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Characterization of FBGs inscribed in Silica/Silicone Hybrid Microstructured Optical Fibers

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ABSTRACT

FBG fabrication and thermal characterization of a silica/silicone hybrid microstructured optical fiber is demonstrated. The thin film of PDMS created on the inner surface of the microstructured optical fiber acts as the cladding. The measured temperature sensitivity is -110.9 pm/°C. Bragg wavelength of the FBG is tuned through UV irradiation and the thermal effect is further explored.

Keywords: Fiber Bragg gratings, microstructured optical fibers, thermo-optic materials, fiber optic sensors

1. INTRODUCTION

Since their first demonstration[1], fiber Bragg gratings (FBGs) have been considered as the backbone of optical fiber technology for a wide variety of applications due to their immunity to electromagnetic interference, light weight, low cost and versatility. FBGs are routinely being inscribed in numerous types of optical fibers using various lasers and irradiation techniques. Among them, microstructured optical fibers (MOFs) possess many unique features compared to conventional single mode fibers (SMFs), as they constitute microscale air-holes spanning along the entire length of the optical fiber. This allows infiltration of different types of materials including liquids[2], metals[3], as well as polymers[4] into the air-hole structures of the fibers to tailor their light guiding and physical properties. Hence, the capability and significance of MOFs in pressure, temperature, gas, refractive index and humidity sensing is well established[5]. To facilitate the increasing demand for these sensors, the phase-mask technique provides an efficient way for mass production of FBGs. Despite the type of fiber, FBG fabrication in silica-based optical fibers generally requires a photosensitive dopant in the fiber core such as Germanium (Ge) or other photosensitivity enhancing techniques such as hydrogen loading. In the scenario of FBG inscription in pure silica cores, which consist of ultra-low photosensitivity, femtosecond laser irradiation[6] procedures are involved which can cause catastrophic material damage, making the FBG fabrication process rather cumbersome.

In comparison with silica optical fibers, polymer optical fibers (POFs) exhibit excellent mechanical properties due to their low Young's modulus and high negative thermo-optic coefficients[7]. Nevertheless, the high loss of the POFs restricts their functionality to short distance sensing applications. Polydimethylsiloxane (PDMS) is a widely used polymer material in photonics and microfluidics. It is cost effective and has commendable mechanical and optical properties together with low shrinkage which ease the fabrication procedure. PDMS has a refractive index of approximately 1.4 and is transparent to a broad wavelength range[8]. Integration of these distinctive optical properties of PDMS with MOFs can lead to broadening the horizons in the development of optical fiber sensors and tunable devices.

In this study, we report for the first time to the best of our knowledge, FBGs inscribed in a silica and silicone hybrid MOF comprising of a six-hole suspended core silica fiber, in which a thin film of PDMS is introduced that acts as the cladding and their temperature characteristics as well as the tunable wavelength range when subjected to UV irradiation. The hybrid fiber possesses beneficial characteristics of both silica and polymer fibers and therefore, results in unique optical properties.

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2. FABRICATION OF SILICA/SILICONE HYBRID FIBER AND FBG INSCRIPTION

2.1 Fabrication of silica/silicone hybrid fiber

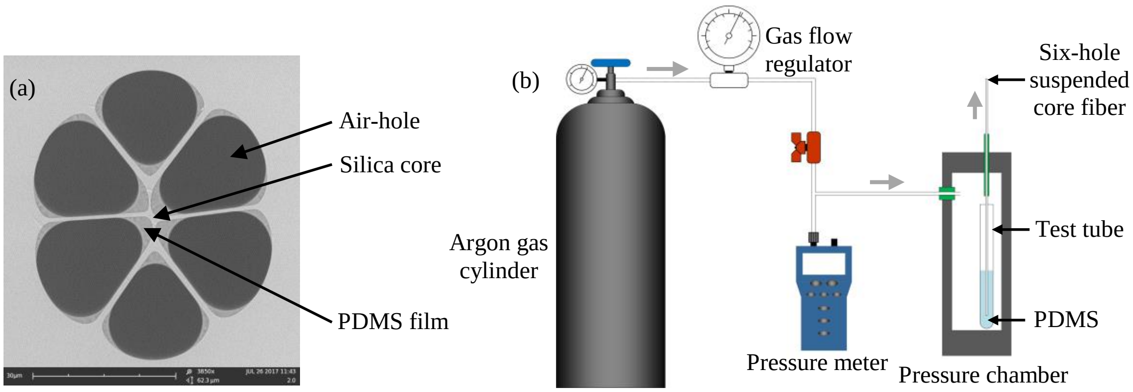

Figure 1. (a) SEM image and (b) fabrication setup of the silica/silicone hybrid fiber.

The six-hole suspended core microstructured optical fiber (SCF) was fabricated in house using the stack-and-draw technique. The scanning electron microscope (SEM) image in Fig. 1(a) shows the cross section of the silica/silicone hybrid optical fiber. The SCF consists of three cores with dimensions of about 3.6×1.6 µm in the central core and six air-holes. In order to create a thin film of PDMS on the inner surface of the SCF as shown in Fig. 1(a), a 15 cm long SCF was dipped in a solution of PDMS (Dow Corning Ltd., Sylgard184) and was inserted into a pressure chamber where silicone was infilled to the air-holes at a pressure of 4 bars. Fig. 1(b) demonstrates a schematic illustration of the experimental setup used to infiltrate silicone to the air-holes of the SCF. The PDMS solution was prepared with an elastomer base to the curing agent ratio of 10:1 and was subjected to a vacuum treatment for 5 min to remove any air bubbles trapped within the solution, prior to dipping of the SCF. After infilling the air-holes with silicone, the silica/silicone hybrid fiber was left to cure at room temperature for 24 h with a subsequent heat treatment at 80 ˚C for 2 h inside an oven to ensure that the silicone film is completely cured. The silicone film of about 3-µm in thickness is adhered to the three cores of the SCF. Two polarization modes of TE mode (polarized along the short axis of core) and TM mode (polarized along the long axis of core) are present in the SCF due to the asymmetrical fiber core geometry.

2.2 FBG inscription

FBGs were inscribed in the silica/silicone hybrid fiber with the aid of a 248 nm KrF excimer laser using the phase-mask technique. The pitch of the phase-mask was 1093.2 nm. A 4-mm long FBG was inscribed with pulse energy of 80 mJ and 30 Hz repetition rate, using the beam scanning method and its reflection spectrum is shown in Fig. 2. It has a 3dB bandwidth of ~0.7 nm. After FBG fabrication, the hybrid fiber was connected to an SMF through free space coupling and then by gluing one end of the hybrid fiber to SMF using PDMS.

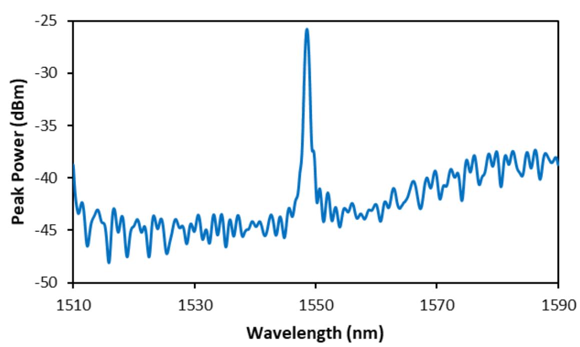

Figure 2. Reflection spectrum of a 4-mm long FBG.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Temperature sensing

In order to characterize the temperature sensitivity of the inscribed FBG, the grating was placed inside a mini oven and was subjected to a heating cycle from 30 to 80 °C at a ramping rate of 2 °C /min. Fig. 3(a) demonstrates the spectral shift of the FBG with increasing temperature from 30 to 80 °C in steps of 10 °C. PDMS has a negative thermo-optic coefficient of -4.5×10^{-4} °C^{-1} [9] which is two orders of magnitude higher than that of silica which is 7×10^{-6} °C^{-1} and positive, thereby, resulting in a total blue shift in the reflection spectra with increasing temperature as shown in Fig. 3(a). Fig. 3(b) exhibits the Bragg wavelength as a linear function of temperature ($R^2 = 0.997$) with a temperature sensitivity of -110.9 pm/°C.

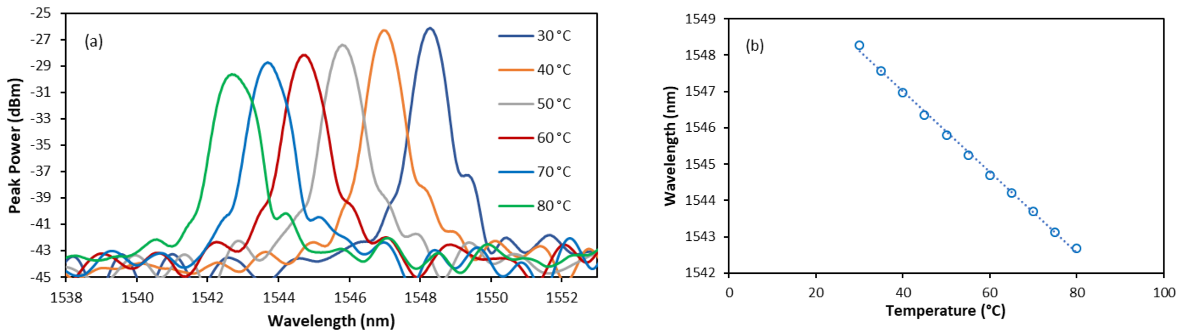

Figure 3. (a) Spectral shift of the FBG inscribed in silica/silicone hybrid fiber with increasing temperature. (b) Measured Bragg wavelengths of the FBG with respect to the temperature.

3.2 UV treatment

The changes induced on the PDMS surfaces and the structural modifications that occur through 172 nm UV irradiation has been explored with X-ray photoelectron spectroscopy (XPS) and spectroscopic ellipsometry (SE)[10]. In this study, the effect of UV irradiation on the optical properties of the FBG inscribed in silica/silicone hybrid fiber was investigated by exposing the grating region of the fiber to a 213 nm solid-state laser beam (Xiton Photonics, Impress 213) for different time periods. After each UV irradiated time period, the thermal response of the grating was measured. As shown in Fig. 4(a), a red shift of the reflection spectra is observed with increasing UV irradiation time. After 120 min of UV exposure, a total Bragg wavelength shift of 3.3 nm was observed compared to its Bragg wavelength (1548.3 nm) prior to UV irradiation, which may be due to the increase of the refractive index of PDMS.

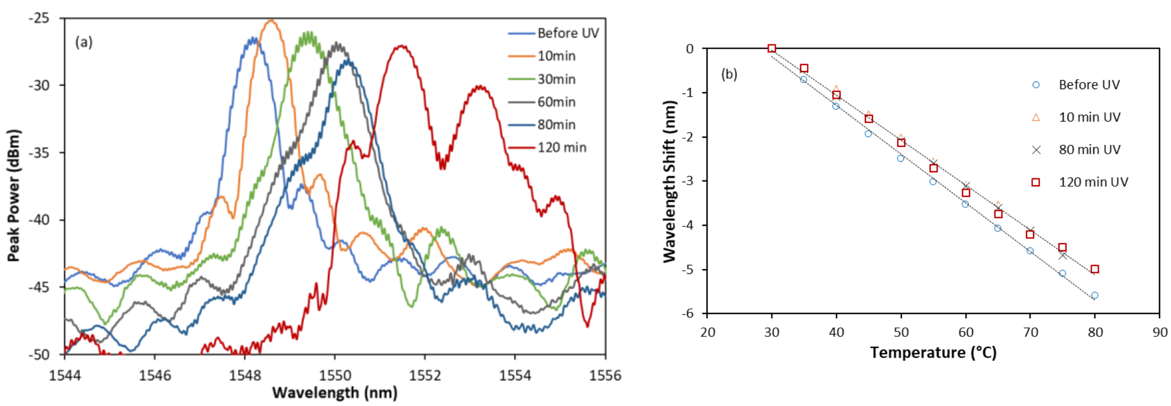

Figure 4. (a) Evolution of the reflection spectra with increasing UV exposure time. (b) Comparison of the thermal response of the FBG inscribed in silica/silicone hybrid fiber before UV irradiation and after UV irradiation times of 10 min, 80 min and 120 min.

However, the reflection spectrum broadened with increasing UV irradiation time. The reflection spectrum was significantly distorted after 120 min of UV irradiation. Fig. 4(b) shows the thermal response of the FBG from 30 to 80 °C, before and after UV irradiation. The results show that the measured temperature sensitivity of the FBG after 10 min, 80 min and 120 min of UV irradiation is the same. It has a value of -101.8 pm/°C, which is about 9.1 pm/°C smaller than the temperature sensitivity of the FBG before UV irradiation.

4. CONCLUSION

In summary, we have reported the thermal characterization of an FBG inscribed in a silica/silicone hybrid fiber consisting of a silica core and a thin film of PDMS which acts as the cladding. The FBG demonstrated a very high temperature sensitivity of -110.9 pm/°C. UV irradiation with 213 nm laser beam has relatively little effect on the FBG's temperature sensitivity. This new class of FBGs inscribed in silica/silicone hybrid fibers offer a new direction of research and can be incorporated in FBG sensing applications.

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