Optics and Lasers in Engineering 91 (2017) 227–231

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Double domain wavelength multiplexed Fizeau interferometer with high resolution dynamic sensing and absolute length detection

Julián Antonacci[a,*], Gustavo F. Arenas[a], Ricardo Duchowicz[b,c]

[a] Instituto de Ciencia y Tecnología en Electrónica (ICyTE), Facultad de Ingeniería, Universidad Nacional de Mar del Plata, Juan B. Justo 4302, Mar del Plata, Argentina & CONICET
[b] Centro de Investigaciones Ópticas (CONICET-CIC), Centenario y 506, Gonnet, La Plata, Argentina
[c] Universidad Nacional de la Plata, Facultad de Ingeniería, Calle 1, 1900, La Plata, Argentina

A R T I C L E I N F O

Keywords:
Fiber optics sensor
Fizeau interferometer
Spectral interferometer
Temporal spectrometer

A B S T R A C T

In this work, we present a simple photonic instrument that has the ability of measuring positions, distances and vibrations with very high resolution by means of two Fizeau interferometers (FI), both using the same optical fiber end as a probe tip itself. On the one hand we have a time domain FI powered with a 1310 nm laser and monitored by an InGaAs detector providing displacement information with resolution around a tenth of nm but regardless of the absolute position of object and of the displacement sense. On the other, a spectral domain FI version based on a super luminescent source (SLED) centred at 800 nm with bandwidth of nearly 40 nm is analysed in real time by means of a digital spectrometer. Each spectrum is acquired in a very small time interval and provides information of both length of the cavity as well as its correct sense of evolution. Resolution of this system is lower than its complementary temporal case, but distance and sense measurements are absolute and can be determined successfully by adequate processing of spectral signal.Both interferometers are optically coupled to a single fiber optic probe and are wavelength modulated.Therefore, combination of both sensors results in a new one which allows the correct knowledge of an object or surfaces under test, i.e. a high resolution of displacement data plus its absolute position and true sense of movement.

1. Introduction

Fiber optic sensors are always attractive due to unique features related to their security, light weight, non-invasive characteristic and in particular, their sensitivity [1,2]. Conventional mechanical sensors have the disadvantage of being invasive and could lead to damage in the analysed surface. With the advances in optical communications, fiber optic sensors continuously become more accessible, and on top of being used in common applications they are even used in special cases where conventional techniques cannot offer solutions [3]. Therefore, contact free sensors with high resolution and speed are highly demanded for industrial applications. A few years ago we centred our attention on a modified extrinsic Fabry-Perot interferometer called *Fizeau* sensor, embedded in optical fiber. This kind of sensors have the ability to be wavelength or cavity-length modulated to obtain several measurements at the same time [4,5]. Additionally in the same sensing system, other sensing techniques like fiber Bragg grating or Mach–Zehnder interferometer can be combined [6,7]. There are two different approaches keeping the same sensing topology depending on how to analyse and obtain measurements: time domain interferometer (TDI) and its complementary version, the spectral domain interferometer (SDI). The TDI technique employs a laser as a source and its readings are measured by means of simple optical detector as a voltage signal and has an excellent resolution sensing variations in the cavity length (around a decimate of the laser wavelength). However, there is an ambiguity on the direction (i.e. it is not possible to determine whether the object under study is moving closer or further away, unless the process under study would be previously known). Nonetheless it is commonly used in applications where only cavity length variation measurements are needed and the movement direction is defined [8]. Very quick changes of direction could also be difficult to determine. Recently, some techniques using optical path modulation have been proposed to solve this issue but this requires moving parts with its consequent robustness degradation [9,10].

Intensity of light detected at the exit of this interferometer is:

$$I = I_0 \cdot \left[1 + \frac{2\sqrt{R_1 R_2 \beta}}{R_1 + \beta R_2 (1 - R_1)^2} \cdot \cos(\boldsymbol{\Delta\varphi}) \right] \quad (1)$$

with $\beta = [1 + 2\frac{A \cdot d}{2\pi}]^{-1}$, and R_1 and R_2 being the fiber optic end and

* Corresponding author.
E-mail addresses: julian.antonacci@fi.mdp.edu.ar (J. Antonacci), garenas@fi.mdp.edu.ar (G.F. Arenas), ricardod@ciop.unlp.edu.ar (R. Duchowicz).

http://dx.doi.org/10.1016/j.optlaseng.2016.12.006
Received 26 August 2016; Received in revised form 19 October 2016; Accepted 5 December 2016
0143-8166/

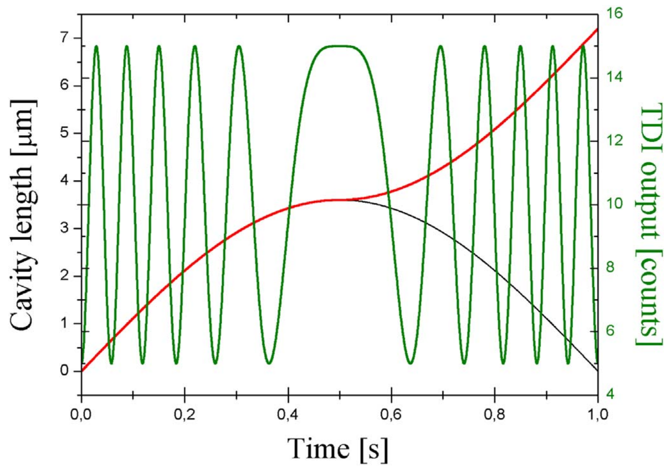

Fig. 1. Simulation showing the main consequences of ambiguity, two different simulated cavity length evolutions (black and red lines) generating the same interferogram (green line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

target surface reflectivities, respectively and d the cavity length. The β value is dependent on the cavity air-gap (d) and is obtained from the expression of the axial loss for single mode fibers with $A = \lambda \cdot \ln(V)/R_2$, where λ is the wavelength of the monitoring beam and V is the effective frequency of the fiber. It also corresponds to the optical coupling efficiency of the first reflective beam from R_2 back into the fiber [8].

The optical path difference in the cavity is given by $\boldsymbol{\Delta\varphi} = \frac{4\pi n_0 d}{\lambda} + \pi$, (with $n_0 = 1$ due to the air gap refractive index). As the cavity changes, the interferogram shows consecutive maxima and minima that occur repetitively as $\Delta\varphi$ varies in 2π, so the separation between two intensity maxima corresponding to two consecutive interference fringes occurs at $\Delta d = \lambda/2$ [11]. More detailed explanation of TDI demodulation can be found in Ref. [8].

It is important to point out that despite knowing the true direction of movement of a certain measurement, if the target velocity drops to zero for a period of time and then continues moving, a new ambiguity will be present. Fig. 1 shows a simulation of a case in which a unique interferogram could represent two different cavity length evolutions.

The SDI version requires a broadband source like SLED and its useful information must be read with a spectrometer. The main advantage of SDI measurements is their direction sensitivity and absolute cavity length determination. The use of a spectrometer make this sensor more expensive than the TDI but it could be replaced by a tilted Michelson interferometer and a CCD with other signal processing [12].

The value of I_0 from Eq. (1) is the resulting laser power intensity in the detector. When a broadband optic source is used then a similar analysis can be made for each wavelength resulting in Eq. (2).

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

As $\lambda = c/f$ then Eq. (1) can be rewritten in terms of the spectral density as:

$$G(f) = G_0(f) \cdot \left[1 + \frac{2\sqrt{R_1 R_2 \beta}}{R_1 + \beta R_2 (1-R_1)^2} \cdot cos\left(\frac{4\pi n_0 d \cdot f}{c}\right)\right] \tag{3}$$

The separation between two maxima of $\cos(4\pi n_0 df/c)$ corresponding to two consecutive interference fringes occurs at $\Delta f = c/2n_0 d$. Then the cavity length is obtained from each spectrum as described in Eq. (4). Two spectra obtained from measuring two different cavities are shown in Fig. 2

$$d = \frac{c}{2n_0 \Delta f}. \tag{4}$$

Several methods of signal processing have been developed to obtain the cavity length from a spectrum using Eq. (4) [13,14]. A comparison between the use of the Fourier Transform method and the iterative phase-locked loop method is in Ref. [15]. Recently a technique using Fuzzy Inference Systems was developed [16].

We propose a combination of TDI and SDI sensors briefly explained above to build a Dual Fizeau Interferometer (DFI) sensor with a simple but powerful technique for those hard cases in which conventional solutions are not worthwhile due to its cost or to not been fully developed yet. The set of possible applications and measurements is large and diverse. Here, we remark profilometry, thermal expansion/ contraction and those processes which affect the material behaviour while curing such as polymer shrinkage. Finally, a self-calibrated, high-resolution cavity sensor with absolute length detection is obtained.

2. Materials and methods

Both TDI & SDI approaches provide information from a resonant cavity formed between the end of an optical fiber and some measurement surface. Being both integrated into a single tip, two readings can be simultaneously obtained from the same physical cavity. The TDI determines high precision variation in length of the cavity, while SDI gets the absolute cavity length. From SDI we obtain cavity length increasing-decreasing time intervals as well as length discontinuity amplitudes if they eventually appear.

In this work, measurements were made with a piezoelectric actuator to change the cavity length with the purpose of easily control its movement on a range of dozens of microns.

Exploiting the high resolution of TDI and the unambiguity of the SDI we propose a new measurement scheme based on a dual configuration that is shown in Fig. 3.

It can be seen that both time and spectral domain approach measurements can be carried out simultaneously at the same probe point. Laser and SLED lights are carried to the sensor probe tip. Reflected light is coupled back to the sensor forming the interference signals where both can be registered with proper detectors.

Temporal method information is used for its resolution which can be lesser than one tenth of the laser wavelength. But the spectral information is used to solve the problems of ambiguity, detection of changes in direction and absolute value of the length (though the latter with lower resolution) when required. Light from both sources is wavelength modulated because the 1310 nm laser is out of the digital spectrometer bandwidth and the InGaAs optic power detector is insensitive at the SLED spectral range (780–820 nm).

2.1. Measurement procedure

After gathering data from a certain experiment, i.e. a collection of SDI spectra and TDI interferogram signal, we proceed to firstly determine the cavity length from the separation between peaks of the spectral density plot. Every spectrum provides a value that is associated with the instant time when it is taken. As a consequence, a cavity length vs. time curve is generated which allows detection of direction changes, increasing-decreasing intervals as well as the initial absolute cavity length (i.e. the actual distance between object and sensor tip). Then, the TDI interferogram signal is demodulated in order to resolve a high resolution plot of the target surface position with the information previously obtained by the SDI.

Finally, we complement both curves to develop a high resolution curve with true sense evolution of the phenomena under test as well as the absolute distance from the tip sensor probe.

To show the performance of the technique a piezoelectric is excited with known electrical signals to discuss the measurements.

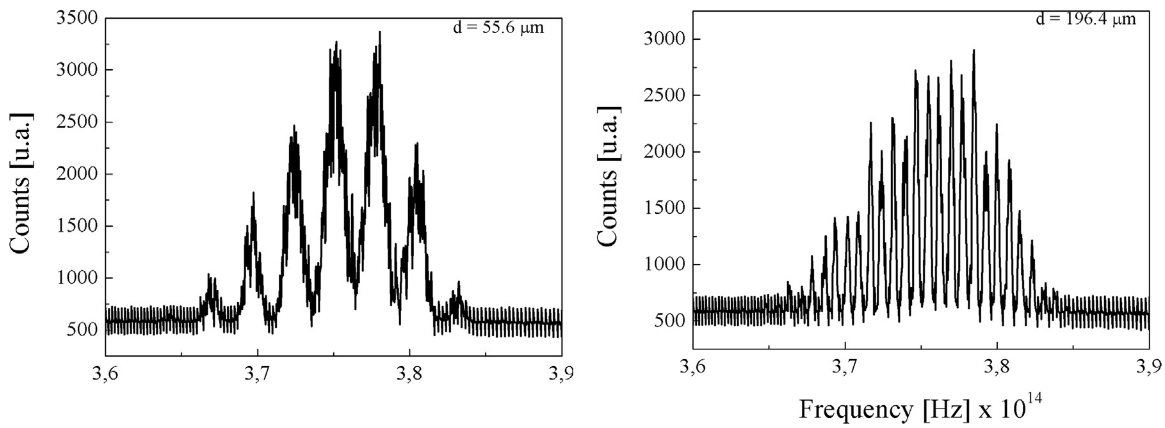

Fig. 2. Typical spectral density [counts] vs. frequency for a two cavity length separation of about 55.6 and 196.4 μm, respectively.

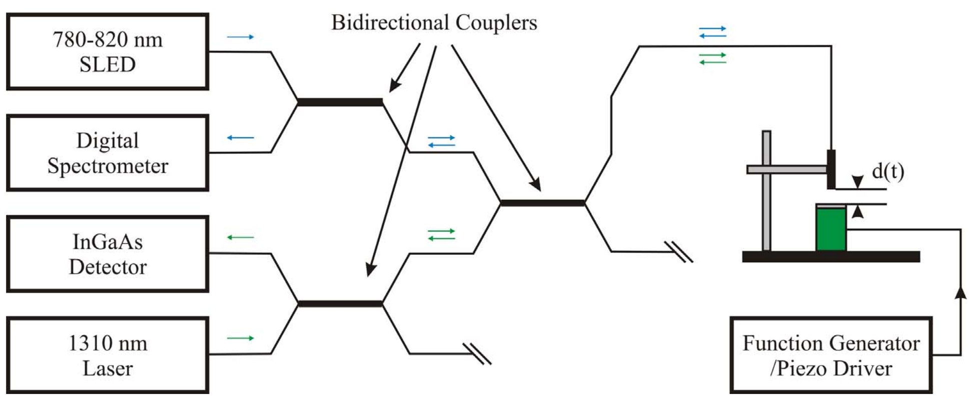

Fig. 3. Dual Fizeau Interferometer scheme.

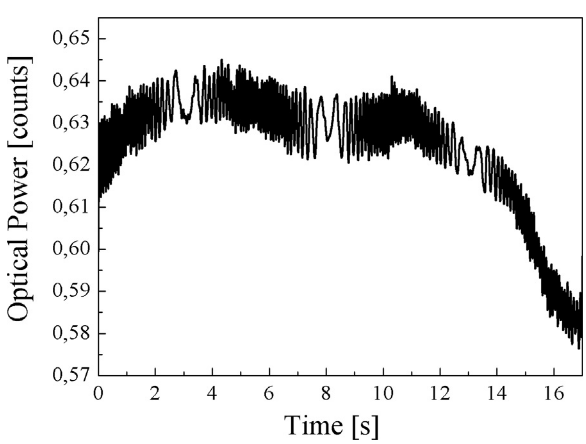

Fig. 4. Interferogram obtained by the TDI.

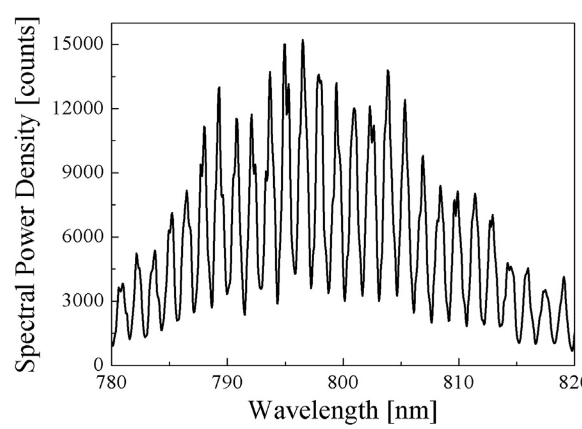

Fig. 5. One of the spectra obtained by the SDI.

3. Results and discussion

A piezoelectric (6F-607 from Thorlabs) is excited with a sinusoidal signal of 100 mHz frequency by a Thorlabs MDT694 Single Channel Piezo Driver and Hewlet Packard 33120A Signal Generator. Measurements were made simultaneously at the same probe point with the configuration setup shown in Fig. 3. In this case, we registered 160 spectrums obtained from SDI and 16,000 samples from TDI in 16 s.

Fig. 4 shows the signal delivered from the time domain side of the dual sensor, while a spectrum obtained by the spectral side is shown in Fig. 5.

Firstly, the cavity length for each spectrum is calculated by Eq. (4). There are several techniques to process this kind of spectra [13–15,17]. A Fourier transform based technique is used in order to reach the fundamental frequency of $\cos(4\pi n_0 d \cdot f/c)$ in Eq. (3). The resolution of this technique is inversely dependent on the bandwidth of the SLED [18], where in this case the resulting resolution is 7.995 μm.

This process is repeated for each spectrum, obtaining a curve of cavity length vs. time which is shown in Fig. 6. From this stage, we obtain true sense of variation of the cavity length and its absolute distance. This is a unique characteristic of spectral interferometer measurements.

Knowing sense and absolute position of the phenomena, the next stage was processing TDI interferogram to develop an intensity-time curve with high spatial resolution but using the information of waxing and waning time intervals and absolute cavity length.

Fig. 7 shows a dual Fizeau curve, one can note that it is not as noisy as the SDI one because resolution of the former is higher than the latter. With this simple procedure, the Dual Fizeau technique measures with

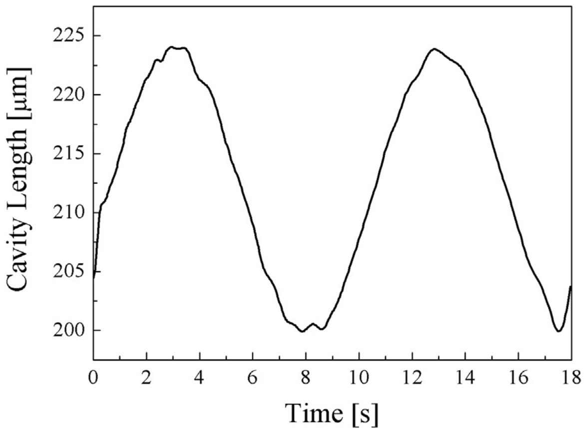

Fig. 6. Cavity length vs. time for SDI.

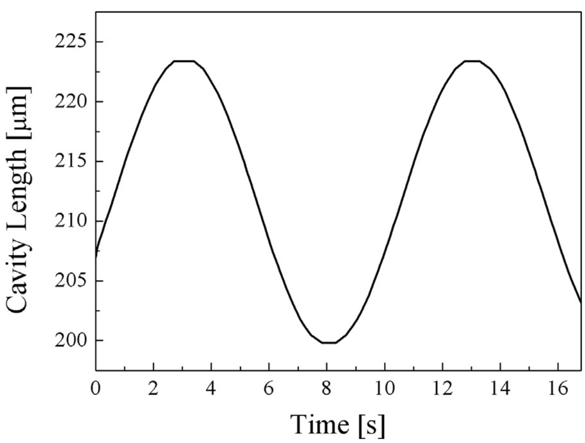

Fig. 7. Cavity length vs. time of a double Fizeau interferometer.

high spatial resolution (TDI) within true sense direction and absolute position (SDI). All steps explained here were programmed in order to generate an automatized measurement.

In order to complement this work, we applied our technique for a case which is more complicated to process with the TDI. This appears when the object under monitoring suddenly changes its sense maintaining its velocity. This behaviour generally remains undetected to TDI

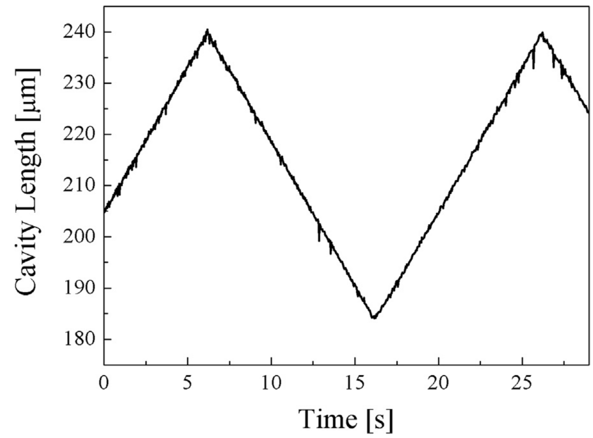

Fig. 9. Cavity length as a function of time, for a triangular wave case measured with the TDI.

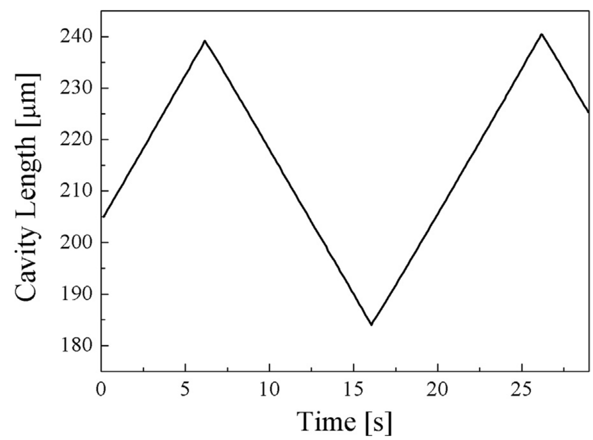

Fig. 10. Cavity length vs. time of a double Fizeau interferometer.

sensor, especially if this change in sense occurs at maxima/minima interferogram points. However, this case is easily reproducible with the same piezoelectric driven with a triangular voltage signal.

As it can be seen in Fig. 8, the TDI interferogram results from a situation in which the target moves along or back from the sensor probe indefinitely. Three parts of the interferogram are zoomed-in to get an

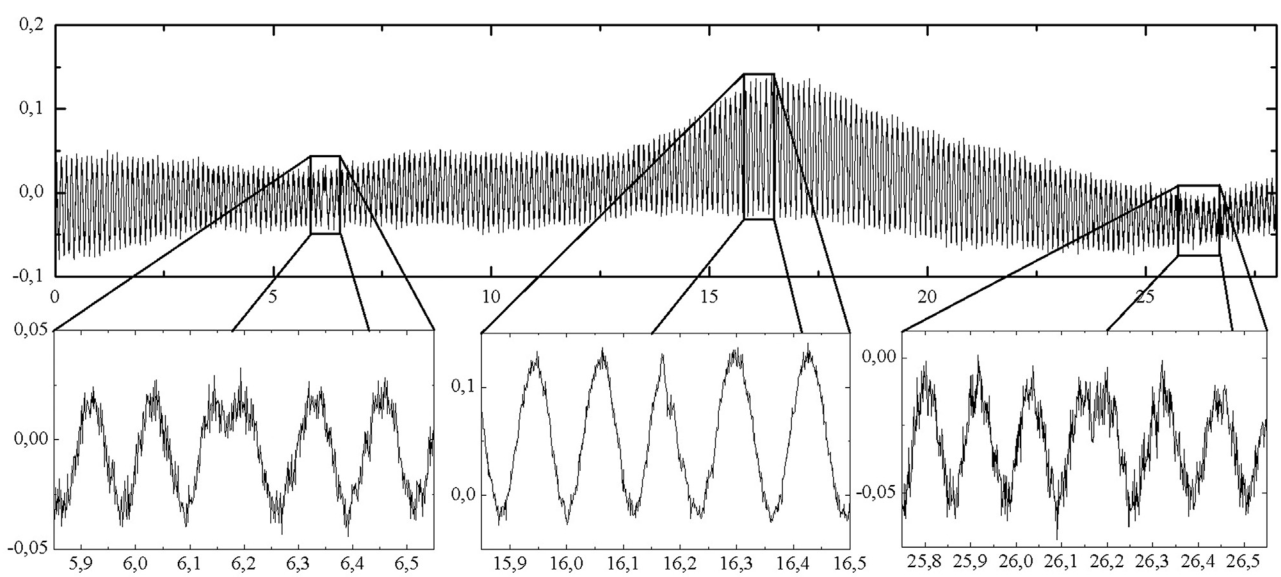

Fig. 8. Interferogram of a cavity varied triangularly and three zoomed-in zones of interest.

idea of the demodulation problem. In particular, the direction change around 16.2 s may be treated as an artefact, while belongs indeed, to a change of direction sense.

After processing the 802 spectra of the SDI, the cavity length vs. time is obtained and shown in Fig. 9.

The cavity changes its sense of movement rapidly in 6.19 s, 16.19 s and 26.19 s. In addition, from SDI readings, we can state undoubtedly that measurement starts when the cavity length increases from a distance of 204.6 µm. All this information is not clear from a single TDI sensor. But again, if we combine the TDI with the SDI, it is possible to develop a non-contact, high resolution cavity length sensor, with true sense of direction for quasi-static measurements.

Finally, the cavity length vs. time curve of the DFI can be seen in Fig. 10.

4. Conclusions

We obtained a measurement system with two coupled interferometers in one fiber end point. This system combines the high resolution of a time domain interferometer and the absolute measurement without ambiguity of the spectral domain one. The resolution of TDI depends on the laser wavelength. In the case of SDI, it depends on the resolution of the employed spectrum analyser (usually 0.05–1 nm) and the SLED wideband. In the second case, higher resolution involves a higher cost of the system.

Two measurements were made exactly at the same end fiber point and the samples were obtained from the same acquisition system. This is the reason why both measurements were made absolutely at the same point and temporally correlated. This sensor resolves the time domain interferometer ambiguity problem in which the path sense is unknown; also for the case when the cavity length stops moving for a period of time where it is impossible to determine if the sense of movement has changed or not.

In particular, this is useful in processes where the target changes the movement direction getting closer or further away. An example of this can be the shrinkage photo-polymerization measurements in which the intrinsic exothermic reaction releases heat that can expand the sample under test at the beginning of the experiment [19].

Funding sources

This work has been supported by the Consejo Nacional de Investigaciones Científicas y Tecnológicas CONICET [PIP 112–201101-00397] and Facultad de Ingeniería-Universidad Nacional de la Plata [Project I169].

Acknowledgements

The authors of this work want to thank especially Federico Schipani, for his fruitful suggestions and corrections.

References

[1] Krohn DA, MacDougall T, Mendez A. Fiber optic sensors: fundamentals and applications, 4th ed. 2015; 2015.
[2] Fiber Optic Sensors, Second ed., CRC Press 2008.
[3] Udd E, Spillman WB. Jr., Fiber optic sensors: an introduction for engineers. Hoboken, New Jersey: John Wiley & Sons; 2011.
[4] Musa SM. Real-time signal processing and hardware development for a wavelength modulated optical fiber sensor system; 2007.
[5] Rao YJ, Jiang J, Zhou CX. Spatial-frequency multiplexed fiber-optic Fizeau strain sensor system with optical amplification. Sens Actuators, A: Phys 2005;120:354–9.
[6] Lee CL, You YW, Dai JH, Hsu JM, Horng JS. Hygroscopic polymer microcavity fiber Fizeau interferometer incorporating a fiber Bragg grating for simultaneo sensing humidity and temperature. Sens Actuators B: Chem 2015;222:339–46.
[7] Yuan L, Yang J. Multiplexed Mach-Zehnder and Fizeau tandem white light interferometric fiber optic strain/temperature sensing system. Sens Actuators, A: Phys 2003;105:40–6.
[8] Arenas GF, Noriega S, Claudia VI, Duchowicz R. Polymerization shrinkage of a dental resin composite determined by a fiber optic Fizeau interferometer. Opt Commun 2007;271:581–6.
[9] Schake M, Schulz M, Lehmann P. High-resolution fiber-coupled interferometric point sensor for micro-and nano-metrology. Tech Mess 2015;82:367–76.
[10] Knell H, Schake M, Schulz M, Lehmann P. Interferometric sensors based on sinusoidal optical path length modulation, Proceedings of SPIE – the international society for optical engineering; 2014.
[11] Duchowicz R, Arenas GF, Vallo CI. Determination of dental composites properties by using a Fizeau fiber interferometer. In: Halsey D, Raynor W, editors. Handbook of interferometers. New York: Research, Technology and Applications, Nova Science; 2009.
[12] Depiereux F, Lehmann P, Pfeifer T, Schmitt R. Fiber-optical sensor with miniaturized probe head and nanometer accuracy based on spatially modulated low-coherence interferogram analysis. Appl Opt 2007;46:3425–31.
[13] Malacara D. Review of interferogram analysis methods, Proceedings of SPIE – the international society for optical engineering, pp. 678–689; 1990.
[14] Malacara D, Servin M, Malacara Z. Interferogram analysis for optical testing S.E., Taylor & Francis Group; 2005.
[15] Gurov I, Hlubina P, Chugunov V. Evaluation of spectral modulated interferograms using a Fourier transform and the iterative phase-locked loop method. Meas Sci Technol 2003;14:122–30.
[16] Antonacci GJMJulián, Passoni LucíaI, Arenas GustavoF. Spectral Fizeau Interferometer spectra processing by means of a fuzzy inference system. In: 2015 XVI workshop on information processing and control (RPIC), Cordoba, Cordoba, Argentina; 2015.
[17] Malacara D SMMZ. Interferogram analysis for optical testing S.E., Taylor & Francis Group; 2005.
[18] Oppenheim AV, Schafer RW. Discrete-time signal processing, 2nd ed; 1999.
[19] Mucci V, Arenas GF, Duchowicz R, Cook WD, Vallo CI. Influence of thermal expansion on shrinkage during photopolymerization of dental resins based on bis-GMA/TEGDMA. Dent Mater 2009;25:103–14.

Julian Antonacci was born in Benito Juarez, Argentina in 1986. He received his electronic engineering degree from the National University of Mar del Plata (UNMdP, Argentina) in 2013, in the same year he joined the Laser Laboratory (Faculty of Engineering, Mar del Plata, Argentina), as an engineer where he worked on fiber optics sensors research and development. His research interests include fiber optics sensors applications in material sciences, general issues on optics and photonics and digital signal processing.

Gustavo F. Arenas was born in Buenos Aires, Argentina, in 1974. He received his electronic engineering degree from the National University of Mar del Plata (UNMdP) in 2001. In 2003 he joined the Laser Laboratory at the Faculty of Engineering, Mar del Plata, Argentina, where he worked on fiber optics sensors research and development. In 2009 he received his Doctoral degree in electronic engineering from the UNMdP. Since 2011 he is full-time researcher member of CONICET and Professor at the UNMdP. His research interests include fiber optics sensors applications in material sciences, general issues on photonics and nanotechnology.

Ricardo Duchowicz is a researcher of the CONICET and professor from the Faculty of Engineering of UNLP, Argentina. He received his Ph.D. and MS degrees in physics from UNLP in 1981 and 1977, respectively. In 1977, he joined the CIOp. He has published extensively on subjects related to fiber optic lasers, fiber sensors, and pulse transmission in fiber optic links.