Femtosecond laser written low-loss single-mode waveguides in PMMA

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We present a reliable and efficient method to written embedded waveguides in polymers with a femtosecond laser. A refocusing effect induces an refractive index increase directly below the material modification of the secondary focus. This zone supports guiding of an almost symmetric fundamental mode with unprecedented low propagation losses in the order of 0.5 dB/cm.

1 Introduction

Ultrafast laser inscription is a standard technique to fabricate embedded waveguides in glasses or crystals. Tightly focused femtosecond laser-pulses induce an increase in refractive index inside the material via non-linear absorption. By moving the sample through the focus virtually arbitrary three-dimensional paths can be created. The transfer of this technique to polymers has already delivered promising results [1, 2] but is limited so far by the reported high propagation losses between 3–6 dB/cm [3]. Here we present a new approach to femtosecond laser writing of waveguides in bulk poly (methyl methacrylate) (PMMA) by exploiting a refocusing effect during the writing process.

2 Experimental Setup

We utilize a home-made Yb:KYW based chirped-pulse oscillator with cavity-dumping. The spectral bandwidth of 8 nm is centred at 1048 nm and the pulses can be compressed to a duration of 600 fs. With an external Pockels-cell based pulse picker the repetition rate of 1 MHz can be decreased. The laser pulses are focused into 1.5 mm thick PMMA substrates by an aspheric lens with 0.55 NA. Three computer controlled translation stages move the sample through the focus. The setup is displayed in Fig. 1.

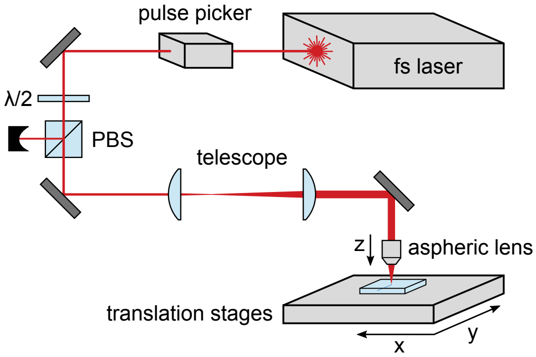

Fig. 1 *Experimental setup for femtosecond laser writing.*

3 Results

Optimal waveguides are obtained at a repetition rate of 100 kHz, pulse energies between 400–650 nJ, and writing speeds between 20–45 mm/s. In this regime a refocusing effect occurs during the writing process and creates an almost symmetric fundamental mode waveguide.

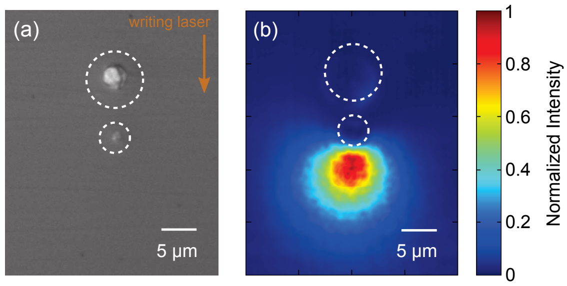

Fig. 2 *Morphology of a typical waveguide written 150 µm below the surface. (a) Bright-field microscope image of a polished end-facet with primary and secondary structure. (b) Intensity distribution of the corresponding guided mode at 660 nm. The white dotted line marks the outside margin of the apparent structural changes.*

Figure 2 (a) shows a polished end-facet of a femtosecond laser written structure. The larger primary structure is located at the preset writing depth of 150 µm. The center region has been revealed by Focused Ion Beam milling to be a hollow channel which corresponds in size approximately to the focal spot of 2 µm in diameter. The core appears white in the figure since it clogs with rubbed-off material during the polishing process. Around the center region is a faint ring of homogeneous material modification. Its radial symmetry hints that heat diffusion is a dominant effect here and that machining takes place in the heat accumulation regime. During the writing process the refractive index change induced by the primary modification acts as a lens on unabsorbed light. Thereby an additional focus occurs and a smaller secondary modification forms at sufficiently high pulse energies.

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Light is butt-coupled into the waveguide from a fiber, the exiting facet is then pictured on a CCD camera by a microscope objective. Figure 2(b) displays the same section as (a) and shows a false colour representation of the intensity distribution of the guided mode at 660 nm. The white dotted lines mark the outside margins of primary and secondary material modification. Other than reports on waveguiding inside the apparent structural changes [2] or in between two modifications [3] we observe the guided mode directly below the secondary material modification as can be clearly seen in Fig. 2. In experiments at different writing parameters where the refocusing effect does not occur we could observe a rather tubular shaped waveguide distributed around the core structure [4]. Therefore the refractive index increase can be attributed to material densification via compression caused by a quickly expanding plasma-core. If refocusing of the writing laser occurs the secondary modification breaks the symmetry and encounters an already existing ring of densified material around the primary modification. The interaction between both zones partly channels the effect downwards and leads to the observed waveguide structure.

By measuring the input and output power one obtains the total insertion losses of a waveguide. Multiple samples of different length including dozens of waveguides written with the same parameters were fabricated. The average of the measured insertion losses as a function of the length allows to calculate the propagation losses as the slope of a linear fit as shown in Fig. 3.

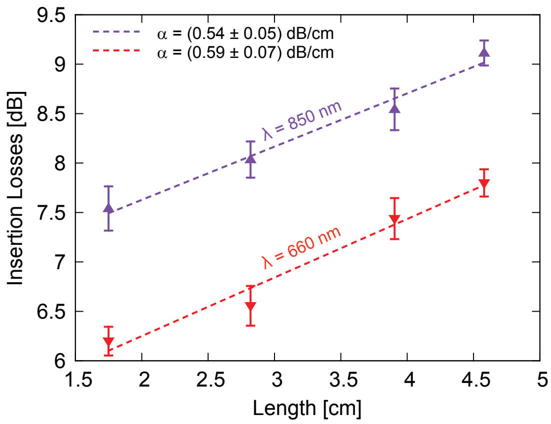

Fig. 3 *Insertion losses of femtosecond laser written waveguides in PMMA at varying sample length for coupled light at 660 nm and 850 nm. A linear fit provides the propagation losses.*

Propagation losses are equally low for 660 nm as well as 850 nm test wavelength and in average go down to 0.5 dB/cm [4] which are – to the best of our knowledge – the lowest losses ever reported for femtosecond laser written waveguides in PMMA. The vertical offset between the two curves represents different coupling efficiencies due to mismatch in mode-field diameter between fibers for each test wavelength and the waveguides. From measuring the numerical aperture the refractive index increase is estimated to be $\Delta n = 6.2 \times 10^{-4}$. The overall writing process presents itself as highly reproducible.

4 Conclusion

We have demonstrated the formation of low-loss single-mode waveguides in PMMA applying the femtosecond laser writing technique and exploiting a refocusing effect. The refractive index increase is created by material densification directly below the irradiated secondary focal volume. The guided fundamental mode shows almost radial symmetry. With propagation losses down to 0.5 dB/cm applications on a larger scale – such as waveguide networks in a polymer foil – become practical with this type of waveguide.

Acknowledgements

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