Interrogation of a Suspended-Core Fabry–Perot Temperature Sensor Through a Dual Wavelength Raman Fiber Laser

A. M. R. Pinto, O. Frazão, *Member, IEEE, OSA*, J. L. Santos, *Member, IEEE, OSA*, M. Lopez-Amo, *Senior Member, IEEE, OSA*, J. Kobelke, and K. Schuster

***Abstract*—sThe interrogation of a Fabry–Perot cavity through a dual wavelength Raman fiber laser is reported. The proposed sensing system is based on the use of a dual wavelength Raman fiber laser to generate two quadrature phase-shifted signals that allow the recovery of the temperature change sensed by the Fabry–Perot interferometric cavity. The dual wavelength Raman fiber laser is based on fiber Bragg gratings combined with a distributed mirror. The Fabry–Perot cavity is fabricated by splicing a short length of a suspended-core microstructured fiber to a single mode fiber. The use of this sensing system allows a passive and accurate interrogation of the temperature, while taking advantage of the Rayleigh scattering growth as a distributed mirror in the laser.**

***Index Terms*—Fabry-Perot, fiber optic, microstructured fiber, Raman laser, temperature sensor.**

I. Introduction

OPTICAL fiber sensors emerged as a consequence of two huge scientific developments in the 60s: the laser in 1960 and the low-loss optical fiber in 1966. In the 70s, the first experiments on low-loss optical fibers were performed, not for communications but for sensor purposes. The main drive for optical fibers first application does not surprise us nowadays. Optical fibers are efficient solutions for sensing due to their high sensitivity, small size, ability for remote monitoring and low cost. Another advantage of great importance is their ability for operational work in the presence of unfavorable environmental conditions such as noise, strong electromagnetic fields and high voltages, nuclear radiation, in explosive or chemically corrosive media, at high temperatures, among others. In these advantages lies the recipe for the success of optical fiber sensors: in undertake difficult measurement situations where the use of conventional electrical sensors is not adequate [1], [2].

Manuscript received July 19, 2010; revised August 27, 2010; accepted September 08, 2010. Date of publication September 23, 2010; date of current version October 27, 2010. This work was supported in part by the Spanish Government project TEC2007-67987-C02 and in part by the European COST Action 299.

A. M. R. Pinto and M. López-Amo Sainz are with the Departamento de Ingeniería Eléctrica y Electrónica of Universidad Pública de Navarra, Pamplona, Navarra 31006, Spain (e-mail: anamargarida.rodriguez@unavarra.es).

O. Frazão and J. L. Santos are with INESC Porto (Instituto de Engenharia de Sistemas e Computadores do Porto) and the Departamento de Física, Faculdade de Ciências of Universidade do Porto, 4169-007 Porto, Portugal.

J. Kobelke and K. Schuster are with the Institute for Photonics Technology, Jena 07745, Germany.

Digital Object Identifier 10.1109/JLT.2010.2078490

The appearance of microstructured fibers (MOFs) was a breakthrough in fiber technology, particularly in the sensing domain. This kind of fiber is characterized by a periodic arrangement of air holes running along the entire length of the fiber centered on a solid core. The microstructured air-filled region lowers the cladding effective refractive index allowing the guiding mechanism to be total internal reflection. Since the cladding refractive index is decreased by the air holes, this fiber can be fabricated entirely with a single material, like silica, and still confine light in the solid core. This kind of structure enables a considerable enhancement in fiber design flexibility, providing a new breach for new and enhanced sensing solutions relative to the situation where the choice was limited to the standard optical fiber technology. Suspended-core MOFs (SC-MOFs) differentiate from other of their kind by having relatively large holes that surround a small core (few μm of diameter) which looks suspended along the fiber axis by small width silica walls. This kind of MOF was initially proposed by Monro *et al.* [3]. Later on, a simple technique for fabrication of these structures as well as its application as a gas sensor was demonstrated [4]. More recently, the geometry of the fiber cross section was exploited to maximize the interaction of light and sample for evanescent field sensing [5] or for optical gas sensing cells [6]. Other authors took advantage of the fact that suspended-core fibers can be made of a single material, in such case silica, and use a four hole SC-MOF for strain and temperature sensing based in a Sagnac interferometer [7] or to construct a Fabry–Perot cavity using a section of SC-MOF between two single mode fibers (SMFs) in order to obtain a refractive index sensor [8].

Fiber-optic interferometric sensors based on Fabry–Perot cavities have long been investigated for detection and measurement of a large variety of physical parameters, such as displacement, strain, refractive index and temperature. In many applications, there is a great necessity for a small sensor head to carry out localized measurement. In a fiber optic Fabry–Perot interferometer the fiber itself is the sensing element. As so, a fiber optic Fabry–Perot interferometer with a short cavity (about several micrometers) is an attractive choice as the basic sensing element, since it is simple and compact [9]. It also offers high resolution and precision, and is immune from environmental fluctuations such as vibration and micro-bend, because any fluctuation that affects optical phase or polarization along the fiber is common to the interfering optical fields and eliminated automatically. Such interferometers can be made of a cleaved distal end face optical fiber as one interface and an external reflecting surface as the other, and combined with a high performance signal processing system to give high precision displacement measurements [10]; or simply by an air-gap as the sensing component, accomplished by fusing a hollow core fiber between two SMFs for strain sensing [11]; or by connecting two single mode fibers to a short section of multimode fiber for temperature and strain measurement [12]; or a micro-notch cavity can be fabricated in a SMF by a one-step fs laser micro-machining in order to obtain highly sensitive refractive index measurement [13]; or by using a hybrid structure composed by a photonic crystal fiber spliced to a hollow core fiber which in turn is spliced to a SMF, forming two Fabry–Perot cavities which act as a high temperature sensor head [14]; or even by fusing a small length of SC-MOF to the end of a cleaved SMF for strain and temperature measurement [15].

Phase is a parameter of light which is easily changed by a large number of physical quantities. Interferometric sensors basis is the modulation of phase. The interferometric phase can be recovered in several ways, but there are two approaches that prevail. One of them relies in the white light concept. In this approach the reflected light from the interferometer is processed by a second interferometer, which means that for phase recovery the processing unit must have two or more interferometers. Another path for phase recovering consists on the generation of quadrature phase-shifted interferometric signals through the utilization of dual-wavelength illumination. Which is saying to get quadrature signals to illuminate the interferometer with two wavelengths, being by using two laser sources or by using two different longitudinal modes of the same laser. The light signals in the cavity are then detected independently of each other. Dual wavelength illumination is an elegant process of interrogation for such remote Fabry–Perot cavities, since it implies a less complex set up than the white light concept and offers greater flexibility of design. Therefore, a fiber Bragg grating (FBG) based dual wavelength laser is a good solution for an interferometer interrogation. The application of FBGs for Fabry–Perot cavities interferometric interrogation has been already successfully accomplished [16], by using a broadband source which illuminated the Fabry–Perot sensor. The interferometric light signal reflected from the sensing cavity was then coupled into two FBG wavelength discriminators. The back reflected interferometric signal and the two FBGs were monitored using two photodiodes.

Multiwavelength fiber lasers are particularly appealing for sensors interrogation. Initially Er-doped fiber amplifiers were utilized for these lasers [17], [18]; being that nowadays Raman amplification, EDFAs and SOAs are more utilized depending on the application and distance to be achieved. Raman laser based sensing systems have been exploited and proved to be an effective method for long distance remote sensing [19], [20]. A common limiting aspect in Raman amplification based architectures is the gain suppression due to Rayleigh scattering growth in the laser cavity associated with the high power used. When Raman gain is high, Rayleigh and double Rayleigh scattering are generated introducing noise in the system. This scattering growth can be a problem for specific applications but can also be used as a distributed mirror in the laser cavity in order to enhance the generation of Stokes combs [21], [22]. When this Rayleigh scattering is used as distributed mirror, is saying when it is used as a part of the laser, the Raman gain associated noise becomes a creative part in the laser, transforming what normally were negative effects in the system to be noteworthy improvements [23]. Recently, a random distributed feedback fiber laser was demonstrated, using a mirrorless open cavity that operated via Rayleigh scattering, amplified through the Raman effect [24].

In this work, the authors present the interrogation of a Fabry–Perot cavity through a dual wavelength Raman fiber laser source. The dual wavelength Raman fiber laser is based on fiber Bragg gratings combined with a distributed mirror. The laser source is used to illuminate a Fabry–Perot cavity based on a suspended-core fiber. The use of this sensing system allows a passive and accurate interrogation of the temperature, while taking advantage of the Rayleigh scattering growth as a distributed mirror in the laser.

II. Theory

The Fabry–Perot cavity is illuminated with two distinct wavelengths to perform interferometric interrogation based on the generation of two signals in quadrature. The phase at each wavelength is

$$\phi_i = \frac{4\pi n L}{\lambda_i}, i = 1, 2 \tag{1}$$

where n is the effective refractive index of the Fabry–Perot cavity, L is the length of the cavity and λ_i are the wavelength discriminators $(i = 1, 2)$. The relative phase difference between the two interferometric signals is given by

$$\Delta\phi = 4\pi n L \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \tag{2}$$

These signals will be in quadrature when the wavelength separation between the resonant wavelengths is an odd multiple (m) of $\lambda^2/(8)$ nL, where the approximation $\lambda_1 = \lambda_2 = \lambda$ was considered. For a given cavity length, it is always possible to define two resonant wavelengths that match the above condition.

The output optical powers p_1 and p_2 used to measure independently light back reflected at each wavelength are then given by

$$\begin{aligned} p_1 &= P_1(1 + \kappa_1 \cos\phi_1) \\ p_2 &= P_2[1 + \kappa_2 \cos(\phi_1 + \Delta\phi)] = P_2(1 + \kappa_2 \sin\phi_1) \end{aligned} \tag{3}$$

where $P_{1,2}$ are constant values of power (dependent on the optical power in the system and gain of the detection instruments) and $\kappa_{1,2}$ is the fringe visibility at each wavelength. Setting $\kappa_1 P_1 = \kappa_2 P_2$, with gain adjustment then it is possible to recover the interferometric phase through the following relation:

$$\phi_1 = \arctan\left(\frac{p_2 - P_2}{p_1 - P_1}\right). \tag{4}$$

The unambiguous phase recovery from $-\pi/2$ to $\pi/2$ can be calculated using the above equation and the signals in (3).

III. Experimental Method and Results

The proposed sensing system consists in a dual wavelength Raman fiber laser and a Fabry–Perot microstructured fiber based

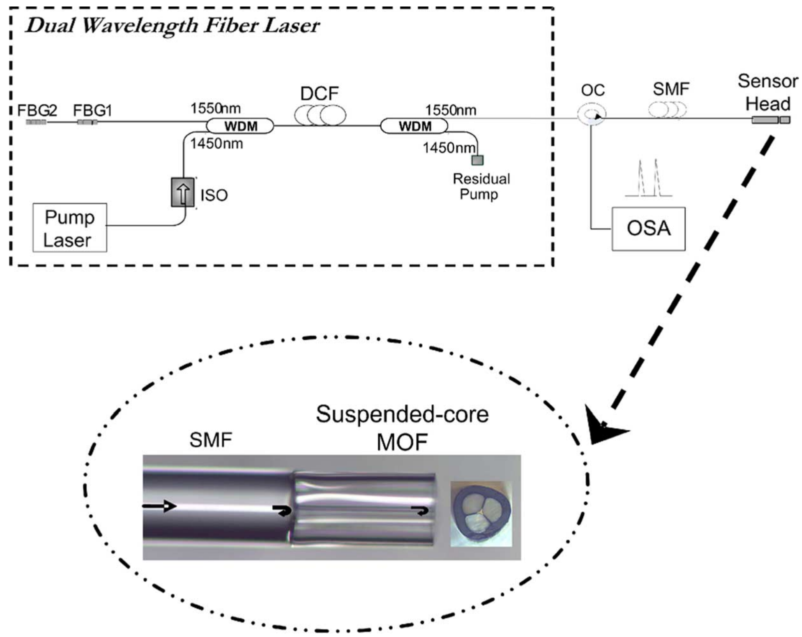

Fig. 1. Experimental setup configuration for the Fabry–Perot sensing system; Inset: photograph of the Fabry–Perot sensing head and the suspended-core MOF cross-section.

cavity. The proposed configuration is presented in Fig. 1. A home-made dual wavelength Raman fiber laser, an optical circulator (OC) and an optical spectrum analyzer (OSA) with a maximum resolution of 10 pm are employed for the interrogation of a Fabry–Perot cavity in reflection.

A. Dual Wavelength Raman Fiber Laser

The dual wavelength Raman fiber laser is composed by a high pump Raman laser at 1445 nm (maximum power of 5 W), two fiber Bragg gratings with high reflectivity (93%), two wavelength division multiplexers (WDMs) (1445/1550 nm) and a dispersion compensating fiber. The DCF is 2.7 km long and presents a dispersion of -343 ps.nm^{-1} km^{-1}.

The dual wavelength Raman fiber laser is created by the combination of the two FBGs with a distributed mirror. The distributed mirror is an outcome of the large Raman gain in the DCF. When high Raman gain is achieved in the DCF, Rayleigh scattering is generated by the pump signal. In turn, this Rayleigh scattering will generate double Rayleigh scattering. This double Rayleigh scattering signal, combined with the amplified spontaneous emission of the Raman amplifier, induces incoherent multiple path interference, which is noise associated with the beating of multiple different delayed replicas of the signal itself [23]. As so, a distributed mirror is created, which in addition to the FBGs generates a stable dual wavelength fiber laser with the output spectrum presented in Fig. 2.

This dual wavelength fiber Raman laser is used to interrogate the Fabry–Perot cavity. The FBGs wavelengths ($\lambda_1 = 1540.38$ nm, $\lambda_2 = 1545.19$ nm) where chosen in order to generate two signals in quadrature, $m = 7$. In this way, they permit phase quadrature for the interrogation of the Fabry–Perot cavity used, following the theoretical basis presented in Section II.

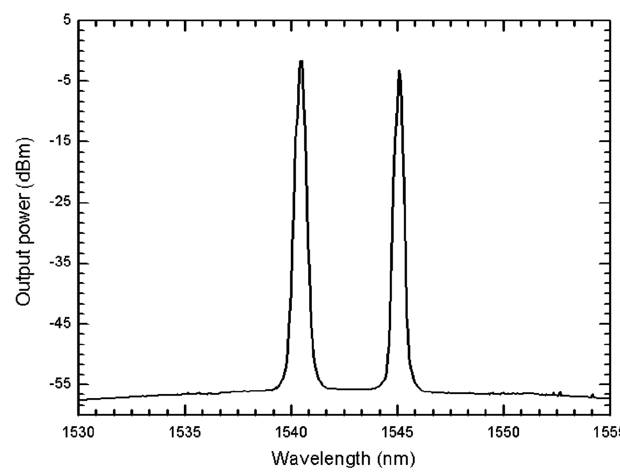

Fig. 2. Dual wavelength Raman fiber laser output spectrum for a 0.6 W Raman pump power.

B. Sensor Fabrication

The sensing element is a Fabry–Perot cavity made using SMF and a suspended-core MOF. The fabrication of the Fabry–Perot cavity was made by splicing a single mode fiber to a short length of suspended-core MOF, with its end cleaved (inset Fig. 1). The total loss of the splice was $\sim$3 dB.

The suspended-core MOF was fabricated at the IPHT (Institute of Photonics Technology, Jena, Germany) and is formed by three holes with a diameter of 52 μm (inset Fig. 1). The core and the cladding have diameters of 4.4 μm and 127 μm, respectively. The core has a slightly triangular shape due to the hole asymmetry originated during the fabrication process. The Fabry–Perot cavity has 299 μm of length and presents the output spectrum presented in Fig. 3, when illuminated by a Raman source amplified by a DCF.

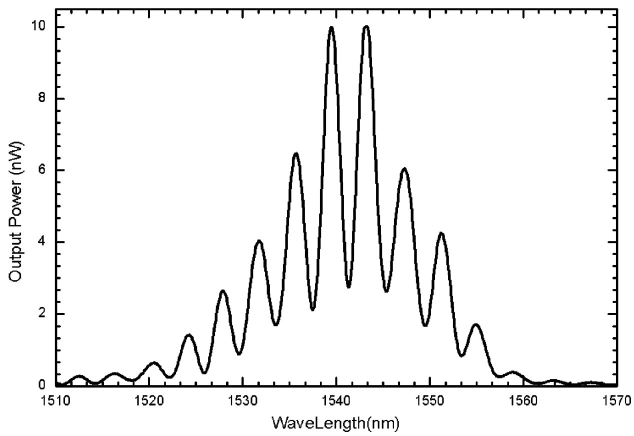

Fig. 3. Output spectrum of the Fabry–Perot cavity sensor.

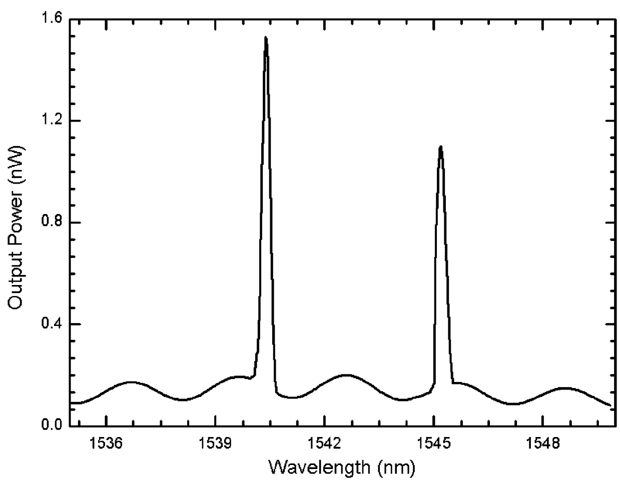

Fig. 4. Output spectrum of the fiber laser sensor.

C. Sensor Interrogation

Using the setup proposed on Fig. 1, the final output spectrum will be the integration of the laser output spectrum presented in Fig. 2 with the Fabry–Perot output signal presented in Fig. 3. As a consequence, the fiber laser sensor output spectrum presents the baseband channeled spectrum originated in the Fabry–Perot cavity and the two Raman fiber laser lines, as it can be observed in Fig. 4. Notice that there is a discrepancy between the output power of the sensing system and the one of the dual wavelength Raman laser. This is due to the fact that the sensor head signal is collected in reflection, which by Fresnel equations means that only 4% of the signal is collected. As mentioned above, the FBGs wavelengths where chosen in order to present the spectral separation set to permit phase quadrature interrogation of the Fabry–Perot cavity used, following the theoretical basis presented in Section II.

Due to the high sensitivity of silica to temperature variations, the Fabry–Perot cavity acts as a high-quality temperature sensor. When temperature changes are enforced to the Fabry–Perot cavity its interferometric output spectrum is shifted in wavelength. This wavelength shift is proportional to the temperature induced variation. On the other hand, the dual wavelength Raman fiber laser maintains its spectrum, as the

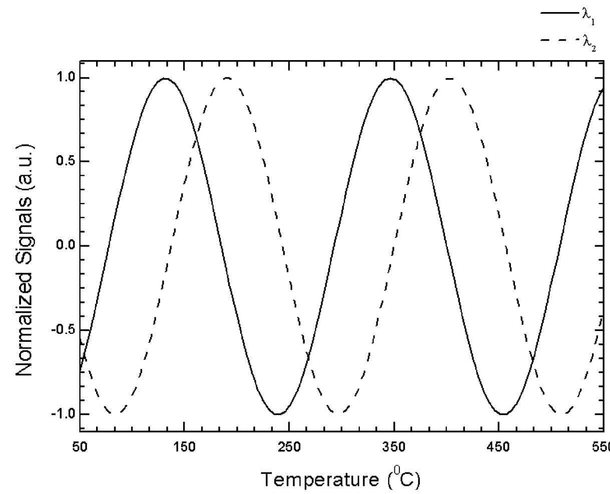

Fig. 5. Variation of the output signals with temperature, for a Fabry–Perot cavity of ~299 μm of length.

FBGs are not subjected to any external force. The final signal of the sensing system will be the integration of both signals: the one of the cavity sensor and the one of the dual wavelength Raman fiber laser. As so, while changing the temperature the interferometric signal of the Fabry–Perot cavity will displace itself, giving the visual sensation that the FBG signals are "fluctuating" on the interferometric signal, as the FBGs power varies between a maximum and a minimum value depending on the interferometric signal displacement. Through the power response of both FBG peaks in quadrature, the temperature at which the sensor is exposed is determined unambiguously.

The sensor system was tested for periodic temperature variations using a Fabry–Perot cavity with ~299 μm of length. The peak values of both FBGs where recorded while varying the temperature. The output signals variation with temperature is presented in Fig. 5.

As it can be seen in Fig. 5, the peak values of the FBGs vary as a sinusoidal with the temperature, as should be expected. Since the peak values depend on the "path traveled" by the interferometric signal, it is not difficult to guess that if the Fabry–Perot cavity changes its length the output signals variation will change and the period of the sinusoidal variation will be different. Is saying, the longer the cavity length is, the shorter the interference peak to peak distance will be. As so, if the peak-to-peak distance in the interference is smaller the sinusoidal response of the FBGs will be faster, giving a smaller temperature period. An illustration of the case in which the Fabry–Perot cavity is larger was presented in EWOFS 2010 by the same authors [25]. In this case the length of the Fabry–Perot cavity was of ~500 μm (this corresponds to the length of the suspended-core MOF). The signals obtained with the temperature variation when using a Fabry–Perot sensor formed by ~500 μm of SC-MOF spliced to a SMF is presented in Fig. 6 ($\lambda_1 = 1540.38$ nm, $\lambda_2 = 1544.9$ nm, $m = 11$).

As explained, a Fabry–Perot cavity of ~500 μm will produce an interferometric signal which has a peak-to-peak distance lower than in the case of a Fabry–Perot cavity of ~299 μm. The temperature range in which a laser sensor, such as the one

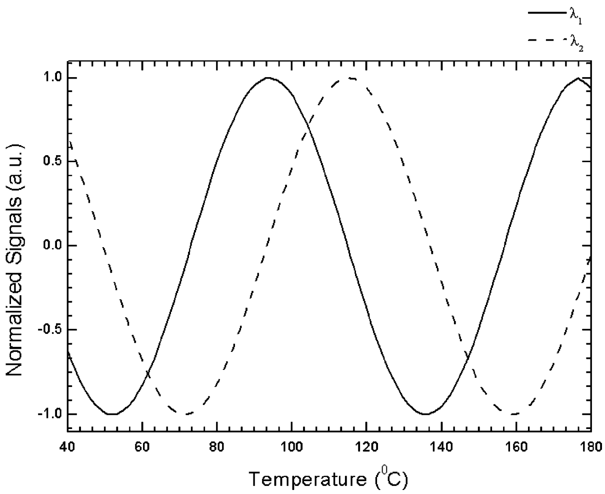

Fig. 6. Variation of the output signals with temperature, for a Fabry–Perot cavity of ~500 μm of length.

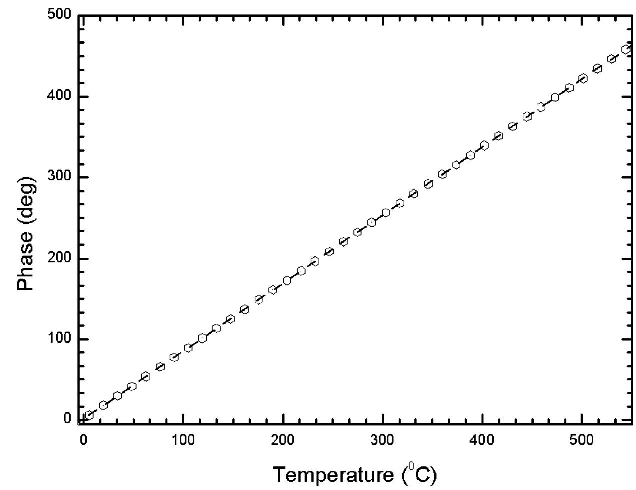

Fig. 8. Phase change of the proposed sensing system versus temperature, for the Fabry–Perot cavity with ~299 μm of length.

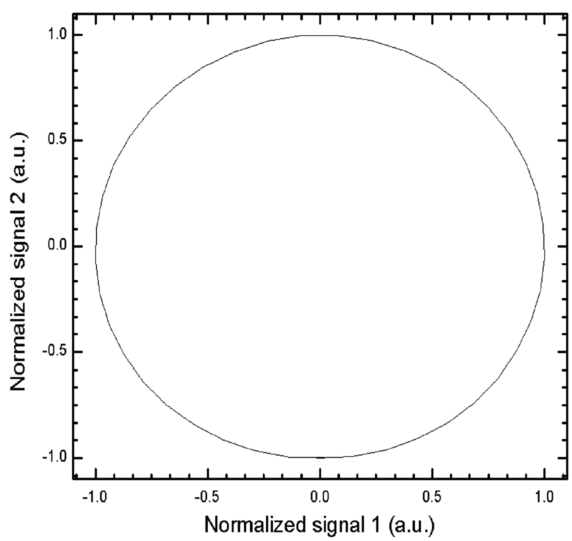

Fig. 7. Lissajous figure associated to the output signals of the sensing system, for the Fabry–Perot cavity with ~299 μm of length.

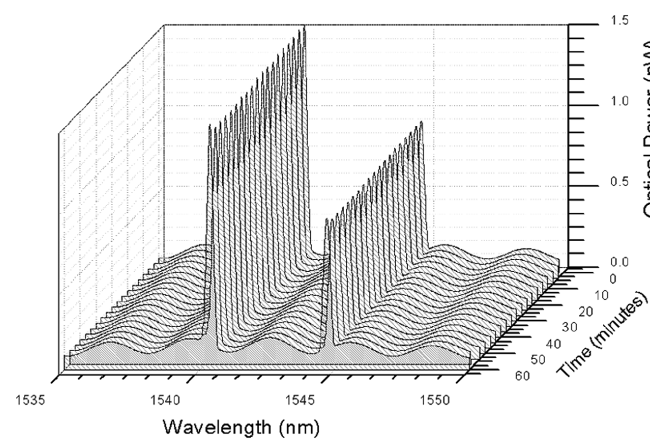

Fig. 9. Repeated scans of output spectrum of the proposed laser sensor, for a Fabry–Perot cavity with ~299 μm of length.

presented in Fig. 1, performs a period is expected to be less for the Fabry–Perot cavity of ~500 μm. And by close observation to Figs. 5 and 6 it can be seen that it is. The temperature range for which the signals in Fig. 5 (Fabry-Perot cavity of ~299 μm) perform a period is ~215° C, whereas the temperature range for which the signals in Fig. 6 (Fabry-Perot cavity of ~500 μm) perform a period is of 85°C. In practical terms this fact is very useful, since by knowing the temperature range needed one can chose the length of the cavity, having this way an optimized process to choose the Fabry–Perot cavity sensor.

Following the theory presented in Section II, if the interrogation system fulfills the gain adjustment condition $\kappa_1 P_1 = \kappa_2 P_2$ and the FBGs were chosen in order to fulfill the quadrature relation, the Lissajous figure associated to the output power signals must be a circle. In Fig. 7 the Lissajous figure of the proposed system is presented.

As it can be seen in Fig. 7, which represents one FBG signal versus the other, the quadrature phase-shifted relation between the two signals is confirmed. From these signals and using (4) of Section II, the interferometric phase shift as a function of temperature variation applied to the Fabry–Perot cavity was calculated and is presented in Fig. 8. The resulting sensitivity of the sensing system is of 0.84 deg/°C.

The output signals were measured during one hour in time intervals of 3 minutes in order to check the system stability. Fig. 9 shows the scanned output spectra of the fiber laser sensor for the Fabry–Perot cavity of ~299 μm. The maximum variation of the peak powers of the FBGs of this sensor system was measured to be ~0.2 dBm over one hour. As so, it can be concluded that the fiber laser sensor proposed in this paper can work stably.

IV. Conclusion

The interrogation of a Fabry–Perot interferometer temperature sensor through a dual wavelength Raman fiber laser illumination source was demonstrated and accomplished. The proposed system was composed by a dual wavelength Raman fiber laser in combination with a Fabry–Perot interferometer. The dual wavelength Raman fiber laser is based on the use of two FBGs combined with a distributed mirror. The distributed mirror is the result of the double scattering produced in the DCF by Raman amplification. This dual wavelength Raman fiber laser acts as the illumination source for the generation of two quadrature phase-shifted signals through which the Fabry–Perot cavity is interrogated. The presented Fabry–Perot interferometer consists in a short length of a suspended-core MOF spliced to a single mode fiber. When the Fabry–Perot cavity was subjected to temperature variations, the system was shown to be proper for temperature measurement, showing a sensitivity of 0.84 deg/°C and a maximum power variation of 0.2 dBm. Changing the Fabry–Perot cavity length was shown to enable the optimization the temperature range of the sensor. The presented interrogation method enables the possibility for remote sensing since the quadrature condition is imposed by the laser itself. Moreover, incrementing the FBGs in the fiber laser the number of illumination lines will be increased, and as a consequence, the possibility for multiplexing several FP cavities at the same time while using a single pump source.

References

[1] K. T. V. Grattan and T. Sun, "Fiber optic sensor technology: An overview," *Sens. Act. A*, vol. 82, pp. 40–61, May 2000.

[2] E. Li, X. Wang, and C. Zhang, "Fiber-optic temperature sensor based on interference of selective higher-order modes," *App. Phys. Lett.*, vol. 89, pp. 0.91119-1–091119-3, Aug. 2006.

[3] T. M. Monro, W. Belardi, K. Furusawa, J. C. Baggett, N. G. R. Broderick, and D. J. Richardson, "Sensing with microstructured optical fibres," *Meas. Sci. Technol.*, vol. 12, pp. 854–858, Jul. 2001.

[4] A. S. Webb, F. Poletti, D. J. Richardson, and J. K. Sahu, "Suspended-core holey fiber for evanescent-field sensing," *Optics Eng.*, vol. 46, pp. 010503-1–010503-3, Jan. 2007.

[5] S. Selleri, E. Coscelli, M. Sozzi, A. Cucinotta, F. Poli, and D. Passaro, "Air-suspended solid-core fibers for sensing," in *Proc. Opt. Sens. Conf.*, Edinburgh, Jan. 2007, pp. 73561L–73561L-8.

[6] I. Dicaire, J. C. Beugnot, and L. Thévenaz, "Suspended-core fibres as optical gas sensing cells: Study and implementation," in *Proc. Photon. Eur. Conf.*, Prague, Sep. 2009, pp. 73570U–.

[7] O. Frazao, J. M. Baptista, J. L. Santos, J. Kobelke, and K. Schuster, "Strain and temperature characterization of sensing head based on a suspended-core fibre in Sagnac interferometer," *Electron. Lett.*, vol. 44, pp. 1455–1456, Dec. 2008.

[8] O. Frazao, J. M. Baptista, J. L. Santos, J. Kobelke, and K. Schuster, "Refractive index tip sensor based on Fabry–Perot cavities formed as a suspended-core fibre," *J. Eur. Opt., Soc.*, vol. 4, pp. 09041–, Aug. 2009.

[9] Y. J. Rao, "Recent progress in fiber-optic extrinsic Fabry–Perot interferometric sensors," *Opt. Fiber Technol.*, vol. 12, pp. 227–237, Jul. 2006.

[10] T. Wang, S. Zheng, and Z. Yang, "A high precision displacement sensor using a low-finesse fiber-optic Fabry-Pérot interferometer," *Sens. Act. A*, vol. 69, pp. 134–138, Aug. 1998.

[11] Y. Lo, J. Sirkis, and C. Chang, "Passive signal processing of in-line fiber etalon sensors for high strain rate loading," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1578–1586, Aug. 1997.

[12] Z. Huang, Y. Zhu, X. Chen, and A. Wang, "Intrinsic Fabry–Perot fiber sensor for temperature and strain measurements," *IEEE Photon. Technol. Lett.*, vol. 17, no. 11, pp. 2403–2405, Nov. 2005.

[13] T. Wei, Y. Han, Y. Li, H. Tsai, and H. Xiao, "Temperature-insensitive miniaturized fiber inline Fabry–Perot interferometer for highly sensitive refractive index measurement," *Opt. Exp.*, vol. 16, pp. 5764–5769, Apr. 2008.

[14] H. Y. Choi, K. S. Park, S. J. Park, U. Paek, B. H. Lee, and E. S. Choi, "Miniature fiber-optic high temperature sensor based on a hybrid structured Fabry–Perot interferometer," *Opt. Lett.*, vol. 33, pp. 2455–2457, Oct. 2008.

[15] O. Frazão, S. H. Aref, J. M. Baptista, J. L. Santos, H. Latifi, F. Farahi, J. Kobelke, and K. Schuster, "Fabry-Pérot cavity based on a suspended-core fiber for strain and temperature measurement," *IEEE Photon. Technol. Lett.*, vol. 21, no. 9, pp. 1229–1231, Sep. 2009.

[16] M. Dalhem, J. L. Santos, L. A. Ferreira, and F. M. Araújo, "Passive interrogation of low-finesse Fabry–Perot Cavities using fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 13, no. 9, pp. 990–992, Sep. 2001.

[17] A. T. Alavie, S. E. Karr, A. Othonos, and R. M. Measures, "A multiplexed Bragg grating fiber laser sensor system," *IEEE Photon. Technol. Lett.*, vol. 5, no. 9, pp. 1112–4, Sep. 1993.

[18] E. Achaerandio, S. Jarabo, S. Abad, and M. López-Amo, "New WDM amplified network for optical sensor multiplexing," *IEEE Photon. Technol. Lett.*, vol. 11, no. 12, pp. 1644–1646, Dec. 1999.

[19] P. C. Peng, H. Y. Tseng, and S. Chi, "Long-distance FBG sensor system using a linear-cavity fiber Raman laser scheme," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 575–577, Feb. 2004.

[20] Y. G. Han and T. V. A. Tran, "Multiwavelength Raman-fiber-laser-based long-distance remote sensor for simultaneous measurement of strain and temperature," *Opt. Lett.*, vol. 11, pp. 1282–1284, Jun. 2005.

[21] A. K. Zamzuri, M. I. Ali, A. Ahmad, R. Mohamad, and M. A. Mahdi, "Brillouin-Raman comb fiber laser with cooperative Rayleigh scattering in a linear cavity," *Opt. Lett.*, vol. 31, pp. 918–920, Apr. 2006.

[22] O. Frazão, C. Correia, J. L. Santos, and J. M. Baptista, "Raman fiber Bragg-grating laser sensor with cooperative Rayleigh scattering for strain-temperature measurement," *Meas. Sci. Technol.*, vol. 20, pp. 045203–, Feb. 2009.

[23] A. M. R. Pinto, O. Frazão, J. L. Santos, and M. Lopez-Amo, "Multiwavelength fiber laser based on a photonic crystal fiber loop mirror with cooperative Rayleigh scattering," *Appl. Phys. B*, vol. 99, pp. 391–395, Apr. 2010.

[24] S. K. Turitsyn, S. A. Babin, A. E. El-Taher, P. Harper, D. V. Churkin, S. I. Kablukov, J. D. Ania-Castañón, V. Karalekas, and E. V. Podivilov, "Random distributed feedback fibre laser," *Nature Photon*, vol. 4, pp. 231–235, Feb. 2010.

[25] A. M. R. Pinto, O. Frazão, J. L. Santos, M. Lopez-Amo, J. Kobelke, and K. Schuster, "Suspended-core Fabry–Perot temperature sensor interrogation through a dual wavelength raman fiber laser," presented at the European Workshop on Optical Fibre Sensors, Porto, Portugal, Sep. 2010.

Ana Margarida Rodrigues Pinto was born in Porto, Portugal, in 1982. She received the degree in physics from Universidade do Minho, Portugal, in 2006 and the M.S. degree in communications from Universidad Pública de Navarra, Spain, 2009, where she is currently pursuing the Ph.D. degree.

From 2007 to 2008, she was with the Optoelectronics and Electronic Systems Unit of Inesc Porto (Portugal) working with a research grant. In the Ph.D. scope, she has done a research period in 2009 at the Optoelectronics and Electronic Systems Unit of Inesc Porto (Portugal) and in 2010 at the Brussels Photonics Team of the Vrije Universiteit Brussel (Belgium). Her present research interests include photonic crystal fibers, fiber optic sensing and optical communications.

Orlando Frazão received the degree in physics engineering (optoelectronics and electronics) from the University of Aveiro, Portugal, and the Ph.D. degree in physics at the University of Porto, Portugal, in 2009.

From 1997 to 1998, he was with the Institute of Telecommunications, Aveiro. Presently, he is a researcher at Optoelectronics and Electronic Systems Unit, INESC Porto. He has published about 250 papers, mainly in international journals and conference proceedings, and his present research interests included optical fiber sensors and optical communications. Dr. Frazão is a member of the Optical Society of America (OSA) and SPIE.

Jose Luis Santos received the Degree in applied physics (optics and electronics) from the University of Porto, Portugal, in 1983, where he received the Ph.D. degree in physics in 1993 for research on fiber optic sensing.

He is an Assiociate Professor in the Physics Department, University of Porto. His main research interest is optical fiber sensing.

Prof. Santos is a member of the Optical Society of America (OSA) and the International Society for Optical Engineers (SPIE).

Manuel Lopez-Amo (M'91–SM'98) was born in Madrid, Spain, in 1960. He received the telecommunications engineering degree and Ph.D. degrees from the Universidad Politécnica de Madrid, Spain in 1985 and 1989, respectively.

From 1985 to 1996, he belonged to the Photonic Technology Department of the Universidad Politécnica de Madrid, where in 1990 he became an Associate Professor. He has been a Visiting Researcher at INTEC of the University of Ghent, Belgium and at British Telecom Research Laboratories, Ipswich, U.K. In 1996, he moved to the Public University of Navarra, Pamplona, Spain, where he became a Full Professor in the Electrical and Electronic Engineering department and he is currently the head of the optical communications group of this department. He has been Chairman of the Optoelectronic Committee of Spain. He has been leader of more than 20 research projects and he has coauthored more than 150 works in international refereed journals and conferences related with fiber-optic networks, optical amplifiers, fiber-optic sensors, and integrated optics.

Dr. Lopez-Amo is a member of the technical committees of the International Conference on fiber optic sensors (OFS), the European Workshop on optical fiber sensors (EWOFS), and European cost 299 action, among others. He is a member of the OSA.

Jens Kobelke studied chemistry at the Technische Hochschule "Carl Schorlemmer," Merseburg, Germany, (1979–1984) and received the Ph.D. degree in heterogenous catalysis in 1986.

He works at IPHT Jena on development and preparation of special optical fibers based on different glass materials (e.g., chalcogenide glasses, HMO glasses, high silica). Actual activities engaged in preparation and characterisation of microstructured fibers based on high silica and other glass materials.

Kay Schuster has been engaged for many years in preparation of specialty fibres, based on heavy metal oxide glasses, chalcogenide glasses and high purity silica. His activities included the preparative operations of glass manufacturing as well as material characterisation (DTA, TG, UV-VIS, FTIR spectroscopy, refractive index) and fibre fabrication (preform and crucible drawing).

Based on his knowledge and experience both, special glass preparation and optical fibre drawing could be highly qualified at IPHT for different applications. Results of these activities were active non silica single mode fibres for amplification (Pr^{3+} doped chalcogenide fibres for 1.3 μm, Er^{3+} doped HMO fibres for 1.5 μm broadband amplification). His recent activities are concentrated on design and preparation of special functionalised microstructured fibres for passive, active and remote sensing applications. Very complex structures of this high silica and silicate glass based fibres have been realized. In the applicative critical field of special sensor fibres for high temperature applications he is intensively engaged in the application and alignment of suitable fibre coating materials (e.g., ORMORCERs, siloxanes, polyimides).