Femtosecond Laser Writing of Optical-Lattice-Like Cladding Structures for Three-Dimensional Waveguide Beam Splitters in $LiNbO_3$ Crystal

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***Abstract*—The waveguide beamsplitters with diverse configurations in $LiNbO_3$ crystal have been produced by direct femtosecond laser writing of a family of optical-lattice-like cladding structures. By on demand design of the lattice tracks with "defect" lines, the efficient beam guiding and tailoring have been implemented in the structures. With a family of three-element integration of structures, three-dimensional (3-D) 1×3 beamsplitting at the telecommunication wavelength of 1550 nm was realized. Different from the Type I modification of $LiNbO_3$ waveguides, the guiding cores of the optical-lattice-like cladding waveguide structures we fabricated locate in regions that are surrounded by the laser-induced-tracks. This paper opens the alternative way to construct complex integrated platforms in $LiNbO_3$ crystal by using femtosecond laser writing.**

***Index Terms*—Beam splitters, laser materials processing, lithium niobate, waveguides.**

I. Introduction

As the basic components in integrated photonics, optical waveguides confine the light propagation in very small volumes with dimensions of several micrometers, achieving relatively higher optical intensities with respect to the bulk materials [1]. Photonic devices including switchers, routers, demultiplexers, and modulators are widely used in optical telecommunication systems [2]. Waveguide beam splitters, which can distribute signals from one input port to two or more output ports, are fundamental elements in photonics applications for signal routing and signal processing.

Several techniques, such as metal-ion indiffusion, ion/proton exchange, ion implantation/irradiation and femtosecond (fs) laser micromachining, have already been used to fabricate optical waveguides in a wide range of optical materials [3]–[9]. Owing to the capability for 3D processing, the femtosecond laser writing has emerged as a powerful and promising method to fabricate optical waveguides in various transparent materials since the pioneering work of Davis *et al.,* in 1996 [10]–[13]. Depending on the parameters of the fs-laser pulses and the nature of the materials, the refractive index change (Δn) induced in the fs-laser-irradiated region may be positive or negative, referring to Type I and II modifications [14], [15]. As a result, typical waveguide geometries (single-line, dual-line and depressed claddings) have been developed accordingly in a number of crystals, which show diverse guiding properties and bulk-related features for versatile applications [8].

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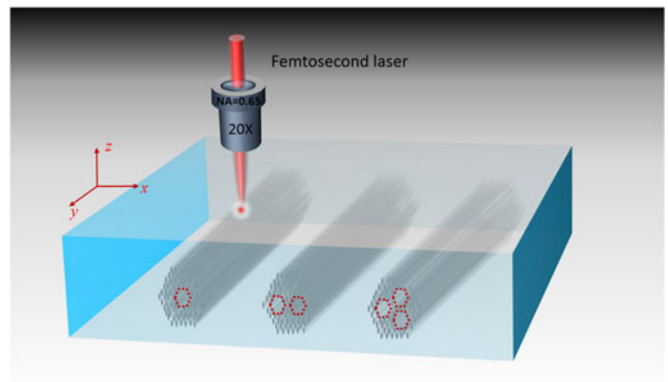

Fig. 1. The schematic fs-laser-writing process of the $LiNbO_3$ waveguide beam splitters.

Lithium niobate ($LiNbO_3$) is one of the most favorite crystals in integrated optics owing to its outstanding features of electro-optic, acousto-optic, piezoelectric and nonlinear optical properties [16]. It has been widely used for active optical applications as electro-optic modulators, surface-acoustic wave devices, holographic storage, and frequency converters [17]–[19]. Femtosecond laser writing of $LiNbO_3$ waveguides has been implemented with diverse configurations [20]–[24]. In previous work, we have fabricated 3D waveguide beam splitters based on Type I modification of n_e in $LiNbO_3$ crystal by laser writing [25]. In this work, we report on the fabrication of 3D waveguide beam splitters in $LiNbO_3$ crystal based on the Type II modification of n_o through so-called optical-lattice-like geometries, which was first applied to Nd:YAG crystal for guided beam tailoring [26]. The guiding properties of the waveguides are investigated at the telecommunication wavelength of 1550 nm.

II. Experiments in Details

Fig. 1 depicts the schematic fs-laser-writing process of the $LiNbO_3$ waveguide beam splitters. The *z*-cut $LiNbO_3$ crystal

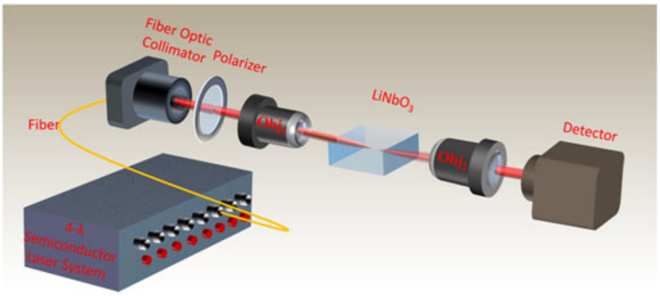

Fig. 2. The schematic end-face coupling arrangement for investigation of the $LiNbO_3$ waveguide beam splitters at 1550 nm.

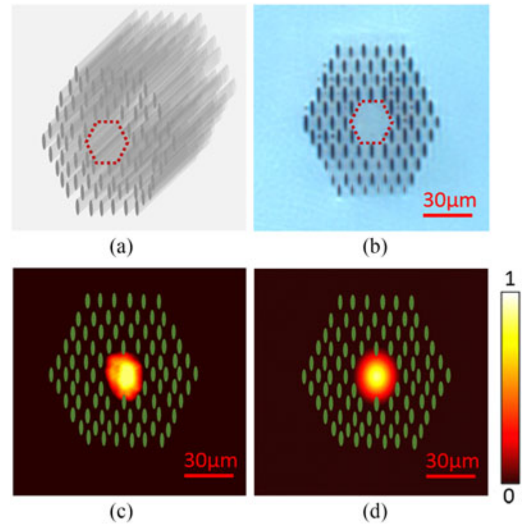

Fig. 3. (a) The cross-sectional sketch (b) microscopic image of the cross section (c) measured near-field modal profile along TE polarization at 1550 nm and (d) simulated modal profile of the 1×1 waveguide beam splitter WG1.

used in this work was cut with dimensions of $10(x) \times 10(y) \times 1(z)$ mm^3 and was optically polished. The waveguide beam splitters of optical-lattice-like cladding structures were fabricated by using the laser facility of Universidad de Salamanca, Spain. A Ti:Sapphire regenerative amplifier (Spitfire, Spectra Physics) was utilized as a laser source to generate linearly polarized pulses (central wavelength of 795 nm, pulse duration of 120 fs, repetition rate of 1 kHz and maximum pulse energy of 50 μJ). The incident fs laser pulse energy was set to 2 μJ with a calibrated neutral density filter, a half-wave plate and a linear polarizer, and then was focused by a 20 $\times$ microscope objective (N.A. = 0.65) at a maximum depth of 180 μm beneath the upper surface $(10 \times 10\ \mathrm{mm}^2)$ of the sample. During the irradiation process, the sample was placed at a micro-positioning *X-Y-Z* motorized stage and was scanned at a constant velocity of 750 μm/s along the *y*-axis, producing a damage track inside the sample. The procedure was performed at different depths of the sample with a lateral separation of 10 μm between each two adjacent tracks. With these conditions, 3-D waveguide beam splitters (with a guiding core surrounded by arrayed damage tracks, i.e., optical-lattice-like geometries) were fabricated in $LiNbO_3$ crystal. As a result, a 1×1 waveguide beam splitter WG1, a 1×2 waveguide beam splitter WG2 and a 1×3 waveguide beam splitter WG3 have been fabricated in $LiNbO_3$ crystal.

A microscope (Axio Imager, Carl Zeiss) was utilized to photograph the cross sections of the waveguide beam splitters in $LiNbO_3$ crystal. An end-face coupling arrangement, as shown in Fig. 2, was applied to experimentally characterize the near-field modal profiles of the waveguide beam splitters. The incident light beam at 1550 nm, which was generated in the 4-λ semiconductor laser system (GCSLS-O, China Daheng Group, Inc.), was coupled into a fiber cable. By using the fiber optic collimator (GCX-L, China Daheng Group, Inc.), the divergent light was collimated. Afterwards, a pair of MIR microscope objective lens (ZnSe, LFO-5-12-3.75, N.A. = 0.13) were used to couple the linearly polarized light (TE or TM mode) into and out of the waveguide beam splitter, and finally a CCD camera was employed to observe and record the near-field intensity distributions at 1550 nm. In order to determine the propagation losses of the waveguide beam splitter, a power meter was utilized to measure the powers from the input and output end-faces.

III. Results and Discussion

Fig. 3(a) shows the cross-sectional sketch of the 1×1 waveguide beam splitter WG1 which was defined as Element 1. Fig. 3(b) depicts the microscopic image of the cross section of the Element 1 in $LiNbO_3$ crystal. The transverse length of the fs-laser inscribed tracks is 10 μm and the separation between two adjacent tracks is 10 μm. The optical-lattice-like structure of the Element 1 has a length of 10 mm and a guiding core with a quasi-hexagonal cross-section $(\sim 30 \times 30\ \mu m^2)$. In order to obtain an approximate value of the maximum refractive index contrast of the waveguide, we measured the N.A. of the waveguide and used the method reported in [27]. Considering the combination of the damage induced refractive index reduction and the stress induced refractive index increment, the maximum refractive index change Δn_o of the Element 1 was estimated to be -5×10^{-3} for the TE mode at 1550 nm. Fig. 3(c) shows the measured near-field intensity distribution of Element 1 for the TE mode at 1550 nm. Based on the reconstructed refractive index distribution, we simulated near-field modal profile of Element 1 for the TE mode at 1550 nm by using the software Rsoft© Beam-Prop [28] through Finite Difference Beam Propagation Method (FD-BPM) [29], as shown in Fig. 3(d). As one can see, the calculated near-field modal profile of Element 1 is basically in agreement with the experimental results.

As the light propagates along the central core of Element 1, we introduced additional damage tracks as "defect lines" in the core region of Element 1 to form Elements 2 and 3, which modify the light propagation to tailor the light intensity distribution. Fig. 4(a) depicts the prototype of 1×2 beam splitter WG2 which is connected by Elements 1, 2 and 3 in sequence, including the schematic sketches (top) and microscopic photographs (below) of Elements 1, 2 and 3, respectively. As we can see, Elements 1, 2 and 3 have the lengths of 2 mm, 4 mm and 4 mm, respectively. Fig. 4(b) shows the measured near-field

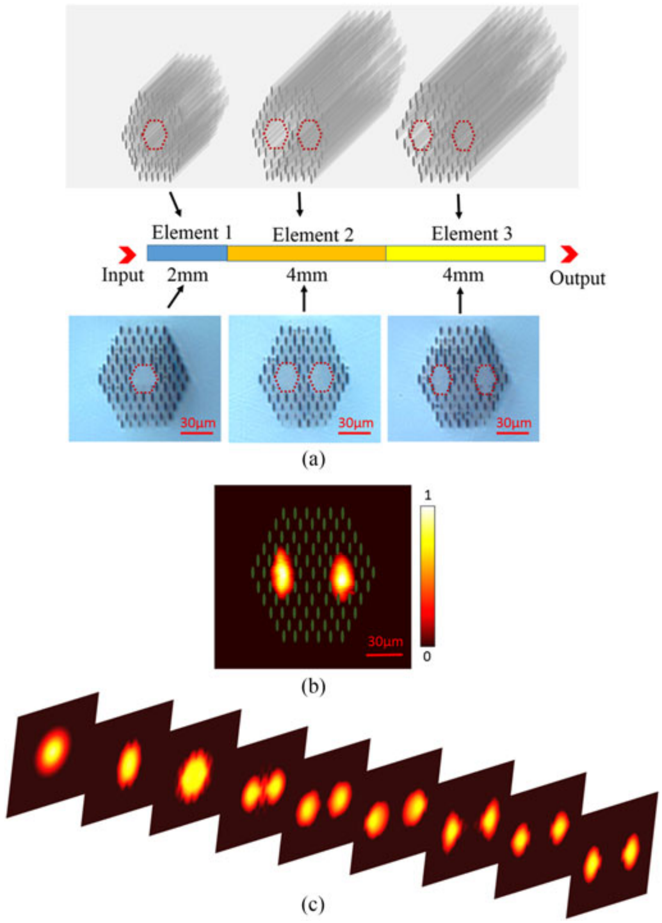

Fig. 4. (a) The prototype of 1×2 beam splitter WG2 connected by Elements 1, 2 and 3 in sequence, including the cross-sectional sketches (top) and microscopic images (below) of the elements. (b) The measured near-field modal profile along TE polarization at 1550 nm and (c) simulated modal profile evolution of the 1×2 waveguide beam splitter WG2.

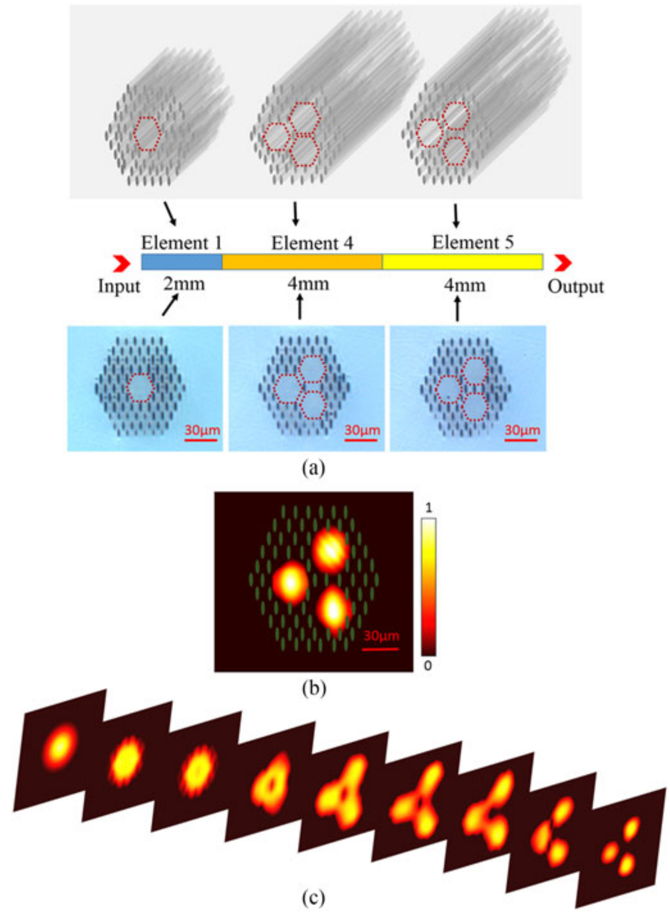

Fig. 5. (a) The prototype of 1×3 beam splitter WG3 connected by Elements 1, 4 and 5 in sequence, including the cross-sectional sketches (top) and microscopic images (below) of the elements. (b) The measured near-field modal profile along TE polarization at 1550 nm and (c) simulated modal profile evolution of the 1×3 waveguide beam splitter WG3.

intensity distribution from the output of the WG2 for the TE mode at 1550 nm, exhibiting a clear beam-profile splitting with a splitting ratio of 0.50:0.50 from the two arms. It indicates that the input light beam propagating through the 1×2 beam splitter is equally divided into two parts and guided out, showing effective performance for a Y-branch-like function. Fig. 4(c) depicts the simulated near-field beam profile evolution of 1×2 beam splitter for the TE mode at 1550 nm, which matches well with the experimental result.

Similarly, we constructed 1×3 beam splitter WG3 by combining Elements 1, 4 and 5 in a joint structure. Fig. 5(a) shows the prototype of 1×3 beam splitter, including the schematic sketches (top) and microscopic photographs (below) of the Element 1, 4 and 5, respectively. As we can see, Elements 1, 4 and 5 have the lengths of 2 mm, 4 mm and 4 mm, respectively. Fig. 5(b) shows the experimental near-field intensity distribution from the output of the 1×3 beam splitter for the TE mode at 1550 nm with a measured intensity splitting ratio of 0.50:0.49:0.51 for the three arms. This result indicates that our fabricated 1×3 beam splitter possesses satisfactory performance with quasi-equal output light powers and we can further improve the splitting ratio by optimizing the processing parameters. The simulated near-field beam profile evolution of 1×3 beam splitter for the TE mode at 1550 nm, as shown in Fig. 5(c), accords with the experimental result.

Fig. 6 shows the all-angle light transmission of the WGs 1-3 to investigate the thorough information of the polarization effects of the guidance at 1550 nm wavelength. It is found that as the light polarization angle changes the output light power varies, showing the light guidance is polarization-dependent. Obviously, there is no guidance along the TM polarization (n_e), and the optimum guidance is realized along the TE polarization (n_o). This is different from the Type I waveguide beam splitters in $LiNbO_3$ (i.e., guided at n_e only) [25].

The total losses of the waveguide beam splitters (including propagation losses and coupling losses) were measured by using the end-face coupling system at 1550 nm. The coupling loss was estimated to be 0.7 dB by considering the overlap of the profiles of the incident light beam and waveguide modes. Table I shows the propagation losses of the WGs 1-3 along TE polarization at 1550 nm. Please note that these values were obtained as sum propagation losses (i.e., the bending loss of

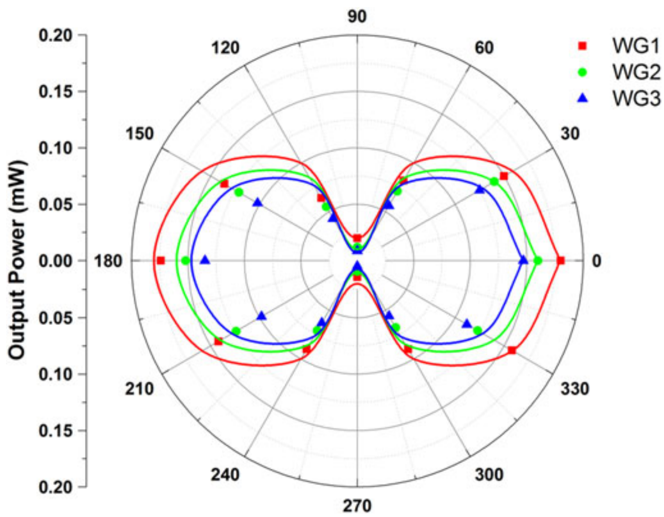

Fig. 6. The Polar images of the output light power of WG1 (red squares), WG2 (green circles) and WG3 (blue triangles) and the corresponding fits (lines) at 1550 nm.

TABLE I
THE PROPAGATION LOSSES OF LASER-WRITTEN WAVEGUIDE BEAM SPLITTERS ALONG TE POLARIZATION AT 1550 NM

Waveguide configurations	Propagation loss (dB/cm)
WG1	1.27
WG2	1.63
WG3	2.11

the structures were included as well). It was clear that, as the number of output arm increases the propagation loss of the beam splitter becomes larger, which may be partly attributed to the imperfections of the multi-arm structures. Further reduction of the propagation loss may be realized by increasing the guiding core volume and amount of the track lattice layers of the waveguide beam splitter [26], [30].

IV. CONCLUSION

We have designed and fabricated 3D waveguide beam splitters supporting guidance along TE (n_o) polarization at 1550 nm in $LiNbO_3$ crystal by direct femtosecond laser writing. The near-field modal profiles of the waveguide beam splitters are experimentally and numerically investigated, and the simulations are in good agreement with the experimental results. The propagation loss of the 1×3 beam splitter is $\sim$2.1 dB/cm and the beam splitting ratio is approximately equal, indicating our approach to 3D waveguide beam splitters for potential application as integrated devices (e.g., electrooptic modulators) based on $LiNbO_3$ crystals.

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