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Microfiber Bragg Grating for Temperature and Strain Sensing Applications

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Abstract: Fiber Bragg grating is inscribed on microfiber with femtosecond laser pulses irradiation. The microfiber is fabricated by stretching a section of single mode fiber over a flame. Periodic grooves are carved on the microfiber by the laser as have been observed experimentally. The microfiber Bragg grating is demonstrated for temperature and strain sensing, and the strain sensitivity is improved with decreased diameters of the microfibers.

Keywords: Fiber Bragg gratings; fiber optics sensors; femtosecond laser micromachining

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1. Introduction

There has been increasing interest in the research of microfiber these years due to its many unique properties such as large evanescent field, configurability, and strong confinement of the conducted light [1]. These distinctive features have been exploited in a wealth of applications ranging from telecommunication devices to sensors [2, 3], and from optical manipulation to high *Q* resonators. Fiber sensors, based on the various fiber components, have been developed in many forms [4–9], and are exhibiting outstanding performances in the field of physical and bio-chemical sensing. Fiber Bragg grating (FBG) is among the most important optical components which has a wide variation of applications [10–13]. Here we fabricate an FBG in the microfibers with diameter down to several micrometers, and the temperature and strain responses of the microfiber FBG are investigated by the experiment.

2. Inscription of FBG in microfiber

The microfiber is produced by the use of a flame torch and a translation stage with a flame-brush method. The flame is placed under the single mode fiber (SMF) to heat the fiber while the fiber is stretched by two translation stages. By controlling the position of the flame, microfibers with diameters from 5 μm to 50 μm are fabricated. Figure 1(a) shows the graphic of a microfiber with a diameter of 10 μm.

The FBG is fabricated with the phase mask method. The femtosecond laser used for the fabrication process is a Ti-sapphire laser system (Spectrum Physics) with pulse duration of 50 fs and repetition rate of 1 kHz at 800 nm. The laser beam is focused into the microfiber through a phase mask (Stocker Yale) by a cylindrical lens. The fiber is located in a distance of 2 mm from the phase mask, and the position of the fiber is adjusted by a high precision 3-axis translation stage. The pulse energy

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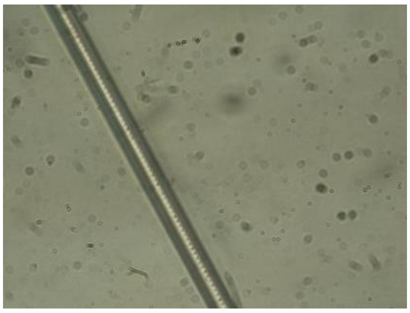
for the fabricating process is about 350 μJ. The exposure time varies from several ms to tens of ms for microfibers with different diameters. We use an amplified spontaneous emission (ASE) light source and an optical spectrum analyzer to collect the spectra of FBG.

Figure 1(b) shows the periodic grating pattern on the microfiber that we observed from a microscope. As can be seen from the figure, the femtosecond exposure is likely to have caused surface ablation on the microfiber, which leads to the many grooves on the microfiber.

(a)

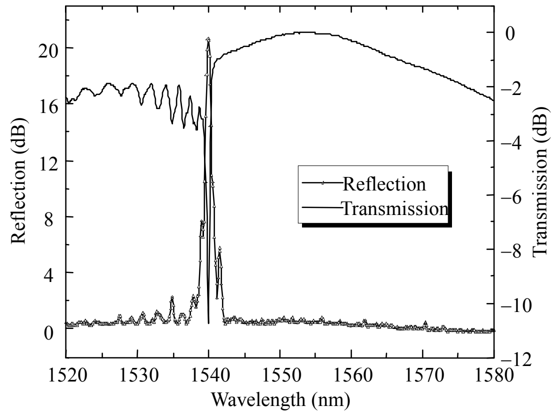


(b)

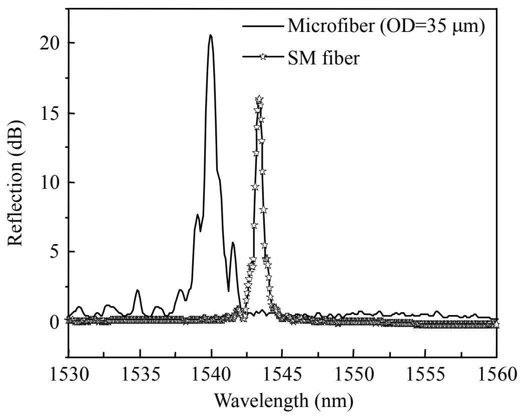
Fig. 1 Femtosecond laser fabrication of microfiber: (a) a section of microfiber with diameter of about 10 μm and (b) periodic grating structure on a microfiber.

The reflection and transmission spectrum of FBG in microfiber with a diameter of 35 μm is shown in Fig. 2(a). Very strong reflection is obtained by such a grating. From Fig. 2(b) we can see that the resonant wavelength of FBG in a 35 μm diameter fiber has a blue shift versus the FBG in an SMF fabricated with the same laser and phase mask. This is because a thinner fiber leads to a drop in the effective refractive index of the modes propagating in the fiber, thus a decrease in λ_B, which can be derived from the Bragg condition [10]:

$$\lambda_B = 2n_{\mathrm{eff}} \cdot \Lambda \tag{1}$$



(a)



(b)

Fig. 2 Spectrum of microfiber FBG: (a) transmission and reflection spectrum of FBG in a microfiber and (b) reflection spectrum of single mode fiber FBG and microfiber FBG.

3. Temperature and strain sensing

A group of FBGs in microfibers with diameters of 9 μm, 35 μm, and 50 μm are fabricated. These samples are heated from room temperature to 400℃ by use of a tube furnace, and the reflection spectra are recorded by an increment of 50℃. Figure 3(a) shows the wavelength shift of FBG in microfiber of 50 μm diameter, from which we can see that there is an obvious red-shift of the Bragg wavelength, which can be explained by the thermal-optic effect and thermal expansion of the grating. The temperature induced shift of the Bragg wavelength λ_B can be written as [13]:

$$\Delta\lambda_B = \lambda_B\left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} + \frac{1}{n_{\mathrm{eff}}}\frac{\partial n_{\mathrm{eff}}}{\partial T}\right)\Delta T = \lambda_B(\alpha_\Lambda + \alpha_n)\Delta T \tag{2}$$

where ΔT is the temperature change, α_n is the thermo-optic coefficient, and α_Λ is the thermo-expansion coefficient. Temperature changes influence two factors: the temperature-induced refractive index variation and the temperature-induced grating pitch variation. The former is the dominating factor of the wavelength variation.

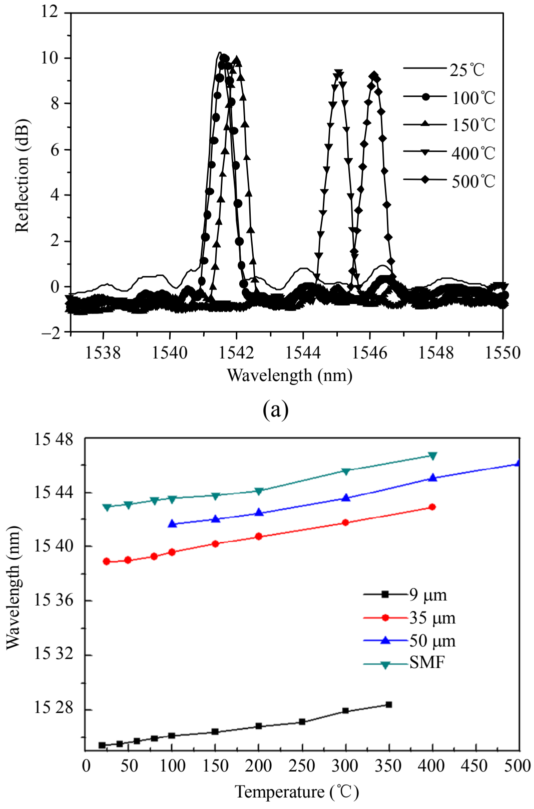


Fig. 3 Wavelength shift and thermal response of FBG: (a) wavelength shift of FBG (50 μm) during heating up and (b) thermal response of FBG with fiber diameters of 9 μm, 35 μm, 50 μm, and an SMF.

Thermal responses of FBGs of different fiber diameters are shown in Fig. 3(b). From Fig. 3(b) we can see that there are no dramatic differences among the temperature sensitivities (around 11 pm/℃) of these FBGs. The results are close to the temperature sensitivity of FBG in a single mode fiber, since the shrinking of the fiber diameter hardly causes changes to the thermo-optic coefficient of the fiber material.

The strain sensitivity of the microfiber Bragg grating is investigated by a setup shown in Fig. 4. The microfiber with FBG in its center is fixed between two precision translation stages where the microfiber is stretched by driving the screw of the stage along the fiber length, and the tensile elongation could be read directly from the scale on the screw.

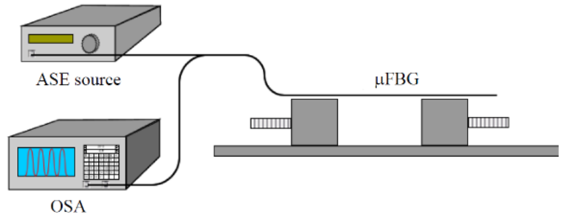


Fig. 4 Setup for strain sensitivity measurement.

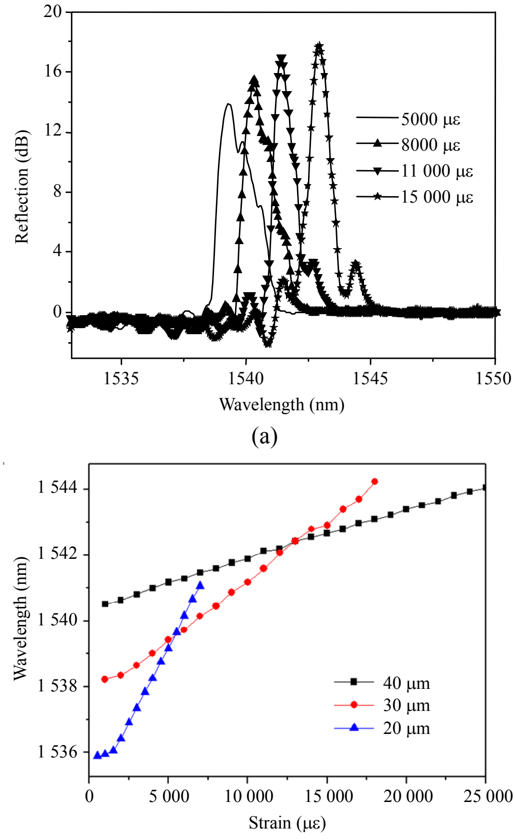


Fig. 5 Strain test of FBGs: (a) wavelength shift of FBG with fiber diameter of 30 μm under strain test and (b) a comparison of tensile strain responses of FBGs in different diameter fibers.

Here we also employ a group of experiments on microfibers with the diameters of 20 μm, 30 μm, and 40 μm for comparison. Figure 5(a) shows the wavelength shift of FBG with fiber diameter of 30 μm when the FBG is stretched. We can see that there is a large change in the resonant wavelength from 1539 nm to 1543 nm when the strain employed on the microfiber increases from 5000 με to 15000 με, which indicates a strain sensitivity of

0.35 pm/με. Later, another two FBG samples with diameter of 20 μm and 40 μm are tested to made comparison, which is shown in Fig. 5(b). It can be seen that a decrease in fiber diameter has a significant contribution to improving tensile strain sensitivity.

The strain sensitivities of these FBGs are 0.228 pm/με, 0.35 pm/με, and 0.8 pm/με for the fiber diameter of 40 μm, 30 μm, and 20 μm, respectively. It should be mentioned that the large value of strain induced in our experiment (tens of thousands of με) is due to a tremendous decrease in the fiber cross-section area, which means that a little tensile elongation would induce a massive strain in the microfiber. This unique character indicates a potential application for the sensing of tiny force.

4. Conclusions

We present the fabrication of Bragg grating on microfibers with diameter down to 9 μm. The microfiber is made by stretching single mode fibers over a flame. Femtosecond laser pulse is used for the grating inscription, and periodic grooves are carved on the microfiber as we have observed experimentally. The microfiber Bragg grating is demonstrated for temperature and strain sensing, and the strain sensitivity can be improved by decreasing the diameter of the microfiber.

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