Fixing solitonic *y* junctions in photorefractive strontium–barium–niobate

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Two-dimensional solitonic orbital waveguides as *y* junctions were formed in a strontium barium niobate crystal. The waveguides are 10–20 μm in diameter and propagate unpolarized light.
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Optical spatial solitons[1] in photorefractive crystals[2] have shown potential to form graded index waveguides which can guide other beams.[3,4] A soliton forms when a photoinduced index change in the material compensates exactly for the diffraction of the beam; i.e., the beam creates its own waveguide. In photorefractive materials, a screening soliton is formed by the screening of an externally applied electric field through the transport of photoinduced carries.[5,6] However, these induced waveguides disappear if the applied field is removed from the material. Our motivation for this letter is to demonstrate the use of soliton formation to create arrays of permanent waveguides[7–13] and *y* junctions (by selectively reorienting ferroelectric domains within the propagating light beam[14]) that can be used to form optical wiring in the bulk of a crystal.

For the experiment, the extraordinary polarized output of an argon-ion laser is focused to a spot size of 12 μm on the front face of a 1 cm cube of strontium–barium–niobate (SBN) crystal. When a 3 kV/cm electric field is applied to the crystal along the direction of spontaneous polarization, the beam self-focuses to its input diameter. The external field is then removed and a uniform background beam that fills the crystal is switched on. The space charge field due to photoinduced screening charges is larger than the coercive field of the ferroelectric domains and causes the domains in the area of the incident beam to reverse their orientation. At equilibrium, a new space charge field, due to the bound charge of the domain boundaries, is locked into place. This new field increases the index of refraction only in the area of the original soliton, so that a waveguide is formed. The waveguides are observed to have the same size as the original soliton, exhibit single mode behavior, and last indefinitely.[14]

To further demonstrate the feasibility of creating optical circuitry, multiple independent waveguides were formed in a SBN:75 crystal. A diffractive optic was inserted into the experimental apparatus behind the focusing lens to form five replicas of incident beam on the entrance face of the crystal [Figs. 1(a) and 1(b)]. The spacing between the beams was 230 μm in the horizontal direction and 225 μm in the vertical direction. A voltage was applied and five 13 μm solitons formed [Fig. 1(c)] and were subsequently fixed [Fig. 1(d)]. The fixed waveguides guided light independently of one another, as evidenced by blocking one or more input beams and observing no change in the transmitted intensity of the remaining waveguides. The waveguides reached equilibrium in the same manner as the single fixed waveguide, transmitting $60\pm2\%$ of the incident power at equilibrium after approximately 60 min. The waveguides were monitored for an additional 140 min and showed no sign of decay.

In addition to fixing single and multiple solitons, a coherent collision of two solitons was used to fixed a *y* junction in the crystal. Typically, two beams were launched in parallel with angles of less than 0.05° in both the horizontal and vertical directions. As a result, two collinear beams were focused to a spot size of 12 μm at the entrance face of the

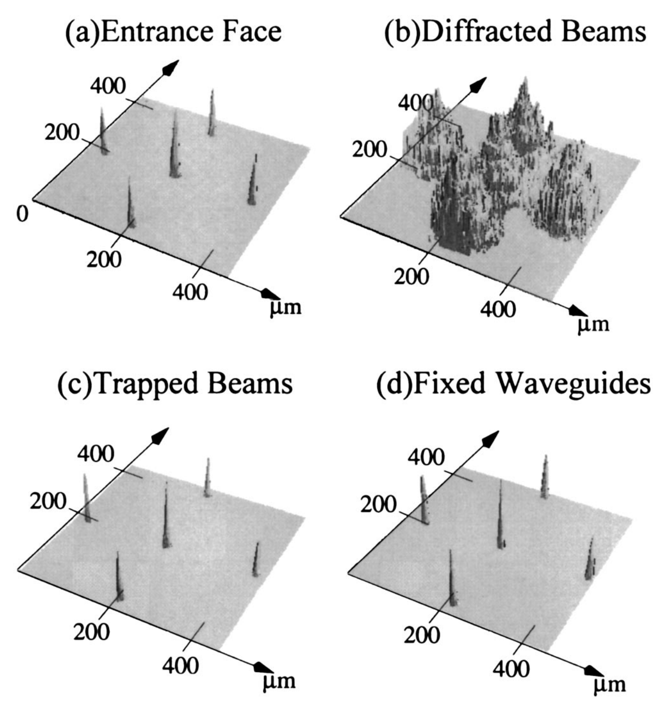

FIG. 1. (a) Input profile of five beams; (b) profile at the exit face; (c) five soliton beam profiles at the exit face; (d) five fixed waveguides guiding light to the exit face.

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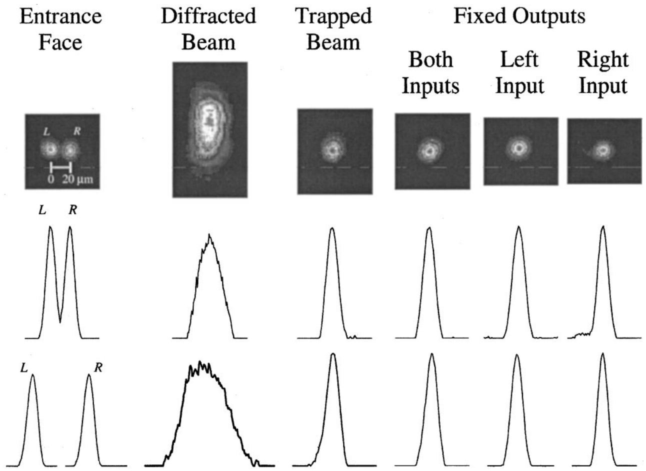


FIG. 2. Collision between two input beams producing a *y* junction.

crystal with a peak to peak separation of 20 μm parallel to the *c* axis of the crystal. The total input power was 0.5 μW, evenly distributed between the two input beams. At a field of 3 kV, the two input beams merged into a single beam at the exit face of 12 μm diameter in the horizontal direction and 13 μm in the vertical direction. The self-induced *y* junction guided 59$\pm$2% of the total incident power. The fixing procedure outlined earlier[14] was then followed to make the *y* junction permanent. After fixing, the output of the *y* junction, with both the left and right inputs incident, guided 46$\pm$2% of the total input power in a 12 μm$\times$13 μm waveguide. If a relative phase difference of π was introduced between the two input beams, it was observed that the output of the fixed *y* junction went to zero. With only the left input incident to the *y* junction, the waveguide diameter remained the same, and guided 42$\pm$2% of the incident power. With only the right input incident, the waveguide diameter again remained constant, and 40$\pm$2%, of the incident power was transmitted. The input and output of the *y* junction are shown in Fig. 2. The higher loss for the fixed *y* junction would be expected since the domain pattern in the waveguide is no longer uniform and the inhomogeneity can result in increased scattering loss.

With the same inputs, a collision with ordinary polarized light was formed, and the fixed output was observed under both extraordinary and ordinary polarized inputs. The collision guided 97$\pm$2% of the incident light with a diameter of 16 μm. After fixing and under illumination by ordinary light, the coupler guided 77$\pm$2% of the incident power, with a full width at half maximum (FWHM) of 20 μm. When extraordinary light was used to illuminate the *y* junction, the size of the guided output reduced to 13 μm and the guided intensity fell to 66$\pm$2%. The improved transmission using ordinary polarized light is due in part to the fact that with ordinary light a larger space charge field is needed to form a soliton. The need for a larger field is due to the significantly lower electro-optic coefficient for ordinary polarized light. The lower coefficient (or index change) results in a more gradual formation of the *y* junction in space and hence greater coupling. In addition, the higher screening field can do a better job in flipping domains within the waveguide, potentially resulting in less scattering loss.

To further test the properties of the fixed *y* junction, a HeNe laser was coupled into the single output of the *y* junction. Initially, colinear beams space 30 μm apart were used to form the collision and the standard fixing procedure[14] was followed. After the *y* junction reached equilibrium, the HeNe laser was coupled into the single output of the *y* junction. Two outputs with a spacing of 30 μm were observed, as shown in Fig. 3. Within the resolution limits of the imaging charge capture device (CCD) ($\pm$1 μm), the size and separation of the HeNe beams exiting the *y* splitter matched those of the argon-ion beams used to form the *y* junction. The *y* splitter split the incident HeNe beam nearly evenly into two components while transmitting 41$\pm$2% of the incident light.

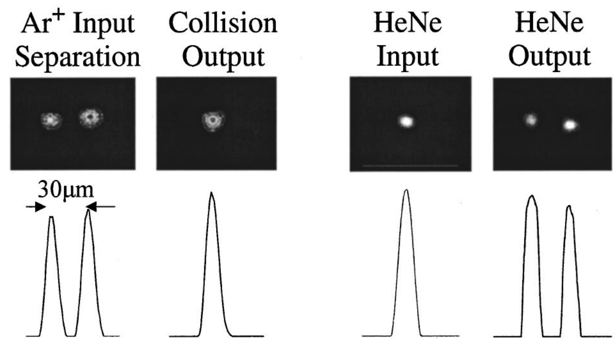
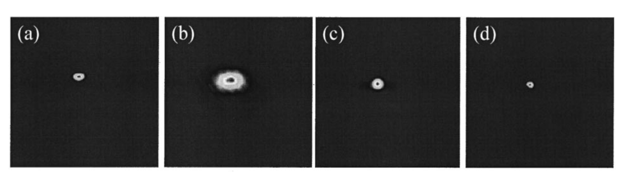


FIG. 3. HeNe beam injected into the output of the *y* junction splitting into two beams.

The two beams used to form the collision were also aligned, with a separation perpendicular to the *c* axis of the crystal of 30 μm, to form a collision in the vertical plane. The input beams were of equal intensity and had input diameters (FWHMs) of 11 μm in the horizontal direction and 12 μm in the vertical direction. The collision between the two input beams had a diameter of 12$\times$12 μm^2 and guided 53$\pm$2% of the total incident power. The fixed *y* junction was found to guide 40$\pm$2% of the collision intensity under excitation of both arms, with an output diameter of 12$\times$13 μm^2. If a single input only was excited the transmitted intensity dropped to 37$\pm$2% for the top input and 35$\pm$2% for the bottom input. The fixed waveguides were monitored for a total of 400 min without showing decay after having reached an equilibrium state after approximately 80 min of continuous illumination.

One of the interesting features of all of the fixed waveguides described in this letter is that they can be used to guide either polarization or both polarizations simultaneously. Figure 4 shows the waveguiding properties of a



ee: 12 X 9.5μm	eo: 27 X 20μm	oo: 12 X 12μm	oe: 8 X 8 μm

FIG. 4. Fixed waveguide properties with different polarizations. Photographs and profiles of (a) extraordinary polarization for fixing and extraordinary for guiding (ee); (b) extraordinary polarization for fixing and ordinary for guiding (eo); (c) ordinary polarization for fixing and ordinary for guiding (oo); and (d) ordinary polarization for fixing and extraordinary for guiding (oe).

single fixed soliton waveguide. In Fig. 4 the waveguide is shown to be fixed and is observed using all four combinations of extraordinary and ordinary polarized light. In Figs. 4(c) and 4(d), for example, the waveguide was fixed using an ordinary polarized soliton but was observed to guide either ordinary or extraordinary polarized light, although at slightly different beam diameters.

In summary, utilizing the fixing technique reported earlier, permanent *y* junctions were formed in SBN:75. It was also demonstrated that they efficiently guide both beams that were used to form them as well as light from a HeNe laser operating at 632.8 nm. The observed long lifetime of the *y* junction waveguides over 12 h under intense illumination demonstrates that the fixing technique does form a permanent index change. The fixed *y* junctions guided 42 to 77±2% of the incident power, depending on the polarization used to fix and to probe the waveguide. Data were presented showing that either ordinary or extraordinary polarized optical beams could be guided by effectively using screening solitons of ordinary polarization. Finally, a set of single waveguides was formed using binary optics to produce multiple input beams at the entrance face of the crystal. Specifically, a two-dimensional array of five single waveguides was fixed in the crystal. The behavior of the set of waveguides was found to be identical to that of single waveguides. These results demonstrate that arrays of single waveguides and *y* junctions can be fixed simultaneously to form optical wiring in the bulk of the crystal.

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