99 (r^2).

This Section presents the functionalisation of an internal pump cavity as a reference cavity, an approach that facilitates the implementation of a reference cavity without the requirement for interrogator channels, thereby optimising the number of available sensor cavities. Notwithstanding the reduction in measurement resolution caused by the presence of two cavities in the same signal, this approach enhances the system's robustness. This enhancement in resilience can be attributed to the presence of a reference cavity within the operational interrogator channels, which ensures uninterrupted functioning in the event of issues with the interrogator channels. In contrast, the traditional approach, which involves the connection of a single sensor or reference cavity to each channel,

renders the system susceptible to failure if the channels connected to the reference cavities become inoperable.

7.4 Conclusions

This Chapter delineated the fabrication and implementation of an interrogation system. The fabrication of a WLI interrogator through MZI implementation was detailed, wherein the actuator assembly adopts a D-shaped configuration. The second prototype exhibited a bandwidth of 275 μm , achieved through the utilisation of a 50 V amplitude sinusoidal control signal. The fourth prototype demonstrated a bandwidth of 180 μm at 750 Hz, attained by employing a 100 V amplitude sinusoidal control signal, exhibiting sensitivities of 25 $\mu\text{m}/^{\circ}\text{C}$ and 7 $\mu\text{m}/\% \text{RH}$. The D-configuration effectively reduced the voltage applied to the PZT, enhancing the interrogation bandwidth, and mitigating the non-linear movement of the PZT, when compared with the Traditional configuration and fulfilling the initial requirements.

Following, an algorithm for analysing the output signal was described, facilitating the implementation of a sampling frequency of 1 kHz. This algorithm employed convolution and correlation operations as filtering and phase signal linearisation methods. This approach allowed for the correction of maxima positions to that of a signal with linear behaviour, such as a triangular wave. The effectiveness of this method was demonstrated by a 50 dB noise reduction in each measurement frame and an 11 dB reduction for frequencies below 1 mHz in long-term measurements.

Finally, the functionalisation of an optical circulator's internal cavity was studied, which exhibited a very low sensitivity to temperature. This allowed the cavity to function as a reference cavity, thereby reducing the impact of interrogator deviation caused by environmental factors. This approach eliminated the necessity for fabricating separate reference cavities while concurrently maximising the number of sensor cavities and enhancing the

robustness of the measurement system. The incorporation of a reference signal into all output signals from different channels serves to further bolster the system's reliability and precision.

Chapter 8

Conclusion and Future Work

The present dissertation comprises two distinct areas of research. Firstly, the implementation of high-power lasers for wireless power transfer is explored. Secondly, the implementation of interferometer sensors, based on the Vernier effect, is investigated for the purpose of amplifying sensitivity. Additionally, sensing systems based on white light interferometry techniques are examined.

This dissertation begins with a comprehensive exposition of the state of the art of high-power lasers. It proceeds to present the various components that constitute optical fibre lasers, along with the performance of optical fibres doped with erbium, thulium, and ytterbium, which are crucial for the development of high-power lasers. In the subsequent analysis, the characteristics of light beam propagation in the atmosphere are presented, wherein the wavelength to be employed is selected. In this instance, 1.5 μm is chosen, thus resulting in the selection of the erbium-doped fibre. This choice is predicated on the fact that this wavelength allows low atmospheric attenuation to be combined with the lower cost of manufacturing and implementing the high-power laser.

The concept of the natural divergence of the light beam is then described mathematically, where it is determined that the initial radius of the light beam must be 10.2 mm and 3.3 mm for the final radius of 50 mm and 150 mm after propagation of 1 km to be achieved. Furthermore, it has been determined that in order to successfully illuminate the target at a distance of 1 km, the M^2 of the

light beam must be less than 2.5. In order to control the beam diameter at the exit of the laser, a telescope based on the zoom beam expander architecture has been developed, allowing a magnification of between 0.2 and 20. The laser is assembled using a triple-cladding optical fibre doped with erbium. The output light beam has been demonstrated to have an M_x^2 of 1.08, an M_y^2 of 1.06, an efficiency of 30%, and a maximum emission power of 20 W. Two configurations of optoelectric converters were also developed, circular and linear, with the linear configuration demonstrating superior performance. The final phase of the study involved the execution of three experiments. The initial experiment, conducted within the laboratory setting, successfully demonstrated the viability of the energy transfer system. This enabled the DC-DC converter to be activated using a 3.4 W laser beam. The second experiment was conducted in the subterranean complex of the Faculty of Science at the University of Porto. An electrical voltage of 950 mV was achieved at the terminals of the opto-electric converter when illuminated with a laser beam emitted from 70 metres away and with a power of 8 W. Finally, the system was tested at the S. Jacinto base, where a distance of 200 metres was used between the transmitter and receiver. In this experiment, only 80 mV was achieved at the terminals of the opto-electric converter when a 20 W light beam was incident. This outcome was attributable to two factors: the temporal constraints imposed on the implementation of the system at the military base, and the incompatibility between the dimensions of the optoelectric converter and the possible diameters that could be generated at a distance of 200 metres.

The approach to fibre optic interferometric sensors begins with a theoretical model encompassing individual interferometric sensors, as well as the Vernier effect and white light interferometry (WLI). The analysis encompasses a range of spectral extremes and the free spectral range (FSR), both of which exhibit an increase as the interferometric cavity decreases. Furthermore, the maximum possible sensitivity, 2 nm/nm, is determined. The subsequent section explores the Vernier effect, which is generated by both 3-wave and 4-wave interferometry.

The variants and states of the effect are evaluated. With regard to the enhanced variant, its sensitivity is double that of the traditional variant when extremes of equal order are considered. With regard to the states of the Vernier effect, it is necessary to divide it into two cases. In instances where the harmonics are achieved through the expansion of the reference cavity, there is an amplification of the sensitivity associated with the extremes of the spectrum, where the amplification factor is given by $m + 1$. In instances where the harmonics are achieved through the expansion of the sensor cavity, no amplification is observed. Consequently, the sensitivity measured at the various harmonics remains constant. In order to differentiate between the various implementations, a novel magnification formulation, designated as M , is proposed, in conjunction with a novel figure of merit, denoted as $FoM_{Vernier}$. The $FoM_{Vernier}$ assumes the values of 0, 1, and 2 for the Reduced, Traditional, and Enhanced variants, respectively. In the case of harmonics being achieved by expanding the reference cavity, $FoM_{Vernier}$ assumes the value of $m + 1$. Conversely, if harmonics are achieved by expanding the sensor cavity, FoM assumes the value of 1. However, this amplification is apparent since it is possible to obtain the sensitivity exhibited by the Vernier effect with an individual interferometer, although this is a more complex operation. Finally, the WLI is described, and the differences in the output signal when implementing a flat source and a Gaussian source are presented. It has been demonstrated that the envelope width of the output signal diminishes in proportion to the increase in optical bandwidth and emission wavelength. The carrier frequency is directly proportional to the emission wavelengths.

Some different sensors that are based on the Vernier effect are also characterised. With a drop-shaped microstructure at the fibre's tip, it was possible to generate the fundamental, first, and second harmonic states, achieving sensitivities of $15.1 \pm 0.1 \text{ nm}/\mu\text{m}$, $24.7 \pm 0.3 \text{ nm}/\mu\text{m}$, and $28.3 \pm 0.3 \text{ nm}/\mu\text{m}$, respectively. However, it should be noted that the figure of merit was always 1. The implementation of the Enhanced Vernier effect can be achieved

by combining two Fabry-Perot interferometers in parallel configuration and applying a push-pull method. This approach has been demonstrated to yield a $FoM_{Vernier}$ of 2.1 ± 0.2 and a maximum sensitivity of 254 ± 6 nm/ $\mu\epsilon$. The first step in the implementation of fibre loop mirrors (FML) was to incorporate Hi-bi fibres, which exhibited sensitivity with opposite signal strain, thereby generating the enhanced Vernier effect in the fundamental and first harmonic states and exhibits sensitivities of 80.0 ± 0.3 pm/ $\mu\epsilon$ and 120 ± 1 pm/ $\mu\epsilon$, respectively. In this instance, a $FoM_{Vernier}$ of 1.10 ± 0.04 was achieved, a value that results from the significant difference in the module of sensitivity. This gives rise to the implementation of FLM in conjunction with the push-pull method. In this instance, the enhanced Vernier effect is employed, resulting in a sensitivity of 10100 ± 100 pm/ $\mu\epsilon$. These results provide validation for the theoretical considerations regarding the Vernier effect.

This dissertation also presents two novel approaches to the implementation of interferometric sensors. One of the systems under consideration consists of an FML comprising two optical circulators and a single-mode fibre, allowing two different optical paths to be generated. The system was characterised in terms of the strain and torsion, where the amplitude and frequency of the spectral fringes were measured. It was determined that by varying the frequency of the fringes, it is possible to measure the strain variation applied to the system, as this is 100 dB greater than the variation obtained through torsion variation. Conversely, the torsional variation can be measured by varying the amplitude, as it is 33 dB greater than that obtained by strain variation. The alternative system involves the exploitation of the internal cavity of a current measurement sensor by means of a magneto-optical crystal. It was determined that this cavity can be functionalised as a temperature sensor, allowing the error function to be generated to correct the deviations of the conductor current measurement with temperature.

Finally, the experimental part associated with the WLI technique is discussed. Five prototypes were developed, achieving a maximum interrogation band of 275 μm for a 50 V amplitude sinusoidal signal applied to the PZT. The final prototype

presented successfully fulfils the objectives mentioned above, achieving an interrogation bandwidth of 180 μm at 750 Hz when a sinusoidal signal with an amplitude of 100 V is applied to the PZT. Furthermore, the system demonstrates sensitivities of 25 $\mu\text{m}/^{\circ}\text{C}$ and 7 $\mu\text{m}/\%\text{RH}$. A real-time analysis algorithm is also described and tested, with filtering capabilities using convolution and correlation operations, signal phase linearisation in order to minimise PZT non-linearities, and a processing time of less than 1 ms. Finally, an internal cavity of the optical circulator is functionalised as a reference, allowing the number of reading channels to be reduced and increasing the system's robustness when some reading channels are lost, despite reducing the measurement bandwidth in each channel.

The research conducted within this PhD programme constitutes a foundation for the development of novel solutions for optical systems in extreme conditions, with the following considerations being highlighted.

- Increasing the power emitted to values close to kW, as well as the improvement in thermal control, will allow the implementation of high-power lasers in environments with low thermal dissipation, such as satellites;
- An increase in the sampling frequency of the system for interrogating, acquiring and analysing the output signal associated with the WLI technique, reaching values above 5 kHz;

Furthermore, the reduction in envelope width can be exploited through the transfer function of the detection and reference cavities. Conversely, the WLI technique, which currently manifests itself as an amplitude-modulated (AM) output signal, has the capacity to be transformed into a frequency-modulated (FM) signal through the implementation of spread-spectrum sources. Finally, the optimisation of the sensor and reference cavities is imperative to reduce noise and increase the sampling frequency of the physical quantity under study by using low-frequency signals in the actuator.

Appendix A

Simulation of beam propagation in a turbulent medium

The simulation was conducted using the Python programming language alongside the AOtools library, incorporating the non-Kolmogorov turbulence models detailed in Chapter 2, Section 2.7.2. The simulation encompassed the propagation of a light beam through a medium characterised by low turbulence ($C_n = 10^{-17}$) and medium turbulence ($C = 5 \times 10^{-16}$) over a propagation distance of 1 km. The beam was assumed to follow a Gaussian profile, with an initial diameter of 10.2 mm and a wavelength of 1.55 μm . Under low-turbulence conditions, the simulation indicated a transmissivity of approximately 95%. In this scenario, beam deflection and wavefront distortion were minimal, enabling stable system operation (Fig. A.1a). In contrast, the moderate turbulence case resulted in a transmissivity of approximately 66%, with significantly increased beam distortion and deviation, potentially impairing the system's performance (Fig. A.1b).

A detailed simulation focusing on low-turbulence propagation over 1 km yielded an average lateral beam deviation of 2.5 ± 0.1 cm (Fig. A.2). It should be noted that, although the implementation of compensation systems is indeed a possibility, these systems will be reactive in nature and therefore unable to completely eliminate the deviation of the light beam.

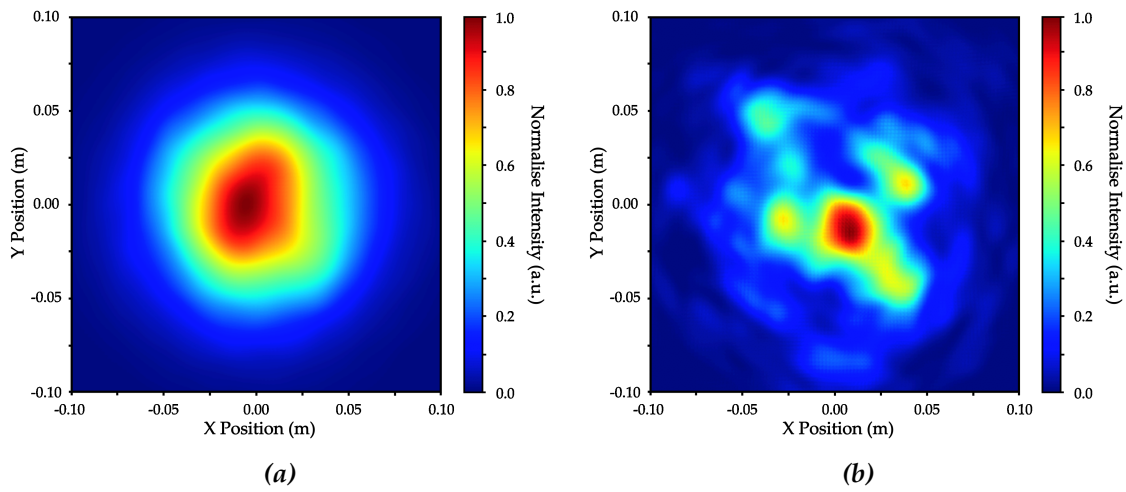


Figure A.1: Simulation of the propagation of a light beam with a diameter of 10.2 mm and a wavelength of $1.55\ \mu\text{m}$ over a distance of 1 km in: a) low turbulence, and b) medium turbulence.

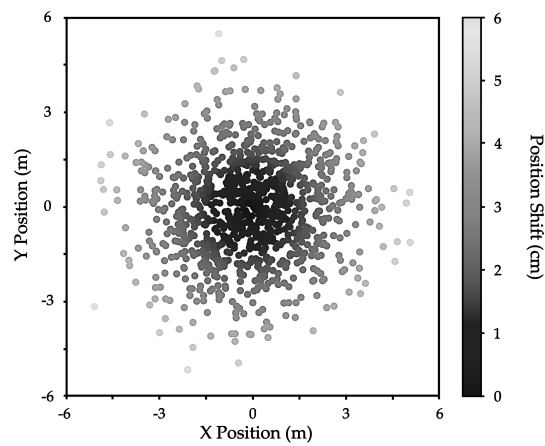


Figure A.2: Simulation of the expected beam deviation during light beam propagation in a low turbulence medium.

Appendix B

Laser Exposure and Cooling

B.1 Maximum Permissible Exposure

One of the most critical aspects to be addressed in the system design is the implementation of laser safety systems. In this context, the quantitative assessment of laser safety is carried out through the evaluation of the optical density (OD). The OD provides a logarithmic measure of a system's ability to attenuate an incident light beam at a specific wavelength. To determine the required OD, it is essential to first calculate two key parameters: the Maximum Permissible Exposure (MPE) - which, in this case, pertains to continuous-wave (CW) laser emission - and the Maximum Working Intensity (MWI) [181]. The project under consideration involves two wavelengths, 976 nm for pumping and 1550 nm for the output signal. Furthermore, the circumstances pertaining to both one-second exposure and prolonged exposure ($> 10s$) will be analysed. There are two MEP values, eye and skin, with the eye MEP being the lower value and the reference value.

For pumping (976 nm), the ocular MPE:

for exposures $> 10s$

$$MPE = 10^{2(\lambda - 0.7)} \times 10^{-3} = 3.5 mW/cm^2 \quad (B.1)$$

and for exposures $18\mu s < t < 10s$

$$MPE = 1.8 \times 10^{2(\lambda-0.7)} \times t^{0.75} \times 10^{-3} = 6.4 \times t^{0.75} \times 10^{-3} J/cm^2 \quad (B.2)$$

which for 1 s implies

$$MPE = 6.4 mW/cm^2 \quad (B.3)$$

For pumping (976 nm), the skin MPE:

for exposures $> 10s$

$$MPE = 0.2 \times 10^{2(\lambda-0.7)} = 713 mW/cm^2 \quad (B.4)$$

and for exposures $10 \mu s < t < 10s$:

$$MPE = 1.1 \times 10^{2(\lambda-0.7)} \times t^{0.25} = 3.9 t^{0.25} J/cm^2 \quad (B.5)$$

which for 1 s implies

$$MPE = 3.9 W/cm^2 \quad (B.6)$$

For the output signal (1550 nm), the eye and skin MPE:

for exposures $> 10s$

$$MPE = 100 mW/cm^2 \quad (B.7)$$

and for exposures $1 ns < t < 10s$:

$$MPE = 1 J/cm^2 \quad (B.8)$$

which for 1 s implies

$$MPE = 1 W/cm^2 \quad (B.9)$$

The intensity of the pumping at the exit of the optical fibre is divergent, and the numerical aperture (NA) is 0.22. In accordance with equation 3.3 and taking

a minimum distance of 30 cm into consideration, it can be deduced that the beam diameter is greater than 13.6 cm. Table B.1 displays the intensity values corresponding to the potential power values (where a diameter of 13.6 cm is considered).

Table B.1: Possible power values and the respective intensities if the pumping beam is divergent.

Power (W)	Intensity (W/cm^2)
100	0.69
200	1.38
400	2.75

The employment of a laser system wherein only the active medium is an optical fibre signifies that the light beam from the pumps is collimated. The table B.2 provides the intensity values associated with three possible power values, considering a diameter of 8 mm.

Table B.2: Possible power values and respective intensities if the pumping beam is collimated.

Power (W)	Intensity (W/cm^2)
100	199
200	398
400	796

Concerning the output signal, in the prototype, the beam diameter is 2 mm. The intensity values for the three most probable powers can be found in Table B.3.

Table B.3: Possible power values and the respective intensities for the output light beam.

Power (W)	Intensity (W/cm^2)
15	0.478
40	1.275
80	2.555

Therefore, the optical density of the protective equipment is given by equation B.10, and the values for each case can be found in the Table B.4.

$$OD = \log_{10}(MWI/MPE) \quad (B.10)$$

Table B.4: Optical density of the safety system for each intensity value, both eye and skin.

Pump				Signal	
Collimated		Divergent			
Ocular					
I (W/cm^2)	OD	I (W/cm^2)	OD	I (kW/cm^2)	OD
199	5.3	0.69	2.8	0.478	5.5
398	5.6	1.38	3.1	1.275	5.9
796	5.9	2.75	3.4	2.55	6.3
Skin					
199	2.5	0.69	-	0.478	2.9
398	2.8	1.38	0.3	1.275	3.3
796	3.1	2.75	0.6	2.55	3.6

Concerning the eye case, it can be concluded that safety equipment should have an OD of 7 for both 796 nm and 1.55 μm wavelengths, given that the highest OD obtained for the 796 nm wavelength is 5.9 and for the 1.55 μm wavelength is 6.3. For the skin, it can be concluded that safety equipment should have an OD of 4 for both 796 nm and 1.55 μm wavelengths, given that the highest OD obtained for these wavelengths is 3.1 and 3.6, respectively.

B.2 Laser cooling

The utilisation of high power invariably gives rise to power losses. These losses primarily manifest as heat, which is detrimental to the effective functioning of the system. The components most sensitive to temperature fluctuations are pump lasers, doped fibre optics, and FBGs (including splices between the different optical components). The systems can be equipped with either air-cooling or liquid-cooling mechanisms, in addition to the Peltier integration. The latter facilitates precise temperature control, yet it does not permit the dissipation power necessary for this scenario. In order to analyse both air and liquid systems, it is first necessary to analyse the mathematical description. In order to consider specific heat, it is important to understand that it represents the amount of energy required per unit mass to raise the temperature of a given material by 1 kelvin (1 K).

$$c = \frac{1}{m} \frac{dQ}{dT}, \quad (\text{B.11})$$

where c is the specific heat, m the mass, Q the heat, and T the temperature. Thus, assuming linear dependence, it follows that

$$Q = c \cdot m \cdot \Delta T. \quad (\text{B.12})$$

Since $m = \rho \cdot V$, with ρ the density of the medium that is used for cooling, and V the volume, this results in

$$P_T = c \cdot \rho \cdot C \cdot \Delta T \quad (\text{B.13})$$

where P_T is the thermal power to be dissipated and $C = V/\Delta t$ is the flow rate and Δt is the time interval. As demonstrated, the implementation of liquid cooling facilitates enhanced power dissipation, attributable not only to the density of the medium but also to the specific heat. Moreover, the utilisation of liquid cooling facilitates the operation of systems at temperatures that are lower than the ambient temperature.

For instance, considering the BWT's K976BN1RN-140.0W pumping laser, which dissipates 312W of power, and assuming a temperature difference between the system and the cooling medium (air or liquid) of only 1 K, the required the required coolant flow rates are $15.2 \text{ m}^3/\text{min}$ and rate of $4.5 \times 10^{-3} \text{ m}^3/\text{min}$, for air and water cooling, respectively. Both systems are possible to implement using existing technology. Whilst liquid cooling systems have been demonstrated to mitigate the impact of ambient conditions on the operation of pump lasers, the prototype under study will be equipped with an air-cooling system due to its ease of transport and implementation for outdoor testing.

Additionally, it is essential to account for the thermal resistance of the heat sink. Thermal resistance is the relationship between the power dissipated and the temperature variation between the cooled region and the region of interest. This relationship can be expressed as follows:

$$R_T = \Delta T / P_T \quad (\text{B.14})$$

where R_T is the absolute thermal resistance. It is evident that, based on typical thermal resistance values for heat sinks of dimensions comparable to those used with the BWT pump laser - ranging from 0.02 to 0.04 K/W - the operating temperature of the pump laser is expected to be approximately 6 to 12 °C above the ambient temperature. Given that the maximum allowable operating temperature for BWT lasers is specified as 30 °C, this imposes a constraint on the maximum permissible ambient temperature for safe operation, which must not exceed 18 °C.

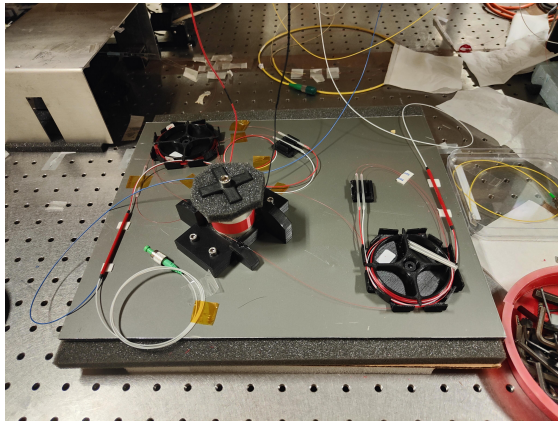
Appendix C

First prototypes of white light interferometry interrogators

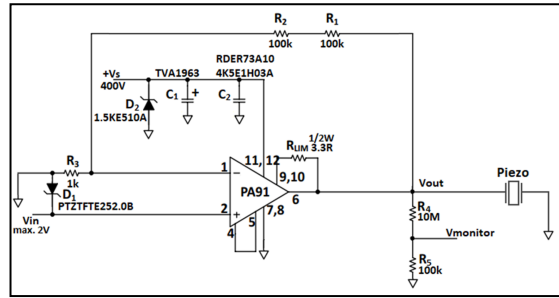
C.1 Traditional configuration

The PZT integration into one of the MZI arms typically necessitates a cylindrical geometry to facilitate the coiling of the optical fibre around it (Fig. C.1a). The PZT employed in this study was the PI PT140.70 model, with dimensions of 40 mm in height, 40 mm in outer diameter, and 38 mm in inner diameter. The PZT exhibits a height variation of 15 μm and a diameter variation of 12 μm for a voltage variation between 0 V and 1000 V and has a capacitance of 70 nF. The PZT was controlled using a Stanford Research Systems model DS345 signal generator, in combination with an amplifier based on the PA91 chip from Apex Microtechnology, as illustrated in the circuit diagram in Figure C.1b.

In consideration of the characteristics of the PZT and assuming a maximum applied voltage of 300 V, it is estimated that each turn of the fibre expands by 22.6 μm , requiring a total of nine turns of optical fibre around the PZT (with each arm requiring 1.2 m of optical fibre). It should be noted that this estimate does not consider the compressibility of the optical fibre coating or the blocking force of the PZT, as no data was available for these factors. Furthermore, the impact of the PZT's performance when subjected to load was not considered,



(a)



(b)

Figure C.1: Prototype based on the traditional configuration: a) photo of the interrogator and b) electrical schematic of the amplifier.

given the necessity for the fibre to be pre-tensioned for optimal PZT functionality. Therefore, 16 turns of optical fibre were coiled around the PZT, and a 400V amplitude signal was applied.

In order to guarantee a difference of less than 1 mm between the two arms of the interferometer, the two fibre sections, one for each interferometer arm, were achieved in the following manner:

- cut a fibre length equal to the combined lengths of both arms;
- align both ends and cut the fibre in half to create two equal sections.

A significant factor to consider when mounting the PZT onto the support is vibration at height. The mitigation of this was achieved through a sponge placed at both the top and bottom to absorb vertical movement and minimise the propagation of vibrations along the interrogator base.

The characterisation of the interrogation band is illustrated in Figure C.2. This characterisation was conducted utilising a triangular signal with voltages ranging from 0 to 400 V, and at room temperature of 20 °C. It has been demonstrated that as the frequency increases, the interrogation band shifts towards a shorter cavity length. The centre cavity of the interrogation band decreases from 850 μm to 400 μm , and the bandwidth expands accordingly. For frequencies exceeding 500 Hz,

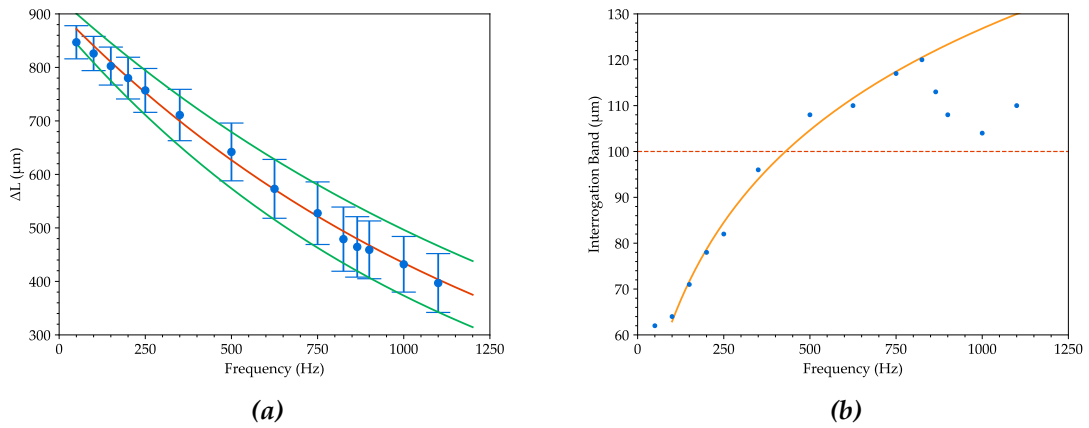


Figure C.2: Characterisation of the interrogation band: a) maximum, central and minimum value of the interrogation band, and b) width of the interrogation band, both as a function of the oscillation frequency of the PZT.

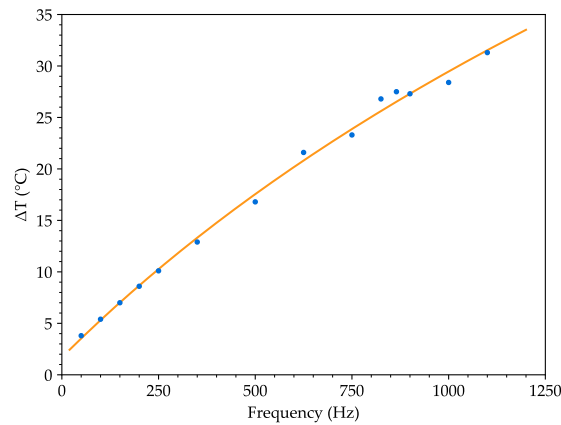


Figure C.3: Characterisation of the working temperature of PZT as a function of oscillation frequency.

the bandwidth exceeds 100 μm . This bandwidth expansion can be attributed to the increased electric current caused by higher frequencies, which in turn raises the temperature.

The operating temperature of the PZT reaches approximately 50 $^{\circ}\text{C}$ at frequencies close to 1 kHz, which is more than 30 $^{\circ}\text{C}$ above room temperature (C.3). This is due to the thermal insulation provided by the fibre coiling, the use of sponges at the top and bottom, and the application of an electrical signal with a maximum voltage of 400 V.

In addition, the output signal from the photodetector and monitor signal are

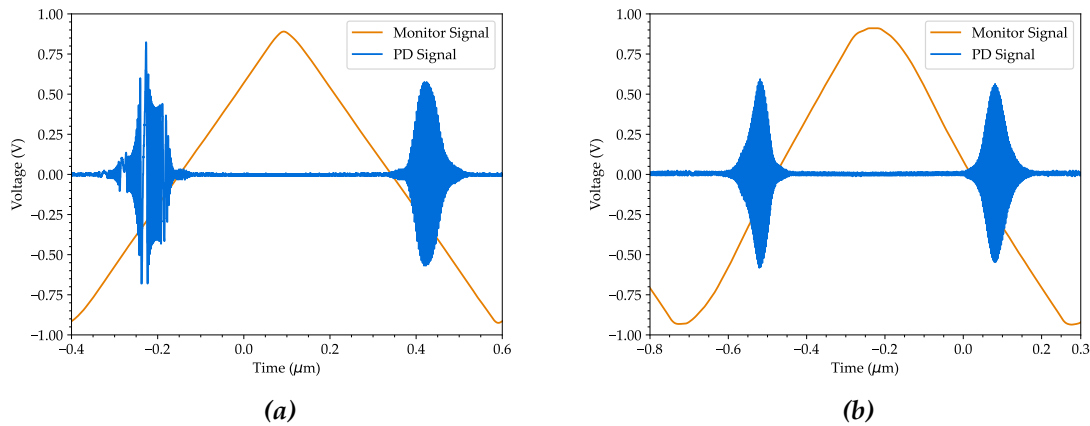


Figure C.4: Output signal from the photodetector and the monitor signal in two measurement frames: a) when a triangular signal is applied, and b) when a sinusoidal signal is applied to the PZT.

depicted in Figure C.4, for the cases when a triangular or sinusoidal signal, at 1 kHz, are applied to the PZT. In the case of the triangular wave (Fig. C.4a), the photodetector signal displays nonlinear behaviour, indicating that the actuator movement is nonlinear. In the case of the sinusoidal wave (Fig. C.4b), the monitor signal exhibits a sinusoidal feature at the extrema and a triangular feature in the middle, thus unable to replicate the sinusoidal movement because it reaches the power limit.

In view of the results obtained for the traditional configuration, it is imperative to modify the interrogator's configuration. This modification is necessary to ensure a reduction in non-linear PZT movement behaviour and voltage applied to the PZT for less than 200 V.

C.2 First prototype of the D-configuration

A D-shaped configuration is proposed for coupling the optical fibre to the PZT in order to reduce the voltage applied to the PZT (Fig. C.6.a). This configuration consists of two supports, each one with a D-shape geometry. The PZT is fixed to these supports by its bases and the fibre is coiled around them. In the prototypes produced, the supports are made of PLA or wood. Taking into account the

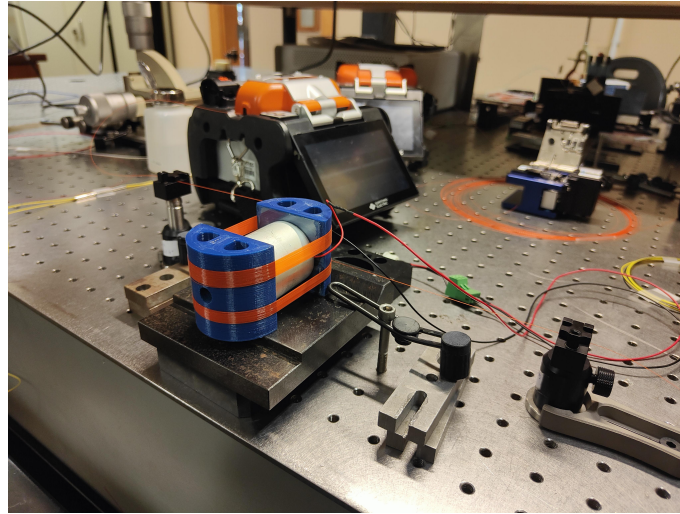


Figure C.5: Picture of the first prototype based on the D-configuration.

rigidity of the materials used, the fact that PLA is deformable at temperatures higher than 40 °C, the need to connect an electrical cable to the inside of the PZT and the fact that the bases of the PZT are a circular crown with a radius of 2 mm, pre-cut glass plates were glued to the supports in the area of contact with the PZT. Additionally, the glass plates help insulate the inner surface from the outer surface when the supports are made of metal. The PZT drive consisted of a Stanford Research Systems Model DS345 signal generator and a Tegam Model 2350 amplifier.

The first prototype consists of PLA supports, designed with a central screw to facilitate the coiling of the optical fibre (which was removed after assembly). To increase the interrogation bandwidth, 56 turns of fibre were coiled, half of which were positioned above and half below the screw area (Fig. C.5). In this configuration, each optical fibre turn contains two equally stretched segments.

The characterisation of the interrogation bandwidth is illustrated in Figure C.6, where a sinusoidal signal with voltages ranging from 0 to 200 V was applied to the PZT. This system exhibits an anti-resonance at 450 Hz and a resonance at 525 Hz. The interrogation bandwidth exceeds 100 μm for frequencies between 500 and 575 Hz.

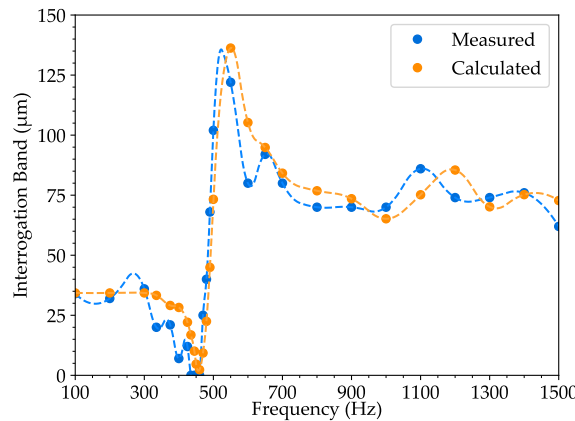


Figure C.6: Characterisation of the first prototype bandwidth as a function of the oscillation frequency of the PZT.

C.3 Second prototype of the D-configuration

In the second prototype, the supports were redesigned to include four distinct parts (see Fig. C.7a and b): an optical fibre support, a stem, a calibration, and a fixation component. The inclusion of a stem that connects the optical fibre support to the fixation area serves to reduce the load on the PZT. The fixing of the supports to the interrogator plate, in conjunction with the incorporation of a calibration area composed of two screws for coupling the PZT to the structure, facilitates the calibration of the load applied to the PZT, thereby optimising the bandwidth and adjusting the resonant frequency. In this configuration, 52 turns of optical fibre were coiled. The PZT drive consisted of a Stanford Research Systems Model DS345 signal generator and a Tegam Model 2350 amplifier.

As demonstrated in Figure C.8, the characterisation of the interrogation bandwidth is illustrated, where a sinusoidal signal with voltages between 0 and 50 V was applied to the PZT. This system exhibits two resonances: one at 4 kHz, with an amplitude of 275 μm , and another at 2.6 kHz, with an amplitude of 130 μm . For a 1 kHz frequency, an amplitude of 25 μm was achieved. Although a bandwidth of 100 μm at 1 kHz can only be achieved by applying a 200 V amplitude signal, the interrogation bandwidth at 4 kHz demonstrates that the D-configuration maximises the interrogator's performance and reduces

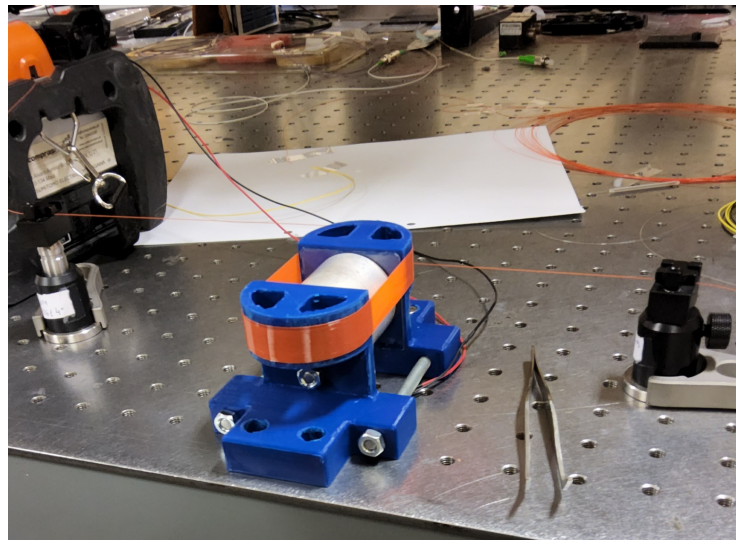


Figure C.7: Picture of the second prototype based on the D-configuration.

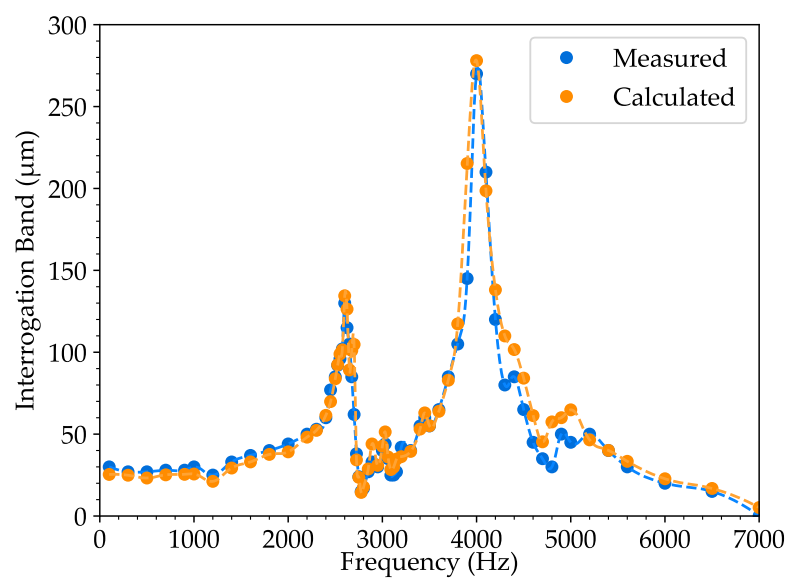


Figure C.8: Characterisation of the second prototype bandwidth as a function of the oscillation frequency of the PZT.

the system's electrical power consumption.

Appendix D

Python implementation of the algorithm for processing the output signal of white light interferometry

```
1
2 import numpy as np
3
4 import matplotlib.pyplot as plt
5
6 from struct import unpack
7 import struct
8 import zipfile
9
10 import scipy.fftpack as spfft
11 from scipy import signal as sps
12 from scipy import interpolate as spi
13
14 from scipy import fft as sp_fft
15 from scipy.fft._helper import _init_nd_shape_and_axes
16 fft , ifft = sp_fft.rfftn , sp_fft.irfftn
```

```

17
18 from collections import Counter
19
20 import os
21
22
23 _DEFINED_ENCODING = '>%sh' # indicates how the bytes are encoded
24 _DEFINED_POINTS = 500000 # Indicates the number of bytes to decode
25 _DEFINED_HEADER = 10 # header size for these files is 10 bytes
26 def parse(binary_sample=None, encoding=_DEFINED_ENCODING):
27     """
28     It serves to decode the data recorded in the binary input
29
30     :param binary_sample:
31     :param encoding:
32     :return:
33     """
34     parsed_sample = unpack(encoding % _DEFINED_POINTS,
35                             binary_sample[_DEFINED_HEADER - 1:-1])
36     return parsed_sample
37
38
39 def _init_freq_conv_axes(in1, in2, mode, axes, sorted_axes=False):
40
41     s1 = in1.shape
42     s2 = in2.shape
43
44     _, axes = _init_nd_shape_and_axes(in1, shape=None, axes=axes)
45     axes = [a for a in axes if s1[a] != 1 and s2[a] != 1]
46

```

```
47     if not s1[0] >= s2[0]:
48         in1, in2 = in2, in1
49     return in1, in2, axes
50
51
52 def _freq_domain_conv(in1, in2, matrix, axes, fshape,
53                       calc_fast_len=False):
54
55     sp1 = fft(in1, fshape, axes=axes)
56     ret = ifft(sp1 * matrix, fshape, axes=axes)
57
58     return ret
59
60
61 def _apply_conv_mode(ret, s1, s2):
62
63     return _centered(ret, s1).copy()
64
65
66 def _centered(arr, newshape):
67     newshape = np.asarray(newshape)
68     currshape = np.array(arr.shape)
69     startind = (currshape - newshape) // 2
70     endind = startind + newshape
71     myslice = [slice(startind[k], endind[k])
72               for k in range(len(endind))]
73     return arr[tuple(myslice)]
74
75
76 def fftconvolve(in1, in2, matrix, fshape, p,
```

```

77         mode="full", axes=None):
78
79     in1 = np.asarray(in1)
80     in2 = np.asarray(in2)
81
82     in1, in2, axes = _init_freq_conv_axes(in1, in2, mode, axes,
83                                           sorted_axes=False)
84
85     ret = _freq_domain_conv(in1, in2, matrix, axes,
86                             fshape, calc_fast_len=True)
87     ret = np.roll(ret, -(len(ret)//2-len(in1)//2+p))
88
89     return ret[:len(in1)]
90
91
92
93
94 def fftconvolve_1(in1, in2, nn, mode="full", axes=None):
95
96     in1 = np.asarray(in1)
97     in2 = np.asarray(in2)
98
99     in1, in2, axes = _init_freq_conv_axes(in1, in2, mode, axes,
100                                           sorted_axes=False)
101
102     s1 = in1.shape
103     s2 = in2.shape
104
105     shape = [len(in1) + len(in2) + len(in2) - 1 ]
106

```

```
107     complex_result = (in1.dtype.kind == 'c' or
108                        in2.dtype.kind == 'c')
109
110
111     fshape = [sp_fft.next_fast_len(shape[a],
112                                   not complex_result) for a in axes]
113
114     sp2 = fft(in2, fshape, axes=axes)
115     sp3 = fft(np.flip(in2), fshape, axes=axes)
116
117
118     return (sp2 * sp3)**nn, fshape
119
120
121
122
123 def env_max_1(out, r):
124     mx=np.array([], dtype = int)
125     i=0
126     while i<len(out)-1:
127         if out[i] > r:
128             j=i+1
129             while out[j] > r and j < len(out)-1:
130                 j+=1
131             if j - i > 1:
132                 a = max(out[i:j])
133                 a = np.where(out[i:j] == a)[0][0]
134                 if int(a) < len(out):
135                     mx = np.append(mx, i + int(a))
136                 i = j+1
```

```

137         else:
138             i+=1
139         return mx
140
141
142 def env_min_1(out, r):
143     mm=np.array([],dtype = int)
144     i=0
145     while i<len(out)-1:
146         if out[i] < r:
147             j=i+1
148             while out[j] < r and j < len(out)-1:
149                 j+=1
150             if j - i > 1:
151                 a = min(out[i:j])
152                 a = np.where(out == a)[0][0]
153                 if int(a) < len(out):
154                     mm = np.append(mm,int(a))
155             i = j+1
156         else:
157             i+=1
158     return mm
159
160
161
162
163 def adaptative_filtration_cccr(y, num_layers, FSR):
164
165     y_1 = np.copy(y)
166

```

```
167     for i in range(num_layers):
168
169         pos_max = np.where(y_1[5000:-5000] ==
170                             np.max(y_1[5000:-5000]))[0][0] + 500
171         y_1 = sps.fftconvolve(y_1, y_1[pos_max-FSR:
172                                     +pos_max+FSR+1], mode='same')
173         pos_max = np.where(y_1[5000:-5000] ==
174                             np.max(y_1[5000:-5000]))[0][0] + 500
175         y_1 = sps.correlate(y_1, y_1[pos_max-FSR:
176                                     pos_max+FSR+1], mode='same')
177         y_1 /= np.max(y_1)
178
179     return y_1
180
181
182 def adaptative_filtration_crcc(y, num_layers, FSR):
183
184     y_2 = np.copy(y)
185
186     for i in range(num_layers):
187
188         pos_max = np.where(y_2[5000:-5000] ==
189                             np.max(y_2[5000:-5000]))[0][0] + 500
190         y_2 = sps.correlate(y_2, y_2[pos_max-FSR:pos_max+FSR+1],
191                             mode='same')
192         pos_max = np.where(y_2[5000:-5000] ==
193                             np.max(y_2[5000:-5000]))[0][0] + 500
194         y_2 = sps.fftconvolve(y_2, y_2[pos_max-FSR:pos_max+FSR+1]
195                                 , mode='same')
196         y_2 /= np.max(y_2)
```

```
197
198     return y_2
199
200
201 #####
202 # Open first file
203 #####
204
205
206
207 ss = '...' #directory
208
209 _DEFINED_ENCODING = '>%sh'
210 _DEFINED_POINTS = 500000
211 _DEFINED_HEADER = 10
212
213 path = # Path to the test file. Edit as performed
214 test_uuid = '2c1b93e6'
215 ziparchive = zipfile.ZipFile(path)
216
217 files = [x for x in ziparchive.filelist
218           if x.filename.startswith(test_uuid)]
219
220
221
222
223 ## Create a directory
224 dir_img = 'img_9'
225 dir_img_1 = ss + dir_img
226
```



```
227 if not dir_img in os.listdir(path=ss):
228     os.mkdir(dir_img_1)
229     print("Directory_ '%_s' _created" % dir_img_1)
230 else:
231     print('Existing_folder')
232
233
234
235
236 #####
237 ##### Initialization ##
238 #####
239
240
241
242
243
244 #####
245 #Adaptive
246 #####
247
248
249
250 contents = zipfile.ZipFile.read(ziparchive ,
251                                 files[0]) # Reading in binary
252 parsed_contents = parse(contents ,
253                          _DEFINED_ENCODING) # Reading already converted
254 y = np.array(parsed_contents) # Matrix
255
256 y = y - np.sum(y)/len(y)
```

```
257 y /= np.max(y)
258
259 x = np.linspace(0, len(y)-1, len(y))
260
261 FSR = 241 # Window size for filtering
262
263
264
265
266
267 #####
268 # Filtration
269 #####
270
271
272 y_cccr = adaptative_filtration_cccr(np.abs(sps.hilbert(y)), 3, FSR)
273 y_crcc = adaptative_filtration_crcc(np.abs(sps.hilbert(y)), 3, FSR)
274
275 yy = y_cccr - np.min(y_cccr) + y_crcc - np.min(y_crcc)
276 yy -= np.sum(yy1)/len(yy)
277 yy /= np.max(yy)
278
279
280
281
282
283 #####
284 # Vectors/Matrices for processing
285 #####
286
```

```
287
288 pos_max = np.where(yy == np.max(yy))[0][0]
289 N = 0.75 # Relative coefficient for the filter window
290 nn = 16 # Filter order
291 ya = yy[pos_max-int(N*FSR):
292         pos_max+int(N*FSR)+1] # Filtering Sample
293
294
295 y = y - np.sum(y)/len(y)
296 y /= np.max(y)
297
298 y_adp = sps.fftconvolve(np.abs(sps.hilbert(y)) ,
299                         ya ,mode = 'same')
300 y_adp = sps.correlate(y_adp, ya,mode = 'same')
301
302 matrix_a , fshape_a = fftconvolve_1(np.abs(sps.hilbert(y)) ,
303                                     ya , nn, mode = 'same')
304 y1 = fftconvolve(np.abs(sps.hilbert(y)) , ya , matrix_a ,
305                 fshape_a , 0, mode = 'same')
306
307 p_adp = np.where(y_adp == np.max(y_adp))[0][0]
308 p_signal = np.where(y1 == np.max(y1))[0][0] - p_adp
309
310
311
312
313
314
315
316
```

```
317 #####
318 #Linearisation function
319 #####
320
321
322 lin_phase_factor = 1.07 # ratio between the phase
323 of a linear phase signal and the phase
324 of the sinusoidal signal at the last point
325
326 i_p = np.unwrap(np.angle(sps.hilbert(y))) # Phase
327 max_conv = i_p[-1] * lin_phase_factor
328 tr = i_p / max_conv * len(y) # Phase retification
329
330 f_lin = spi.interp1d( tr , tt , kind = 1) # Linearisation function
331
332
333
334
335
336
337
338
339 #####
340 ##### Start of the analysis ##
341 #####
342
343
344 max_pos = np.zeros(len(files)) # Maxima position array
345
346
```

```
347
348 for i in range(len(files)):
349
350     try:
351         contents = zipfile.ZipFile.read(ziparchive, files[i])
352         parsed_contents = parse(contents, _DEFINED_ENCODING)
353         y = np.array(parsed_contents)
354     except struct.error:
355         print(str(i), 'It_does_not_have_50000_points')
356
357     y = y - np.sum(y)/len(y)
358     y /= np.max(y)
359
360
361     y1 = y ** 2
362     #y1 = sps.hilbert(y)
363
364     y_1 = fftconvolve(np.abs(y1), ya, matrix_a, fshape_a,
365                       p_signal, mode = 'same')
366
367
368     max_pos[i] = f_lin(np.where(y_1 == np.max(y_1))[0][0])
369
370
371
372 np.savetxt(ss+'max_pos.txt', max_pos, delimiter = '\t')
```


Bibliography

- [1] K. Kosiel and M. Śmietana, *Detection in Harsh Environments*, ch. 13, pp. 441–476. John Wiley & Sons, Ltd, 2020. doi: <https://doi.org/10.1002/9781119534730.ch13>.
- [2] Y. Deng and J. Jiang, “Optical fiber sensors in extreme temperature and radiation environments: A review,” *IEEE Sensors Journal*, vol. 22, no. 14, pp. 13811–13834, 2022. doi: <https://doi.org/10.1109/JSEN.2022.3181949>.
- [3] E. J. Friebele, C. G. Askins, A. B. Bosse, A. D. Kersey, H. J. Patrick, W. R. Pogue, M. A. Putnam, W. R. Simon, F. A. Tasker, W. S. Vincent, and S. T. Vohra, “Optical fiber sensors for spacecraft applications,” *Smart Materials and Structures*, vol. 8, p. 813, dec 1999. doi: <https://doi.org/10.1088/0964-1726/8/6/310>.
- [4] T. H. Maiman, “Stimulated Optical Radiation in Ruby,” *Nature*, vol. 187, pp. 493–494, Aug. 1960. doi: <https://doi.org/10.1038/187493a0>.
- [5] C. J. Koester and E. Snitzer, “Amplification in a fiber laser,” *Appl. Opt.*, vol. 3, pp. 1182–1186, Oct 1964. doi: <https://doi.org/10.1364/AO.3.001182>.
- [6] K. Kao and G. Hockham, “Dielectric-fibre surface waveguides for optical frequencies,” *Proceedings of the Institution of Electrical Engineers*, vol. 113, pp. 1151–1158, 1966. doi: <https://doi.org/10.1049/piee.1966.0189>.

- [7] E. Agrell, M. Karlsson, A. R. Chraplyvy, D. J. Richardson, P. M. Krummrich, P. Winzer, K. Roberts, J. K. Fischer, S. J. Savory, B. J. Eggleton, M. Secondini, F. R. Kschischang, A. Lord, J. Prat, I. Tomkos, J. E. Bowers, S. Srinivasan, M. Brandt-Pearce, and N. Gisin, "Roadmap of optical communications," *Journal of Optics*, vol. 18, p. 063002, may 2016. doi: <https://doi.org/10.1088/2040-8978/18/6/063002>.
- [8] M. Elsherif, A. E. Salih, M. G. Muñoz, F. Alam, B. AlQattan, D. S. Antonysamy, M. F. Zaki, A. K. Yetisen, S. Park, T. D. Wilkinson, and H. Butt, "Optical fiber sensors: Working principle, applications, and limitations," *Advanced Photonics Research*, vol. 3, no. 11, p. 2100371, 2022. doi: <https://doi.org/10.1002/adpr.202100371>.
- [9] C. Pendão and I. Silva, "Optical fiber sensors and sensing networks: Overview of the main principles and applications," *Sensors*, vol. 22, no. 19, 2022. doi: <https://doi.org/10.3390/s22197554>.
- [10] Q. Yan, H. Ouyang, Z. Tao, M. Shen, S. Du, J. Zhang, H. Liu, H. Hao, and T. Jiang, "Multi-wavelength optical information processing with deep reinforcement learning," *Light, science & applications*, vol. 14, p. 160, 04 2025. doi: <https://doi.org/10.1038/s41377-025-01846-6>.
- [11] Y. Zheng, G. Zhang, Z. Huan, Y. Zhang, G. Yuan, Q. Li, G. Ding, Z. Lv, W. Ni, Y. Shao, X. Liu, and J. Zu, "Wireless laser power transmission: Recent progress and future challenges," *Space Solar Power and Wireless Transmission*, vol. 1, no. 1, pp. 17–26, 2024. doi: <https://doi.org/10.1038/10.1016/j.sspwt.2023.12.001>.
- [12] K. Bremer, M. Wollweber, F. Weigand, M. Rahlves, M. Kuhne, R. Helbig, and B. Roth, "Fibre optic sensors for the structural health monitoring of building structures," *Procedia Technology*, vol. 26, pp. 524–529, 2016. 3rd International Conference on System-Integrated Intelligence: New Challenges for Product and Production Engineering.

- [13] A. Abramovici, W. E. Althouse, R. W. P. Drever, Y. Gürsel, S. Kawamura, F. J. Raab, D. Shoemaker, L. Sievers, R. E. Spero, K. S. Thorne, R. E. Vogt, R. Weiss, S. E. Whitcomb, and M. E. Zucker, "Ligo: The laser interferometer gravitational-wave observatory," *Science*, vol. 256, no. 5055, pp. 325–333, 1992. doi: <https://doi.org/10.1126/science.256.5055.325>.
- [14] S. Zhao, Q. Liu, and Z. He, "Ultrahigh resolution fiber-optic thermometer by using an ultrastable probe laser," in *Optical Fiber Sensors Conference 2020 Special Edition*, p. W4.33, Optica Publishing Group, 2020. doi: <https://doi.org/10.1364/OFS.2020.W4.33>.
- [15] H. Xu, L. Wang, Y. Zu, W. Gou, and Y. Hu, "Application and development of fiber optic gyroscope inertial navigation system in underground space," *Sensors*, vol. 23, no. 12, 2023. doi: <https://doi.org/10.3390/s23125627>.
- [16] A. Javan, W. R. Bennett, and D. R. Herriott, "Population inversion and continuous optical maser oscillation in a gas discharge containing a he-ne mixture," *Phys. Rev. Lett.*, vol. 6, pp. 106–110, Feb 1961. doi: <https://doi.org/10.1103/PhysRevLett.6.106>.
- [17] A. L. Bloom, "Gas lasers," *Appl. Opt.*, vol. 5, pp. 1500–1514, Oct 1966. doi: <https://doi.org/10.1364/AO.5.001500>.
- [18] Z. Zhou, N. Tang, Z. Li, W. Huang, Z. Wang, W. Wu, and W. Hua, "High-power tunable mid-infrared fiber gas laser source by acetylene-filled hollow-core fibers," *Opt. Express*, vol. 26, pp. 19144–19153, Jul 2018. doi: <https://doi.org/10.1364/OE.26.019144>.
- [19] M. Xu, F. Yu, and J. Knight, "Mid-infrared 1 w hollow-core fiber gas laser source," *Opt. Lett.*, vol. 42, pp. 4055–4058, Oct 2017. doi: <https://doi.org/10.1364/OL.42.004055>.

- [20] R. Röder and C. Ronning, "Review on the dynamics of semiconductor nanowire lasers," *Semiconductor Science and Technology*, vol. 33, p. 033001, feb 2018. doi: <https://doi.org/10.1088/1361-6641/aaa7be>.
- [21] J. C. Norman, D. Jung, Z. Zhang, Y. Wan, S. Liu, C. Shang, R. W. Herrick, W. W. Chow, A. C. Gossard, and J. E. Bowers, "A review of high-performance quantum dot lasers on silicon," *IEEE Journal of Quantum Electronics*, vol. 55, no. 2, pp. 1–11, 2019. doi: <https://doi.org/10.1109/JQE.2019.2901508>.
- [22] S. Addanki, I. Amiri, and P. Yupapin, "Review of optical fibers-introduction and applications in fiber lasers," *Results in Physics*, vol. 10, pp. 743–750, 2018. doi: <https://doi.org/10.1016/j.rinp.2018.07.028>.
- [23] P. D. Dragic, M. Cavillon, and J. Ballato, "Materials for optical fiber lasers: A review," *Applied Physics Reviews*, vol. 5, no. 4, p. 041301, 2018. doi: <https://doi.org/10.1063/1.5048410>.
- [24] O. Svelto, *Principles of Lasers*. Springer US, 1988. doi: <https://doi.org/10.1007/978-1-4757-6266-25>.
- [25] J. O. White, "Parameters for quantitative comparison of two-, three-, and four-level laser media, operating wavelengths, and temperatures," *IEEE Journal of Quantum Electronics*, vol. 45, no. 10, pp. 1213–1220, 2009. doi: <https://doi.org/10.1109/JQE.2009.2020607>.
- [26] N. G. Boetti, D. Pugliese, E. Ceci-Ginistrelli, J. Lousteau, D. Janner, and D. Milanese, "Highly doped phosphate glass fibers for compact lasers and amplifiers: A review," *Applied Sciences*, vol. 7, no. 12, 2017. doi: <https://doi.org/10.3390/app7121295>.
- [27] L. Meng, Z. Huang, Z. Han, H. Shen, and R. Zhu, "Simulation and experiment studies of aberration effects on the measurement of laser beam quality factor (m^2)," *Optics and Lasers in Engineering*, vol. 100, pp. 226–233, 2018. doi: <https://doi.org/10.1016/j.optlaseng.2017.09.005>.

- [28] H. Lin, Y. Feng, Y. Feng, P. Barua, J. K. Sahu, and J. Nilsson, "656 w er-doped, yb-free large-core fiber laser," *Opt. Lett.*, vol. 43, pp. 3080–3083, Jul 2018. doi: <https://doi.org/10.1364/OL.43.003080>.
- [29] V. Balaswamy, S. Ramachandran, and V. R. Supradeepa, "High-power, cascaded random raman fiber laser with near complete conversion over wide wavelength and power tuning," *Opt. Express*, vol. 27, pp. 9725–9732, Apr 2019. doi: <https://doi.org/10.1364/OE.27.009725>.
- [30] Q. Fang, J. Li, W. Shi, Y. Qin, Y. Xu, X. Meng, R. A. Norwood, and N. Peyghambarian, "5 kw near-diffraction-limited and 8 kw high-brightness monolithic continuous wave fiber lasers directly pumped by laser diodes," *IEEE Photonics Journal*, vol. 9, no. 5, pp. 1–7, 2017. doi: <https://doi.org/10.1109/JPHOT.2017.2744803>.
- [31] R. Li, H. Xiao, J. Leng, Z. Chen, J. Xu, J. Wu, and P. Zhou, "2240 w high-brightness 1018 nm fiber laser for tandem pump application," *Laser Physics Letters*, vol. 14, p. 125102, nov 2017. doi: <https://doi.org/10.1088/1612-202x/aa7d84>.
- [32] K. Rottwitt, J. Povlsen, A. Bjarklev, O. Lumholt, B. Pedersen, and T. Rasmussen, "Optimum signal wavelength for a distributed erbium-doped fiber amplifier," *IEEE Photonics Technology Letters*, vol. 4, no. 7, pp. 714–717, 1992. doi: <https://doi.org/10.1109/68.145248>.
- [33] R. Hui and M. O'Sullivan, "Chapter 1 - fundamentals of optical devices," in *Fiber Optic Measurement Techniques* (R. Hui and M. O'Sullivan, eds.), pp. 1–128, Boston: Academic Press, 2009. doi: <https://doi.org/10.1016/B978-0-12-373865-3.00001-X>.
- [34] B. Ghosh and S. Mandal, "Fiber bragg grating-based optical filters for high-resolution sensing: A comprehensive analysis," *Results in Optics*, vol. 12, p. 100441, 2023. doi: <https://doi.org/10.1016/j.rio.2023.100441>.

- [35] J. Zhao, Y. Zhao, Y. Peng, R. qing Lv, and Q. Zhao, "Review of femtosecond laser direct writing fiber-optic structures based on refractive index modification and their applications," *Optics & Laser Technology*, vol. 146, p. 107473, 2022. doi: <https://doi.org/10.1016/j.optlastec.2021.107473>.
- [36] N. A. Mohammed, T. A. Ali, and M. H. Aly, "Performance optimization of apodized fbg-based temperature sensors in single and quasi-distributed dwdm systems with new and different apodization profiles," *AIP Advances*, vol. 3, p. 122125, 12 2013. doi: <https://doi.org/10.1063/1.4859115>.
- [37] P. Robalinho, V. Piaia, L. Soares, S. Novais, A. L. Ribeiro, S. Silva, and O. Frazão, "Phase-shifted fiber bragg grating by selective pitch slicing," *Sensors*, vol. 24, no. 21, 2024. doi: <https://doi.org/10.3390/s24216898>.
- [38] H. Li, B. Yang, M. Wang, C. Gao, B. Wu, L. Zeng, X. Xi, Z. Chen, X. Wang, Z. Wang, and J. Chen, "Femtosecond laser fabrication of large-core fiber bragg gratings for high-power fiber oscillators," *APL Photonics*, vol. 8, p. 046101, 04 2023. doi: <https://doi.org/10.1063/5.0130238>.
- [39] H.-K. Choi, Y.-J. Jung, B.-A. Yu, Y. L. Lee, Y.-C. Noh, and I.-B. Sohn, "Femtosecond laser direct writing of fiber bragg grating with high-speed and high-resolution scanning technique," *Optik*, vol. 321, p. 172168, 2025. doi: <https://doi.org/10.1016/j.ijleo.2024.172168>.
- [40] A. R. Maurer, "Optical waveguide light source," 1974. doi: <https://patents.google.com/patent/US3808549> (accessed April 28, 2020).
- [41] E. Snitzer, H. Po, F. Hakimi, R. Tumminelli, and B. C. McCollum, "Double clad, offset core nd fiber laser," in *Optical Fiber Sensors*, p. PD5, Optical Society of America, 1988. doi: <https://doi.org/10.1364/OFS.1988.PD5>.

- [42] S. Liu, H. Zhan, K. Peng, S. Sun, Y. Li, J. Jiang, L. Ni, X. Wang, J. Yu, R. Zhu, J. Wang, F. Jing, and A. Lin, "Fabrication and laser performance of triple-clad yb-doped aluminophosphosilicate fiber," *Optical Fiber Technology*, vol. 46, pp. 297–301, 2018. doi: <https://doi.org/10.1016/j.yofte.2018.10.021>.
- [43] P. Laperle, C. Paré, H. Zheng, and A. Croteau, "Yb-doped lma triple-clad fiber for power amplifiers," *Proc SPIE*, vol. 6453, 02 2007. doi: <https://doi.org/10.1117/12.699075>.
- [44] R. Dauliat, A. Benoît, D. Darwich, R. Jamier, J. Kobelke, S. Grimm, K. Schuster, and P. Roy, "Demonstration of a homogeneous yb-doped core fully aperiodic large-pitch fiber laser," *Appl. Opt.*, vol. 55, pp. 6229–6235, Aug 2016. doi: <https://doi.org/10.1364/AO.55.006229>.
- [45] H. Zhan, Y. Wang, K. Peng, Z. Wang, L. Ni, X. Wang, J. Wang, F. Jing, and A. Lin, "2kw (2 + 1) gt-wave fiber amplifier," *Laser Physics Letters*, vol. 13, p. 045103, mar 2016. doi: <https://doi.org/10.1088/1612-2011/13/4/045103>.
- [46] H. Zhan, Q. Liu, Y. Wang, W. Ke, L. Ni, X. Wang, K. Peng, C. Gao, Y. Li, H. Lin, J. Wang, F. Jing, and A. Lin, "5kw gtwave fiber amplifier directly pumped by commercial 976nm laser diodes," *Opt. Express*, vol. 24, pp. 27087–27095, Nov 2016. doi: <https://doi.org/10.1364/OE.24.027087>.
- [47] Q. Xiao, Y. Huang, J. Sun, X. Wang, D. Li, M. Gong, and P. Yan, "Research on multi-kilowatts level tapered fiber bundle n×1 pumping combiner for high power fiber laser," *Frontiers of Optoelectronics*, vol. 9, 03 2016. doi: <https://doi.org/10.1007/s12200-016-0609-0>.
- [48] J. K. Kim, C. Hagemann, T. Schreiber, T. Peschel, S. Böhme, R. Eberhardt, and A. Tünnermann, "Monolithic all-glass pump combiner scheme for

- high-power fiber laser systems," *Opt. Express*, vol. 18, pp. 13194–13203, Jun 2010. doi: <https://doi.org/10.1364/OE.18.013194>.
- [49] Z. Li, X. Tian, C. Lei, H. Zhang, Z. Chen, B. Yang, X. Xi, X. Wang, Z. Wang, and J. Chen, "Fabrication of a side pump combiner and realization of a 2 kw single mode all-fiber laser oscillator," *OSA Continuum*, vol. 3, pp. 1240–1248, May 2020. doi: <https://doi.org/10.1364/OSAC.393164>.
- [50] D. Stachowiak, "High-power passive fiber components for all-fiber lasers and amplifiers application—design and fabrication," *Photonics*, vol. 5, no. 4, 2018. doi: <https://doi.org/10.3390/photonics5040038>.
- [51] W. Wu, Z. Chen, Z. Wang, and J. Chen, "Novel 3 x 1 signal combiner with high-power fiber laser output of high beam quality," *Optik*, vol. 225, p. 165353, 2021. doi: <https://doi.org/10.1016/j.ijleo.2020.165353>.
- [52] D. J. Richardson, J. Nilsson, and W. A. Clarkson, "High power fiber lasers: current status and future perspectives [invited]," *J. Opt. Soc. Am. B*, vol. 27, pp. B63–B92, Nov 2010. doi: <https://doi.org/10.1364/JOSAB.27.000B63>.
- [53] D. Marcuse, "Influence of curvature on the losses of doubly clad fibers," *Appl. Opt.*, vol. 21, pp. 4208–4213, Dec 1982. doi: <https://doi.org/10.1364/AO.21.004208>.
- [54] T. Bhutta, J. I. Mackenzie, D. P. Shepherd, and R. J. Beach, "Spatial dopant profiles for transverse-mode selection in multimode waveguides," *J. Opt. Soc. Am. B*, vol. 19, pp. 1539–1543, Jul 2002. doi: <https://doi.org/10.1364/JOSAB.19.001539>.
- [55] M. E. Fermann, "Single-mode excitation of multimode fibers with ultrashort pulses," *Opt. Lett.*, vol. 23, pp. 52–54, Jan 1998. doi: <https://doi.org/10.1364/OL.23.000052>.

- [56] D. Donlagic, "In-line higher order mode filters based on long highly uniform fiber tapers," *Journal of Lightwave Technology*, vol. 24, no. 9, pp. 3532–3539, 2006. doi: <https://doi.org/10.1109/JLT.2006.878497>.
- [57] J. Knight, T. Birks, R. Cregan, P. Russell, and J.-P. de Sandro, "Large mode area photonic crystal fibre," *Electronics Letters*, vol. 34, pp. 1347–1348(1), June 1998. doi: <https://doi.org/10.1049/el:19980965>.
- [58] A. E. Siegman, "Gain-guided, index-antiguide fiber lasers," *J. Opt. Soc. Am. B*, vol. 24, pp. 1677–1682, Aug 2007. doi: <https://doi.org/10.1364/JOSAB.24.001677>.
- [59] D. Hanna, R. Percival, I. Perry, R. Smart, P. Suni, J. Townsend, and A. Tropper, "Continuous-wave oscillation of a monomode ytterbium-doped fibre laser," *Electronics Letters*, vol. 24, pp. 1111–1113(2), August 1988. doi: <https://doi.org/10.1049/el:19880755>.
- [60] R. Mears, L. Reekie, I. Jauncey, and D. Payne, "Low-noise erbium-doped fibre amplifier operating at 1.54 μm ," *Electronics Letters*, vol. 23, pp. 1026–1028(2), September 1987. doi: <https://doi.org/10.1049/el:19870719>.
- [61] E. Desurvire, *Erbium-doped fiber amplifiers: principles and applications*. New York: John Wiley & Sons, Ltd, 2002.
- [62] S. D. Jackson and T. A. King, "High-power diode-cladding-pumped tm-doped silica fiber laser," *Opt. Lett.*, vol. 23, pp. 1462–1464, Sep 1998. doi: <https://doi.org/10.1364/OL.23.001462>.
- [63] S. D. Jackson, "Continuous wave 2.9 μm dysprosium-doped fluoride fiber laser," *Applied Physics Letters*, vol. 83, no. 7, pp. 1316–1318, 2003. doi: <https://doi.org/10.1063/1.1603353>.

- [64] N. Simakov, A. Hemming, W. A. Clarkson, J. Haub, and A. Carter, "A cladding-pumped, tunable holmium doped fiber laser," *Opt. Express*, vol. 21, pp. 28415–28422, Nov 2013. doi: <https://doi.org/10.1364/OE.21.028415>.
- [65] A. C. Tropper, J. N. Carter, R. D. T. Lauder, D. C. Hanna, S. T. Davey, and D. Szebesta, "Analysis of blue and red laser performance of the infrared-pumped praseodymium-doped fluoride fiber laser," *J. Opt. Soc. Am. B*, vol. 11, pp. 886–893, May 1994. doi: <https://doi.org/10.1364/JOSAB.11.000886>.
- [66] S. Jackson, "The spectroscopic and energy transfer characteristics of the rare earth ions used for silicate glass fibre lasers operating in the shortwave infrared," *Laser & Photonics Reviews*, vol. 3, no. 5, pp. 466–482, 2009. doi: <https://doi.org/10.1002/lpor.200810058>.
- [67] S. D. Jackson, "Cross relaxation and energy transfer upconversion processes relevant to the functioning of 2 μm tm^{3+} -doped silica fibre lasers," *Optics Communications*, vol. 230, no. 1, pp. 197–203, 2004. doi: <https://doi.org/10.1016/j.optcom.2003.11.045>.
- [68] Z. Li, A. M. Heidt, J. M. O. Daniel, Y. Jung, S. U. Alam, and D. J. Richardson, "Thulium-doped fiber amplifier for optical communications at 2 μm ," *Opt. Express*, vol. 21, pp. 9289–9297, Apr 2013. doi: <https://doi.org/10.1364/OE.21.009289>.
- [69] A. Sincore, J. D. Bradford, J. Cook, L. Shah, and M. C. Richardson, "High average power thulium-doped silica fiber lasers: Review of systems and concepts," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 3, pp. 1–8, 2018. doi: <https://doi.org/10.1109/JSTQE.2017.2775964>.
- [70] M. N. Zervas and C. A. Codemard, "High power fiber lasers: A review," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, no. 5,

- pp. 219–241, 2014. doi: <https://doi.org/10.1109/JSTQE.2014.2321279>.
- [71] H. M. Pask, R. J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechnie, P. R. Barber, and J. M. Dawes, “Ytterbium-doped silica fiber lasers: versatile sources for the 1–1.2 μm region,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 1, no. 1, pp. 2–13, 1995. doi: <https://doi.org/10.1109/2944.468377>.
- [72] F. Beier, C. Hupel, S. Kuhn, S. Hein, J. Nold, F. Proske, B. Sattler, A. Liem, C. Jauregui, J. Limpert, N. Haarlammert, T. Schreiber, R. Eberhardt, and A. Tünnermann, “Single mode 4.3 kw output power from a diode-pumped yb-doped fiber amplifier,” *Opt. Express*, vol. 25, pp. 14892–14899, Jun 2017. doi: <https://doi.org/10.1364/OE.25.014892>.
- [73] P. Barua, E. Sekiya, K. Saito, and A. Ikushima, “Influences of yb³⁺ ion concentration on the spectroscopic properties of silica glass,” *Journal of Non-Crystalline Solids*, vol. 354, no. 42, pp. 4760–4764, 2008. doi: <https://doi.org/10.1016/j.jnoncrysol.2008.04.020>.
- [74] P. Zhou, X. Wang, H. Xiao, Y. Ma, and J. Chen, “Review on recent progress on yb-doped fiber laser in a variety of oscillation spectral ranges,” *Laser Physics*, vol. 22, pp. 823–831, May 2012. doi: <https://doi.org/10.1134/S1054660X12050404>.
- [75] E. A. Shcherbakov, V. V. Fomin, A. A. Abramov, A. A. Ferin, D. V. Mochalov, and V. P. Gapontsev, “Industrial grade 100 kw power cw fiber laser,” in *Advanced Solid-State Lasers Congress*, p. ATh4A.2, Optical Society of America, 2013. doi: <https://doi.org/10.1364/ASSL.2013.ATh4A.2>.
- [76] M. A. Kabir, M. M. Hossain, M. Z. Amin, and M. S. Ahsan, “A theoretical investigation of erbium-doped fiber laser as a function of ion-clustering, temperature, pumping wavelength, and configuration,” *Microwave and*

- Optical Technology Letters*, vol. 62, no. 2, pp. 531–539, 2020. doi: <https://doi.org/10.1002/mop.32071>.
- [77] P. Myslinski, D. Nguyen, and J. Chrostowski, “Effects of concentration on the performance of erbium-doped fiber amplifiers,” *Journal of Lightwave Technology*, vol. 15, no. 1, pp. 112–120, 1997. doi: <https://doi.org/10.1109/50.552118>.
- [78] L. V. Kotov, M. E. Likhachev, M. M. Bubnov, O. I. Medvedkov, M. V. Yashkov, A. N. Guryanov, J. Lhermite, S. Février, and E. Cormier, “75w 40% efficiency single-mode all-fiber erbium-doped laser cladding pumped at 976 nm,” *Opt. Lett.*, vol. 38, pp. 2230–2232, Jul 2013. doi: <https://doi.org/10.1364/OL.38.002230>.
- [79] M. Fermann, D. Hanna, D. Shepherd, P. Suni, and J. Townsend, “Efficient operation of an yb-sensitised er fibre laser at 1.56 μm ,” *Electronics Letters*, vol. 24, pp. 1135–1136(1), September 1988. doi: <https://doi.org/10.1049/el:19880772>.
- [80] D. Y. Shen, J. K. Sahu, and W. A. Clarkson, “Highly efficient er,yb-doped fiber laser with 188w free-running and>100w tunable output power,” *Opt. Express*, vol. 13, pp. 4916–4921, Jun 2005. doi: <https://doi.org/10.1364/OPEX.13.004916>.
- [81] Y. Jeong, S. Yoo, C. A. Codemard, J. Nilsson, J. K. Sahu, D. N. Payne, R. Horley, P. W. Turner, L. Hickey, A. Harker, M. Lovelady, and A. Piper, “Erbium:ytterbium codoped large-core fiber laser with 297-w continuous-wave output power,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 13, no. 3, pp. 573–579, 2007. doi: <https://doi.org/10.1109/JSTQE.2007.897178>.
- [82] X. Zhao, Q. Han, D. Wang, H. Hu, K. Ren, J. Jiang, and T. Liu, “Optimal design of high-power cascade co-pumping er/yb-codoped fiber lasers,”

- Opt. Lett.*, vol. 44, pp. 1100–1103, Mar 2019. doi: <https://doi.org/10.1364/OL.44.001100>.
- [83] V. Kuhn, P. Weßels, J. Neumann, and D. Kracht, “Stabilization and power scaling of cladding pumped er:yb-codoped fiber amplifier via auxiliary signal at 1064 nm,” *Opt. Express*, vol. 17, pp. 18304–18311, Sep 2009. doi: <https://doi.org/10.1364/OE.17.018304>.
- [84] M. A. Jebali, J.-N. Maran, and S. LaRochelle, “264 w output power at 1585 nm in er-yb codoped fiber laser using in-band pumping,” *Opt. Lett.*, vol. 39, pp. 3974–3977, Jul 2014. doi: <https://doi.org/10.1364/OL.39.003974>.
- [85] P. O. Minott, “Scintillation in an earth-to-space propagation path,” *J. Opt. Soc. Am.*, vol. 62, pp. 885–888, Jul 1972. doi: <https://doi.org/10.1364/JOSA.62.000885>.
- [86] K. E. Wilson, J. R. Lesh, K. Araki, and Y. Arimoto, “Overview of the Ground-to-Orbit Lasercom Demonstration (GOLD),” in *Free-Space Laser Communication Technologies IX* (G. S. Mecherle, ed.), vol. 2990, pp. 23 – 30, International Society for Optics and Photonics, SPIE, 1997. doi: <https://doi.org/10.1117/12.273703>.
- [87] K. E. Wilson, P. Leatherman, R. Cleis, J. Spinhirne, and R. Fugate, “Results of the compensated earth-moon-earth retroreflector laser link (cemerll) experiment,” 1997.
- [88] S. Golmohammady, M. Yousefi, and F. Dabbagh Kashani, “Analysing the atmospheric effects on optical communication link parameters through a slant path in the non-kolmogorov turbulence,” in *2019 2nd West Asian Colloquium on Optical Wireless Communications (WACOWC)*, pp. 62–68, 2019. doi: <https://doi.org/10.1109/WACOWC.2019.8770191>.
- [89] L. Andrews and R. Phillips, “Laser beam propagation through random media,” 2005. doi: <https://doi.org/10.1117/3.626196>.

- [90] N. Kawashima, K. Takeda, H. Matsuoka, Y. Fujii, and M. Yamamoto, "Laser energy transmission for a wireless energy supply to robots," in *Proceedings of the 22nd International Symposium on Automation and Robotics in Construction*, (Ferrara, Italy), International Association for Automation and Robotics in Construction (IAARC), September 2005. doi: <https://doi.org/10.22260/ISARC2005/0068>.
- [91] A. Kolmogorov, "The Local Structure of Turbulence in Incompressible Viscous Fluid for Very Large Reynolds' Numbers," *Akademiia Nauk SSSR Doklady*, vol. 30, pp. 301–305, jan 1941. doi: <https://doi.org/10.1098/rspa.1991.0075>.
- [92] R. F. Lutomirski and H. T. Yura, "Wave structure function and mutual coherence function of an optical wave in a turbulent atmosphere," *J. Opt. Soc. Am.*, vol. 61, pp. 482–487, Apr 1971. doi: <https://doi.org/10.1364/JOSA.61.000482>.
- [93] D. L. Fried, "Scintillation of a ground-to-space laser illuminator," *J. Opt. Soc. Am.*, vol. 57, pp. 980–983, Aug 1967. doi: <https://doi.org/10.1364/JOSA.57.000980>.
- [94] K. Chaudhary and D. Kumar, "Satellite solar wireless power transfer for baseload ground supply: clean energy for the future," *European Journal of Futures Research*, vol. 6, 06 2018. doi: <https://doi.org/10.1186/s40309-018-0139-7>.
- [95] L. Summerer and O. Purcell, "Concepts for wireless energy transmission via laser," 01 2009.
- [96] K. Anbarasi, C. Hemanth, and R. Sangeetha, "A review on channel models in free space optical communication systems," *Optics & Laser Technology*, vol. 97, pp. 161–171, 2017. doi: <https://doi.org/10.1016/j.optlastec.2017.06.018>.

- [97] F. Steinsiek, K. Weber, W. Foth, H. Foth, and C. Schafer, "Wireless power transmission experiment using an airship as relay system and a moveable rover as ground target for later planetary exploration missions," in *8th ESA Workshop on Advanced Space Technologies for Robotics and Automation*, pp. 1–10, 2004. http://robotics.estec.esa.int/ASTRA/Astra2004/Papers/astra2004_F-04.pdf.
- [98] N. Kawashima, K. Takeda, and K. Yabe, "Application of the laser energy transmission technology to drive a small airplane," *Chin. Opt. Lett.*, vol. 5, pp. S109–S110, May 2007. <https://opg.optica.org/col/abstract.cfm?URI=col-5-101-S109>.
- [99] T. He, S. Yang, H.-Y. Zhang, Z. Changming, Y.-C. Zhang, P. Xu, and M. Muñoz-García, "High-power high-efficiency laser power transmission at 100 m using optimized multi-cell gaas converter," *Chinese Physics Letters*, vol. 31, p. 104203, oct 2014. doi: <https://doi.org/10.1088/0256-307X/31/10/104203>.
- [100] "Researchers transmit energy with laser in historic power beaming demonstration," 2019. <https://www.nrl.navy.mil/Media/News/Article/2504007/researchers>.
- [101] "Darpa airborne energy well seeks laser propulsion on aircrafts to power rechargeable unmanned aerial systems," 2022. <https://idstch.com/military/air/darpa-airborne-energy>.
- [102] "First in-space laser power beaming experiment surpasses 100 days of successful on-orbit operations," 2023. <https://www.nrl.navy.mil/Media/News/Article/3457014/first-in-space>.
- [103] Z. Jia, Q. Zhu, and F. Ao, "Atmospheric attenuation analysis in the fso link," in *2006 International Conference on Communication Technology*, pp. 1–4, 2006. doi: <https://doi.org/10.1109/ICCT.2006.341919>.

- [104] T. R. Oke, G. Mills, A. Christen, and J. A. Voogt, *Urban Climates*. Cambridge University Press, 2017. doi: <https://doi.org/10.1017/9781139016476>.
- [105] J. A. Shaw and P. W. Nugent, "Physics principles in radiometric infrared imaging of clouds in the atmosphere," *European Journal of Physics*, vol. 34, pp. S111–S121, oct 2013. doi: <https://doi.org/10.1088/0143-0807/34/6/s111>.
- [106] A. S. El-Wakeel, N. A. Mohammed, and M. H. Aly, "Free space optical communications system performance under atmospheric scattering and turbulence for 850 and 1550 nm operation," *Appl. Opt.*, vol. 55, pp. 7276–7286, Sep 2016. doi: <https://doi.org/10.1364/AO.55.007276>.
- [107] M. Grabner and V. Kvicera, "Multiple scattering in rain and fog on free-space optical links," *Journal of Lightwave Technology*, vol. 32, no. 3, pp. 513–520, 2014. doi: <https://doi.org/10.1109/JLT.2013.2294356>.
- [108] K. Sunilkumar, N. Anand, S. K. Satheesh, K. K. Moorthy, and G. Ilavazhagan, "Performance of free-space optical communication systems: effect of aerosol-induced lower atmospheric warming," *Opt. Express*, vol. 27, pp. 11303–11311, Apr 2019. doi: <https://doi.org/10.1364/OE.27.011303>.
- [109] J. W. Hardy, *Adaptive Optics for Astronomical Telescopes*. Oxford University Press, 1998.
- [110] Y. Liu, K. Zhang, Z. Chen, and J. Pu, "Scintillation index of double vortex beams in turbulent atmosphere," *Optik*, vol. 181, pp. 571–574, 2019. doi: <https://doi.org/10.1016/j.ijleo.2018.12.046>.
- [111] M. Cheng, L. Guo, J. Li, X. Yan, R. Sun, and Y. You, "Effects of asymmetry atmospheric eddies on spreading and wander of besel–gaussian beams

- in anisotropic turbulence," *IEEE Photonics Journal*, vol. 10, no. 3, pp. 1–10, 2018. doi: <https://doi.org/10.1109/JPHOT.2018.2842243>.
- [112] M. Ijaz, G. Harris, B. Adebisi, W. Popoola, and S. Rajbhandari, "Experimental study of the beam wander mitigation in free space optical communications using single input multiple output system," in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 1–5, 2017. doi: <https://doi.org/10.1109/PIMRC.2017.8292601>.
- [113] J. Vitasek, E. Leitgeb, T. David, J. Latal, and S. Hejduk, "Misalignment loss of free space optic link," in *2014 16th International Conference on Transparent Optical Networks (ICTON)*, pp. 1–5, 2014. doi: <https://doi.org/10.1109/ICTON.2014.6876494>.
- [114] M. Atakora and H. Chenji, "Overcoming alignment delay in rf+fso networks," in *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, pp. 628–633, 2017. doi: <https://doi.org/10.1109/IWCMC.2017.7986358>.
- [115] M. Mansour Abadi, M. Cox, R. Alsaigh, S. Viola, A. Forbes, and M. Lavery, "A space division multiplexed free-space-optical communication system that can auto-locate and fully self align with a remote transceiver," *Scientific Reports*, vol. 9, p. 19687, 12 2019. doi: <https://doi.org/10.1038/s41598-019-55670-1>.
- [116] J. Ouyang, Y. Che, J. Xu, and K. Wu, "Throughput maximization for laser-powered uav wireless communication systems," 2018. arXiv, eprint <https://arxiv.org/abs/1803.006901>.
- [117] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Communications Surveys Tutorials*, vol. 19, no. 1, pp. 57–96, 2017. doi: <https://doi.org/10.1109/COMST.2016.2603518>.

- [118] L. Ma and S. A. Ponomarenko, "Optical coherence gratings and lattices," *Opt. Lett.*, vol. 39, pp. 6656–6659, Dec 2014. doi: <https://doi.org/10.1364/OL.39.006656>.
- [119] S. A. Ponomarenko, "Complex gaussian representation of statistical pulses," *Opt. Express*, vol. 19, pp. 17086–17091, Aug 2011. doi: <https://doi.org/10.1364/OE.19.017086>.
- [120] Y. Huang, Y. Yuan, X. Liu, J. Zeng, F. Wang, J. Yu, L. Liu, and Y. Cai, "Propagation of optical coherence vortex lattices in turbulent atmosphere," *Applied Sciences*, vol. 8, no. 12, 2018. doi: <https://doi.org/10.3390/app8122476>.
- [121] X. Liu, J. Yu, Y. Cai, and S. A. Ponomarenko, "Propagation of optical coherence lattices in the turbulent atmosphere," *Opt. Lett.*, vol. 41, pp. 4182–4185, Sep 2016. doi: <https://doi.org/10.1364/OL.41.004182>.
- [122] X. Xiao, D. G. Voelz, I. Toselli, and O. Korotkova, "Gaussian beam propagation in anisotropic turbulence along horizontal links: theory, simulation, and laboratory implementation," *Appl. Opt.*, vol. 55, pp. 4079–4084, May 2016. doi: <https://doi.org/10.1364/AO.55.004079>.
- [123] Y. Kaymak, R. Rojas-Cessa, J. Feng, N. Ansari, and M. Zhou, "On divergence-angle efficiency of a laser beam in free-space optical communications for high-speed trains," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 9, pp. 7677–7687, 2017. doi: <https://doi.org/10.1109/TVT.2017.2686818>.
- [124] G. Sk, A. Tripathi, A. Mandloi, and S. Gupta, "Compensating rain induced impairments in terrestrial fso links using aperture averaging and receiver diversity," *Optical and Quantum Electronics*, vol. 51, 07 2019. doi: <https://doi.org/10.1007/s11082-019-1962-1>.

- [125] S. Basu, "A simple approach for estimating the refractive index structure parameter (cn2) profile in the atmosphere," *Opt. Lett.*, vol. 40, pp. 4130–4133, Sep 2015. doi: <https://doi.org/10.1364/OL.40.004130>.
- [126] N. Anand, S. K. Satheesh, and K. K. Moorthy, "Dependence of atmospheric refractive index structure parameter (cn2) on the residence time and vertical distribution of aerosols," *Opt. Lett.*, vol. 42, pp. 2714–2717, Jul 2017. doi: <https://doi.org/10.1364/OL.42.002714>.
- [127] S. Blundell and K. M. Blundell, *Concepts in thermal physics / Stephen J. Blundell and Katherine M. Blundell*. Oxford: Oxford University Press, 2009.
- [128] J. P. McHugh, G. Y. Jumper, and M. Chun, "Balloon Thermosonde Measurements over Mauna Kea and Comparison with Seeing Measurements," *PASP*, vol. 120, p. 1318, dec 2008. doi: <https://doi.org/10.1086/595871>.
- [129] J. C. Wyngaard, *Turbulence in the Atmosphere*. Cambridge University Press, 2010.
- [130] V. I. Tatarski, R. A. Silverman, and N. Chako, "Wave propagation in a turbulent medium," *Physics Today*, vol. 14, no. 12, pp. 46–51, 1961. doi: <https://doi.org/10.1063/1.3057286>.
- [131] X. Ma, D. Liu, Y. Wang, H. Yin, H. Zhong, and G. Wang, "Propagation of rectangular multi-gaussian schell-model array beams through free space and non-kolmogorov turbulence," *Applied Sciences*, vol. 10, no. 2, 2020. doi: <https://doi.org/10.3390/app10020450>.
- [132] L. Thylén and C. M. Lee, "Beam-propagation method based on matrix diagonalization," *J. Opt. Soc. Am. A*, vol. 9, pp. 142–146, Jan 1992. doi: <https://doi.org/10.1364/JOSAA.9.000142>.

- [133] M. Chatterjee and F. Mohamed, "Investigation of profiled beam propagation through a turbulent layer and temporal statistics of diffracted output for a modified von karman phase screen," *Proceedings of SPIE*, vol. 8971, 02 2014. doi: <https://doi.org/10.1117/12.2033442>.
- [134] H. Zhan, E. Wijerathna, and D. Voelz, "Is the formulation of the fried parameter accurate in the strong turbulent scattering regime?," *OSA Continuum*, vol. 3, pp. 2653–2659, Sep 2020. doi: <https://doi.org/10.1364/OSAC.404983>.
- [135] H. F. Rashvand, A. Abedi, J. M. Alcaraz-Calero, P. D. Mitchell, and S. C. Mukhopadhyay, "Wireless sensor systems for space and extreme environments: A review," *IEEE Sensors Journal*, vol. 14, no. 11, pp. 3955–3970, 2014. doi: <https://doi.org/10.1109/JSEN.2014.2357030>.
- [136] D. H. Nguyen, G. Tumen-Ulzii, T. Matsushima, and C. Adachi, "Performance analysis of a perovskite-based thing-to-thing optical wireless power transfer system," *IEEE Photonics Journal*, vol. 14, no. 1, pp. 1–8, 2022. doi: <https://doi.org/10.1109/JPHOT.2022.3146365>.
- [137] "Atmospheric attenuation measurement system for commercial solar plants based on optical spectrum analysis," *Solar Energy*, vol. 236, pp. 782–789, 2022. doi: <https://doi.org/10.1016/j.solener.2022.03.057>.
- [138] A. S. Alatawi, A. A. Youssef, M. Abaza, M. A. Uddin, and A. Mansour, "Effects of atmospheric turbulence on optical wireless communication in neom smart city," *Photonics*, vol. 9, no. 4, 2022. doi: <https://doi.org/10.3390/photonics9040262>.
- [139] E. Hecht, *Optics*. Addison Wesley, 4th edition ed., 2002.
- [140] F. Pedrotti and L. Pedrotti, *Introduction to Optics*. Prentice Hall international editions, Prentice Hall, 1993.

- [141] L. Li, L. Xia, Z. Xie, and D. Liu, "All-fiber mach-zehnder interferometers for sensing applications," *Opt. Express*, vol. 20, pp. 11109–11120, May 2012. doi: <https://doi.org/10.1364/OE.20.011109>.
- [142] J. Guo, S. Lian, Y. Zhang, Y. Zhang, D. Liang, Y. Yu, R. Chen, C. Du, and S. Ruan, "High-temperature measurement of a fiber probe sensor based on the michelson interferometer," *Sensors*, vol. 22, no. 1, p. 289, 2022. doi: <https://doi.org/10.3390/s22010289>.
- [143] X. Zhang, W. Peng, and Y. Zhang, "Fiber fabry-perot interferometer with controllable temperature sensitivity," *Opt. Lett.*, vol. 40, pp. 5658–5661, Dec 2015. doi: <https://doi.org/10.1364/OL.40.005658>.
- [144] R. Philip-Chandy, P. Scully, P. Eldridge, H. Kadim, M. Grapin, M. Jonca, M. D'Ambrosio, and F. Colin, "An optical fiber sensor for biofilm measurement using intensity modulation and image analysis," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 6, no. 5, pp. 764–772, 2000. doi: <https://doi.org/10.1109/2944.892616>.
- [145] G. Zuo, W. Li, Z. Yang, S. Li, R. Qi, Y. Huang, and L. Xia, "Double phase matching in mzi with antiresonant effect for optical fiber sensor application," *Journal of Lightwave Technology*, vol. 39, no. 2, pp. 660–666, 2021. doi: <https://doi.org/10.1109/JLT.2020.3030770>.
- [146] E. T. Jelly, Z. A. Steelman, H. Zhang, K. K. Chu, C. C. Cotton, S. Eluri, N. J. Shaheen, and A. Wax, "Next-generation endoscopic probe for detection of esophageal dysplasia using combined oct and angle-resolved low-coherence interferometry," *Biomed. Opt. Express*, vol. 15, pp. 1943–1958, Mar 2024. doi: <https://doi.org/10.1364/BOE.515469>.
- [147] X. Zhang, L. Ren, X. Wu, H. Li, L. Liu, and L. Xu, "Coupled optofluidic ring laser for ultrahigh- sensitive sensing," *Opt. Express*, vol. 19, pp. 22242–22247, Oct 2011. doi: <https://doi.org/10.1364/OE.19.022242>.

- [148] P. Robalinho, A. Gomes, and O. Frazão, "Colossal enhancement of strain sensitivity using the push-pull deformation method," *IEEE Sensors Journal*, vol. 21, no. 4, pp. 4623–4627, 2021. doi: <https://doi.org/10.1109/JSEN.2020.3033581>.
- [149] Y. Chen, L. Zhao, S. Hao, and J. Tang, "Advanced fiber sensors based on the vernier effect," *Sensors*, vol. 22, no. 7, 2022. doi: <https://doi.org/10.3390/s22072694>.
- [150] J. Li, M. Zhang, M. Wan, C. Lin, S. Huang, C. Liu, Q. He, X. Qiu, and X. Fang, "Ultrasensitive refractive index sensor based on enhanced vernier effect through cascaded fiber core-offset pairs," *Opt. Express*, vol. 28, pp. 4145–4155, Feb 2020. doi: <https://doi.org/10.1364/OE.384815>.
- [151] X. Mu, J. Gao, Y. Yang, J. Wang, and L. Bi, "Parallel polydimethylsiloxane-cavity fabry-perot interferometric temperature sensor based on enhanced vernier effect," *IEEE Sensors Journal*, vol. 22, no. 2, pp. 1333–1337, 2022. doi: <https://doi.org/10.1109/JSEN.2021.3133457>.
- [152] P. Robalinho, V. Piaia, A. L. Ribeiro, S. Silva, and O. Frazão, "Optical harmonic vernier effect: Conditions required for effective sensitivity amplification," *accepted in the IEEE Lightwave journal*. doi: <https://doi.org/10.1109/JLT.2025.3634488>.
- [153] X. Fang, W. Zhang, J. Li, C. Lin, Z. Chen, M. Zhang, S. Huang, D. Lu, M. Wan, and X. Qiu, "Signal processing assisted vernier effect in a single interferometer for sensitivity magnification," *Opt. Express*, vol. 29, pp. 11570–11581, Apr 2021. doi: <https://doi.org/10.1364/OE.418783>.
- [154] A. D. Gomes, M. S. Ferreira, J. Bierlich, J. Kobelke, M. Rothhardt, H. Bartelt, and O. Frazão, "Optical harmonic vernier effect: A new tool for high

- performance interferometric fiber sensors," *Sensors*, vol. 19, no. 24, 2019. doi: <https://doi.org/10.3390/s19245431>.
- [155] P. M. R. Robalinho, A. D. Gomes, and O. Frazão, "High enhancement strain sensor based on vernier effect using 2-fiber loop mirrors," *IEEE Photonics Technology Letters*, vol. 32, no. 18, pp. 1139–1142, 2020. doi: <https://doi.org/10.1109/LPT.2020.3014695>.
- [156] R. Boeck, N. A. F. Jaeger, N. Rouger, and L. Chrostowski, "Series-coupled silicon racetrack resonators and the vernier effect: theory and measurement," *Opt. Express*, vol. 18, pp. 25151–25157, Nov 2010. doi: <https://doi.org/10.1364/OE.18.025151>.
- [157] W. Naku, J. Huang, and C. Zhu, "Optical fiber sensors based on advanced vernier effect: A review," *IEEE Sensors Journal*, vol. 24, no. 9, pp. 13758–13772, 2024. doi: <https://doi.org/10.1109/JSEN.2024.3378713>.
- [158] M. He, B. Zhu, and Z. Zhang, "High sensitivity temperature sensor based on harmonic vernier effect," *Photonic Sensors*, vol. 13, p. 230204, 06 2023. doi: <https://doi.org/10.1007/s13320-023-0677-x>.
- [159] P. Robalinho and O. Frazão, "Nano-displacement measurement using an optical drop-shaped structure," *IEEE Photonics Technology Letters*, vol. 33, no. 2, pp. 65–68, 2021. doi: <https://doi.org/10.1109/LPT.2020.3044118>.
- [160] P. Robalinho and O. Frazão, "Giant displacement sensitivity using push-pull method in interferometry," *Photonics*, vol. 8, no. 1, 2021. doi: <https://doi.org/10.3390/photonics8010023>.
- [161] Y. Liu, B. Liu, X. Feng, W. Zhang, G. Zhou, S. Yuan, G. Kai, and X. Dong, "High-birefringence fiber loop mirrors and their applications as sensors," *Appl. Opt.*, vol. 44, pp. 2382–2390, Apr 2005. doi: <https://doi.org/10.1364/AO.44.002382>.

- [162] O. Frazão, J. M. T. Baptista, and J. L. Santos, "Recent advances in high-birefringence fiber loop mirror sensors," *Sensors*, vol. 7, no. 11, pp. 2970–2983, 2007. doi: <https://doi.org/10.3390/s7112970>.
- [163] Z. Tian and S. S.-H. Yam, "In-line single-mode optical fiber interferometric refractive index sensors," *Journal of Lightwave Technology*, vol. 27, no. 13, pp. 2296–2306, 2009. doi: <https://doi.org/10.1109/JLT.2008.2007507>.
- [164] F. Xia, "Ri sensing system with high sensitivity and large measurement range using a microfiber mzi and a photonic crystal fiber mzi," *Measurement*, vol. 156, p. 107603, 02 2020. doi: <https://doi.org/10.1016/j.measurement.2020.107603>.
- [165] Z. Ding, Z. Tan, S. Xiao, and H. Gao, "Sensitivity amplification of high birefringence fiber loop mirror temperature sensor with vernier effect," *Applied Physics B*, vol. 127, 05 2021. doi: <https://doi.org/10.1007/s00340-021-07612-x>.
- [166] I. Armas-Rivera, L. Rodriguez-Morales, G. Beltrán-Pérez, M. Durán-Sánchez, M. Andrés, and B. Ibarra-Escamilla, "Polarization properties of a fiber optic loop mirror," *Optics & Laser Technology*, vol. 140, p. 107070, 2021. doi: <https://doi.org/10.1016/j.optlastec.2021.107070>.
- [167] A. Layeghi and H. Latifi, "Tunable ferrofluid magnetic fiber sensor based on nonadiabatic tapered hi-bi fiber in fiber loop mirror," *Journal of Lightwave Technology*, vol. 36, no. 4, pp. 1097–1104, 2018. doi: <https://doi.org/10.1109/JLT.2017.2781623>.
- [168] X. Wang, S. Lou, X. Sheng, and S. Liang, "Simultaneous measurement of torsion, strain and temperature using a side-leakage photonic crystal fiber loop mirror," *Infrared Physics & Technology*, vol. 76, pp. 603–607, 2016. doi: <https://doi.org/10.1016/j.infrared.2016.04.029>.

- [169] Z. Zhang, Z. Wu, Z. Zhang, L. Su, A. Wu, Y. Li, and J. Lan, "Characteristics and recent development of fluoride magneto-optical crystals," *Magnetochemistry*, vol. 9, no. 2, 2023. doi: <https://doi.org/10.3390/magnetochemistry9020041>.
- [170] P. Robalinho, B. Soares, A. Lobo Ribeiro, S. Silva, and O. Frazão, "Fiber loop mirror based on optical fiber circulator for sensing applications," *Sensors*, vol. 23, no. 2, 2023. doi: <https://doi.org/10.3390/s23020618>.
- [171] S. Yang, H. Wang, L. Meng, Y. Chen, B. Dong, T. Yuan, X. Zhang, and L. Yuan, "Dual-fbg and f-p cavity compound optical fiber sensor for simultaneous measurement of bending, temperature and strain," *Journal of Lightwave Technology*, vol. 41, no. 5, pp. 1582–1588, 2023. doi: <https://doi.org/10.1109/JLT.2022.3224756>.
- [172] Q. Jia, Q. Han, Z. Liang, Z. Cheng, H. Hu, S. Wang, K. Ren, J. Jiang, and T. Liu, "Temperature compensation of optical fiber current sensors with a static bias," *IEEE Sensors Journal*, vol. 22, no. 1, pp. 352–356, 2022. doi: <https://doi.org/10.1109/JSEN.2021.3128937>.
- [173] P. Mihailovic, S. Petricevic, and J. Radunovic, "Improvements in difference-over-sum normalization method for faraday effect magnetic field waveforms measurement," *Journal of Instrumentation*, vol. 1, p. P12002, dec 2006. doi: <https://doi.org/10.1088/1748-0221/1/12/P12002>.
- [174] P. Robalinho, M. Melo, O. Frazão, and A. B. L. Ribeiro, "Temperature-monitored fibre optic current sensor using channelled-spectrum analysis," *IEEE Photonics Technology Letters*, vol. 34, no. 23, pp. 1308–1310, 2022. doi: <https://doi.org/10.1109/LPT.2022.3214105>.

- [175] C. Delisle and P. Cielo, "Application de la modulation spectrale à la transmission de l'information," *Canadian Journal of Physics*, vol. 53, no. 11, pp. 1047–1053, 1975. doi: <https://doi.org/10.1139/p75-133>.
- [176] J. F. Bille, ed., *High Resolution Imaging in Microscopy and Ophthalmology: New Frontiers in Biomedical Optics*. Cham, Switzerland: Springer Cham, 1st ed., 2019. doi: <https://doi.org/10.1007/978-3-030-16638-0>.
- [177] S. Diddams and J.-C. Diels, "Dispersion measurements with white-light interferometry," *J. Opt. Soc. Am. B*, vol. 13, pp. 1120–1129, Jun 1996. doi: <https://doi.org/10.1364/JOSAB.13.001120>.
- [178] A. Gosteva, M. Haiml, R. Paschotta, and U. Keller, "Noise-related resolution limit of dispersion measurements with white-light interferometers," *J. Opt. Soc. Am. B*, vol. 22, pp. 1868–1874, Sep 2005. doi: <https://doi.org/10.1364/JOSAB.22.001868>.
- [179] Q. Liu and W. Peng, "Fast interrogation of dynamic low-finesse fabry-perot interferometers: A review," *Microwave and Optical Technology Letters*, vol. 63, no. 9, pp. 2279–2291, 2021. doi: <https://doi.org/10.1002/mop.32922>.
- [180] P. Robalinho, A. Vaz Rodrigues, S. Novais, A. Lobo Ribeiro, S. Silva, and O. Frazão, "Novel digital signal processing method for data acquired from low coherence interferometry," *IEEE Sensors Journal*, vol. 24, no. 24, pp. 40896–40903, 2024. doi: <https://doi.org/10.1109/JSEN.2024.3483433>.
- [181] A. Maini, *Lasers and optoelectronics: Fundamentals, devices and applications*. John Wiley & Sons Ltd, Aug. 2013. doi: <https://doi.org/10.1002/9781118688977>.