Hydrostatic pressure dependence of FBG inscribed in perfluorinated GI-POF

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Abstract: We investigate the hydrostatic pressure dependence of the Bragg wavelength of a fiber Bragg grating (FBG) inscribed in a perfluorinated POF at 1550 nm. At 0.5 MPa, the Bragg wavelength increased with time and became almost constant ~150 min later. The pressure-dependence coefficient without considering the time constant was calculated to be 1.3 nm/MPa, which is over 5 times the values of other types of POF-FBGs. The pressure-dependence coefficient was then measured to be –0.13 nm/MPa, the absolute value of which was comparable to those of other POF-FBGs, but the sign was opposite.

1. Introduction

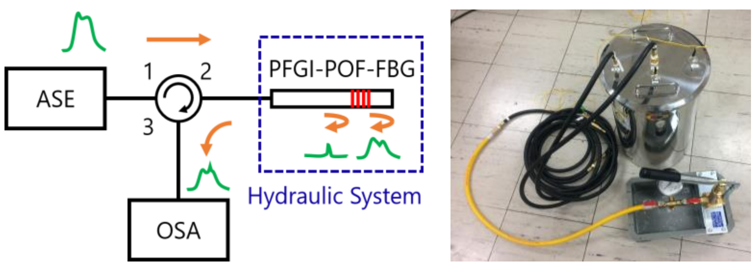
Fiber Bragg gratings (FBGs) have been exploited to develop fiber-optic sensors for strain, temperature, humidity, refractive index, and many other physical parameters [1]. Pressure sensing is one of the major targets in FBG research community, and a number of relevant results have been reported using FBGs inscribed in glass optical fibers [2–5]. In the meantime, as polymeric materials are generally softer than glass materials, higher pressure sensitivities have been achieved using FBGs inscribed in some types of plastic optical fibers (POFs) [6–8]. For instance, at telecom wavelength, FBGs in a single-mode (SM-) poly(methyl methacrylate) (PMMA-) POF [7] and a multimode microstructured (MM-m) POF [8] are reported to have pressure sensitivities of ~0.25 nm/MPa (corresponding to a fractional sensitivity (Bragg wavelength shift divided by the initial Bragg wavelength for fair comparison) of ~163×10^{-6}/MPa) and ~0.1 nm/MPa (corresponding to ~64×10^{-6}/MPa), respectively, the absolute values of which are approximately ~82 and ~32 times larger than the typical value of an FBG in a silica single-mode fiber (SMF) (–3.1 pm/MPa, corresponding to -2.0×10^{-6}/MPa) [9]. However, such conventional POF-FBGs suffer from extremely high propagation loss at 1550 nm.

Recently, in order to tackle this problem, some research groups [10,11] have developed an FBG inscription technique in perfluorinated graded-index (PFGI-) POFs [12] with relatively low propagation loss even at 1550 nm, where amplified spontaneous emission (ASE) can be directly used as a wideband light source for interrogating the Bragg wavelength. Besides, the core refractive index of PFGI-POF-FBGs is close to that of water, which is beneficial for some bio-sensing applications [13]. To date, the strain, temperature, and humidity sensing characteristics of PFGI-POF-FBGs have been investigated [10,14], but no reports have been provided regarding their pressure dependence.

In this paper, at 1550 nm, we investigate the hydrostatic pressure dependence of the Bragg wavelength of a PFGI-POF-FBG for the first time to the best of our knowledge. At 0.5 MPa, the Bragg wavelength increases with time and, ~150 min later, becomes almost constant. The pressure-dependence coefficient is then measured to be –0.13 nm/MPa, which is compared with those of a silica fiber and other types of plastic fibers.

2. FBG inscription and measurement setup

A 2-mm-long FBG was inscribed in a 1.3-m-long PFGI-POF. The PFGI-POF (GigaPOF-50SR, Chromis Fiberoptics) has a three-layered structure: core (diameter: 50 μm; refractive index: ~1.35), cladding (diameter: 70 μm), and overcladding (diameter: 490 μm). The core and cladding consist of doped and undoped amorphous fluoropolymer (CYTOP®), respectively, the water absorption of which is negligibly small [15], and the overcladding is composed of



(a) (b)

Fig. 1. (a) Experimental setup. ASE: amplified spontaneous emission; OSA: optical spectrum analyzer. (b) Photograph of hydraulic system.

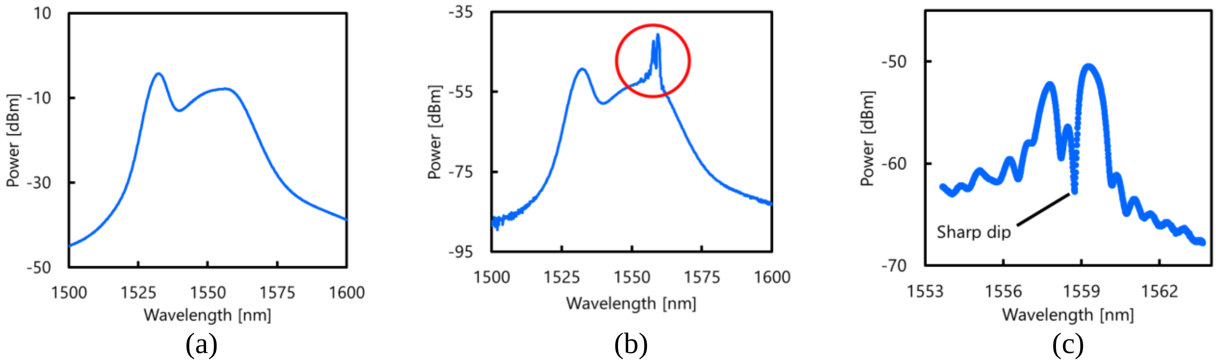


Fig. 2. (a, b) Measured optical spectra of the ASE output and the reflected light, respectively. (c) Magnified view of the red-circled part in (b), around the FBG-induced peaks.

polycarbonate. The optical propagation loss is relatively low (~0.25 dB/m) even at 1550 nm. The FBG was inscribed without removal of the overcladding using a femtosecond laser system (High Q femtoREGEN) operating at 517 nm, with a 220-fs pulse duration, 1-kHz repetition rate and laser pulse energy of ~100 nJ [10]. The PFGI-POF was mounted on an air bearing translation system (Aerotech) for accurate two-axis motion and the laser beam was focused from above using a long working distance x50 objective (Mitutoyo). Accurate synchronization of the laser pulse repetition rate and stage motion allowed for plane-by-plane grating inscription, writing the grating to the desired length and index modulation value.

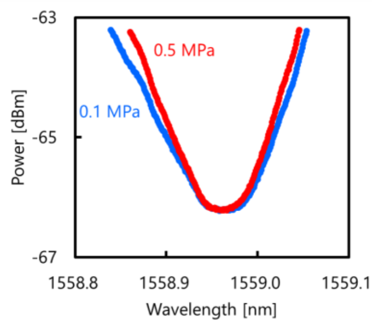


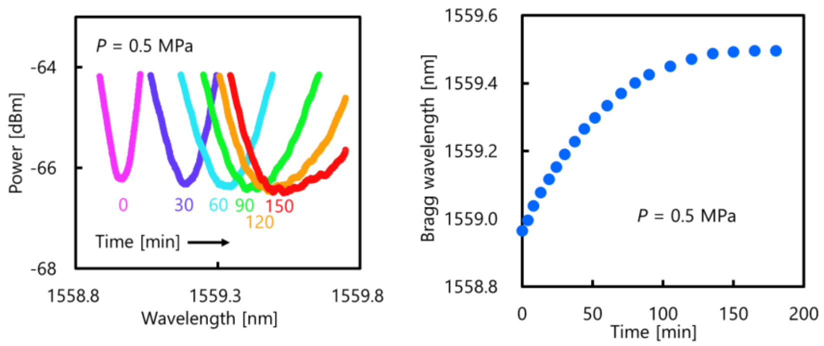
Fig. 3. FBG-reflected spectra around the sharp dip measured at 0.1 MPa (blue) and 0.5 MPa (red).

Figure 1(a) shows an experimental setup for measuring the Bragg wavelength of the FBG. All the optical paths except the PFGI-POF were silica SMFs. The output from an ASE source was injected into the PFGI-POF, and the reflected light from the FBG was guided via an optical circulator to an optical spectrum analyzer. The PFGI-POF was placed in a hydraulic system (Fig. 1(b)), in which the hydrostatic pressure P can be controlled from 0.1 MPa (atmospheric pressure) to 0.5 MPa. One end of the PFGI-POF was connected to a silica SMF using a so-called butt-coupling technique [16], and the other end was kept open.

3. Experimental results

First, we measured the optical spectra of the ASE output and the FBG-reflected light, as shown in Figs. 2(a) and (b). The spectrum of the light Fresnel-reflected at the open end of the POF was overlapped with the FBG-reflected spectrum, which was still clearly observed at 1559 nm. The magnified view of the FBG-reflected spectrum around its peaks is shown in Fig. 2(c). Multiple peaks and dips, caused by the multimode nature of the POF [17], were observed in the spectrum. The wavelength of any peak or dip (including the highest peak) could be selected as a Bragg wavelength, but here, the clear and sharpest dip at 1558.97 nm was used to enhance the measurement accuracy.

Subsequently, we measured the FBG-reflected spectra around the dip before and after the pressure P was abruptly (within 20 s) increased from 0.1 MPa (atmospheric) to 0.5 MPa, as shown in Fig. 3. Although the linewidth of the dip was slightly reduced, the Bragg wavelength shift was negligibly small. After that, however, when the pressure P was maintained at 0.5 MPa, the Bragg wavelength shifted as time proceeded, as shown in Fig. 4(a). Figure 4(b) shows the temporal dependence of the Bragg wavelength at 0.5 MPa. The Bragg wavelength increased with time and, approximately 150 min later, became almost constant. A total Bragg wavelength shift was approximately 0.5 nm. The positive dependence of the Bragg wavelength on pressure was the same as those of other types of POFs [7,8], but the wavelength shift accompanying a time constant of over several tens of minutes was first observed in this measurement. Such a long time constant appears to be caused by the structure of the PFGI-POF, which is composed of two different polymer materials (CYTOP and polycarbonate). Suppose that the Bragg wavelength dependence on pressure without considering



(a) (b)

Fig. 4. (a) Temporal dependence of the FBG-reflected spectrum at 0.5 MPa. (b) Temporal dependence of the Bragg wavelength at 0.5 MPa.

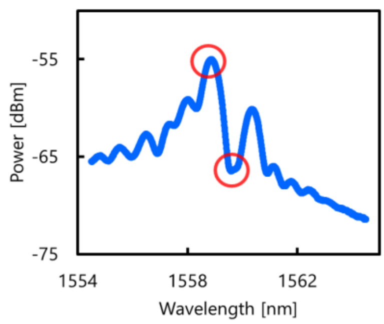
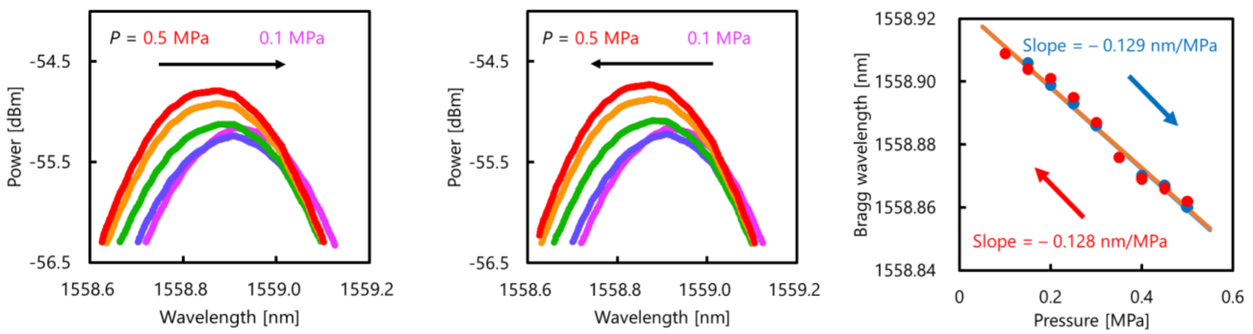


Fig. 5. FBG-reflected spectrum measured after 0.5-MPa pressure was applied for 240 minutes.



(a) (b) (c)

Fig. 6. (a, b) Pressure dependences of FBG-induced spectra around the sharp peak when the pressure was decreased from 0.5 MPa to 0.1 MPa and when the pressure was then increased from 0.1 MPa to 0.5 MPa. (c) Measured Bragg wavelength dependence on pressure; the red points indicate the data when the pressure was decreased, and the blue points are the data when the pressure was then increased. The two lines are their linear fits, which are overlapped and appear to be one line in this figure.

the time constant (i.e., when the Bragg wavelength is measured at each pressure after waiting for a sufficiently long time for the signal to be constant) is linear, the dependence coefficient is calculated to be ~1.3 nm/MPa (corresponding to ~860×10^{-6}/MPa). This value is ~5.2 and ~13 times larger than those of the FBGs in an SM-PMMA-POF [7] and MM-mPOF [8], respectively. Note that the linewidth of the dip increased with time, and compared with Fig. 2(c), the FBG-reflected spectrum was so much changed (Fig. 5) that the dip was no longer sharp, therefore we used the highest peak for the following measurements.

Finally, the pressure dependence of the Bragg wavelength (measured using the highest peak, as discussed above) was measured in a short period (< 1 min). Figures 6(a) and (b) show the pressure dependences of the FBG-reflected spectra when the pressure P was decreased from 0.5 MPa to 0.1 MPa and when P was then increased from 0.1 MPa to 0.5 MPa, respectively. In both cases, as the pressure became higher, the Bragg wavelength grew shorter. The spectral power change seems to have been caused by the multimode nature of the POF. The Bragg wavelength was then plotted as a function of pressure P, as shown in Fig. 6(c). Irrespective of the direction of the pressure change, the Bragg wavelength exhibited a negative dependence on pressure with a coefficient of –0.13 nm/MPa (corresponding to a fractional sensitivity of -84×10^{-6}/MPa). This absolute value is ~42, ~0.52, and ~1.3 times larger than those of the FBGs in a silica SMF [9], SM-PMMA-POF [7], and MM-mPOF [8], respectively. The negative dependence, which is opposite to those of other types of POFs [7,8], will be discussed elsewhere (due to the space limitation).

4. Conclusion

The hydrostatic pressure dependence of the Bragg wavelength of an FBG inscribed in a PFGI-POF was investigated at 1550 nm. The Bragg wavelength shift was negligibly small shortly after the pressure was abruptly increased to 0.5 MPa. However, when the FBG was maintained at 0.5 MPa, the Bragg wavelength increased with time and became almost constant ~150 min later. A simply calculated pressure-dependence coefficient was 1.3 nm/MPa, which is over 5 times the values of other types of POF-FBGs. The pressure-dependence coefficient was then measured to be –0.13 nm/MPa, the absolute value of which was not largely different from those of other POF-FBGs, but the sign of the pressure-dependence coefficient was negative unlike other POF-FBGs. Our results indicate the feasibility of high-sensitivity pressure sensing with a short response time by removing the overcladding of the PFGI-POF-FBG.

5. Acknowledgements

The authors are indebted to Prof. D. J. Webb, Aston University, for his insightful comments. This work was supported by JSPS KAKENHI Grant Numbers 17H04930 and 17J07226, and by research grants from the Japan Gas Association, the ESPEC Foundation for Global Environment Research and Technology, and the Association for Disaster Prevention Research.

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