The ability to control the angular position and the spot size of a laser beam with high speed is of interest in many applications, including optical communications, optical data storage, laser printing, analog to digital conversion and display technologies. Of the many competing technologies, solid-state electrooptic devices based on ferroelectrics—such as lithium niobate (LiNbO\(_3\)) and lithium tantalate (LiTaO\(_3\))—have several advantages over mechanical and other systems. The advantages include the absence of moving parts, small device sizes and high operating speeds (in the gigahertz range). In addition, devices based in these materials can provide a versatile solid-state platform for microphotonics, where optical scanning, shaping, focusing and frequency conversion can be seamlessly integrated on the same chip.

The electrooptic effect is the change of the index of refraction of a material with an applied electric field. The electrooptic effect, also called the electric-field tunable refractive index, is currently of great interest for light modulation at speeds of tens of gigahertz. The index of refraction of a material determines the speed of polarized light traveling through that material. The index of refraction changes when an electric field is applied to the material.

Two important materials that possess the electrooptic effect and have excellent optical properties are LiNbO\(_3\) and LiTaO\(_3\). They are ferroelectric materials, which is a class of materials that possesses spontaneous polarization of the lattice that can be realigned with the application of an external electric field.
Regions of uniform polarization within a material are called domains. The boundaries between two domains are called domain walls. LiTaO$_3$ and LiNbO$_3$ have two allowed domain orientations. One points in the positive direction along the $z$ crystallographic axis (up domain). The other points 180° to this direction, i.e., along the $-z$ crystallographic axis (down domain).

The sign of the electrooptic coefficient depends on the orientation of these domains. Therefore, light shining through the crystal under a uniform electric field sees a decrease in the index of refraction in one domain orientation and an increase in the other domain orientation. There is a double-value index change at the domain wall. Active deflection and shaping of laser beams can be achieved by patterning the domain in these materials into particular shapes.

**Scanner Design**

The tunable index change present at domain walls can be exploited to deflect light and create optical scanners by patterning the domains into a series of prisms. Initial scanner designs were first proposed by Lotspeich in 1968. They consisted of identical prisms placed in sequence. When the deflected light beam exited the electrooptic material into air, the output deflection was enhanced further by Snell’s law.

A beam propagation method (BPM) simulation of such a scanner has been demonstrated (Fig. 1(a)). The beam must be contained in the stack for maximum deflection. Therefore, this sets the limitation for increasing the angle by decreasing the width and increasing the length simultaneously.

An improvement of this design allows the width of the scanner to stay as small as permitted by beam diameter at the input but gradually increased to just accommodate the trajectory of the beam. This is the so-called horn-shaped scanner, because the width of the scanner flairs toward the end of the device to accommodate the additional beam deflection. A LiTaO$_3$ scanner has been demonstrated (Fig. 1(b)).

A design concept called the cascaded horn-shaped scanner has been proposed. It consists of a series of individual scanners aligned so that subsequent scanners in the stack are aligned to the previous scanner’s peak deflection. A two-stage cascaded scanner has been demonstrated (Fig. 1(c)). At peak operating field, the first scanner first deflects the beam through a given angle and deflects it along a given direction. The second scanner is oriented along this direction, so that when a field is applied to it further deflection occurs.

All scanners are fabricated in the same piece of electrooptic crystal. Each scanner in the stack has a separate electric field supply, in effect cascading the scanners. The advantage of this design is that additional stages can be appended until a final target deflection is achieved or the field requirements can be decreased for a given required scan angle (by increasing the number of stages). The trade-off is in more complex drive controllers, because each scanner must work in tandem with the others.

A comparison of these scanner designs has been made, where the input aperture, applied field and number of interfaces are the same for the rectangular, horn-shaped, and cascaded horn-shaped scanners. Deflected beam paths as a function of distance passing through each scanner have been determined. It is evident that the horn-shaped scanner offers much improved performance. The cascaded horn-shaped scanner demonstrates even better performance.

**Lens Design**

Similar to the scanners in a domain reversed ferroelectric material, patterning domains in the shape of lenses can create lens stacks to focus and diverge beams passing through...
the crystal. The domain can be patterned into a stack of simple thin lenses.

A BPM simulation of a tunable focusing lens stack has been developed (Fig. 2). It is designed to focus a highly diverging beam input, for example, the output of a fiber-optic cable, and to focus the beam to a collimated output. Many lenses are needed because the index contrast is small.

**Fabrication**

The key to fabrication of devices is the creation and shaping of domain areas in a single crystal, called domain micropatterning. In this process, commercially obtained crystals 0.3 mm thick are diced pieces ~20 × 20 mm. A lithographic process is used to create a tantalum-metal pattern on the surface of the crystal. The pattern resembles the desired device, i.e., a horn-shaped scanner, with the metal defining the complement of the area of the prisms (or lenses) to be created.

A uniform water electrode is placed in contact with the bottom crystal surface. A large external electric field greater than the coercive field of the material (21 kV/mm or ~6000 V across the 0.3 mm crystal) is applied to the patterned tantalum film. This reverses the domain orientation in areas between the top metal electrode and the bottom water electrode.

Precise control of the domain movement is achieved by monitoring the external currents flowing in the circuit. Also, the domain nucleation and growth is directly observed in-situ using monitoring electrooptic imaging microscopy (EOIM). This process takes advantage of the index difference across a domain wall on application of an electric field. This is the same concept used for operation of the electrooptic scanner.

The index difference at the wall causes scattering of transmitted or reflected light in the crystal. This can be used to image domain walls through the crystal thickness in a z-cut crystal in an optical microscope, with or without polarizers. In this way, the movement of the 180° domains can be directly observed during the domain patterning process.

Frames were selected from the in-situ observation of such a poling process during device fabrication (Fig. 3). The spacing between successive frames is 3 s. A white triangular-shaped area in each frame is the vertex of one of the prism triangles that does not have a tantalum film. The rest of each frame is the tantalum electrode. Nucleation occurs at the electrode edges and advances into the tantalum electrode.

**Testing**

The input and output faces are polished after domain patterning to an optical grade using diamond suspensions. Uniform metal electrodes are then sputtered on each side of the device and connected to copper tape that forms the leads of the device. The entire device with the exception of the input and output faces is then encapsulated in silicon gel to inhibit breakdown during device operation.

The device is then placed in the path of a helium–neon laser with a wavelength of 632.8 nm. The beam is focused using a lens to cleanly pass through the device and shine onto a CCD camera. A different bias applied to the device deflects the beam in the plane of the device for a scanner, or changes the focal length of the beam for a lens.

Precise angular displacement information can be obtained by measuring the deflection or spot size of the beam with the CCD camera. The positions of the device relative to the focal point of the beam and the CCD camera position relative to the output face of the crystal are varied to test the lenses. An analytical expression can be fit to the data by measuring the beam waists for a variety of positions.

**Device Performance**

Several device designs have been fabricated and tested. One device is an integrated lens and scanner device (Fig. 4(a)). The lens stack consists of 32 biconvex lenses. It is designed to focus a highly divergent beam, such as the output from a fiber-optic cable shining on the input face, and make it a collimated beam that then passes into the scanner portion. Performance details have been determined (Figs. 4(b) and (c)).

Various beam sizes can be obtained for a fixed position along the x-axis and for various applied voltages. The displacement is linear with applied voltage and in excellent agreement with simulations. For polarized input light, the measured voltage dependence of the deflection angle is 31.45 mrad/kV (1.802°/kV) and the maxi-
The deflection angle is measured as a function of applied voltage. For extraordinary polarized input light (along the ferroelectric polarization direction), the measured voltage dependence of the deflection angle is $102.0 \text{ mrad/kV}$ for scanner 1 and $99.5 \text{ mrad/kV}$ for scanner 2. The maximum deflection angle for the device is $±12.7°$ (a total of $25.4°$) with $±1.1 \text{ kV}$ on both scanner stages. A theoretical estimate as determined by the BPM simulation has been plotted.

The simulation predicts that the voltage dependence of the deflection angle is $104.7 \text{ mrad/kV}$ for scanner 1 and $102.2 \text{ mrad/kV}$ for scanner 2 with a maximum total deflection of $±13.04°$ (total $26.8°$) for peak fields on both scanners. The maximum number of resolvable spots for this device is estimated as 29.75 spots at maximum total deflection. Finally, the scanner operation also has been tested up to 5 kHz. No noticeable degradation of the scan angle was observed, and higher scan speeds should be possible with higher-power drivers.

**Future Developments**

The further development of these devices can be used in next-generation optical devices and systems, including space-based communication systems, where noninertial beam deflection is required. Integrating these devices with other structures currently fabricated in ferroelectrics, such as second-harmonic generation structures, allows integration of several important optical functions. Examples include beam deflection, beam shaping and frequency doubling, all seamlessly integrated on the same optical chip.

**Editor’s Note**

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