Characteristics of Bragg Gratings in All-Solid Photonic Bandgap Fiber

Bai-Ou Guan, Zhi Wang, Yang Zhang, and Da Chen

Abstract—We report on fiber Bragg gratings in all-solid photonic bandgap fiber that was composed of a triangular array of high-index Ge-doped rods in pure silica background with fluorine-doped index-depressed layer surrounding the Ge-doped rod. Fiber Bragg gratings were photowritten with 193 nm ArF excimer laser and characterized for their response to strain, temperature, bending, and torsion. These gratings couple light from the forward core mode to not only backward core mode but also backward rod modes. This results in multiple resonance peaks in the reflection spectrum. All resonance wavelengths exhibited the same temperature and strain response with coefficient similar to that of Bragg gratings in standard single-mode fiber. The strength of the resonance peaks corresponding to the backward rod modes showed high sensitivity to bending and torsion.

Index Terms—Fiber Bragg gratings, fiber optic sensors, microstructured optic fibers, photonic bandgap fibers.

1. Introduction

Microstructured optical fibers (MOFs), silica fibers containing air holes running along the fiber axis, have been of great interest in the last decade because of their unique abilities such as endless single-mode transmission, enhanced nonlinearity. According to the mechanisms for guiding light, the MOFs are classified into two categories: index-guiding MOFs and photonic bandgap fibers (PBGFs). The PBGFs guide light in the central air-hole by coherent Bragg scattering of the air-hole lattices in the cladding region. Recently, a new type of PBGFs, all-solid PBGFs consisting of an array of high-index rods in a lower-index matrix and guiding light in a solid core formed by missing one or several rods, has attracted interests of the researchers.

Fiber gratings are one of the most extensively used photonic devices in telecommunication and sensing systems. Different methods have been developed for grating fabrication in the MOFs. Both fiber Bragg gratings (FBGs) and long-period gratings (LPGs) have been successfully fabricated in the index-guiding MOFs. LPGs were also formed in the PBGFs using mechanical pressure or micro-particles. Recently, FBGs were successfully inscripted in PBGFs using 248 KrF excimer laser.

In this paper, we present a demonstration of FBGs in PBGF that is composed of a triangular array of high-index Ge-doped rods with a fluorine-doped index-depressed layer surrounding the Ge-doped rod.

2. Bragg Grating Inscription

The fiber used in the experiments was manufactured by Yangtze Optical Fiber and Cable Co. Ltd., China. The inset of Fig. 1 shows the image of the cross section of the fiber. This fiber was composed of a triangular array of high-index Ge-doped rods in pure silica background and a core formed by omitting one of the rods. A fluorine-doped index-depressed layer was introduced to surround the Ge-doped rod to minimize the bending loss of the fiber. The diameter of the fiber was 175 μm and the pitch A was 5 μm.

Fig. 1. Experimental setup for Bragg grating inscription. Inset shows the image of the cross section of all-solid PBGF.

The experimental set-up for Bragg grating inscription is shown in Fig. 1. The PBGF was exposed to UV light from a 193 nm ArF excimer laser through a phase mask with period of 1065 nm. The energy and repeat frequency of the 193 nm laser were set to 8 mJ/pulse and 200 Hz, respectively. Fig. 2 shows the transmission and reflection spectrum of an FBG in the all-solid PBGF. From the
reflection spectrum, three groups of resonances peaks (Group A at 1540 nm, Group B at 1535 nm, and Group C at 1532 nm) were observed obviously.

3. Simulation

In our simulation, the index of the silica background was 1.4575. The index contrasts of the Ge-doped rod and fluorine-doped region to the background material were 2.6% and −0.6%, respectively. The pitch \( A \) was 5 \( \mu \)m. The outer diameters of Ge-doped rod and fluorine-doped layer were 2 \( \mu \)m and 4 \( \mu \)m, respectively.

The photonic band structures of the cladding were calculated by the fully-vector plane-wave method using the MIT plane-wave package\(^7\). Fig. 3 shows the photonic band structure of the cladding and the effective index of the core guided mode in the all-solid PBGF. There is a cladding mode band between the curves of the effective cladding index and the upper edge of the fundamental bandgap. The fundamental bandgap locates between \( \text{LP}_01 \) and \( \text{LP}_{11} \) rod modes bands at the wavelength region where the second bandgap exists, whereas \( \text{LP}_{11} \) rod modes band overlaps with other high order rod mode band (e.g. \( \text{LP}_{02} \)) at longer wavelength.

The core guided modes in the PBGFs are calculated by using a full-vector finite element method. As shown in Fig. 3, the dispersion curve of core mode well locates in the fundamental bandgap and below the core line (represents the refractive index of core). The mode field of a quarter is shown in the inset of the figure. Note that although most energy of core mode distributes in the pure silica region, some energy distributes in the Ge-doped high index rods around the core. This feature contributes to the mode couple between the core mode and rod modes by the FBG inscribed in the doped rods.

The resonance of the FBG in all solid PBGF occurs between the forward core mode and backward core or rod modes. The relationship of resonant wavelength and period of FBG can be presented as

\[
\lambda_{\text{res}} = (n_{\text{co}} + n_{\text{res}}) A_{\text{FBG}}
\]

where \( \lambda_{\text{res}} \) is the resonant wavelength, \( A_{\text{FBG}} \) is the period of the FBG, \( n_{\text{co}} \) and \( n_{\text{res}} \) are the effective index of forward core modes and backward resonant mode, respectively.

The relationship of resonant wavelength and period of FBG are shown in Fig. 4. The dash curve is the phase match condition of the resonance between forward and backward core mode. There is an individual resonant band below this curve. This band corresponds to the resonance between forward core mode and backward \( \text{LP}_{01} \) rod modes. Many resonant bands overlapping each other locate upon the core mode resonant curve. In our experiment, the period of the FBG is 532.5 nm. Then the resonant wavelength corresponding to the backward core mode is about 1545 nm in our simulation. Although the dispersion curves of the rod modes is quasi-continuous in photonic band, only the rod modes whose mode field mainly distributes in the rods near the core can effectively couple with the core mode. As a result, the resonant wavelength can be divided into some groups according the style of the rod modes.

According to the simulation, the weak peaks around 1544 nm in the reflection spectrum in Fig. 3 result from the resonance of backward \( \text{LP}_{01} \) rod modes. Group A peaks result from backward core mode resonance, and Group B and Group C peaks result from the resonances of backward...
higher order rod modes, such as LP_{02} and LP_{11} rod modes.

4. Response to Strain, Temperature, Bending and Torsion

4.1 Strain Response

To measure the strain response of the grating, both sides of one FBG were fixed onto translation stages with epoxy. The fiber was stretched with the translation stage. Fig. 5 shows the peak wavelength shift as function of axial strain. All resonance wavelengths exhibit the same linear response to the axial strain. The strain coefficient was estimated, using linear regression fits, as 1.03 pm/με, which is similar to that of FBGs in standard single-mode fibers. No obvious reflectivity fluctuation was detected in the experiment.

4.2 Temperature Response

To measure the temperature response of the grating, the fiber with the FBG was passed through a tube oven. The resonance wavelengths of the grating were recorded from the fiber with the FBG was passed through a tube oven. The resonance wavelengths exhibit the same linear response to temperature at a coefficient of 11.5 pm/°C, which is also similar to that of FBGs in standard fibers.

However, in the process of temperature response measurement, we observed the peak strength in Group B and Group C changed with temperature. The resonance peak strength as function of temperature was plotted in Fig. 7, where the peak strength was normalized to the spectrum of the broadband source to eliminate the effect of the power density fluctuation with wavelength. No obvious strength changes for peaks in Group A were observed. The reason for the peaks strength change with temperature needs further investigation.

4.3 Bending Response

A fiber containing the FBG was attached to 0.7-mm-thick 18-mm-wide 220-mm-long metal plate bent by depressing the center of the metal plate with a micrometer driver. Fig. 8 shows the peak strength as function of curvature. The resonance strength of the peaks in Group B and Group C showed high sensitivity to bending. This is expected from the nature that the peaks group B and C arise from the backward rod mode resonances. No obvious change was observed for the three strong peaks in group A, but the weak peaks at shorter wavelength side of these three strong peaks changed with bending. This denotes that these weak peaks in group A do not result from backward core mode resonance.

4.4 Torsion Response

To investigate response of the grating to torsion, one side of a FBG was glued onto a fixed stage, and another side was fixed onto a fiber rotator. The FBG was twisted with the rotator. No obvious wavelength shift for all resonance peaks was observed, whereas the strength of peaks in Group B and Group C changed with rotation, as plotted in Fig. 9. This may be explained by the facts that the FBG is inscribed in the Ge-doped high-index rods and Group B and Group C arise from rod mode coupling, but further investigation is needed for more deeply under-
standing the mode coupling characteristics in FBGs in the all-solid PBGF.

![Resonance strength change with axial rotation angle.](image)

**Fig. 9. Resonance strength change with axial rotation angle.**

## 5. Conclusion

The FBGs were photowritten in an all-solid PBGF consisted of an array of high-index Ge-doped rods in pure silica background with index-depressed layer surrounding the Ge-doped rod and were characterized for their response to strain, temperature, bending and torsion. In such FBGs, mode coupling occurs not only between the forward core mode and the backward core mode but also between the forward core mode and backward rod modes. As a result, the FBGs possess multiple resonance peaks in the reflection spectrum. These resonance peaks shows different response to the surrounding perturbations. All the resonance wavelengths exhibit the same temperature and strain response with coefficients similar to that of FBGs in standard single-mode fibers. The core mode resonances are insensitive to bending and torsion, whereas the strength of the rod mode resonances exhibits high sensitivity to bending and torsion. These properties have potential applications a for bending or torsion sensing and multi-parameter measurement. Further investigation is needed to explain the mechanism for the split of core mode resonance peak and the strength change of rod mode resonances with temperature.

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### References


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