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Thermal and chemical treatment of polymer optical fiber Bragg grating sensors for enhanced mechanical sensitivity

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ABSTRACT

An investigation of the thermal annealing effects on the strain, stress, and force sensitivities of polymer optical fiber Bragg grating sensors is performed. We demonstrate for the first time that the fiber annealing can enhance both stress and force sensitivities of Bragg grating sensors, with the possible cause being the molecular relaxation of the polymer when fiber is raised above the β-transition temperature. A simple, cost-effective, but well controlled method for fiber annealing is also presented in this work. In addition, the effects of chemical etching on the strain, stress, and force sensitivities have been investigated. Results show that fiber etching too can increase the force sensitivity, and it can also affect the strain and stress sensitivities of the Bragg grating sensors.

1. Introduction

Polymer optical fiber (POF) sensors have received high attention recently due to their unique properties compared to the conventional silica optical fiber sensors [1]. Advantages such as higher flexibility in bending, biocompatibility [2], higher failure strain [3], and higher fracture toughness are significant for many sensing applications. The lower Youngs modulus of POF [4] provides enhanced sensitivity when POF sensors are used for stress [5], pressure [6], and acoustic wave detection [7]. There are also some hydrophilic polymeric materials such as poly(methyl methacrylate) (PMMA) that can absorb water, enabling them to be applied for humidity detection applications [8]. Furthermore, the material properties of polymers can be chemically modified using organic techniques to achieve specific desirable characteristics. An example is the perfluorinated POF, commercially known as CYTOP, in which the carbon–hydrogen bonds have been replaced with carbon–fluorine bonds to reduce the fiber attenuation [9]. One of the drawbacks of POF is its viscoelastic nature. When cyclic loading is applied to the POF sensor, creep and hysteresis effects may be introduced due to the strain and stress phase mismatch [3], which can degrade the accuracy of the sensor reading. It has been demonstrated that these effects can be reduced by applying thermal treatment to POF sensors [10].

Thermal annealing was initially used for POF Bragg grating sensor multiplexing [11], due to the tendence of the anisotropically drawn polymer fiber to physically shrink in length when heated above the β-transition temperature. The fiber shrinkage can induce a permanent blue shift of the Bragg wavelength, and device multiplexing is feasible by using only one phase mask to record multiple Bragg gratings, with different annealing times. At a later stage, it was demonstrated that fiber annealing can also offer other benefits to POF sensors such as strain [12] and humidity [13] sensitivity enhancement, and a higher operational range for temperature monitoring [14]. Chemical etching has also been utilized to improve the performance of POF Bragg grating sensors. Etching the fiber sensor to reduce its diameter can offer enhanced force sensitivity when force is applied along the fiber axis [15]. This is because for a constant force, the reduction of the area over which force is applied leads to a higher fiber stress. The reduction of the fiber diameter can also improve the response time to humidity changes [16] in POF sensors. This is because the distance between the fiber surface exposed to the external environment and the fiber core is less, which can reduce the time that water requires to reach the Bragg gratings location and be detected. However, recently it was shown that etching PMMA with acetone can change not only the physical dimensions of the POF, but also its material properties, such as its Youngs modulus [17].

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In this study, both thermal treatment and chemical etching have been applied to POF Bragg grating sensors in order to investigate their influence on strain, stress, and force sensitivity. First, various Bragg grating sensors were photo-inscribed in a single mode PMMA optical fiber using the phase mask technique. Then, each device was characterized with respect to its strain, stress, and force sensitivity. In the next step, some sensors were thermally annealed and some were chemically etched. At this point, the sensitivities of the sensors were characterized again and were compared with the pre-treatment sensitivities. Finally, a combination of both treatments was also conducted in order to investigate any possibility for further improvement in performance. Results show that the thermal treatment can enhance not only the strain sensitivity of POF Bragg grating sensors as already reported in the literature, but also the stress and force sensitivities. We also report a simple, cost-effective and well-controlled thermal treatment that has been used to enhance the performance of the POF sensors in this way. In the case where POF etching is used to reduce the fiber diameter for force sensitivity enhancement, changes also occur in the strain and stress sensitivities. However, the changes are not consistent and the possible reasons for this are discussed.

2. Experimental details

2.1. Fabrication of sensors

A single mode PMMA based micro-structured optical fiber was used, in which the Bragg grating sensors were photo-inscribed. The fiber core was doped with benzyl dimethyl ketal to enhance the photo-sensitivity of the material in the ultraviolet spectrum region. Details of the fiber and its production are reported in reference [18]. The phase mask technique and a continuous wave He-Cd laser (Kimmon IK3301R-G) operating at 325 nm were used for the grating inscription as shown in Fig. 1. Two phase masks with periods Λ_{PM} = 557.5 nm and Λ_{PM} = 580.0 nm were used to photo-inscribe gratings with Bragg wavelengths λ_B=829 nm and λ_B = 862 nm respectively, indicating that the POF in this wavelength region has an effective refractive index of n = 1.49 since

$$\lambda_B = n\Lambda_{PM}. \tag{1}$$

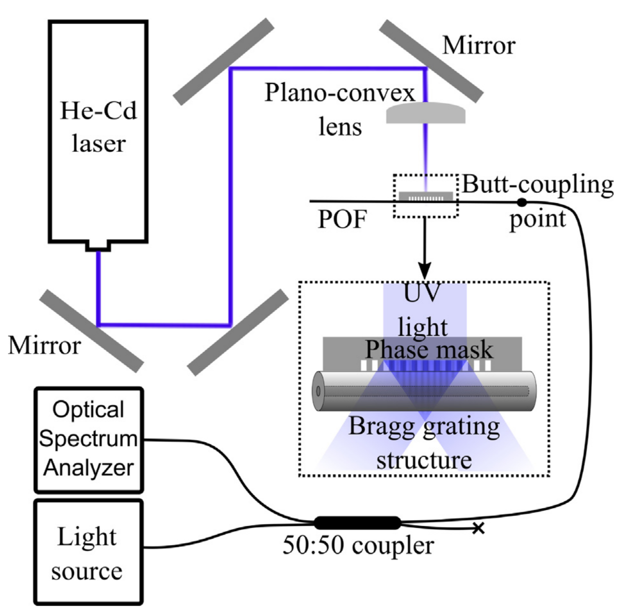

Fig. 1. Fabrication setup of POF Bragg grating sensors.

An optical spectrum analyzer (HP 86142A) and a super luminescent diode (Superlum SLD-371) were used to monitor the Bragg grating spectrum in reflection by connecting all together with a 50:50 single mode coupler as shown in Fig. 1. The physical length of the inscribed gratings varies between 1.2 and 10 mm, and their total inscription time between 1 and 13 min. However, it is believed that these values define only the strength of the Bragg gratings reflectivity and they do not have any impact in the experimental results described in this work. For practical reasons, POF sensors were glued into demountable FC/PC connectors after the photo-inscription process, in order to make possible easier interrogation of the Bragg spectrum in contrast with the butt-coupling method.

2.2. Characterization of sensors

The strain, stress, and force sensitivity of each POF Bragg grating sensor was characterized before and after any thermal or chemical treatment was applied. The strain sensitivity can be expressed as $\Delta\lambda_B/\varepsilon$, where $\Delta\lambda_B$ is the Bragg wavelength shift under the applied fiber strain ε. In order to strain the POF, fiber clamps (Thorlabs HFF01) with V-grooves of 125 m were used to hold the fiber as shown in Fig. 2. However, these fiber clamps were designed for silica optical fibers and as a result the POF was able to slip through the clamp, especially in the case in which it had reduced diameter after etching. As a solution, a polycaprolactone (PCL) material, which has a melting point of 42 °C [19], was used as a glue to hold the POF in the fiber clamp. First, a small amount of PCL material was melted using a hot plate at 50 °C. Then, the POF was placed in the V-groove along with some melted PCL material. Finally, the fiber clamping arm was closed with the adjustable knob providing a holding force of 2.0 N. We waited at least 5 min before applying any strain to the fiber to allow the PCL material to become solid again and bond with the POF. Using the PCL, we were able to increase the area over which force from the clamp was applied to the fiber and thereby the POF slippage was avoided. After attaching the POF, the translation stage with an accuracy of 1 m was used to strain the fiber up to 0.5% along the fiber axis, where POF remains in its elastic limit [20]. After the fiber straining, the POF part that is bonded with the PCL material, was placed on the hot plate at 50 °C. After few seconds the PCL became liquid again and could be removed from the POF.

In order to characterize the stress and force sensitivity, each POF was held perpendicular to the ground and by successively adding masses with a known value, the gravitational force was used to stress the fiber as depicted in Fig. 3. The stress equals

$$\sigma = \frac{F}{A} = \frac{mg}{\pi\left(\frac{d}{2}\right)^2}, \tag{2}$$

where F is the gravitational force applied to the cross-sectional area A of the POF. The applied force is equal to the added mass m multiplied by the gravitational acceleration of the Earth g = 9.8 m/s^2. The cross-sectional area can be calculated when the fiber diameter d is measured with a microscope at the location of the Bragg grating

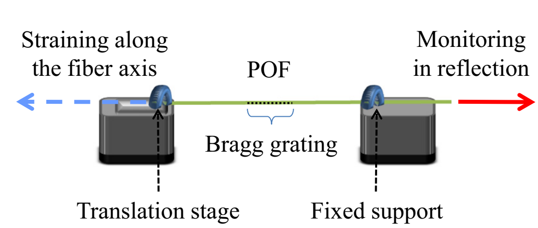

Fig. 2. Setup for POF straining.