Comparative study of long-period gratings written in a boron co-doped fiber by an electric arc and UV irradiation

2010 Meas. Sci. Technol. 21 025309

(http://iopscience.iop.org/0957-0233/21/2/025309)

Meas. Sci. Technol. **21** (2010) 025309 (8pp) doi:10.1088/0957-0233/21/2/025309

Comparative study of long-period gratings written in a boron co-doped fiber by an electric arc and UV irradiation

M Smietana[1,2], W J Bock[1] and P Mikulic[1]

[1] Centre de recherche en photonique, Université du Québec en Outaouais, 101 rue Saint-Jean-Bosco, Gatineau, QC, J8X 3X7, Canada

[2] Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, Poland

E-mail: msmietan@elka.pw.edu.pl

Received 1 October 2009, in final form 30 November 2009
Published 19 January 2010
Online at stacks.iop.org/MST/21/025309

Abstract

The paper presents for the first time a comparative study of long-period gratings (LPGs) written by point-by-point UV irradiation and by electrical arc discharges. 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 grating. Two reasons could explain the observed small differences between the spectra: a slight mismatch of the period of the gratings and an unintentional tapering of the fiber during the arc-based processes. We also found that the UV irradiation at $\lambda = 248$ nm can cause clearly visible damage to the fiber's surface. As a result of the UV writing, a coupling to the asymmetrical cladding modes can take place. Moreover, the gratings written using the two technologies show a very similar refractive index and temperature-sensing properties. The only differences between them can come from a physical deformation of the fiber induced by the electric arc discharges.

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

1. Introduction

A long-period grating (LPG) is a periodic modulation of the refractive index along the length of the optical fiber [1]. 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. 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 [2], electrical arc discharges [3, 4] or even mechanical pressure [5]. 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 [3, 6]. The second method, employing electrical arc discharges, is often applied due to its simplicity and flexibility, the low cost of the fabrication process [7] and its applicability to photonic crystal fibers (PCFs) made of pure silica [4].

The aim of this work is to compare LPGs written in a boron co-doped fiber using the two methods mentioned above: point-by-point UV exposure at $\lambda = 248$ nm and electric arc discharges. 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 [8]. In the case of LPG

0957-0233/10/025309+08$30.00

writing with the arc technique, a partial stress relaxation takes place, which induces a refractive-index difference [9]. These effects 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 refractive index and temperature. To date, LPGs made in various fibers and with particular writing methods have been examined by a number of authors [8, 10]. On the other hand, to the best of our knowledge, only a few attempts have been made to compare different LPG writing methods applied to the same fiber. The authors of [6] investigated LPG inscription using various UV wavelengths. Gratings written in an SMF28 germanosilicate fiber with a femtosecond laser, UV and arc were compared by Allsop *et al* [11] with respect to their high temperature sensitivity and polarization dependence. It was shown that both UV and arc methods allow for fabrication of only slightly polarization-dependent gratings. The authors of [12] discussed the refractive-index sensitivity of both UV- and arc-written gratings, where cladding had been thinned. However, they compared LPGs written with different methods and with different periods, and that fact made their comparison incomplete. In both these experiments [11, 12], the germanosilicate fibers used had to be loaded with hydrogen before the UV irradiation. The hydrogenation process causes significant temporal instabilities of the transmission spectrum [6]. This kind of pre-processing, necessary in the case of the SMF28 fibers, significantly changes the properties of the fibers used to fabricate the LPGs. Consequently, comparing such gratings to LPGs written with the arc method without hydrogenation does not seem to be informative.

In our experiment we used a high B/Ge co-doped fiber. Besides the widely used hydrogen-loading technique, doping the fiber core with boron is a well-known method to increase fiber photosensitivity [8]. The fiber containing boron shows a much higher photosensitive response than that with an equivalent germanium concentration without the boron [13]. A dopant such as boron decreases the refractive index of the core and therefore allows the manufacturer to incorporate more germanium into the core, while keeping constant the core–cladding refractive-index difference [14]. Consequently, the increased germanium content allows for a higher UV absorption than a standard germanosilicate fiber, while the presence of boron itself does not affect the absorption [8, 15]. It was found that the saturated index change for the B/Ge fiber was higher and was achieved faster than that for any other fiber [13]. The additional photosensitivity-enhancing mechanism operating in the boron-containing fiber is based on the stress-induced refractive-index changes that boron is known to cause in silica-based fibers. This enhancement can be achieved by an increase in the fiber-drawing tension [15]. The authors of [16] found that the viscosity decrement coefficient of B_2O_3 is significantly higher than that of GeO_2. Enhancing the viscosity difference between the layers through the use of boron increases the difference in the initial elastic strains and thus in the induced mechanical stress.

The incorporation of boron can dramatically lower the transition temperature of germanosilicate glass, a fact that makes it possible to use LPG writing methods other than UV irradiation. Besides the UV-based technique, gratings have already been successfully written in the B/Ge fiber with an electric arc [9] and a CO_2 laser [2]. Using this kind of fiber as a suitable platform for the LPGs written with various techniques, we avoided the time-consuming hydrogenation pre-processing and were able to directly compare the effects of the two point-by-point writing methods.

2. Experimental details

In this experiment, we used a commercially available PS 1250/1500 fiber from Fibercore. The boron and germanium concentrations were not disclosed by the manufacturer, but according to [3, 17], the PS 1250/1500 can consist of 10% of GeO_2 and 20% of B_2O_3. The core radius for that fiber is usually assumed to be 3.5–4.5 μm. Each of our samples contains a 10 cm middle section of the B/Ge fiber with both ends spliced to the SMF28 fibers. The gratings were written only in the boron-doped fiber segment.

First the LPGs were written with a point-by-point technique using a Pulse Master 840 high-power KrF excimer laser ($\lambda = 248$ nm) from Light Machinery. The laser generates pulses 12–20 ns in length. The beam goes through a slit 150 μm in width and a cylindrical lens with a focal length of 75 mm. Each point on the fiber was irradiated by about 40 000 pulses at a power of 150 mJ cm^{-2}. The fiber could then be shifted by a Newport positioning stage capable of working with a resolution of 1 μm. The second set of LPGs was written with a computer-assisted precision arc-discharge apparatus, described in [18]. 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 during the fabrication process. The arc discharge time was established at $\tau = 300$ ms.

The chosen grating period for the two sets of LPGs was 350 μm and 400 μm, respectively. 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.

The LPG response to temperature variations in the 20–70 °C range and to changes in the external refractive index in a range from 1.33 to 1.47 RIU (refractive index units) was further investigated. For refractive-index measurements, several mixtures of glycerin and water were prepared and their refractive indexes (n_D) were determined using a VEE GEE PDX-95 refractometer working with accuracy of $\pm 10^{-4}$ RIU. For temperature measurements two thermoelectric coolers (TEC) were used. The measurements were performed in a temperature-isolated chamber. For temperature readouts, we used a thermocouple probe placed next to the LPG. Each measurement was preformed after stabilizing 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 Optigrating v4.2 software by Optiwave.

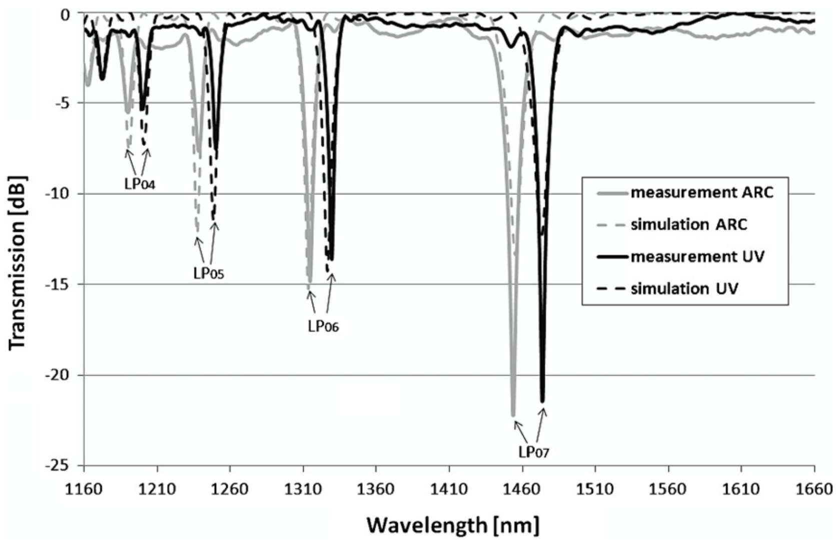

Figure 1. Transmission spectra of LPGs written with electric arc (ARC) and UV methods. The period of both gratings was determined to be 350 μm.

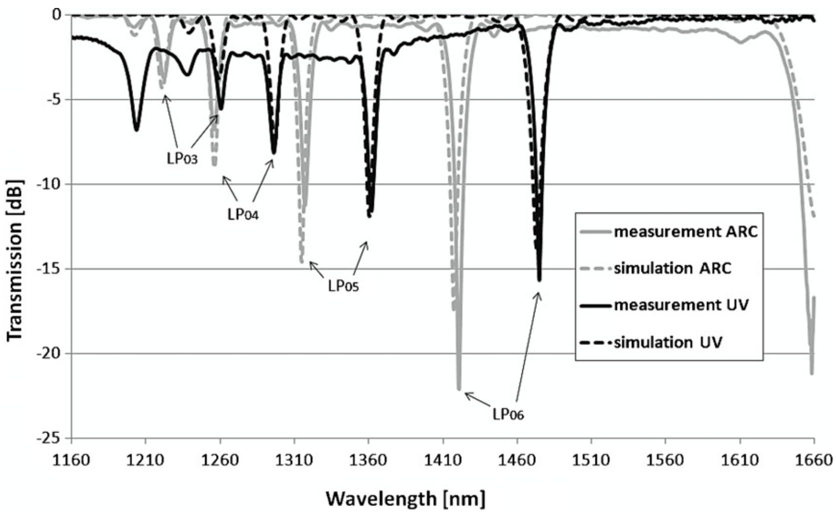

Figure 2. Transmission spectra of LPGs written with electric arc (ARC) and UV methods. The period of both gratings was determined to be 400 μm.

3. Results and discussion

In figures 1 and 2, the spectra of gratings written with two different period lengths, 350 μm and 400 μm, are presented and compared in terms of the fabrication method. It can be seen that both these methods allow good quality LPGs to be written in the B/Ge fiber, with transmission of the last resonance reaching below −20 dB. For both periods, the spectra of the gratings fabricated by arc discharge are shifted to the shorter wavelength, significantly so in the case of the 400 μm period (figure 2). We also found that the gratings written with UV irradiation show some distortions and an extra resonance at 1200 nm. This specific difference will be discussed further in this section.

All the spectra were simulated using the grating and fiber properties summarized in table 1. Due to lack of detailed data about the PS 1250/1500 such as the 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 [14, 19], and stay in agreement with Fibercore specifications. The characteristics of the gratings, while influenced by the fiber properties, depend mainly on the period, on the induced change in the refractive index, on the writing technology and on the grating length [7]. As a result of the agreement between the measured and the simulated spectra, we were able to correctly determine the order of the cladding modes responsible for the observed resonances. To achieve an accurate fit, we assume slightly reduced core radius and cladding radius for simulating the fiber grating written with the arc method (compared to the UV method). Moreover, for UV-written LPG having a period of 400 μm, we slightly increase the refractive index of the core (8×10^{-5}). Similar good agreement can be achieved assuming that the gratings fabricated by UV irradiation had longer periods than

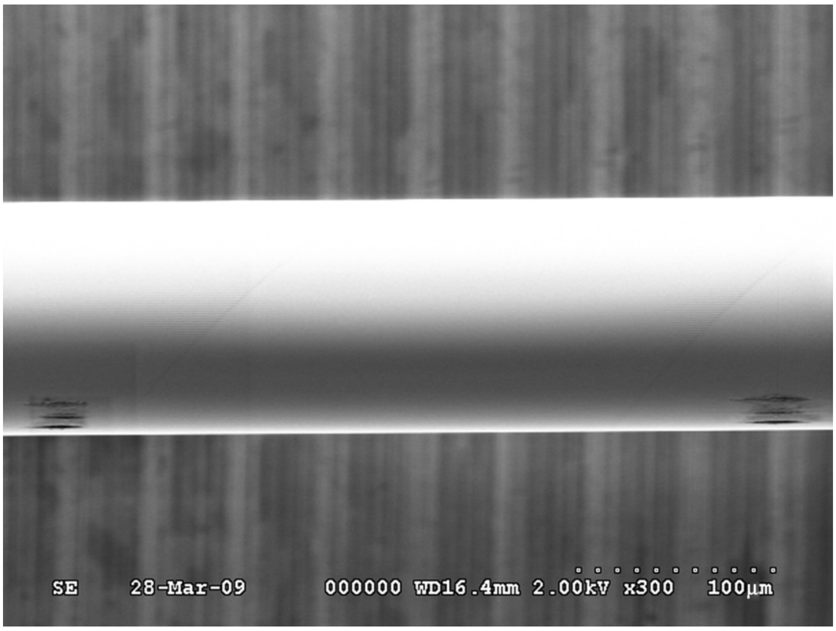

Figure 3. Burn spots induced by UV irradiation on the bottom surface of the fiber.

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

Period Λ (μm)	350		400	
Writing method	ARC	UV	ARC	UV
Grating length L (mm)	20.3	20.3	22.4	22.6
Refractive-index change	2.7×10^{-4}		2.7×10^{-4}	
Numerical aperture	0.1243	0.1243	0.1243	0.1252
Core radius (μm)	3.73	3.8	3.635	3.8
Cladding radius (μm)	62.505	62.7	62.235	62.7

those fabricated by arc discharge. The difference between the spectra can be explained by arc discharge induced tapering of the fiber resulting in decreased core and cladding diameters. That hypothesis can be proven by the good agreement between the measured and simulated data in the case of the UV method for periods of both 350 μm and 400 μm lengths. The tapering of the fiber is caused by a longitudinal tension applied to the fiber during grating fabrication. It was found in the case of the arc method [20] that the increase of the tapering ratio, as well as the shortening of the grating period, induces a blue shift of the resonance wavelengths for each of the cladding modes. Despite the fact that a decrease in the cladding diameter contributes to a red shift, the dominant effect remains the decrease of the core. This in turn reduces the effective refractive index of the guided mode, leading to a blue shift of the resonances [9]. A tapering artifact probably affected the grating characteristics, despite our best efforts to avoid any tapering of the fiber during the writing process.

As mentioned before, some anomalies were observed for the UV-written gratings, including a distortion of the spectra and the presence of extra resonances. Microscopy analysis of these gratings showed significant periodic damage to the cladding surface, which was more visible in the case of the gratings written with the 400 μm period (figure 3). This grating could be irradiated with a higher dose, which in terms of simulation modeling is represented by a higher refractive index of the core. It was found [6] that the B/Ge fiber required significantly higher UV irradiation to obtain a grating effect than did the hydrogenated fibers. Moreover, Kalachev *et al* noted that the spectra of a grating written in the non-hydrogenated boron-doped fiber are characterized by noticeable 'gray' losses but no such losses are experienced by LPGs inscribed in the hydrogen-loaded fiber. They also reported some cladding damage induced by the UV exposure. We believe that the damage observed in our experiments, like that reported by certain other authors [6, 8], results from the relatively high power used for irradiation. Nevertheless, LPGs fabricated using UV exposure are usually considered as symmetric in terms of the refractive-index modulations induced in the fiber [3]. The resonance observed at a wavelength of 1200 nm in the spectrum of the UV-irradiated grating (figure 2) is most probably the result of a significant coupling to the asymmetrical cladding modes. Periodic damage to the SMF28 fiber cladding surface was also observed for irradiation with 352 nm high intensity pulses, which in the opinion of Nikogosyan [8] confirms a non-uniform energy distribution occurring in the irradiated fiber. The damage was similar to results obtained for gratings fabricated by CO_2 laser exposure. The polarization-dependent loss (PDL) measurements proved a strong azimuthally asymmetric refractive-index change, due to single-side exposure and deposition of the energy in the cladding [8]. As for the germanium-doped core of the fiber, the highest absorption takes place at $\lambda = 248$ nm, the wavelength emitted by the KrF excimer laser. However, for pure silica cladding, the absorption is significantly lower, so that the irradiation can be highly selective [6]. The selectivity should be the main

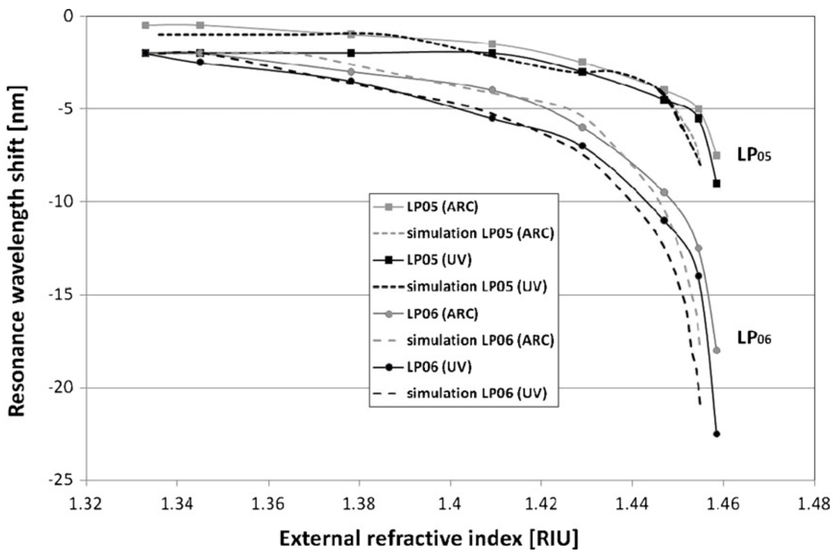

Figure 4. Resonance wavelength shifts of the LP_{05} and LP_{06} cladding modes induced by variations of the external refractive index. The period of both arc- and UV-induced gratings was determined to be 400 μm.

reason for symmetrical mode coupling. For certain conditions of B/Ge fiber exposure to UV light, gratings fabricated with the point-by-point technique showed no presence of such asymmetrical coupling [21]. The good quality spectra obtained in our experiment for the 350 μm grating period prove the possibility of achieving coupling to only the symmetrical cladding modes, by reducing the power of the laser and thus avoiding damage to the fiber's surface. For the B/Ge fiber, where stress relaxation takes place at temperatures as low as 300 °C [22] and where coupling to only symmetrical cladding modes was present, it was shown [2] that even with a low-energy dose from a CO_2 laser, it was possible to fabricate good quality LPGs. In our case, the gratings written by arc in this kind of fiber are of a quality superior to some of those written by UV irradiation. The statement that gratings fabricated with the arc method are asymmetric [8] seems to be not necessarily true considering these fabricated in the B/Ge fiber. Following Rego *et al* [20, 23] also for the arc-based method, there may be certain conditions where the perturbations induced in the gratings are asymmetric, but these conditions are usually dependent on the relative position of the fiber and the electrodes.

There are many external influences that can shift the resonance wavelengths of LPGs. According to a number of works on the sensing properties of LPGs, the most commonly measured parameters are external refractive index, temperature, bending, strain and pressure [18, 24, 25]. The influence of the LPG writing method on two particular parameters, sensitivity to the external refractive index and sensitivity to temperature, is discussed in the following two subsections.

3.1. Refractive-index sensitivity

Since coupling to the cladding modes is dependent on the external refractive index, the LPGs are particularly sensitive to the external medium [24, 25]. To increase this sensitivity, the period of the grating should be relatively short [10, 26] since the higher-order cladding modes intensely penetrate the external medium [24]. With an increase of the external refractive index, a shift of the resonances toward the shorter wavelengths can be seen. The highest refractive-index sensitivity of the LPGs is observed when the medium's refractive index is close to that of the cladding. The core of the fiber is then surrounded by an infinite medium, and the cladding modes cannot be generated, nor can coupling take place [27].

Figures 4 and 5 show the wavelength shifts experienced by two resonances of the highest observed cladding modes for each grating when the external refractive-index changes. The highest shift occurs for the resonance of the highest-order cladding mode, which in the observed wavelength range was found to be the LP_{07} cladding mode in the LPG with the 350 μm period (figure 5). For both periods under consideration, the gratings written by UV irradiation are slightly more sensitive than those written by arc discharge. The higher wavelength shifts for the UV-written gratings are in agreement with the calculated ones, assuming the properties of the fiber and grating given in table 1. The higher sensitivity of the UV-written gratings is most probably due to the fact that their resonances take place at longer wavelengths than do those of the arc-written gratings. Following the dispersion relations for water [28] and for glycerin [29] and comparing them to the relation for fused silica [30], it can be found that the difference between the refractive indexes of the liquid and the cladding material increases with the wavelength, so that the resonances observed at the longer wavelength will shift even more. Note that for our refractive-index measurements, we used mixtures of glycerin, the optical properties of which were measured at $\lambda = 589$ nm. The simulations require that the values of the refractive index be given in the infrared range, and these are lower than the values in the visible range. This is the

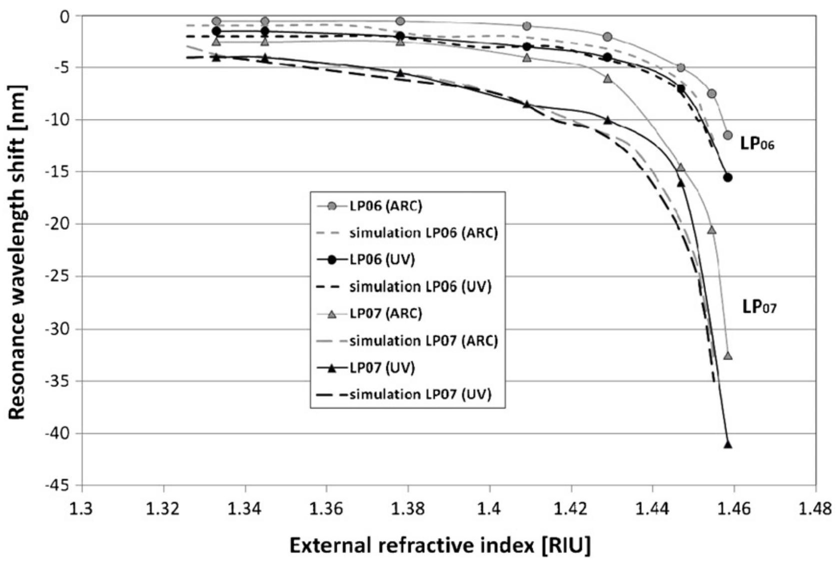

Figure 5. Resonance wavelength shifts of the LP_{06} and LP_{07} cladding modes induced by variations of the external refractive index. The period of both arc- and UV-induced gratings was determined to be 350 μm.

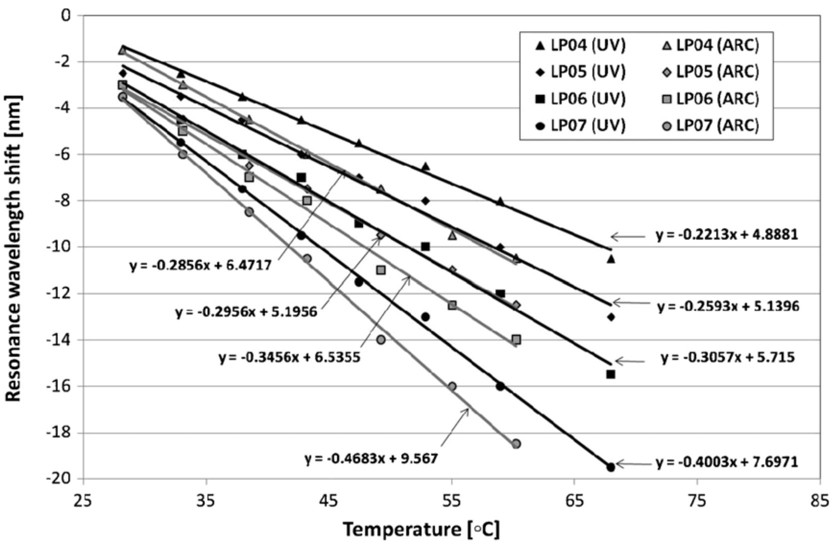

Figure 6. The resonance wavelength shifts of all the observed cladding modes induced by the increase in temperature (over the room temperature of 23 °C). The period of both arc- and UV-induced gratings was 350 μm.

main reason for the small discrepancy between the simulated and the measured wavelength shifts in terms of the external refractive index.

According to our results, for both periods considered, the calculated values match the measured data better for the UV-irradiated than for the arc-written gratings. The reason for this may lay in some tapering of the arc-induced LPGs, an effect that was not taken into consideration in the simulations. The authors of [12] reported that the decrease in fiber diameter induces a lowering of the effective refractive index of the cladding modes, and simultaneously more interaction of the evanescent cladding modes with the external medium, which in turn leads to an increase of the refractive-index sensitivity. This small reduction in the core radius and cladding radius is present in LPGs written with the arc method. This reduction is 0.07 μm for the core and 0.125 μm for the cladding radius (grating period 350 μm) or 0.165 μm for the core and 0.3 μm for the cladding (grating period 400 μm).

3.2. Temperature sensitivity

There are contradictory reports comparing the temperature sensitivity of LPGs written by the arc and that of LPGs written with UV technology in the SMF28 germanium-doped fiber. Humbert and Malki, for example, show that UV-fabricated LPGs have higher temperature sensitivity [7], while Allsop *et al* find arc inscription a better method to achieve high temperature sensitivity [11]. In the case of the B/Ge fiber where the temperature sensitivity is several times higher than that for the SMF28, any influence from the LPG fabrication method on the sensitivity should be more clearly visible. The slight difference in temperature sensitivity between the SMF28 and B/Ge fibers can be explained on the basis of the thermo-optic coefficients of the core and the cladding materials [19, 31]. The presence of boron alters the temperature dependence of the refractive index [9]. The difference in thermo-optic coefficients for the B/Ge fiber is higher, so that the sensitivity is also higher. The temperature sensitivity of LPGs based on the B/Ge fiber is one of the highest ever observed in a range of up to 300 °C [16]. However, this sensitivity depends not only on the fiber properties but also on the period of the LPGs, which strongly affects the order of the coupled cladding modes [8]. For each particular mode there is a fractional power in both the core and the cladding, and the resulting ratio leads to a higher sensitivity of the resonances in the case of the higher-order cladding modes [19].

According to our results, the resonances for LPGs written in the B/Ge fiber experience a negative (blue) shift with an increase in temperature. The sensitivity is in the range of −0.22 to −0.47 nm $^{\circ}C^{-1}$, depending on the order of the cladding modes observed (LP_{04} to LP_{07}). For LPGs written with the 350 μm period, the temperature sensitivity is slightly higher for the arc-induced grating (figure 6). However, for LPGs written with the 400 μm period, the sensitivity was found to be independent of the writing method and equal to 0.27, 0.32 and 0.37 nm $^{\circ}C^{-1}$ for the LP_{04}, LP_{05} and LP_{06} cladding modes, respectively. These results are in agreement with the values obtained by other authors. A sensitivity of −0.14 nm $^{\circ}C^{-1}$ for the LP_{03} cladding mode was reported for the LPG written by a CO_2 laser [16]. In the case of the UV-written LPG, reported values are −0.4 nm $^{\circ}C^{-1}$ for the LP_{07} cladding mode [21] and −0.369 and −0.493 nm $^{\circ}C^{-1}$ for the LP_{05} and LP_{07} cladding modes, respectively [14, 19]. Despite the fact that in our case the LPGs with a 350 μm period written by the arc method had slightly higher temperature sensitivity, we believe that temperature sensitivity in general is not dependent on the writing method.

4. Conclusions

In our study, we used experiments and computer simulations to compare the properties of LPGs written with the two currently most popular point-by-point methods: UV irradiation and electrical arc discharges. In order to make reliable comparisons, we inscribed all the gratings for this study in highly photosensitive boron co-doped fiber. This fiber offers a convenient universal platform for both inscription methods, because it does not require complicated and time-consuming preprocessing. Using the two methods, we were able to obtain similar, good quality gratings. A small wavelength shift between gratings produced by the two methods comes most probably from unintentional fiber tapering induced by the arc-based process. Some disadvantages of the point-by-point UV irradiation technique such as damage of the fiber's surface and the possibility of coupling to the asymmetrical cladding modes were also discovered.

The gratings written using the two methods show very similar refractive index and temperature-sensing properties. In terms of sensitivity to the external refractive index, the only difference between the two types of grating is likely due to physical deformation of the fiber (tapering) taking place during the arc inscription process, which slightly decreases the sensitivity of arc-induced gratings compared to UV-written ones.

Acknowledgments

The authors gratefully acknowledge support for this work from the Natural Sciences and Engineering Research Council of Canada, the Canada Research Chairs Program and the Ministère de l'Éducation, du Loisir et du Sport du Québec. Support from the development grant R02-022-01 from funds of Polish Ministry of Science and Higher Education during years 2006–2009 is also acknowledged.

References

[1] Vengsarkar A M, Lemaire P J, Judkins J B, Bhatia V, Erdogan T and Sipe J E 1996 Long-period fiber gratings as band-rejection filters *J. Lightwave Technol.* **14** 58
[2] Liu Y, Chiang K S, Rao Y J, Ran Z L and Zhu T 2007 Light coupling between two parallel CO_2-laser written long-period fiber gratings *Opt. Exp.* **15** 17645
[3] Rego G, Ivanov O V and Marques P V S 2006 Demonstration of coupling to symmetric and antisymmetric cladding modes in arc-induced long-period fiber gratings *Opt. Exp.* **14** 9594
[4] Bock W J, Chen J, Mikulic P, Eftimov T and Korwin-Pawlowski M 2007 Pressure sensing using periodically tapered long-period gratings written in photonic crystal fibres *Meas. Sci. Technol.* **18** 3098
[5] Noordegraaf D, Scolari L, Lægsgaard J, Rindorf L and Tanggaard Alkeskjold T 2007 Electrically and mechanically induced long period gratings in liquid crystal photonic bandgap fibers *Opt. Exp.* **15** 7902
[6] Kalachev A I, Pureur V and Nikogosyan D N 2005 Investigation of long-period fiber gratings induced by high-intensity femtosecond UV laser pulses *Opt. Commun.* **246** 107
[7] Humbert G and Malki A 2002 Electric-arc-induced gratings in non-hydrogenated fibres: fabrication and high-temperature characterizations *J. Opt. A: Pure Appl. Opt.* **4** 194
[8] Nikogosyan D N 2007 Multi-photon high-excitation-energy approach to fibre grating inscription *Meas. Sci. Technol.* **18** R1
[9] Rego G, Marques P V S, Santos J L and Salgado H M 2005 Arc-induced long-period gratings *Fiber Integr. Opt.* **24** 245
[10] Allsop T, Webb D J and Bennion I 2003 A comparison of the sensing characteristics of long period gratings written in three different types of fiber *Opt. Fiber Technol.* **9** 210
[11] Allsop T, Dubov M, Dobb H, Main A, Martinez A, Kalli K, Webb D J and Bennion I 2006 A comparison of the spectral properties of high temperature annealed long period gratings inscribed by fs laser, UV and fusion-arc *Proc. SPIE* **6193** 61930M
[12] Iadicicco A, Campopiano S, Cutolo A, Korwin-Pawlowski M L, Bock W J and Cusano A 2008 Refractive index sensitivity in thinned UV and arc induced long-period gratings: a comparative study *Int. J. Smart Sens. Intell. Syst.* **1** 354

[13] Williams D L, Ainslie B J, Armitage J R, Kashyap R and Campbell R 1993 Enhanced UV photosensitivity in boron codoped germanosilicate fibres *Electron. Lett.* **29** 45

[14] Shu X, Allsop T, Gwandu B, Zhang L and Bennion I 2001 High-temperature sensitivity of long-period gratings in B–Ge codoped fiber *IEEE Photonics Technol. Lett.* **13** 818

[15] Fokine M 2002 Photosensitivity, chemical composition gratings, and optical fiber based components *PhD Thesis* Royal Institute of Technology, Stockholm

[16] Kim C-S, Han Y, Ha Lee B, Han W-T, Paek U-C and Chung Y 2000 Induction of the refractive index change in B-doped optical fibers through relaxation of the mechanical stress *Opt. Commun.* **185** 337

[17] Pissadakis S, Konstantaki M and Violakis G 2006 Recording of type IIA gratings in B–Ge codoped optical fibres using 248 nm femtosecond and picosecond laser radiation *Proc. ICTON 2006* p 183

[18] Bock W J, Chen J, Mikulic P and Eftimov T 2007 A novel fiber-optic tapered long-period grating sensor for pressure monitoring *IEEE Trans. Instrum. Meas.* **56** 1176

[19] Ng M N and Chiang K S 2002 Thermal effects on the transmission spectra of long-period fiber gratings *Opt. Commun.* **208** 321

[20] Ivanov O V and Rego G 2007 Origin of coupling to antisymmetric modes in arc-induced long-period fiber gratings *Opt. Exp.* **15** 13936

[21] Kalachev A I, Nikogosyan D N and Brambilla G 2005 Long-period fiber grating fabrication by high-intensity femtosecond pulses at 211 nm *J. Lightwave Technol.* **23** 2568

[22] Rego G M, Santos J L, Marques P V S and Salgado H M 2003 Study of the properties of arc-induced long-period gratings and Bragg gratings in B/Ge doped fibers *Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides, Technical Digest (Optical Society of America, 2003) (MD23)*

[23] Rego G and Ivanov O V 2007 Two types of resonances in long-period gratings induced by arc discharges in boron/germanium co-doped fibers *Opt. Lett.* **32** 2984

[24] Patrick H J, Kersey A D and Bucholtz F 1998 Analysis of the response of long period fiber gratings to external index of refraction *J. Lightwave Technol.* **16** 1606

[25] Bhatia V 1999 Applications of long period gratings to single and multiparameter sensing *Opt. Exp.* **4** 457

[26] Shu X and Zhang L 2002 Sensitivity characteristics of long-period fiber gratings *J. Lightwave Technol.* **20** 255

[27] Erdogan T 1997 Cladding-mode resonances in short- and long-period fiber grating filters *J. Opt. Soc. Am.* A **14** 1760

[28] Daimon M and Masumura A 2007 Measurement of the refractive index of distilled water from the near-infrared region to the ultraviolet region *Appl. Opt.* **46** 3811

[29] Rheims J, Koser J and Wriedt T 1997 Refractive-index measurements in the near-IR using an Abbe refractometer *Meas. Sci. Technol.* **8** 601

[30] Malitson I H 1965 Interspecimen comparison of the refractive index of fused silica *J. Opt. Soc. Am.* **55** 1205

[31] Shu X, Allsop T, Gwandu B, Zhang L and Bennion I 2001 Room-temperature operation of widely tunable loss filter *Electron. Lett.* **37** 216