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New electro-optic architecture outperforms opto-mechanics

Scott Davis and Michael H. Anderson

When liquid crystals are combined with optical waveguides, unprecedented voltage control over light becomes possible, enabling new types of light-controlling devices.

Active control over light is essential for numerous applications, including robotic vision, optical computing, telecommunications, holographic data storage, remote sensing, cold-atom optics, industrial process analysis, and others. To satisfy this need, scientists and engineers have investigated and developed a diverse array of technologies over the past several decades, such as micro-electro mechanical systems,[1] photonic crystals,[2] thermo-optics,[3] and electro-optic materials such as inorganic crystals and organic poled-polymers.[4] While tremendous progress has been made, there are still numerous applications, such as beam-steering and large optical phase delay, where bulky and power-consumptive opto-mechanical techniques are still superior. This is, at least in part, because typical electro-optic approaches do not allow enough control over light to replace traditional opto-mechanics. Another technique, known as micro-electric mechanical, is still inherently mechanical, imposing vibration and inertia design challenges. Most importantly, this technique still provides only limited control over optical phase.

Over the past several decades, one of the most technically and commercially successful approaches for light control has been liquid-crystal (LC) optics. LCs have the largest known electro-optic response ($\Delta n > 0.2$ over 5 volts for a typical LC, which corresponds to 10^5–10^6 pm/V, i.e., several orders of magnitude larger than any other approach), are environmentally stable, and are inexpensive.[5] This has enabled the now more than $50 billion a year display market. A typical "display-like" LC-optic is shown in Figure 1. The light traverses a thin (less than 20μm) LC layer sandwiched between glass sheets. Transparent electrodes are used to apply an electric field, which, in combination with polarizers, may be used to either block or transmit the light.

While undeniably potent for information displays, this traditional LC-optic has two significant limitations. First, the light must transmit through transparent electrodes, which in turn limits the control over total optical power. Second, and arguably more significant, the LC layer must be extremely thin. The LC material is rendered as a single-domain crystal via thin alignment layers. The LC molecules adjacent to these alignment layers (shown in red in Figure 1) are highly ordered, meaning they are fast and experience low light-scattering loss. If one were to make the LC cell thicker, the bulk LC material (shown as blue in Figure 1) would become prohibitively slow and opaque. Therefore, though the LC material has a tremendous electro-optic effect, the need for a thin LC layer imposes significant constraints. In order to circumvent these limitations, we have invented and

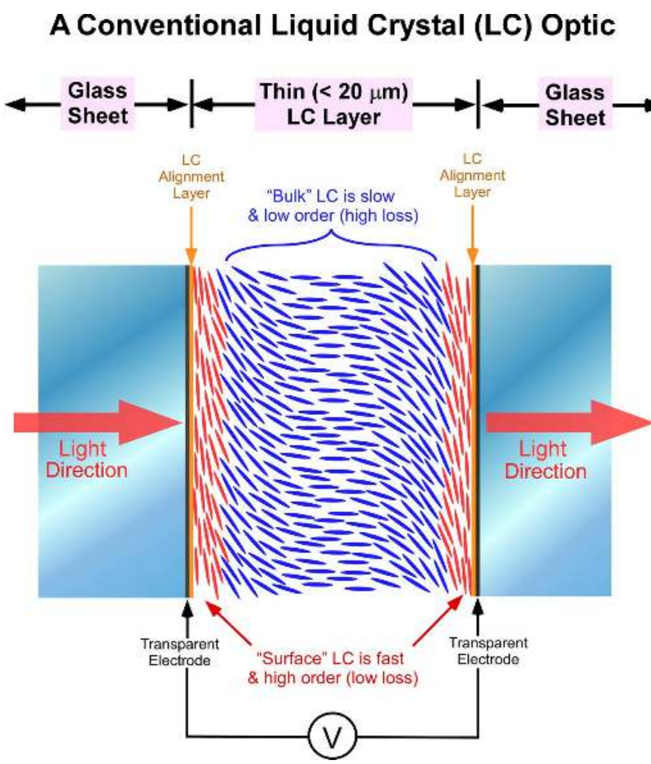

Figure 1. *A typical LC-optic, such as is used in the ubiquitous liquid crystal display.*

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are developing the LC-clad waveguide architecture, as shown in Figure 2.

Rather than transmitting light *through* an LC cell, which by necessity must be thin (typically less than 20μm), we utilize the LC

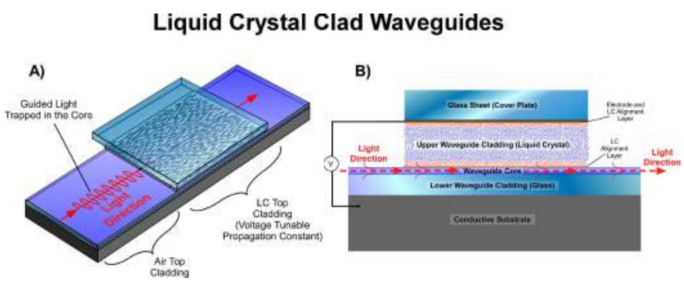

Figure 2. *A) The basic geometry of an LC-waveguide. The light is confined to a core and the upper cladding is an electro-optic LC. As the index of refraction of the upper cladding is tuned, the effective index of the guided mode is also tuned. B) A side view of a liquid crystal waveguide. In a slab waveguide, the light is guided in the x dimension, but is free to propagate as Gaussian beams, sheets, or even 1D images in the plane.*

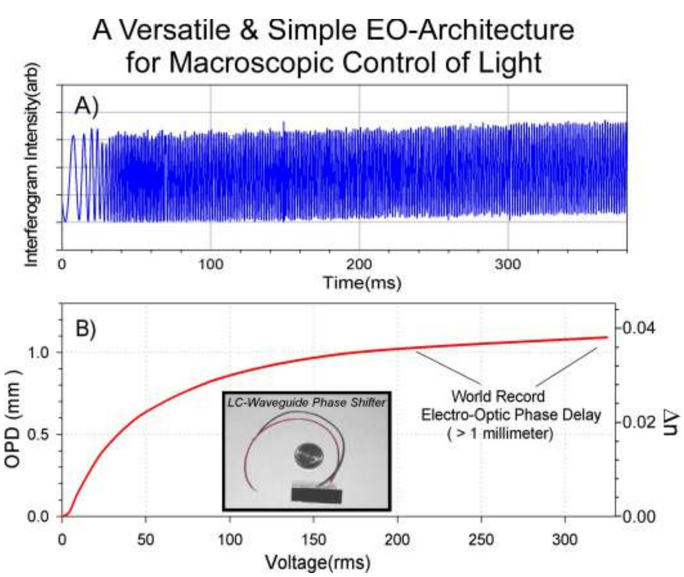

Figure 3. *(A) The transmission of an LC waveguide between polarizers. The figure was recorded over a longer sweep time so that individual waves could be observed. This is a plot of the relative phase shift induced by the LC-waveguide, each minima or maxima on the plot corresponds to one wavelength (1.3μm) of optical phase change. (B) The tunable optical phase delay versus applied voltage. For this device, greater than one millimeter of optical phase delay (OPD) was achieved. The inset shows a picture of the device (next to a nickel for scale). EO: electro-optic.*

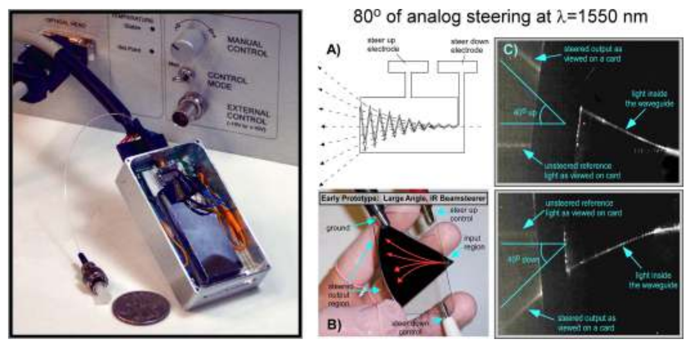

Figure 4. *(Left) A picture of one our commercial prototypes for compact, non-mechanical wide angle beamsteering. (Right)* **A:** *The lithographically patterned electrode for controlling beam deflection.* **B:** *A picture of a large-angle electro-optic beamsteerer. The red lines are drawn to help show the angle of the beam. This device was made on Si, but it could have been made on glass.* **C:** *Images recorded of the prototype beamsteerer in action. The device produced 80^o ($\pm$ 40 $^\circ$of non-mechanical beamsteering, with only two control voltages).*

as an active cladding layer in a waveguide architecture. In other words, light skims *along* the surface of an LC layer, as shown in Figure 2. This *electro-evanescent* architecture circumvents limitations of traditional LC-optics because: the light never crosses a transparent electrode, the light only interacts with the well-behaved LC-surface layer via the evanescent field, and the interaction length is now divorced from the thickness of the LC-layer. Figure 3 shows sample operation of a device that exhibited more than 1mm of voltage tunability over optical phase. We know of no other technology that can provide similar performance. Furthermore, the LC waveguide switching time is faster than normal liquid crystals by about one order of magnitude. Typical relaxation times for LC waveguides are on the order of 500μsec.

Electro-optic beamsteering for micro-ladar (which uses a laser beam in a similar manner to the radio pulses used in radar) applications is one important field that is benefiting from LC waveguides. We have demonstrated analog angle tuning of 80° in a device with only two control voltages. Figure 4 shows a two-electrode device, where each electrode shape comprises several prisms in series. The refractive index under each electrode can be tuned by as much as 0.05, giving a deflection at each prism by Snell's law. The latest LC-waveguide beamsteerer devices are shown in a short video that is available online.[6]

Another device that demonstrates the utility of giant electro-optic control is a Fourier transform spectrometer (FTS). When the LC-waveguide is placed between polarizers, the transmitted

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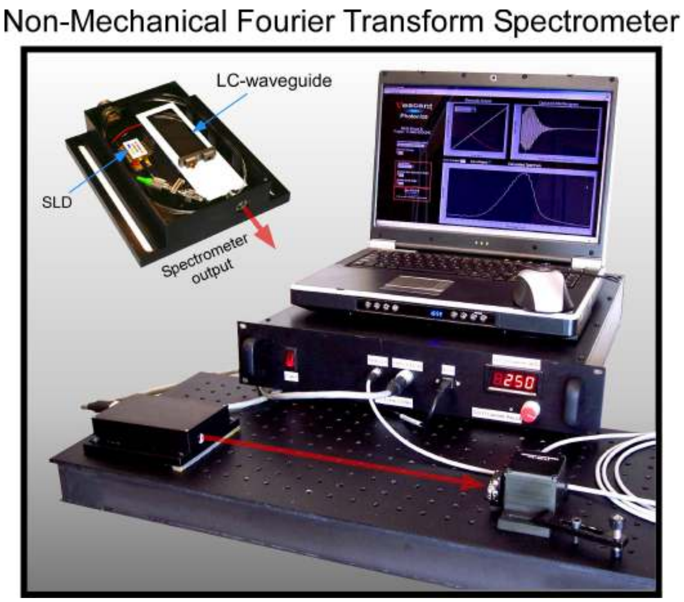

Figure 5. *LC-Waveguide Electro-Optic Fourier Transform Spectrometer prototype built for NASA.*

intensity undergoes extrema as the voltage across the LC layer is tuned. Different wavelengths experience different numbers of extrema and this can be used to analyze the wavelength content of the light. Figure 5 illustrates a non-mechanical FTS prototype developed for NASA. This device exhibited a resolution better than 5nm.

The LC-waveguide architecture is a new electro-optic approach that provides unprecedented voltage control over optical phase (greater than 1mm). This greater level of control makes possible new devices with remarkable performance attributes. To date we have demonstrated: ultra-wide field of view (80^o), non-mechanical laser beamsteerers, Fourier transform spectrometers on a chip with less than 5nm resolution, widely tunable chip-scale lasers (nearly 40nm tunability demonstrated), ultra-low power (less than 5μW) tunable micro-ring filters, and Mach-Zehnder switches. Furthermore, all of these devices may be housed in small LCD-like packages that could eventually be as inexpensive as a calculator display.

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Scott R. Davis is a co-founder and Vice President of Technology of Vescent Photonics. He is developing a range of LC-waveguide based devices, including: tunable ring-resonators, LC-waveguide Fourier spectrometers, LC-waveguide polarization modulators, and wide-angle beamsteerers. He received his PhD from JILA at the University of Colorado, Boulder.

Michael H. Anderson is a co-founder and President of Vescent Photonics. He is one of the inventors of the liquid-crystal waveguide architecture. He has designed and built numerous tunable waveguide devices, including an LC-waveguide tunable laser. He received his PhD from JILA at the University of Colorado, Boulder.

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