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Highly Tunable Bragg Gratings in Single-Mode Polymer Optical Fibers

Z. Xiong, G. D. Peng, B. Wu, and P. L. Chu

***Abstract*—A Bragg grating in a single mode polymer optical fiber (POF) has been created. The novel grating has a length of 1 cm with a reflectivity of 80% and a linewidth of about 0.5 nm. The wavelength tunability of the POF grating by stretching was investigated and a wavelength tunable range of 20 nm has been achieved. Based on the properties of the polymer, we believe that this kind of grating has a wavelength tuning potential of more than 100 nm.**

***Index Terms*—Bragg reflectors, diffraction and gratings, fiber materials, polymer waveguide/fibers, polymers.**

I. INTRODUCTION

SINCE Hill *et al.*'s first report in 1978 [1], the fiber grating has become a very attractive optical device in high-performance optical communications systems. In addition to the applications where the gratings are used as reflectors, wavelength tuning and optical fiber sensing are two other major applications of fiber gratings [2]. In these applications, the grating period is modulated by relevant external environment such as strain and temperature [3]. However, for silica optical fiber gratings, the change in Bragg wavelength due to the changes in temperature and strain is small, typically a few nanometers [2], which are not sufficient for WDM systems since the bandwidth of these systems will be more than 100 nm in the future [4]. This is because silica glass has small thermal effect and large Young's modulus. In the case of polymer optical fiber, the situation is different. Its Young's modulus (0.1×10^{10} N/m^2), for example, is more than 70 times smaller than that of glass (7.13×10^{10} N/m^2), and the refractive index changes that can be induced by photoreaction are relatively high $\Delta n \sim 10^{-2}$. Therefore, it is expected that a Bragg grating written into a polymer optical fiber (POF) would be tunable over a very wide wavelength range. In addition, the POF gratings are ideal devices for inclusion in an organic solid-state fiber laser [5] which in turn provides a compact and low-cost optical source over a broad range of wavelength throughout the visible spectrum [6].

We recently fabricated a photosensitive POF, whose refractive index in the core region can be changed under irradiation of a pulse UV laser beam, and have shown that it was possible to write gratings in these multimode fibers [7]. The purpose of this letter is to report on the fabrication and the tunability of Bragg gratings in single mode POF's. We show that these gratings can be readily tuned over a wavelength range of 12 nm without changing their reflection spectra. This is about ten times the range achieved in glass fiber gratings.

II. FABRICATION OF POF GRATINGS

The photosensitive polymer optical preforms for the purpose of grating writing were prepared in two steps. The cladding (PMMA) of the preforms was firstly fabricated using the method described in our previous publication [8]. In order to increase its photosensitivity, the core was prepared in a slightly different way from that of the cladding. It is well known that no photodielectric effect can be observed for PMMA samples with excessive initiator or annealed near the glass transition temperature [9]–[11]. Hence, the core monomer mixture (MMA+EMA+BzMA) of our polymer optical preform was then prepared with a much lower level of lauryl peroxide and chain transfer agent than that of the cladding and polymerized at lower temperatures. The polymerized preform was then drawn into single-mode fibers (SMF's) following the procedure described in [8].

To write the grating in the POF, the experimental setup illustrated in Fig. 1 was adopted. We used a phase mask with a period of 1.0614 μm designed for operation at a wavelength 248 nm. At this wavelength, the zero diffraction order from the phase mask is minimum (<1%). The UV writing beam was obtained from a frequency-doubled OPO pumped by a frequency-tripled Nd:YAG pulse laser. The preliminary experiment reported in [7] showed that the POF fiber gratings could not be created by using the 248-nm UV laser beam because of the large fiber absorption. It was found that a more suitable wavelength is 325 nm. However, at this wavelength, the intensity of the zero diffraction order has increased which is detrimental to the creation of Bragg gratings [12], [13]. We therefore had to steer the zeroth-order beam away from the fiber by means of three quartz prisms as shown in Fig. 1. These prisms constitute a modified Sagnac interferometer where the two first-order diffraction beams form the required interference pattern for the grating. In this way, the intrusion of the zeroth-order beam can be blocked. In order to write a long grating, the phase mask together with the POF can be transversely shifted by virtue of a stepping motor.

A typical transmission spectrum of the POF grating is shown in Fig. 2. The grating was detected by launching a white light into the POF through a multimode silica optical fiber coupler. The use of the coupler was to monitor the dynamics of the

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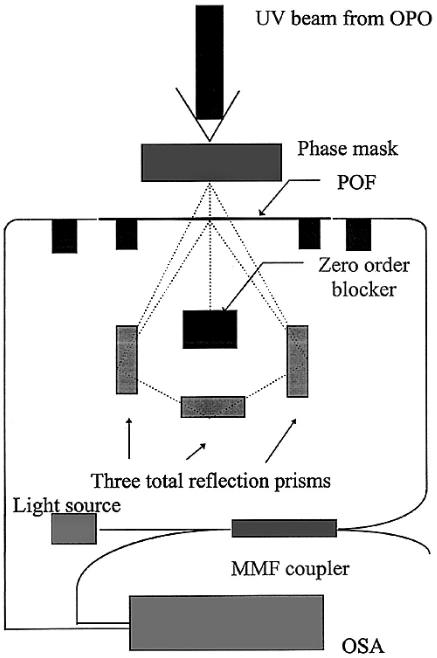

Fig. 1. Experimental setup. Note that the POF fiber was put underneath (but in the same vertical plane of) the phase mask.

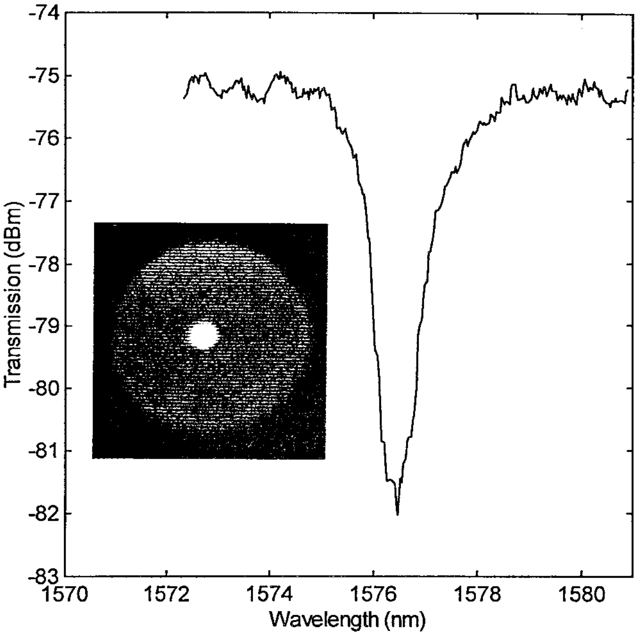

Fig. 2. Typical transmission spectrum of the POF grating with a grating length of 1 cm and linewidth of 0.5 nm. The inset is the near-field pattern of the POF fiber.

grating formation by detecting its reflection spectrum. The inset in Fig. 2 is the near-field pattern of the POF fiber which has a cladding refractive index of 1.48 and an index difference between the core and cladding of 0.01. The overall diameter of the POF is about 100 μm with the core diameter of about 7 μm. The UV laser beam was not focused and has an effective spotsize of 3 mm. The length of the grating was extended by shifting the phase mask and the POF fiber by about 10 mm, which is equal to the length of the phase mask we used. The reflectivity of the POF grating was approximately 80% with a linewidth of about 0.5 nm. The index change in the grating region due to the UV laser irradiation is estimated to be 10^{-4}.

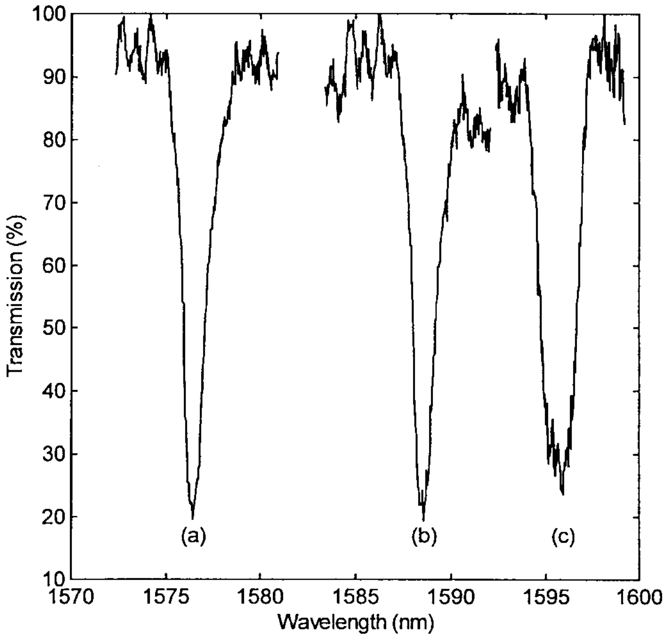

Fig. 3. Shift in Bragg grating spectrum with strain on the POF fiber. The values of the strain are: (a) 0%, (b) 0.8% and (c) 1.3%, respectively.

The mechanisms responsible for the formation of periodic structures in polymer have been explained in the literature [11], [14]–[17]. They can be classified in to photolysis, oxidization and laser ablation for the surface relief gratings, while chain scission, cross-linking and photopolymerization are considered to be responsible for bulk or volume gratings and the in-fiber gratings. In our case, the most likely photo effects are cross-linking and photopolymerization, because the process we used to manufacture the POF enables it easily to produce free radicals under UV laser irradiation. The free radicals can either react with the residual monomers in polymer for further polymerization or form cross links between adjacent polymer chains. Both effects increase the refractive index by transferring the residual monomers to polymer in photo-polymerization [18] and drawing the polymer chains closer together in cross-linking, respectively [11].

III. TUNABILITY OF POF GRATINGS

We investigated the tunability of the POF grating subject to an external force. A piece of the POF of 25-mm length with a Bragg grating written inside was mounted to a glass slide with both ends glued to it. The external force was exerted onto the fiber by pulling the fiber laterally at its midpoint. The change in the Bragg wavelength is recorded as the strain is applied and this is shown in Fig. 3. The left-most spectrum (curve a) is the result when zero strain is applied. It has a spectral width of 0.5 nm. As the strain increases, the spectrum moves to the right linearly. When the strain is 0.8%, the spectrum has shifted by more than 12 nm without change of shape (curve b). Further increase in strain starts to broaden the spectrum. When the strain reaches 1.3%, the wavelength has shifted by 20 nm and the spectral width is now 0.9 nm. However, the spectrum immediately returns to its original position (with zero strain) as the fiber is released completely. This indicates that the strain of the fiber did not exceed its elastic limit. Therefore, the broadening of the spectrum is not due to the unrecoverable deformation of the polymer material. It may result from the nonuniform tension from one side of the pulling point to the other. The tension difference is expected to produce a slight difference in wavelength shift between the two unbalanced arms, which in turn broadens the spectrum.

To confirm that the broadening did not result from the polymer yielding, we measured the stress-strain relationship of a similar POF but without grating. It was found that the value of the yield strain was 6.1%, which is much larger than the value we used. The yield strain for a polymer optical fiber depends on its processing procedure, drawing temperature and speed. But the elastic limits of POF's are normally high, for example, PMMA may have a recoverable strain of 13% [19]. Therefore, the wavelength tuning of a POF grating can be as large as 100 nm at the 1550 nm wavelength window.

IV. CONCLUSION

We have shown that Bragg gratings can be written in single-mode polymer optical fibers. The grating created has an index change of 10^{-4}, linewidth of 0.5 nm and a reflectivity of 80%. The length of the grating is 10 mm. These figures can obviously be improved by increasing the grating length. We were not able to do so because the phase mask used was 10 mm in length. A more exciting conclusion is that the grating can be tuned over a very wide wavelength range by simply pulling it at the midpoint. At a strain of 0.8%, a tuning range of 12 nm was obtained without any change in the wavelength spectrum. At 1.3% strain, a tuning range of 20 nm was obtained with a slight increase in the spectral width.

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