Fast, reconfigurable light-induced waveguides

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Fast and reconfigurable one-dimensional waveguides are produced by interband photorefraction. The index barriers are induced by ultraviolet light. The guiding of a red laser beam with a full width at half-maximum of 15 μm is demonstrated. Buildup and decay times of the waveguide in pure KNbO₃ are of the order of 100 μs and 10 ms, respectively. The intensity of the guided light has no influence on the guiding properties over the range from 4 mW/cm² to 200 W/cm². By reconfiguration of the waveguide, deflection angles of as much as 1.75 deg inside the crystal are achieved. © 1999 Optical Society of America

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Optical waveguides play a key role in the field of optoelectronics. In crystalline materials, waveguides can be fabricated by various techniques, including ion diffusion, ion exchange, ion implantation, etching, and epitaxial thin-film deposition. For some applications, such as optical switching and dynamic optical interconnection, reconfigurable waveguides are desirable. A further advantage would be achieved if the fabrication step could be fully omitted. In this Letter we demonstrate a technique by which a waveguide is created in real time by means of light illumination only. The waveguide’s shape reflects the spatial distribution of top surface illumination and can be reconfigured with a few tens of microseconds’ time.

To form a waveguide, the illumination must induce an increase in the refractive index in the core region. This increase can be produced by several physical mechanisms, such as χ⁽⁽⁾⁾ nonlinear optical effects,¹ light-controlled domain switching,² and the photorefractive effect.³ The two last-named approaches are particularly interesting, as they allow significant refractive-index changes to be obtained for low-power illumination. So far, waveguide formation by means of the photorefractive effect⁴ has been demonstrated either with the combined effect of multiple-exposure illumination of aligned focused spots⁵,⁶ or by use of the self-induced channel generated by a self-focused or spatial soliton beam.⁷,⁸ These approaches make use of the conventional photorefractive effect and are therefore associated with a relatively slow response time. Waveguides formed by spatial soliton beams also critically depend on the beam intensity and the self-focusing conditions. In addition, except for a small amount of bending that is due to charge diffusion effects, soliton-induced waveguides are essentially straight, which precludes the possibility of constraining light propagation along an arbitrary path.

The reconfigurable waveguides described here are generated by means of the interband photorefractive effect.⁹,¹⁰ As in the case of conventional photorefractivity, inhomogeneous illumination produces a change in the space-charge distribution inside an electro-optic material. However, photoexcitation of the charges occurs not between an impurity level and one of the conducting bands but directly across the bandgap, e.g., for KNbO₃ between the valence band formed by the filled O²⁻ 2p orbitals and the conduction band formed by Nb⁵⁺ 5d orbitals. These band-to-band phototransitions yield a much faster response time.¹⁰

In analogy with the cases of beam self-focusing and light-induced domain switching,²,⁷ the mechanism that underlies waveguide formation is the local screening of an external electric field E. By use of an electrooptic crystal, if the light polarization and field direction are chosen properly the refractive index will decrease homogeneously across the sample, except in the regions that are externally illuminated. The field is screened by bipolar charge transport. Because the desired structure can be imaged onto the surface by a deflector or a photolithographic-like process, various waveguide configurations can easily be produced in this way.

All experiments were carried out with a pure, single-domain KNbO₃ crystal of dimensions a = 13.8 mm × 3.9 mm × 7.3 mm and were performed at room temperature. The field was applied along the c axis by silver paste electrodes. A schematic view of the setup is given in Fig. 1. A mask with a slit width of 100 μm was homogeneously illuminated by an Ar⁺ laser (λ = 364 nm) polarized parallel to the c axis. This controlling light had a photon energy larger than the 3.3-eV bandgap of KNbO₃.¹⁰ The slit was imaged by cylindrical lens CL₂ (f = 50 mm) onto the b surface of the sample. The imaged UV stripe had a width of 25 μm along the c axis at the incident surface and was aligned with the exit faces of the waveguide.

Fig. 1. Schematic (a) top and (b) front views of the experimental setup. L₁ and L₂ and CL₁ and CL₂ are spherical and cylindrical lenses, respectively. (b) The intensity distribution of the He–Ne beam at the front and exit faces of the waveguide.
parallel to the $a$ axis. Because of the strong absorption of UV light in pure KNbO$_3$ (absorption coefficient $\alpha_c = 540 \pm 50$ cm$^{-1}$), the UV stripe could induce field screening only for $\sim 150$ $\mu$m below the surface. A $c$-polarized He–Ne laser beam ($\lambda = 633$ nm) was focused by spherical lens $L_1$ ($f = 80$ mm) to a FWHM of 15 $\mu$m and fed into the waveguide entrance. The opposite exit face was imaged by lens $L_2$ ($f = 100$ mm) onto a calibrated CCD camera that monitored the beam intensity distribution. Additional background illumination of the crystal was provided by a mercury-arc lamp with a total intensity of $\sim 30$ mW/cm$^2$. This background light produced a homogeneous conductivity that permitted a better definition of the narrow stripe region where the external field was screened. Because of the extremely large photoconductivity induced by interband illumination, already weak intensity sidelobes could enlarge the width of the induced waveguides in the absence of background illumination.

Figure 2 depicts the output beam profile under the influence of the external field and of the striped UV illumination in several situations. Without both the electric field ($E = 0$) and the imaged slit (UV off), one observes the expected natural diffraction of the He–Ne beam, which expands to a FWHM of 88 $\mu$m after traversing the 13.8-mm-long crystal [Fig. 2(a)]. No significant change in the intensity distribution was observed either when the slit was imaged onto the crystal surface (UV on, here $I_{UV} = 3$ W/cm$^2$) or when an external field was applied, each separately, as shown in Figs. 2(b) and 2(c). Only the combination of electric field and slit illumination led to waveguide formation and to the decrease of the beam width along $c$ to 15 $\mu$m [FWHM; Fig. 2(d)], which corresponds to the width at the waveguide entrance. The guiding properties were found to be unchanged as the intensity of the He–Ne beam was varied from 0.004 to 200 W/cm$^2$, confirming the robustness of interband photorefractive gratings observed earlier. The total losses in the induced waveguide correspond to a loss coefficient $\alpha < 0.02$ cm$^{-1}$, i.e., less than 0.1 dB/cm. In contrast to the beam width along $c$, the one along $b$ (profiles not shown in Fig. 2) remained practically unchanged. On waveguide formation, we observed an improved, more Gaussian-like, beam profile as well as a slight attraction of the beam’s enter toward the UV-illuminated surface of the crystal, where the change in refractive index is the highest.

By the electro-optic effect the refractive-index decrease in the unilluminated regions is given by $\Delta n = -(n^3/2)\varepsilon_{\text{eff}}E$, where $\varepsilon_{\text{eff}}$ is the active effective electro-optic coefficient and $n$ is the undisturbed refractive index. For our configuration, with $n = 2.1687$, $\varepsilon_{\text{eff}} = \varepsilon_{333} = 55$ pm/V,$^{11}$ and $E = 4.8$ kV/cm, we expect the refractive index inside the illuminated region (core) to be larger by $\Delta n_c = 1.34 \times 10^{-4}$ than that of the surrounding regions (cladding). For a simple model of a step-profile planar waveguide of 25-$\mu$m width along $c$ and infinite extent along the $b$ axis, waveguide theory$^{12}$ implies then that the two lowest-order modes should be guided. The ground mode TM$_0$ of such a waveguide is expected to have a width of 17 $\mu$m (FWHM), in excellent agreement with the measurements.

We now analyze the influence of the experimental parameters on the guiding properties. In Fig. 3(a), the red beam’s exit face FWHM along the $c$ axis is plotted versus the applied field, while the UV intensity was kept constant at 3 W/cm$^2$, corresponding to a total UV power of 10 mW. The beam width continuously decreased from 88 $\mu$m at $E = 0$ and reached 15 $\mu$m for $E = 4.7$ kV/cm. Figure 3(b) shows the width as a function of UV intensity for a constant electric field. A value of 15 $\mu$m was reached at $I_{UV} = 2.5$ W/cm$^2$ and did not change for higher UV intensities.

To determine the buildup and decay times of the induced waveguide, we inserted an acousto-optic modulator into the beam path of the Ar$^{2+}$ laser. The CCD camera was replaced by a horizontally aligned slit (width, 50 $\mu$m) in the image plane of lens $L_2$ in Fig. 1(a). The transmission through the slit was high only if the He–Ne beam was guided inside the crystal. The observed time constants in the transmission dynamics reflect those of the waveguide formation and destruction processes. In Fig. 4 the exponentially fitted buildup time $\tau_b$ (1 − 1/e) and the dark decay time $\tau_d$ (1/e) are plotted versus the incident UV intensity during waveguide formation ($E = 4.8$ kV/cm). For the buildup process, as expected for dominant bipolar conductivity,$^{10}$ we found that $\tau_b \approx I^{-1/2}$ and had values of 63 $\mu$s for an UV intensity of 2.65 W/cm$^2$.
found that the waveguide decay time constant $\tau_d$ and of $780 \mu s$ for $I_{UV} = 20 \text{ mW/cm}^2$. In contrast, we found that the waveguide decay time constant $\tau_d$ is directly proportional to the square root of the intensity used for recording. This dependence is not fully understood yet.

One big advantage of our approach is that it permits a reconfiguration of the waveguide structure. Simply modifying the image mask makes possible various waveguide designs, e.g., Y or multiple branches, Mach–Zehnder-like interferometers, and switches. To demonstrate the feasibility of such structures we replaced the simple slit mask [Slit #1 in Fig. 1(b)] by a mask [Slit #2 in Fig. 1(b)], which permitted continuous rotation of one of its arms. The guided red beam encountered the pivot point of this rotation after 1/4 of its propagation in the crystal. By using the mask to rotate the other 3/4 of the induced waveguide, we could deflect the guided beam. The beam profiles for different deflection angles are shown at the top of Fig. 5. The corresponding integrated relative intensities of the guided and nonguided portions are plotted underneath. For increasing deflection angles, the intensity of the guided beam decreased continuously from 100% at 0 deg to 2.3% at 1.75 deg. For an angle of 0.7 deg, the deflected and nondeflected beams were of equal intensity. We could also demonstrate the formation of a Y branch by using a suitable mask. On illumination, a single red guided beam could be split in real time into two 15-μm-wide guided beams with a separation of 200 μm at the exit face.

The absorption of KNbO$_3$ in the near IR is nearly vanishing. A single-mode waveguide of the same dimensions as those presented here and propagation along the $a$ axis can in principle be induced also for the important telecommunication wavelength of 1.55 μm with a field of less than 8 kV/cm. Instead, by use of geometries that permit access to larger electro-optic coefficients of KNbO$_3$, the required field for getting a given waveguide width can be reduced by as much as a factor of 6. With the same procedure the waveguide width can be reduced by approximately two and one-half times for a constant applied field.

In conclusion, we have recorded all-optical dynamic waveguides by interband photorefraction with a response time of the order of 100 μs. Real-time beam deflection and formation of light-induced Y branches have been experimentally demonstrated. The method presented here appears attractive for creation of active all-optical devices such as switches, tunable Y branches, and reconfigurable optical interconnectors compatible with telecommunication wavelengths. These kinds of dynamic waveguide do not necessarily require the use of coherent controlling light. Electro-optic materials that support interband photorefractive effects other than KNbO$_3$ may be used as well.

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