Characteristics of photo polymerized polymer optical fibres, optical properties and femtosecond laser inscription of Bragg gratings

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1. Introduction

Polymer optical fibres (POFs) are of interest for a number of applications, from illumination, light harvesting and sensing, to short-range data transmission in automobiles, buildings and industrial automation. A key requirement for the successful development of POF is precisely controlled fibre production. Current POF production is inflexible requiring a number of techniques and manufacturing steps to arrive at the final fibre product, which impacts the fibre's optical and mechanical properties. The fibre supply chain typically consists of separate processes for chemical formulation and polymer manufacture, compound addition and fibre production. Unsurprisingly, the production process is long and complex and it is rarely possible to produce identical properties for two separate batch production runs, particularly when the fibre is produced with the heat-drawing process from a preform.

2. A new type of polymer fibre

In this paper, we present a new type of polymer optical fibre that has been developed by Intellisiv based on an advanced, single-step and highly scalable UV curing (photo-polymerization) process, a readily customizable production process that optimizes resources [1]. The key advantages may be summarised as follows, there is no polymer or master-batch at the production starting point, instead formulations of commercially available monomers & other additives are used as required; a liquid formula injection process is followed by very fast fibre UV polymerization; thus fibre formation and polymerization occurs simultaneously. This approach is highly customisable and flexible, whilst offering environmental advantages, such as a process that is essentially solvent/VOC-free, water-free, with very low emission (<1%).

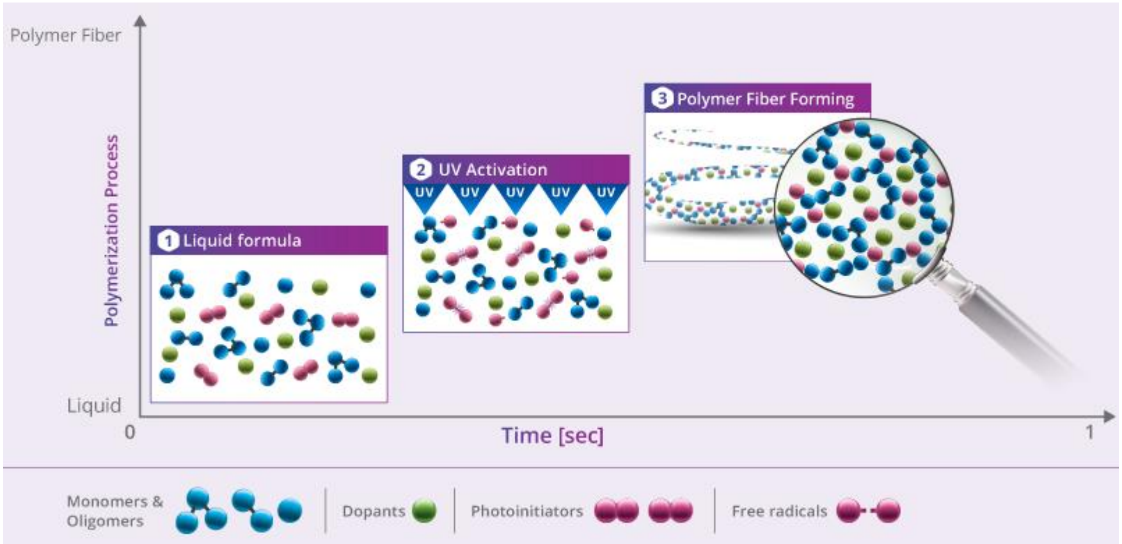

Figure 1. Intellisiv fibre polymerisation process

3. Optical transmission of the fibres

We have measured the optical transmission properties of two representative POFs manufactured by Intellisiv. Measurements were performed by the cut-back method [2] in which light is coupled into a given length of fibre and the transmitted power is measured as the fibre is shortened. Due to the uncertainty regarding the coupling efficiency into the fibre, the measurement of the power output will not yield unequivocally the value of the transmission loss per unit length of the fibre. This uncertainty can be eliminated by successively shortening the fibre at its output end (cut-back), without changing the input coupling conditions, measuring the transmitted power and calculating the loss from the changes in power transmission with fibre length.

Cut-back measurements were performed in two ways: using discrete wavelength light, and also with a broadband visible source and a spectrometer, producing continuous spectral information. The latter approach appears more attractive since it can supply more information, but, as will be detailed below, is more prone to experimental errors. Thus our approach was to first accurately measure the cut-back loss at 532nm using a laser source and then perform the spectroscopic cut-back measurements. When the spectroscopic measurement yielded a result consistent with the laser measurement at 532nm, then the entire spectroscopic measurement was considered verified.

For the discrete measurement, our source was a 5mW 532nm laser (Global Laser Tech) coupled into a 600 μm core NA=0.39 silica fibre patch-cord, with SMA connectors (Thor Labs M21L05). The POF under test was cleaved with a razor blade, inserted into an appropriate SMA connector and butt-coupled to the silica fibre with an SMA fibre adapter. The output end of the POF was also cleaved and the power output was measured with an integrating power meter detector (Newport 818-IS-1). The fibre was cut-back three times to determine the attenuation.

The basis of the spectroscopic cut back measurement was to use as input broadband 300-1000 nm light coupled into the above mentioned 600 μm core NA=0.39 silica fibre patch-cord and similarly butt-coupled to the POF. The transmitted light was detected with a spectrometer. This approach has an inherent problem: the positional and angular coupling to the spectrometer – which quite likely will vary for each fibre cut - influences the resultant spectrum. These issues have very little effect on the previously mentioned monochromatic cut-back measurement, since the detector (power meter) has a large collecting area.

Accordingly, we decided to permanently attach a second silica NA=0.39 fibre patch-cord (with core diameter larger than that of the POF) to the spectrometer SMA fibre input and butt-couple the POF between the two silica fibre patch-cords for the spectroscopic cut-back measurements (see Figure 2). The POF was successively cut back 3 times and each time butt-coupled to the "spectrometer" silica fibre, touching neither the input to the POF nor the coupling between the silica "spectrometer" fibre and the spectrometer. In this way we eliminated the uncertainties (and variations between measurements) also at the input to the spectrometer. We also expect that in this set-up, insertion losses will be essentially wavelength independent. This set-up leaves as the only uncertainty the quality of the POF cleaves and the butt-coupling to the silica "spectrometer" fibre. As stated above, our validation is the compatibility of the spectroscopic 532nm result with that previously obtained with the 532nm laser.

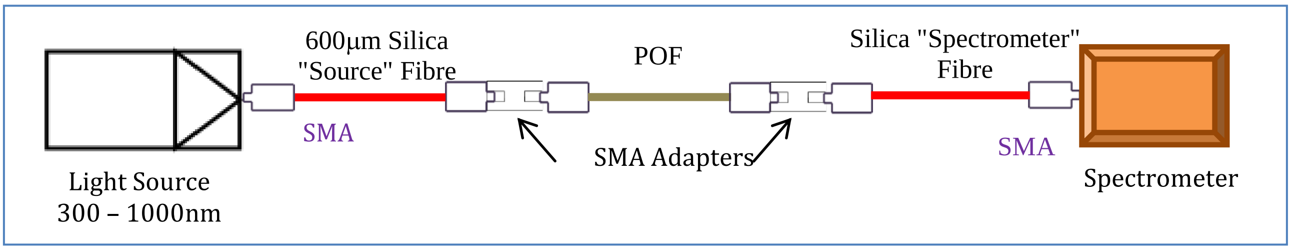

Figure 2: Set-up for spectroscopic cut-back measurements

In Figure 3 (blue curve) we present our results for an acrylate based Intellisiv fibre designated CR002CL0013 (750μm core diameter, NA=0.47). Having learned these results, the fibre composition and the manufacturing process were refined, with the aim of decreasing losses. Consequently a new fibre was produced, designated

NTO34NTCR (580 μm core, NA=0.47). The losses in the latter (brown curve of Figure 3) are indeed significantly lower, as designed. Both fibres show relatively flat spectral transmission over most of the visible range (which for the second fibre is 3-5 dB/m), with a steep increase in attenuation from 850nm.

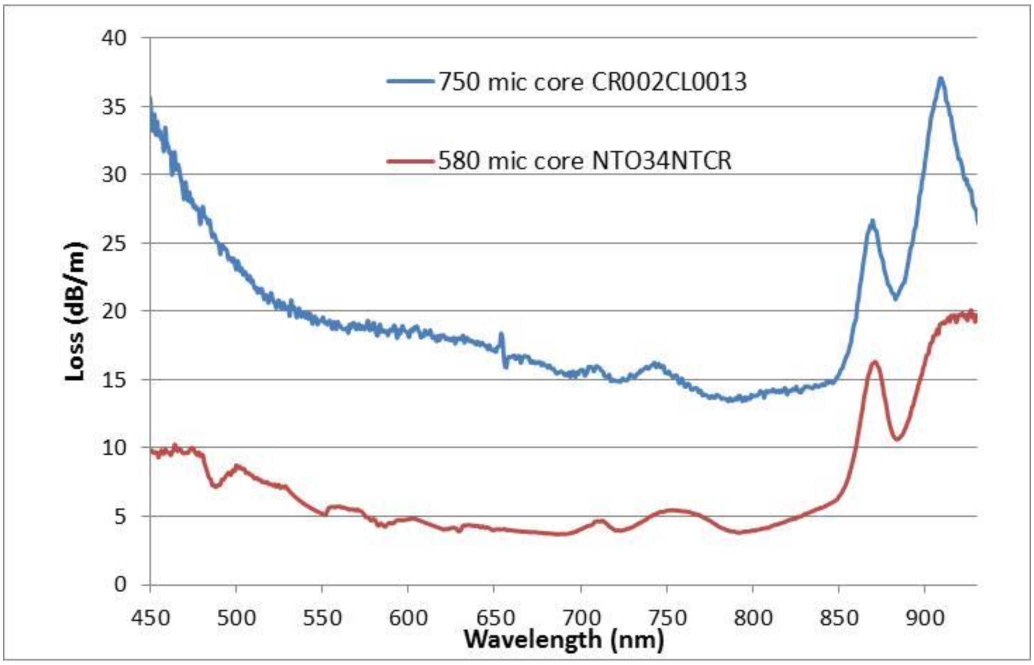

Figure 3: Optical characterization of 2 POFs

4. FBG inscriptions and results

The inscriptions of fibre Bragg gratings (FBGs) were performed using a femtosecond laser system (HighQ laser femtoREGEN) operating at 517-nm, with a 220-fs pulse duration. The fibre sample was mounted on an air bearing, two-dimensional translation stage system (Aerotech) for accurate computer controlled two-axis motion during the inscription. The laser beam was focused from above using a long-working-distance x50 objective (Mitutoyo) mounted on a third stage in order to control the laser focal spot into the optical fibre. The fibre that was tested was the multimode Acrylate fibre CR002CL0013 with a core diameter of a 750-μm. All the grating inscriptions were undertaken with the outer cladding in place to ensure a robust sensing fibre. We used the plane-by-plane femtosecond laser inscription method [3]; this offers sufficient control of the inscription parameters, as the depth, width and the height of the inscription planes can be fully controlled by the user. A pulse picker was used to operate the laser at 2-kHz repetition rate and the laser emitted pulses with energies of ~50nJ/pulse. We undertook two inscription processes on two different fibre samples, both of the higher loss fibres described in the preceding paragraph.

First we inscribed a single grating with 200 periods across the centre of the fibre core in a sample having a total fibre length of ~10-cm. For the second inscription we used a longer sample ~75-cm and we inscribed two gratings, each consisting of 1000 planes, with a physical distance between them of ~500-μm. The period of the gratings was approximately Λ=2.2-μm, with a small difference in the period of the second grating in order to form a two distinct sensor FBG array.

Following the inscription, the gratings were characterized using a broadband source (Thorlabs ASE730) centred at 1560nm coupled to the fibre via a (silica) fibre circulator, and a I-MON spectrometer from Ibsen Photonics. A small amount of index gel was used to reduce the Fresnel reflections from the end of the silica fibre. The reflection spectra of the two fibre samples are shown in Fig. 4; Fig. 4a shows the reflection spectrum of the first grating (inscribed on the short fibre) and Fig. 4b shows the reflection spectrum of the 2-FBG array, when measured from the long side, around ~75cm away from the FBG. The exposure time of the spectrometer was set to 3ms.

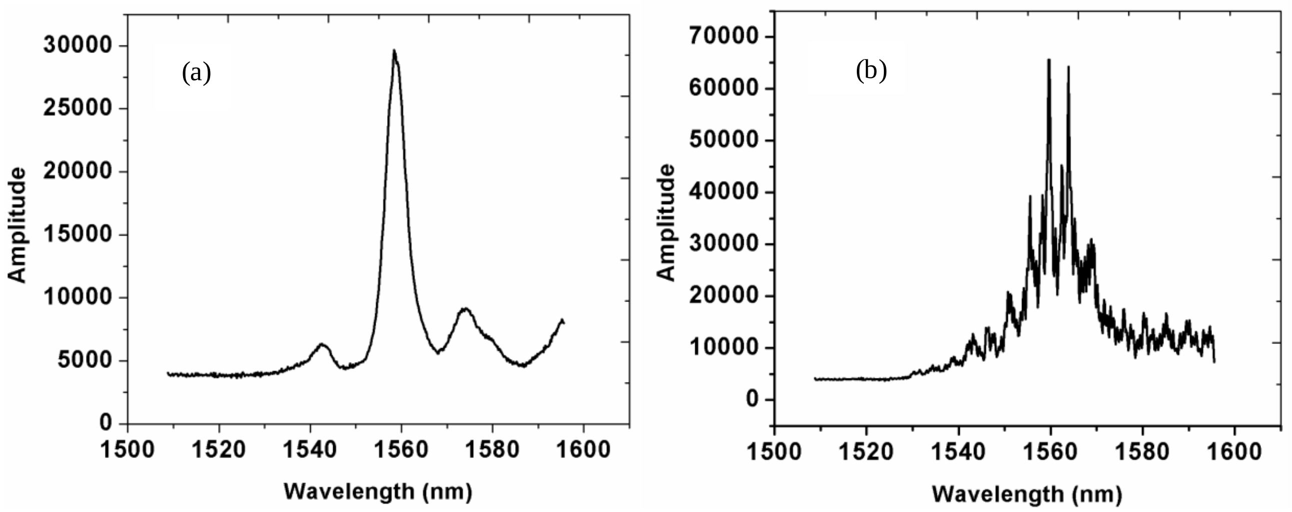

Figure 4: The reflection spectra of the inscribed FBGs in the two fibre samples

As may be seen, all 3 inscriptions were successful, yielding significant reflection spectral profiles, with the 2-FBG array exhibiting much lower signal-to-noise ratio due to the relatively long fibre length (75cm) that has to be traversed twice. We remind the readers also that at these wavelength regions the fibre loss is extremely high. As for the reflection widths, as could be expected the shorter FBG of 200 periods (Figure 4a) shows a broader reflection spectrum of about 3nm, whereas the FBGs in the array, having 1,000 periods each, show a much narrower response.

5. Summary

To summarise, we have shown that fibre Bragg gratings may be inscribed onto the new type of polymer optical fibres that has been developed based on an advanced, single-step and highly scalable UV curing (photo-polymerization) process. The fibres show, at the moment, relatively high transmission losses but further improvements are under way. The FBGs were straight-forward to inscribe, with the fibres showing good mechanical properties. The FBG responses were measured and presented showing expected characteristics. These are just initial results that will be studied more deeply and improved in the near future.

6. References

[1] http://www.intellisiv.co.il/

[2] see, for example: M.G. Kuzyk, *Polymer Fiber Optics: Materials, Physics, and Applications* (CRC Press Boca Raton, Fla.) 2007, p 146.

[3] A. Lacraz, M. Polis, A. Theodosiou, C. Koutsides, and K. Kalli "Femtosecond laser inscribed Bragg gratings in low loss CYTOP polymer optical fiber", IEEE Photonics Technology Letters, 27(7), 693–696, 2015.