A New Generation of Previously Unrealizable Photonic Devices as Enabled by a Unique Electro-Optic Waveguide Architecture

Scott R. Davis,* Scott D. Rommel, George Farca and Michael H. Anderson
Vescent Photonics Inc., 4865 E. 41st Ave., Denver CO 80216

ABSTRACT

A new electro-optic waveguide platform, which provides unprecedented electro-optical phase delays (> 1 mm), with very low loss (< 0.5 dB/cm) and rapid response time (sub millisecond), is presented. This technology, developed by Vescent Photonics, is based upon a unique liquid-crystal waveguide geometry, which exploits the tremendous electro-optic response of liquid crystals while circumventing historic limitations of liquid crystals. The exceedingly large optical phase delays accessible with this technology enable the design and construction of a new class of previously unrealizable photonic devices. Examples include: a 1-D non-mechanical, analog beamsteerer with an 80° field of regard, a chip-scale widely tunable laser, a chip-scale Fourier transform spectrometer (< 5 nm resolution demonstrated), widely tunable micro-ring resonators, tunable lenses, ultra-low power (< 5 microWatts) optical switches, true optical time delay (up to 10 ns), and many more. All of these devices may benefit from established manufacturing technologies and ultimately may be as inexpensive as a calculator display. Furthermore, this new integrated photonic architecture has applications in a wide array of commercial and defense markets including: remote sensing, micro-LADAR, OCT, laser illumination, phased array radar, optical communications, etc. Performance attributes of several example devices are presented.

Keywords: liquid crystal waveguides, electro-optic waveguides, LC optics, tunable micro-ring, non-mechanical beamsteerer, tunable laser

1. INTRODUCTION

Numerous applications require active control over light including: robotic-vision, optical computing, telecommunications, holographic data-storage, remote sensing, cold-atom optics, industrial process analysis, and many more. In response to this need a diverse array of technologies have been investigated and developed over the past several decades: micro-electro mechanical systems (MEMs),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 beamsteering and large optical phase delay, where bulky and power-consumptive macroscopic opto-mechanical techniques are still the best. This is, at least in part, because typical electro-optic approaches do not realize sufficient control over light (R matrix values of typically < 300 pm/V) to replace traditional opto-mechanics. MEMs techniques are still inherently mechanical, which imposes vibration and inertia design challenges, and developing MEMs architectures that provide macroscopic (> 1 mm) control over optical phase has been challenging.

Vescent’s proprietary liquid-crystal(LC) waveguide architecture5-9 provides unprecedented voltage control over optical phase (> 1 mm), orders of magnitude more than any other technology, e.g., liquid crystal optical phased arrays10 or MEMs. This previously unresolved level of control makes possible new devices with remarkable performance attributes. To date we have demonstrated: ultra-wide field of view (80°) non-mechanical laser beamsteers, FTIR spectrometers on a chip with < 5 nm resolution, chip-scale widely tunable lasers (nearly 40 nm tunability demonstrated), ultra-low power (< 5 µWatts) tunable micro-ring filters and Mach-Zehnder switches, and many more. All of these devices may be in small LCD-like packages that can ultimately be as low cost as a calculator display.

* Corresponding author. Tel.: 303-296-6766; fax: 303-296-6783.
Email address: davis@vescentphotonics.com
2. THE ENABLING INNOVATION

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 world largest electro-optic response (Δn > 0.2 over 5 volts for a typical LC, which corresponds to 10⁵-10⁶ pm/V, i.e., several orders of magnitude larger than any other approach), are environmentally stable, amenable to high-volume manufacturing, and inexpensive.¹¹ This has enabled the now > $50 billion a year display market. A typical “display-like” LC-optic is shown in Figure 1. The light traverses a thin (< 20 µm) LC layer that is 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 total optical power that may be controlled. Second, and arguably more significant, the LC layer must be extremely thin. The LC material is rendered a single-domain crystal via thin alignment layers. The LC-molecules adjacent these alignment layers are highly ordered, which means low scattering loss, and fast response to changes in voltage. If one were to make the LC cell thicker, the bulk LC material would become prohibitively slow and opaque. Therefore, even though the LC material has a tremendous electro-optic effect, the necessarily short interaction length mitigates this effect. In order to circumvent these limitations we have invented and are developing the LC-clad waveguide architecture.

2.1. Giant control over optical phase: LC-waveguides

Rather than transmit through an LC cell, which by design must be thin (typically < 20 µm), we utilize the LC as an active cladding layer in a waveguide architecture, i.e., the light skims along the surface of an LC layer, as shown in Figure 2. This electro-evanescent architecture circumvents limitations of traditional LC-optics: i) the light never crosses a transparent electrode, ii) the light only interacts with the well-behaved LC-surface layer via the evanescent field, and iii) the interaction length is now decoupled from the LC-layer thickness.

For a given liquid crystal and waveguide structure we have modeled the LC upper cladding and the voltage dependent field profile of the guided light. This is shown in Figure 3. Specifically, our model includes: LC surface energy, pretilt, elastic coefficients of the LC, electrical properties of the LC (dielectric constants), optical properties of the LC (birefringence), electrode spacing, and electrical properties of the waveguide materials. With this information we have numerically solved for the LC upper cladding index profile as a function of voltage, following an established routine outlined by S. T. Wu.¹¹ Then, for a given index profile we solve Maxwell’s equation for the guided mode and determine the effective waveguide index. The index modulation is the magnitude of the difference between the effective index at zero volts and the effective index at a higher voltage. This model does an excellent job of predicting the experimental results. Furthermore, the model shows that $\Delta n_{eff} = 0.05$ is possible by using highly-birefringent liquid crystals and by keeping the ratio of core thickness to wavelength less than one. While this represents a four-fold decrease in
birefringence from the raw liquid crystal, this is more than offset by a possible 10,000-fold increase in the interaction length.

Example operation of an LC-waveguide optical phase shifter is given in Figure 4. The core of the waveguide is LPCVD deposited Si$_3$N$_4$ ($n=2.0$) and was approximately 500 nm thick, the sub-cladding is SiO$_2$ and the substrate is a P-doped Si wafer. This device exhibited more than 1 millimeter 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 500 µsec, though as will be shown this can be further reduced via choice of operational voltages and device design.

**Liquid Crystal Clad Waveguides**

Figure 2: A) The basic geometry of an LC-waveguide. The light is confined to a core and the LC is an electro-optic upper cladding. 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: The green lines show the calculated index profile of an LC clad waveguide for different applied voltages. As the voltage is increased the index of the upper cladding also increases. The blue lines show the intensity profile for TM light as a function of voltage. This was obtained by direct solving of Maxwell’s equations for the waveguide boundary conditions.

Figure 4: The performance of an LC waveguide filled with a nematic liquid crystal with a birefringence of about $\Delta n \sim 0.2$. A) The transmission of the LC waveguide between polarizers. The figure was recorded over a longer sweep time so that individual waves could be observed. B) The tunable optical phase delay versus applied voltage. For this device greater than one millimeter of OPD was achieved.
3. NEW PHOTONIC DEVICES

This extremely large OPD makes possible a whole new class of photonic devices. Figure 5 illustrates a few possibilities. In addition to these LC-waveguides may be used for optical coherence tomography, true optical time delays, tunable lenses, optical switches, and many more. In the rest of this proceedings we provide some examples of new photonic devices that are enabled by LC-waveguides: i) a chip-scale non-mechanical Fourier Transform Spectrometer, ii) non-mechanical wide angle beamsteerers, iii) chip-scale widely tunable lasers, iv) ultra-low power optical switch, and v) voltage tunable micro-ring resonator. These are only some of the devices that we are developing at Vescent and only a small subset of possible LC-waveguide devices.

Figure 5. The unprecedented electro-optic phase delays provided by LC-waveguides enable a vast array of new photonic devices. Some examples shown here are: chip-scale polarization based FTIR, telecom tunable optical add/drops (ROADMS), tunable lasers (non-mechanical ECDLs), multiplexed Mach-Zender bio sensors, and a new type of non-mechanical beamsteerers. We have demonstrated prototypes for many of these applications.

3.1. Chip-Scale Fourier Transform Spectrometer Based Sensor

The essential elements of a traditional Fourier Transform Spectrometer (FTS) absorbance sensor are shown in Figure 6. Very briefly, emission from a broadband light source, which is typically a heated element for the mid- to far-IR or a tungsten lamp in the near-IR, passes through the analyte and the interferometer (preferred order dependent upon application) prior to detection. FTS sensors may also work in solar occultation mode, wherein the sun provides a broadband light source. The interferogram, i.e., intensity recorded by the detector as a function of the optical path difference (OPD) between the two arms of the interferometer, is digitized and Fourier transformed. This OPD is typically generated via a linear translation of a Michelson interferometer (see Fig. 6). This transform provides the full spectrum, which represents the broadband light source emission and detector sensitivity profiles modified with depleted
regions arising from the analyte absorbance spectra. From analysis of this spectra constituent quantification is extracted. The extraordinary power of FTS arises from this ability to achieve detailed spectral information, over a broad region, from a single interferogram.

While the potency of FTS sensors is extremely well established with a long history of success, the moving mirror assembly provides size, weight, power and durability design challenges. This is especially true for space-based deployment, which is a strong motivation for our collaboration with NASA to develop a non-mechanical FTS. Specifically, the increased variety of future exploratory platforms including: flybys, orbiters, landers, airplanes or balloons in planetary atmospheres, Earth orbiting telescopes and sample return missions to various solar System bodies. Furthermore typical instruments have an onboard calibration laser to calibrate the linear motion, which further adds to the cost. An alternative technology free from this moving mirror assembly is therefore sought.

In principle electro-optics can be used to replace the moving mirror assembly. Figure 7 illustrates how the complicated opto-mechanical interferometer (left of Figure 7) may be replaced with a non-mechanical electro-optic medium. In typical electro-optic crystals, such as KTP or LiNbO$_3$, the birefringence of medium may be voltage tuned. If the input light is polarized at 45° with respect to the crystal axis then the speed at which the two polarizations propagate through the crystal may be voltage tuned. For a given length of crystal this translates into a voltage tunable optical path difference between the two polarizations. These two “arms” of the interferometer may then be recombined via another polarizer and a completely non-mechanical EO interferometer constructed. While this approach has long been known the key challenge to replacing the opto-mechanics has been realizing an EO material that provides sufficient voltage tunability over OPD. Typical EO crystals realize only a few microns of tunability of OPD, which is suitable for intensity.
modulators but hardly provides a viable replacement for opto-mechanics. This is especially true for FTS applications, where the magnitude of OPD is inversely related to the spectral resolution.

3.1.1. Liquid Crystal Waveguide Interferometer

A schematic of how a LC-waveguide may be used as an interferometer is depicted in Fig 8. Specifically, the light is polarized 45° to the waveguide surface, and therefore equally couples into both the TE and TM modes. An LC waveguide section is used to vary the optical-path-difference (OPD) between the TE and TM modes, which replaces the movable mirror. Finally, the two polarization-separate beams are recombined by means of a polarizer, which is aligned 45° with respect to the waveguide surface. To obtain the interferogram, one varies the OPD between TE and TM modes (via the LC waveguide), and records at the detectors the OPD dependent interference between them. All these elements will be integrated into a monolithic opto-block, thereby eliminating all moving components and surmounting the foremost impediment to FTS miniaturization and cost reduction.

Depicted in Fig. 8 are two detectors. Two detector signals will be phase shifted with respect to one another. Auto-balancing circuits based on the two individual signals ratio-ed to their sum can be used to minimize the impact of source fluctuations. Also not shown are electrodes that are used for active waveguide dispersion compensation. This is key, since optical waveguides possess significant geometric dispersion.

Similar to a conventional FTS, the spectral resolution, $\Delta \sigma$, of the EO-FTS is related to the maximum optical path difference, $\Delta_x$, or equivalently, the maximum time delay, $\delta_{\text{max}}$, between the two interfering waves: $\Delta \delta = \frac{1}{2 \pi \Delta \beta} = \frac{1}{2 \pi (n_o - n_e)}$. Our current LC-waveguide devices have greater than 1 mm of OPD, and we have designs for up to 1 or even 10 cm of OPD in a wrapped channel device. Thus the spectral resolution of $<0.3$ cm$^{-1}$ (i.e. in sub-nanometer range at about 2μm IR spectral band) can in principle be realized.

3.1.2. Prototype Construction and Testing

A preliminary E-O FTS, operational in the near-IR band, has been built. The current device, along with an exploded view schematic and a total spectrometer system picture, is shown in Figure 9. All of the elements are included, but they are coupled as separate discrete elements. Integration into a monolithic assembly, and utilizing micro-controller electronics, will reduce size/mass and increase durability.
Example performance of a prototype device is shown in Figure 10. The left figure depicts LC-waveguide obtained interferograms of narrow-band light sources. The bottom interferogram is for a single frequency laser. The top interferogram is for two lasers. The beat pattern of the two lasers is clearly visible in the interferogram. The insets show the spectrum of the light sources. The figure on the right shows interferograms and FFT obtained spectra of a broadband SLD with some broadband spectral absorption features. In these experiments both filter and acetylene absorption spectra were recorded. For these current devices the spectral resolution is only about 3-5 nm. New designs will improve the resolution to <0.5 nm.

3.2. Electro-Optic Laser Scanners

The challenge of non-mechanical beam control is a long-standing one, and has been the subject of extensive past efforts (e.g., The Steered Agile Beam or STAB project funded by DARPA in 2000). A diverse array of technical
approaches have been directed toward this problem including: i) planar electro-optic prisms constructed from KTP,\textsuperscript{21} Lithium Niobate,\textsuperscript{21} ferroelectric domain LiTaO\textsubscript{3},\textsuperscript{18, 22} and electro-optic polymers,\textsuperscript{23} ii) thermo-optic planar prisms,\textsuperscript{24} iii) diffractive liquid crystal phased arrays\textsuperscript{10, 19}, and iv) diffractive acousto-optic techniques\textsuperscript{25}. Each of these approaches has advantages and drawbacks. Electro-optic crystals are very fast but have extremely small electro-optic coefficients, which means very small steering angles and kilovolts to operate. Furthermore, EO crystals are quite expensive. Liquid-crystal optical-phased array beamsteerers tend to be slow, provide non-continuous diffractive steering, and have a very limited steering range because thick LC layers are problematic. Acousto-optic beamsteerers have a larger steering range but are also diffractive, require very large power supplies and expensive crystals.

LC-waveguides provide an entirely new approach to electro-optic laser-beams scanning.\textsuperscript{5} The basic concept is shown in Figure 11 wherein a lithographically patterned electrode provides a 1-D prism whose refractive index can be tuned relative to the surrounding area, providing truly analog steering, i.e., it is not diffractive. This lithographically patterned electrode is similar to, albeit much simpler than, the patterned electrodes required for traditional liquid crystal displays. In principle, the pointing precision is only limited by the noise on the control voltage.

We have designed and built several prototype LC-waveguide beamsteerers. In order to realize a larger deflection angle each steer electrode is patterned to have multiple interfaces in series. In this way the amount of deflection is accumulated along the length of the waveguide. The vertical dimensions of the later electrodes may be expanded to

![Figure 12 (Left Top) A picture of one of our commercial prototypes for compact, non-mechanical wide angle beamsteering.](image1)

![Figure 12 (Left Bottom) Frames from a moving showing an LC-waveguide scanner directing an IR beam across a parking lot (Right)](image2)

![Figure 11: A 1-D LC-waveguide beamsteerer. A single control voltage is applied to a prism-shaped electrode having a non-normal interface to the beam propagation direction. As voltage is applied, the index under the patterned electrode is changed relative to the surrounding area and the beam is steered via Snell’s law refraction.](image3)
prevent optical clipping of the steered beam, as is discussed in ref\textsuperscript{18}. An example of a multiple interface electrode pattern is shown in Figure 12A. A picture of a prototype waveguide device is shown in Figure 12B, and Figure 12C shows the performance as viewed with a high-gain InGaAs CCD camera. A small amount of non-steered light was deliberately allowed onto the exit card, so an accurate beamsteering angle could be measured. This device exhibited a total analog steer range of over $80^\circ$ for a 1 mm input aperture, with only two control electrodes. To our knowledge this is the largest electro-optic steering ever realized for a two-electrode device. Performance examples of LC-waveguide beamsteerer devices are shown in several short videos online (http://www.vescentphotonics.com/SEEOR.html).

The switching speed of liquid crystal devices is generally limited by the “voltage-off” relaxation time. As already mentioned for the LC-waveguide architecture this is greatly reduced due to the close proximity of the liquid crystal molecules to the surface alignment layer. Figure 13 shows two characteristic temporal responses for an LC-waveguide beamsteerer. On the left a photo-diode is placed to detect the maximally steered beam. The voltage is switched on and the beam arrival from no-deflection to maximum-deflection is recorded. As it can be seen the temporal response is approximately $50 \mu$sec. On the right of Figure 11 the same experiment is repeated except that the beam is now relaxed from a maximum-deflection to a no-deflection point. Even though this operation requires the longest response time of the device, the transition time of $< 600 \mu$sec still ensures a $> 1$ kHz full scan rate. This is also the worst-case scenario for random access transition times. If required, optimization of both the LC-waveguide and the electronics can significantly improve upon the speed.

![Figure 13: Data scans showing the speed of a prototype LC-waveguide beamsteerer.](image)

An infrared video of a beam-steerer in action is available in Video 1. It shows the beam scanning with increased speed, well beyond the frame rate of the camera followed by a sequence of fast random deflections. In the second part it shows the operation outside the laboratory. The IR camera had to be placed behind the device since its field of view is smaller than the angular scanning of the beam-steerer.
3.2.1. Beamsteerer Resolution or Number of Resolvable Spots

There are two kinds of resolution that need be considered. One is the smallest amount one can deflect the beam and the other determines how many spots the scanner can resolve. Because our scanner is analog the first type of resolution is effectively determined by the noise on the drive signal or the bit resolution of a D/A converter. An advantage of the analog scanning feature ensures that the entire domain within the field of view can be illuminated such that the point density is determined in principle only by the pulse repetition rate of the laser or the noise on the analog voltage signal.

The other type of resolution is the number of far-field resolvable spots. Dividing the angular stroke by the diffraction angle of a Gaussian beam gives the number of resolvable spots,

\[ N_{\text{spots}} = \frac{\theta_{\text{max}}}{\theta_{\text{diff}}} = \frac{30^\circ}{4 \lambda / \pi d} \approx 800. \]

For LC-waveguide devices under construction we will steer a 3 mm beam diameter over a 30\(^\circ\) field of regard. For \(\lambda=1550\) nm light this translates into approximately 800 resolvable spots.

Some typical performance attributes of the LC-waveguide beamsteerers are summarized in Table 1.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Compact and Conformal: &lt; 5 cm(^3) optical head</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt; 15 grams for optical head</td>
</tr>
<tr>
<td>Operating Power</td>
<td>&lt; 100 (\mu)Watts</td>
</tr>
<tr>
<td>Angular Coverage</td>
<td>&gt; ±40(^\circ) for 1-D sweeps</td>
</tr>
<tr>
<td>Transmission</td>
<td>&gt; 80%</td>
</tr>
<tr>
<td>Control Speed</td>
<td>&lt; 1 millisecond (full FOV)</td>
</tr>
<tr>
<td>Steering Resolution</td>
<td>Analog control (&gt; 800 resolvable spots possible)</td>
</tr>
</tbody>
</table>

3.3. Chip-Scale Widely Tunable Lasers

LC-waveguides may be used to construct tunable filters by placing beamsteering elements upstream from edge-bonded reflection gratings, or by placing LC over waveguides with Bragg gratings or ring resonators. An application of a
tunable filter is for a tunable diode laser. We have exploited the giant electro-optic effect to replace the mechanical components in an external cavity diode laser in Littrow configuration. One electrode controls the tuning wavelength and the other controls the optical path length of the cavity enabling mode-hop-free tuning over very large ranges. The device is completely electronic, robust, and low cost. The upper left picture in Figure 14 shows the design of a tunable diode laser based on a tunable Littrow grating filter. The lower left of Figure 14 shows an example of a prototype LC-waveguide laser. Tuning performance is shown in the right of Figure 14.

Figure 14. An LC waveguide tunable diode laser and some recent performance data. The upper left hand picture shows a drawing of the basic structure. A typical external cavity laser architecture is integrated onto an LC-waveguide. A picture of a micro-assembly of a laser is shown in the lower left hand corner. The plot on the right shows experimental wavelength tuning with voltage. The jumps or discontinuities in the tuning are due to laser mode-hops, which can be mitigated with new laser designs.

3.4 Ultra-Low Power Optical Switch

LC-waveguide may also be used to provide a low power alternative to thermo-optic waveguide devices. As an example we have built prototype LC-waveguide 2×2 Mach Zehnder Interferometer (MZI) switches. A microscope picture of the device and experimental operation is shown in Figure 15. In this example light from a single frequency laser was coupled into one of the entrance ports. While voltage to the LC-waveguide was ramped the intensity at an exit port was monitored. As can be seen from the plot the index modulation was sufficient to scan through several minima and maxima, i.e., it was enough to switch the device several times. Further device performance is shown in Figure 16 and Table 2. This device, developed in collaboration with LioniX photonics, utilized a Triplex LPCVD channel waveguide structure, with an active LC cladding. These devices provide substantial improvements over thermo-optic designs: i) larger index modulation which permits a more compact switch, ii) faster switching time by more than an order of magnitude over thermo-optics, and iii) a factor of 10,000 less electrical power consumption. The electrical driving requirements for LC-waveguide devices are equivalent to driving a small capacitor, typically a few nanofarads.
Figure 15: Left: Close-up view of a single voltage tunable MZI switch. This is analogous to a single pixel on an LC display. The planar waveguide sub-structure is constructed from well established silica on silicon technology. The top cladding contains liquid crystal, which may be voltage tuned, thereby tuning the optical phase delay of the MZI tune arm. Right: Example performance and picture (inset) of a voltage tunable 2×2 MZI optical switch. The separation between the reference and tune arm was 500 µm. Light was fiber coupled into the top left port and the bottom right port was monitored as a function of voltage. The light wavelength was 1550 nm.

Figure 16: Shown on the left is the voltage tunable optical phase delay and index modulation realized with this LC-waveguide architecture. Shown on the right are switching times. The control voltage is a DC balanced square wave, whose amplitude is altered. For this switching data the amplitude was altered between approximately 100 and 80 volts. Voltage driving at lower values will yield a slower response (~400 µsec), but still faster than typical thermo-optics (e.g. 5 milliseconds).

Table 2: Measured performance of LC-Waveguide 2×2 MZI optical switch

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Speed</td>
<td>&lt; 100 µsec for 100 V&lt;sub&gt;rms&lt;/sub&gt; operation</td>
</tr>
<tr>
<td></td>
<td>&lt; 400 µsec for 15 V&lt;sub&gt;rms&lt;/sub&gt; operation</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>&lt; 30 µWatts measured,</td>
</tr>
<tr>
<td></td>
<td>&lt; 3 µWatts expected</td>
</tr>
<tr>
<td>Index Modulation</td>
<td>Δn = 7×10&lt;sup&gt;-3&lt;/sup&gt; by 50 V&lt;sub&gt;rms&lt;/sub&gt;</td>
</tr>
<tr>
<td>LC-Waveguide Loss</td>
<td>&lt; 0.3 dB/cm (upper limit)</td>
</tr>
</tbody>
</table>
3.5. Voltage Tunable Micro-Ring Resonator

Finally, another type of thermo-optic device that may be rendered electro-optic with the LC-waveguide architecture is the tunable micro-ring resonator. The left side of Figure 17 shows the basic architecture of the voltage tunable LC-waveguide micro-ring. The right of Figure 17 shows a microscope picture of the micro-ring device along with the resonance spectrum of the micro-ring. The channel structures were constructed using the triplex waveguide design (this was on the same wafer as the MZI switches). The input and output channels were three microns wide and the channel in the ring was 15 microns wide and a lateral coupling scheme was used. While the ring channel width was not single mode it is our experience that improper coupling between the input channel and the rings is the most common failure mode for first designs. The large channel width in the ring and the large ring diameter were specifically chosen to help mitigate this risk. The spectral response of the ring was measured both with and without LC in the top cladding with no noticeable change in the finesse, indicating that LC scattering losses were minimal.

Voltage tunability of the device and switching speed are shown in Figures 18 and 19. With the wavelength held fixed at 1550 nm, the intensity of the drop port was monitored as a function of voltage. The results are plotted in Figure 14. As can be seen the device tuned over nine resonances (> 3 nm), with extremely minimal power consumption (< 50 µWatts). The reason that the peak widths appear to broaden at higher voltages is due to the non-linear index modulation with voltage. Measurement of finesse as a function of voltage showed no discernable change. Also, this finesse was the same with SiO₂ as a top cladding, indicating that LC induced losses are not yet contributing. Other performance attributes are shown in Figure 19.

![Voltage Tunable Micro-ring Resonator](image-url)  
**Drop Port Signal as a Function of Laser Wavelength**

Figs 17. Left: Close-up view of a single voltage tunable micro-ring resonator. This is analogous to a single pixel on an LC display. The planar waveguide sub-structure is constructed from silica on silicon technology. The top cladding contains liquid crystal, which may be voltage tuned, thereby tuning the effective index of the waveguide ring. When tuned to resonance for a given wavelength of light within an input channel, the light can be transferred from one straight channel, through the ring, to the other straight channel. Right: A prototype LC-waveguide micro-ring demonstration. The inset shows a microscope image of the device, and the plot shows the intensity of the drop-port signal as a function of input port wavelength (we used a single mode tunable laser). In this case the voltage to the LC was held at zero. The ring design only provided a finesse of 40, and the ring was multi-modal. Nevertheless, we were able to use this device to demonstrate voltage tuning of the LC-waveguide ring architecture.
Scanning Through > 9 FSR (> 3 nm) with Voltage
(Δ held fixed at 1550 nm)

Fig. 18: The wavelength is held fixed at 1550 nm. The voltage on the LC-clad ring is swept from 0 to 100 Volts. As can be seen, > 9 FSR (> 3 nm) are tuned across. This is for a 600 μm radius ring.

Fig. 19: For the same transmission mode, the resonance wavelength vs. applied voltage is plotted on the left. This is for the 600 μm ring. This level of tuning agrees well (within 5%) with theoretical predictions. The temporal response is shown on the right, both for a voltage increase and decrease (typically with LC’s the voltage decrease is the slower response). The tuning times are comparable to those measured for the MZI switch, which is also expected. The different resonance heights, multi-modal resonance, and varying baseline are a property of the ring-resonator foundry run, and not induced by the LC.

4. CONCLUSION AND FUTURE WORK

The LC-waveguide architecture is a new electro-optic approach that provides unprecedented voltage control over optical phase (> 1 mm). This previously unrealizable level of control makes possible new devices with remarkable performance attributes. To date we have demonstrated: FTIR spectrometers on a chip with < 5 nm resolution, widely tunable non-mechanical beamsteerers, chip-scale widely tunable lasers (nearly 40 nm tunability demonstrated), ultra-low power tunable micro-ring filters and Mach-Zehnder switches. All of these devices may ultimately be in small LCD-like packages that can ultimately be as low cost as a calculator display. At Vescent we are continuing to develop these and other LC-waveguide devices. Future efforts include: full 2-D EO beamsteerers, active polarization cancellation in tunable MZI switches, improved tunable lasers, true time delay devices, and more.

5. ACKNOWLEDGMENTS

This work has been supported by the Air Force Office of Scientific Research, the National Science Foundation, the National Institute of Standards and Technology, the National Aeronautics and Space Administration, and the Environmental Protection Agency. The authors also wish to acknowledge the Colorado Advanced Photonics Technology Center (http://www.captcenter.org), Charles Lee at AFOSR, and Don Snyder at AFRL for their help with the beamsteerer development, David Walba and Eva Korblova at the University of Colorado Boulder for help with custom
liquid crystal chemistries, and Tien-Hsin Chao and Jet Propulsion Laboratory for help with the FTS development. The authors also wish to acknowledge Rene Heideman and Arne Leinse at LioniX Photonics for their invaluable help with the micro-ring and MZI switch design and fabrication.

6. REFERENCES