Microstructured PMMA POF chirped Bragg gratings for strain sensing

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Abstract

We demonstrate a chirped microstructured polymer fiber Bragg grating based on taper technology for strain sensing application. The effective bandwidth of the grating is dependent on strain and remains practically constant with respect to temperature and humidity changes. We report a sensitivity of 0.90 pm/με for the central wavelength under stable temperature and humidity values. The 3-dB bandwidth of the grating has been measured under different temperature and humidity conditions.

Keywords: Polymer optical fibers, fiber Bragg gratings, optical fiber devices, optical filters

1. Introduction

Over the last three decades, fiber Bragg gratings (FBG) inscribed in silica fiber have become a mature and recognized technology for both sensing and telecommunications. Compared to conventional sensing techniques, fiber sensors present significant advantages such as immunity to electromagnetic interference, lightweight and compactness for numerous sensing applications. These include strain [1], temperature [1], refractive index [2] [3], deformation [4], ultrasound [5] and liquid level indications [6]. Polymer optical fibers (POFs) share several of the advantages of silica fibers. Recently, POF sensors are receiving increased attention for their fundamental mechanical advantages over silica fibers including a lower Young's modulus, a higher thermo-optic coefficient, a higher elastic limit and biocompatibility for sensing applications. Materials such as poly (methyl methacrylate) (PMMA) [7], cyclic transparent optical polymer (CYTOP) [8], TOPAS [9] and Zeonex [10] have been successfully used for POF fabrication to date. Non-uniform FBGs have been recently implemented in POF: tilted FBGs (TFBG)

[11], phase-shifted FBGs (PS-FBG) [12] and chirped FBGs (CFBG) [13], where the applications of these devices are attractive due to the benefit of POF.

POFBGs have been reported for strain measurement [14] by monitoring the resonant wavelength shift. However, other parameters such as temperature and humidity also cause wavelength shifts. Such effect is typically overcome by incorporating some interrogation scheme in order to distinguish one parameter from another, either by using different polymers, reference sensors or other related techniques [15]. One option is TOPAS, a humidity insensitive optical fiber material with a humidity sensitivity of less than 0.59±0.02 pm/% at 1568 nm, 50 times lower than PMMA fibers [16]. Nonetheless, TOPAS and PMMA have similar temperature sensitivity. Static strain sensing requires appropriate compensation under varying ambient temperature levels [16].

W. Zhang et al [17] investigated the response of PMMA POF grating based humidity sensors with different diameters and demonstrated that shorter response times could be obtained with lower fiber diameters. A dual FBG structure has been proposed to avoid the effects of temperature and humidity fluctuation, where an effective reference FBG is isolated from the parameter for measurement [18]. It has been reported that the humidity furcation effect on the wavelength shift of a grating under strain is different when compared with a strain free FBG [19]. In silica fiber, CFBGs glued at a slant orientation can be used as displacement sensor and accelerometer through bandwidth measurement with temperature insensitive performance [20-21], and tapered CFBGs have been demonstrated for strain sensing [22], where a 3-dB bandwidth modulation is shown that remains insensitive to humidity and temperature changes. Also, CFBGs have found important applications in healthcare, mechanical engineering, and shock waves analysis, among others [23,24].

In this paper, we present a tapered CFBG in PMMA mPOF, combining the benefits of tapered chirped Bragg gratings and fundamental POF characteristics. A sensitivity of 0.90 pm/με is obtained, higher value when compared with uniform FBGs, and fast measurements can be obtained through bandwidth measurements. This bandwidth observation is shown to be stable against humidity and temperature, making this concept suitable for its usage in temperature and humidity variable environments.

2. Strain response

Endlessly single-mode BDK-doped PMMA mPOF [25] was produced by using the center hole doping technique. In order to remove any residual stress incurred during the drawing process, the fiber was pre-annealed at 70°C for 12 hours without humidity control in temperature chamber. A 20 cm long fiber sample was cleaved with a portable cleaver [26] and polished with sand paper to enhance the quality of the end face. Prior to inscription, the fiber section was tapered in acetone using a computer driven translation stage to obtain the desired profile, as shown in Fig. 1 (a).

A CFBG was inscribed using the phase mask method (total length 10 mm) and a single 15 ns pulse from a 2.5 mJ pulsed Coherent Bragg Star Industrial-LN krypton fluoride (KrF) excimer laser at 248 nm. The reflected spectral power of the CFBG is shown in Fig. 1 (b).

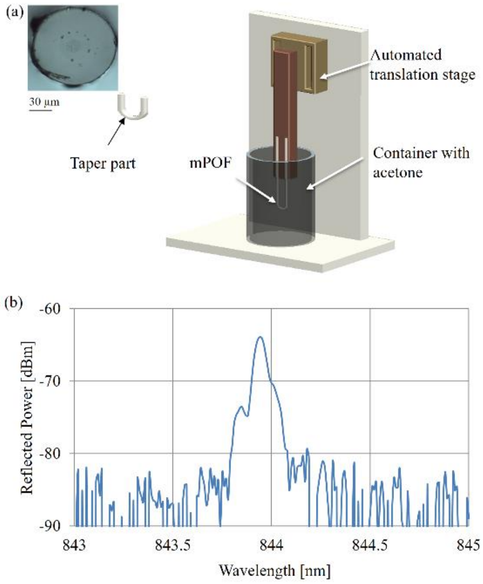

Fig. 1. (a) Taper setup for POF, inset: end face of mPOF; (b) Reflected power by an FBG obtained with one pulse KrF laser irradiation.

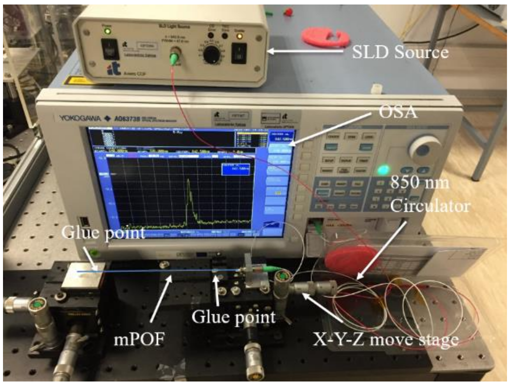

Fig. 2. Strain measurement setup.

The strain sensitivity was tested using the setup depicted in Fig. 2. The fiber was fixed with epoxy in order to avoid sliding. Axial strain was applied to the fiber through longitudinal displacement controlled by a 3D translation stage. The grating reflected spectrum was monitored using a super luminescent diode (Superlum SLD-371-HP1) and an optical spectrum analyzer (Yokogawa AQ6373B) with 20 pm spectral resolution.

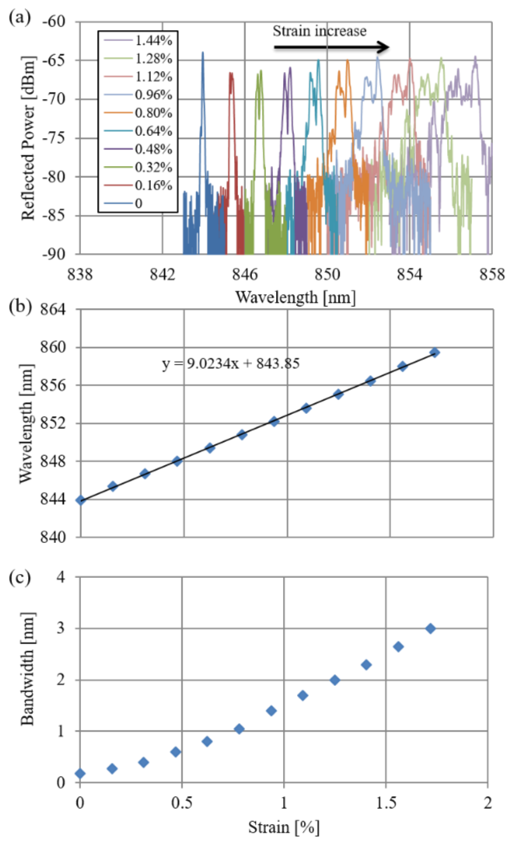

Fig. 3 (a) Spectral reflected power vs strain; (b) Wavelength shift vs strain; (c) Bandwidth vs strain.

Figure 3 (a) shows how the reflected power spectrum of the grating changes with the application of strain. A 12.62 cm section of POF had strain applied on the grating in 200 µm steps, causing a positive wavelength shift as shown in Fig. 3 (a). Fig. 3 (b) indicates that the central wavelength of the grating increases with strain. The obtained strain sensitivity is 0.90 ± 0.02 pm/με, higher than that of a uniform POFBG in the same material and geometry (~0.71 pm/με) due to the tapered etching of the fiber [26]. Fig. 3 (c) shows the bandwidth of the grating increase with strain, which can be used to measure this magnitude instead of measuring the central wavelength of the grating provided temperature and humidity sensitivities are compensated.

3. Temperature response

Figure 4 (a) shows the reflected optical spectrum of the grating when temperature is set between 22 to 52 °C under 60 % humidity without strain. In this condition, the temperature response achieves a stable value in less than 5 minutes, and the temperature sensitivity is measured as -57.9 ± 2.0 pm/°C. This value is similar to the one reported for PS-FBGs [12] with the same polymer fiber material and geometry. Fig. 4 (c) shows the 3-dB bandwidth of the grating which is around 0.18 ± 0.02 nm under temperature increase from 22 to 52 °C. This data confirms the temperature independent behavior previously observed in silica fiber [24].

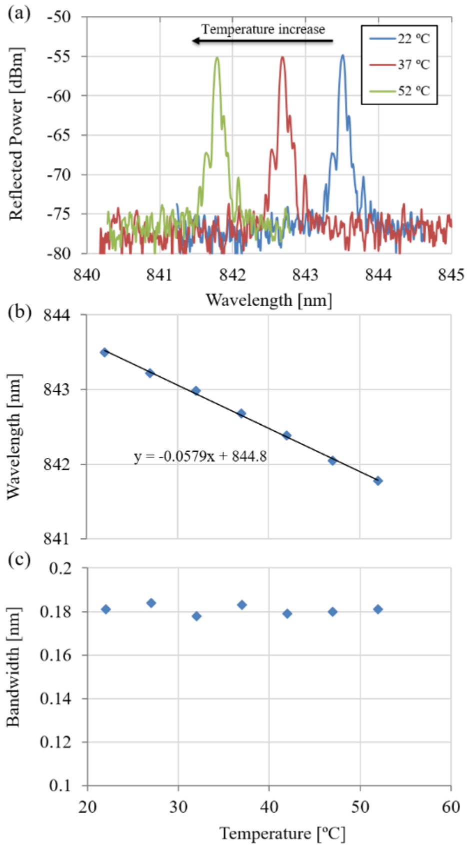

Fig 4. (a) Grating spectral response under temperature variations; (b) Central wavelength shift vs temperature; (c) 3-dB bandwidth vs temperature.

Figure 5 (a) shows the reflected spectrum of the grating between 22 and 52 °C with 60 % humidity and 1.25 % strain. Fig. 5 (b) indicates the 3-dB bandwidth fluctuation under temperature increases from 22 to 52 °C, with data collected every 5 min intervals in order to get temperature stabilization after each 5 °C step. The 3-dB bandwidth remains constant at 2.00 ± 0.05 nm over the temperature increase from 22 to 52 °C. The temperature sensitivity was found to be -58.8 ± 2.0 pm/ °C (see Fig. 5 (b)), similar to the one obtained without applied strain.

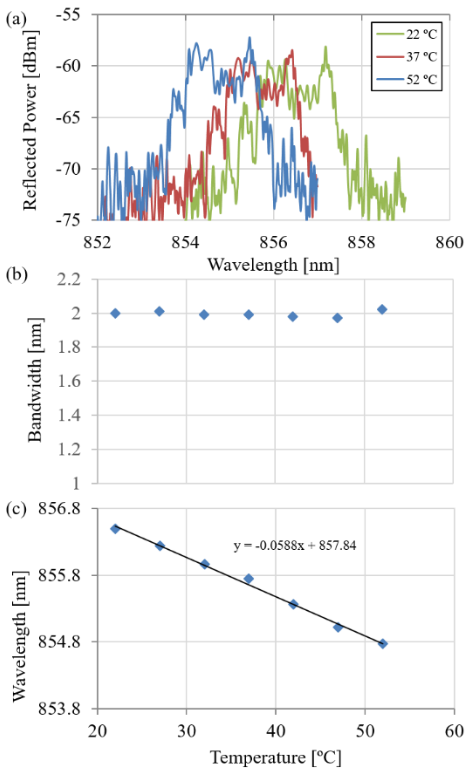

Fig. 5. (a) Grating spectral response with temperature change under 1.25 % strain; (b) 3-dB bandwidth under 1.25 % strain vs temperature; (c) Central wavelength shift under 1.25 % strain vs temperature.

4. Humidity response

Humidity is usually a challenge for practical applications of POFBGs [18]. During the experiment described as follows, the grating was left at a constant temperature of 22 °C and no strain was applied. Figure 6 (a) shows the central wavelength stabilization curve when humidity was decreased from 60% to 30%, with stability was observed after 50 minutes. Fig. 6 (b) indicates the resulting curve when the ambient humidity is changed from 30 % to 90 %, 100 minutes are required until stability is observed. The obtained humidity sensitivity of the grating is 26.0 ± 0.5 pm/% with no applied strain, higher than the values (19.9±2.5 pm/%) obtained by *L. Pereira* et al [12] with PS-FBGs in the same wavelength region (due to the high etch) [22]. Fig. 6 (c) depicts the reflected power spectrum of the grating under 30 % humidity, during humidity change and at 90 % humidity. We observe that the profile is acceptably homogeneous under these changes. We can observe that the 3-dB bandwidth is 0.18 ± 0.02 nm, as shown in Fig. 6 (d).

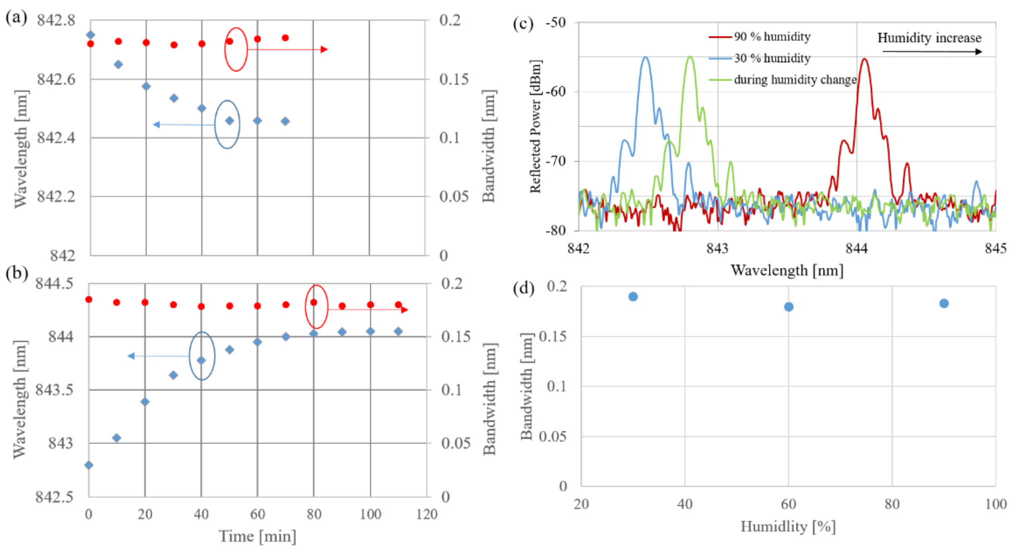

Fig. 6. (a) FBG central wavelength and 3-dB bandwidth vs time under humidity change from 60% to 30%; (b) FBG central wavelength and 3-dB bandwidth vs time under humidity change from 30% to 90%; (c) Reflected spectral power vs wavelength under different humidity changes; (d) 3-dB bandwidth vs humidity change from 30% to 90%.

Figure 7 (a) displays the reflected spectrum of the grating under 30 % humidity, during humidity change and 90 % humidity for a grating subjected to an axial strain of 1.25 %. The humidity sensitivity of the grating is 11.7 ± 0.4 pm/%, slightly lower than the value obtained without strain. A similar performance is explained in [17] as a reduced swelling coefficient in the fiber under strain when compared with the fiber under no strain condition.

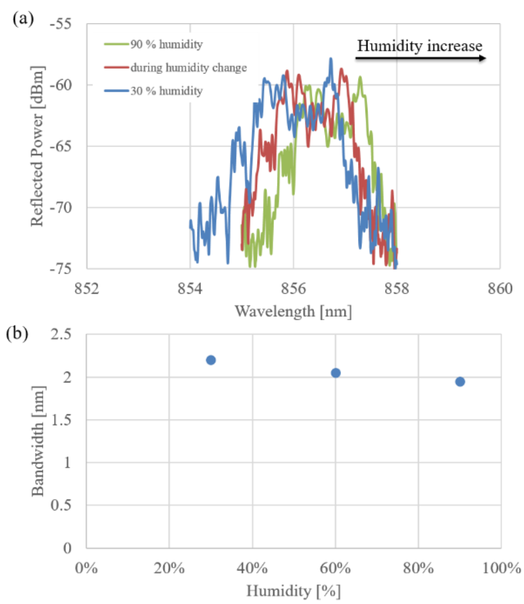

Fig. 7. (a) Reflected spectral power vs wavelength under humidity change, (b) 3-dB bandwidth vs humidity change from 30% to 90%.

We found the 3-dB bandwidth decreases with humidity increases and a sensitivity about -4.2 ± 0.4 pm/% is obtained under high strain condition and 60 % humidity fluctuation. Actually, from Fig. 7 (b), this sensitivity is lower than the one shown by the central wavelength. Therefore, our CFBG in POF performs comparably to ones in silica, showing the bandwidth decreases as long as humidity increases under high strain conditions.

5. Conclusion

We presented a tapered CFBG in PMMA mPOF for strain sensing, with a measured sensitivity of 0.90 ± 0.02 pm/με. We have shown wavelength and bandwidth measurements, where the latter are less sensitive to humidity changes when the fiber is under no strain. A low humidity sensitivity performance around -4.2 ± 0.4 pm/% was achieved under high strain conditions. The grating response time is significantly improved by measuring the 3-dB bandwidth, which is a great benefit towards commercial strain sensing applications using POFBGs, especially under variable temperature and humidity conditions. Furthermore, we can notice a high level of experimental repeatability to fabricate this kind of device achieving similar performance from the sensor even using other type of POF structure.

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