True Analog Non-Mechanical Beam Steering Using Liquid Crystal Waveguide Techniques

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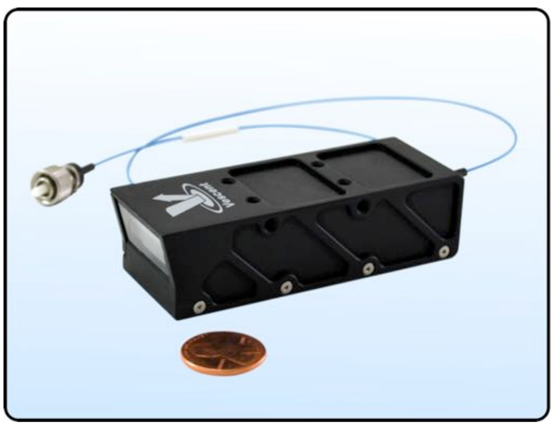
The world has long sought an electro-optic (EO) alternative to mechanically moving lenses and/or mirrors. Unfortunately, despite significant past efforts, for many optical-beam-control needs, opto-mechanics remains the only practical solution. This restriction can impose significant limitations on many important performance criteria including: cost, size, weight, vibration immunity, power consumption, speed, and device lifetime. To help alleviate this we have developed a new EO architecture that provides simple and cost effective electro-optic control over a beams direction, focus, and/or delay. For example, Figure 1 shows an EO laser scanner with a $30^{o}\times 5^{o}$ field of view. The output angle may be voltage set to any value within this field of regard with only three control electrodes. These scanners, and others enabled by our new EO architecture, have very low power consumption, are small, fast, rugged, and simple to use.



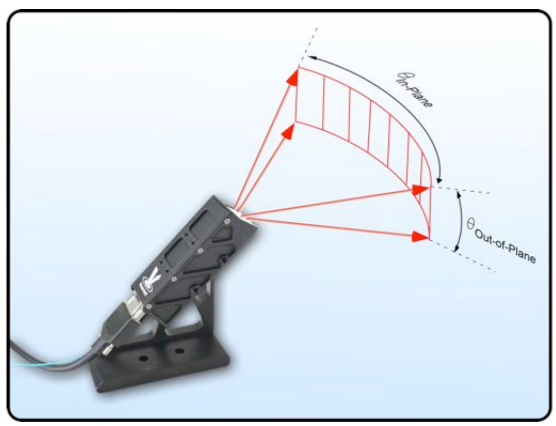
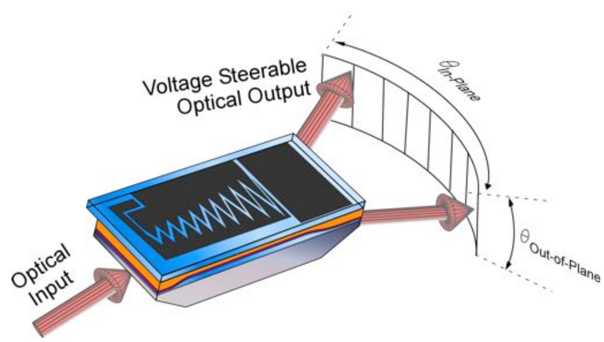


Figure 1: Pictures of simple, wide field of view EO scanners. LEFT) The optical head. A short-wave infrared beam enters the device through the single mode polarization maintaining fiber and an EO scannable beam exits through the window. RIGHT) The photonics package mounted and a cartoon depiction of the EO scannable field of view.

EO scanners that provide high-speed, wide field-of-views (FOVs), are compact, simple, and low cost have been a long-standing dream of the optical community.[1-5] Unfortunately, they are still not available. This is not for lack of effort; for example, liquid crystal (LC) based tunable diffraction gratings or "optical phased arrays" have been in development for more than thirty-five years.[2, 5-7] Other diffractive approaches such as MEMs arrays (though these are still inherently mechanical),[8] electro-wetting arrays,[9] and acousto-optics have also been explored. Typically, these diffractive approaches have been limited to small angle scanners because the grating efficiency drops as scan angle increases. Rather than continue down this well-trodden "diffractive-path" we have taken a new approach. We exploit a new EO architecture that provides unprecedented voltage control over optical phase, which enables previously unrealizable *refractive* scanners.[10]

The enabling innovation is to utilize liquid crystals (LCs), which have by far the largest electro-optic response of any known material (e.g., $>10^5$ times larger than lithium niobate), in a new configuration. Rather than transmit through an LC cell, which by design must be thin (typically <20 μm), we utilize the LC as a cladding layer in an "LC-waveguide" architecture, as shown in the bottom of Figure 2. The evanescent field of the guided wave extends into an adjustable-index liquid-crystal cladding. This selectively utilizes the well-ordered LC-surface region that provides low scattering losses (<0.5 dB/cm) and fast response times (in the range of 10 to 500 μs). Furthermore, the interaction length is now decoupled from the thickness of the LC layer. This allows us to circumvent the historic LC-limitations of a short interaction length and slow relaxation times. We realize substantially larger voltage control over optical phase than any other approach that we are aware of. Optical phase delays of greater than 2 mm have been achieved.



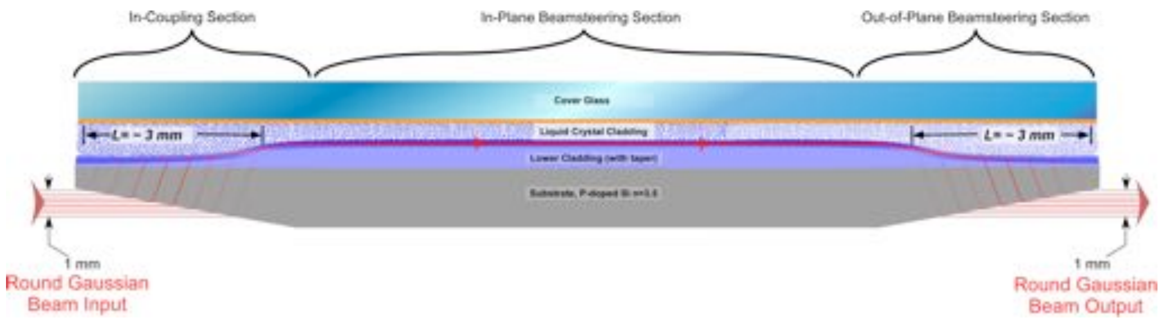


Figure 2 TOP LEFT) A 2-D electro-optic laser scanner. Voltage applied to the zig-zag patterned electrode (top left) provides in-plane scanning and voltage applied to the rectangular electrode provides out-of-plane scanning. TOP RIGHT) A picture of an EO scanner chip next to a quarter for scale. BOTTOM) A side view of a liquid crystal waveguide scanner. Integrated tapered-couplers provide both convenient coupling of round Gaussian beams and out-of-plane scanning control.

This giant control over optical phase provides a natural solution to the problem of non-mechanical beam control. For scanning in the plane of the waveguide we pattern an electrode into refractive shapes, as shown in the top of Figure 2. Voltage applied to the electrodes tunes the index inside the refractive shapes, thereby providing a tunable Snell's law refraction. To realize scan control out of the plane of the waveguide we utilize integrated prism couplers.[11] Voltage tuning the LC-waveguide index of refraction in the out-coupler region controllably alters the out-of-plane scan angle. The steering is non-diffractive and analog. New 2-D devices provide $30^{o}\times5^{o}$ of scan control. A short video of a 2-D scanner in operation may be viewed online.[12] Because the scanning is refractive there are no 2π resets and no blind spots – known challenges with prior diffractive approaches. Full refractive scanning provides continuous, high-speed sweeps across the field of view.

Since the voltage control over optical phase is so much larger than other technical approaches we can realize dramatically larger EO control over optical beams. By way of example we have recently demonstrated in-plane beam steering of 270^{o} (an unheard of amount for any technology) in a package that is smaller than a dime, as shown in Figure 3. A movie of this is also available online.[12] In this figure the images are of the

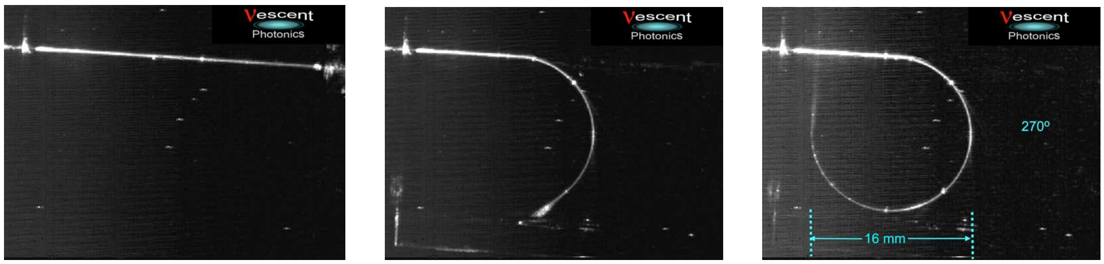


Figure 3: Example data from an electrode pattern that provided steering of 1550 nm light by 270º in a package that is smaller than a dime.

scattered streak of light as it propagates through the device. Similarly, the refractive shapes may be curved or lens shaped, providing voltage tunable lenses. Figure 4 shows operation of an example tunable lens that provides continuous voltage tuning of the focal length from infinity to 0.5 centimeters. The top image shows a collimated beam at zero volts and the bottom image shows a voltage-controlled focused beam.

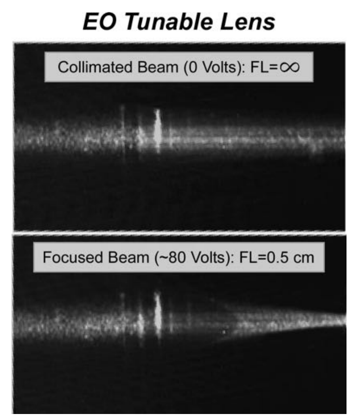


Figure 4: Operation of a voltage tunable lens.

The LC-waveguide architecture is a new electro-optic innovation that provides unprecedented voltage control over optical phase (>2 mm). This previously unrealizable level of control makes possible new electro-optic alternatives to opto-mechanics. These devices can provide wide field of view laser scanners, voltage-tunable lenses, and other formerly mechanical functionalities. Finally they are small, low power, and simple to use.

Acknowledgments

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