White Light Interferometry: Absolute and High Precision Measurement for Long-Cavity Fibre Fabry-Perot Sensors

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Abstract. White Light Interferometry, known for its absolute measurement capability and high precision, had its greatest scientific impact towards the end of the 20th century. In this work, it was assembled and characterized a fibre Mach-Zehnder interferometer (MZI) as an interrogator and a fibre Fabry-Perot interferometer (FPI) as a displacement sensor. A measurement bandwidth between 65 μm and 95 μm was obtained for FPI cavities close to 2.35 mm, at sampling frequencies between 600 Hz and 1500 Hz. Additionally, a resonant frequency at 550 Hz was achieved, allowing for an interrogation band higher than 135 μm. It was also determined a minimum absolute resolution of ± 66 nm, corresponding to a relative resolution of ± 9.4×10⁻⁴ in relation to the total band.

1 Introduction

White Light Interferometry (WLI) is an optical interrogation technique that combines intensity and phase measurements, also known as low-coherence interferometry (LCI). It was first proposed in 1975 and demonstrated in 1976 [1]. However, the complete description of this technique for optical fibre systems was published only in 1984 when the implementation of a displacement measurement system was described. Since then, WLI has been widely used due to its ability to provide not only high-precision measurements but also more stable and absolute measurements using affordable optical systems [2,3]. This work demonstrates the use of WLI for displacement sensing. A Fabry-Perot cavity was utilized, which was interrogated by a MZI modulated by a piezoelectric transducer (PZT) in one of its arms.

2 Interrogator

WLI is a technique that involves using optical sources with low temporal coherence, such as SLDs, LEDs or gas lamps. The technique uses at least two cascaded interferometers, with one serving as a sensor and the other as an interrogator. In this type of system, the two interferometers are typically low finesse cavities such as the FPI, MZI, Michelson interferometer, among others, typically described as two-wave interferometers (eq. 1):

I_{out} \propto I_{in} \left( \text{ACOS}^2(\beta L/2) + (1 - A) \right) \tag{1}

where I_{out} is the output light intensity, I_{in} is the spectral intensity profile of the optical source, A is the intensity amplitude of the interference pattern fringes, β is the propagation constant and is given by β = 2πnλ/λ, n is the refractive index, λ is the wavelength, and L is the length difference associated with the two waves. The final equation is achieved considering that the photodetector is a wavelength-integrating system that can be described as follows:

P_{ph} \propto k_2 \text{sinc}(k_2[nL_1- nL_2]) - k_1 \text{sinc}(k_1[nL_1- nL_2]) + k_2 \text{sinc}(k_2[nL_1+ nL_2]) - k_1 \text{sinc}(k_1[nL_1+ nL_2]) \tag{2}

The operation consists in controlling and varying the optical path of the interferometer-based interrogator. The shape of the curve displayed on the oscilloscope is determined by the spectrum of the optical source, and it reaches its maximum value when the optical paths of the interrogation and sensing cavities are equal.

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2.1 Experimental Setup

The experimental setup consisted of several components, including a Gaussian-shaped optical source with a 90 nm FWHM spectral width centred at 1550 nm, a variable optical-path fibre MZI used as the interrogator, a fibre FPI employed as the sensor, an optical circulator, a photodetector, an electric signal generator, an electric signal amplifier, and an oscilloscope. A schematic diagram of the experimental setup is shown in Figure 1. The variable fibre MZI consists of two arms, one of which is free and the other coiled around the PZT using polymer supports. This configuration has 55-turns, and each turn has a 260 mm perimeter. A sinusoidal voltage signal of 200 V amplitude was applied to the PZT. In addition, two 3-dB fibre couplers were used.

2.2 Results

The initial length of the MZ cavity was determined after the fabrication of the MZI. Figure 2.a) shows the spectral response of the MZI, with a visibility of 90.5% and an initial physical length of 3.2 mm. Next, the FPI sensor was calibrated to ensure that the cavity was within the interrogator's measurement band (2.35 mm long-air-cavity), resulting in Figure 2.b). Despite the low visibility caused by the cavity length of the FPI, the optical output power of the system is sufficient for low-noise measurements.

The range of the system was characterized as a function of the frequency of the signal applied to the PZT, using a tuneable FPI (performed with a micrometric translation stage). Figure 3 shows the characterization results obtained using two different methods: (in blue) direct measurement through the tuneable FPI performed when the maximum of the electrical signal coincides with the extremes of each curve observed on the oscilloscope, and (in orange) calculation based on the fast frequency oscillations of the oscilloscope curve resulting from the successive constructive and destructive interferences when the interrogator cavity is varied. The interrogation scan provides a range of 35 μm for frequencies below 350 Hz. An anti-resonance point is observed at 450 Hz, causing the range to become null. At 550 Hz, a resonance point is achieved, which allows for a range higher than 135 μm. The range for frequencies varying from 600 Hz to 1500 Hz is between 65 μm and 95 μm. Figure 4 shows the characterization of the sensor's variation along the interrogator measurement band at 1 kHz. The sinusoidal signal applied to the PZT was used to linearize the measurements, utilizing the applied signal function from the signal generator. The minimum possible step of 2 μm in the tuneable FPI was used to investigate the minimum resolution. The system sensitivity was determined to be 3.28 ± 0.1 V/μm with an r² value of 0.990, implying a minimum resolution of 66 nm. As the total band is 70 μm, this indicates a relative resolution of 9.4×10⁻⁴.

3 Conclusion

The use of WLI enables the absolute measurement of physical quantities and has shown to accurately interrogate cavity bands at higher sampling frequencies compared to existing spectrometers and Optical Spectrum Analyzers. This technology offers a more compact, lightweight, cost-effective, and flexible solution for a variety of applications, including those in the fields of biology and space exploration.

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