Tuned Pressure Sensitivity of Dual Resonant Long-Period Gratings Written in Boron Co-Doped Optical Fiber

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(Invited Paper)

***Abstract*—This paper presents a pressure sensor based on a long-period grating (LPG) written in boron co-doped photosensitive fiber and operating at the phase-matching turning point. It is shown that the pressure sensitivity can be tuned by varying the UV exposure time during the LPG fabrication process as well as by varying ambient temperature during pressure measurements. The achieved pressure sensitivity in certain pressure range can reach over 1 nm·bar^{-1}, and is at least four times higher than for previously presented gratings working away from the double-resonance regime. In terms of an intensity-based measurement, the sensitivity at the turning point can reach 0.212 dB·bar^{-1}.**

***Index Terms*—Fiber-optic sensors, gratings, long-period fiber gratings, optical fiber devices.**

I. Introduction

DURING the past decade, various concepts for optical-fiber-based pressure sensors have been worked out. Most of them employ a Fabry–Perot resonator effect in the form of an extrinsic or intrinsic sensor [1], [2]. A number of papers also deal with the use of fiber Bragg gratings (FBGs) [3], [4] or long-period gratings (LPGs) [5]–[8] as pressure-sensitive devices. LPGs are a periodic modulation of the refractive index along the length of an optical fiber. Under special phase-matching conditions, the grating will couple the fundamental core mode to discrete cladding modes that are rapidly attenuated due to absorption and scattering. The coupling from the guided mode to the cladding modes is wavelength-dependent, so one can obtain a spectrally selective loss. Two parameters of the transmission spectrum of LPG structures can vary under the influence of an external stimulant: the resonance wavelength and the resonance transmission. In our previous works we have reported the significant sensitivity of LPGs written with a cost-effective electric arc method in standard germanium-containing single-mode fiber (Corning SMF28) [5], pure fused silica endless-single-mode photonic crystal fiber (PCF ESM-12-01) [6] and germanium and boron (B/Ge) co-doped photosensitive fiber (Fibercore PS 1250/1500) [7]. The sensitivity of the structures was as high as 13 and 220 pm·bar^{-1} for the SMF28 and PS 1250/1500 fibers, respectively [8]. The LPGs written in boron co-doped fiber show the highest pressure sensitivity reported to date in the literature. Incorporation of boron can dramatically lower the transition temperature of the germanosilicate glass and simultaneously can increase the photosensitivity by means of electronic and structural changes [9]. Moreover, boron co-doping was also found to be the reason for the high pressure sensitivity of these LPGs [7]. The pressure sensing phenomenon is based on different pressure-optic coefficients of the core and cladding materials. A pressure-optic coefficient is defined as variation of the refractive index of the material with the pressure at a constant temperature. Incorporating B_2O_3 into fused silica greatly increases the pressure-optic coefficient of the silica, so that the core material has a higher pressure-optic coefficient than the cladding. This relation directly explains the positive pressure sensitivity of the LPGs written in boron co-doped fiber [7].

Up to a certain point, an increase in LPG sensitivity follows an increase in the order of the coupled cladding mode [8]. Shu *et al.* found that when the grating period of the LPG is short (typically $\sim$170 μm for standard fibers), it is possible to couple energy into the same cladding mode at two discrete wavelengths resulting in the appearance of dual resonant peaks of higher-order cladding modes [10]. The dual resonant wavelengths shift in opposite directions with the variation of a number of parameters. At this point the gratings are extremely sensitive not just to external perturbations but also to fiber properties [11]. Several applications of LPGs operating at the turning point for temperature, strain, and refractive index sensing have been shown, including a number of chemosensors and biosensors [10], [12]–[17].

The UV writing method was used in our experiment in order to achieve the phase-matching turning point and maximize the

Manuscript received July 20, 2011; revised September 14, 2011; accepted September 14, 2011. Date of publication September 22, 2011; date of current version March 09, 2012. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, the Canada Research Chairs Program, NanoQuébec, and in part by the European Union in the framework of European Social Fund through the Warsaw University of Technology Development Program.

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Digital Object Identifier 10.1109/JLT.2011.2169234

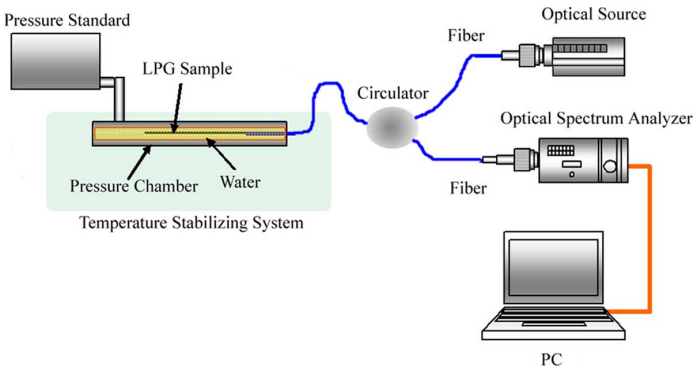

Fig. 1. Schematic diagram of the experimental setup for pressure measurements. Elements of the diagram are not to scale.

pressure sensitivity of the LPGs, while avoiding the limitations of the arc method in terms of lowering the grating's period and coupling of the higher-order modes [8]. The LPGs can be written in boron co-doped fiber by UV illumination without any complicated and time-consuming hydrogenation process, and have a sensitivity comparable to those written with the electric arc method, when the same order of cladding modes is concerned [18]. Tuning of the pressure sensitivity is also discussed.

II. Experimental Details

To fabricate the LPGs for our experiment, 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 [19] 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 in the PS1250/1500 fiber segment only, using a Pulse Master 840 high-power KrF excimer laser ($\lambda = 248$ nm) from Light Machinery and an amplitude chromium mask ($\Lambda = 169.7$ μm) [18]. 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. After the fabrication, a gold reflector was deposited on one end-face of the fiber by means of a thermal evaporation method.

For pressure measurements, the LPGs were installed inside a steel housing in a reflection configuration (Fig. 1). The housing was filled with distilled water and connected to a hydrostatic pressure standard DWT-35, capable of generating and calibrating pressures up to 1000 bar with a relative 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.

For the temperature tuning, the housing was installed inside a Julabo F32 Refrigerating/Heating Circulator equipped with a container filled with Exxon instrument oil. The temperature at the housing was monitored with an absolute accuracy of 0.1°C.

III. Results and Discussion

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 m^{th} 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

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

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 [10] on LPG sensitivity to strain, refractive index and temperature, the analytical expression for pressure sensitivity is given in (2). In this expression γ, Γ_{press} and β are factors dependent respectively on the waveguide dispersion as a general sensitivity factor, pressure dependence of the waveguide dispersion as a specific sensitivity factor, and the compressibility of the fiber material. The waveguide dispersion is described in (3)

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

$$\gamma = \frac{\frac{d\lambda_{\text{res}}^m}{d\Lambda}}{n_{\text{eff}}^{01} - n_{\text{eff}}^{0m}} \tag{3}$$

The γ factor can be positive or negative depending on order of the cladding mode and the investigated wavelength range [10]. At the turning point, $\gamma \to \infty$, 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 ($\lambda = 1100$ to 1700 nm) [8]. 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 [8], [10].

The final factor in (2), the pressure-dependent waveguide factor, is described in (4), where (υ_{co}) and (υ_{cl}) are the pressure-optic coefficients of the core and cladding, respectively

$$\Gamma_{\text{press}} = \frac{\upsilon_{\text{co}} n_{\text{eff}}^{01} - \upsilon_{\text{cl}} n_{\text{eff}}^{0m}}{n_{\text{eff}}^{01} - n_{\text{eff}}^{0m}}. \tag{4}$$

The Γ_{press} increases with the difference between the coefficients. Fused silica increases its pressure-optic coefficient as a function of doping, so $\upsilon_{\text{co}} n_{\text{eff}}^{01} > \upsilon_{\text{cl}} n_{\text{eff}}^{0m}$, which makes the Γ_{press} positive. The effect can be especially well seen for B/Ge co-doped fiber, where the difference between the pressure-optic coefficients of the core and cladding is higher than for the standard germanium-doped fiber [8].

The β parameter corresponds to variations in dimensions of the fiber induced by the applied pressure. Since the fiber volume is dominated by a fused silica, the parameter is mainly dependent on silica's elastic properties. The compressibility is the inverse of the bulk modulus, and is around $2.5 \cdot 10^{-6}$ bar^{-1} for

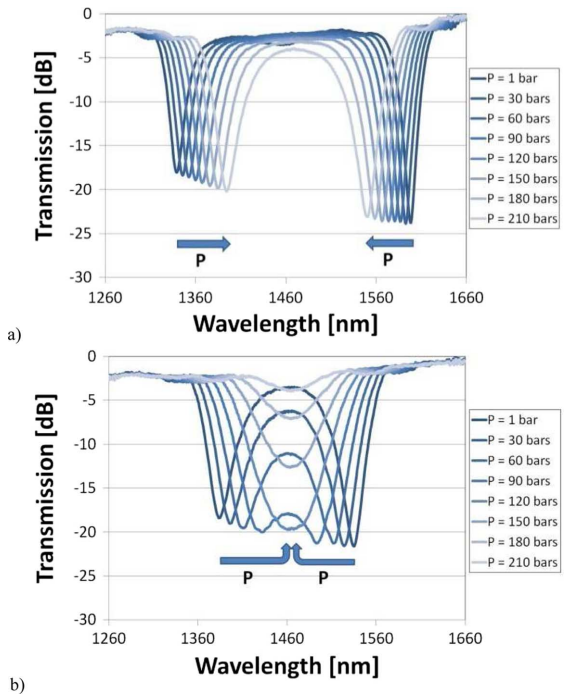

Fig. 2. Spectral response to pressure of the LPG samples. (a) S1 written with shorter UV exposure, and (b) S2, with longer UV exposure.

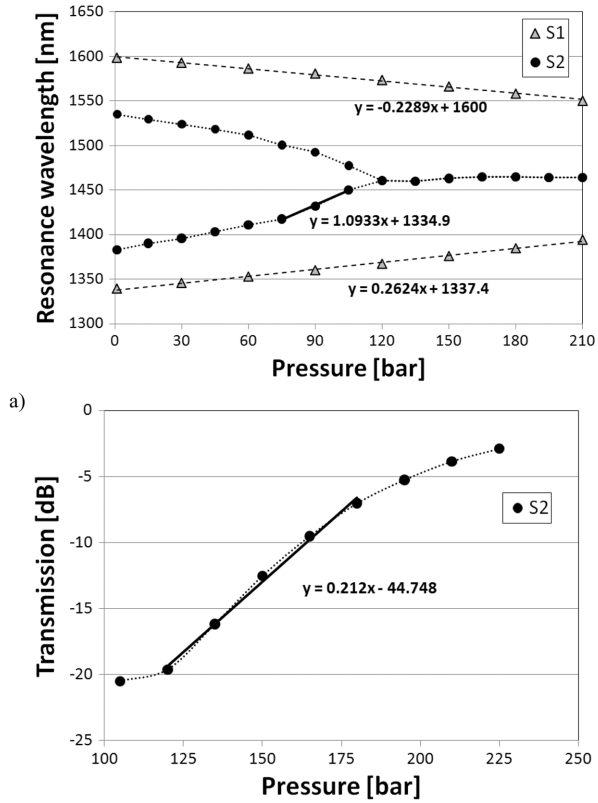

Fig. 3. Sensitivity to pressure of the investigated LPGs written with different UV exposure times, in terms of (a) resonance wavelength and (b) transmission.

the relatively low pressure range applied in our experiment [20]. This finding means that in general $\beta \ll \Gamma_{\mathrm{press}}$, so it negligibly contributes to the pressure sensitivity [10].

The pressure sensitivity of the B/Ge co-doped fiber can then be optimized by creating conditions for obtaining the 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 [11], [14]. Various ways of tuning of the notch separation have been reported, including careful selection of the thickness of deposited nanocoating [14]–[16], thermal annealing [14] or well controlled chemical etching of the cladding [11]. It is also known that the dual resonant peaks get closer to each other with increased modulation of the average core refractive index [13], which is dependent on irradiation energy [14]. The increase in modulation typically follows an increase in the UV exposure time, so it can be precisely adjusted. Moreover, since the spectral response of the LPG depends on temperature [10], the temperature effect can be applied as a specific way of tuning the pressure sensitivity. Both the tuning possibilities are discussed below.

A. Pressure Sensitivity Tuned by UV Exposure Time

It can be seen in Fig. 2 that for the LPGs fabricated in boron co-doped fiber, under the influence of pressure in the range of up to 210 bars, the resonance experienced a significant red shift for resonances at shorter wavelengths and a significant blue shift at longer wavelengths. The direction of the shift is determined here by the γ factor, which is positive for the short-wavelength dip and negative for the long-wavelength one. When the UV exposure time was longer (sample S2, Fig. 2(b)), the spectrum experienced higher variations versus pressure than when the time was shorter (sample S1, Fig. 2(a)). At certain pressure values, both peaks merged and no further shift in wavelength was observed, but instead a significant increase in transmission took place (Fig. 2(b)). Furthermore, peaks at shorter wavelength experienced a higher shift with pressure than those at longer wavelengths. A similar relation has been reported when temperature and strain sensitivity was discussed [10].

It is clear that the initial position of the resonances, i.e., when there is no pressure applied in the measurement setup, determines the level and range of sensitivity. For the sample S1, when initial spectral distance between peaks is about 260 nm, the sensitivity is linear in the investigated pressure range and reaches 262 and -229 pm·bar^{-1}, for lower and higher wavelength resonance respectively (Fig. 3(a)). In this case, the LPG is only about 20 % more sensitive than gratings written using the arc method [8]. When the resonances are initially close to each other, i.e., the spectral distance is below 100 nm, the pressure response becomes nonlinear in the range over $\mathrm{P} = 75$ bars. In this range, a higher sensitivity can be obtained, reaching over 1 nm·bar^{-1}. Moreover, it can be seen that at a certain pressure ($\mathrm{P} = 120$ bar for S2) the mode exhibits a single broad resonance that is wavelength-independent with pressure. It is known that under these conditions, intensity measurement can be realized [10]. For this interrogation scheme, at fixed resonance wavelength ($\lambda = 1460$ nm) the sensitivity in the range from 120 to 180 bars can be as high as 0.212 dB·bar^{-1} (Fig. 3(b)).

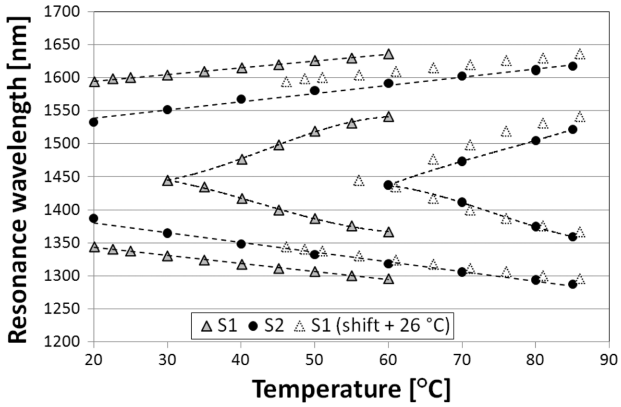

Fig. 4. Sensitivity to temperature for the investigated LPGs. For comparison the results for sample S1 were also shifted by 26°C.

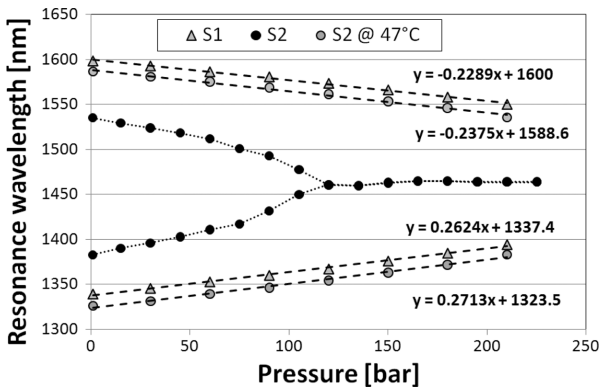

Fig. 5. Comparison of sensitivity to pressure of LPGs measured at different temperatures, where sample S1 was investigated at $\mathrm{T} = 20°\mathrm{C}$ and sample S2 at $\mathrm{T} = 20°\mathrm{C}$ and 47°C.

B. Pressure Sensitivity Tuned by Temperature

High temperature-sensitivity of the LPGs written in boron co-doped fibers has been discussed in detail by Shu [10]. It is known that the separation between the resonances increases with temperature, in contradistinction to the effect induced by pressure. The temperature sensitivity comes from a significant difference between the thermo-optic coefficients of core and cladding materials. Response of the investigated LPGs to temperature is shown in Fig. 4. At a certain temperature ($\sim 30°\mathrm{C}$ and $\sim 60°\mathrm{C}$ for S1 and S2, respectively) an immediately higher-order cladding mode fulfills conditions for the phase-matching turning point. When we graphically shift the results for sample S1 by 26°C we can see that the responses match well. The effect suggests that the working point, that is followed, for example, by pressure sensitivity, can be also tuned by the temperature. In Fig. 5 we compared pressure sensitivity results for sample S1 working at $\mathrm{T} = 20°\mathrm{C}$ with results for S2 investigated at $\mathrm{T} = 47°\mathrm{C}$. It can be seen that the resonances experience very similar sensitivities. The result proves that the pressure sensitivity of the LPG can be alternatively tuned by adjusting temperature during the measurements.

IV. Conclusion

Highly pressure-sensitive structures based on UV-written LPGs in boron co-doped fiber working at the phase-matching turning point have been successfully designed, manufactured and tested. We have shown that both the level and range of sensitivity can be simply tuned by varying the UV exposure time during the fabrication process, as well as post-factum by adjusting temperature during the pressure measurement. To the best of our knowledge, the pressure sensitivity reported here of over 1 nm·bar^{-1} in certain pressure range is the highest ever achieved in the field of gratings. Adjustment of the wavelength separation of the bands will allow for further increased sensitivity. For the intensity-based interrogation scheme, at the turning point the pressure sensitivity can reach 0.212 dB·bar^{-1}.

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