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Waveguides and proportional beam splitters in bulk poly(methyl methacrylate) produced by direct femtosecond-laser inscription

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ABSTRACT

Waveguides fabricated by direct femtosecond-laser inscription were reported in bulk poly(methyl methacrylate) (PMMA). Optimization of waveguide structures was conducted and 1×2 beam splitters with equal and proportional splitting ratio were fabricated. Three-dimensional structures of 1×4 beam splitters were also achieved based on 1×2 beam splitters. The largest change of the refractive index between femtosecond laser modified area and unmodified area was estimated to be 1.1×10^{-3}. The minimum insertion loss of the single-mode waveguide measured with the He–Ne laser at the wavelength of 632.8 nm was 4.32 dB and propagation loss was calculated to be as low as 3.57 dB/cm.

1. Introduction

In integrated photonics, optical waveguides are defined as cores of high refractive index with claddings of low refractive index. Functional guiding devices including gratings [1], couplers [2,3], splitters [4–8], optical amplifiers [9] and laser oscillators [10] can be manufactured in organic and inorganic materials based on waveguide structures. Among these devices, optical waveguide power splitters, which can switch optical signal from single input to multiple outputs, play as essential elements for integrated photonic circuits. Compared to inorganic materials for waveguides fabrication, polymers have numerous advantages, such as low cost and ease of processing [11]. Moreover, polymeric materials can be doped with various fluorescent materials, by which optical properties can be adjusted. Among various polymers, poly(methyl methacrylate) (PMMA) is one of the most common materials for optical fibers [3] because of the high transmittance in visible and near-infrared regions.

A few techniques have been applied for waveguides fabrication, including liquid-phase epitaxy [12], ion-beam implantation/irradiation [13], ion/proton exchange [14], and femtosecond laser inscription [15]. Among these techniques, femtosecond laser micro-processing has been developed to be one of the most efficient and low-cost ways for waveguides fabrication in diverse materials. Femtosecond laser micro-processing is widely applied because of its unique advantages such as little damage around the processing area, ultrahigh precision and ability for direct three-dimensional (3D) micromachining [16].

Waveguides can be directly fabricated by focusing the laser beam beneath the sample surface, which will not cause any damage on the surface. Positive changes of refractive index emerge inside or beside the laser track, through which waveguides of diverse structures will be induced. Various optical structures including tubular waveguides [17,18], symmetric waveguides [3], couplers [19] and splitters [20] have been successfully achieved in bulk PMMA based on Type-I waveguides. In this configuration, positive changes of refractive index can be induced on the femtosecond laser track, which serves as the waveguide core. The part around the laser track, with unchanged refractive index, serves as the waveguide cladding [15]. Three-dimensional waveguides fabricated in PMMA by femtosecond laser micro-processing indicate the possibility of high-efficiency and low-cost photonic devices.

In this work, Type-I, coupler-like and tubular-like waveguides were successfully produced in bulk PMMA by direct femtosecond-laser inscription. A slit of 500 μm was used to reshape the laser beam. The impact of the slit and laser parameters on waveguide modification was studied and the relationship between scan speed and waveguide loss was investigated. In addition, planar 1×2 beam splitters and 3D 1×4 beam splitters were fabricated based on Type-I waveguides.

2. Experiments

The bulk PMMA (Goodfellow) was cut to the dimensions of $10 \times 10 \times 5$ mm^3 and optically polished. A fiber femtosecond laser

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system (Origami-10XP, Onefive), which provides 1031 nm central wavelength and 450 fs pulse duration, has been employed for direct waveguide inscription. The repetition rate ranges from 1 Hz to 1 MHz and the diameter of output laser beam is about 1.5 mm. A precise *X–Y–Z* motorized stage with resolution of 1 μm was utilized and a 40× microscope objective with a numerical aperture of 0.60 was employed to focus the laser beam. The shutter and attenuator were used to regulate the intensity of the laser and a 500 μm slit was placed in front of the microscope objective for laser beam reshaping. The schematic diagram of fabrication was depicted in Fig. 1(a). By using the fabrication system, 1 × 2 and 1 × 4 splitters based on Type-I waveguides were successfully achieved.

Propagation losses and near-field modal profiles were measured by the end-face coupling system, as shown in Fig. 1(b). In this system, a 6-axes optical stage was utilized to place the sample and waveguides were characterized by a He–Ne laser at the wavelength of 632.8 nm. Two 20× microscope objective lens of 0.4 numerical aperture were used for laser focusing and collection. The charge coupled device (CCD) and the power meter were used to observe the waveguide near field intensity distributions and measure the intensity of the output laser, respectively. Changes of the refractive index between the modified area and unmodified area of the sample were calculated through the maximum incident angular, which can be measured by adding a fused silica cubic glass between the He–Ne laser device and the incident microscope objective.

3. Results and discussion

The laser beam was focused 200 μm beneath the sample surface. Fig. 2 shows CCD camera images of the fabricated waveguide structures on PMMA at 100 kHz and 1 MHz repetition rate. Pulse energies of 125, 155, 185, 215, 245 nJ (no slit) at 1 MHz were employed for waveguides fabrication. Type-I waveguides were successfully fabricated with different pulse energies (155, 185, 215 nJ) as shown in Fig. 2(a–c). No waveguides were observed when the pulse energy was turned to 125 nJ and sample damage occurred for pulse energy exceeding 245 nJ. It can be seen that slight energy dissipation occurred in Fig. 2(a) and (c), but none in Fig. 2(b). This can be interpreted that the induced change of the refractive index on the laser track was not large enough to confine light in the waveguide core as the pulse energy was low at 155 nJ. While the pulse energy was high at 215 nJ, positive changes of refractive index occurred not only in the core area but also in cladding area, which resulted in the decrease of refractive index contrast between cores and claddings. And then the decreased contrast of refractive index caused larger propagation loss. When the pulse energy was adjusted to 185 nJ, appropriate change of refractive index was induced between core and cladding and light is well confined in waveguide to achieve lower loss. A different phenomenon happened as the repetition rate is tuned down to 100 kHz, whose results are shown in Fig. 2(d) and (e). Fig. 2(d) shows the CCD image at pulse energy of 330 nJ without a slit and Fig. 2(e) shows the image for a waveguide produced with a pulse energy of 4.05 μJ, which was measured behind a 500 μm slit. Obviously it can be seen that the propagation of light was not on the laser track from the pictures. Thus positive changes of refractive index were confirmed to be occurred beside or around the laser track, which demonstrated that thermal diffusion played a dominant role in femtosecond laser micro-processing at 100 kHz repetition rate. The cross section of the waveguide was modified to be circular in Fig. 2(e), which may be the tubular waveguide as reported in the literature [17]. This may suggest that a slit was beneficial for symmetric waveguides fabrication at low repetition rate.

Fig. 3 shows the microscope view (a)–(f) and near-field intensity profiles images (A)–(F) of waveguides inscribed with different scan speeds of 1, 2, 4, 6, 8, 10 mm/s at 1 MHz repetition rate, 185 nJ pulse energy without a slit. Fig. 3(G) displays the relationship between scan speed and insertion loss. It can be obviously seen that insertion loss presents a minimum value of 4.32 dB and propagation loss was calculated to be 3.57 dB/cm at 4 mm/s. Thus, the measured loss was better than the reported value of 4.2 dB/cm in the literature [3]. The insertion loss increased when the scan speed was above 4 mm/s, because every spot on the laser track cannot absorb enough laser pulse to induce larger change of the refractive

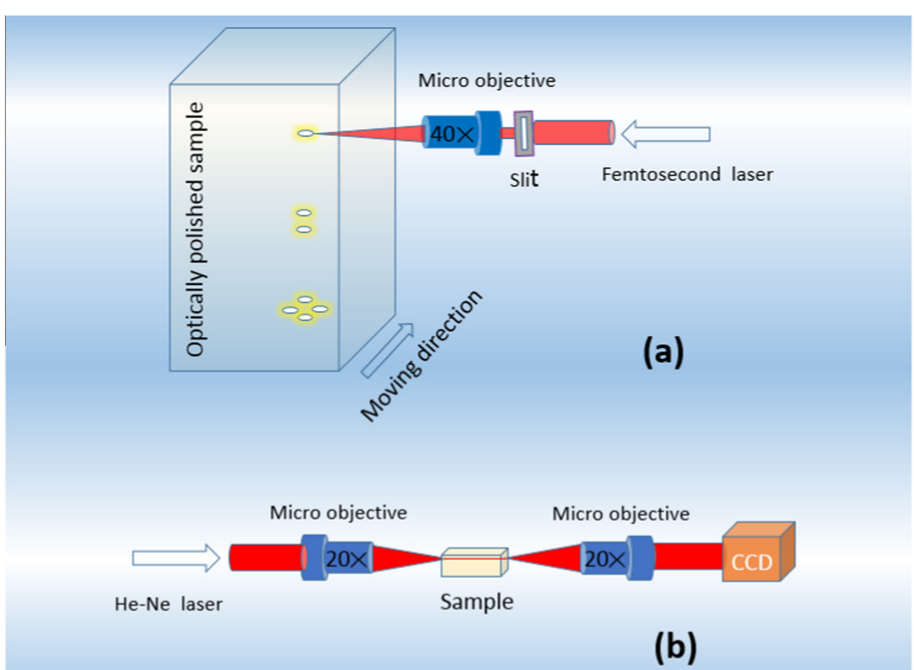

Fig. 1. The schematic diagram of experimental setup for waveguides: (a) fabricating system; (b) end-face coupling system.