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Improved spectral resolution in time-varying interferometry

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ABSTRACT

In this work, we present a procedure that allows increasing the resolution of dynamic length measurements made by spectral interferometry. The proposed scheme leads to obtaining a compact photonic instrument with the ability to measure distances, variations on positions and vibrations with a very high resolution. This measurement system includes a superluminescent source (SLED), a digital spectrometer and a Fizeau interferometer. Spectral data is processed by applying Fourier domain techniques previously applied in optical coherence tomography. The resolution of the spectral measurement system is determined by the spectrometer bandwidth and the light source employed. A signal is obtained by analysing the time evolution of a single pixel from the spectrometer CCD sensor, which is later analysed using time domain interferometry (TDI) techniques. This procedure works by detecting changes in the optical path below those that can be detected by spectral analysis. The original resolution obtained with the solely spectral techniques was 2.2 µm but was improved to 40 nm by complementary analysis of temporal signals.

1. Introduction

Fibre optic sensors are very attractive due to their sensitivity characteristics, non-invasively and electrical noise immunity [1,2] and on top, they have the capability of being multiplexed two or more sensors in the same system [3,4]. They are useful for measurements within the volume of the samples as in thickness measurements of paints and coatings [5]. Conventional mechanical sensors can damage or deform the analysed surface leading to inaccurate measurements.

The development of optical communications has made fibre optic sensors accessible by providing components that allow the design of complex devices with high sensitivity and resolution. These sensors besides being potentially used in conventional applications are particularly useful where traditional techniques do not offer solutions [6]. Some years ago, we focused our attention on an extrinsic distance sensor based on a Fizeau interferometer. This sensor does not require calibration and is contact-free with the surface being studied. Also, it includes all the known common goodness of interferometric fibre optics sensors [3,7].

The Fizeau interferometer (FI) used as a time domain interferometry (TDI) instrument is implemented with a laser as a source and a power detector. TDI has become a very precise technique for the measurement of distances variations in the cases where the direction of the displacement is not a variable to be determined, and this was demonstrated in previous work in the determination of contraction of dental resins [8] and the characterisation of polymer vitrification [9].

Although TDI does not provide absolute information about the cavity length, it is a very attractive technique because of its high resolution and low cost. On the other hand, spectral domain interferometry (SDI) could lead to absolute value measurements with the same Fizeau interferometer using a broadband source and a spectrometer instead of a LASER and a power detector.

Recently, in previous work, we presented the possibility to simultaneously measure the same length [10] using the same measurement system, without moving parts, for two different interferometric techniques (SDI and TDI). The signals from both techniques were obtained from the same interferometer having their sources and detectors decoupled in wavelength. TDI does not provide absolute information of the cavity length but can give information of the variations in this length with greater resolution than the spectral technique. Then, better results are obtained by combining both techniques (TDI + SDI) than with each one.

Following this path, in this work we present a substantial advance on the system design, reducing the number of components, leading to higher light efficiency, improving the resolution of length variations measurements and reducing the system cost. It is reached measuring absolute lengths using the SDI, improving the measurement resolution of length variations by TDI but without adding couplers, a laser and a

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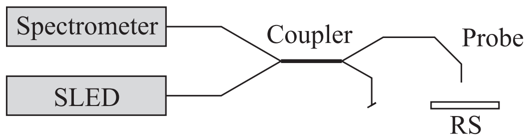

Fig. 1. Fibre optic Fizeau interferometer. RS: Refractive surface.

detector as used in reference [10], leading to a higher light efficiency and reducing the system price. The system is constituted by a single interferometer without moving parts using a single broadband light source and a spectrometer. The TDI signal can be obtained following the power measured by a single pixel of the spectrometer.

The dynamic range of TDI depends on the coherence length of the laser in [10]. If the laser source spectral density is assumed to be Gaussian, the coherence length is directly proportional to $\lambda_0{}^2/\Delta\lambda$ being λ_0 the central wavelength and $\Delta\lambda$ the wideband [1]. By applying this technique, the degradation of interferograms visibility depends on the bandwidth of a spectrometer pixel instead of the source, increasing the dynamic range remarkably.

It is possible to achieve several interferograms from the same measurement simply by choosing as individual pixels as required. It also can be useful to avoid the ambiguity when a cavity sense change occurs at interferogram maxima or minima. A study of the range of applicability of this method is also performed.

2. Materials and methods

The Fizeau interferometer considering two different detection schemes, TDI and SDI, are described as follows:

The fibre optic Fizeau interferometer scheme is depicted in Fig. 1. In this type of instrument, the light reflected at the end of the pigtail interferes with the light reflected on the surface under analysis. A detailed study of the device can be found in reference [10] and [11].

Here, a SLED broadband light emitter operating at 800 nm with a normalised spectral distribution S(λ) is employed as a light source, where λ is the spectral wavelength. The unilateral power spectral density at the output of the interferometer is given by Eq. 1 [10]

$$\mathrm{G}(\boldsymbol{\lambda}) = G_0 \cdot S(\boldsymbol{\lambda}) \left[1 + \frac{2\sqrt{R_1 R_2 \boldsymbol{\beta}}}{R_1 + \boldsymbol{\beta} R_2 (1 - R_1)^2} \cdot \cos\left(\frac{4\pi n_0 d}{\boldsymbol{\lambda}} \right) \right] \tag{1}$$

where G_0 is the mean power spectral density, n_0 is the cavity refraction index, and d is the cavity length to be determined. R_1 and R_2 are the reflectivities at the end of the fibre and the surface to be measured, respectively. The β parameter is the cavity length dependence and can be calculated as:

$$\boldsymbol{\beta} = [1 + 2 \cdot \mathrm{A}d/(2\pi)]^{-1} \tag{2}$$

Eq. (2) is obtained from the axial loss for single-mode (SM) fibres, with $\mathrm{A} = \lambda \cdot \ln(V)/\mathrm{R}_2$, where V is the effective frequency of the fibre ($\mathrm{V} \leq 2.404$ for SM fibres).

a. Fourier Transform-Spectral Domain Interference (FD-SDI)

Changing the variable λ by defining $u = 2/\lambda$, Eq. (1) can be expressed as:

$$\mathrm{G}(u) = G_0 S(u) \left[1 + \frac{2\sqrt{R_1 R_2 \beta}}{R_1 + \beta R_2 (1 - R_1)^2} \cdot \cos(2\pi \cdot d \cdot u) \right] \tag{3}$$

Althoughβhas a λ dependence, it changes much slower than the cosine of $4\pi \mathrm{n}_0 d/\lambda$ [8]. Eq. (3) shows two spectrally separated components, both modulated by $\mathrm{G}_0 S(u)$. G(u) have one constant term and a second term which frequency is d.

Therefore, the value to be obtained (d) is found as the frequency of a sinusoid modulated by the curve of the spectral density of the source. Filtering can remove the low-frequency component. Different types of techniques have been developed to obtain d from Eq. (3). A comparison between the use of the Fourier Transform (FT) and the iterative phase-lock method can be found in reference [12]. Also, a technique based on the use of fuzzy inference systems was developed in reference [13].

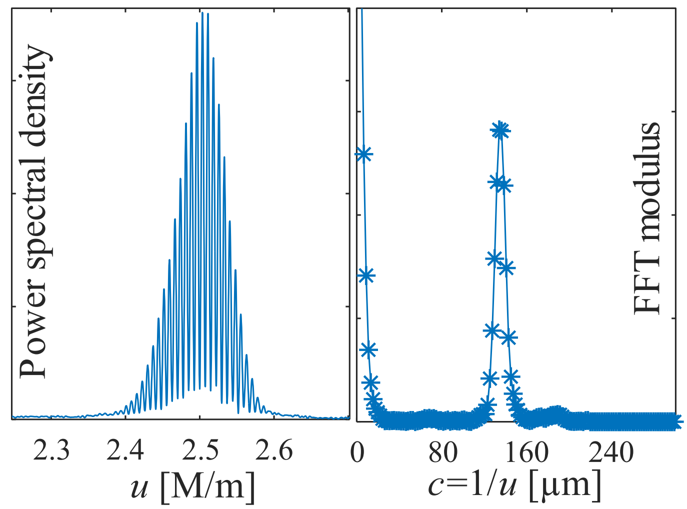

Fig. 2. Spectrum for a 135 µm cavity and its FFT.

The FT of G(u) from u domain to the $c = 1/u$ domain can be defined as $\mathrm{D}(c) = \mathrm{F}\{\mathrm{G}(u)\}$. Based on the linearity of the FT we can distribute the relation as follows:

$$\mathrm{D}(c) = F\{G_0 S(u)\} + F\left\{ G_0 S(u) \frac{2\sqrt{R_1 R_2 \boldsymbol{\beta}}}{R_1 + \boldsymbol{\beta} R_2 (1 - R_1)^2} \cos(2\pi \cdot d \cdot u) \right\} \tag{4}$$

Finally, using the product properties in the untransformed domain and knowing that the unilateral FT of cos($2\pi du$) is δ(c-d) then D(c) can be written:

$$\mathrm{D}(c) = F\{G_o S(u)\} + F\left\{ G_o S(u) \frac{2\sqrt{R_1 R_2 \beta}}{R_1 + \beta R_2 (1 - R_1)^2} \right\} \otimes \delta(c - \mathrm{d}) \tag{5}$$

where the "⊗" operator represents the convolution product.

The FT is defined for a continuous function, for discrete functions the discrete Fourier transform (DFT) must be used. In this work, the DFT is computed by the fast Fourier transform (FFT) algorithm [14].

A typical spectrum regarding u, obtained from a cavity of 135 µm, can be seen in Fig. 2 (left), while in Fig. 2 (right), the amplitude of its FFT is shown. It is possible to easily discriminate the low-value components of c and those convolved with δ(c-d). The d value of the cavity can be obtained as the location in c of the peak in the amplitude of D(c). In this case, the value is 134 µm. The difference between the measured value and the real value is that the FFT has equally-spaced points, where each $\Delta c = 1/\mathrm{AB}_u$, and AB_u is the bandwidth of the measurement regarding u. If it is expressed as a function of the wavelength, we can obtain the resolution of the d measurement:

$$\Delta c = (u_{\max} - u_{\min})^{-1} = \left(\frac{2}{\lambda_{\min}} - \frac{2}{\lambda_{\max}} \right)^{-1} = \frac{1}{2} \cdot \left(\frac{1}{\lambda_{\min}} - \frac{1}{\lambda_{\max}} \right)^{-1} \tag{6}$$

Defining $\lambda_{\min}$ and $\lambda_{\max}$ as the minimum and maximum wavelength of the spectrometer and not the source, for the spectrometer used ($\lambda_{\min} = 740$ nm and $\lambda_{\max} = 890$ nm), $\Delta c \approx 2.2$ µm.

b. Time domain Interference (TDI) analysis

The TDI signal is generated following the power value from a pixel of the spectrometer as a function of time. The pixel acts as an optical power sensor in which the received intensity depends on the detection bandwidth of the spectrometer´s pixel ($\Delta\lambda$) and the central wavelength of the pixel λ_0. The bandwidth detected by the pixel is determined by dividing the bandwidth of the spectrometer by the total number of pixels. Then, the detected intensity is given by the integral of Eq. (1) within