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Laser Beam Deflector Based on a Domain-Inverted Electro-Optic Polymeric Waveguide Prism Array

Lin Sun[a], Jeffery J. Maki[b], John M. Taboada[a], Dechang An[a],
Zhong Han[a], Xuejun Lu[a], Ray T. Chen[a], and Suning Tang[b]

[a]Microelectronics Research Center,
The University of Texas at Austin, Austin, TX 78758

[b]Radiant Research, Inc., 3006 Longhorn Blvd., Suite 105, Austin, TX 78758

ABSTRACT

We report the demonstration of a compact laser-beam deflector based on electro-optic prisms formed within a thin-film polymer waveguide. We fabricate planar waveguides using a polymer that can be readily poled and cured through the simultaneous application of a poling voltage and heat. The index of refraction of each prism in the cascade, but not of the surrounding polymer, is modulated by the electro-optic effect through the application of a drive voltage. A laser beam, to be deflected, is coupled into and out of the planar waveguide by cylindrical lenses. The application of a drive voltage creates a sequence of prisms in the planar waveguide, which change the path of propagation of beam through the planar waveguide with a variable angle of refraction depending upon the voltage. The deflection efficiency is observed to be nearly 100% and the laser beam maintains its Gaussian intensity profile after propagating through the device.

Keywords: planar waveguide, polymer, electro-optic effect, prism, domain inversion, laser beam, deflector, optical switch, optoelectronic interconnect

1. INTRODUCTION

The most promising technology for high-speed steering of a laser beam without any moving parts is beam deflection based on the electro-optic effect. Several device concepts for electro-optic (EO) deflectors have been reported in the literature.[1-5] Devices using bulk crystals are generally larger, heavier, and require higher driving voltages over a few kV. One can realize more efficient devices with lower operating voltages by using metallic electrodes on both sides of thin wafers of an electro-optic crystal.[1-3] This requires very expensive and difficult wafer processing techniques for reducing the thickness of standard wafers. Thin EO crystal wafers are not commercially available. Multichannel phased-array devices[2] have the advantage of a low operating voltage (32V), but suffer from the presence of multiple grating lobes. Devices with slanted electrodes[3] also allow lower operating voltages (150V) than bulk devices, but dielectric break down may occur when opposite voltages are applied to closely spaced electrodes on the same side of the wafer. Thin-film waveguide devices have also been demonstrated using angled electrodes formed on the waveguide surface.[5] However, they are also subject to dielectric breakdown between the closely spaced electrodes, and they exhibit wavefront distortion arising from the non-ideal variation of the electric field between the electrodes. A deflector has been demonstrated that uses leaky modes of a planar waveguide.[6] This device is unique among planar devices in that the deflection is in the direction perpendicular to the plane, but somewhat higher operating voltages (5kV) are required.

Although many beam steering devices have been reported in the literature,[1-6] their performance does not meet the demand imposed by many applications. Several problems must be solved prior to implementation of EO deflectors. First, the deflection angle has to be increased to cover a large dynamic range. The EO coefficient associated with a χ_2 nonlinear optical material is too small in may cases to provide a large scanning angle based on any existing device scheme. Second, it is necessary to reduce the driving voltage from the range of few kV down to 50 V or less. This will also reduce the possibility of dielectric breakdown between closely spaced electrodes. Third, it is necessary to extend the speed of deflectors to a few GHz in order to enable more applications. Fourth, innovative device schemes are needed to develop laser beam deflectors

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with simplified fabrication methods, where improved performance is also expected. The technical development demonstrated so far, in general, adds to device complexity, and/or imposes difficult fabrication processes.[1-6]

Non-mechanical beam steering devices are needed in a wide variety of commercial and military applications, including advanced laser radar (ladar), fiber-optic switching networks, photonic phase array antennas, optical sensors, and laser printers. In particular, thin-film electro-optic beam deflectors have the potential for creating a new class of integrated fiber-optic switches in addition to free-space laser beam steering.[7-10] The resulting fiber-optic switch can actively and selectively route a large number of fiber channels using only one electrode, which provides significant advantages over existing devices. These advantages include simplified operating scheme, low driving voltages, large number of routing channels, high switching speed, small size, low cost, and high reliability.

Current active fiber-optic routers are very complex, costly, and too large for practical applications. The number of techniques for achieving selective fiber-optic routing are limited. Counted among them are such methods as electrical-mechanical switches, micromachined fiber-optic mechanical switches, and cascaded electro-optic 2×2 waveguide directional couplers. These methods suffer from various problems including low-speed, high insertion loss, and complicated electrical driving schemes. The involvement of moving components and multiple electrical driving sources set severe limits on the possible applications. The current micromachined fiber-optic switches rely upon the movement of silicon or metallic structures that allow the end of one input fiber to be selectively butt coupled to two or more output fibers. This mechanical movement provides for switching times on the order of 10 ms. The device we are considering has no moving components, which will outperform these mechanical fiber-optic switches.

In this paper, we report a device concept for constructing a reconfigurable optical interconnect that is based on a guided-wave electro-optic beam deflector fabricated using thin-film polymer. We also present some experimental results on domain-inverted poling and beam deflection from our polymer-waveguide device.

2. DEVICE CONCEPT

We shown in Fig. 1 a schematic drawing of our waveguide electro-optic beam deflector. It is a multilayer structure. The first layer deposited on a silicon wafer substrate is a metal film. The second layer is a polymer that forms an optical waveguide cladding. The third layer is a different polymer, which forms an optical waveguide core and has the specific attribute of possessing the electro-optic effect, if poled. The fourth layer is composed of the same polymer material as the second layer of the device and forms another optical waveguide cladding. The fifth layer is a top electrode. We prepare the three layers of polymer by spin coating. The figure depicts patterned top electrodes that we use to induce a bulk second-order nonlinear optical response in the waveguide core polymer by electric-field poling. In the final device, these top poling electrodes should be replaced with a uniform electrode structure to drive the electro-optic response. The detailed nature of the poling process is complicated. The essential feature is that the prism-shaped poling electrodes cause the core polymer to possess the electro-optic effect in regions that follow the shape of these poling electrodes. A voltage applied across the preferred uniform top driving electrode (not depicted) and the electrode underneath the polymer layers produces an electric field within the core polymer. This applied electric field within the core polymer, if it has been previously poled, causes a change in the index of refraction of the prism-shaped regions. We use this effect to form a variable beam deflector.

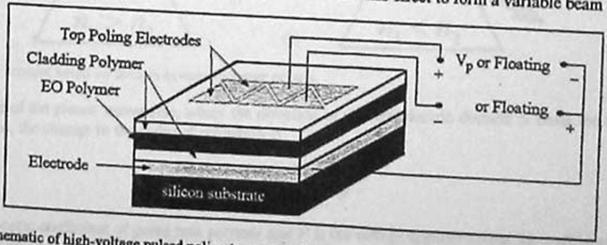

FIG. 1 Schematic of high-voltage pulsed poling to create an interleaving collection of domain-inverted prisms.

A light beam propagating within the planar waveguide formed by the polymer layers will have its direction of propagation modified as if propagating through a set of physical prisms. The index of refraction of the prisms, though, is adjustable. Thus, we can adjust the refraction that occurs at each prism interface by adjusting the applied voltage. This modification of the index of refraction causes the beam to emerge from the device in a different direction. By varying the applied voltage, we can vary arbitrarily the pointing direction of the laser beam. The deflection from the beams original path is 100% due to the use of refraction instead of diffraction.

We use pulsed electric fields to pole the device shown in Fig. 1. Only one of the two interleaved prism-array top electrodes has a voltage applied to it at a given time. In addition, we use opposite polarity to achieve the domain inversion of one sequence of prisms with respect to the other. When voltages are alternately applied to the dual top electrode structure shown in Fig. 1 to pole the polymer core, the electric field lines extend from the top electrode to the bottom electrode, which is uniform. Since the various polymer layers are very thin, the field lines do not extend out beyond the edge of the top electrode by any appreciable extent. The polymer is thus poled essentially in only the regions where the patterned top electrodes exist.

As described in relation to Fig. 1, a light beam propagating through the deflector refracts at the prism interfaces because of the difference in the indices of refraction, $n_1 - n_2$, between adjacent regions (see Fig. 2). In the presence of a uniform electric field E, the indices in the two domain inverted regions are

$$n_1 = n_e + \Delta n(E) \ , \tag{1a}$$

$$n_2 = n_e - \Delta n(E) \ , \tag{1b}$$

where n_e is the index of refraction in the absence of the applied electric field and $\Delta n(E)$ is the index change induced by the electric field E via the electro-optic effect. The amount of deflection depends upon $n_1 - n_2 = 2\Delta n(E)$. Variable laser beam deflection can therefore be obtained by varying the applied electric field.

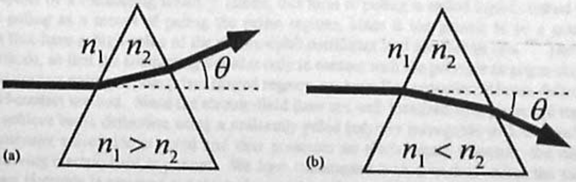

FIG. 2 Deflector concept based on domain-inverted polymer prisms.

For an optical TM mode of the planar waveguide, where the direction of the ferroelectric domain is along the electric field direction as in our device, the change in the index of refraction is

$$\Delta n(E) = \frac{1}{2} n_e^3 r_{33} E = \frac{1}{2} n_e^3 r_{33} \frac{V}{d} \ , \tag{2}$$

where r_{33} is the electro-optic coefficient of poled core polymer and V is the voltage applied across the multilayer polymer of overall thickness d. The device produces a deflection angle[12]

$$\theta = n_e^3 r_{33} \frac{V}{d} \frac{L}{h} \ , \tag{3}$$

where L and h are the length and width of the prism or possibly array of prisms, respectively. This model is based only on the total phase retardation possible across the wavefront. The deflection angle in this model depends only on the overall dimension of the prisms, since the accumulated phase difference across the wavefront is independent of how the deflector is subdivided into individual prisms, as long as the interfaces between adjacent prisms are straight lines. Such a simplified model may not be adequate if the incident angles of light at the interfaces are large, since there can be a significant amount of both refraction and reflection.

3. FABRICATION

We have fabricated planar waveguides using polymer. The waveguide core material is based on LD-3, which is a double-ended thermally-crosslinked polymer consisting of a poly-methyl-methacrylate (PMMA) backbone and an azobenzene-sulfone chromophore.[13] It can be readily poled and cured through the simultaneous application of a poling voltage and heat. The application of heat causes the small crosslinker molecules dianisidine diisocyanate, which are added to the LD-3 polymer, to form covalent bonds with the LD-3 polymer chain. The material, hence, becomes a fully crosslinked polymer matrix. When the poling electric field is removed and the device returns to a nominal temperature, the poling induced orientation of the NLO chromophores is essentially locked in place because of the complete crosslinking. The cladding material is Norland Optical Adhesive 61 (NOA-61), which is an UV-curable resin. The waveguides have been fabricated on silicon substrates by spin coating. The solvent used is cyclopentanone rather than tetrahydrofuran as was used in the initial demonstrations[14] of waveguides fabricated using LD-3. Shown in Fig. 3 is a photograph of the polished end face of one of our planar waveguides. The thickness of the core material is $4.0\,\mu m$ and the thickness of the two cladding layers are each $2.4\,\mu m$. The silicon substrate has a uniform coating of gold placed on it before the polymer layers are deposited. A second gold electrode is placed on top of the LD-3/NOA-61 polymer layers after poling. The edges of the device at each end of the prism cascade are polished to allow light to be coupled into and then out of the polymer planar waveguide by cylindrical lenses, so that a laser beam, to be deflected, can pass through without disruption of its Gaussian mode profile.

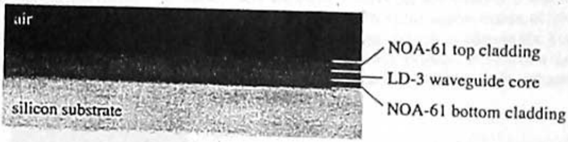

FIG. 3 Microscope photograph of the polished end face of a LD-3/NOA-61 planar waveguide. Not visible are the gold top and bottom electrodes.

We have developed a technique of poling polymer that uses a top electrode that is placed in electrical and physical contact with the polymer by a conducting liquid.[15] Hence, this form of poling is called liquid-contact poling. We are pursuing liquid-contact poling as a means of poling the prism regions, since it has proven to be a good method of poling polymer waveguides that have a high value of the electro-optic coefficient and are low in loss.[15] The idea is to pattern the liquid-contact electrode, so that the conducting liquid is only in contact with the polymer in prism-shaped regions. In pursuing the use of liquid-contact poling to pole prism shaped regions, we have first constructed beam deflectors that are poled uniformly by the liquid-contact method. Since the electric-field lines are well localized by a patterned top drive electrode, it should be possible to achieve beam deflection using a uniformly poled polymer waveguide with a patterned top electrode. Although the entire polymer waveguide is poled and thus possesses an electro-optic response, the electro-optic effect occurs only where the driving electric field is present. We have constructed such a device. After the sample is poled and cured, the liquid-contact electrode is removed and the surface of the polymer waveguide is cleaned. A patterned gold electrode is then produced on top of the polymer waveguide to form the device structure depicted in Fig. 4. Figure 5 is a photograph of one of these devices.

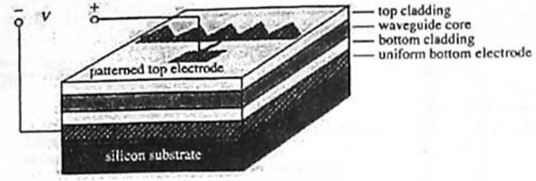

FIG. 4 Device structure demonstrating beam deflection.

The electrode structure shown in Fig. 5 is patterned by wet etching. The top electrode consists of five prism-shaped regions of thin-film gold. For electrical continuity, each prism is connected at its base to the next prism. The design includes a contact pad for easy application of the driving voltage. Each prism has a height $h = 1\,\text{mm}$. Thus, the cascade has a length $L = 5\,\text{mm}$. The device has a ratio $L/h = 5$. The performance can be improved by decreasing the height h to 0.5 mm and increasing the length L to 5 cm. The combined affect would be to raise the ratio to $L/h = 100$, which is a factor of 20× increase in L/h over the value for the current design. Of course, there are many choices for the value of L and h that increase the value of L/h . Clearly, though, the height h of the prisms, which is the width of the active-region of the device, should be as small as possible to increase the deflection sensitivity with voltage, but large enough to contain the laser beam profile. Note that the amount of beam deflection a single-domain prism-cascade device can produce is 50% of a cascade of interleaved domain-inverted prisms for a given value of the applied voltage, since only half the difference in refractive indices is possible.

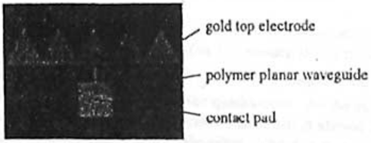

FIG. 5 Close-up photograph of a beam-deflector device, which shows the patterned gold electrode used to drive the EO response.

4. EXPERIMENTAL RESULTS

We have pursued the development of a laser beam deflector based upon an array of domain-inverted electro-optic prisms formed by pulsed poling within a polymer thin-film planar waveguide. We have made two primary achievements. One achievement is the demonstration of domain inversion in electro-optic polymer and the other achievement is the demonstration of beam deflection by an array of prism-shaped regions with controllable refractive index via the electro-optic effect.

4.1 Domain Inversion

We have investigated domain-inverted poling of LD-3 polymer, which is a technique necessary to make the interleaved cascade of prisms. We use liquid-contact poling. The bottom electrode is uniform over the area of the two regions to be poled. The top electrode is actually two rectangular regions of indium-tin-oxide (ITO) patterned on a glass plate with a gap of approximately 2 mm to isolate the two electrodes electrically. This top electrode structure is placed in contact with the polymer film using hexatriacontane, which melts at 75°C and becomes electrically conductive. The conductivity is larger than that of the polymer, but not so large as to cause a short across the gap. The top ITO-electrode structure is held at a spacing of approximately $10\,\mu\text{m}$ from the surface of the polymer by epoxy spacers. A static poling voltage of 275 V is applied across each region at a temperature of 165°C for 55 minutes, which poles and cures the polymer. We demonstrate that the two regions are poled in opposite directions (i.e., domain inverted) by measuring the electro-optic coefficient of each region using an extension of the reflection technique of Teng and Man.[16] The experimental setup is shown in Fig. 6(a). The sample is driven by a voltage with the same magnitude and polarity for each of the two regions. The applied voltage is

$V_m \sin(\omega_m t)$, which oscillates at the angular frequency ω_m, where the peak voltage is V_m. A HeNe laser beam at 632.8 nm impinges upon the sample with equal amounts of s and p polarization. The reflected light picks up a phase lag dependent upon the magnitude and sign of the electro-optic effect. After passing through the $\lambda/4$ waveplate and the linear polarizer, this phase lag turns into an intensity modulation whose magnitude depends upon the strength of the electro-optic effect.

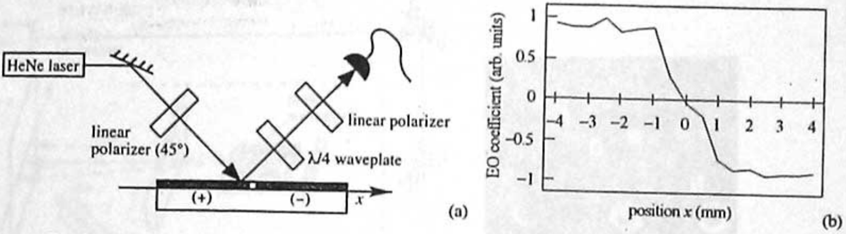

FIG. 6 (a) Schematic of the experimental setup using the reflection technique to measure the magnitude and relative sign of the EO coefficient. (b) Recorded signal showing the change in sign of the EO coefficient r_{33}.

The total intensity received by the photodetector is

$$I(x) = I_o + I_m(x) , \tag{5}$$

where I_o is the unmodulated portion of the total intensity. The essential contributions to the modulated intensity is

$$I_m(x) \propto r_{33}(x) V_m \sin(\omega_m t) . \tag{6}$$

Equation (6) makes explicit the dependence of the modulated intensity upon the spatial variation of the poling-induced electro-optic coefficient r_{33}. We use a lock-in amplifier to measure the portion of the optical signal oscillating at angular frequency ω_m. For the signal coming from reflection off of the "+" region, the phase of the lock-in amplifier is set to make the signal positive and maximum in value for one of the quadratures. As the sample is translated over to the "−" region, the magnitude and sign of this quadrature signal is recorded. The result is shown in Fig. 6(b). The signal changes sign as the probing laser beam crosses over from one region to the other. There is some variation of the magnitude of the response in the gap region. Figure 6(b) shows that the two regions have electro-optic coefficients r_{33} that are opposite in sign.

4.2 Free Space Beam Deflection

Shown in Fig. 7(a) is the experimental setup to demonstrate the polymeric beam deflector shown in Fig. 7(b). The planar waveguide sample is mounted on a sample stage with two cylindrical lenses. The laser is a grating-feedback diode laser from New Focus, which has been set to operate at 790 nm. The laser has a good Gaussian intensity profile. The collimated laser is coupled into the planar waveguide of the beam deflector using a somewhat short focal-length cylindrical lens ($f = 6.35\,\mathrm{mm}$). After propagating through the planar waveguide, the beam exits the waveguide and is recollimated by a longer focal-length cylindrical lens ($f = 25.4\,\mathrm{mm}$). As Fig. 7 depicts, an opaque white-board screen is placed 2 ft. (610 mm) away from the center of the prism cascade of the beam deflector. The transmitted laser beam is incident upon the screen. A video camera is placed to view the spot formed on the screen. The video camera output is recorded as still images by a frame grabber and stored as digital images.

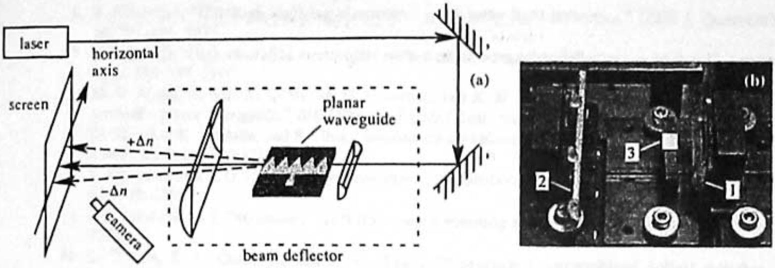

FIG. 7 (a) Schematic of the beam-deflector test bed and (b) photograph of the beam deflector. The screen for observing the beam deflection is placed 2 ft. (610 mm) from the center of the planar waveguide sample. Cylindrical lenses "1" (6.35 mm focal length) and "2" (25.4 mm focal length) couple the TM-polarized laser beam into and out of the planar waveguide "3," respectively. The electrical connections to apply the DC drive voltage are not shown.

We have observed beam deflection using our electro-optic-polymer prism-cascade device. The experimental setup given in Fig. 7 is used to record the beam deflection. The beam deflects in the negative horizontal direction for negative values of the induced index difference Δn and in the positive horizontal direction for positive values of the induced index difference Δn. The amount of deflection is symmetric with the applied voltage. Figure 8 shows pictures of the recorded laser-beam spots for $\Delta n = 2.5 \times 10^{-4}$. Note that the horizontal axis is calibrated by taking a picture of a ruler marked in millimeters, which is placed on the screen at the location of the incident laser beam. From this calibration, we calculate that the range of deflection is 0.14° for $\Delta n = 2.5 \times 10^{-4}$. In addition, Fig. 8 shows that essentially all the beam is deflected. There is no residual undeflected beam. Thus the deflection efficiency is ~100%. The fabricated device successfully demonstrated the feasibility of the proposed concept of forming a beam deflector in thin-film electro-optic polymer. The result also shows that a laser beam maintains its Gaussian intensity profile after propagating through the device.

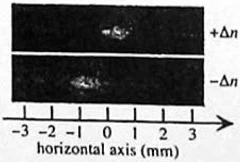

FIG. 8 Images of the transmitted laser beam incident upon the observation screen for positive and negative values of induced index difference.

5. CONCLUSIONS

We have demonstrated a compact laser-beam deflector based on electro-optic prisms formed within a thin-film polymer waveguide. The deflection efficiency is nearly 100% and the laser beam maintains its Gaussian intensity profile after propagating through the device. This laser-beam deflector can form an integral component in future optical interconnects. The demonstrated amount of deflection is sufficient to form a 1×2 interconnect. Future work will demonstrate a 1×N interconnect, where N is 10 or more.

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