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Submitted to: 1999 Proceedings of SPIE

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Fabrication and characterization of high-speed integrated electro-optic lens and scanner devices

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ABSTRACT

We demonstrate two high-speed electro-optic devices: an integrated lens/scanner and a variable radius collimating lens stack fabricated on a single crystal of Z-cut LiTaO₃. The lens and scanner components consist of lithographically defined domain-inverted regions extending through the thickness of the crystal. A lens power of 0.233 cm⁻¹kV⁻¹, a deflection angle of 12.68 mrad kV⁻¹, and a scan rate of 225 kHz at 375 V were observed. The collimating lens stack is theoretically capable of collimating the output from 2-10 micron diameter channel waveguides.

Keywords: ferroelectrics, beam propagation method, integrated devices

1. INTRODUCTION

Control of the position and spot size of a laser beam with high speed is useful for many applications including optical data storage, laser printing, and heads-up display technology. These functions have traditionally been performed using separate elements for focusing and scanning, thus requiring multi-step manufacturing processes and sometimes difficult alignment procedures. Integration of these components into a single manufacturing step promises to greatly reduce the cost of producing such devices while improving reliability as well. In addition, a recent report of an integrated quasi-phase-matched second-harmonic generator and electro-optic scanner for blue laser light¹ suggests that integration of such a device with an electro-optic lens to couple the second-harmonic waveguide output to the scanner may greatly enhance device performance.

Selective inversion to create shaped 180° ferroelectric domains by electric-field poling² is a common technique for fabricating nonlinear and electro-optic devices in LiTaO₃. For example, second harmonic generation gratings^{3,4}, electro-optic scanners^{1,5-7}, and electro-optic lenses^{8,9} have all been realized with this technique. In a previous paper¹⁰, we reported the successful integration of an independently-controlled electro-optic lens and scanner on a single crystal LiTaO₃ wafer. Here, we present further experimental results characterizing the high frequency response of the scanner portion of the device as well as a novel design for a variable radius electro-optic lens stack designed to collimate the output of narrow channel waveguides. We briefly discuss design and fabrication of these devices by photolithography and room-temperature electric-field poling in Section 2, followed by a discussion of device performance including focusing and deflection characteristics in Section 3. Our conclusions are given in Section 4.

2. DESIGN

A schematic of the integrated lens/scanner device is shown in Figure 1a. The lens component consists of a series of $N_l = 10$ cylindrical plano-convex 180° domain-inverted lenses. The scanner is separated from the lens component by a 1 mm spacing and consists of a series of $N_s = 7$ domain-inverted triangles or prisms. With an electric field, $|E| = V/t$, present across either the lens or scanner component, the electro-optic effect induces a change in refractive index by an amount $\Delta n = \frac{1}{2} \epsilon_r r_{33} V/t$, where n_e is the linear refractive index of the medium, r_{33} is the electro-optic coefficient in the vertical (polarization) direction, V is the applied voltage, and t is the thickness of the wafer. If the electric field, E , is parallel (antiparallel) to the spontaneous polarization direction, P_s , of the ferroelectric domains, the index $n_e \Rightarrow n_e - (+) \Delta n$. For the lens to focus, E should be antiparallel to P_s inside the lens shaped domains. The scanner will function with E of either polarity, with one polarity deflecting the beam to the right, for example, while the other polarity deflects the beam to the left. Thus, the beam may be focused by the lens or deflected by the scanner by an amount proportional to the applied field. A one-dimensional fast Fourier transform beam propagation^{11,12} simulation for this device is shown in Figure 1b. An electric field through both the lens and scanner of 8 kV/mm, and domain dimensions measured from images of the actual device (see Figure 2) were used.

Figure 1. (a) Diagram of the ferroelectric domains of the lens/scanner. The side view (top) shows the path of the laser through the device and the position of electrodes. The view from above (middle) shows the domain boundaries defining the lens stack and scanner which extend through the crystal. Six devices were fabricated on a single 17 mm x 10 mm x 225 μm crystal. (b) Simulated propagation of a 632.8 nm He-Ne laser beam through the lens/scanner.

The 600 μm diameter incident beam is focused about 17 mm from the output of the device to a spot size of 60 μm and deflected by an angle of about 25 mrad (Figure 1b).

The device was fabricated in a $225 \pm 5 \mu\text{m}$ thick, Z-cut single crystal of LiTaO_3 wafer. Domain microengineering to form the lens and scanner was performed by a combination of chemical patterning of the surface followed by electric field poling, as described in detail in Refs. [2,10]. Figure 2 shows the domain walls defining (a) the lenses and (b) the prisms as seen using polarized light microscopy¹³. The dimensions of the domains measured from these images are reduced to $R = 540 \mu\text{m}$, $W_l = 1080 \mu\text{m}$, and $d_l = 84 \mu\text{m}$ for the lens component, and $L_s = 940 \mu\text{m}$, $W_s = 720 \mu\text{m}$, and a separation distance of $d_s = 40 \mu\text{m}$ between the prisms.

The surfaces of the poled crystal are coated with an electrode layer over each component (see Figure 1a). An uncoated border of 1 mm thickness is maintained around each electrode to inhibit discharge between neighboring electrodes. Contact with the electrodes is established with copper tape and the device is then mounted between two insulating rubber layers to further inhibit discharge or corona formation during operation. Voltages of up to 2 kV across the lens and up to ± 1.2 kV across the

Figure 2. Images of ferroelectric domains of part of the lens (a) and scanner (b) made using polarized light microscopy.

Figure 3. Polarized light microscopy images of domain structure of two portions of the variable radius collimating lens. The total length of the 43 lens stack is 6.5 cm. The crystal thickness is $210 \pm 5 \mu\text{m}$. Images are in negative for clarity.

scanner, corresponding to the limits of our power supplies, were applied independently without inducing breakdown.

Another device fabricated using these techniques is the variable radius collimating lens stack depicted in Figure 3. The stack consists of a series of plano-convex lenses of increasing radius. This lens is designed to collimate light diverging from small apertures (i.e., a channel waveguide). The smaller the radius of curvature of a lens, the greater its focusing power per unit length. The lenses are thus designed such that the radius increases proportionate to the beam waist as the beam propagates through the lens stack. In this way the total length of the device is minimized. A smaller device length has the advantage of decreasing the surface area of the electrodes, thus decreasing the capacitance of the device and in turn increasing the maximum scanning frequency. The various radii and number of lenses used are given in Table 1.

An FFT beam propagation shown in Figure 4 demonstrates the collimation of a 632 nm He-Ne beam focused to a spot size of $4 \mu\text{m}$ at a distance of 0.5 mm in front of the first lens in the stack. The crystal width is assumed to be $210 \mu\text{m}$, and the applied voltage is 2240 V. The approximate diameter of the collimated beam at the output is $160 \mu\text{m}$. Further simulations show that beams with an initial spot size between 1 and 10 microns will be collimated at approximately the same voltage level with this device. Such a lens may be useful, for instance, when integrated with a periodically-poled second-harmonic generation (SHG) device. Narrow channel waveguides are often patterned in the periodically-poled region to increase SHG efficiency. The variable radius lens may be integrated directly after the waveguide to collimate or focus the device output.

Number of Lenses	Radius (μm)
6	75
4	95
6	115
6	150
12	180
9	195

Table 1. Number and radius of curvature of collimating lenses.

Figure 4. Fast Fourier-transform beam propagation simulation of a 632.8 nm He-Ne beam collimated by a variable radius lens stack. The initial spot size is 4 μm , the diameter of the collimated output is about 160 microns, and $E = 10.7 \text{ kV/mm}$.

3. TESTING

In our previous work¹⁰, we tested the integrated scanner and lens components to determine the scan angle and lens power as a function of applied voltage using the apparatus depicted in Figure 5. For completeness, we include these results here along with new measurements performed using this apparatus. Collimated, vertically-polarized light from a 632.8 nm HeNe laser is focused in the vertical (y) direction with a cylindrical lens such that the beam passes cleanly through the crystal without scattering from the top or bottom surfaces. A beam-profiling CCD camera (Coherent LaserCam) placed at the output of the device is used to record the intensity profile of the beam. Applying a voltage across the lens component of the device focuses the beam in the horizontal (x) direction. For example, the intensity profile observed at a distance of $D = 132 \text{ mm}$ from the output face of the device for three different values of the applied voltage $V_l = 0, 100$, and 260 V (left to right) is shown in Figure 6. The width of the beam along the x -axis (defined here as the horizontal distance at which the intensity drops to $1/e^2$

Figure 5. Diagram of device testing apparatus. A vertically polarized beam from the HeNe laser is first collimated with a circular lens (not shown) and then focused in the vertical direction by a cylindrical lens ($f = 100 \text{ mm}$) through the electro-optic device. The electric fields are applied independently to the lens and scanner components to focus and deflect the beam observed with a CCD camera placed some distance from the output.

of the peak value) decreases from $w_x = 549 \mu\text{m}$ at $V_l = 0$, to $w_x = 226 \mu\text{m}$ at $V_l = 260 \text{ V}$, a ratio of 2.42:1. This decrease in spot size more than doubles the number of resolvable spots in this plane. In order to quantify the focusing properties of the electro-optic lens component, we placed the CCD array at a range of distances from 10 to 30 cm from the output of the device. For each distance, we recorded the voltage, V_l , at which the horizontal (x) width of the intensity profile was minimized. Treating the device as a thin lens, and assuming the beam is collimated in the x -direction at the entrance to the device, the effective focal length, f , of the electro-optic lens stack at the recorded voltage is given by the distance to the CCD array. The lens power, $\phi = 1/f$, was found to increase linearly with the applied voltage with a dependence of $0.233 \pm 0.016 \text{ cm}^{-1}\text{kV}^{-1}$. A theoretical estimate of the power dependence may be derived by modelling the array as a series of thin lenses⁸, each contributing a power of $\phi = 2\Delta n/R$. The power dependence of the electro-optic lens stack is then $\phi N_l = 0.230 \text{ cm}^{-1}\text{kV}^{-1}$,

Figure 6. (a) CCD images of the beam profile at a distance of 132 mm from the output face of the device for three different values of the lens voltage, $V_l = 0, 100, \text{ and } 260 \text{ V}$. The corresponding $1/e^2$ diameter of the beam along the x -axis, through the centroid of the intensity distribution, is shown below the images. (b) Multiple-exposure image of the beam profile at $D = 143 \text{ mm}$ over a range of scanning voltages from $V_s = -750$ to 750 V . A lens voltage of $V_l = 300 \text{ V}$ is applied to maximize the number of resolvable spots in this plane. A line plot below the image shows the intensity profile along the horizontal dotted line in the image.

in agreement with the measured dependence.

To determine the deflection angle of the scanner, we measured the change in the position of the centroid of the intensity distribution in the horizontal plane of the camera located a distance, $D = 194 \text{ mm}$, from the device. For a centroid displacement of Δx , the deflection angle is given by $\theta = \tan^{-1}(\Delta x/D)$. The measured voltage dependence of the deflection angle is $12.68 \pm 0.22 \text{ mrad/kV}$. A theoretical estimate for the deflection angle is given by $\theta = 2\Delta n L/W = 12.65 \text{ mrad/kV}$, where $L = N_s L_s$ is the total length of the scanner prisms¹⁴, in good agreement with the experimental results.

The scanner component may be operated separately or in concert with the lens. To illustrate the latter regime, a multiple exposure image of the beam profile measured at a distance of 143 mm from the output of the device is shown in Fig. 10. The voltage for each exposure was varied incrementally from -750 V to $+750 \text{ V}$ such that each profile was separated by approximately one spot diameter from the next with a maximum angular deflection of about 9.6 mrad . In addition, the lens voltage was set at $V_l \approx 300 \text{ V}$ to minimize the spot diameter at this distance. With $V_l = 0$, the spot diameter at this distance is nearly 2.5 times larger than the minimum and thus, fewer spots may be resolved. The spreading of the profiles in the vertical direction is a consequence of focusing by the cylindrical lens prior to entering the device and may easily be compensated by placing a second cylindrical lens after the device to recollimate the beam in the vertical direction. We have not done so here since our primary concern is with horizontal focusing and deflection of the beam.

The ability to operate the scanner at high frequency was tested using a high-voltage differential amplifier driven by an arbitrary function generator. The frequency response of the amplifier was limited to 100 kHz at the full voltage range ($\pm 1200 \text{ V}$). By overdriving the input voltage, we succeeded in driving the device at 225 kHz and 375 V . An analysis of the deflection pattern showed no reduction in device performance under these conditions. Unpublished results from tests of similar devices in our laboratory indicate that scan frequencies greater than 10 MHz at a few tens of volts may be achieved, but an upper limit of device response has not yet been established.

We have also performed preliminary tests on the variable radius collimating lens stack. For these tests, the incident beam was focused onto the input face of the crystal, approximately 0.5 mm from the surface of the first lens. For a 20 micron initial spot size, the collimating voltage was found to be approximately 1800 V , near the limit of our 2 kV DC voltage power supply. We anticipate the ability to collimate beams with smaller waists using a higher voltage source.

4. CONCLUSIONS

We have successfully demonstrated a stand-alone integrated electro-optic lens and scanner fabricated in a single crystal LiTaO_3 wafer. Independent control of the lens and scanner components permits optimization of the device to achieve a

maximum number of resolvable spots at an arbitrary distance from the device, an important characteristic for printing and optical read/write applications. We report a measured deflection angle of $12.68 \text{ mradkV}^{-1}$ and a lens power of $0.233 \text{ cm}^{-1}\text{kV}^{-1}$ for a device patterned in a $225 \mu\text{m}$ thick crystal. A scan frequency of 225 kHz at $\pm 375 \text{ V}$ was demonstrated and frequencies greater than 10 MHz are theoretically achievable. These values are typical of those reported previously for individual lens and scanner devices in LiTaO_3 . More importantly, we have demonstrated that both functions may be integrated in a single crystal wafer and that the lens and scanner may be independently controlled.

We have also demonstrated a variable radius collimating lens. Initial tests demonstrate that a beam focused to a spot size of 20 microns at a distance of 500 microns from the device is collimated with a voltage of approximately 1800 V . Theoretical simulations indicate that beams focused to spot sizes as small as 1 micron may be collimated at slightly higher voltages.

We thank Dr. Yi Chiu for providing us the FFT-BPM simulation code.

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