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ULTRASENSITIVE UV-TUNABLE GRATING IN ALL SOLID PHOTONIC BANDGAP FIBERS

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ABSTRACT

We demonstrate ultra-high sensitivity of a long period grating's resonance wavelength to 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 a sensitivity of 21,000 nanometers per refractive index unit with a 8.8nm resonance width, leading to detectable changes of refractive index of $3\cdot10^{-6}$.

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 cutoff 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 aren't very sharp, so that the smallest detectable refractive index changes aren't 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. It had been predicted that this could lead to LPGs having extreme refractive index sensitivities when n_{high}-n_{low} is small [12]. Here, we study the sensitivity to refractive index changes of a microbend LPG in a low index-contrast all-solid SC-PBGF. We demonstrate a sensitivity of $2.1.10^4$ nm per refractive index unit (nm/RIU), leading to a detection limit of the order of 3.10^{-6} RIU [11].

2. Experimental setup

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 $\Lambda\simeq6.7\mu m$, and rod diameter $d\simeq3.2\mu m$. 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 [14].

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

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

where r is the distance from rod's center, $\alpha \approx 4.7$, $\Delta n_{GI} \approx 0.0203$ and $r_o \approx 1.6\mu m$. 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 1200nm.

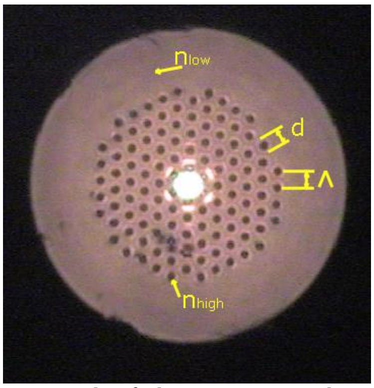

Fig. 1: Optical micrograph of the SC-PBGF used in the experiment. Dimensions are given in the text.

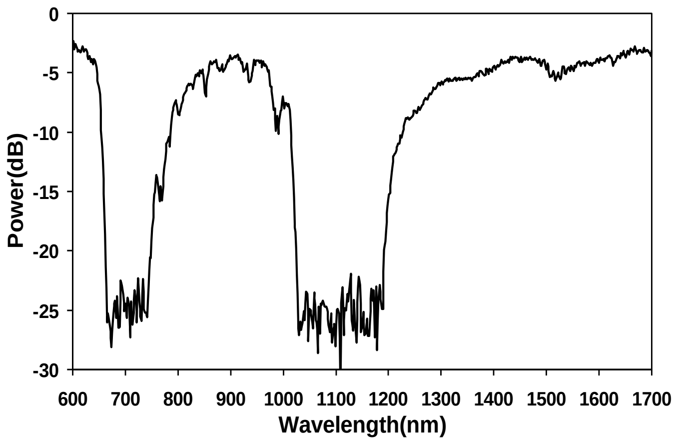

Fig. 2: Transmission spectrum of the SC-PBGF

In order to improve the photosensitivity of the Ge-doped inclusions, the SC-PBGF was hydrogen loaded [15,16].

Two experiments were carried out: In a 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 a hydrogen-loaded SC-PBGF to UV light using a frequency doubled continuous-wave Argon-ion laser (244nm, ~80mW). 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 10.5cm 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 a 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 5cm 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.

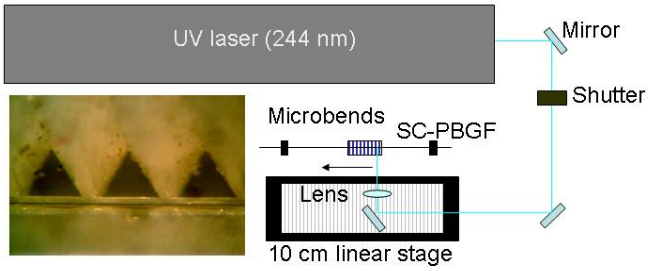

Fig. 3: Schematic of the experimental setup. Bottom left, detail of the threaded rod applied to the SC-PBGF to generate the microbend LPG.

3. Results

Figure 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 9 sweeps. The shift in bandgap is due to the UV-induced refractive index change in SC-PBGF, and is consistent with previous results [14], demonstrating our setup can successfully tune the refractive index of the Ge-doped rods.

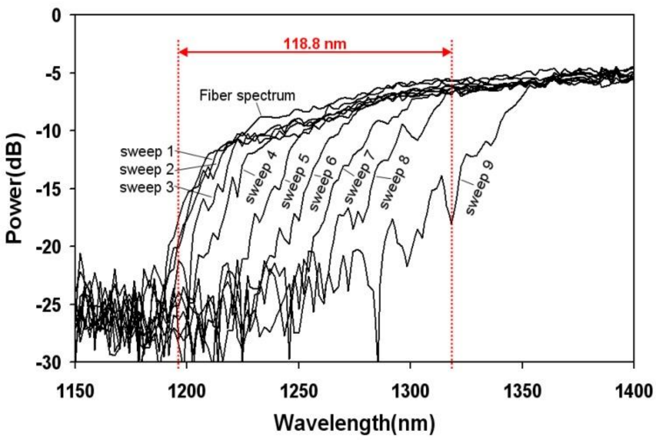

Fig. 4: Shift of transmission bands of the SC-PBGF after successive exposures to UV light.

Once our ability to tune bandgaps of the SC-PBGF was demonstrated, we proceeded to our second experiment. Figure 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 of the LPG is much sharper, allowing greater precision in detecting shifts. A shift of 53 nm has been obtained after a total UV energy of 300 J/cm^2. We also note that the depth of the resonance dip decreases, 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.

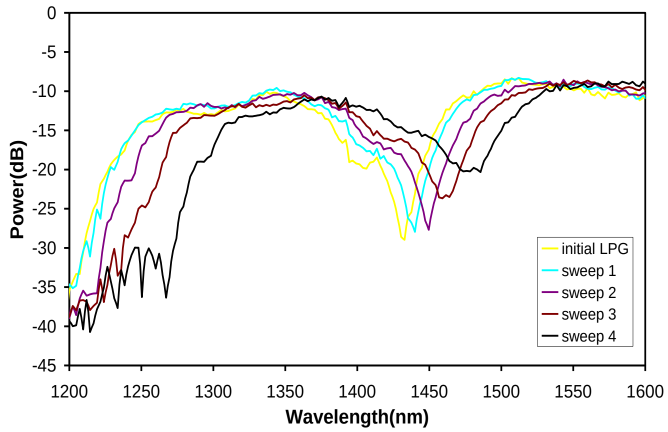

Fig. 5: Shift of the resonance of our microbend SC-PBGF LPG with succesive UV exposures.

4. Sensitivity

High-transmission bands of SC-PBGFs are delimited by the cutoffs of high index inclusions [9]. Approximating the graded index profile by a step index rod, the lowest band is delimited by the cutoff of the lowest order rod modes, having normalized frequency given by

$$V_c = \frac{2\pi r_0\sqrt{n_h^2 - n_l^2}}{\lambda} \simeq 2.405$$

Where $n_h = n_{silica}(1+\Delta n_{GI})$ and $n_l = n_{silica}$. To first order, a change $\delta\lambda$ of the wavelength of the edge of the band thus corresponds to a change δn in n_h given by

$$\delta n \simeq \frac{n_h^2 - n_l^2}{\lambda n_h}\,\delta\lambda$$

With $\delta\lambda$=53nm, we obtain $\delta n \simeq 0.0025$, or alternatively a sensitivity of $2.1\cdot10^4$nm/RUI. Considering that the LPG resonance dip has a 3-dB width of 8.8nm, the detectable change of refractive index assuming a signal to noise ratio of 60dB 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 realized a tunable LPG in an SC-PBGF, and have demonstrated its resonant wavelength is extremely sensitive to changes in refractive index of the high-index inclusions. Such an LPG could be used as a UV adjustable notch filter as-is. In such a case uniform exposure to maintain the depth and width of the LPG notch will be primordial. The most promising application remains however in sensing. We have demonstrated that our setup allows in principle to detect changes in refractive index of $3\cdot10^{-6}$. If the all-solid fiber is replaced by a fluid filled SC-PBGF, ultra sensitive fluid refractive index sensors can be achieved. The small detectable change results from the combination of the large sensitivity of the bandgaps with the narrow feature of the long period grating.

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