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2011 Meas. Sci. Technol. 22 015201

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Increasing sensitivity of arc-induced long-period gratings—pushing the fabrication technique toward its limits

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Received 28 August 2010, in final form 16 October 2010

Published 1 December 2010

Online at stacks.iop.org/MST/22/015201

Abstract

This paper presents an investigation of the sensing properties of long-period gratings (LPGs) written with the electric-arc technique in commonly used standard germanium-doped Corning SMF28 and boron co-doped Fibercore PS1250/1500 fibers. In order to increase the sensitivity of the LPGs, we studied and established for each fiber the writing parameters allowing for the coupling of the highest possible order of cladding modes at a resonance wavelength around $\lambda = 1550$ nm. The sensitivity of the LPGs to refractive index, to temperature and to hydrostatic pressure was investigated. The experimental results were supported by extensive numerical simulations. Thanks to the well-established and precisely controlled arc-writing process, we were able to reduce the minimum period of the gratings down to 345 and 221 μm , respectively, for LPGs based on the SMF28 and PS1250/1500 fibers. To the best of our knowledge, these are the shortest periods ever achieved for these fibers using the arc-manufacturing technique. The pressure sensitivities of 13 and 220 pm bar^{-1} are the highest ever measured for LPGs written in the SMF28 and PS1250/1500 fibers, respectively. Moreover, a reduction in the diameters of the SMF28 fiber induced by the arc was found, which significantly affected the distribution of resonances generated by the coupled cladding modes.

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

1. Introduction

Long-period gratings (LPGs) have been known for over a decade [1]. They are a periodic modulation of the refractive index along the length of an optical fiber. Under special phase-matching conditions, the grating couples the fundamental core mode to the discrete cladding modes, which 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. A variety of techniques have been used to write LPGs. The majority of these employ lasers working at a wavelength in the spectral range from ultraviolet (UV) to far infrared (IR). Besides the laser-based technique, LPGs have been

successfully written with an electric arc [2–4]. This method, employing electric arc discharges, is often favored due to its simplicity and flexibility, as well as the low cost of the fabrication process and its applicability not only to commonly used photosensitive fibers, but also to photonic crystal fibers, which are made of pure silica [5, 6]. Advantages of arc-induced gratings are that they are resistant to thermal annealing and the fibers from which they are manufactured do not require time-consuming preprocessing such as hydrogenation, which is considered to be a cause of significant temporal instabilities of the transmission spectrum [7].

Numerous sensors based on LPGs have been proposed. 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. The sensitivity of an LPG is then typically defined as a shift of the resonance wavelength induced by a measurand [8]. A shift of the resonance wavelength λ_{res}^m induced by a number of external influences has been reported, notably for temperature, strain, bending, refractive index and pressure sensing [3, 8]. According to equation (1), which describes wavelength-dependent coupling from the guided core mode to the m th cladding mode,

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

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 shift can be induced by a variation in either the period of the grating and or the effective refractive indices of the modes. It has also been shown [8–10] that the sensitivity of LPGs written in certain fibers is strictly dependent on the order of the coupled cladding mode. Typically, the resonances coming from coupling of higher-order cladding modes offer higher sensitivity, and obviously these are the most desirable for sensing purposes. An increase in the order of the coupled cladding mode is obtained by decreasing the grating period. The arc-based technique is somewhat limited in this respect due to the width of the arc, which produces overlapping of the refractive-index modulations when the period is short. The minimum period that can be achieved depends on the properties of the used fiber. To the best of our knowledge, the shortest LPG period successfully written so far with the arc method is 240 μm for a grating induced in custom-made nitrogen-doped fiber [4].

The aim of the present work is to explore the capability of coupling the highest possible order of cladding modes using the electric-arc technique. In our experiment, we used two commercially available fibers, currently those most frequently employed for LPG fabrication: standard germanium-doped Corning SMF28 and boron co-doped Fibercore PS1250/1500 fibers. The results achieved by our measurements are supported by numerical simulations. Since LPGs written in the investigated fibers show a range of very interesting sensing properties [8, 10–12], the sensitivity of the gratings to refractive index, temperature and pressure is also investigated.

2. Experimental details

In this experiment, we used commercially available Corning SMF28 and Fibercore PS1250/1500 fibers. A set of LPGs was written with a computer-assisted precision arc-discharge apparatus, described in detail in [3, 9]. The system is based on a Fitel S182K Fusion Splicer equipped with standard S182A electrodes, which are 2 mm wide and have a conical tip of height 4 mm. Constant tension of the fiber during the writing process was maintained by 2 g weight [3]. Our goal was to obtain a resonance coming from the coupling of the highest possible cladding mode at $\lambda = 1550$ nm. The optical transmission of the fiber in the range of $\lambda = 1160$ –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 (resolution 0.2 nm; wavelength stability ± 0.01 nm) for this purpose.

For refractive-index measurements, several mixtures of glycerin and water were prepared and their refractive indexes (n_D), ranging from 1.33 to 1.47, were determined using a VEE GEE PDX-95 refractometer working with an accuracy of $\pm 10^{-4}$ refractive-index unit (RIU).

Temperature measurements were performed in a water-filled chamber, where the temperature was stabilized in the range from 20 to 50 °C with an accuracy of 0.1 °C.

For pressure measurements, the LPGs were installed inside a steel housing in a transmission configuration [3]. 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 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 pressure and refractive-index measurements were performed at room temperature ($T = 23$ °C). The gratings were kept under a constant tension during all the investigations.

The theoretical data were fitted to the measured spectra using OptiGating v4.2 software by Optiwave. The software uses the coupled mode theory to model interactions of guided modes in the gratings. It has build-in mode solvers providing modal constants and fields needed to formulate coupled mode equations. The equations are then solved using the transfer matrix method.

3. Results and discussion

The spectra of the gratings written with the shortest possible period in both fibers are shown in figure 1. After a series of experiments, we achieved periods as short as 345 and 221 μm for the SMF28 and PS1250/1500 fibers, respectively. The optimized writing parameters for each fiber are summarized in table 1. The spectra for the two gratings look similar. In order to obtain a desirable resonance effect, both current and discharge time had to be higher for the gratings written in the SMF28 fiber. A probable presence of some slight asymmetrical coupling can be noticed at shorter wavelengths in the spectrum of these gratings [13]. Based on the measurements, on the parameters of the fibers given by the manufacturers and on the LPG writing conditions, we were able to fit the parameters of both gratings and fibers using the simulation software. The achieved values are also given in table 1 and corresponding results of simulations are shown in figure 1. Very good agreement between the measurements and the simulations, especially for the gratings written in PS1250/1500 fiber, is evident from this figure.

The main mechanisms responsible for the formation of arc-induced gratings can be summarized as periodic modification of the glass structure (densification), relaxation of drawing-induced or viscoelastic stress and geometric modulation (tapering) of the fiber [4]. The tapering effect is unavoidable when the arc-based technique is used [9]. Some tension must be applied to the fiber during the LPG fabrication

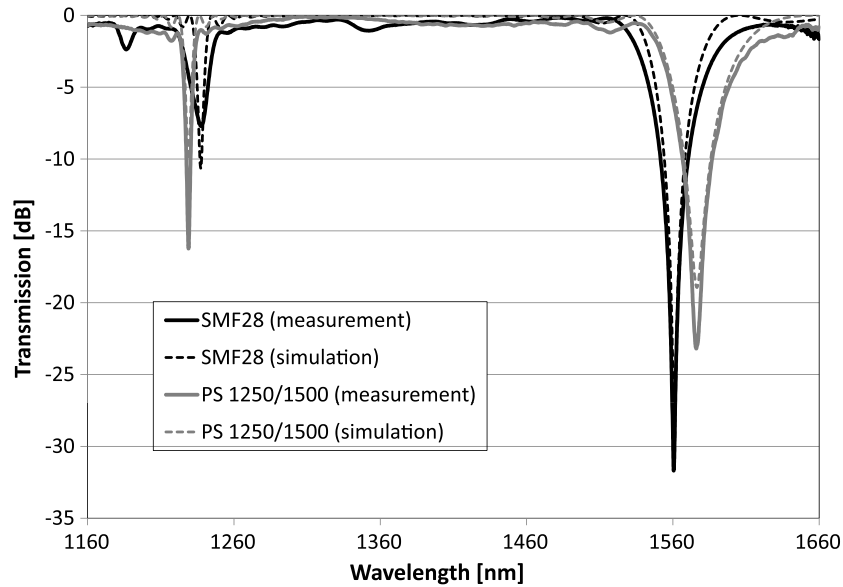


Figure 1. Spectra of LPGs written in the SMF28 and PS1250/1500 fibers (periods of 345 and 221 μm , respectively). The simulations were done using parameters given in table 1.

Table 1. Parameters of the fibers and the LPG writing process used in the experiment and for the corresponding simulations.

| | | SMF 28 | PS1250/1500 |
|------------|---|-----------------------|----------------------|
| Writing | Arc discharge time (τ) (ms) | 400 | 300 |
| | Arc current (a.u.) ^a | 77 | 47 |
| | Grating length (L) (mm)/Number of fusions | 37.26/108 | 36.465/165 |
| Simulation | Period (Λ) (μm) | 345 | 221 |
| | Core radius (r_{co}) (μm) | 3.305 | 4.1 |
| | Cladding radius (r_{cl}) (μm) | 50.06 | 58.965 |
| | Core refractive index (n_{co} @ $\lambda = 1550$ nm) | 1.44922 | 1.44937 |
| | Cladding refractive index (n_{cl} @ $\lambda = 1550$ nm) | 1.44402 | 1.44402 |
| | Refractive-index modulation (Δn_{co}) | 1.55×10^{-4} | 1.7×10^{-4} |

^a The splicer manufacturer defines the current of the arc in arbitrary units.

process, which is the main reason for tapering when the fiber is exposed to the arc discharge. According to the parameters of the fibers specified by the manufacturers, both fibers have similar radii (core and cladding are 4.1 and 58.4 to 58.9 μm , respectively, for the SMF28 and PS1250/1500 fibers). Data summarized in table 1 show that due to the arc discharge, the dimensions of the SMF28 fiber were significantly reduced, whereas for the PS1250/1500 they stayed almost unchanged. This result corresponds well to the amount of energy generated by the arc in each of these two writing processes. Given higher-energy discharge, the fiber experiences a significant tapering, resulting in the reduction of diameters of both the core and the cladding. The phenomenon is less visible in the case of the boron co-doped PS1250/1500 fiber which is more sensitive to the temperature generated by the arc than the standard germanium-doped SMF28 fiber. It was found elsewhere [14] during the experiments with UV exposure that the saturated-index change for the boron co-doped fiber was higher and was achieved faster than for any other fiber. Moreover, the incorporation of boron can dramatically reduce the transition temperature of germanosilicate glass. The tapering effect is significantly less in this fiber because of the lower energy generated in it by the arc process, but must clearly be taken into consideration in the case of the SMF28 fiber.

The conclusions arising from the simulation are confirmed in part by microscopic images. It can be seen in figure 2 that the SMF28 fiber is slightly tapered and that its average diameter is reduced due to the arc discharges, while the PS1250/1500 fiber shows no modification of its diameter. However, the diameter reduction of the SMF28 fiber is less than expected, at 1 μm in the overall radius of the fiber for less tapered regions, and 2.5 μm for more tapered regions. The finding indicates the need for a more accurate numerical model, which would take into consideration the full complexity of the tapering effect.

Based on the parameters obtained in the LPG simulations, we were able to plot a relation between the grating period and the resonance wavelength of the series of cladding modes for each of the fibers (figure 3). For LPGs written in the SMF28 and PS1250/1500 fibers, at around $\lambda = 1550$ nm we achieved a resonance of the LP_{07} and LP_{010} modes, respectively. The difference in the distribution of the resonances comes mainly from the tapering effect observed for the LPGs based on the SMF28 fiber. The reduction in the fiber diameter has already been discussed [4, 15]. In reducing the cladding diameter, one limits the number of higher-order cladding modes that can be propagated and coupled to the core mode. For each of the

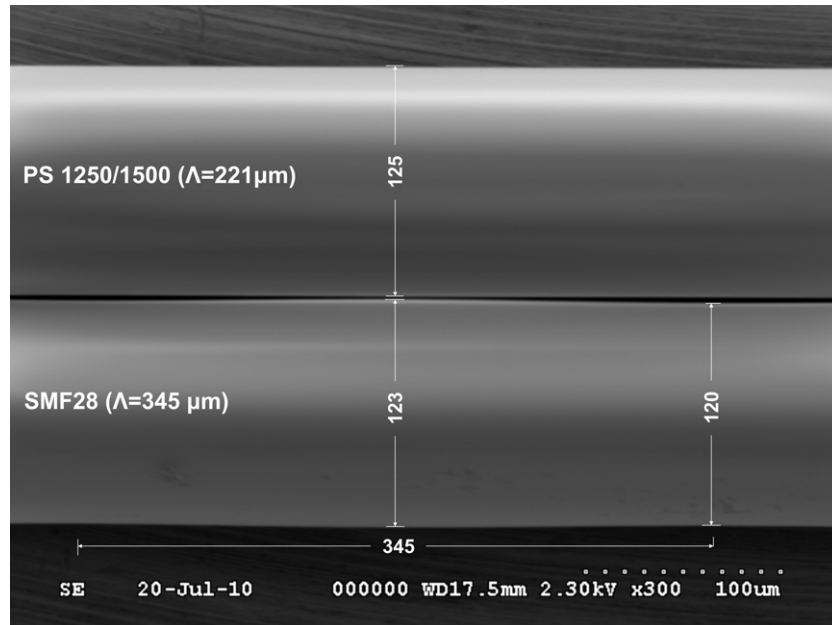


Figure 2. Scanning electron microscope (SEM) images of the investigated fibers. The values are given in μm .

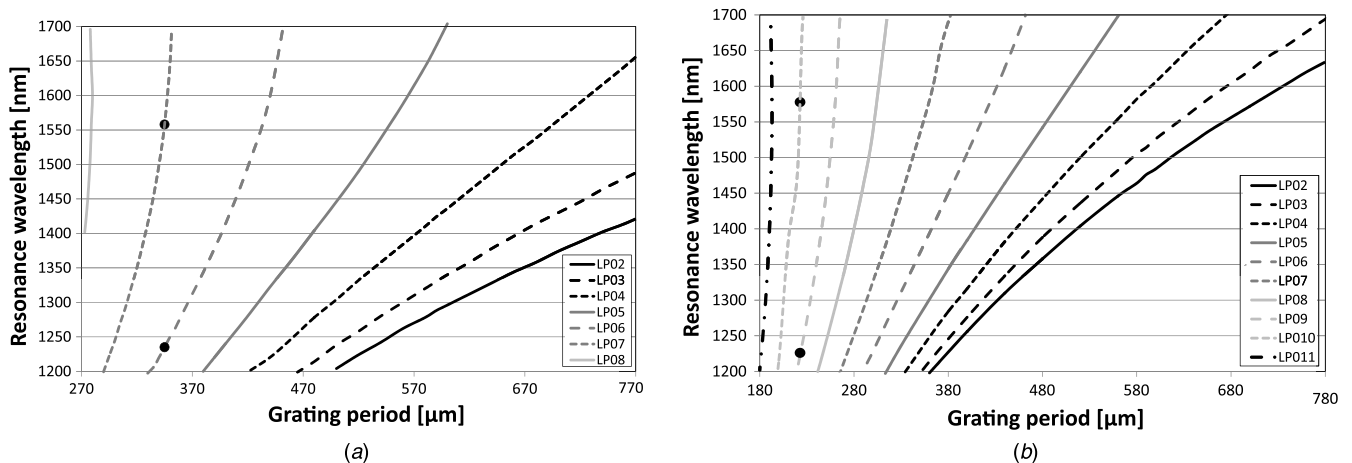


Figure 3. Spectral position of the resonances resulting from the coupling of cladding modes (LP_{02} to LP_{011}) versus the grating period, showing dependence for LPGs written in (a) SMF28 and (b) PS1250/1500. Dots show cases corresponding to the investigated LPGs. The simulations were done using the parameters given in table 1.

gratings, we deal with a mode one order lower than the one involved in the so-called turning point. A turning point in the phase-matching curves takes place when a coupling to the same cladding mode at two different wavelengths produces dual-resonance bands in the transmission spectrum [16]. It has been shown in [8] that the region of dual resonance offers the highest sensitivity to several measurands. In order to obtain the resonances coming from these modes while keeping the parameters of the fibers constant, the periods would need to be 280 and 193 μm for the SMF28 and PS1250/1500 fibers, respectively. Unfortunately, according to our experiments, these values seem too low to be achievable using the arc technique.

The sensitivity of the obtained gratings to refractive index, temperature and pressure was investigated next. The unique feature of LPGs compared to other fiber gratings is their

high sensitivity to changes in the external refractive index [17]. In figure 4 the changes of resonance wavelength of the higher-order cladding modes versus external refractive index are shown for both gratings. Following equation (1), with an increase in the external refractive index, a shift of the resonances toward the shorter wavelengths can be seen due to the increase of the n_{eff}^{0m} , which is dependent on the external refractive index. The highest refractive-index sensitivity of the LPGs is observed when the medium's refractive index is close to that of the cladding. For comparison purposes, we determined the sensitivities for each grating in their linear range (n_D from 1.33 to 1.41). It can be seen that the gratings written in PS1250/1500 fiber are significantly more sensitive. The result can be explained mainly by the different order of cladding modes investigated for each fiber, which was higher for the LPGs written in the PS1250/1500 fiber

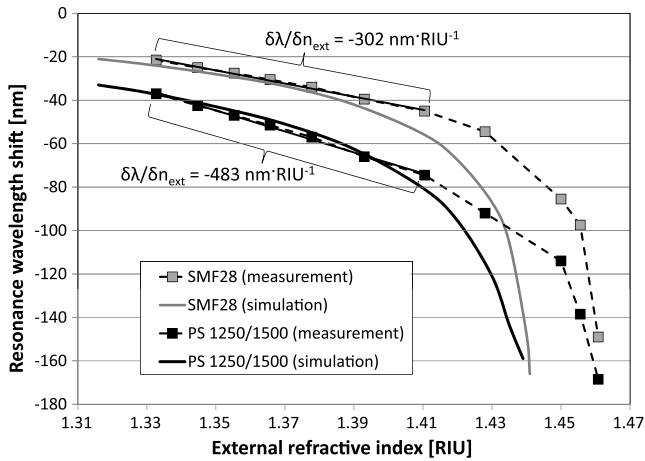


Figure 4. Resonance wavelength shift induced by a change of the external refractive index (n_{ext}) for LPGs written in the SMF28 ($\Lambda = 345 \mu\text{m}$) and PS1250/1500 ($\Lambda = 221 \mu\text{m}$) fibers. The sensitivity was determined for each grating in the range of n_{ext} from 1.33 to 1.41.

[9]. The higher-order cladding modes intensely penetrate the external medium, which results in higher sensitivity of the device. The results of the simulations shown in figure 4 were obtained using the values for the external refractive index given at $\lambda = 1550 \text{ nm}$, while for the actual measurements we used the available values determined at $\lambda = 589 \text{ nm}$. For all the used liquids, the refractive indices in the visible range are higher than their values in the IR region. This fact explains discrepancies between the measurement and the simulation results. Nevertheless, a similar tendency for both the experimental and the simulation results is evident.

The spectral responses of both gratings to temperature and pressure changes are shown in figure 5. A slightly different starting value of the resonance wavelengths is caused by different tensions applied to the fibers during the pressure and temperature measurements. The difference is more visible in the case of the SMF28-based LPGs than in the PS1250/1500

fiber, due to the y-axis scaling-down applied to the former. A significant difference in the sensitivities of the gratings written in both these fibers can easily be noticed. The phenomenon of LPG temperature and pressure sensitivity has been discussed in detail elsewhere [9, 10]. The causes of the different sensitivities are mainly the different thermo-optic and pressure-optic coefficients of core and cladding materials used in the fibers. According to equation (1), in the boron co-doped fiber, the increasing temperature generates a less rapid increase of the n_{eff}^{01} than in the indices of the cladding modes (n_{eff}^{0m}), causing a blue shift of the resonance wavelength. The difference in the thermo-optic coefficients for the PS1250/1500 fiber is larger than for the SMF28 fiber and opposite, so its sensitivity is higher and shows the opposite sign. Co-doping the fiber core with boron also increases its pressure-optic coefficient [10]. The investigated grating written in the boron co-doped fiber is more than 9 times more sensitive to temperature and almost 17 times more sensitive to pressure than the grating written in the SMF28 fiber. Moreover, the relation between the pressure sensitivity ($\delta\lambda/\delta P$) and the temperature sensitivity ($\delta\lambda/\delta T$) stays at the level of -0.18 and 0.1 for the gratings written in the PS1250/1500 and SMF28 fibers, respectively. The gratings written in PS1250/1500 fiber are not only more sensitive to pressure, but also have a higher pressure-to-temperature sensitivity ratio. The pressure sensitivity of 13 and 220 pm bar^{-1} achieved in this work is the highest ever measured for LPGs written in the SMF28 and PS1250/1500 fibers, respectively.

4. Conclusions

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 performed using the electric-arc

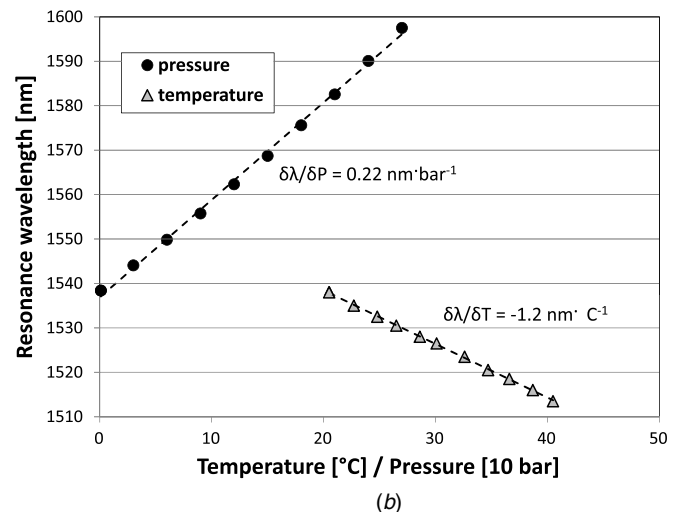
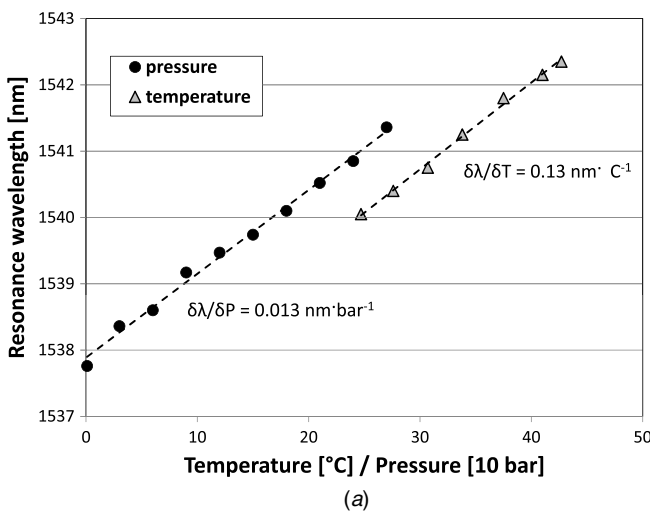


Figure 5. Resonance wavelength shift induced by changes in pressure and temperature for LPGs written in (a) PS1250/1500 ($\Lambda = 221 \mu\text{m}$) and (b) SMF28 ($\Lambda = 345 \mu\text{m}$) fibers.

technique, supported by numerical simulations, allowed us to practically achieve periods in LPGs as short as 345 μm for the SMF28 fiber and 221 μm for the PS1250/1500 fiber. The 221 μm period is, to the best of our knowledge, the shortest ever achieved using the arc technique. During the fabrication process, the gratings induced in the SMF28 fiber required significantly higher arc energy. A visible periodic tapering took place in this fiber, resulting in a reduction of the average fiber diameter. This effect has a significant influence on the distribution of resonances generated by the coupled cladding modes and must therefore be taken into account in the arc-induced LPG-based sensor design process.

Regarding the sensing properties of the gratings under investigation, LPGs based on the boron co-doped PS1250/1500 fiber are significantly more sensitive to such measurands as refractive index, temperature and pressure. However, due to the high temperature sensitivity of LPGs based on that fiber, SMF28-based gratings seem to be a better platform for refractive-index sensing. For pressure sensing, on the other hand, LPGs based on the PS1250/1500 fiber are a better choice due to their higher pressure sensitivity and a higher pressure-to-temperature sensitivity ratio. The pressure sensitivity of 220 pm bar⁻¹ we reported here is the highest ever measured for any kind of fiber grating.

Acknowledgments

The authors gratefully acknowledge support for this work from the Natural Sciences and Engineering Research Council of Canada, the Canada Research Chairs Program, the Ministère de l'Éducation, du Loisir et du Sport du Québec and NanoQuébec.

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