Beam Splitters Fabricated by Nonlinear Focusing of Femtosecond Laser Writing in Pure YAG Crystal

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We report on the fabrication of waveguides and beam splitters in pure YAG crystals by femtosecond laser direct writing (FLDW). During the femtosecond laser writing process, a positive refractive index is induced through the nonlinear focusing above the focus position, resulting in an unusual guiding cross-sectional configuration. The supported guiding modes at 632.8 nm are measured and analyzed using the end-face coupling system. The propagation loss can be as low as 1.9 dB/cm for the single-line waveguide. Different from the geometry of the traditional fs-laser modified area, this novel structure might offer a new approach in the quest toward integrated photonics.

Keywords: optical waveguide, femtosecond laser direct writing, YAG crystal, beam splitter, integrated photonics device

INTRODUCTION

Optical waveguides, as the basic component of integrated photonics, can confine the propagation of light within small volumes and play a non-negligible role in optical communication and optical information processing. FLDW has emerged to become an effective and mature piece of technology for optical waveguide fabrication over decades of fast development [1]. Compared with the other traditional waveguide fabrication techniques, such as ion implantation and reactive ion etching, FLDW has the unique features of flexible 3D fabrication configurations, good compatibility with a wide range of materials, and simplicity in use [2–4]. A femtosecond laser (fs-laser) will induce multiphoton absorption when modifying material properties and tailoring microstructures inside the transparent bulk materials with a much shorter timescale. Therefore, the thermal energy exchange between photo-excited electrons and lattice ions will be curbed. A smooth photo-modified region with extremely high spatial resolution can be achieved.

Due to the complex interaction between the fs-laser pulses and the materials, the modified guiding structures in glass, crystalline materials, and ceramics have greater diversity [5]. Normally, the structural types can be categorized as single-line waveguide with positive refractive index changes induced at the focused area, stress-field-induced double-line waveguides based on damage and negative refractive index changes generated at the focused area, and depressed-cladding waveguide formed by the combination of small tracks with negative refractive index change [5, 6]. Until now, those aforementioned guiding structures fabricated by FLDW have been demonstrated in a handful of host materials, including silica glass, ZBLAN, LiNbO3, KTN, YAG, YCOB, etc. [7–13]. It is beyond doubt that the designable prototypes of FLDW enable us make significant breakthroughs, from scientific research to technological devices, for example, beam splitters, optical couplers, MZI EO modulators, waveguide lasers, waveguide-based frequency converters, and topological fractal
insulators [14–23]. Among these devices, optical waveguide power splitters, which can switch the optical signal from single input to multiple outputs, act as essential elements for integrated photonic circuits.

In this work, we report on the formation of new single-line waveguides and a beam splitter (1 × 3) in pure YAG crystals by FLDW. Pure YAG crystals are one of the most significant optical window materials, with high mechanical strength and stable physical and chemical properties. Meanwhile, the most distinctive feature of the obtained structures in the material is that the guiding area does not exist at the focused area but is positioned at the area formed by the self-focus of the pulse lasers. The guiding properties of the guiding structures have been investigated. It is noted that both of the single-line waveguides and the beam splitter support fundamental-mode laser propagating in the structures at 632.8 nm with polarization-insensitive properties.

**EXPERIMENTS**

An amplified Ti:sapphire laser system (Astrella, Coherent, United States), which delivered linearly polarized pulses of 40 fs and a central wavelength of 800 nm at a repetition rate of 1 kHz, was utilized to fabricate single-line waveguides and a beam splitter in the pure YAG crystal with dimensions of 20 × 10 × 2 mm³. During the fabricating process, the pure YAG sample was placed at a computer-controlled XYZ translation stage, and the fs-laser beam was focused using a 25 × microscope objective (N.A. = 0.4) at a depth of 100 μm beneath one of the 20 × 10-mm² surfaces. As shown in **Figure 1**, three single-line waveguides (WG1, WG2, and WG3, 20 mm in length) and a waveguide beam splitter (WG4 with configurations of 1 × 3 splitters) were fabricated. The structure of the beam splitter was designed as follows: the length of every straight waveguide is 2 mm, the lengths of every two splitting waveguides are 7 mm and the splitting angle is 0.8°, the straight input arm was split into two branches and four branches, and finally, three straight waveguides are output because two of them were combined into one. These guiding configurations were fabricated with different pulse energies and scanning speeds. The micromachining parameters are listed in **Table 1**.

To further explore the guiding properties of the fabricated structures, we used an end-face coupling system to measure guiding-mode profiles at 632.8 nm, excited from the He–Ne laser. A Glan–Taylor prism and a half-wave plate were employed together to control the polarization of the incident laser beams. The laser is then focused to the input face of the waveguide after passing through a microscope objective (40 ×, N.A.

**FIGURE 1** | Schematic diagram of the laser writing single-line waveguides (WG1–WG3) and the beam splitter (WG4) in the pure YAG crystal. The insets are the microscope images of the input face (B) and the output face (A) of the waveguide beam splitter WG4 in the pure YAG crystal.

**TABLE 1** | Processing parameters and the losses of the waveguides.

|              | WG1 | WG2 | WG3 | WG4 |
|--------------|-----|-----|-----|-----|
| Pulse energy (μJ) | 4.94 | 4.94 | 6.42 | 4.94 |
| Scanning speed (mm/s) | 0.2 | 0.1 | 0.2 | 0.2 |
| Total loss (dB) | 7.50 | 8.37 | 9.11 | 13.08 |
| Coupling loss (dB) | 3.64 | 3.64 | 2.60 | 3.64 |
| Propagation loss (dB/cm) | 1.93 | 2.37 | 3.26 | 4.72 |

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equals 0.65). Another microscope objective with a long working distance (50×, N.A. = 0.42) is used to collect the light field from the exit end face of the waveguide. The modal profiles are imaged using a CCD camera (WCD-UCD 12-1310, DataRay, United States), and the output intensities are measured using a power meter.

RESULTS AND DISCUSSION

Figure 1 depicts a brief diagram of beam propagation. The insets are microscopic images of the input face and the output face of the waveguide beam splitter (WG4). In Figure 1B, we found that the induced track shows relatively complicated structures compared with the traditional modified region. The upper region (Area I) was formed by the self-focus of the pulse. The lower region (Area II) with local minimum area was formed by the laser focus. Both regions expand elliptically. Area I expands elliptically and is identified as the guiding area, which is confirmed through the microscope observation and the end–face coupling research. In a manner of speaking, the guiding volume is surrounded by irregular regions with a low refractive index, where the fs-laser intensity is higher than the ionization threshold of the material. As shown in the schematic diagram of the FLDW processing, the size of WG1–WG3 increases in order due to the gradual changes in the processing parameters.

Figure 2 displays the 2D and 3D modal profiles of the output light field collected from WG1, WG2, and WG3. We can see that the modal profiles exhibit fundamental modes at TM polarization and TE polarization, which is beneficial for excitation and coupling, reducing losses, and avoiding signal distortion. Meanwhile, the beam splitter WG4 supports the laser propagating at both TM and TE polarizations. It can be identified that these guiding structures perform insensitive propagating properties to the polarization of the laser. Figure 3A depicts the experimental, measured 2D and 3D guiding-mode profiles of the WG4 at TM polarization. Although the branch configurations are introduced to the design, the guiding mode still exhibited the fundamental-mode feature, which demonstrates the opportunity for this structure to contribute to the photonics circuits. The measured output intensity–splitting ratio for the three arms is about 1:1.84:1, which is very close to the simulated result (i.e., 1:1.95:1). Moreover, we can optimize the structure design and processing parameters to improve the splitting ratio. Figure 3B shows the simulated results of the 2D and 3D guiding-mode profiles. By comparing the experimental and simulated laser profiles, one can come to the conclusion that the experiment data match quite well with the simulated results. We believe that it is possible to achieve an adjustable beam-splitting ratio through improved structural design.

Table 1 reveals the losses of the waveguides at 632.8 nm when the incident laser is with different polarizations. The total losses α
are measured using the power meter and the end–face coupling system using the following formula:
\[ \alpha = 10 \cdot \lg \frac{P_{\text{in}}}{P_{\text{out}}}, \]
where \( P_{\text{in}} \) and \( P_{\text{out}} \) correspond to the input and output laser powers, and the coupling losses are roughly calculated using the BeamPROP module of Rsoft Photonics CADSuite. By subtracting the coupling loss from the total loss for each polarization component, we can calculate the propagating loss. According to the calculated results, the difference in coupling losses is mainly related to the dimensions of these waveguides. Also, the propagating losses at TE polarization are slightly larger than those at TM polarization. The reason for this is that the geometries of the fabricated guiding structures are not centrosymmetric. The width along TM polarization is a little larger than that along TE polarization. The propagation loss can be as low as 1.9 dB/cm for the single-line waveguide WG1. Comparing the propagation losses of the single-line waveguide WG1 and the beam splitter WG4 with the same fabrication parameters, the additional losses may be partly attributed to the radiation loss caused by beam deflection and the mode coupling between the straight waveguides and the branch waveguide. For the splitter waveguide, the propagation losses in these two polarizations are roughly the same, which may be related to the structural design of the beam splitter.

CONCLUSION

In summary, we have demonstrated the fabrication of a waveguide beam splitter in a pure YAG crystal by femtosecond laser direct writing. For the waveguides and the beam splitter with positive refractive index changes, fundamental-mode guidance is achieved along both TE and TM polarizations at the wavelength of 632.8 nm. The experimentally measured modal profiles of the waveguide beam splitter are in good agreement with the simulation results. The research shows that the excellent beam-splitting performance of the structure is helpful for us to split beams in a certain proportion, which implies that our fabrication on the waveguide beam splitter has a potential application in integrated photonics.
DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

HL and PW proposed the original idea and supervised the project. SY performed the experiments and measurements and was responsible for writing the manuscript. YR supported the project. SY performed the experiments and measurements and HL and PW proposed the original idea and supervised the project.

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