On the use of Optical Fiber Sensors (CCGs and PCFI) for Harsh Environments

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Invited paper

Abstract

Two different technologies of fiber optic sensors have been developed for measuring in harsh environments. The first technology is based on photonic crystal fiber (PCF) interferometric (PCFI) sensors and the second is based on Chemical Composition Gratings (CCGs). PCFIs have been made from pure silica and their multiplexation has been done using a frequency division multiplexing technique. CCGs technology has been developed for high temperature measurements, too. We have reported the creation of CCGs in two different types of fiber: standard single mode fiber (Corning SMF-28) and photosensitive optical fiber (Fibercore PS 1250). We have analyzed the formation process, the sensing properties and the operational limits of this kind of optical fibre sensors for high temperature measurements. CCGs solve two of the main problems for the previous mentioned sensor technologies: multiplexation and usage in harsh environments.

Keywords. Fiber optic sensors, temperature, Photonic Crystal Fiber, Regenerated Gratings, multiplexing, interferometry.

1. Introduction

Fibre optic sensors are an enabling technology that makes possible to measure a variety of parameters in conditions under which other sensor technologies fail or simply cannot. In addition these sensors have intrinsic advantages, including insusceptibility to electromagnetic interference, non-electrical conductibility, passive measurements, and the capability of multi-point measurements. Fibre optic sensor for harsh environments, such as those posed by space applications or high temperatures (up to 1000 ºC) is an increasing and important field. A Structural Health Monitoring (SHM) system that provides information about the temperature, strain vibration, etc. in extreme conditions (till 1200ºC and more than 2500 microstrains) at different points is one of the most important technology challenges. Thus, only simple and robust sensors can survive under such operating conditions. Optical fiber sensors can meet these requirements and also can add significance advantages over other technologies in terms of size, weight and ability to multiplex the sensors [1]. Among them, those based on specialty optical fibers such as sapphire optical fibers, Photonic Crystal Fibres (PCF) or chemically modified fibers such as Chemical Composition Gratings (CCGs) are emerging as good candidates [2-5].

PCFs for example can be made of a single material and are characterised by an array of microscopic holes. The fabrication technologies of PCFs had advanced remarkably in the past few years. PCFs with literally any pattern can be fabricated over lengths up to kilometres. Proper selection of the PCF microstructure allows designing compact two-mode interferometers with interesting features, such as broad operation wavelength or temperature range and high stability over time. We have implemented a technique that creates the interferometer collapsing the micro-holes over a localized region of few hundred micrometers. The collapsed region allows the excitation and recombination of the two modes. These interferometers allow us to design functional and robust sensors with PCFs. The interferometers are suitable for strain, pressure, high temperature sensing, etc., with sensitivities higher than those achieved with other fiber optic sensing techniques [6 - 9].

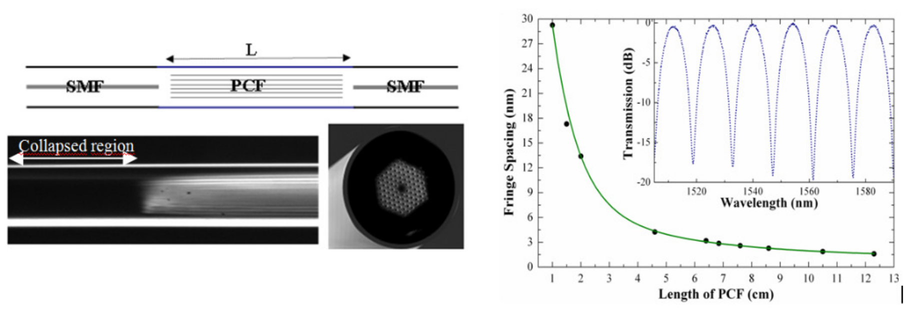

Figure 1. *(Left) Drawing of the interferometer and micrographs of the splice and the PCF employed. L is the length of the PCF and SMF stands for singlemode optical fiber. (Right) Period versus length of PCF measured at 1550 nm (dots) and fitting to the data (continuous line). The inset shows the pattern of an 18.88 mm-long interferometer.*

Fibre optic sensors are an enabling technology that makes possible to measure a variety of parameters in conditions under which other sensor technologies fail or simply cannot

Meanwhile, Fiber Bragg Gratings (FBGs) have been widely used for structural health monitoring and ambient sensing. The main important advantages of FBG based sensors compared with other optical sensing techniques are the measurement of the reflected light, the wavelength encoded sensing and the multiplexing capability [10]. But, depending on the fiber type, for high temperature sensing the decay in the refractive index modulation in standard FBGs limits the maximum temperature to 600ºC-700ºC. Recently several techniques have been proposed to increase the FBG temperature stability. One of the most recent and promising technique is the so-called Chemical Composition Gratings (CCGs) [11-13]. CCGs can increase the temperature sensing range of the FBGs above 1000ºC allowing extreme temperature sensor operation. We have successfully created CCGs into two different types of fibers: standard telecommunications Germanium doped fibers (Corning SMF-28) and photosensitive Boron-Germanium co-doped fibers (Fibercore PS1250/1500) and we have compared the results obtained.

2. Photonic crystal fiber interferometer

The PCF modal interferometer is represented in Fig. 1(left). It consists of a short piece of index-guiding PCF longitudinally spliced between two standard single mode fibers (SMF-28). The fabrication of the interferometer only involves cleaving and fusion splicing for which conventional tools and equipment are required. The key element of the interferometer is the splice in which the voids of the PCF are fully collapsed over a short region, whose length is typically a few hundred micrometers [6-8]. The collapsed region broadens the propagating beam which in turn allows the excitation of two core modes in the PCF. The two modes propagate over the PCF with different phase velocity and are recombined in the lead-out SMF fiber. The transfer function of the interferometer can be expressed as:

$$H(\lambda) = I_1(\lambda) + I_2(\lambda) + 2\sqrt{I_1(\lambda) + I_2(\lambda)}\cos(\delta\phi), \qquad [1]$$

where $I_1(\lambda)$ and $I_2(\lambda)$ are the optical powers of the two interfering modes, λ is the wavelength of the optical source, and $\delta\phi$ is the phase difference between the modes. The transmission spectrum of this type of interferometers is truly sinusoidal with high visibility as can be seen in the inset of Fig. 1(right). For a limited wavelength range the period of the interference pattern can be considered constant and can be expressed as $P = \lambda_0^2/(\Delta n L)$, where λ_0 is the central wavelength of the source (typically a LED) and Dn is the effective refractive index difference between the modes. Note from Fig. 1(left) that the period of these modal interferometers can be precisely controlled with the length of PCF. Later, we will see that this property simplifies the multiplexing of the interferometers.

Like any other fiber-based interferometer the PCF modal interferometers described above can be exploited for sensing different physical or chemical parameters [7-9, 14-15]. Note that a change in Δn or L (or both) will result in a shift of the interference pattern. For a single device the detection of the shift is straightforward, see for example [6-8]. However, by cascading several such interferometers in a single fiber a complex pattern arises that often is not simple to demodulate. We can demultiplex several cascaded PCF modal interferometers without interference between sensors if the period between them follows a determined relationship. The basic scheme for serial multiplexing is shown in figure 2. Light from a broadband source, such as

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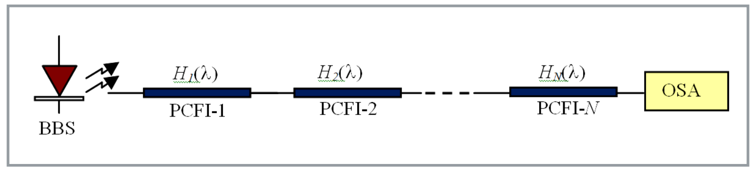
an amplified spontaneous emission (ASE) source or a light emitting diode (LED), or from a tunable laser is launched into a given number (N) of PCFI (PCF interferometric) sensors connected in series. The composed output spectrum is acquired by an optical spectrum analyzer (OSA). The transfer function of the i-th PCFI sensor is denoted as $H_i(\lambda)$. Thus, if we consider negligible the back-reflections of the devices then the total transfer function $H_T(\lambda)$ will be the product between all individual transfer functions, i.e.:

$$H_T(\lambda) = \prod_{i=1}^{N} H_i(\lambda) \qquad [2]$$



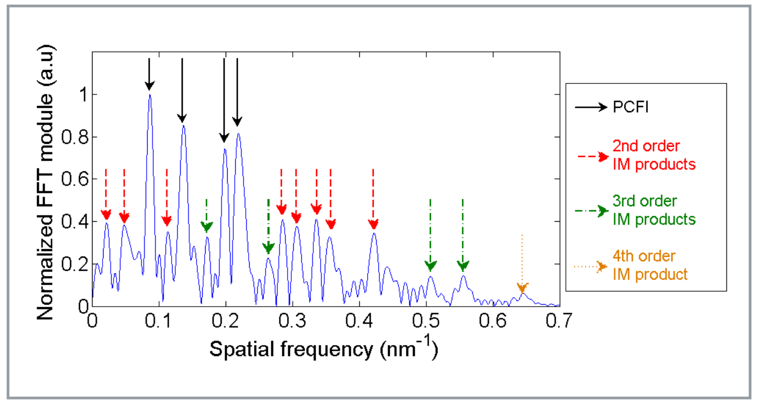
■ **Figure 2.** *Interrogation scheme for serial multiplexing. BBS stands for broadband source, PCFI for photonic crystal fiber interferometer and OSA for optical spectrum analyzer.*

The Fourier transform of the i-th transfer function is

$$H_i(k) = \mathcal{F}\{H_i(\lambda)\}, \qquad [3]$$

where $k = 2\pi\nu$ is the wavenumber and ν is the spatial frequency. Note that a shift of the interference pattern experienced by any interferometer will be transformed in a phase change in the spatial frequency domain. If we denote as $\Delta\theta_i$ the FFT phase shift at the spatial frequency ν_i corresponding to the i-th PCFI sensor then the wavelength shift can be obtained as follows:

$$\Delta\lambda_i = \frac{\Delta\theta_i}{2\pi\nu_i}. \qquad [4]$$



■ **Figure 3.** *Normalized FFT modulus of four PCFIs multiplexed in series showing the sensors and the different intermodulation (IM) products.*

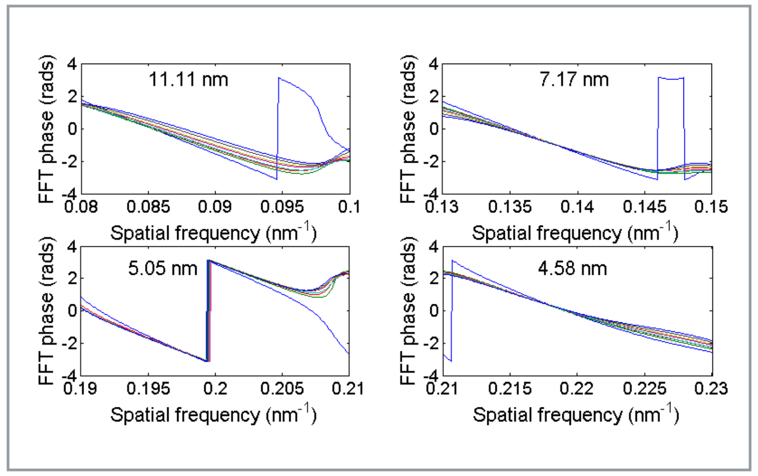
The information of the PCFI sensors is encoded in the phase of the Fourier transform. In absence of crosstalk between sensors at the spatial frequency ν_i corresponding to one of the sensors the phase contribution of the other sensors must be constant. The Fourier transform of any PCFI sensor can be decomposed in modulus and phase. Thus, for the i-th PCFI sensor with spatial frequency $\nu_i = 1/P_i$ the contribution of the other sensors is constant if we force its modulus to be zero at the spatial frequencies of the other sensors, i.e.

$$|H_i(k_j)| = 0 \quad \forall j \neq i. \qquad [5]$$

This is the fundamental requirement we must accomplish to multiplex PCFI sensors. Note that the presence of two or more sensors in series will give rise to intermodulation products that may overlap with the sensor spatial frequencies. Such products can be avoided if the periods of the sensors are selected properly. The spatial frequencies of the sensors can be found numerically replacing the sinc functions of the individual Fourier transform with two delta functions. The later must be situated at spatial frequencies corresponding to the period of each PCFI sensor. We initially select two spatial frequencies that accomplish the entire number of period condition. Then, we obtain the convolution of these two PCFI sensors. After that, we obtain the possible free periods for the following sensors but only those in which the intermodulation products are null are valid. The process is repeated for the new sensors. Note that by adding more sensors to the network the periods that can be selected will be reduced due to the high number of intermodulation products.

We have multiplexed four PCFI sensors to demonstrate the feasibility of the multiplexing technique described above. The selection method of the periods discussed previously was followed. The four different spatial frequencies for the sensors were found to be 0.09, 0.14, 0.2 and 0.22 nm^{-1} which correspond to PCF interferometers with periods of 11.11, 7.14, 5 and 4.54 nm, respectively. These wavelength periods were selected to have an integer number of periods in the measured wavelength span (from 1520 to 1620 nm). The fabricated interferometers had periods of 11.11, 7.17, 5.05, and 4.58 nm due to some fabrication errors. The corresponding spatial frequencies were 0.09, 0.1393, 0.1997 and 0.2179 nm^{-1}, respectively. Figure 3 shows the normalized FFT modulus of the four PCFI multiplexed in series. In the FFT modulus we can distinguish the four sensors present in the system as well as the multiple intermodulation products.

Figure 4 shows the FFT phase evolution around the four PCFI sensors spatial frequencies when strain is applied to the sensor with the lowest spatial frequency (period of 11.11 nm). The different lines represent the measurements while increasing the strain in that sensor. We can see that the phase change varies linearly with the applied strain in the device subjected to strain while that of the rest of sensors remains almost constant. The analysis of the results show that the maximum error is observed in the PCFI sensor with spatial frequency 0.22 is 0.2 radians which is ~3% of the full scale. The corresponding maximum error for the device with the lowest spatial frequency was found to be less than 0.1 radians. These errors can be further reduced by optimizing the fabrication process.



■ **Figure 4.** *FFT phase evolution observed around the PCFI sensors spatial frequencies when only the interferometer with period of 11.11 nm was subjected to axial strain.*

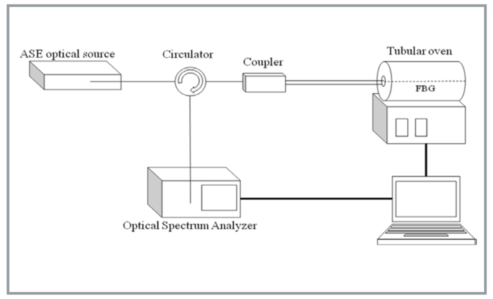
3. Chemical composition gratings

As we have shown in the previous section, the multiplexation PCF sensors is possible but we must have a precise manufacturing process to achieve the required lengths of the PCF interferometers. In comparison, Fiber Bragg Gratings (FBGs) allow to multiplex a great number of sensors in the same optical fiber. But FBGs are not suitable for high temperature applications because the refractive index modulation will decay very quickly for temperatures higher than 600 ºC. Chemical Composition Gratings (CCGs) can overcome the FBG maximum temperature limitation. CCGs were firstly formed in fluorine doped fibers but recently the formation of CCGs in other types of fibers has been reported. [11-13]. Chemical composition gratings (CCGs), unlike standard FBGs, do not suffer a significant decrease in reflectance when they are exposed to elevated temperatures. CCGs are created by a UV exposure in hydrogen loaded optical fibers as standard FBGs and a later annealing treatment at high temperatures. The annealing process replaces the refractive index modulation formed by the UV exposition by a more temperature stable chemical structures. During this process, the original FBG is erased completely and regenerated for this reason this gratings is also known as Regenerated Fibre Bragg Gratings (RFBGs).

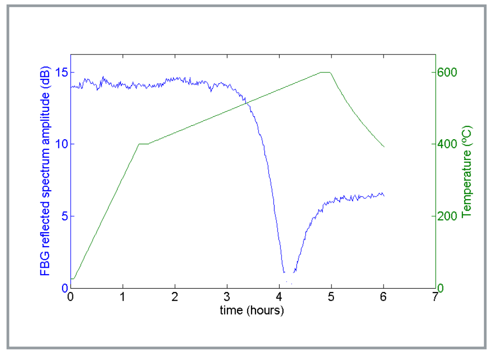
The formation process and the properties of the created CCGs strongly depend on the type of optical fiber used. For this reason, two different optical fibres have been used to create these high temperature gratings: Corning SMF-28 germanium and Fibercore PS 1250 germanium/boron codoped fiber. The Corning fiber is a standard single mode telecommunications optical fiber while the Fibercore fiber is a commonly photosensitive fiber used for the inscription of FBGs.

In order to create a CCG several steps must be followed. First, we must hydrogen load the optical fiber by introducing the optical fiber inside a high pressure hydrogen chamber for several days. This first step allow us introduce a high reactive element inside the fiber that can modify the chemical structure of the optical fiber core. Hydrogen load is essential since no regeneration has been observed in non hydrogen loaded fibers. The next step is to inscribe a standard FBG in the core of the fiber. This FBG is the seed of the later CCG and the refractive index modulation will be reproduced in the regenerated FBG during the annealing process so in consequence the CCG will maintain the spectral characteristics of the original FBG. Finally, an annealing process is necessary in order to supply the required energy to the chemical reactions. Fig. 5 shows the setup used to generate and monitor the formation of the CCGs.

Figure 6 shows the regeneration process for the Fibercore PS 1250 fiber. It can be seen how the original FBG is completely erased first and regenerated later. We can observe that the grating amplitude is not completely recovered after the annealing process. Experimental measurements with different original grating amplitudes show that there is a direct relationship between the



■ **Figure 5.** *Setup for monitoring the CCG formation.*



■ **Figure 6.** *CCG formation for Fibercore PS 1250 fiber.*

We have multiplexed four PCFI sensors to dem-onstrate the feasibility of the multiplexing technique

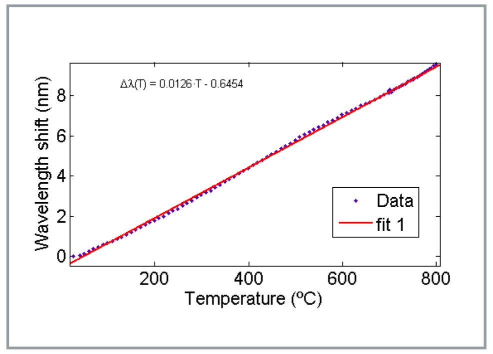


Figure 7. *CCG in Fibercore PS 1250 fiber wavelength shift versus temperature.*

original FBG and the CCG amplitudes. We can observe the temperature necessary to create the CCG in this type of fiber is approximately 550 ºC. For lower temperature the original FBG is erased and no regeneration is observed.

Figure 7 shows the wavelength shift with the temperature for Fibercore PS 1250 fiber. We can observe that this relationship is quite linear. This behavior with the temperature is due to the presence of boron as dopant.

In order to determine the operational limits of the CCGs, isochronal accelerated aging tests have been performed. Figure 8 (Left) shows the CCG amplitude with the increasing temperature. In these tests, the temperature has been increased from 700 ºC to 850 ºC in steps of 50ºC remaining 5 hours in each temperature step. As we can appreciate, the CCG amplitude decays according to a combination of time and temperature in increasing rate at higher temperatures. This decay is similar to the one reported in standar FBGs with the difference that the operational temperature range is extended in about 200 ºC. In figure 8 (Right) is represented the decay rate as a function of temperature. With this chart we can estimate the lifetime of a CCG in Ge/B co-doped fibre. The decay rate of these CCGs is about 1.5 dB/h at 850 ºC.

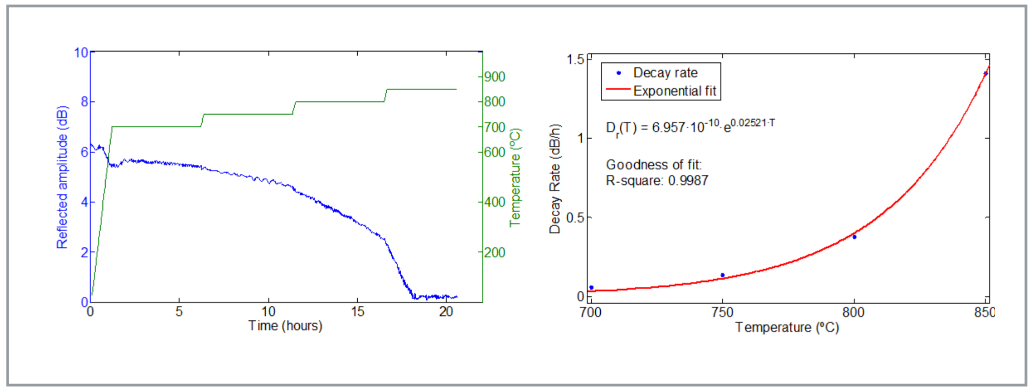


Figure 8. *CCGs in Fibercore PS 1250 fiber. Left, accelerated aging for determine the operational limits. Right, decay rate with temperature.*

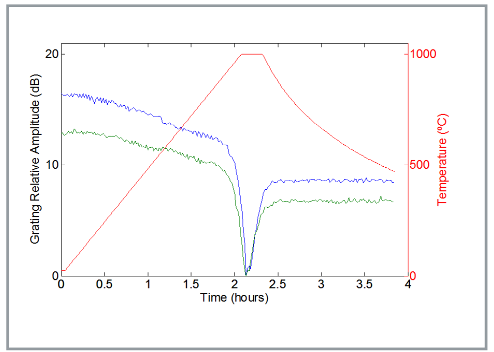


Figure 9. *Formation process of CCGs for Corning SMF-28 fiber.*

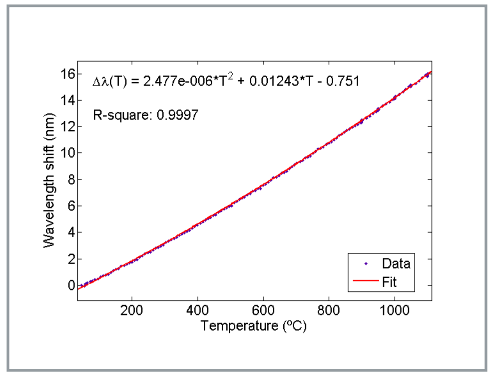


Figure 10. *CCG in Corning SMF-28 wavelength shift with Temperature.*

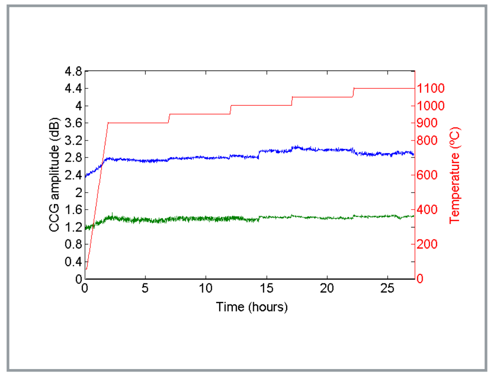


Figure 11. *Temperature cycle of two different CCGs on Ge doped fibre, from 900ºC to 1100ºC.*

CCGs based on Ge-doped fibre have a higher operation limit.
We have observed an operation limit of 1100ºC.

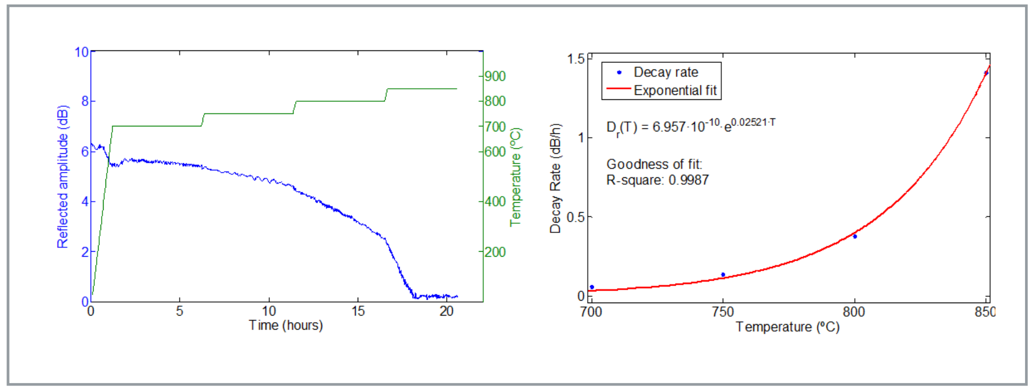


Figure 12. *Hysteresis test for three different CCGs. Left, wavelength shift with temperature cycles. Right, Wavelength shift versus temperature.*

For the Corning SMF-28 fiber, the regeneration process is quite similar but important differences can be found. Figure 9 shows the regeneration process for this fiber. The first important difference is that for the Corning SMF-28 fiber the minimum temperature for regenerate the CCG is 950 ºC that is significantly higher than the Ge/B codoped fiber regeneration temperature and also maximum operative temperature.

Other important difference that can be found is the CCG wavelength shift with the temperature shown in figure 10. While for the Ge/B codoped fiber this relationship is linear for this kind fiber has a nonligible quadratic term.

The accelerated aging test in order to find the operational limits in CCGs on Ge doped fibre has been also performed. The results are shown in figure 11, where the performance results for two CCGs created with different amplitudes are represented. The temperature follows a isochronal pattern and is held constant for five hours in steps of 50 ºC from 900ºC to 1100ºC. The differences between this CCG type and the one based in Ge/B co-doped fibre is clear. For the CCG based in Ge doped fibre there is no significant decay despite we reach 1100 ºC.

Also a hysteresis tests were performed for the Ge doped fibres. Several temperature cycles between 500ºC to 1000ºC were performed for three different CCGs at the same time. The results are shown in figure 12, we can see there is no significance hysteresis in the CCGs.

Conclusions

Two different technologies of fiber optic sensors have been developed for measuring in harsh environments. The first technology is based on photonic crystal fiber (PCF) interferometric sensors and the second is based on Chemical Composition Gratings (CCGs). PCFIs have been made from pure silica and can resist temperatures near the silica fusion temperature (1300ºC) and chemical active atmospheres, but they exhibit a sinusoidal interference pattern that difficult the serial multiplexing of this kind of fiber optic sensors The study of the multiplexation of this sensors have been reported using a frequency division multiplexing technique combined with a simple fast Fourier transform demodulation method. To avoid the crosstalk between the sensors, we have calculated the optimal relationship between their periods. The crosstalk between sensors was found to be relatively low. The crosstalk is the major source of error which can be eliminated if the sensors are fabricated with the exact theoretical period. The technique presented here can be adapted to multiplex other fiber sensors that exhibit periodic patterns.

CCGs technology has been developed for high temperature measurements, too. The creation process and the sensor properties strongly depend on the optical fiber used. We have reported the creation of CCGs in two different types of fiber: standard single mode fiber (Corning SMF-28) and photosensitive optical fiber (Fibercore PS 1250). We have analyzed the formation process, the sensing properties and the operational limits of this kind of optical fibre sensors for high temperature measurements. CCGs solve two of the main problems for the previous mentioned sensor technologies: multiplexation and usage in harsh environments.

CCGs based on Ge/B co-doped fiber have a lower creation temperature and theier response is more linear than the CCGs based on Ge-doped fibre. But, the CCGs based on Ge-doped fibre have a higher operation limit. We have observed an operation limit of 1100ºC.

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Biographies

David Barrera was born in Valencia (Spain) in 1981. He received the M. Sc. degree in Telecommunications Engineering from the Universidad Politécnica de Valencia (UPV) in 2006. Since then, he has been working at the Optical and Quantum Communications Group of the ITEAM Research Institute. Her research interests includes fibre Bragg gratings, optical fibre sensing and Polymer Optical Fibres. He is currently working towards the Ph.D. degree at Universidad Politécnica de Valencia and focusing on optical fibre sensing.

Vittoria Finazzi is Ramón y Cajal Fellow at the Institut de Ciències Fotòniques (ICFO), Castelldefels, Spain, where she belongs to the Optoelectronic group lead by Prof. Valerio Pruneri. She received her laurea degree in Electronic Engineering (B.Eng) from the Università degli Studi di Pavia (Italy) in 1999 and her Ph.D in Optoelectronics from the University of Southampton in 2004. She has published 22 journal papers and 47 contributions to international conferences. Her research is now focused on micro- and nano-structured fibre devices for sensor applications.

Joel Villatoro received the PhD degree from the National Institute for Astrophysics, Optics, and Electronics, Puebla, Mexico, in 1999. He was a Visiting Scholar for two-and-a-half years at the Centro de Instrumentos, National Autonomous University of Mexico, Mexico City. In 1999, he joined the Case Western Reserve University, Cleveland, OH, as a Research Associate. One year later, he joined the University of Valencia, Valencia, Spain, as a Postdoctoral Fellow. From November 2001 to November 2005, he worked as a Research Scientist with the Centro de Investigaciones en Optica A.C., Leon, Mexico. Since January 2006, he has been working as a Research Fellow at for the Institute of Photonic Sciences, Barcelona, Spain. His main research interests are the fabrication of sensors and devices based on nanoparticles, optical micro-nanofibers and photonic crystal fibers.

Antonio Bueno was born in Valencia (Spain) in 1981. He received the B.Sc. degree in Telecommunications from the Universidad Politécnica de Valencia (UPV), Spain, in 2008. He is currently working towards the M.Sc. degree in Technologies, Systems and Networks of Communication in the Universidad Politécnica de Valencia (UPV), Spain, and working in optics at the Universidad Politécnica de Valencia in the Optical and Quantum Communications Group (OQCG) at iTEAM Research Institute. His fields of interest are Fiber Bragg Grating and Brillouin fiber sensors.

Salvador Sales
See page 28

Valerio Pruneri is currently an ICREA Professor and group leader at the Institute of Photonic Sciences (ICFO) in Spain. Prior to ICFO he had worked for Avanex Corporation, Corning, Pirelli Cables and Systems and the Optoelectronics Research Centre- University of Southampton. His group, composed of about 15 members, focuses on applied research topics, including photonic crystal fibres and nanowires, transparent electrodes based on ultrathin metal films and micro- and nano-engineered electro-acousto-optic devices, for a wide range of industrial applications, from sensors for aerospace to 3-D and head-up displays, photovoltaics and quantum communication. He has 200 journal/conference papers (40 invited), 19 granted patents/patent applications. He was awarded the Philip Morris Prize for Scientific and Technological Research and has been Pirelli Research Fellow. Valerio Pruneri has received his PhD in Laser Physics/Optoelectronics from the University of Southampton (UK) and his 'Laurea' cum laude in Nuclear Engineering from Politecnico di Milano (IT).