Femtosecond fabrication of waveguide-like micro-structures in a photorefractive polymer

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In this letter, we report on, for the first time, the successful femtosecond micro-fabrication of continuous waveguide-like channels in the photorefractive polymer consisting of the nonlinear chromophore 2,5-dimethyl-4-(*p*-nitrophenylazo)anisole (DMNPAA), the photosensitive compound 2,4,7-trinitro-9-flourenone (TNF), and the plasticiser N-ethylcarbazole (ECZ) all doped in the polymer matrix poly(methyl methacrylate) (PMMA). These channels are caused by the change in refractive index as a result of the localised heating of the polymer and therefore have an important potential for micro-photonic devices in future.

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Structures with detail as fine as a fraction of a micrometer have been shown to be achievable using laser light focused through a microscope objective. Femtosecond laser micro-fabrication has recently become an effective method in the fabrication of photonic structures in glasses[1–4] and polymers[5–8] as well as in fabrication of three-dimensional bit arrays for high-density optical storage in polymer materials[9–15]. The use of polymer materials for micro-fabrication has proven to be advantageous because photosensitive materials such as organic dyes[9–15] and quantum dots[16,17] can be easily doped into a polymer matrix, which leads to a variety of new functional materials and provides many new opportunities for fabricating micro-photonic devices.

For example, a photorefractive polymer consists of a photoconducting polymer for charge transportation, a photosensitive material that produces charges upon illumination, and a nonlinear chromophore which produces a modulation of refractive index by the electro-optic effect[18]. As a result, upon the femtosecond illumination of low power, the illumination induces free charges in a photorefractive polymer, which are redistributed and thus result in a space-charge field for modulating the local refractive index[18]. It has been demonstrated that such a process in a photorefractive polymer can be generated by two-photon absorption if a high numerical-aperture objective is employed for focusing[12,13], which provides a reversible mechanism for three-dimensional bit optical storage[19]. When the illumination power increases, the heating effect leads to a localized melting process, which, in turn, modifies slightly the refractive index in the focal region. If the illumination power is higher than a threshold, a micro-explosion process can be caused by multi-photon ionization and results in the generation of micro-voids[15]. While an array of micro-voids is useful for high-density optical storage[15], the continuous void channels have recently been fabricated for the generation of photonic crystals[8]. It is therefore necessary to explore the feasibility of fabricating continuous channel structures based on the change in refractive index caused by the heating process in the photorefractive polymer.

The aim of this letter is to report on the fabrication of continuous refractive index channels within a volume of the photorefractive polymer using focused femtosecond laser pulses. This technique is also used to fabricate a crossed waveguide-like structure within the polymer.

The fabrication was performed in a sample of photorefractive polymer consisting of the nonlinear chromophore 2,5-dimethyl-4-(*p*-nitrophenylazo)anisole (DMNPAA), the photosensitive compound 2,4,7-trinitro-9-flourenone (TNF), and the plasticiser N-ethylcarbazole (ECZ), all doped in the polymer matrix poly(methyl methacrylate) (PMMA), in the concentrations 30 : 1 : 16 : 53, respectively. PMMA was chosen for its good optical properties, low refractive index, and high melting point[13]. The photorefractive polymer was polished to thickness 200 μm, and mounted on a microscope slide.

The optical set up for fabrication is shown in Fig. 1. The laser used was a titanium:sapphire ultra-short pulsed laser (Spectra-Physics, Tsunami), which was capable of delivering a pulse width of 80 fs at a repetition rate of 82 MHz. The Tsunami has a tunable wavelength range from 700 to 1080 nm. In our fabrication experiment, the laser was operated at 800 nm, which was outside the absorption band of the material and possible to achieve multi-photon excitation[12,13]. The beam was focused through a 100 μm pinhole, which acted as a spatial filter, removing the uneven intensity distribution of light from around the edges of the beam. The laser was focused onto the sample using a 0.8 numerical-aperture objective (Olympus). The intensity of the laser was controlled with a variable neutral density filter. The wavelength of the beam was observed by directing a small part of the light to a spectrum analyser. The fabrication process was observed by the use of a charge coupled device (CCD) camera. The photomultiplier was used to produce a reflection signal to align the system. Investigations of recorded patterns were performed using a transmission optical microscope (Olympus, FluoView 300).

The sample was translated along the x, y and z axes by a 200 μm piezo electric scanning stage. The scanning stage and shutter speed were controlled using programs written in LabView. Continuous scanning was conducted at 5 and 10 μm beneath the surface of the sample. The scanning range was kept to 100 μm with an averaged

power of 45 mW over the objective aperture. The scanning speed was varied for a number of straight-channel patterns to measure the effect of the exposure speed on the width of channels. Figure 2 depicts the dependence of the channel diameter on the scanning/recording speed. The diameter of the channels was the full-width at maximum (Fig. 2(b)) of the cross-section image (Fig. 2(c)) of the channel structures under the transmission microscope. The channel diameter can be significantly altered by the numerical aperture of the recording objective. It is clear that Fig. 2 suggests that a linear-dependence region exits for fabricating continuous refractive-index channels. Beyond that region, a void-based channel structure may be produced.

It is interesting to note that the large change in signal occurs in a ring structure surrounding the focus, as shown by the two dips in Fig. 2(b), rather than at the centre of the channel. This feature may be caused by the thermal expansion in the focus, which leads to the increased optical density in the surrounding region. Such a concentric double-layer structure will be useful for guiding light by a process of total internal reflection caused by the surrounding wall.

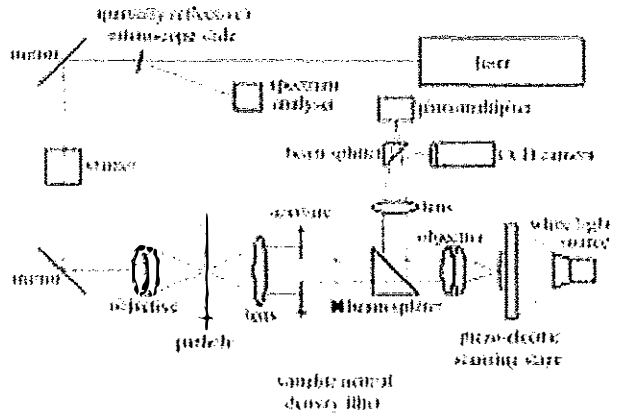

Fig. 1. Experimental set up for micro-fabrication.

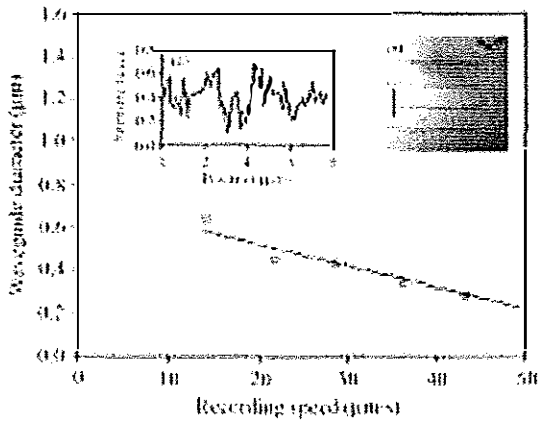

Fig. 2. Dependence of the diameter of the waveguide-like structures on the speed of recording. Inset (a) is the cross-section image of a waveguide-like structure (the arrows indicate the position where the full width is measured) and inset (b) is the transmission image of the four parallel waveguide-like channels (the vertical bar presents 5 μm).

To further demonstrate the applicability of this fabrication technique into micro-photonics, we have fabricated waveguide junction micro-structures. Figure 3(a) shows an x-junction waveguide-like structure imaged under a transmission optical microscope. To characterise the waveguide nature, the cross-section images at different propagating positions of a y-junction structure were measured and are shown in Fig. 3(b). It is confirmed that the individual channels have a concentric two-layer structure as shown in Fig. 2(b) and they are combined at the junction. It is interesting in future that the smoothness of the interface between the two layers should be examined using electron microscopy. Finally, it should be pointed out that the aspect ratio of the channel between the transverse direction (perpendicular to the direction of the writing laser beam) and the axial direction (along the direction of the writing laser beam) is different because the focusing objective has a limited value of numerical aperture. For example, for an objective of numerical aperture 1.2, the aspect ratio of the transverse direction to the axial direction is approximately 0.3[20]. This feature may prove advantageous because it provides a way to fabricate birefringent waveguides.

In conclusion, we have demonstrated the condition of femtosecond fabrication of waveguide-like structures in the photorefractive polymer under multi-photon excitation. This technique allows three-dimensional multiple signal splitting to be possible, which can be used in micro-photonic interconnection, in particular in the device including three-dimensional photonic crystals. While the coupling efficiency of these structures should be characterised in future, it is no doubt that this technique will result in important impacts on micro-photonics. First, the use of a photopolymer facilitates the application of multi-photon excitation caused by an infrared laser beam. As a result, Rayleigh or Mie scattering is significantly reduced, which makes it possible to fabricate

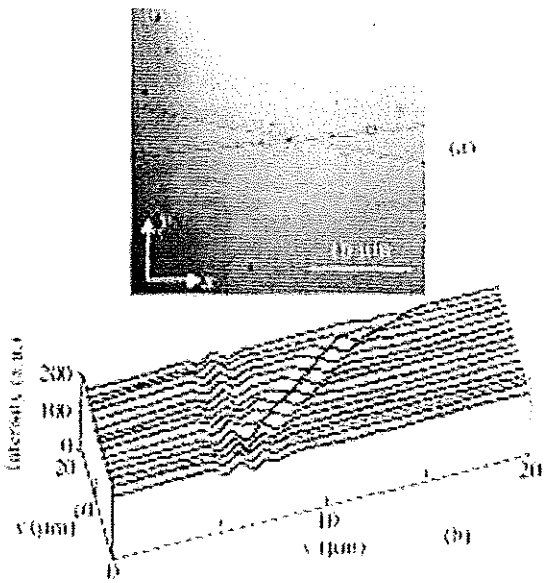

Fig. 3. An x-shaped junction structure fabricated within the photorefractive polymer block (a) and the three-dimensional view of a y-junction imaged under a transmission optical microscope (b).

a structure within a bulk medium. Second, due to the nonlinear dependence of multi-photon excitation on the illumination power, the fabrication occurs only in the focal region, which provides a tool for fabricating three-dimensional micro-structures. Third, the use of a doped polymer facilitates the development of functional devices.

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