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

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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). PCFs have been made from pure silica and their multiplexation has been done using a frequency division multiplexing technique. CCG 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 FS 1250). We have analyzed the formation process, the sensing properties and the operational limits of this kind of optical fiber 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

Fiber 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 to parameters, fiber optic sensors can meet these requirements and survive under such operating conditions. Optical fiber sensors can be employed for sensing different physical, chemical and environmental parameters in harsh environments, such as those posed by space applications or high temperatures (up to 1000 °C). These sensors can be used for monitoring, strain and pressure, temperature sensors, 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 those, those based on specialty optical fibers such as photonic crystal fibers, Photonic Crystal Fibers (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 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].

Meanwhile, Fiber Bragg Gratings (FBGs) have been widely used for structural health monitoring and ambient sensing. The main important advantages of FBGs 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 600°C-700°C. 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 1000°C 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 in-line-guiding PCF longitudinally split 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 re-combined in the lead-out SMF fiber. The transfer function of the interferometer can be expressed as:

$$I(\lambda) = I_0(\lambda) + f_1(\lambda) \cos(d_1)$$

where $I_0(\lambda)$ and $f_1(\lambda)$ are the optical powers of the two interfering modes, $I$ is the wavelength of the optical source, and $d_1$ 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 $P = \lambda_0/(d_1 \sin(\theta))$, where $\lambda_0$ is the central wavelength of the source (typically a LED) and $D_0$ 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 $\Delta n$ 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 is not simple to demodulate. We can demultiplex several cascaded PCF modal interferometers without interfering between sensors if the period of the beat between them follows a determined relationship. The basic scheme for serial multiplexing is shown in Fig. 2. Light from a broadband source, such as
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 PCF (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 $H_i(j\nu)$. Thus, if we consider negligible the back reflections of the devices then the total transfer function $H(j\nu)$ will be the product between all individual transfer functions, i.e.:

$$H(j\nu) = \prod_{i=1}^{N} H_i(j\nu).$$

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 by replacing the sinc functions of the individual Fourier transform with two delta functions. The latter 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 reflectance when they are exposed to elevated temperatures. CCGs are created by a UV exposure in hydrogen loaded optical fibers as standard FBGs for laser annealing 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, which correspond to PCF interferometers with periods of 11.11, 7.14, 5.45 and 4.58 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, 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 nm which is ~3% of the full scale. This error further reduces by optimizing the fabrication process.

3. Chemical composition gratings

As we have shown in the previous section, the multiplexing of PCFI 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°C. 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 was reported [11-13]. Chemical composition gratings, unlike standard FBGs, do not suffer a significant decrease in their spectral response 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 CCG 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 fibers have been used to create these high temperature gratings:Coming 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 photo-sensitive 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 allows us introduce a high refractive 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
original FBG and the CCG amplitudes. We can observe the temperature necessary to create the CCG in this type of fiber is approximately 550 °C. 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 °C to 850 °C in steps of 50°C remaining 3 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 standard FBGS with the difference that the operational temperature range is extended in about 200 °C. 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 °C.

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

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 °C 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 an isochronal pattern and is held constant for five hours in steps of 50 °C from 900°C to 1100°C. 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°C.

Also a hysteresis tests were performed for the Ge doped fibres. Several temperature cycles between 500°C to 1000°C 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 photosensitive optical fiber (Fibercore PS 1250) and photoreactive 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 fibre have a lower creation temperature and their response is more linear than the CCGS based on Ge-doped fibres. But, the CCGS based on Ge-doped fibre have a higher operation limit. We have observed an operation limit of 1100°C.

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