Optics & Laser Technology 78 (2016) 104–109

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

[INVITED] New advances in polymer fiber Bragg gratings

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ARTICLE INFO

Article history:
Received 4 August 2015
Accepted 11 August 2015
Available online 28 August 2015

Keywords:
Fiber Bragg gratings
Polymer optical fibers
Photosensitivity
End face

ABSTRACT

During the last years, fiber Bragg gratings (FBGs) written in polymer optical fibers (POFs) have been pointed as an interesting alternative to silica FBGs for applications in sensors and in optical access networks. In order to use such components in real applications, the manipulation of POFs, as well as the increase of quality in the production of FBGs has to be achieved. In this article some of the recent advances regarding these two aspects are reported and include recent developments to produce smooth POFs end face with high quality, benefiting the current splicing process and the inscription of high quality FBGs in a few seconds. Furthermore, additional characterizations to strain, temperature, pressure, and humidity are also shown.

1. Introduction

Nowadays, polymer optical fiber Bragg gratings (PFBGs) are considered, for some applications, as an interesting alternative to silica fiber Bragg gratings due the advantages of polymer materials when compared with silica. Until now, polymethylmethacrylate (PMMA) has been the main choice for the production of polymer optical fibers (POFs). Indeed, when compared with silica material, PMMA has a negative and much larger thermo-optic coefficient, smaller Young modulus [1], high water absorption capabilities [2] and biological compatibility [3]. These advantages are well attractive for sensor applications especially when large strains can be imposed in POFs without breaking the fiber [4]. Additionally the use of microstructured polymer optical fibers (mPOFs) have attracted enormous interest, due to the ability to remain single mode (SM) in a large wavelength range [5] and the capability to control the modal properties, such as confinement loss and dispersion [6]. This paves the way for high capacity wavelength division multiplexing (WDM) optical communications in plastic optical fibers. Therefore, the need for the ability to write high quality PFBGs is now a reality. To date PFBGs have been written in different spectral regions, in doped [8,9], undoped [7,9], step-index (SI) [8,9] fibers, mPOFs [7–11], and graded-index (GI) POFs [12], with inscription wavelengths equal or above 325 nm. The PFBGs written with such UV radiations have demonstrated their potential applications in sensing. For example, PFBGs have been used to detect strain [4,12], temperature [12,13], pressure [14], humidity [15] or refractive index and viscosity [13].

One of the major drawbacks on the inscription of PFBGs with a 325 nm laser was the inscription time, which could take tens of minutes [7], leading to have practical challenges due to the need of mechanical stability. The best result with this wavelength was established in 7 min [11]. A more efficient process was needed. In fact, it is known that PMMA has strong photosensitivity under deep UV radiation, making it desirable for PFBG inscription. However, this UV radiation was not being considered for the inscription because, according to Peng et al. (i.e. [4,9]), the grating produced in a polymer preform was a surface relief grating. The authors concluded that the obtained results were due to the strong PMMA absorption. These results may be explained by the high fluences and long exposure time used, imposing ablation and removal of the polymer surface. However, in a recent work [16], we have demonstrated that the use of a 248 nm UV radiation, conventionally used for the inscription of silica FBGs, was effective for the production of high quality PFBG on an mPOF in only few seconds. The success was inherently due to the use of low fluences, low repetition rate and also low exposure time.

In addition to the challenges in the inscription of PFBG, it is well known that when working with PFBGs, the coupling process can be a problem mainly due to the POFs end face quality. Therefore, many authors have dedicated their work on this subject, to produce the best quality end face POF. Those works cover different techniques, as the semiconductor dicing (SD) saw [17], the focused-ion-beam (FIB) milling [17], the ultraviolet (UV) laser cleaving [17,18], the hot blade cleaving [19–21], the connectorization process [22,23], and more recently the liquid nitrogen cleaving method [24]. Among the different techniques the most promising candidate seems to be the cleaving process. However there is a variety of parameters that should be taken into account for each fiber type. Regarding the connectorization

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http://dx.doi.org/10.1016/j.optlastec.2015.08.010
0030-3992/

process, problems associated with core shift imposes problems to the coupling processes, especially when the coupling is done between thin core fibers. Finally for the SD saw, FIB milling, UV laser cleaving and liquid nitrogen cleaving appear to be good candidates for laboratory purposes but not for field applications. Regarding the conventional techniques used for the POF end face preparation, the development of a process capable to produce POFs end face in a fast and easy way is mandatory. Recently, we demonstrated a new fast semi-automatic method capable to produce a smooth POFs end face [25]. With this new achievement in the manipulation of POFs, along with the ability to produce high quality PFBG in a few seconds, the required conditions to move forward to a more mature technology based in PFBG are now available, allowing new applications based on PFBG. In this work we explore these recent developments in POF manipulation and PFBG inscription and how they can be used to produce high quality PFBG sensors.

Initially, different POFs were selected and processed for a smooth end face. Additionally, the prepared POFs were used to write high quality PFBG in less than 30 s using the 248 nm UV laser. The fast grating growth was due to the combination of low repetition rate and low fluences. The exposure time was also controlled in order to avoid the cumulative energy. The characterization of the PFBG under different parameters, as strain, temperature, pressure and humidity were also undertaken, revealing sensitivities values similar to the ones obtained for PFBGs written under conventional UV wavelengths. The following sections detail these procedures.

2. POF end face preparation and quality analysis

Before the FBG inscription, the fibers were prepared on both ends by a semi-automatic method. The mPOFs were acquired from Kiriama Pty Ltd. and the SI-POF from Paradigm Optics. The fibers are totally composed of PMMA except the FM w/ Rh6G and the SM-MORPOF02, which are doped with Rhodamine 6G and polystyrene respectively. The fiber specifications are shown on Table 1. The POFs end face preparation was started by cleaving the POFs in short lengths (i.e. 20 cm). The preparation of the POFs end face is done by using a dedicated device designed to polish connector silica fibers (REVTM connector polisher, from Krell Technologies). This machine, with some additional tools and techniques was used to produce a clear end face of the POFs. Therefore, ferrules of physical contact connectors (FC-PC), with 2.5 mm external diameter, were used to fill the support of the FC-PC connector machine.

These ferrules were chosen to have an inner diameter (bore) close to the diameter of the POFs used. In that way, the fibers were inserted on different bore ferrules (i.e. 125, 240, 250 and 260 μm) in order to verify the one that best matches the external diameter of the POFs. After selecting the ferrule bore, the POF is inserted on it and a hand-made cleaving process is done. This step is intended to avoid crack formation and at the same time to allow the creation of a flat surface, perpendicular to the longitudinal axes of the fiber. For that reason, the fiber is laid down onto a piece of glass that is at room temperature were a heated blade is used to cleave the POF. The blade temperature is set to be below the melting point of PMMA which is between 70 and 80 °C. The next step, and the most important one, is the polishing procedure starting with a polishing film (PF03.0S-P-2) during 15 s followed by another with thinner grain size (PF00.XW-P-2). In order to give a clear and smooth end face POF. To avoid contamination of the fiber tip with dust particles, water spray was spread onto the second polishing film.

Image processing algorithms were used to measure the structures presented on the POFs. Hence, different vision tools were applied on the collected microscope images to detect the edges and to calculate the dimensions. The parameters selected to be measured were: the ellipticity of the cladding, defined as the ratio between the diameter of the major and minor axes; the mean holes ellipticity; and the core shift, measured as the difference between the center of the cladding and the mean center of the hole layers.

Table 1
POF specifications

Fiber name	Mode property	Type	Hole d [μm]	Hole layers	Cladd D [μm]	Core d [μm]
G3-250	Multimode	mPOF	–	3	250	34
MM-150	Multimode	mPOF	3.5	3	150	40
FM w/ Rh6G	Few-mode	mPOF	–	4	180	11
FM-250	Few mode	mPOF	3.2	6	250	18
SM-125	Single-mode	mPOF	1.4	6	125	4
SM-MORPOF02	Single-mode	SI	–	–	115	3.5

3. Production and characterization of PFBGs

Before the PFBGs inscription process, the prepared POFs were annealed at 65 °C during 24 h to remove any residual stresses created during the fabrication process. Afterwards, the fibers were introduced on the inscription setup and the coupling process was done using a beam profiler placed at the end of the POF. After correct coupling the light from the 9 μm pigtail silica fiber into the core, the setup was ready for the inscription process.

The inscription of the PFBGs was done using a 248 nm UV radiation from a KrF excimer laser. The inscription was based on the phase mask method. Real time monitoring is used to control the exposure time. A special arrangement comprising two 3 xyz linear stages and two clamps to secure the POFs was used. Additionally, a magnification lens and a beam profiler were added to couple the light inside the POFs. Index matching gel was used between the SM pigtail silica fiber to the POFs to reduce the Fresnel reflections.

The complete setup for the FBG inscription can be seen on Fig. 1. The slit has 4.5 mm width and the phase mask has a pitch of 1033 nm. The PFBGs were written with repetition rate of 1 Hz and 3 mJ energy, giving a fluence of 33 mJ/cm^2.

After the PFBGs fabrication, a characterization study on four of the six POFs containing the FBGs was performed for strain, temperature, pressure, and humidity variations. In order to perform these tests, the POFs were spliced to silica pigtail fibers by a Norland 78 UV glue making the connection strong enough to move the fibers to different places. The wavelength shift obtained for each change of the external parameter was recorded with a SM-125 interrogator, with 1 pm resolution. For the strain

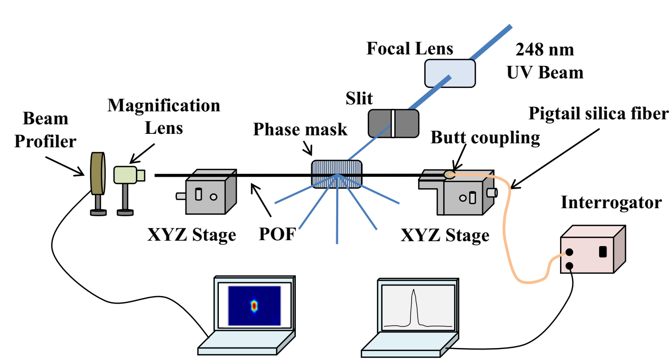

Fig. 1. Setup used for the inscription of PFBGs.