FBG responses to polarization, SRI, temperature, and strain in silica-based multimode graded-index fiber

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In this work, fiber Bragg gratings (FBGs) are fabricated in commercially available multimode graded-index fiber using Noria FBG automation manufacturing system at 193 nm. Then, the properties of the FBG to polarization, surrounding refractive index (SRI), axial strain, and temperature are investigated among different mode groups and cross-mode groups in parabolic graded-index multimode fiber. It shows insensitive properties to the polarization and SRI, making the proposed FBG a good candidate for high-quality filters. Besides, the axial strain and temperature sensitivity do not depend on the mode under investigation.

Introduction

Multimode optical fiber (MMF) have attracted more and more attention due to their excellent properties, ease of installation and many potential applications in optical communications and fiber sensing [1]. Among multimode fibers (MMFs), the fiber with a parabolic graded-index refractive index profile has received much attention due to its low modal dispersion property. For sensing purpose, fiber Bragg gratings are a classical, efficient, and convenient technology. To date, there are some articles focusing on the characteristics of the fiber Bragg grating spectra in graded-index silica-based multimode fibers [2,3]. The FBG in graded-index MMF is also used in sensing applications such as, angle measurement [4], and radiation measurement [6]. However, although, the fiber is multimode, these articles are all focused on the Bragg wavelength shift of the fundamental mode only. Investigation of the higher order modes properties is nevertheless interesting to understand the connection between the multi-peak like spectra and the variable parameters in the graded-index MMF.

In this work, firstly, we inscribe FBGs in the graded-index silica-based multimode fiber using the phase mask technique. The locations of the peak resonance wavelengths are numerically computed, and are correlated with the experimental ones. Then the FBG responses to the polarization, surrounding refractive index, applied strain and temperature are investigate among different mode groups and cross-mode groups.

FBG fabrication

We use a commercially available graded-index MMF (ThorLabs 50/125), with a core diameter, a cladding diameter and a numerical aperture of 50 µm, 125 µm and 0.2, respectively [7]. The FBG fabrication system is a Noria FBG automation manufacturing sytem [8] working at 193 nm. The period of the phase mask is 1075 nm and the length of grating is 9 mm. A super-wideband light source (from Amonics) across 1250 nm to 1650 nm, an optical spectrum analyser (AQ6370 from YOKOGAWA) with a resolution of 0.02 nm in 600 nm to 1700 nm, and a multimode coupler are used to measure the reflection spectrum of the FBG in the GI MMF fiber. It is important to note that this OSA can be directly connected with multimode fibers due to the free space input structure [9]. Figure 1 depicts the reflection spectrum of the FBG, which shows a multi-peak like spec-

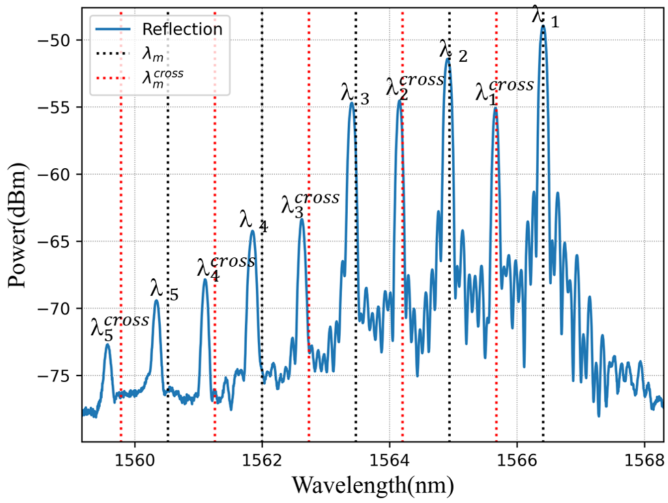

Figure 1 - *The reflection spectrum of FBG in GI multimode fiber (ThorLabs 50/125).*

tra due to the multimode properties of the fiber. Although there are many modes in this graded-index fiber, they can be clustered in groups of modes having nearly the same propagation constant and refrred to as mode group [2, 10]. The effective refractive index n_m of the m^{th} mode group is expressed as [2, 11]

$$n_m = n_{\text{co}}\sqrt{1-4m\Delta/\mathrm{V}}, \tag{1}$$

where the normalized frequency $V = 2\pi a\mathrm{NA}/\lambda$, $\mathrm{NA} = n_{\text{co}}\sqrt{2\Delta}$ is the numerical aperture, and $\Delta = (n_{\text{co}}^2 - n_{\text{cl}}^2)/(2n_{\text{co}}^2)$ is the index difference between core and cladding. The cross-mode is a mode excited by two neighboring mode groups m and $m+1$, and the resonance wavelength of the m^{th} mode group and m^{th} cross-mode group are:

$$\lambda_m = 2n_m\Lambda \tag{2}$$

$$\lambda_m^{\text{cross}} = (n_m + n_{m+1})\Lambda \tag{3}$$

with $\Lambda = 537.5\,\text{nm}$. In Fig. 1, the black dotted lines and red dotted lines represent the computed resonance wavelengths of the mode groups and the cross-mode groups, respectively. It is clear that the experimental resonance wavelengths locations have a good agreement with the computed ones.

Sensitivity to polarization, SRI, applied strain and temperature

To characterize the FBG properties of the GI multimode fiber, we investigate their polarization dependence, surrounding refractive index (SRI) response, axial strain sensitivities, and temperature sensitivities in different mode groups. As shown in Fig. 2 (a), with orthogonally polarized launch conditions (polarization 1 and polarization 2), the spectra show a maximum 1.7 dB polarization-dependent-loss for different mode groups, and the lower-order mode groups shows a more stable polarization response compared with the higher-order mode groups. For SRI response, the FBG spectral profile presents a stable response among the amplitude and the wavelength shift as shown in Fig. 2 (b). It means that this kind of FBGs presents a high stability to the refractive index change of the surrounding environment. The responses of FBG to axial strain among different mode groups and

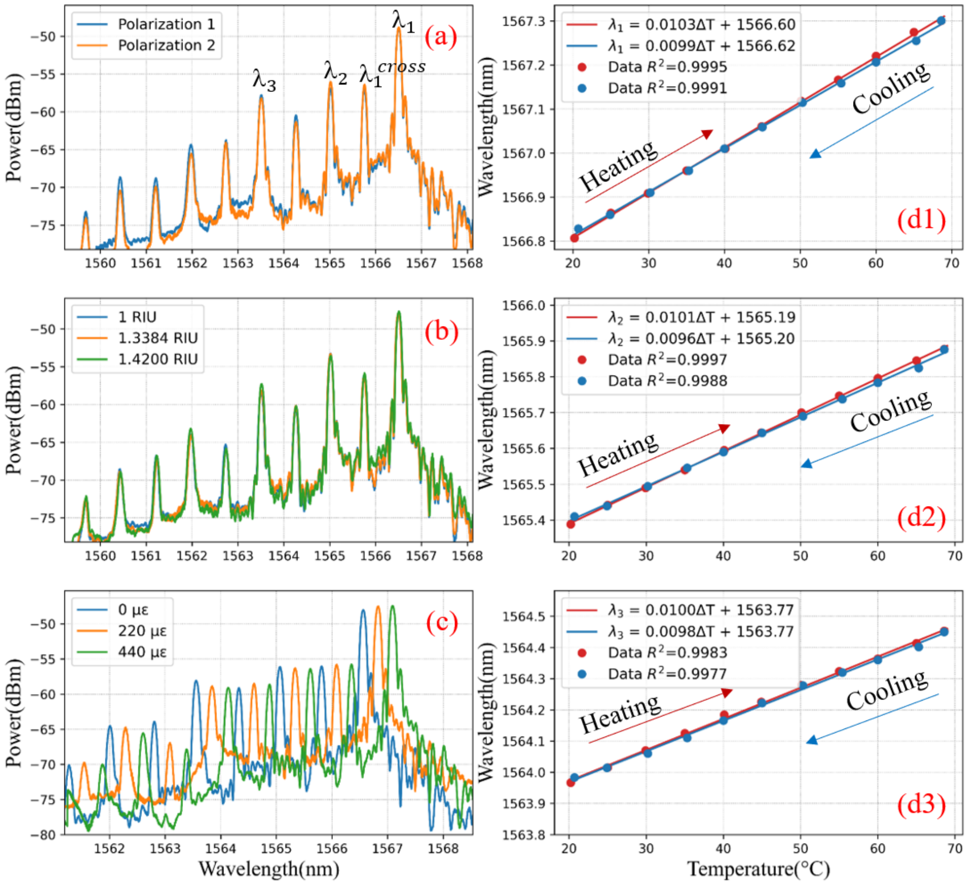

Figure 2 - *The responses of the FBG in ThorLabs 50/125 GI multimode fiber to (a) polarization, (b) SRI, (c) axial strain, and (d) temperature.*

cross-mode groups are shown in Fig. 2 (c). The axial strain responses with approximately the same sensitivity of 1.21 pm/µε over the range of 0 µε to 440 µε is demonstrated for the different mode groups and cross-mode groups.

To measure the temperature sensitivities, a climate chamber (Weiss SB 22 [12]) is used to control the temperature and humidity during the experiment, with a temperature range of –40 °C to 180 °C and a relative humidity range of 10 % to 98 %. From Fig. 2 (d1) to (d3), we use a range of temperatures from 20 °C to 70 °C, and the humidity is kept approximately constant around 60 % to measure the temperature response of FBG in heating process (red line) and cooling process (blue line) in different mode groups (first mode group λ_1, the second mode group λ_2, and the third mode group λ_3). It is clear that: 1) the temperature sensitivity is practically independent of the monitored mode for both heating process and cooling process, 2) all modes evolve linearly with the temperature with a coefficient of determination R^2 always higher than 0.99, 3) in the heating up process, the mean value of the temperature sensitivity of the each mode group is approximately 10.3 pm/°C, and 4) in the cooling down process, the mean value of the temperature sensitivity of the each mode group is approximately 9.8 pm/°C.

Conclusion

The FBG is successfully inscribed in the graded-index multimode fiber (ThorLabs 50/125) using the phase mask technique and a excimer laser at 193 nm. The locations of the resonance wavelengths of each mode group and cross-mode group are calculated in theory. Comparing the experimental spectra with the computations shows that the experimental resonance wavelength locations of the mode groups and the cross-mode groups have a good agreement with the computed results.

To highlight the characteristics of the FBG, we investigate its response to polarization, SRI, applied strain and temperature among different mode groups and cross-mode groups. It is seen that this kind of FBG is insensitive to the polarization of the launch light and to the change of the surrounding refractive index. It is found that the strain and temperature sensitivities do not depend on the mode group or cross-mode group under investigation, with a value around 1.21 pm/$\mu\varepsilon$ for the axial strain sensitivity and 9.98 pm/°C for the temperature sensitivity.

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