Fiber Bragg gratings inscription in doped PMMA polymer optical fiber by 400 nm femtosecond laser pulses

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In this paper, we report photo-inscriptions of uniform Bragg gratings in both step-index and microstructured polymer optical fibers. The Bragg grating inscriptions were performed by a femtosecond laser emitting at 400 nm and the phase mask technique. The photosensitive dopants in both fibers are trans-4-stilbenemethanol (TS) and benzyl dimethyl ketal (BDK), respectively, which enable Bragg gratings to reach saturation in slightly more than 1 minute (reflectivity 84%) for the step-index fiber and in ~20 seconds (reflectivity 40%) for microstructured fibers.

Introduction

Fiber Bragg gratings (FBGs) were first written in polymer optical fibers (POFs) in 1999 [1]. POFs present several attractive characters for sensing applications. In comparison to FBGs written in silica fibers, they are more sensitive to temperature and tension [2] because of the larger thermo-optic coefficient and smaller Young's modulus of polymer materials. Although different polymer materials can be used to manufacture POFs, the most popular one is poly (methyl methacrylate) (PMMA), which also presents the advantages of being intrinsically biocompatible and humidity-sensitive [3,4]. Besides, FBGs in such POFs are also sensitive to surrounding refractive index [5,6] and pressure [7]. With respect to grating inscriptions, several kinds of laser beams have been used up to now, such as continuous wave He-Cd laser at 325 nm [2], excimer (KrF) pulse laser at 248 nm [8], femtosecond pulses laser at 800 nm [9] for PMMA based fibers and at 517 nm [10] for CYTOP based fibers. Different central wavelengths were also obtained in the visible and near-IR wavelength windows. The manufacturing of FBGs in the C+L bands is particularly interesting to achieve for both sensing and telecommunication purposes, as the major part of cost-effective optical fiber devices are available in that wavelength range. Here, we report the FBG photo-inscription in both step-index and microstructured PMMA optical fibers using femtosecond laser pulses at 400 nm and the phase mask technique. The gratings were produced at around 1570 nm. Compared to classical He-Cd lasers, the advantage of using 400 nm femtosecond pulses is the capability to obtain highly reflective gratings in less than a few tens of seconds under static exposition.

The step-index polymer optical fiber (SI-POF) used in this work was supplied by the Hong Kong Polytechnic University. It is characterized by a core diameter of 8.2 μm and a cladding diameter of 150 μm. The cladding is in pure PMMA while the core is composed of PMMA doped with diphenyl sulfide (5 % mole) and trans-4-stilbenemethanol (TS)(1 % w.t.). The refractive indices are computed equal to 1.5086 and 1.4904 for the core and the cladding, respectively, at the wavelength of 589 nm. The material TS in the core presents a negative refractive index change when illuminated with UV light [11]. Furthermore, the presence of the dopant in the core decreases not only the writing time but also the laser power required to manufacture FBGs.

The microstructured polymer optical fiber (mPOF) was made at DTU Fotonik, Technical University of Denmark. The fiber core was doped with a photosensitizer benzyl dimethyl ketal (BDK) [12]. The photopolymerization process starts in the core under UV light radiation at 325 nm and induces a positive index change. The doped mPOF is characterized by a hole diameter of 1.5 µm and a pitch of 3.79 µm. So, the ratio of the hole diameter to the pitch was calculated to be 0.4, confirming that the mPOF is endlessly single-mode.

Experimental set-up

An amplified Ti:Sapphire laser with central wavelength of 800 nm was used as the primary radiation source, which contains a Mai Tai tunable ultrafast laser, an Empower pump source and a Spitfire Ti-Sapphire regenerative amplifier. Then, second-harmonic pulses at 400 nm were generated by sending the fundamental beam into a BBO crystal. At the output, the 400 nm laser beam has a diameter of 8 mm and a diaphragm with a 6 mm aperture was used to select the uniform part of the beam for FBG inscriptions up to 6 mm in length. The photo-inscription optical power was adjusted by a variable attenuator, placed in front of the frequency-doubler. A 50-mm-focal-length cylindrical lens was then used to focus the beam on the fiber core. A first order phase mask with a uniform pitch of 1060 nm was put in front of the fiber. The position of phase mask was adjusted by the translation stage. The scheme of grating inscription set-up is shown in Figure 1.
Because of the higher loss of POFs compared to their silica counterparts, short POF sections were used. The two ends of POF were connected by silica fiber pigtails with optical UV glue (Norland 86H), which were fixed by standard silica fiber clamps on both sides, in order to monitor the transmission spectrum during the photo-inscription process. In order to preserve the POF stability during the inscription, a prestrain was applied. The transmitted amplitude spectrum measurements were obtained with an FBG interrogator (FS2200SA from FiberSensing) that presents a wavelength resolution of 1 pm and a scanning rate of 1 Hz.

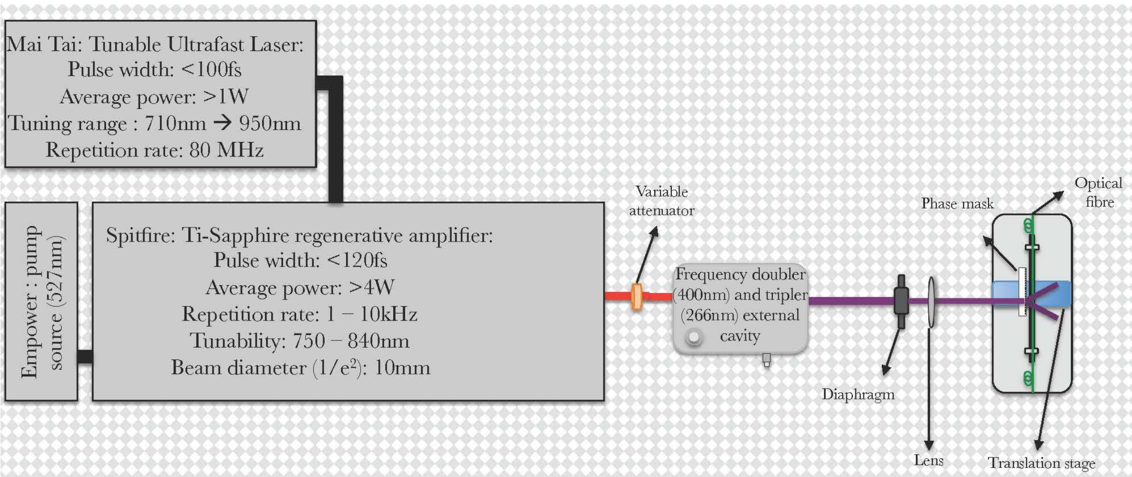

Figure 1. Femtosecond laser composition and sketch of the inscription set-up.

Results

For the SI-POFs, uniform FBGs were inscribed with 3 different mean beam powers, namely 8 mW, 13 mW and 20 mW. Figure 2 shows the corresponding FBG growth dynamics measured from the insertion loss of the main core mode resonance in the transmitted amplitude spectrum. At 8 mW laser beam power, the insertion loss increases slowly until a saturation is reached in slightly more than 5 minutes. Oppositely, at 20 mW laser beam power, the insertion loss grows fast and can reach a higher value, measured here close to 8 dB, which corresponds to a reflectivity of 84%. The latter was achieved in slightly more than 1 minute, as shown in Figure 2. A power of 13 mW shows an intermediate behavior, compared to the other two cases. With the beam power of 13 mW during inscription, the spectra were recorded every 15 seconds until saturation of the resonance dip in the transmitted amplitude spectra. The grating growth is accompanied by a blue wavelength shift, as shown in Figure 3.

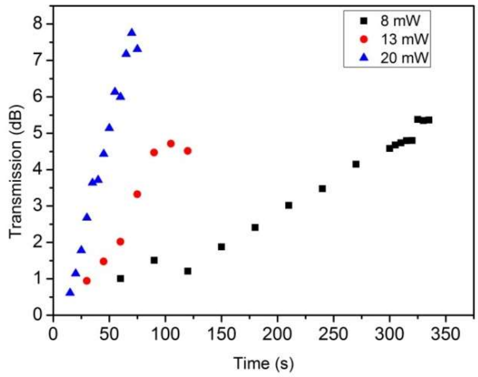

Figure 2. FBG growth dynamics in insertion loss in transmitted amplitude spectra.

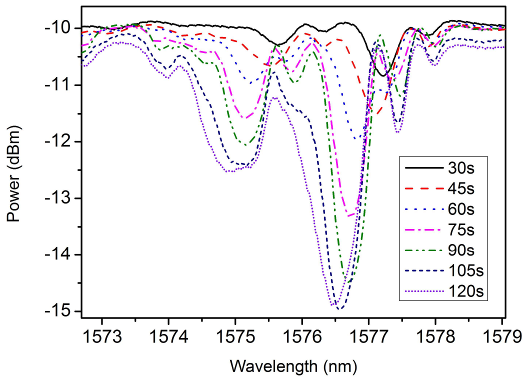

Figure 3. Spectrum evolution with 13 mW beam power.

For mPOFs, the gratings were inscribed at 8 mW laser beam power. During the photo-inscription process, the grating evolutions were recorded in both reflection and transmission modes, as shown in Figures 4 and 5, respectively. FBG reflection peaks appeared and grew gradually with a blue wavelength shift probably because of the accumulated heat from the laser. Although the grating spectra present a good shape in both reflection and transmission modes, the noise level in reflection started to increase dramatically after 16 seconds and the transmission losses grew at a rate of 0.1 dB/s.

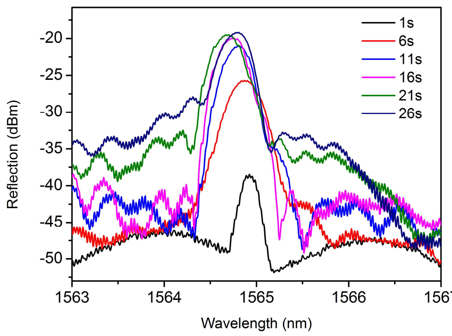

Figure 4. Evolution of the reflected amplitude spectrum during the photo-inscription process.

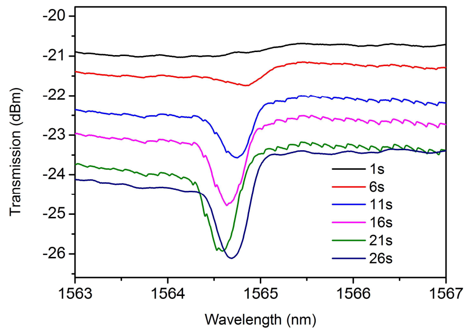

Figure 5. Evolution of the transmitted amplitude spectrum during the photo-inscription process.

Thus, in order to keep a grating shape of sufficiently good quality, the photo-inscription process was limited to ~20 s. The corresponding FBG reflectivity has been computed equal to 40 %, which is by far enough for sensing applications. The aforementioned phenomena might be attributed to the BDK-doped core that, compared to pure PMMA, has a lower glass transition temperature (T_g) and a lower melting point.

Conclusion

We have reported fast FBG manufacturing into both photosensitive PMMA SI-POFs and mPOFs at ~ 1570 nm with a femtosecond laser at 400 nm and the phase mask technique. For the SI-POFs, the maximum reflectivity 84% was achieved with 20 mW beam power in 70 seconds. For the mPOFs, the FBG reflectivity reached 40% with 8 mW beam power in 21 seconds.

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