

Electro-activation and electro-morphing of photorefractive funnel waveguides

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Abstract: We demonstrate the electro-activation of funnel waveguides through the quadratic electro-optic effect in paraelectric potassium-lithium-tantalate-niobate. This allows us to achieve electro-optic intensity modulation in a single optical beam, a 1x2 switch, and finally the electrically controlled morphing of a single waveguide into a 1x2 and a 1x4 divider.

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1. Introduction and motivation

In distinction to electric signals, optical signals can be used to handle links and information channels in massively parallel full three-dimensional geometries. A step towards the harnessing of this enormous potential is the identification and demonstration of a viable means to create compact and miniaturized optical circuits and devices that can be integrated together into functional assemblies. Ideally, this should be achieved directly inside a single three-dimensional solid-state support. Applications range from miniaturizing optical technology for telecommunications or data processing, or for more pioneering enterprises, such as building dense three-dimensional circuits for the study of neural networks. The challenge in standard geometries is that working in the solid volume excludes conventional fabrication techniques, such as lithography. One solution is to use light to write the required structure in the solid in a single-step, through an appropriate photosensitive process, such as occurs in UV-cured epoxy [1], photopolymerization [2, 3, 4], photorefraction [5], combinations of these [6], or amorphization [7]. Optical writing faces two general issues: (I) as the writing light enters into the volume it is distorted by diffraction; and (II) conventional photosensitive techniques do not support the integration of devices, such as electro-optic modulators, switches and filters. Both issues can be, in principle, overcome in photorefractive media. Diffraction can be overcome when the writing light is itself sensitive to the changes it produces in the material and guides itself through it, a process termed self-writing [8] supported by the formation of a photorefractive spatial soliton [9, 5], whereas active devices can be supported by soliton electro-activation, a versatile technique to produce a wide family of fast electro-optic functions using the self-written waveguides [10, 11, 12, 13]. The solution requires a quadratic electro-optic response, such as observed in room-temperature potassium-lithium-tantalate-niobate (KLTN) [10], in nano-poled strontium-barium-niobate (SBN) [14] and in organic photorefractive glass [15]. Self-writing, however, becomes impractical when multiple-waveguide structures are involved, since the underlying solitons interact nonlinearly, a feature that influences even the writing of a simple two-soliton-based directional coupler [16].

In a recent set of experiments we successfully addressed the first issue (I) developing a non-solitonic method to write waveguides in the volume using the index pattern generated by a linear diffracting beam termed funnel waveguides [17, 18]. Since no solitons are involved, no nonlinear beam interaction intervenes and the waveforms need not coincide with those leading to self-trapping (soliton existence conditions). To achieve a funnel waveguide, the optical response is deactivated during the writing phase (WP) but activated during the reading phase (RP). It is saturation that distorts the index pattern written by the diffracting beam (the "funnel") into a tubular-like waveguide pattern during readout [17]. The idea of funnel waveguides is general, can be directly extended to noncentrosymmetric crystals [18], such as lithium-niobate (LiNbO_3) and SBN, but has yet to be demonstrated in these and in other photosensitive settings, such as glasses, polymers, and thermo-optic materials.

Here we demonstrate the electro-activation of funnel waveguides to achieve a single channel

intensity modulator and a 1X2 switch in the RP, effectively addressing also the issue (II). To render explicit the vast possibilities of the technique, we also demonstrate the electro-optic morphing of a single waveguide into a 1x2 and a 1x4 splitter.

Novelty lies in waveguide electro-activation. The mechanism can be readily grasped considering the simplifying case in which all electric fields are parallel and the beam intensity changes only along their common direction (say the x axis). Appropriately illuminating the sample gives rise to the internal electric field $E(x) = E_w + E_{sc}(x)$, the superposition of the external homogeneous bias field E_w and the so-called space-charge field $E_{sc}(x)$ due to the semi-permanent rearrangement of light induced charges that typically screen E_w where the optical intensity is higher, i.e., at the beam center. For a quadratic electro-optic response, the index of refraction pattern $\Delta n_w = c(E)^2 = c(E_w^2 + 2E_w E_{sc} + E_{sc}^2)$ is focusing for $c < 0$, simply because E is screened and hence lower at the center of the beam. Now, if the optical beam is attenuated or a non-absorbed (near-infrared) wavelength is used (in which case slight changes in the actual index values and electro-optic coefficients also intervene), the charges remain dislocated and E_{sc} remains fixed, even though the external bias field can be set to an arbitrary E_r , typically different from E_w . When $E_r \neq E_w$ the resulting index pattern $\Delta n_r \neq \Delta n_w$. For example, setting $E_r = 0$, $\Delta n_r = c(E_{sc}^2)$ which produces a defocusing effect ($c < 0$) on the beam, since the originally screening $E_{sc} \neq 0$ only in the beam path. The effect is clearly absent in linear electro-optic crystals, where $E_r \neq E_w$ only changes an additive constant to the index pattern.

2. Electro-optic intensity modulation

Our experiments are carried out in a zero-cut and polished $L_x = 2.4$ mm $L_y = 3$ mm $L_z = 1$ mm sample of KLTN kept at $T = 19^\circ\text{C}$, above its ferroelectric Curie point at $T_C = 14^\circ\text{C}$. The electro-optic response is quadratic, with background index of refraction $n_0 = 2.35$, static relative dielectric constant $\epsilon_r(T) = 1.9 \times 10^4$, and the relevant components of the quadratic electro-optic tensor are $g_{12} = -0.02\text{m}^4\text{C}^2$ and $g_{11} = 0.16\text{m}^4\text{C}^2$.

In the WP, the writing beam is a Gaussian TEM₀₀ beam from a He-Ne laser operating at $\lambda = 543$ nm, continuous wave, with average power $P_w = 800$ nW, a minimum Full-Width-at-Half-Maximum (FWHM) $\Delta x_0 = \Delta y_0 = 7.5\mu\text{m}$ and linearly polarized in the y direction ($\mathbf{p}_w \parallel \hat{y}$). It is launched in the z direction and is focused either onto the input facet $z_0 = 0$ of the sample ("single funnel geometry"), or half-way through the sample at $z_0 = L_z/2$ ("double funnel geometry"). The bias field is delivered in the x direction through two electrodes on the x facets L_x apart by appropriately applying the bias voltages $V_w = V^\pm = \pm 1.1\text{kV}$, so that the field is prevalently in the x direction ($\mathbf{E}_w = \mathbf{E}^\pm \parallel \hat{x}$). Given the relative orientation of \mathbf{E}_w and \mathbf{p}_w , the maximum index of refraction modulation experienced during writing is $\Delta n_w = -(1/2)n_0^3\epsilon_0^2(\epsilon_r - 1)^2g_{12}E_w^2 \sim -3 \times 10^{-5}$, a value insufficient to alter the beam diffraction. The duration of the WP for each beam Δt (the "exposure") determines the saturation of the observed response in the RP and hence the guiding properties of the waveguide.

In the RP, the same writing beam is used but with a reduced intensity $P_r = 10$ nW, so that the resulting exposure (and nonlinearity) during the inspection is negligible, the polarization is rotated so that $\mathbf{p}_r \parallel \hat{x}$, and $z_0 = 0$. The reading bias field is determined by the value of V_r which can vary and is in general $V_r \neq V_w$. In particular, for $\mathbf{E}_r \equiv \mathbf{E}_w$ ($V_r = V_w$), the fact that $\mathbf{p}_r \parallel \mathbf{E}_r$ implies that the relevant maximum index of refraction change is $\Delta n_r \sim 4 \times 10^{-4}$, now capable of altering the diffracting beam propagation, i.e. the pattern is activated.

Beam propagation in both WP and RP is detected through the corresponding images of the output transmitted beam intensity distribution through a CCD camera and an appropriate imaging system.

In Fig. 1 we illustrate the demonstration of an intensity modulator based on the electro-activation of a single funnel waveguide. In the WP, a single beam is used with $z_0 = 0$ and

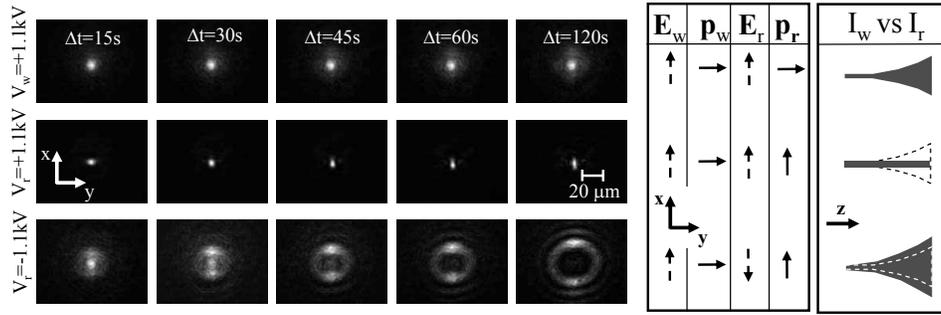


Fig. 1. Electro-optic response and activation of a single funnel waveguide (see text). Boxed illustration summarizes the relative orientation of \mathbf{E}_w , \mathbf{p}_w , \mathbf{E}_r , and \mathbf{p}_r in the xy plane in the three cases of the three rows, along with the behavior of the light beam in the WP I_w (dashed regions) and in the RP I_r (the dark grey regions), as seen in a superimposed top view.

$V_w = V^+$, centered around the position (x_0, y_0) . The output of the beam for different values of Δt is shown in the top row of Fig. 1. The output FWHM of the beam remains approximately constant at $\Delta x \simeq \Delta y \simeq 15\mu\text{m}$, as expected. In the RP, the reading beam is launched in (x_0, y_0) and the output distributions for the different values of Δt , for $V_r = V^+$ (second row of Fig. 1), and for $V_r = V^-$ (third row of Fig. 1), are shown. For $V_r = V^+$, for $\Delta t \simeq 30$ s, the beam is guided into a mode of $\Delta x \simeq \Delta y \simeq 8\mu\text{m}$, and becomes elongated in the x direction for longer exposures, a process that does not lead to further changes for $\Delta t > 100$ s. For $V_r = V^-$ ($\mathbf{E}_r = -\mathbf{E}_w$), only a weak defocusing effect is observed for low values of $\Delta t = 15, 30, 45$ s). For longer values of Δt saturation spreads from the central region and antiguiding emerges. For $\Delta t = 120$ s, light transmission can be efficiently switched on and off by changing the value of V_r : for $V_r = +1.1\text{ kV}$, light is transmitted, for $V_r = -1.1\text{ kV}$, light transmission is blocked (second and third row of Fig. 1 for $\Delta t = 120$ s).

3. Electro-optic 1x2 switching

To demonstrate 1x2 electro-optic switching, the WP involves two funnels *written* with opposite bias fields $V_{w1} = V^+$ and $V_{w2} = V^-$ (i.e., $\mathbf{E}_{w1} = -\mathbf{E}_{w2}$), with $z_0 = L_z/2$. The two waveguides are formed shifted along the y direction, in the positions (x_0, y_0) and $(x_0, y_0 + 30\mu\text{m})$, each is written for an interval $\Delta t = 60$ s, alternating the two writing processes at $\delta t = 3$ s intervals. The shift is in the y direction so that the anisotropic components (along the x direction) do not intervene, and the double-funnel geometry is used to reduce the mutual tail overlap, simplifying and rendering practical the RP (see Fig. 2). In the RP, the same reasons that allow a single funnel waveguide to guide also allow a double-funnel to guide, so that when the beam is launched in (x_0, y_0) , for $V_r = V_{w1}$, it is guided (Fig. 2(a)). Analogously, when the beam is launched in $(x_0, y_0 + 30\mu\text{m})$, for $V_r = V_{w2}$ it is guided (Fig. 2(b)). When the read beam is launched in between the two patterns, in $(x_0, y_0 + 15\mu\text{m})$, it is routed on waveguide 1 when $V_r = V_{w1}$ ($\mathbf{E}_r = \mathbf{E}_{w1}$) (Fig. 2(c)) and on waveguide 2 for $V_r = V_{w2}$ (Fig. 2(d)), demonstrating the electro-optic 1x2 switch. For these two last conditions, the underlying pattern can be detected by launching a plane-wave as opposed to a focused down read beam for $V = +1.1\text{ kV}$ ($V = -1.1\text{ kV}$), as shown in Fig. 2(e), Fig. 2(f).

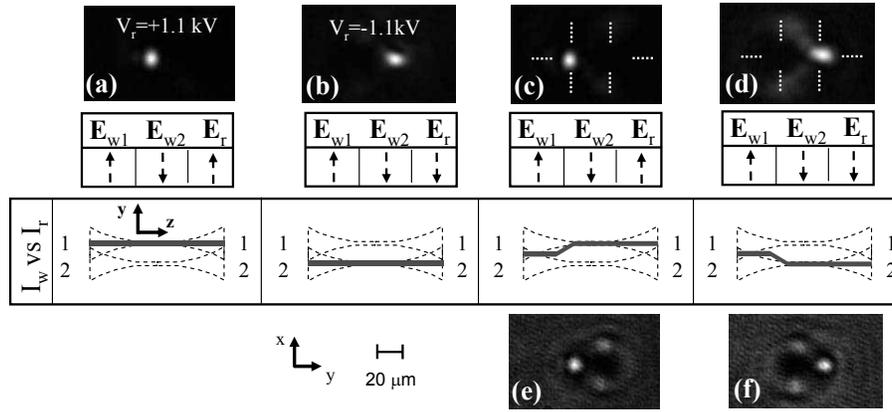


Fig. 2. Schemes and output intensity distribution relative to the electro-optic 1x2 switching using two double-funnels 1 and 2 (see text). Boxed illustrations beneath images (a-d) summarize the relative orientation of \mathbf{E}_{w1} , \mathbf{E}_{w2} , and \mathbf{E}_r , along with the behavior of the light beam in the WP and RP, as in Fig. 1, from the two input positions 1 and 2 to the two corresponding output positions.

4. Electrically controlled pattern morphing

We now demonstrate the electro-optic morphing of a waveguide into a y-junction, i.e. a static 1x2 splitter, as shown in Fig. 3. In the WP, two equally polarized double-funnel waveguides with $V_{w1} = V_{w2} = V^-$ ($\mathbf{E}_{w1} = \mathbf{E}_{w2}$) are stacked in the x direction, in the positions (x_0, y_0) and $(x_0 - 40\mu\text{m}, y_0)$, as illustrated in Fig. 3(a),(b). In the RP, the read beam is launched in $(x_0 - 20\mu\text{m}, y_0)$, in between the two, for $V_r = V_{w1,2}$ the beam is split into two (Fig. 3(a),(c)), whereas it is guided in the center for $V_r = -V_{w1,2}$ (Fig. 3(b),(d)). The reason for this can be appreciated observing the effect on a plane wave, as shown in Fig. 3(e): the anisotropic lobes of Fig. 1 third row now superimpose in the central region making it guiding. Analogous effects are observed for a lower read voltage. In particular, the case of $V_r = \pm 0.88$ kV is shown in Fig. 3(f),(g),(h). The beam splitting is here more effective, as illustrated in Fig. 3(f), and the underlying pattern is evidence in the propagation of a plane wave, as shown in Fig. 3(h), where the defocusing effect of the two waveguides is weakened. So it is that the optimal morphing of a waveguide into a 1x2 y-junction is achieved for the cases Fig. 3(d) and (f), through the patterns of Fig. 3(e) and (h).

In the WP, three double-funnels can be written as illustrated in Fig. 4, two with $V_{w1} = V_{w2} = V^+$ (a,b) in positions (x_0, y_0) and $(x_0, y_0 + 20\mu\text{m})$, and a third with $V_{w3} = V^-$ (c) in $(x_0, y_0 + 10\mu\text{m})$. In the RP, each guides a beam launched into it when $V_r = V_{wi}$ ($i = 1, 2, 3$), as shown in the output intensity distributions (Fig. 4(a-c)). However, when the read beam is launched in the $(x_0, y_0 + 10\mu\text{m})$ (central waveguide), as for Fig. 4(c), applying $V_r = -V_{r3} = V_{r1,2}$ gives rise to the electro-activation not of a 1x2, but a 1x4 divider, as shown in Fig. 4(d). This only apparently unexpected result is the product of the superposition of the three funnels, which provides the remarkable result of producing a whole set of guiding structures in and around the three funnel geometry, as illustrated in Fig. 5. When the same pattern is biased with $V_r = +1.1$ kV, four different and independent waveguides are formed along a diamond geometry, as illustrated in Fig. 5(a), where the output intensity distribution of a beam launched successively in the

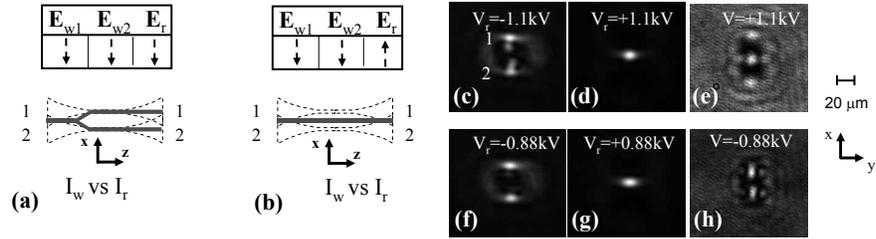


Fig. 3. Electro-optic morphing of a waveguide into a 1x2 splitter (see text). Illustrations are as in previous figures.

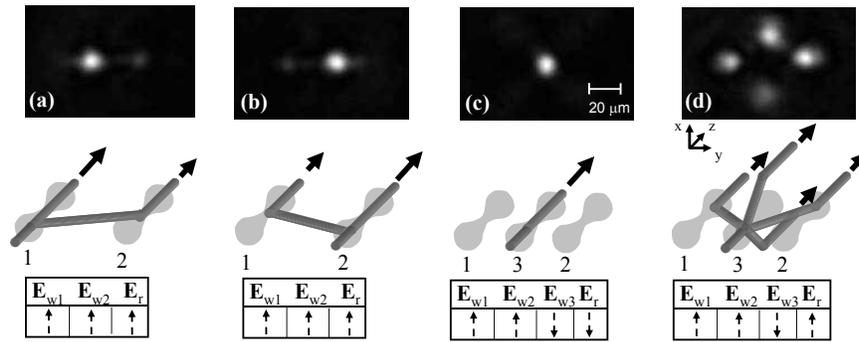


Fig. 4. Electro-optic morphing from a waveguide to a 1x4 divider (see text). Illustrations are as in previous figures, except that here they are extended into a 3D perspective. The light grey region is a representation of the double-funnel volume structure of the I_w in the WP, whereas the dark grey tubes represent the I_r in each of the steps.

four waveguides is shown, and finally the pattern is inspected with a plane wave read-out. The activated waveguides, illustrated in dark grey, are superimposed with a different array of five waveguides, illustrated in light grey, that are in turn activated when $V_r = -1.1\text{kV}$, and ($\mathbf{E}_r = \mathbf{E}_3$), as demonstrated in Fig. 5(b), where the guiding properties of each single member of the array is inspected launching in it the read beam. Again the pattern is detected through a plane-wave read out (bottom image), and the illustration indicates how the waveguide arrays have morphed from the original structure of a to b.

5. Conclusion

Concluding, we have demonstrated the electro-activation of funnel waveguides, a system in which saturation, spatial layout, anisotropy, polarization and applied electric fields allow the morphing of different and complex photonic devices through simple linear writing strategies.

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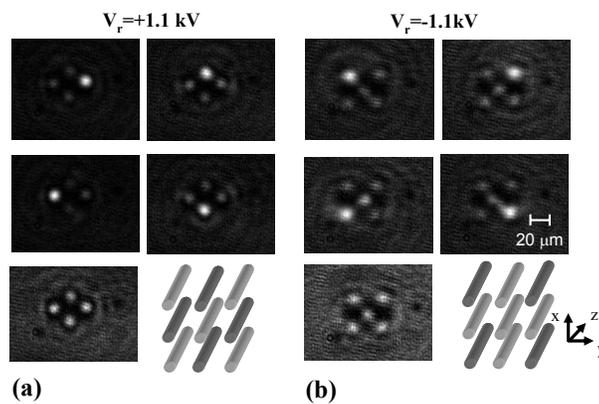


Fig. 5. Electro-optic morphing of one waveguide array into another, as described in the text.

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