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Highly sensitive pressure sensor based on long-period gratings written in a boron co-doped optical fiber

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Abstract

The paper presents a novel pressure sensor based on long-period gratings (LPGs) written with an arc-induced method in a boron co-doped photosensitive fiber. The achieved pressure sensitivity for these gratings is at least four to eight times higher than for gratings written in other fibers which have been presented to date. The sensitivity is strongly dependent on the investigated order of modes, and for the 7th cladding mode can reach $\delta\lambda/\delta p = 78$ pm bar^{-1}. It was found that the incorporation of B_2O_3 in the core of the fiber is responsible for the higher pressure sensitivity of these LPGs. This conclusion is based on consideration of variations in the elastic properties of the glass versus its composition. According to our simulations, the pressure-optic coefficient of the B/Ge-doped core of the fiber is 2.03 RIU bar^{-1}. The sensitivity of the structure to temperature and to external refractive index is discussed from the point of view of the possible indirect influence of these conditions on the pressure response. It is proven that the experiment was conducted in such a way that the measured pressure sensitivity was not significantly affected by variations in either the temperature or the external refractive index.

Keywords: fiber-optic components, long-period gratings, optical device fabrication, fiber-optic sensors

1. Introduction

During the last 10 years, various concepts of optical-fiber-based pressure sensors have been studied and proposed. Most of them employ a Fabry–Perot resonator in the form of an extrinsic or an intrinsic sensor [1]. A number of papers have been published dealing with the use of fiber Bragg gratings (FBGs) [2] or long-period gratings (LPGs) [3, 4] as the pressure-sensitive devices. In our previous works we have reported the significant sensitivity of LPGs written with a cost-effective electric arc method in a standard germanium-containing single-mode fiber (Corning SMF28) [3] and in a pure fused silica endlessly single-mode photonic crystal fiber (PCF ESM-12-01) [4]. The sensitivity of these structures determined for the 3rd cladding mode was as high as 5.1 and 11.2 pm bar^{-1} for the SMF28 and PCF fibers, respectively.

In the study reported here, a commercially available boron co-doped photosensitive PS 1250/1500 (B/Ge) fiber from Fibercore was used. This fiber is widely employed for fabricating both FBGs and LPGs by UV illumination due to the possibility of writing the gratings directly, without a complicated and time-consuming hydrogenation process. Such gratings have also been successfully written in B/Ge fibers by an electric arc and a CO_2 laser [5, 6]. The incorporation of boron can dramatically lower the transition temperature of the germanosilicate glass and simultaneously increase the photosensitivity through the electronic and structural changes introduced [7, 8]. It has been shown [9] that for boron co-doped fibers, the mechanical stress induced in the fiber during the drawing process is the main cause of the index change during LPG fabrication. In this experiment, the thermal generation of the drawing-induced stress has been used to fabricate the LPGs by means of the electric arc. The arc technique, with its great simplicity, allows for flexible and low-cost LPG fabrication.

For the transmission spectrum of the LPG structure, two parameters can vary under the influence of an external stimulant: the resonance wavelength and the resonance transmission. The sensitivity is then typically defined as the shift of the resonance wavelength induced by a measurand [10]. In our study, in addition to measuring pressure sensitivity, we also measured the sensitivity of the grating to temperature and to the external refractive index. We discuss the latter sensitivities from the point of view of their possible indirect influence on the pressure response.

2. Experimental details

The LPGs were manufactured and tested following a procedure similar to that described in [4]. A 6 cm long segment of the Fibercore PS 1250/1500 fiber, with polymer coating mechanically removed, was spliced between two SMF28 fibers. The boron and germanium concentrations for PS 1250/1500 were not disclosed by the manufacturer, but according to [5] the core of the fiber may contain 10% GeO_2 and 20% B_2O_3 in addition to the SiO_2. The core radius of that fiber is usually assumed to be 3.5 to 4.5 μm. The LPG was written in the PS 1250/1500 fiber with a computer-assisted precision arc-discharge apparatus. The discharge current was adjusted to be low enough to heat the fiber locally and not to produce any visible tapers due to the axial tension applied to the fiber. The grating period was $\Lambda = 375$ μm and the length of the grating was $L = 20$–25 mm. The arc discharge time was established at $\tau = 300$ ms. The optical transmission of the fiber was monitored during the LPG fabrication process in order to obtain the desired spectral attenuation notch. We used an Agilent 86142B optical spectrum analyzer and an Agilent 83437 A broadband light source. Typically, the resonant wavelengths were around 1550 nm, with the depth of the transmission dips being about −25 dB.

For pressure measurements, the LPGs were installed within the steel housing in a transmission configuration. In order to keep the fiber at a constant axial tension under different pressures, a fiber loop was formed inside the small inner channel of the housing. The housing was filled with 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 pressure measurements were performed at room temperature ($T = 23$ °C).

The pressure measurements were accompanied by investigation of the LPG responses to temperature variations in the range of 20–70 °C and to external refractive index changes up to 1.47 Refractive Index Units (RIU). Several different mixtures of glycerin and water were made and their refractive indexes (n_D) were determined using a VEE GEE PDX-95 refractometer working with an accuracy of $\pm 10^{-4}$ RIU. For temperature measurements, two main devices were used. The first was a set of two thermoelectric coolers (TECs) used for adjusting the temperature. The second device was a thermocouple probe placed next to the LPG that was responsible for temperature monitoring and read-outs. The measurements were performed in a temperature-insulated chamber. Each measurement was performed after stabilization of the temperature in the chamber. The gratings were kept under constant tension during all the investigations.

The spectral behavior of the gratings was simulated using the Optigrating v4.2 software by Optiwave.

3. Results and discussion

There are many influences that can shift the resonance wavelengths $\lambda_{\mathrm{res}}^{m}$ of an LPG. According to equation (1), which describes a wavelength-dependent coupling from the guided core mode to the *m*th cladding mode:

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

where n_{eff}^{01} is the effective refractive index of the propagating core mode, n_{eff}^{0m} is the effective refractive index of the *m*th cladding mode and Λ is the period of the LPG; a wavelength shift can be induced by a variation of either the period of the grating or the effective indexes of the modes. The most significant influences are generated by temperature, strain, external refractive index and pressure changes. As can be seen in figure 1, for structures fabricated in a boron co-doped fiber, the resonances experience a red shift and reach a linear sensitivity of 78, 56 and 45 pm bar^{-1} under the influence of pressure in a range of up to 240 bar, for the 7th, 6th and 5th cladding modes, respectively. Lower-order cladding modes (3rd and 4th) experience a shift of 41 nm bar^{-1}. It was found that the sensitivity of the fiber to pressure is 4 to 8 times higher than that measured earlier for some other fibers when the same order of cladding mode is considered [3, 4], and 7 to 16 times higher when sensitivity of the 7th cladding mode is compared.

To determine the cause of the resonance wavelength shift obtained in this pressure experiment, we investigated the response of the LPG to temperature variations and to changes in the external refractive index in order to analyze their possible indirect influence on the pressure response, i.e. whether temperature variations in the chamber under the influence of pressure or variations in the refractive index of the working liquid versus pressure had any second-order influence on the pressure sensitivity.

A blue shift of the resonance wavelength can be seen when the refractive index of the pressure medium increases (figure 2). The highest sensitivity to external refractive index changes occurs for resonances coming from higher-order cladding modes, which are present in the investigated wavelength range only for LPGs fabricated with a short period [10]. An LPG shows the highest sensitivity to the external refractive index in the vicinity of $n = 1.47$, when the cladding modes can hardly be guided by the cladding, given that the external refractive index matches the refractive index of the cladding material. In our case, where the range considered is that of the refractive index of water ($n_D = 1.3327$), the studied

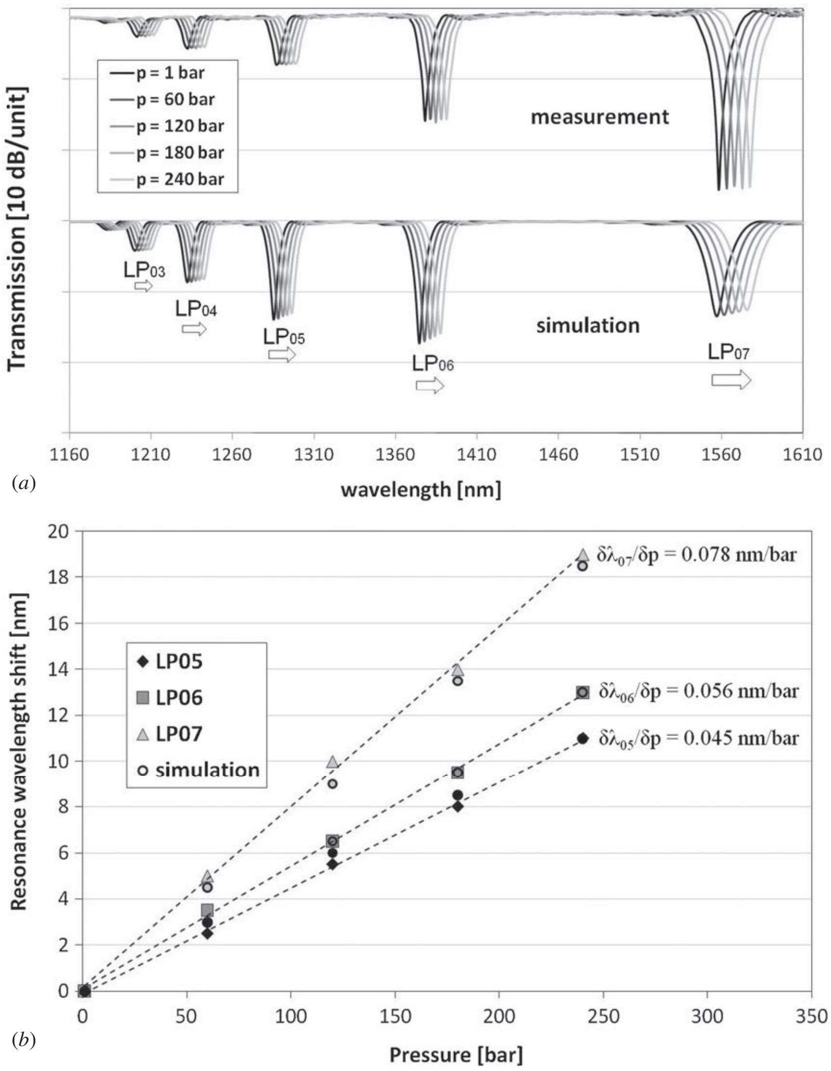

Figure 1. Sensitivity to pressure of the investigated LPGs written in the PS 1250/1500 fiber, where (*a*) shows variations of the transmission spectrum and (*b*) shows the resonance wavelength shift of LP_{05}, LP_{06} and LP_{07} modes.

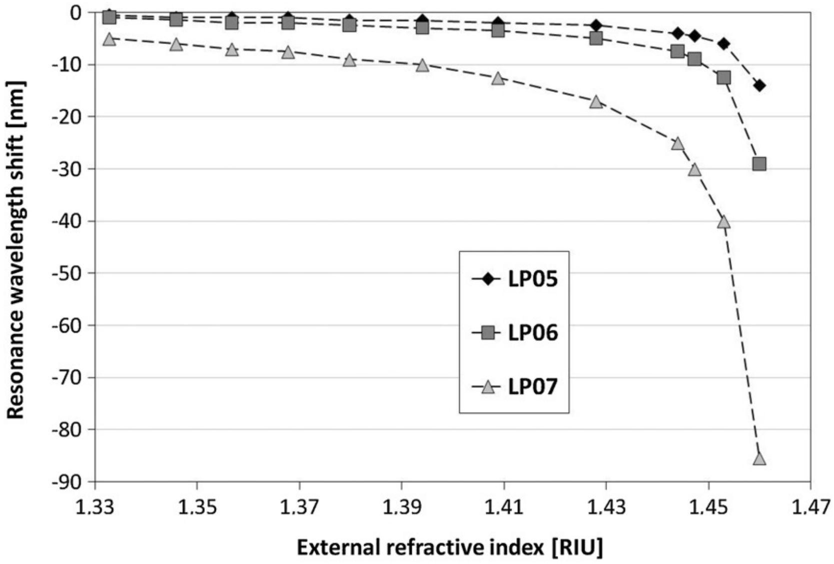

Figure 2. Sensitivity to external refractive index variations for LP_{05}, LP_{06} and LP_{07} modes of the investigated LPGs written in the PS 1250/1500 fiber.

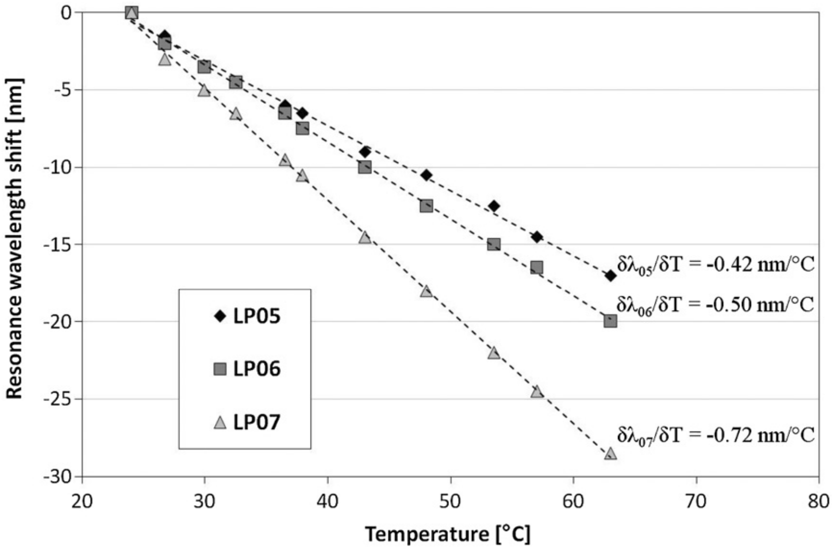

Figure 3. Sensitivity to temperature variations for LP_{05}, LP_{06} and LP_{07} modes of the investigated LPG written in the PS 1250/1500 fiber.

LPGs are only slightly sensitive to the external refractive index. It was shown [11] that water can change its refractive index depending on pressure. In the range from 1 to 260 bar, the refractive index increase can be estimated to be equal to 1.44×10^{-5} RIU bar^{-1} and at this level it cannot significantly disturb the pressure measurements. The influence of variation in the refractive index of a liquid should be taken into consideration when liquids with a higher refractive index are used in the pressure setup. In the case of certain oils whose refractive index can reach $n_D = 1.46$, the refractive index sensitivity of the LPG is over 100 times higher than when water is used.

The experiment was carried out with LPGs fabricated in the B/Ge fiber while ensuring that pressure in the chamber increased very slowly. Fulfilling this requirement should prevent heating up of the LPG due to rapid compression inside the setup. It can be seen in figure 3 that the resonances of LPGs written in the B/Ge fiber experience a negative (blue) shift with an increase in temperature. The sensitivity to temperature increases with the order of cladding modes, reaching $\delta\lambda/\delta T = -0.72$ nm $^{\circ}\mathrm{C}^{-1}$ for the 7th cladding mode. Similar behavior has been observed by other authors [12]. While the temperature of the LPGs is increasing, two effects can take place: thermal expansion of the glass material, which is very small and can be neglected for lower-order cladding modes, and change of its refractive index [13]. Following [14], the temperature sensitivity of the PS 1250/1500 can be explained on the basis of the thermo-optic coefficients of the core and cladding materials. They were found to be 7.8×10^{-6} RIU $^{\circ}\mathrm{C}^{-1}$ and 7.3×10^{-6} RIU $^{\circ}\mathrm{C}^{-1}$ respectively for pure silica and for B/Ge-containing glass (9.7 mol% B_2O_3 and 4 mol% GeO_2). According to equation (1), the effective refractive index of the core mode increases less rapidly with temperature than do the effective refractive indexes of the cladding modes, causing a blue shift of the resonance wavelength. The difference between the thermo-optic coefficients for the B/Ge fiber is larger than for the SMF28 and opposite, so its sensitivity is also higher and shows the opposite sign. Consequently, the variation of temperature has no direct influence on pressure measurements. As mentioned above, an increase in temperature has a slight effect on pressure sensitivity, most probably due to temperature dependence of the pressure-optic coefficients of the glass.

Taking the above into account, the pressure sensitivity of the LPGs fabricated in the PS 1250/1500 optical fiber can be discussed primarily in terms of the different elastic properties of the silica and the B/Ge-containing silica glass. Considering the origins of temperature sensitivity of the LPG [15], one can conclude that the shift of the resonance wavelength results from the pressure sensitivity of the fiber itself (the pressure-optic coefficient of the glass) and from a contribution of the grating effect (variations of the grating period versus pressure). Equation (2) takes both these effects into account:

$$\frac{\partial \lambda_{\mathrm{res}}^{m}}{\partial P} = \Lambda\left(\frac{\partial n_{\mathrm{eff}}^{01}}{\partial P} - \frac{\partial n_{\mathrm{eff}}^{0m}}{\partial P}\right) + \left(n_{\mathrm{eff}}^{01} - n_{\mathrm{eff}}^{0m}\right)\frac{\partial \Lambda}{\partial P}. \qquad (2)$$

Since most of the volume of the fiber is fused silica, the properties of the silica will mainly determine the contribution of the grating effect to the pressure sensitivity. Referring to our previous work [3] where similar fiber structure was investigated, this effect seems to be negligible. The properties of glass, such as density, refractive index, elastic moduli, thermal expansion and viscosity, can be changed by an addition of various oxides to the silica dioxide matrix [16]. For optical fibers, the main oxides used are glass-forming oxides, e.g. germanium, boron or phosphorus. The addition of GeO_2, widely used in the process of fabricating optical fibers, gives a simultaneous increase in density and in the refractive index of the optical fiber core. On the other hand, the addition of B_2O_3 decreases the density and the refractive index of silica-based glasses. It has been shown [16] that the incorporation of B_2O_3 has a significantly lower influence on the refractive index than the addition of GeO_2. However, adding B_2O_3 to SiO_2 decreases the number of network bonds, and so also decreases the bulk modulus (K) of the glass [17], i.e. the resistance of

Table 1. Parameters of the LPGs and a boron co-doped fiber assumed for simulation.

Period Λ (μm)	375
Grating length L (mm)	22
Refractive index change (RIU)	2.7×10^{-4}
Numerical aperture	0.1243
Core radius (μm)	3.73
Cladding radius (μm)	62.505
Core pressure-optic coefficient (RIU bar^{-1})	2.03×10^{-6}
Cladding pressure-optic coefficient (RIU bar^{-1})	1.76×10^{-6}

the material to a uniform compression. Ghosh [18] proposed a model for determining the refractive index variations versus pressure applied to the optical materials. The pressure-optic coefficient of silica glass was calculated to be in range of 1.76×10^{-6} RIU bar^{-1} at $\lambda = 1.55$ μm. The coefficient is dependent mainly on isothermal compressibility, that is, the inverse of K and positive, and on excitonic band-gap variations with pressure that is negative [18]. Taking into consideration the first effect, the incorporation of B_2O_3 into fused silica increases its pressure-optic coefficient, so that the core material has a higher pressure-optic coefficient than the cladding. This relation can directly explain the positive pressure sensitivity of the LPGs written in the B/Ge-containing fiber.

All the spectra measured during the pressure experiment were simulated using the grating and fiber properties summarized in table 1. Due to the lack of detailed data about the PS 1250/1500, such as core radius or dopant concentration in the core determining its refractive index, we had to work out our own model of the fiber by fitting the simulated data to the measurement results. The properties of the fiber assumed for the simulation are similar to those given by other authors [13] and are in agreement with Fibercore specifications. The simulations performed using the above-mentioned pressure-optic coefficient for silica glass and assuming a value of 2.03×10^{-6} RIU bar^{-1} for the core of the fiber resulted in a good fit to measured data (figure 1).

4. Conclusions

A new application for a boron co-doped fiber was found. To the best of our knowledge, the linear pressure sensitivity of 78 pm bar^{-1} is one of the highest ever achieved in the field of gratings. The authors of [2] dealing with FBG structures fabricated in the PS1250/1500 photosensitive fiber reported sensitivity to pressure of 16 pm bar^{-1}, which is approximately one-fifth the sensitivity reported in this paper. The sensitivity increases with the order of coupled cladding modes, so we believe that it can be further improved by reducing the period of the grating. According to the assumed relation between the pressure-optic coefficient and the B_2O_3 content in the core of the fiber, the pressure sensitivity can also be increased by modifying the composition of the glass forming the fiber. The remarkable pressure sensitivity achieved by LPGs written in the B/Ge-doped fiber highlights their promising potential in the field of intrinsic sensing as well as the merit of continuing to investigate this kind of structure.

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