Light coupling in single-track guiding structures obtained by femtosecond laser writing in lithium niobate

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In this Letter we present a study of light coupling into a pair of Type II waveguides made of lithium niobate crystals by using femtosecond laser writing. Simulations based on the beam propagation method and optical fiber coupling experiments with the guiding structures showed good agreement. The presented results can be a suitable tool for designing high-performance optical circuits using femtosecond laser writing techniques for different technological requirements.

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Integrated photonics is currently considered to be the key area able to support the high levels of information transmission and data processing required by optical communications and video and audio systems. Several aspects, either fundamental or applied, related to the above topics need deep study and serious analyses. To cover this demand, there are many research groups around the world that are devoted to exploring and solving these technological challenges.

In particular, light manipulation through evanescent coupling is an important skill that can enhance the performance of integrated photonics systems with regard to any of the above requirements.

As examples, there are several integrated optical elements that are currently being used in many technological fields concerned with light coupling, i.e., directional couplers used in optical amplifiers, ring resonators used for frequency filtering in communications, and angular velocity rate sensors, among other systems [1–4].

There are several standard and well-established methods available for fabricating the guiding structures for these optical circuits, e.g., proton exchange, metal in-diffusion, and ion implantation. The optimal guiding structures should have low propagation losses and guide single-mode light in the communications wavelength range [5].

Femtosecond laser writing is considered a powerful tool for the fabrication of optical circuits. This technique can offer rapid prototyping, a one-step process, and low cost, and it can be applied to a wide range of materials. Furthermore, the three-dimensional possibility offered by this method boosts its range of applicability to photonics purposes [6,7].

Laser energy deposition is based on multiphoton absorption and avalanche ionization. This nonlinear process can be exploited in writing structures into the bulk of materials. In consideration of the range of energy used to write the structures, Type I and II waveguides have been reported [7].

Type I modifications take place at low laser fluences, and these waveguides are characterized by an increase in the extraordinary refractive index, while the ordinary index is decreased. Type I waveguides can be erased by heating above 150°C and even by being maintained at room temperature for a few months.

On the other hand, the significant damage done to the crystal structure at higher fluences leads to the formation of Type II structures. The crystal network is completely destroyed at the focal volume, and the resulting stress fields induce refractive index changes in the surrounding regions where the waveguides are formed. Furthermore, Type II structures are thermally stable up to 300°C and higher, as was demonstrated in Nd:YAG waveguides by Benayas *et al.* [8].

Because of its high nonlinearity as well as its wide transparency range, lithium niobate (LNB) is one of the most important materials in integrated optics, and it has been implemented technologically as an electro-optical modulator for optical communication or sensing.

In this Letter, we present a thorough analysis of an optical integrated coupler in the communications wavelength range. These systems are composed by two Type II waveguides that are fabricated by ultrashort laser writing in LNB and are separated by a variable distance.

Experimental results for the coupled modes at the output are analyzed as a function of the different gaps proposed for the study. The coupling constant for different gaps will be estimated experimentally. In addition, computational simulations based on the beam propagation method (BPM) using commercial software (RSoft) are also included to complete the discussion on the coupling between the guiding structures presented in this Letter.

For the fabrication of the different waveguide pairs on the x-cut $LiNbO_3$ (LNB) crystal, a Ti:sapphire laser system was used. This laser system can deliver laser pulses centered at 800 nm with 1 kHz repetition rate, 120 fs pulse width, and up to 1 mJ of energy per pulse. This chirped pulse amplification system is composed of an oscillator system (Mai Tai) pumped by a diode and a regenerative amplifier (Spitfire), both systems from Spectra Physics (USA). The optical losses for each single Type II waveguide are close to 1 dB/cm as it was also reported in [7].

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Four sets of Type II waveguides with varying distances between them were recorded. For the fabrication procedure, the laser beam focused into the crystal using a 20× microscope objective. Thus, by moving the sample at a constant speed through a motorized station, the guides were written inside the LNB sample. The writing speed was set at 0.03 mm/s and the laser pulse energy used was 0.4 μJ. The different separations between the waveguide sets were chosen as 20, 25, 30, and 35 μm.

The studied couplers consist of the right and the left waveguides corresponding to two consecutive optical breakdown tracks made in the LNB sample by the femtosecond laser interaction.

To register the shape and intensities corresponding to the propagation modes coupled between the different pairs of waveguides, we used a beam profile analyzer (Newport LBP-4). To couple light into these structures, an optical fiber system was used at the entrance, while a 10× microscope objective was used to collect the near-field measurements in the output end face. The light launched to produce such coupling between the waveguides was a distributed feedback laser diode with 1.55 μm wavelength.

When two straight waveguides are close (i.e., separated by some micrometers), the propagating modes can interfere and generate optical coupling. This is due to the overlap that occurs between the evanescent fields of one waveguide with the other.

The parameter that determines the coupling between the waveguides is called the coupling constant κ [9]. This parameter is determined by the overlap between the guided fields of the waveguides and their refractive indices; it decreases as the separation between the waveguides increases. This is because the fields in directions transverse to the waveguides tend toward zero at infinity. If the two waveguides have the same characteristics, the efficiency of coupling between them has a maximum value when the power of one is completely transferred to the other. This power transfer occurs periodically and it is characterized by the coupling length Lc, which is the shortest length at which the power of a waveguide is fully transferred to the other waveguide. For a coupling efficiency of 100%, the coupling constant κ and the coupling length Lc are related by $Lc = \pi/2\kappa$ [9,10].

To simulate the coupling between two straight Type II waveguides, the method known as BPM was used. This method uses the paraxial approximation to simplify the scalar Helmholtz equation, which solves the paraxial or Fresnel equation. As is well known, this approach assumes that the envelope of the field varies slowly in the direction of propagation (SVEA) [5].

The simulations were performed using RSoft. This has a specific tool called BeamProp, which is based on the BPM technique. To solve the equations, RSoft uses finite differences with the well-known Crank–Nicolson method. The boundary conditions imposed at the limits of the simulation window are called transparent boundary conditions [5,11].

The experimental coupled modes were measured by using a beam profile analyzer for the different waveguides fabricated in this work. Guided modes are registered by imaging the end edge for the LNB sample with a length of 6700 μm, as shown in Fig. 1. In these pictures, the positions of the optical breakdown tracks are marked with open white ellipses, whereas the red arrows indicate the position of the coupled light at the entrance.

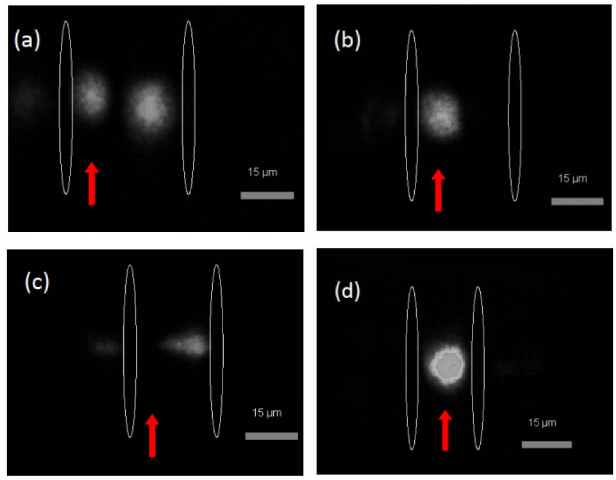

Fig. 1. Guided modes obtained in a pair of waveguides with separation between tracks of (a) 35 μm, (b) 30 μm, (c) 25 μm, and (d) 20 μm.

Each of these images corresponds to different spacing between the tracks. Figure 1(a) corresponds to 35 μm. As can be seen, there are two modes, the intensities of which are distributed approximately as 40% and 60%, corresponding to the left and the right modes, respectively. Figure 1(b) shows an intensity distribution of approximately 100% to the left mode. The opposite occurs in Fig. 1(c), where the intensity distribution is approximately 100% to the right mode. In Fig. 1(d), a single central mode is shown; this occurs for a waveguide separation of 20 μm or lower and for these cases, the laser modifications give rise to the so-called double-track guiding structures [7].

To perform computational simulations for the optical coupling between two straight Type II waveguides, a refractive index profile as a sum of Gaussian functions was suggested [12], as is shown in Fig. 2. As can be seen, there is a central zone, shown in black, that corresponds to the optical breakdown tracks where the refractive index presents an important decrease with respect to the unmodified LNB. The tracks are surrounded by two

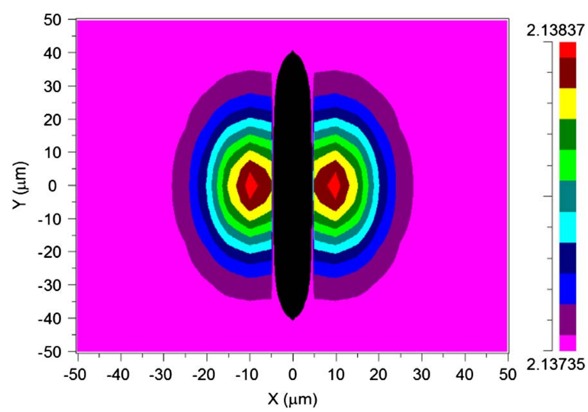

Fig. 2. Refractive index profile proposed for simulation corresponding to a single-track written waveguide in LNB.

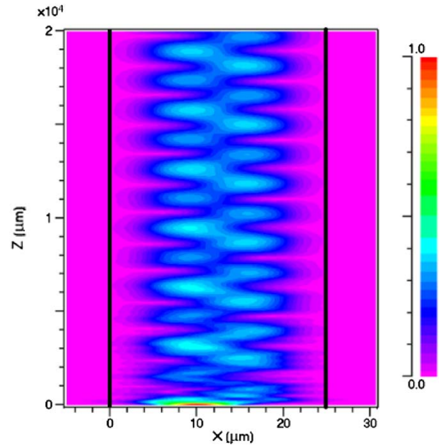

Fig. 3. Simulation of the coupled modes showing the propagation of the electric field module along the waveguide pair with a 25 µm gap.

zones, each with a positive increment of the refractive index, corresponding to the waveguides themselves [12,13].

In all, 14 simulations were performed varying the distance between the waveguides (tracks), and in this way we have obtained the coupling length as a function of the gap. These distances ranged from 22 to 35 µm. Figure 3 shows one of these simulations, which corresponds to a gap of 25 µm. This simulation shows how the electric field module periodically propagates from one waveguide to the other. The black lines represent the tracks defined by laser writing. To determine the length of coupling for each of the simulations, we have measured the distance at which the field of a waveguide was transferred to the other. As expected, we found different coupling lengths for the several gaps studied. Finally, we have plotted these obtained values and the fitting by means of an exponential function (Fig. 4).

The inset in Fig. 4 corresponds to the experimental mode profile measured at the output for a gap of 35 µm for the sample of 2300 µm length.

From the results presented in Fig. 4, it can be seen that the coupling length for different gaps follows an expected exponential growth. By considering this plot

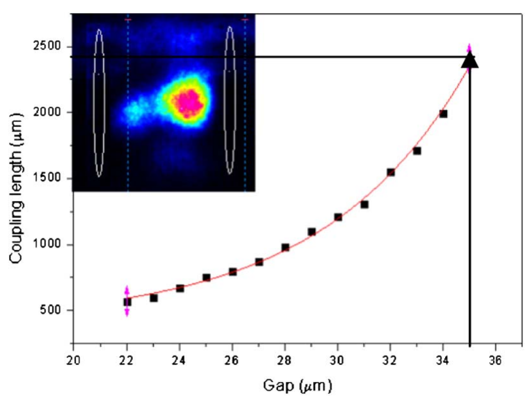

Fig. 4. Coupling length versus gap. The inset shows the intensity of the coupled mode corresponding to a 35 µm gap for a sample length of 2300 µm.

and Fig. 1, we can explain the behavior observed for the mode intensity at the output for each case. For Fig. 1(a), the pair of waveguides with a gap of 35 µm shows a relation close to the 50% for each side at the output. Considering the constant coupling for this gap from Fig. 4 (2400 µm) and the length of this sample (6700 µm), a relation close to 0.4 and 0.6 for the intensity is found, corresponding to the left and right modes, respectively.

On the other hand, considering the pair of waveguides with gaps of 30 and 25 µm [Figs. 1(b) and 1(c)], respectively, we see a contrasting behavior; in Fig. 1(b) the light goes to the end at the same side of the coupling. This fact is due to the alternating exchange of energy in the waveguides, taking into account the sample length used for the initial experiment (6700 µm). By considering Fig. 4, it can be seen that the coupling length for a gap of 30 µm is around 1200 µm. Therefore, there are six exchanges of energy from the waveguides and, as observed, the energy comes out from the input channel. A contrasting behavior is observed in Fig. 1(c), which corresponds to a pair of waveguides with a 25 µm gap. In this case, from Fig. 4, the coupling constant is around 750 µm and the coupling length of 6700 µm gives a relation close to 9; thus, it is expected that the output is to the right of the waveguides, as was observed in our experiment.

Finally, we reduced the length of the studied LNB sample to 2300 µm. In this case, the gap for the pair of waveguides was 35 µm. From Fig. 4, we have a coupling length for the waveguides of 2400 µm; in this sense we expect to transfer the power fully from the left to the right waveguide, as is presented in the inset of Fig. 4.

In summary, we have presented the study of waveguide coupling for Type II structures obtained by femtosecond laser writing in LNB crystals. Simulations and experiments showed good agreement when considering the beam propagation model and the refractive index profile used for the simulation, in comparison with experimental measurements. The results shown in this work can be regarded as a suitable tool for designing optical circuits in LNB with this fabrication waveguide technology.

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