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Two dimensional dynamic focusing of laser light by ferroelectric domain based electro-optic lenses

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The authors demonstrate the proof of concept of two dimensional focusing of laser light. This has been achieved by using a combination of two cylindrical electro-optic ferroelectric domain lens stacks in an orthogonal geometry. The devices were fabricated on z-cut lithium tantalate ($LiTaO_3$) wafers and tested with helium-neon laser at 633 nm. Continuously tunable optical power ranging from $-129\ \mathrm{m}^{-1}$ to $129\ \mathrm{m}^{-1}$ is obtained in both directions by varying the applied voltage. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2739368]

The current trend in optical data storage technology is towards improving data storage density and increasing data read/write rate. The ability to dynamically focus the laser beam has led to multilayered storage systems resulting in higher storage density. Dynamic focusing in current technology has been accomplished by means of liquid crystals and electromechanical devices.[1,2] Such devices have a modest frequency response on the order of kilohertz. Therefore, aimed at improving the bandwidth, micro-optical devices based on ferroelectric materials such as integrated high power electro-optic lenses and cascaded large-angle scanners[3–8] have been demonstrated earlier. The intrinsic electro-optic response of these ferroelectric materials enable high speed (gigahertz) operation, limited in practice by only the voltage requirements and the power supply. However, the dynamic performance of these devices is limited to one dimension. The effectiveness of these devices in increasing data storage density could be improved further if their dynamic performance can be extended to two dimensions (2D). In this letter, we successfully demonstrate the proof of concept of dynamic focusing of a laser beam along two dimensions with electro-optic lenses fabricated in ferroelectric lithium tantalate.

Lithium tantalate ($LiTaO_3$) is a uniaxial ferroelectric with $3m$ point group symmetry. It has two possible domain orientations with the spontaneous polarization (P_s) pointing along $\pm Z$ axes. The direction of P_s in these domains can be switched by application of an external coercive field. Additionally, the application of an external field along the c axis ($\mathbf{E}_3$) can be used to create an electric-field tunable refractive index (Δn) across the domain wall, given by $\Delta n = n_e^3 r_{33}|\mathbf{E}_3|$, where n_e is the extraordinary index and r_{33} is the corresponding electro-optic coefficient. Thus, by creating lens shaped ferroelectric domains, the variation in refractive index across the domain wall can be utilized to create an electro-optic lens with tunable optical power. In addition, power scaling can be achieved if a stack of several such lenses is fabricated in the device.

The optical power of a stack of cylindrical lenses is defined by

$$D = \frac{n_e^3 r_{33} V N}{tR}, \tag{1}$$

where N is the number of individual lenses, R is the radius of curvature of the cylindrical surface, V is the applied voltage, and t is the thickness of the crystal. Therefore, according to expression (1), the device can act either like a converging or diverging lens depending on the direction of the applied electric field. Figure 1(a) shows the simulation of the focusing performance of an electro-optic lens stack obtained by means of the beam propagation method.[9] The lens stack is made up of ten cylindrical domains with a radius of curvature of 407 μm. The spacing between each cylindrical lens is 10 μm. Other parameters used in the simulation were $V=5$ kV, $N=10$, $t=300\ \mu$m, $n_e=2.1806$, and $r_{33}=30.5$ pm/V.[10] As observed, the beam diameter along the X axis can be modulated by placing a device along the X-Z plane. Similarly, if the device is placed along the Y-Z plane, the beam diameter along the Y axis can be modulated. As a result, if two devices are positioned in mutually orthogonal directions along the X-Z and Y-Z planes, we can dynamically focus the incident laser beam along both X and Y axes simultaneously.

In order to demonstrate this concept, lens structures similar to Fig. 1(a) were fabricated on commercially available z-cut $LiTaO_3$ wafers with a thickness of 300 μm. To start with, the crystal was diced into rectangles of $11 \times 7\ \mathrm{mm}^2$. A tantalum electrode pattern similar to Fig. 1(a) was lithographically defined. The lens shaped domains were created by using the well established domain reversal techniques.[11] An image of the domain pattern obtained using polarized light microscopy is shown in Fig. 1(b). The devices were annealed to undo the effect of the internal field across the domain wall. Tantalum electrodes were deposited on $+z$ and $-z$ surfaces of the crystal to provide a pair of parallel

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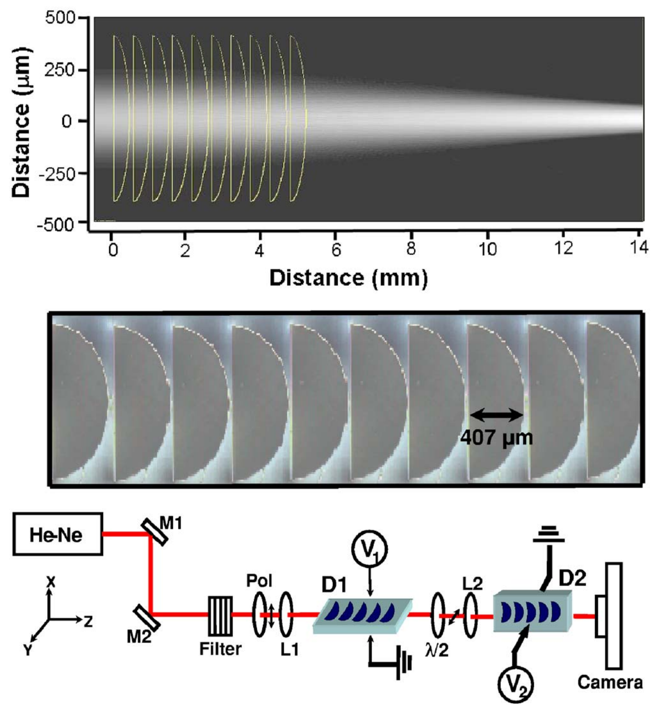

FIG. 1. (Color online) (a) Simulation showing the performance of an electro-optic lens stack obtained using the beam propagation method. (b) Images of lens shaped ferroelectric domains in $LiTaO_3$ obtained with polarized light microscopy. The spacing between individual lenslets is 10 μm. (c) Schematic representation of the device testing experimental setup.

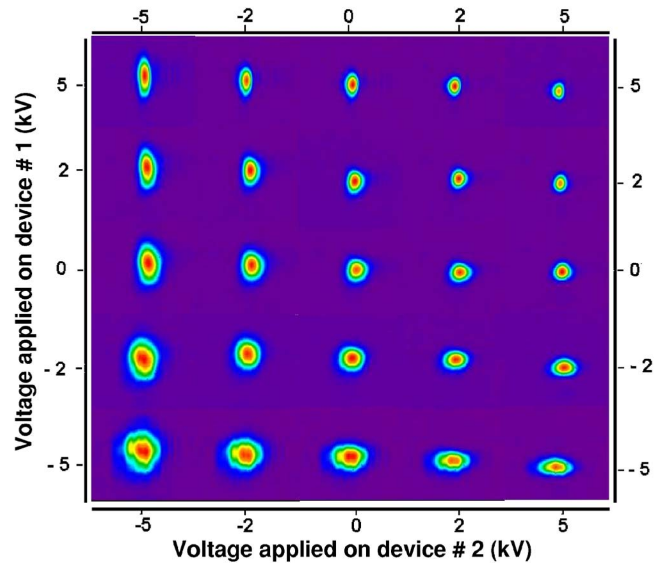

FIG. 2. (Color online) Images of the far field spatial distribution of the output Gaussian beam at different applied voltages with both devices working simultaneously.

plates in order to obtain uniform electric field across the thickness of the crystal. The input and output edges were polished to optical grade (rms value of 0.02 μm) to avoid losses due to reflection. An insulating layer of photoresist was spin coated on the $+z$ and $-z$ surfaces and baked to inhibit surface charge conduction. The contact to the electrodes was established with copper tape and the device was packaged using insulating silicone glue and rubber. Two such packaged devices were mounted on homemade device holders primarily designed to reduce the overall size of the assembly. The packaged devices were mounted on three dimensional translation and rotational stages to ensure the following: (a) input beam is parallel to and passing through the center of the cylindrical lens stack, (b) laser beam is not clipping the top and bottom surfaces of the crystal, and (c) the polarization of the incident laser beam is parallel to the spontaneous polarization in the crystal.

A helium-neon laser at 633 nm was used for testing the devices as shown in Fig. 1(c). Two high voltage power supplies V1 and V2 were employed to apply a uniform and stable electric field across the first (D1) and second (D2) devices, respectively. While applying the external field, precautionary measures were taken to not exceed the coercive field of $LiTaO_3$ (21 kV/mm) which could destroy the domain pattern in the crystals. In addition, a polarizer (P) and a half wave plate (W) were used to ensure that the polarization of the input beam was along the extraordinary axis of the crystal in both devices. The laser beam was confined within the thickness of the crystal in both the first and second devices. This was achieved by using spherical lenses with focal lengths of 100 and 50 mm before devices 1 and 2, respectively. The focal length and position of both the lenses chosen were based on *ABCD* matrix theory for Gaussian beam propagation. The intensity profiles of the output beam were recorded by placing a CCD camera (COHU 4812) beyond the exit face of D2.

In order to highlight the combined performance of both devices, a representative sample of the far field spatial distribution of the incident beam as a function of the applied voltage on D1 and D2 is shown in Fig. 2. As clearly observed, both horizontal and vertical diameters of the input beam can be modulated by varying the applied voltage on D1 and D2, respectively. The output beam diameter (ω_x, ω_y) is found to vary between (973 μm, 1039 μm) and (312 μm, 432 μm) from -5 to $+5$ kV at an image plane 93 mm away from the exit face of D2. As expected, output beam diameters increase when the devices act as diverging lenses and decrease when they act as converging lenses. Furthermore, the output beam is found to maintain a Gaussian profile.

In order to characterize the focusing properties of the device, the variation of intensity profile as a function of applied voltage was recorded at different image planes. From these profiles, the Gaussian beam waist (ω) was extracted and plotted as a function of propagation distance (z) at a fixed voltage, as shown in Figs. 3(a) and 3(b). The focusing and defocusing effects of both devices can be clearly observed at positive and negative voltages, respectively. In addition, theoretical analysis of this optical system based on the *ABCD* matrix theory for Gaussian beam propagation was performed.[10,12] Each lens stack was approximated to behave like a thin lens due to the small Δn values. These theoretical predictions agree with the experimental values, as shown in Figs. 3(a) and 3(b). Thus, tunable optical power ranging continuously from 129 to -129 m^{-1} can be obtained in two dimensions. The frequency response of the device was recorded at 20 kHz with applied voltage sinusoidally varying between $+1$ and -1 kV, as shown in Fig. 4. A photodiode was employed to monitor the intensity of the laser beam at the output. The intensity variation of the laser beam results from the focusing and defocusing effects of the electro-optic lens with varying applied voltage. Nevertheless, the maximum modulation speed achievable is in the order of gigahertz and is chiefly limited by the time constant of the power supply in use.

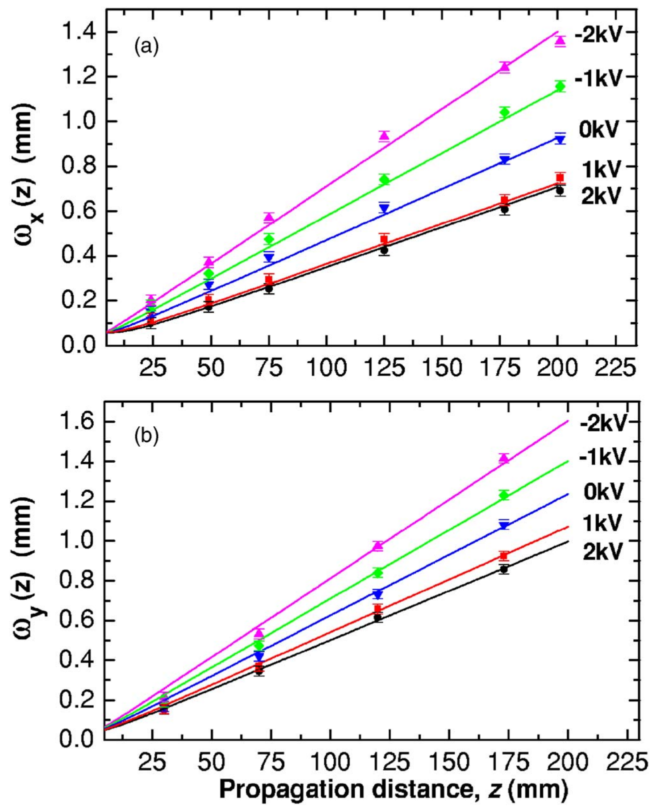

FIG. 3. (Color online) Beam radius as a function of the propagation distance obtained at different values of the applied voltage: (a) for device 1 and (b) for device 2. Solid lines correspond to the values predicted by *ABCD* analysis for Gaussian beam propagation.

In summary, we have demonstrated the concept of 2D dynamic focusing accomplished by adopting an orthogonal arrangement of two electro-optic lenses fabricated on $LiTaO_3$ based on domain microengineering. The primary advantage of this device is the high frequency response and the possibility of extending this concept to perform 2D scanning. For commercial applications, the high values of the applied field could be reduced by decreasing the thickness of the crystal, decreasing the aperture of the cylindrical domain lenses, or by using materials with high electro-optic coefficients.

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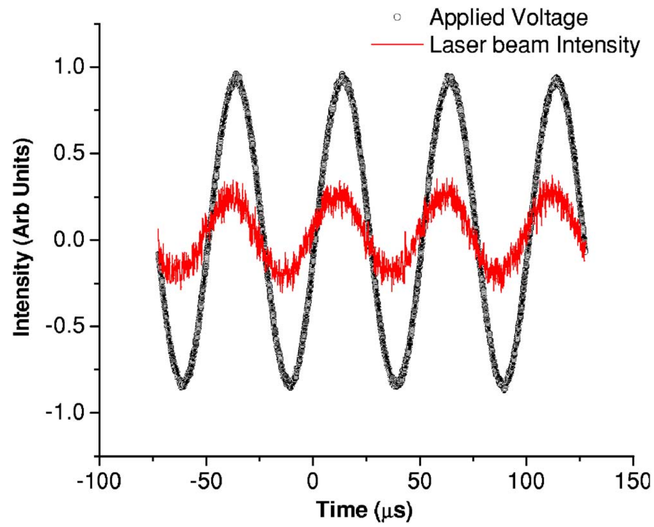

FIG. 4. (Color online) Performance of the device operated with a sinusoidally varying applied voltage between +1 and −1 kV at 20 kHz.

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