Applications of Long Period Gratings in Solid Core Photonic Bandgap Fibers

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Applications of Long Period Gratings in Solid Core Photonic Bandgap Fibers

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Abstract. Solid core photonic bandgap fibres are photonic crystal fibres with a solid core surrounded by high index inclusions. The guidance properties of these fibers are very sensitive to the refractive index of the inclusions, making them widely tunable and making them very promising for sensing applications. Combining these fibers with long period gratings unleashes their full potential, enabling narrow band notch filters tunable over hundreds of nm, refractive index sensors with sensitivity comparable to that of surface plasmon resonance sensors, but also the extraction of the full band diagrams of these bandgap fibres.

Keywords: Photonic crystal fibers, long period gratings, tunable filters, optical fiber characterization.

SOLID CORE PHOTONIC BANDGAP FIBERS

Solid core photonic bandgap fibers (SC-PBGFs) are microstructured optical fibers with a more or less periodic array of high-index inclusions (index n_{high}, radius ρ) in a lower-index background material (n_{low}), with a core consisting of a missing high index inclusion (Fig. 1). Light guidance in the core of these fibers can be attributed to bandgap effects, or antiresonant reflecting optical waveguide (ARROW) effects [1-5]. As predicted by the ARROW model, transmission and loss bands of SC-PBGFs are delimited by the cutoffs of the high index inclusions' modes, and thus occur at constant normalized frequencies $V=2\pi\rho/\lambda\,(n_{\text{high}}^2-n_{\text{low}}^2)^{1/2}$, where λ is the wavelength of light.As a consequence, changes in the refractive index of high-index inclusions n_{high} are accompanied by a shift in wavelength of the fiber's high-transmission regions. It was soon realized that this shift could be used for sensing, or for widely tunable filters and other tunable photonic devices [6]. One of the main limitations with SC-PBGF geometries in that context is that the features (transmission and loss bands) are broad in wavelength: taking the example of refractive index sensing applications, it is hard to define (and thus measure) the edge of gaps with precision, so that even though the gaps can shift dramatically with small index changes, the wavelength shift can only be determined with relatively poor precision, diminishing the overall sensitivity of the device.

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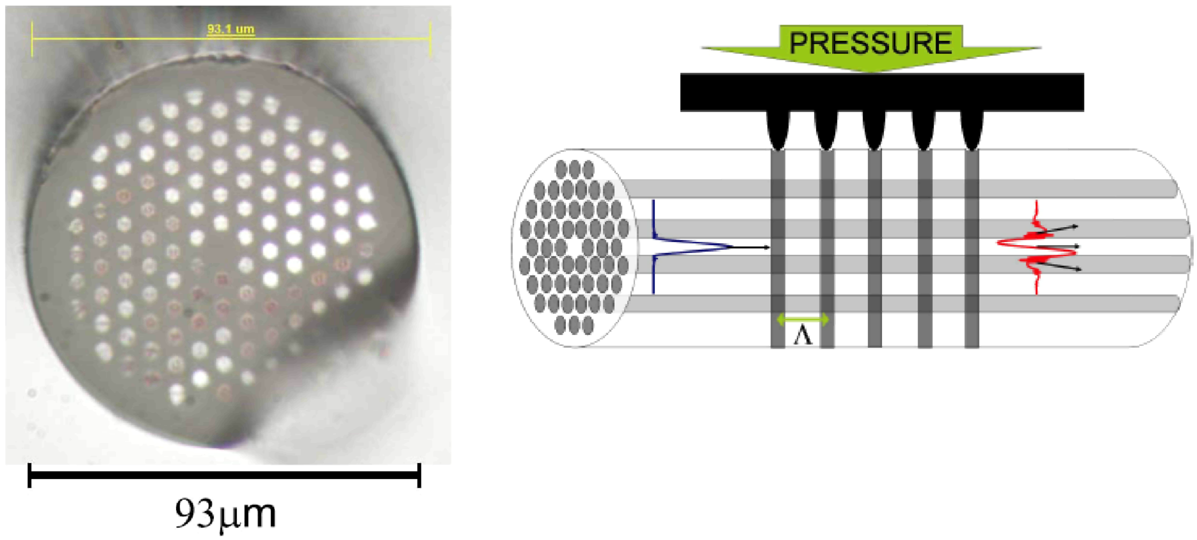

FIGURE 1. Left: micrograph of the all solid SC-PBGF used in our experiments. The fiber is made of fused silica, with the bright regions being Ge-doped. The refractive index difference between high and low index region is 2%. Right: Microbend induced long period grating as used in our proof of concept experiment.

LONG PERIOD GRATINGS

Sharper features that can be measured with higher accuracy and still follow large shifts in wavelength with changes in effective index can be introduced using additional resonant features, be it anti crossings with higher order modes [7], or more readily using long period gratings (LPGs)[8-10]. LPGs are periodic corrugations of the refractive index or geometry of a fiber, with periodicity Λ much larger than the wavelength (typically hundreds of micrometers) (Fig. 1). LPGs work by coupling two co-propagating modes, typically the fundamental core mode and cladding modes, whose effective indices satisfy the phase matching condition

$$\left| n_{eff}^{core} - n_{eff}^{clad} \right| = \frac{\lambda}{\Lambda}. \qquad (1)$$

When this phase matching condition is satisfied, light couples from the core mode to the cladding mode, resulting in a notch in the transmission curve of the core mode at the phase matching (or resonant) wavelength. The resonant wavelength of LPGs is thus sensitive to the effective index of cladding modes, and anything that will affect the effective index of the cladding modes will affect the resonant wavelength. To first order, a change in refractive index in part of the cladding will cause a proportional shift in the effective indices of cladding modes, resulting in a shift in resonant wavelength. This effect is the one exploited in conventional, index guiding LPG sensing schemes [11]. However, in a bandgap guiding geometry, in addition to this effect, the dispersion curves of the core and cladding modes are invariant in normalized frequency (within the ARROW model), which means that the LPG transmission dip will also shift along with the bands of the SC-PBGF [10]. While with LPG sensors in index guiding geometries there is a compromise between width of a resonance and its sensitivity to index change, the sensitivity and sharpness of LPG resonances in bandgap guiding fibers rely on different mechanisms, and can thus to a great extent be adjusted independently. This allows LPGs to be made with almost arbitrarily narrow transmission notches that can be tuned over hundreds of nanometers, or conversely to build refractive index sensors with sensitivities improved by an order of magnitude compared to LPGs in index guiding configurations, with capabilities comparable to that of surface plasmon resonant sensors. One could then imagine biochemical sensor tips exploiting LPGs in PBGFs with appropriate antibody/antigen treatment which would only require nanoliter sample sizes, be mass producible, biocompatible and usable in situ. There are, however, a number of important details to be taken into account:

LOW-INDEX INCLUSION BANDGAP FIBERS

First, this geometry only works when the inclusions are of refractive index higher than that of the background material, and is most sensitive when the refractive index contrast n_{high}-n_{low} is as small as possible [10]. As most biomedical samples are water-based solutions having a refractive index lower than that of polymers or glasses which can be drawn into fiber, applying LPGs in SC-PBGFs for biomedical applications seems doomed. This problem could be solved by using coatings with refractive indices higher than that of SC-PBGF's background material. We have indeed shown that photonic crystal fibers with high-index coated holes can be bandgap guiding, even if the refractive index inside the coated holes is lower than that of background material [12]. Similarly to other bandgap fibers, the bands of these coated fibers are delimited by cutoffs of the coated inclusions, and also shift with the (low) refractive index of the coated holes' content. We derived the expression of cutoffs of these coated inclusions to carry out a sensitivity analysis of coated SC-PBGFs for low index sensing.

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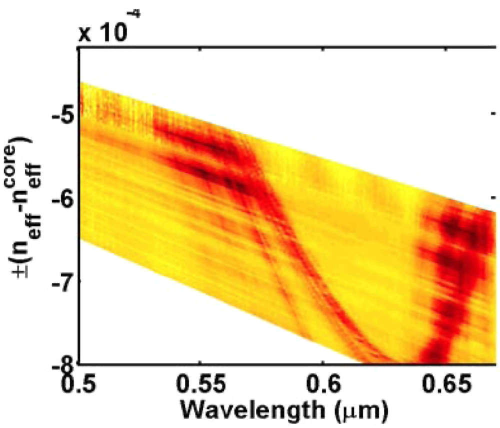

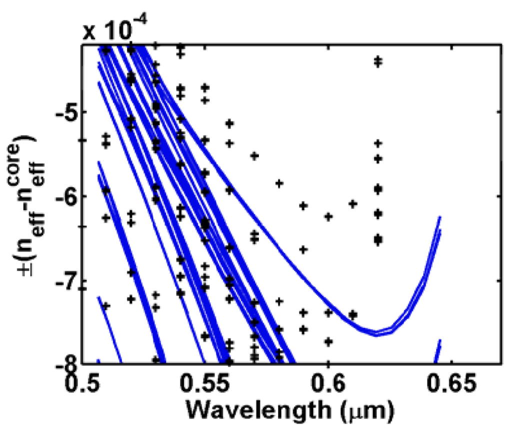

FIGURE 2. Experimentally reconstructed (left) and modeled (right) band structures of an all-solid solid-core photonic bandgap fiber. Blue curves correspond to plane wave simulations, crosses to multipole simulations. Both simulations and experimental results approximately agree, with discrepancies of approximately 10%.

EXPERIMENTAL RECONSTRUCTION OF PBGF BANDS

Second, the extreme sensitivity comes at a cost, which is that the effective index of cladding modes is also very sensitive to minute details of the PBGF's structure, so that design and manufacturing tolerances may prove to be too tight for practical, reproducible implementations. To investigate this issue, we have devised a method to experimentally reconstruct the bands of SC-PBGFs using acoustic long period gratings, and used it to measure the dispersion properties of cladding modes of an all-solid SC-PBGF consisting of germanium doped rods in a silica background [13] (Fig. 1). We then modeled the same fiber using different techniques; comparison between experimental results and the various models showed that it is very hard to predict the SC-PBGF's cladding mode band structure with an accuracy of better than 10% (Fig.2). While this makes *ab-initio* design of LPG sensors more difficult, our technique makes it possible to use the measured cladding mode dispersion to design SC-PBGF sensors and devices.

ULTRASENSITIVE UV-TUNABLE GRATING IN SC-PBGF

As a demonstration of the tuneability and sensitivity, we fabricated a microbend induced LPG in an all-solid SC-PBGF including germanium doped rods (Fig. 1). We hydrogen-loaded the fiber and exposed the LPG to uniform UV radiation to change the rods' refractive index along its entire length. Preliminary results show a 8.8nm wide 18dB transmission dip shifting by 3.10^4nm per refractive index unit (RUI), leading to detectable changes of refractive index of 3.10^{-6}RUI. While this result is for an all solid bandgap fiber, which as such could be used as notch filter that can be fine tuned after fabrication, the same geometry with identical sensitivity can be implemented using fluid filled holey fibers for refractive index sensing in biochemical contexts. This proof of concept demonstration was done without any design consideration, using a somewhat arbitrary combination of fibers and corrugation, so that we are confident the sensitivity can be improved further by appropriate design.

CONCLUSION

The sensitivity of a photonic bandgap fiber to the refractive index of its inclusions, combined with sharp features of long period gratings offer interesting possibilities for sensing and tunable filter application. While in principle a sensitivity improved by at least one order of magnitude over other fiber index sensing technologies could be achieved, some difficulties need to be overcome. In particular, for sensing applications in which low refractive index fluids need to be measured, appropriate coating geometries need to be devised. Furthermore, for every single fibre geometry careful analysis of the band structure and appropriate design of the LPG are required, which cannot solely be based on simulations. Our simple proof of concept experiment already showed very encouraging results, with detectable changes in refractive index of only 3.10^{-6}. This is comparable to the best published fiber sensing devices, and we are confident that there is still plenty of room for improvement.

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