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Optimization of waveguide structures for beam splitters fabricated in fused silica by direct femtosecond-laser inscription

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ABSTRACT

The Type-I waveguides fabricated by femtosecond laser inscription were reported in fused silica. Optimization of waveguide structures was conducted for fabricating 1×2 and 1×4 beam splitters. The change of the refractive index between femtosecond laser modified area and unmodified area was estimated to be 9×10^{-4}. The minimum loss of the waveguides measured with the He–Ne laser at the wavelength of 632.8 nm was determined to be as low as 1.34 dB.

1. Introduction

In integrated photonics, optical waveguides are basic components that are defined as cores of high refractive index with claddings of low refractive index [1]. The functional guiding devices such as gratings [2], couplers [3], splitters [4–6], optical amplifiers [7,8] and laser oscillators [9] can be manufactured on chip-scale wafers of diverse materials based on waveguide structures [10]. Among these devices, splitters are the essential elements of integrated photonic circuits. A few techniques [1] have been applied for the waveguides fabrication, including ion/proton exchange, chemical vapor deposition (CVD), femtosecond laser inscription, etc. Among these techniques, direct femtosecond-laser inscription seems to be one of the most efficient techniques for three-dimensional (3D) microfabrication of transparent optical materials [11], including optical crystals [12,13], ceramics [14,15], glasses [16–20] and polymers [21,22]. By focusing the laser beam into the sample (generally near surface), positive or negative refractive index changes emerge inside the laser-induced tracks, through which waveguides can be fabricated inside the track cores or the surrounding regions. The fabrication of Type-I waveguide is of great importance to achieve direct inscription of 3D optical structures in transparent materials. In this configuration, positive refractive-index changes (Δn) will be induced by the femtosecond laser in the irradiated focal volume, which serves as the waveguide core [1].

In this work, Type-I waveguide, 1×2 and 1×4 beam splitters were successfully produced in fused silica glass by direct femtosecond-laser inscription. The relationship between laser parameters and waveguide loss was investigated to understand the underlying mechanism. In addition, the impact of the slit and annealing treatment on waveguide end-face shape modification was studied and the minimum loss was estimated to be 1.34 dB. The 1×2 beam splitters of planar structure and 1×4 beam splitters of 3D structure were fabricated based on Type-I waveguide. The splitting ratio of the two types was 1:1 and 0.95:1:0.95:1, respectively.

2. Experiments

The fused silica glass was cut to the dimensions of $10\times10\times2$ mm^3. The largest and the two edge faces of the sample were optically polished. Waveguides were directly inscribed with a compact commercial femtosecond laser device (Origami-10XP, Onefive) of 1031 nm center wavelength, providing the maximum pulse energy of 40 μJ and the minimum pulse duration of 450 fs. The repetition rate of the device was tuned from 1 Hz to 1 MHz and the diameter of output laser beam is about 1.5 mm. Resolution of the *X*–*Y*–*Z* motorized stage was 1 μm. We employed the 40× microscope objective with a numerical aperture of 0.60 and working distance of 3.330 mm. The schematic diagram of fabrication was depicted in Fig. 1(a).

The end-face coupling device, as shown in Fig. 1(b), was employed for investigating the waveguide near-field modal

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profiles. The changes of the refractive index between the femtosecond laser modified area and unmodified area of the sample can also be obtained. In the end-face coupling device, the sample was placed on a 6-axes optical stage. The He–Ne laser beam at the wavelength of 632.8 nm was focused on the polished end face of the sample into the fabricated waveguide with a 20 × microscope objective lens of 0.4 numerical aperture. Another microscope objective lens was employed for the collection of the output laser. Afterwards, 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.

3. Results and discussion

The laser beam was focused into the sample while the focal point was 200 μm distance beneath the surface. The 5 kHz repetition rate was applied for the waveguide inscription at the scan speed of 5 mm/s and the incident pulse energy was tuned from 1.14 to 10.2 μJ. A 800 μm slit was placed between the attenuator and the microscope objective lens in order to modify the cross section of the fabricated waveguides [23]. The slit can attenuate the laser pulse energy and reshape the laser beam. One can see that the single-mode waveguides were successfully fabricated when the pulse energy was lower than 4.86 μJ as shown in Fig. 2 (A–C), while it became multi-mode in higher pulse energy as shown in Fig. 2 (D–F). The waveguide of the highest output power at 3.58 μJ pulse energy corresponding to Fig. 2(B) was single-mode, compared to multi-mode without the slit. This demonstrated that a slit can be beneficial for fabricating single-mode wavguides.

The increment of refractive index induced by femtosecond laser can be explained with two possible mechanisms as reported in the literature [24,25]. Bhardwaj et al. reported that fused silica glass consists of large number of five- and six-fold ring structures [24]. As the laser irradiation, the Si–O bond was partially broken and structures were rearranged which led to the decrease of five- and six-fold ring structures and increase of three- and four-fold ring structures [24]. This gave rise to the glass densification and refractive index increment. Saliminia et al. reported that the free electrons produced by multiphoton excitation and a partial avalanche ionization can transfer their high energy to the glass structure, which led to local heating and melting the glass [25]. The rapid cooling process led to the densification and refractive index increase on the irradiation region [25].

In our work, the degree of densification was increased and the change of refractive index was enhanced as the pulse energy increased from 1.14 μJ to 3.58 μJ, which resulted in the decrease of waveguide loss. This is consistent with the conclusions in the literature [24,25]. However, between the energy regions of 6.20–10.2 μJ, the overlarge pulse energy led to the densification emerging not only at the laser focus track but also beside the focus point. Therefore, the multi-mode was observed from near-field intensity distribution. It was found that discontinuity of the waveguide structure appeared as the pulse energy increasing continuously, leading to larger loss. It should be noted that waveguides loss increased sharply when the laser pulse energy

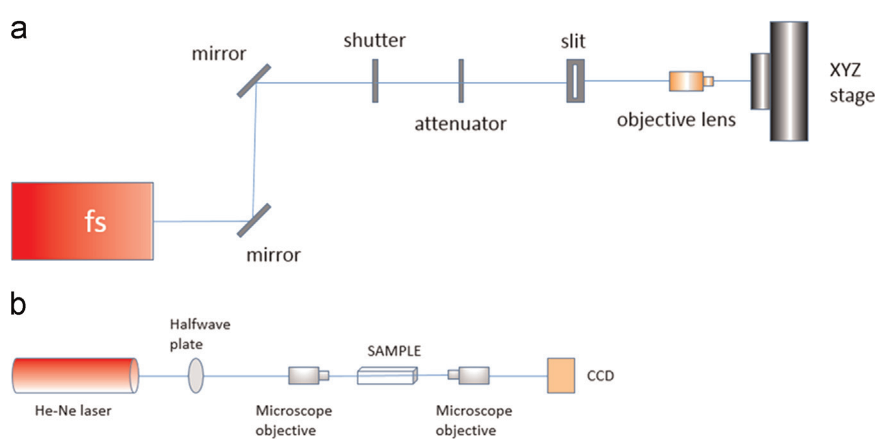

Fig. 1. The schematic diagram of experimental set up for waveguides: (a) fabricating system; and (b) end-face coupling system.

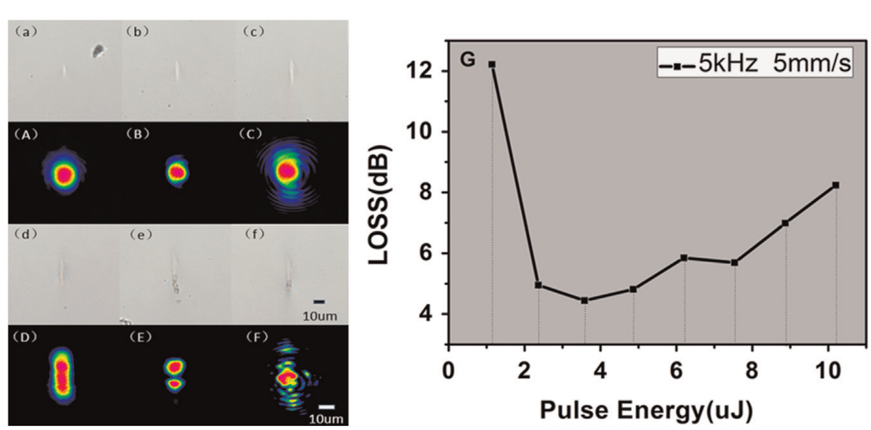

Fig. 2. The microscope view (a)–(f) and near-field intensity profile images (A)–(F) of the waveguides inscribed with different pulse energy of 2.36, 3.58, 4.86, 6.20, 7.53, and 8.87 μJ at 5 kHz repetition rate, 5 mm/s stage moving speed, 800 μm slit and (G) the image of relationship between pulse energy and loss.