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Periodic refractive index modifications inscribed in polymer optical fibre by focussed femtosecond pulses

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Abstract: Focussed femtosecond laser pulses were used to inscribe a periodic array of modifications in the core of a polymer optical fibre. Structural and refractive-index modifications have been observed at different pulse energies using DIC microscopy.

Introduction

A key component in any optical fibre system is the in-fibre Bragg grating filter. The fabrication of such filters through photosensitivity in silicate glass fibres is a relatively mature technology. Compared with silica fibres, polymer optical fibres (POFs) are relatively cheap and easy to produce; however their main advantage is their much higher breaking strain (i.e. approximately 45%, instead of 1% in silica fibre) making them very attractive for applications in strain sensing. As interest in applications of polymer fibres has grown (e.g. in short distance telecommunication and sensing), so has the need for grating filters in polymer fibre. Existing grating-writing techniques using UV illumination in doped-core POFs require some improvement for widespread application, particularly in terms of grating strength and linewidth.[1,2]

An alternative approach for fabricating fibre Bragg gratings is to use focussed infrared femtosecond pulses. Although glass and polymer are transparent at infrared wavelengths, the high peak power of a femtosecond pulse enables multi-photon absorption and ionisation processes to take place which, together with modern precision positioning equipment, provides a new approach to writing gratings with additional flexibility. The first fibre Bragg grating fabricated in silica fibre with infra-red (IR) femtosecond pulses was reported in 2003[3], however in their experiment a phase mask was used to provide the periodic modulation of the beam intensity along the length of the grating. Direct writing of gratings in silica fibre, i.e. in which each period of the grating was inscribed point-by-point by a single, tightly-focussed IR pulse was first reported by Wikszak in 2004.[4] This technique has been used to inscribe strong gratings (>30 dB transmission extinction) with narrow linewidth (~100 pm) without any apodization in a variety of non-photosensitive, silica optical fibres.[5]

Here we report the use of the femtosecond point-by-point writing technique to inscribe period arrays of refractive index modifications in the core of a PMMA polymer optical fibre. To our knowledge, this is the first demonstration of femtosecond point-by-point inscribed features in a POF. Images of the inscribed features were acquired using differential interference contrast microscopy and brightfield microscopy. We present results for grating inscription at different pulse energies, showing two distinct regimes – one with damage in the core, the other with only refractive index modification.

Grating Inscription Method

A schematic diagram of the grating inscription setup is shown in figure 1. The femtosecond laser used to inscribe the grating structures produced pulses less than 120 fs in duration at a centre wavelength of 800 nm, with pulse repetition frequency up to 1 kHz. The femtosecond pulses were focussed through the side of the POF by a 20x magnification oil-immersion objective (NA 0.8). The POF was clamped taut between two fibre chucks and mounted on a 3-axis, computer-controlled precision motion stage (Aerotech FA-130). The fibre was translated at a constant velocity with respect to the focal point of the objective. As each pulse from the laser corresponds to a single grating period, the pitch of the grating is therefore given by the ratio of the fibre translation speed to the laser pulse repetition frequency.

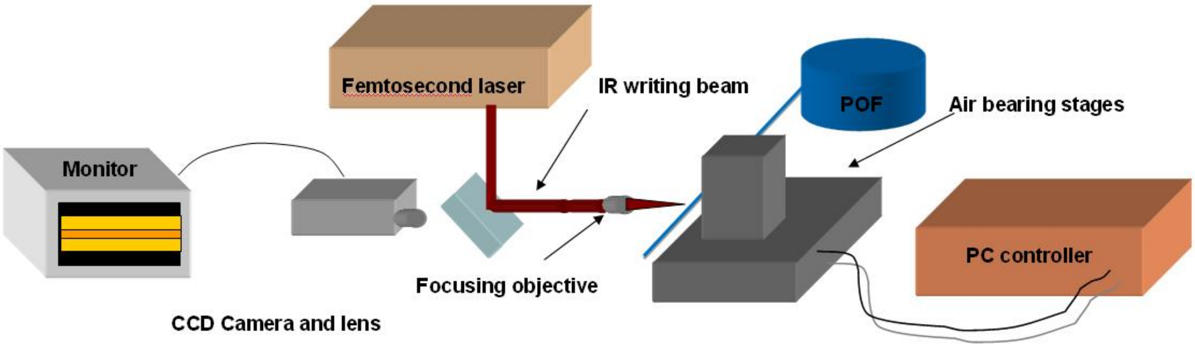


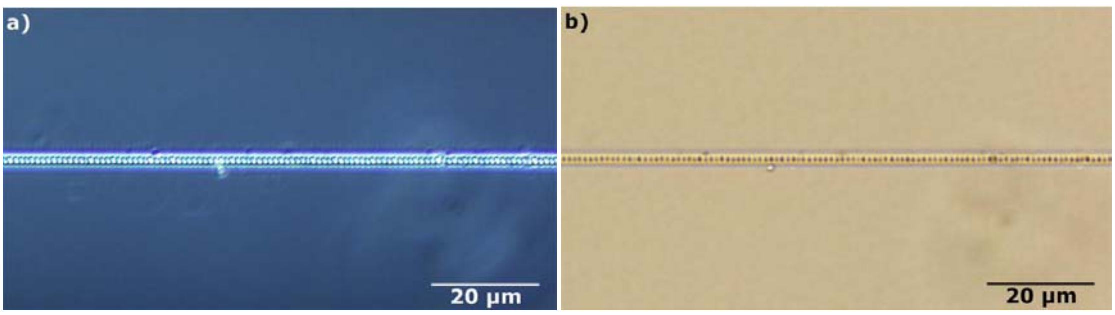
Fig. 1: Experimental grating writing setup used

Results and Discussion

The polymer optical fibre used in our experiments was a commercially available fibre designed for single-mode operation in the C-band (core diameter 3.3 µm; cladding diameter 115 µm).

In silica, the threshold pulse energy for inducing damage at the focal point of the objective is approximately 120 nJ (for our system). Due to the lower glass melting temperature in polymers, we anticipated a lower pulse energy for damage. Using our en-situ vision system we were able to roughly identify the threshold pulse energy for damage in the POF. We subsequently wrote gratings in the POF at a range of pulse energies from 40 nJ to 90 nJ, to include both below-threshold and above-threshold modification regimes.

The gratings were subsequently imaged with a differential interference contrast (DIC) inverted microscope (Olympus IX 81). The microscope was also used in brightfield mode. The DIC imaging mode provides contrast where there is a gradient in the refractive index, allowing refractive index features to be observed which would not be observable in standard brightfield mode. Therefore, comparison between corresponding images taken in DIC and brightfield allowed us to discern between laser-induced modifications which feature damage, and laser-induced modifications which only consist of refractive index change. Three images are shown in figure 2, two images of the same grating written with pulse energy above threshold for damage, the third of a grating written below the damage threshold. In this third image, the laser-induced refractive index modifications can clearly be seen. The corresponding brightfield image of the below-threshold grating (not shown) does not show any visible features.



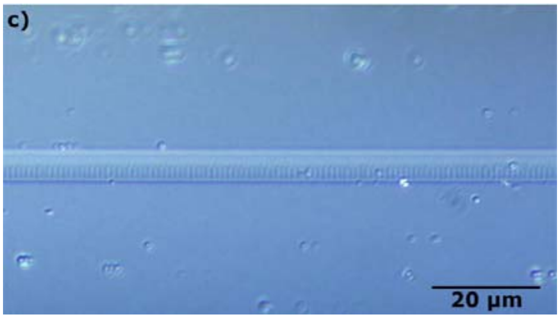


Fig. 2: A grating written with pulse energy above threshold for damage, imaged in DIC mode (a) and in brightfield mode (b); and a DIC image of a grating written below the damage threshold, in which the laser-induced refractive index modifications can clearly be seen (c).

The gratings were probed in reflection and transmission using a C-band, swept-wavelength characterization system, by butt-coupling from silica single-mode fibre into the polymer optical fibre and using a fibre circulator. Under both conditions there was very high loss and no grating resonance detected. It is believed that this is largely due to pre-existing damage in the commercial polymer optical fibre (bubbles and defects, possibly due to poor preform preparation). Some small defects can be seen in figure 2(c) – other larger defects were observed in other sections of the fibre. Not only would the defects in the core lead to high losses, but defects in the cladding can affect the femtosecond writing beam before it is brought to a focus in the fibre core, leading to random and significant errors in the grating structure – these can easily destroy a fibre grating resonance.

Conclusion

For the first time, refractive index changes have been written into polymer optical fiber using an ultrafast femtosecond laser and the point-by-point technique. Brightfield and DIC images of the grating structures show that two distinct writing regimes have been used: above a certain threshold of pulse energy (approximately 60 nJ in our setup), localized damage is induced in the fibre core; below that threshold, refractive index modifications are induced in the fibre core without damage. The synonymous threshold for damage is approximately 120 nJ in silica, for our system.

We plan to further investigate the potential of this technique for inscribing gratings in polymer optical fibres, including long period gratings and microstructures polymer optical fibres.

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