INFLUENCE OF FABRICATION TECHNOLOGY ON METROLOGICAL PROPERTIES OF LONG PERIOD FIBER GRATINGS FOR PRESSURE MEASUREMENTS

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Abstract: The paper presents for the first time a comparative study of long-period gratings (LPGs) written by UV irradiation and by electrical arc discharges and applied to hydrostatic pressure measurements. These gratings were inscribed in a highly photosensitive boron co-doped fiber that can be considered as a suitable platform for LPG writing using either technology. The experimental transmission data for the manufactured LPG devices fit well when compared to the simulations we carried out in parallel. As a result of each of these writing processes, we were able to obtain a remarkably good quality of gratings with highest sensitivities to pressure ever reported, but with the sensitivity depending clearly on the limits of each fabrication technology.

1. FUNDAMENTALS

A long-period grating (LPG) is a periodic modulation of the refractive index along the length of the optical fiber. Under certain phase-matching conditions, the grating couples the fundamental core mode to the discrete cladding modes that are attenuated due to absorption and scattering. The coupling is wavelength dependent, so one can obtain a spectrally selective loss.

There are many influences that can shift the resonance wavelengths (λ_{res}^{m}) of the LPG. The main relation describing wavelength-dependent coupling from the guided core mode (LP_{01}) to the mth cladding mode (LP_{0m}) is shown in (1), where (n_{eff}^{01}) is the effective refractive index of the propagating core mode, (n_{eff}^{0m}) is the effective refractive index of the mth cladding mode and (Λ) is the period of the LPG.

$$\lambda_{res}^{m} = \left(n_{eff}^{01} - n_{eff}^{0m}\right)\cdot \Lambda \qquad (1)$$

A resonance wavelength shift can be induced by variation of either the period of the grating or the effective indexes of the modes. As far as the influence of pressure is concerned, in line with the discussion in [2] on LPG sensitivity to strain, refractive index and temperature, the analytical expression for pressure sensitivity is given in (2). In this expression β, γ and Γ_{press} are factors dependent respectively on the compressibility of the fiber material (which is mainly fused silica), waveguide dispersion as a general sensitivity factor, and pressure dependence of the waveguide dispersion as a specific sensitivity factor. The waveguide dispersion is described in(3).

$$\frac{d\lambda_{res}^{m}}{dP} = \lambda_{res}^{m}\cdot\gamma\cdot\left(\beta + \Gamma_{press}\right) \qquad (2)$$

$$\gamma = \frac{\frac{d\lambda_{res}^{m}}{d\Lambda}}{n_{eff}^{01} - n_{eff}^{0m}} \qquad (3)$$

When the grating period diminishes, the resonance may split and achieve a so-called turning point. At the turning point, $\gamma\rightarrow\infty$, so it determines the condition of maximum sensitivity for each cladding mode. An LPG, therefore, exhibits very high sensitivity for a particular wavelength when a cladding mode and period are selected that are very close to the turning point. The highest coupled mode achieved in a grating written in the PS1250/1500 fiber using the arc technique was LP_{010}, and for that mode the phase-matching turning point was beyond the typically investigated spectral range (λ = 1100 to 1700 nm). The turning point in the investigated spectral range for the LP_{011} mode can be obtained for an LPG written in PS 1250/1500 fiber when the period is $\Lambda \sim 170$ µm [1].

A relatively long period of the modulation gives the possibility of LPG fabrication not only by ultraviolet (UV) irradiation, as commonly used to write fiber Bragg gratings (FBGs), but also by a variety of other methods such as those based on infrared irradiation, electrical arc discharges or even mechanical pressure. However, modifications of the refractive index of the LPGs are most often realized by UV exposure or arc discharges. The first method, based on UV inscription, is assumed to be a superior one in terms of good quality symmetrical coupling and fabrication repeatability. At the UV wavelength used for irradiation of fiber doped with germanium, the core experiences the highest absorption, and at the same time the silica cladding is transparent, so that the color-center model of refractive index modulation should be valid. The second method, employing electrical arc discharges, is often applied due to its simplicity and flexibility, the low cost of the fabrication process and its applicability to photonic crystal fibers made of pure silica.

In the case of LPG writing with the arc technique, a partial stress relaxation takes place, which induces a refractive-index difference.

The aim of this work is to compare LPGs written in a boron co-doped fiber using the two methods mentioned above: UV exposure at λ=248 nm and electric arc discharges, pushing both fabrication methods to their limits to show their best performances as LPG-based pressure sensors. The effects induced in the fiber have been compared in the experiments reported here. Moreover, both types of grating were investigated in terms of their sensitivity to changes in the external hydrostatic pressure. To date, to the best of our knowledge, only a few attempts have been made to compare different LPG writing methods applied to the same fiber, but never in the context of pressure measurements.

2. LPG FABRICATION METHODS

To fabricate the LPGs for our experiment using our UV micromachining facility, a 5-cm long segment of Fibercore PS 1250/1500 fiber mechanically stripped of its polymer coating was spliced between two SMF28 fibers. The boron and germanium concentrations for the PS 1250/1500 fiber were not disclosed by the manufacturer, but according to the core of the fiber can have 10% GeO_2 and 20% B_2O_3, in addition to SiO_2. The core radius of that fiber is usually assumed to be between 3.5 and 4.5 μm. The gratings were written using both the methods in the PS1250/1500 fiber segment only.
After the LPG fabrication described for both the methods below, a gold reflector was deposited on one end-face of the fiber by means of a thermal evaporation method.

2.1. Arc-induced writing process

Arc-induced LPGs are easiest and most cost-effective to fabricate, and the technology is relatively popular since the first papers on it has been published. Using our well-established and precisely controlled arc-writing process described elsewhere [4] we were able to reduce the minimum period of the gratings down to 221 μm for the LPGs based on the boron co-doped photosensitive Fibercore PS1250/1500 optical fiber [1]. A series of gratings was manufactured with different technological parameters such as power and duration of arc discharge. The system is based on Fitel S182K Fusion Splicer equipped with standard S182A electrodes, which are 2 mm wide and have conical, 4 mm in height shape of the tip. The constant tension of the fiber during the writing process was maintained by 2 g weight.

Our goal was to obtain a resonance coming from coupling of the highest possible cladding mode at λ=1550 nm. The optical transmission of the fiber in the range of λ=1160-1660 nm was monitored during the LPG fabrication process in order to obtain the desired spectral attenuation notches. We used an Agilent 83437A broadband light source and an Agilent 86142B optical spectrum analyzer for this purpose. To the best of our knowledge, this is a shortest period ever achieved for this fiber using the arc-manufacturing technique. Consequently, we were able to achieve the highest pressure sensitivity of almost 220 pm·bar^{-1} ever reported for this LPG manufacturing technique which will be discussed later. However, the minimum period of 221 μm is still too short to achieve an LPG operation in Dual Resonant Regime (DRR), the phase-matching turning point, which potentially can yield the highest pressure sensitivity.

2.2. UV-induced writing process

The gratings were written in the PS1250/1500 fiber using a Pulse Master 840 high-power KrF excimer laser (λ=248 nm) from Light Machinery and an amplitude chromium mask. Using this mask with different grating periods available, and by optimizing the UV exposure conditions, we were able to achieve a grating operation below a so-called phase-matching turning point, when the resonance splits and the sensitivity for each cladding mode is maximum. This condition occurred for the boron co-doped fiber it the investigated wavelength range at the grating period equal to Λ = 169.7 μm.

Several gratings were fabricated with different UV exposure times, typically less than a minute. The optical transmission of the fiber was monitored during the LPG fabrication process in order to obtain the desired spectral attenuation notch.

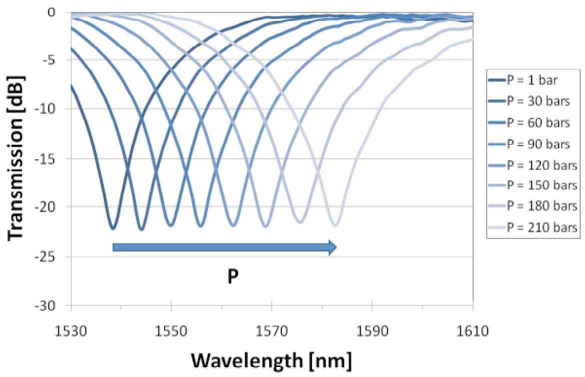
3. EXPERIMENT

3.1. Experimental set up

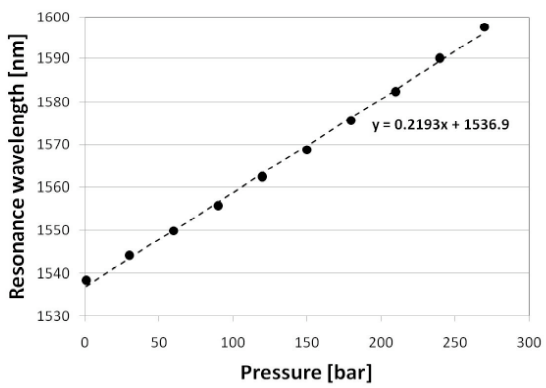
For pressure measurements, the LPGs were installed inside a steel housing in a reflection configuration [4]. The housing was filled with distilled water and connected to a hydrostatic pressure standard DWT-35, capable of generating and calibrating pressures up to 100 MPa with an accuracy of at least 0.1%. The response of the structure was monitored using a circulator, an Agilent 86142B optical spectrum analyzer and an Agilent 83437A broadband light source.

3.2. Experimental results

In Fig. 1 we show the experimental data of a spectral response of the gratings written with the arc process to pressure changes up to 210 bars, generated in the set up described above.



a)



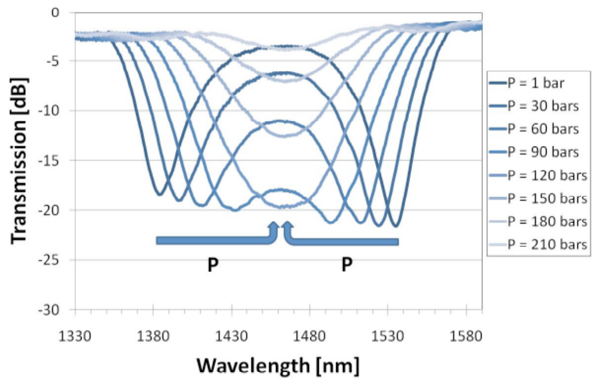
b)

Fig. 1. Spectral response (1a) and resonance wavelength shift (1b) induced by pressure changes for LPGs written in PS1250/1500 boron co-doped fiber for LPGs written with arc method (Λ = 221 μm).

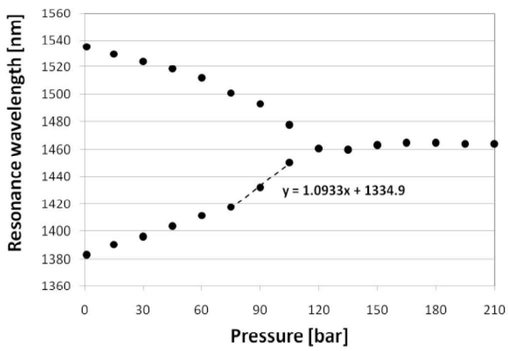
The spectra of the gratings written with an as short period as possible are shown here. After a series of experiments, we achieved the periods as short 221 μm for the PS 1250/1500 fiber [5]. The optimized writing parameters for this fiber are arc discharge time 300 ms and grating length (mm) / number of fusions 36.465/165. In order to obtain desirable resonance effect, both current and discharge time had to be optimized. A probable presence of some slight asymmetrical coupling can be noticed at shorter wavelengths in the spectrum of these gratings.

Arc-induced LPGs are attractive because of simplicity, flexibility, low cost of the fabrication and high thermal stability of the written gratings. However, for sensing purposes a further improvement of the fabrication process is needed. The series of experiments supported by numerical simulations, allowed us to achieve the shortest ever reported period of 221 μm, which gives the most sensitive LPGs ever obtained using the arc technique.

To explore the limits of the second manufacturing technology from the sensitivity point of view, we wrote the gratings in the same fiber using a Pulse Master 840 high power KrF excimer laser at λ = 248 nm [2]. Using an amplitude chromium mask with different grating periods available, and by optimizing the UV exposure conditions, we were able to achieve a grating operation below a so-called phase-matching turning point, when the resonance splits and the sensitivity for each cladding mode is maximum. This condition occurred for the boron co-doped fiber at the grating period equal to Λ = 169.7 μm. A spectral response of such a grating as a function of pressure is shown in Fig. 2.



a)



b)

Fig 2. Spectral response (a) and resonance wavelength shift (b) induced by pressure of an LPG based on the boron co-doped fiber manufactured using UV-micromachining and operating at a turning point Λ = 169.7 μm.

The pressure sensitivity of the B/Ge co-doped fiber can then be optimized by creating conditions for obtaining the phase-matching turning point at which the sensitivity is the highest. The precise tuning of the grating up to that turning point can be realized in several ways. For example, the spectral position of the resonances can be tuned by variations in the grating period. However, even the smallest variation produces a great change in the peak separation. Various ways of tuning of the notch separation have been reported, including carefully selecting the thickness of deposited nanocoating, thermal annealing or well controlled chemical etching of the cladding. It is also known that the dual resonant peaks get closer to each other with increased modulation of the average core refractive index, which is dependent on irradiation energy. The increase in modulation typically follows an increase in the UV exposure time, so it can be precisely adjusted.

It is important to underline that in this case we have been able to obtain an unprecedented pressure sensitivity of over 1 nm·bar^{-1}, which is by far the highest ever achieved by any kind of a fiber-optic grating. This achievement can see an immediate application as a highly sensitive but very cost–effective fiber-optic pressure sensor for real-time down-hole pressure measurements in oil industry.

References:

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