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Ultrasensitive UV-tunable grating in all-solid photonic bandgap fibers

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ABSTRACT

We study the shift of a long period grating's resonance wavelength with UV induced refractive index changes in an all-solid photonic bandgap fiber. A long period grating is mechanically imprinted in an all-solid photonic bandgap fiber with Germanium doped silica high-index rods in a lower-index silica background. The index of the high-index rods is modified through UV exposure, and we observe that the long period grating's resonance shifts with the bandgaps. With a sensitivity of 21,000 nanometers per refractive index unit and a 8.8 nm resonance width changes of refractive index of 3×10^{-6} are in principle detectable

1. Introduction

Solid core photonic band gap fibers (SC-PBGFs) are photonic crystal fibers [1] in which a solid core of refractive index n_{low} is surrounded by a cladding consisting of a periodic arrangement of inclusions having a refractive index (n_{high}) higher than that of the background (n_{low}) (Fig. 1). SC-PBGFs can be made either by infiltrating high-index fluids into holey fibers [2], or by incorporating high-index Germanium doped silica inclusions in a lower-index silica background at the preform stage [3], leading after drawing to all-solid SC-PBGFs. The light guidance for SC-PBGFs can equivalently be explained in terms of antiresonant reflecting optical waveguide (ARROW) or bandgap effects [4–8]. In particular, SC-PBGFs have high and low transmission wavelength bands, which are delimited by the cutoffs of the high-index inclusions' modes [4,5], and are thus sensitive to the refractive index of the high-index inclusions [9]. This sensitivity, in particular when the inclusions are high-index fluids, can be used to create refractive index sensors [10] or temperature tunable filters [9]. While the wavelength shift of transmission bands can be quite dramatic with refractive index changes, the edges of the bands are not very sharp, so that the smallest detectable refractive index changes are not necessarily competitive with other sensing techniques [11]. By introducing sharper features in the transmission spectrum of SC-PBGFs this limitation could be overcome, under the condition that these features also shift with the transmission bands of the SC-PBGF with changes in refractive index.

Steinvurzel et al. showed that long period gratings (LPG) can be used for that purpose [12]. LPGs are corrugations of the refractive index or geometry of a fiber with a period much longer than the wavelength, of the order of hundreds of micrometers [13]. LPGs couple light between co-propagating modes, typically between a core mode and a cladding mode. When in a SC-PBGF, resonant wavelengths at which such coupling occur have a sensitivity to refractive index changes similar to that of the SC-PBGF's transmission bands themselves. Steinvurzel et al. predicted that this could lead to LPGs having extreme refractive index sensitivities when $n_{high} - n_{low}$ is small [12], and in particular to sensitivities that exceed those possible in index guiding LPGs [14] thanks to an almost perfect overlap of the cladding mode with the high-index inclusions.

In this paper, we verify Steinvurzel et al's prediction that LPGs in low-index-contrast SC-PBGFs have extreme sensitivities. We

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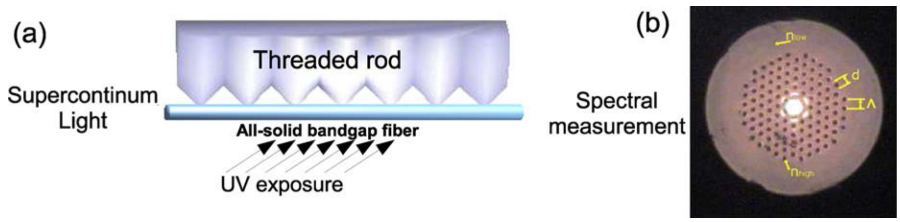

Fig. 1. (a) Principle of the experiment; and (b) optical micrograph of the SC-PBGF used in the experiment. Dimensions are given in the text.

do this using an all-solid silica SC-PBGF in which high-index regions are Germanium doped silica with an index-contrast of only 2%. We imprint a microbend LPG in these fibers and then expose the grating to intense UV light to modify the high-index inclusion's refractive index. We observe that the LPG resonances indeed shift with UV exposure, and with a sensitivity of 2.1×10^4 nm per refractive index unit (nm/RIU) we infer a detection limit of the order of 3×10^{-6} RIU [11].

2. Experimental setup

The principle of the experiment is illustrated in Fig. 1. A microbend LPG is imprinted on an all-solid SC-PBGF (Fig. 1b) using a threaded rod. The refractive index of the SC-PBGF's Germanium doped high index rod is then altered through exposure to intense UV light, while the transmission spectrum of the LPG is measured. The change in index of the high index rods causes the transmission bands of the SC-PBGFs and the LPG's transmission dips to shift in wavelength.

We use an all-solid SC-PBGF. The cladding of this fiber consists of a hexagonal array of high-index inclusions made out of 20% Germanium doped silica, in a silica background (Fig. 1). The fiber has a centre to centre distance between inclusions of $\Lambda \simeq 6.7$ µm, and rod diameter $d \simeq 3.2$ µm. Since Ge-doped silica is photosensitive, the refractive index of the high index regions can be tuned after fabrication by exposing the fiber to UV light [15].

Each Ge-doped inclusion has a cylindrical graded refractive index distribution described by

$$n(r) = \begin{cases} n_{\text{silica}} \cdot (1 + \Delta n_{GI} \cdot (1 - (r/r_o)^{\alpha}) & r < r_o \\ n_{\text{silica}} & r >= r_o \end{cases} \quad (1)$$

where r is the distance from rod's center, $\alpha \approx 4.7$, $\Delta n_{\text{GI}} \approx 0.0203$ and $r_o \approx 1.6$ µm. The transmission spectrum of the fiber before any UV exposure is shown in Fig. 2, and displays the typical high- and low-transmission windows of bandgap fibers. In the remainder of the article we will concentrate on the lowest order high-transmission window, above 1200 nm.

Two experiments were carried out: In the first experiment, we simply demonstrated our ability to modify the refractive index of the Ge-doped rods through exposure to UV light, which was observed through the resulting wavelength shift in the transmission bands. For this, we exposed an 18 cm long section of hydrogen-loaded [16,17] SC-PBGF to UV light using a frequency doubled continuous-wave Argon-ion laser (244 nm, ~80 mW). The laser light was focused with a cylindrical lens on the fiber so as to have a spot size of the same size as the fiber diameter. The laser spot was then swept a number of times over a length of 10.5 cm of the fiber using a translation stage. Total exposure after each sweep was calculated using the sweep time, measured laser power and measured spot size.

In the second experiment, a new piece of hydrogenated SC-PBGF was placed between a stainless steel threaded rod and an aluminium frame, and butt-coupled to a supercontinuum source and an optical spectrum analyzer (Fig. 3). The threaded rod creates a 5 cm long microbend LPG with 0.7 mm periodicity. The SC-PBGF was then exposed to UV using the same method as in the first experiment, but with sweeps covering the length of the LPG only.

3. Results

Fig. 4 shows the results for our first experiment, in which we measure the evolution of the edge of the lowest order transmission window with total UV exposure, without an LPG. Each sweep lasts 23 min, with an estimated deposited energy of ~55 J/cm^2 per sweep. A shift of ~119 nm is obtained for a total UV energy of ~500 J/cm^2 after nine sweeps. The shift in bandgap is due to the UV-induced refractive index change in SC-PBGF, and is consistent with previous results [15], demonstrating our setup can successfully tune the refractive index of the Ge-doped rods. As noted in Ref. [15], with UV exposure the short wavelength edge of the transmission bands are red-shifted, while the long wavelength edge remains constant to first order. This is because the fiber is exposed to UV light only over about half the total fibre length; the unexposed parts of the fiber have low transmission at wavelengths longer than the unperturbed band edge. We also note that the band edges become slightly less sharp with successive exposures. This may indicate that the exposure across the fiber is inhomogeneous, an effect that is expected from the absorption of the UV light across the fiber.

Fig. 5 shows the transmission spectrum of the SC-PBGF with the microbend LPG, before any UV exposure and after successive sweeps of 41 min duration, each corresponding to an energy of approximately 75 J/cm^2 per sweep. The dip in transmission due to the LPG shifts in wavelength with successive sweeps, at a rate comparable to that of the edge of the band. However, the feature

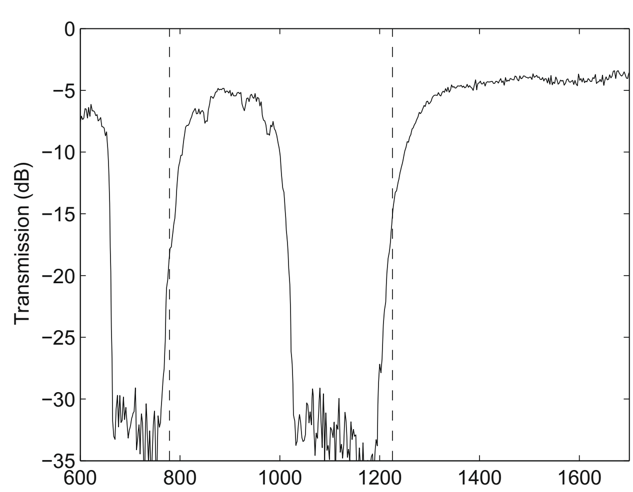

Fig. 2. Transmission spectrum of the unexposed SC-PBGF, without grating. Dashed vertical lines are the cutoff-wavelengths of the lowest order modes of a single high-index inclusion (cf. text).

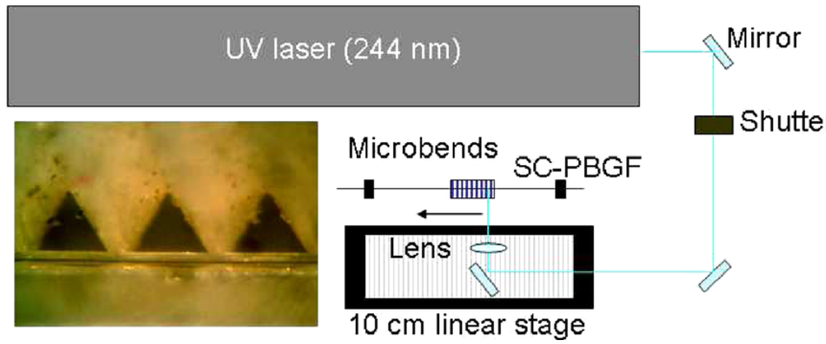

Fig. 3. Schematic of the experimental setup. Bottom left, detail of the threaded rod applied to the SC-PBGF to generate the microbend LPG.

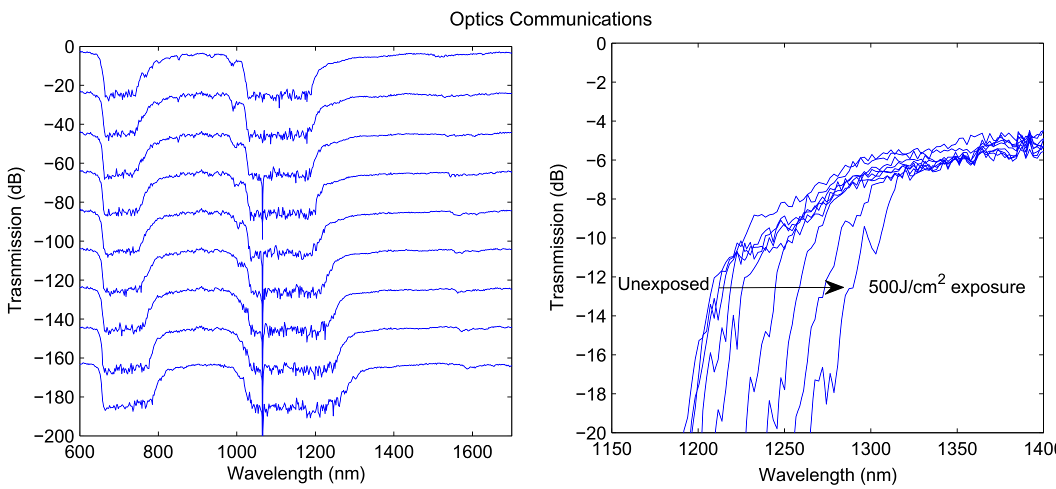

Fig. 4. Left: shift of transmission bands of the SC-PBGF with successive exposures to UV light. Top curve: transmission of unexposed fiber; bottom: after nine exposures of 55 J/cm^2 each. Successive curves are shifted by −20 dB for clarity. Right: detail of the transmission around the short wavelength edge of the first gap, for successive exposures.

of the LPG is much sharper, allowing greater precision in detecting shifts. The depth of the resonance dip decreases with increasing exposure, which we attribute to imperfections in the uniformity of the UV exposure, mostly as a result of the difficulty to maintain the fiber at the same position in the UV beam during sweeps. Below 200 J/cm^2 a very clear peak is maintained with a 3 dB width below 10 nm. For an exposure of 150 J/cm^2 (third curve in Fig. 5) we measure a shift of the resonance wavelength and of the band edge of 18 nm and a resonance width of 8.8 nm.

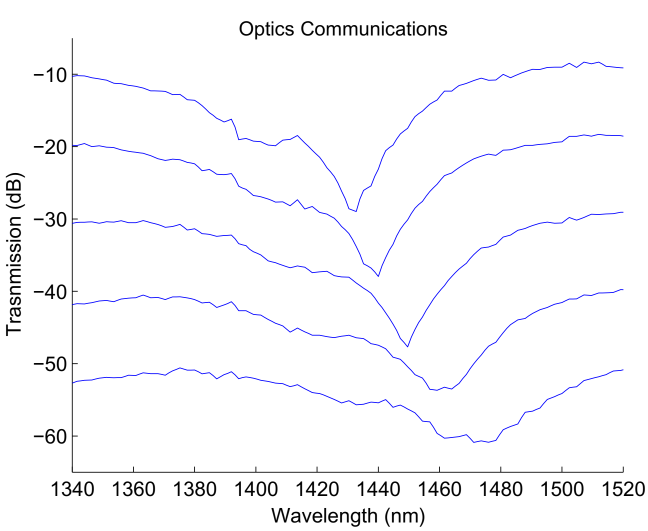

Fig. 5. Shift of the resonance of our microbend SC-PBGF LPG with successive UV exposures of 75 J/cm^2 each. Top: unexposed LPG; bottom: after four exposures. Successive curves are shifted by −10 dB for clarity.

4. Sensitivity

Our experiment demonstrate that the LPG resonance indeed shifts with the bands, even for low-index-contrast SC-PBGFs where that shift is very sensitive to refractive index change. For geometries that would use this effect for refractive index sensing, it is important to estimate the sensitivity of that shift, as well as the resulting smallest detectable change in refractive index.

The sensitivity can be inferred from the shift of the edges of the bands. According to the ARROW model [9] high-transmission bands of SC-PBGFs are delimited by the cutoffs of high index inclusions. Approximating the graded index profile by a step index rod, the lowest bands are delimited by the cutoff of the lowest order rod modes, having normalized frequency given by

$$V_c = \frac{2\pi r_0\sqrt{n_h^2 - n_l^2}}{\lambda} \simeq Z \tag{2}$$

where $n_h = n_{silica}(1 + \Delta n_{GI})$ and $n_l = n_{silica}$, and where for the two lowest order modes Z is a first zero of the Bessel function of order 0 or 1. The dashed lines in Fig. 1 show the corresponding cutoff-wavelengths. Eq. (2) implies that when the refractive index of the rods n_h change by δn, the cutoffs and thus the bands shift by $\delta\lambda$, related by

$$\frac{\delta\lambda}{\delta n} \simeq \frac{\lambda n_h}{n_h^2 - n_l^2} \quad (3)$$

Given that to first order the LPG resonance shifts with the bands [12], Eq. (3) can also be used to estimate the shift in the LPG's resonant wavelength. With our structure, we calculate a sensitivity defined by Eq. (3) of 2.1×10^4 nm/RUI, meaning that the measured band edge and LPG resonance shift of $\delta\lambda = 18$ nm after an exposure of 300 J/cm^2 corresponds to $\delta n \simeq 0.0025$. Considering that the LPG resonance dip has a 3-dB width of 8.8 nm (after exposure), the detectable change of refractive index assuming a signal to noise ratio of 60 dB would be 3×10^{-6} [11].

This is comparable to the best published fiber-based refractive index sensing devices, and can be improved in particular by designing the LPG to have narrower resonances. Our results represent an order of magnitude improvement in sensitivity compared to previous studies of LPGs in SC-PBGFs [12], due to the use of smaller index-contrast high-index inclusions.

5. Conclusions

We have studied the wavelength shift of LPG resonances in an all-solid, low-index-contrast SC-PBGF with induced refractive index changes. In agreement with earlier predictions [12], we have demonstrated that LPG resonances follow the bands when the refractive index of the high-index inclusion is modified, even for small index-contrasts where the sensitivity of the bands to refractive index is very large. We demonstrated that this large sensitivity in conjunction with the small resonance width of LPGs leads to detectable refractive index changes as small as 3×10^{-6}. While we have used an all-solid SC-PPBGF to explore the potential of LPGs in low-index-contrast SC-PBGFs, the most promising application lies in refractive index sensing, with high-index fluid infiltrated photonic crystal fibers.

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References

[1] Ph. Russell, Science 299 (17) (2003) 358.
[2] R.T. Bise, R.S. Windeler, K.S. Kranz, C. Kerbage, B.J. Eggleton, D.J. Trevor, in: OSA Trends in Optics and Photonics (TOPS), Optical Fiber Communication Conference, Technical Digest, Post Conference Edition, Optical Society of America, Washington DC, vol. 70, 2002, p. 466.
[3] F. Luan, A.K. George, T.D. Hedley, G.J. Pearce, D.M. Bird, J.C. Knight, P.St.J. Russell, Opt. Lett. 29 (2004) 2369.
[4] N.M. Litchinitser, A.K. Abeeluck, C. Headley, B.J. Eggleton, Opt. Lett. 27 (18) (2002) 1592.
[5] T.P. White, R.C. McPhedran, C.M. de Sterke, N.M. Litchinitser, B.J. Eggleton, Opt. Lett. 27 (22) (2002) 1977.
[6] P. Steinvurzel, C.M. de Sterke, M.J. Steel, B.T. Kuhlmey, B.J. Eggleton, Opt. Exp. 14 (19) (2006) 8797.
[7] J. Laegsgaard, J. Opt. A – Pure Appl. Opt. 6 (2004) 798.
[8] T.A. Birks, J.A. Pearce, D.M. Bird, Opt. Exp. 14 (20) (2006) 9483.
[9] N.M. Litchinitser, S.C. Dunn, P.E. Steinvurzel, B.J. Eggleton, T.P. White, R.C. McPhedran, C.M. de Sterke, Opt. Exp. 12 (8) (2004) 1540.
[10] N.M. Litchinitser, E. Poliakov, Appl. Phys. B 81 (2005) 347.
[11] I.M. White, X. Fan, Opt. Exp. 16 (2008) 1020.
[12] P. Steinvurzel, E.D. Mägi, B.J. Eggleton, Opt. Lett. 31 (2006) 2103.
[13] A.M. Vengsarkar, P.J. Lemaire, J.B. Judkins, V. Bhatia, T. Erdogan, J.E. Sipe, J. Lightwave Technol. 14 (1996) 58.
[14] L. Rindorf, O. Bang, J. Opt. Soc. Am. B. 25 (2008) 310.
[15] Long Jin, Zhi Wang, Qiang Fang, Yange Liu, Bo Liu, Guiyun Kai, Xiaoyi Dong, Opt. Exp. 15 (23) (2007) 15555.
[16] J. Albert, B. Malo, F. Bilodeau, D.C. Johnson, K.O. Hill, Y. Hibino, M. Kawachi, Opt. Lett. 19 (1994) 387.
[17] W.X. Xie, P. Niay, P. Bernage, M. Douay, J.F. Bayon, T. Georges, M. Monerie, B. Poumellec, Opt. Commun. 104 (1993) 185.