Design and simulation of planar electro-optic switches in ferroelectrics

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Conceptual design and numerical simulation of two polarization dependent planar optical switches based on the electro-optic effect in ferroelectrics operating at 1.55 μm wavelength are presented. The first design is a 3 × 3 optical switch based entirely on electro-optic beam steering (prism elements) and ion-exchanged lenses for collimation. The second design is a 1 × N optical switch based on a combination of electro-optic beam steering and electro-optic focusing (lens) elements. The scalability of this device has been improved by compensating the in-plane divergence of the laser. Analytical expressions for the dependence of scalability are presented. © 2008 American Institute of Physics. [DOI: 10.1063/1.2967469]

In optical communications, optical switches facilitate selective switching of the optical signal from M number of incoming fibers to N number of outgoing fibers. The primary desirable characteristics of an ideal optical switch are speed (kiloherzt to gigahertz) and scalability (large number of input/output ports per switch). Past and current switch technologies include inkjet technology, liquid crystals, micro-electromechanical systems, photochromic effect, and electro-optic effect. Of these, the electro-optic mechanism promises the fastest switching speeds (up to 1011 Hz) and is used as the preferred technology today for 10–40 GHz lithium niobate (LiNbO3) based optical modulators. Further advantages include small size, low operating power, and nonmechanical operation. The ferroelectric domain walls in LiNbO3 provide additional advantages when shaped as optical components, including high-speed switches, dynamic focusing lenses, laser beam steering elements, beam shaping, and integration of multiple such functions on the same chip. Total internal reflection (TIR) at a ferroelectric domain wall has been used to demonstrate high-speed optical switches; however, the operation is limited to 1 × 2 using a single domain wall, or 2 × 2 using a pair of walls, and device length scales unreasonably with the number of ports.

In this letter, we present two alternate M × N (M input and N output ports) electro-optic switch designs. These devices are designed using a combination of electro-optic prisms and lenses based on uniaxial ferroelectrics such as lithium tantalate or niobate. Design I involves only electro-optic beam steering elements and is a variant similar to the TIR switches described above but involves beam steering instead of reflection. Design II uses a combination of electro-optic steeing and electro-optic focusing elements, which leads to significant advantages.

We consider lithium tantalate as an illustrative material for our design calculations. In congruent lithium tantalate (LiNbO3), the direction of spontaneous polarization (P_s) can be reoriented between equilibrium directions (±z-axes) by applying an external electric field of ~21 kV/mm along the z direction. This phenomenon can be exploited to define an arbitrary domain pattern in the material by well-established domain reversal techniques. Furthermore, when the material is subjected to an external electric field (E_z) along the z axis, there is an associated creation of a change in the refractive index (∆n) across the domain wall, given by

$$\Delta n = -\frac{1}{2} \frac{n_e n_o}{n_o^2 + n_e^2} E_z$$

where n_e is the extraordinary refractive index and r_33 is the corresponding electro-optic coefficient. This index change has been used by shaping ferroelectric domains as prisms and lenses for laser beam steering and focusing, respectively. However, in order to exploit the electro-optic effect, the incident laser beam should be polarized along the crystallographic z-axis.

The first design is a 3 × 3 switch, whose schematic is illustrated in Fig. 1(a). It is composed of input (A, B, C) and output (P, Q, R) rows of electro-optic steering domain elements with corresponding rows of collimating ion-exchanged domain lenses. The shape optimized horn-shaped scanner is used as the laser beam steering element in the design. The incident laser beam from the input fiber, polarized along the crystallographic z axis of lithium tantalate crystal, is butt coupled into the device. The diverging incident beam is collimated along the x-axis by the passive double-ion-exchanged cylindrical lenses at the input of each port. The beam is confined in the thickness direction using a planar waveguide formed by the standard annealed proton-exchanged or Ti-diffused waveguide mode matched in dimensions to standard telecommunications fibers. The light is deflected by the first set of horn-shaped scanners (A/B/C) and is collected by the second set (P/Q/R) of scanners that restraighten the path of the beam along the optic axis of the device. The light from the output ports is focused into the output fiber by another stack of ion-exchanged cylindrical lenses in front of each output fiber as shown in Fig. 1(a). Each of these scanners in the first and second column can be independently operated by depositing metal electrodes on the z ± z surface. Thus, the input beam from any of the three input ports can be switched to any of the three output ports (nine combinations) by varying the voltage across the scanners. The beam path and the size are calculated using the beam propagation method (BPM) at 1.55 μm. The beam path and the size in a horn-shaped scanner used in this design are calculated using the BPM as shown in Fig. 1(b). The material constants for LiTaO3 used in the BPM simulation were n_e = 2.1224 and r_33 = 27.4 pm/V at 1.55 μm. The input aperture of the horn-shaped scanner is 264 μm, the out-

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put aperture is 793 μm, and the device length is 10 mm. The wavelength of the laser beam is 1.55 μm and has a Gaussian beam diameter of 200 μm at the input aperture of the scanner. The distance between the end of the input port and input aperture of the output port is 28.5 mm. The total length and width of this optical switch are 48.5 and 5 mm, respectively. All the nine possible combinations in a 3×3 optical switch are numerically simulated using the BPM and superimposed as shown in Fig. 1(c). The external electric field required on the input and the output ports ($E_{\text{input}}$ and $E_{\text{output}}$, respectively) to deflect the incident beam are as follows: $A\rightarrow P$ (0, 0 V/μm), $A\rightarrow Q$ (−3.3, 3.3 V/μm), $A\rightarrow R$ (−6.6, 6.6 V/μm), $B\rightarrow P$ (3.3, −3.3 V/μm), $B\rightarrow Q$ (0, 0 V/μm), $B\rightarrow R$ (−3.3, 3.3 V/μm), $C\rightarrow P$ (6.6, −6.6 V/μm), $C\rightarrow Q$ (3.3, −3.3 V/μm), and $C\rightarrow R$ (0, 0 V/μm). To reduce the actual voltage requirements to less than 100 V, thin slices (10–30μm) from the pre-engineered domain pattern could be prepared by precision polishing or crystal ion slicing. The frequency response of the devices based on instantaneous electro-optic effect is of the order of 10–40 GHz, comparable to the lithium niobate modulators used in current technology. The frequency response is only dependent on the power supply used to drive the device. The thickness of the devices can be reduced to minimize the voltage requirements, thereby increasing the frequency response of the devices. The insertion loss due to reflection at the input and output faces can be calculated using the Fresnel coefficients in near-normal incidence. The value has been calculated to be 0.6 dB at each air/lithium tantalate interface due to reflection. The coupling losses due to mode mismatch can be calculated using the overlap integral method. In order to minimize coupling loss due to mode mismatch, the thickness of the slices should be comparable to the mode field diameter of the single mode fiber used at the output port. More scanner ports can be appended to the input or output port to realize any $M \times N$ optical switch.

The scalability ($M$) of an optical switch design is defined as the maximum number of output ports that could be accommodated in the switch. Analytical expressions for scalability can be derived by assuming Gaussian beam propagation inside the device. In the case of thin laser beam deflectors, the scalability is given by

$$M = 1 + \left(\frac{\theta_{\text{max}}}{r \theta_{\text{beam}}}\right),$$

where $\theta_{\text{max}}$ is the maximum total deflection angle of the deflector, and $\theta_{\text{beam}}$ is the divergence of the laser beam. However, in the design described above, the output of the scanner is larger than the output. Therefore, the scalability of this design becomes roughly

$$M = 1 + \left(\frac{\theta_{\text{max}}}{r \theta_{\text{beam}}}\right),$$

where $r$ is the ratio of the output to the input aperture of the beam deflector. Since $r$ is greater than 1 for the design under consideration, the design can be optimized to increase its scalability. Increasing scalability requires increasing $\theta_{\text{max}}$ and decreasing $\theta_{\text{beam}}$. For increasing $\theta_{\text{max}}$, horn-shaped scanners are employed instead of rectangular scanners. However, the wider end of each horn-shaped scanner (−0.79 mm here) limits the number of input/output ports that can be added adjacent. The other characteristic of this design is the divergence of the laser beam propagating from the input to the output ports in the plane of the device ($x$-$y$). Even if the focal point of the laser beam is at the center of the device, the in-plane divergence would result in the reduction of the scalability. These issues have been addressed in the following design.

The schematic of a second design is shown in Fig. 2(a) for a $1 \times N$ switch, which has significantly improved scalability, as well as alleviates the beam divergence issue. This design can be considered as half of an $M \times N$ switch, as will be described later. The design is a combination of a set of electro-optic prisms and lenses. We exploit the fact that if an incident laser beam is offset from the principal axis of a lens, it is deflected toward the focal point.

Now let us look at the working principle of the $1 \times N$ design. First, the angular position of the incident beam is controlled using a horn-shaped scanner. Second, a lens reflects the laser beam and makes it parallel to the optic axis at the output port. This ensures that the coupling and insertion losses are minimized, as well as close packing of output ports is achieved. An additional key advantage of this design is that the lenses also compensate for the natural divergence of the laser beam inside the crystal and ensure that the output beam diameter (225 μm) is comparable to the input beam diameter (200 μm). Thus, it plays a significant role in increasing the number of output ports. The scalability of this design is given by $3(D-L)\theta_{\text{max}}/2h$, by assuming a clipping ratio of 3, where $L$ is the length of the laser beam deflector and $h$ is the input aperture of the scanner. The scalability is found to have a direct dependence on the length of the device.
The optical power of an electro-optic lens is defined as
\[ P = \frac{D n}{R} \]
where \( R \) is the radius of curvature of the lens. Due to the small values of \( \Delta n \) (~\( 10^{-4} \)), the optical power of an electro-optic lens is lower in comparison to the conventional lens. Therefore, in order to increase the net optical power, a stack of 23 lenses with a radius of curvature of 3000 \( \mu m \) each and separated by 5 \( \mu m \) gaps is cascaded in sequence as shown in Fig. 2(a). The external field \( E_L \) applied across the stack of lenses is kept constant in this particular design. The input aperture of the 8 mm long scanner is 250 \( \mu m \). The external field \( E_L \) applied across the horn-shaped scanner is varied to deflect the beam to the corresponding output port. The beam path and the size are numerically calculated using the BPM at the following combinations \([E_G, E_L]\); port A, (16, 16.6 V/\( \mu m \)); port B, (8.3, 16.6 V/\( \mu m \)); port C, (0, 16.6 V/\( \mu m \)); port D, (−8.3, 16.6 V/\( \mu m \)); port E, (16, 16.6 V/\( \mu m \)) and superimposed as shown in Fig. 2(b). The device is 85 mm long and 10 mm wide. Based on the diameter of the output beam (~225 \( \mu m \)) for a fixed \( E_L \), the maximum number of resolvable spots, which determines the number of output ports, that can be accommodated in this design is 4 spots/mm. The maximum number of output ports in the proposed design can be further increased by using a cascaded beam deflector with an associated increase in the lateral de-
vice size. The concept used in this design could also be extended to realize a quasi-\( M \times N \)-switch shown in Fig. 2(c), where an \( M \times 1 \) and a \( 1 \times N \) scanner can be combined on a single ferroelectric chip to give rise to a quasi-\( M \times N \)-switch. Note that, in the \( M \times N \) configuration, only one input and one output port can be in operation at a time. The proposed design is comparable with the present-day technology, where the typical spacing between adjacent optical fibers in a fiber optic array is 150 \( \mu m \), which would be able to accommodate a maximum of 6 ports/mm.

In summary, we have presented two designs for \( M \times N \) optical switching using a combination of electro-optic prisms and lenses fabricated on a ferroelectric chip. The primary advantages of the \( M \times N \) switch are high scalability, i.e., large number of output ports, high-speed electro-optic operation, design space over a wide wavelength range of transparency of the ferroelectric (0.35–4.5 \( \mu m \)), small size, low cost, and ease of fabrication. These advantages make it an ideal candidate for high-speed optical switching applications over a wide wavelength range.

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