Rethinking Wireless Communications: Advanced Antenna Design Using LCD Technology

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Abstract

For mobile satellite communications applications such as the connected car, a scanning antenna is required. Kymeta has developed a novel, electronically scanned antenna technology achieved through the use of high-birefringence liquid crystals. Kymeta's technology is positioned for mass production by leveraging the manufacturing capabilities of the LC display industry.

Author Keywords

High-birefringence liquid crystal; metamaterials; leaky wave antennas; surface scattering antennas

1. Introduction

For broadband satellite communications applications where the platform is mobile, where the satellite is non-geostationary, or both, a scanning antenna is required. The satellite communications industry, however, is dominated by either statically-pointed dish antennas fixed at geostationary satellites, or dish antennas mounted on motorized gimbals. These solutions are too large, heavy, and power-consuming to offer solutions for mobile applications such as the connected automobile, or a personal satellite terminal. The other alternative is phased array technology. This technology is typically only available to military customers, however, because of its expense and power consumption.

Kymeta has addressed these obstacles by developing a novel, electronically-scanned antenna technology based on a metamaterials concept. The approach is called Metamaterial Surface Antenna Technology (MSAT). Electronic scanning is achieved through the use of high-birefringence liquid crystals. The use of liquid crystals (LC) as a tunable dielectric at microwave frequencies permits large-angle (> 60°) beam scanning with power consumption of < 10 Watts and antenna thickness ~ 2.5 cm, with no moving parts.

Kymeta's engineering approach, through the use of liquid crystals and optimization of the materials and design for compatibility with liquid crystal display (LCD) manufacturing processes, positions the technology for mass production by leveraging the manufacturing infrastructure of the LCD industry. Kymeta will thus be able to produce electronically scanned antennas at consumer electronics price points and volumes, enabling concepts like the connected automobile and low Earth orbit (LEO) satellite constellations that provide global, high-bandwidth internet connectivity.

The remainder of this report will describe the fundamentals of Kymeta's approach, radio frequency design concepts, liquid crystal modeling and optimization, and lastly some concluding remarks.

2. Background

Prior work with LC-based microwave antennas has focused on producing phase shifters for phased-array antennas with improved figures of merit (FoM) over traditional microwave phase shifters [1]. The MSAT approach is fundamentally different from the phased array approach; it is a leaky wave approach in which the antenna aperture is synthesized from a large number of sub-wavelength radiating elements. Other LC-tuned leaky wave approaches have been demonstrated in the literature as well, but these approaches typically employ a slotted waveguide concept in which the entire waveguide cavity is filled with liquid crystal. The antenna beam is thus steered by adjusting the propagation constant through the entire waveguide as the refractive index of the LC changes with applied voltage [2].

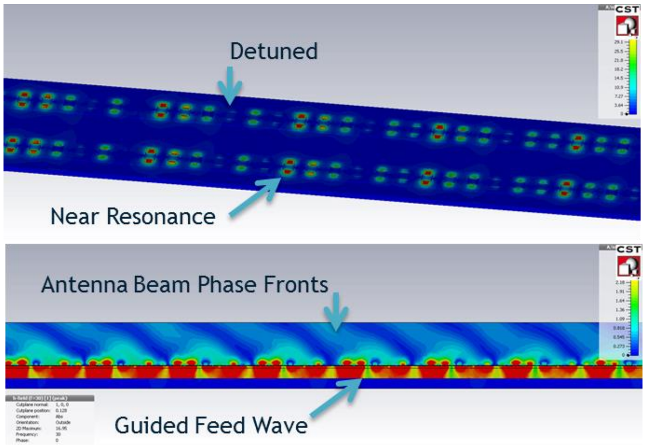


Figure 1. Top view and cross section showing the antenna elements, feed structure, and the antenna beam produced from the pattern of radiating and non-radiating elements.

With MSAT (see Figure 1) each antenna element is coupled to a travelling wave feed structure comprised of a microwave waveguide. Near their resonant frequency, the antenna elements couple energy from the feed wave and scatter this energy from the surface of the antenna. Antenna elements that have been detuned from their resonant frequency do not scatter energy from the feed wave. Due to the dense spacing of elements along the direction of the feed wave, elements with the correct phase to produce an antenna beam at the desired angle can be tuned to radiate (turned "on"). Elements with the wrong phase can be detuned and prevented from radiating (turned "off"). The pattern of "on" and "off" elements, hence the antenna beam pointing angle and polarization state, can be changed dynamically in software.

The metamaterial nature of MSAT arises from the multitude of subwavelength radiating elements and the periodic pattern of activated and deactiviated elements. The far field antenna beam is produced by scattering energy over a number of periods of this pattern, where the radiating elements comprise an "effective" or "continuous" medium to the feed wave. The idea of an effective medium is a core metamaterials concept, where the coupling strength of each individual radiating element is engineered such that the feed wave, as it propagates through several wavelengths of the metamaterial surface, sees one effective refractive index.

3. Holographic Beam Forming Using LC

The pattern of activated and deactivated antenna elements is determined from a holographic beam forming principle. With this approach, the feed wave is analogous to a reference beam (equation 1), and the wave coming off the antenna is analogous to an object beam (equation 2). Hence, the antenna surface becomes a diffractive grating, where the diffraction pattern is determined by the interference of these two waves (equation 3):

$$\Psi_{ref} \approx \exp\left(-i\vec{K}_s \cdot \vec{r}\right) \tag{1}$$

$$\Psi_{obj} = \exp\left(-i\vec{K}_f\left(\theta_o, \varphi_o\right) \cdot \vec{r}\right) \tag{2}$$

$$\Psi_{\text{int} f} = \Psi_{obj}\Psi_{ref}^{*} \tag{3}$$

In the equations above, $\vec{K}_s$ is the feed wave wavenumber, $\vec{K}_f$ is the free space wavenumber, which is a function of the desired azimuth and elevation scan angles, and * denotes the complex conjugate. This calculation is run onboard the antenna control electronics so that as the look angle between the antenna and the satellite changes, azimuth and elevation are updated and a new diffraction pattern to produce the beam at the new look angle is generated. The amplitude of scattered energy from each individual radiating element on the surface of the array is then controlled to reproduce this diffraction pattern.

As discussed previously, the resonant frequency of each antenna element is adjusted to change the amount of microwave energy scattered from those elements. Referring to the circuit model shown in Figure 2, there is a portion of the capacitance of each element that is tunable, producing a resonant frequency shift as 1/sqrt(C*L), where L is the inductance of the antenna element and C is the capacitance.

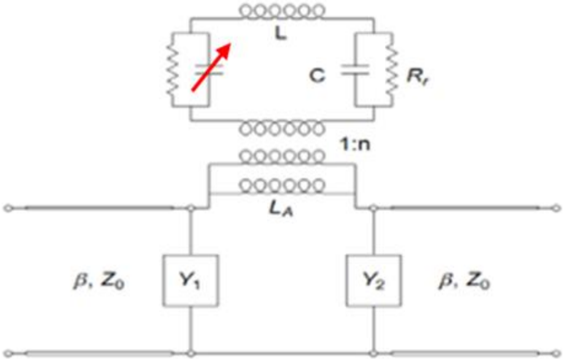


Figure 2. Transmission line model of a MSAT antenna element coupled to a feed transmission line.

Using LC as a tunable dielectric material, the capacitance of each antenna element can be adjusted through applied voltage to either tune or detune the antenna elements and control the scattering strength of those elements. The antenna elements are designed such that the Radio Frequency (RF) structure that couples energy from the feed wave and radiates that energy (a slot-coupled patch in this case) also comprises the electrodes for driving the LC. The basic structure is shown in Figure 3, where vertical switching is employed with uniaxial nematic LCs that present either a perpendicular permittivity to the RF field in the voltage off condition, or a parallel permittivity in the voltage on condition as shown in the dielectric permittivity tensor in Figure 4.

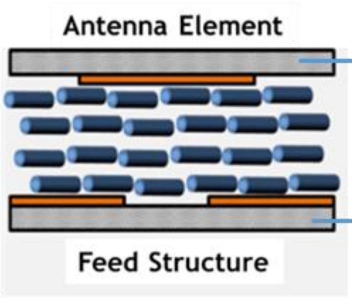
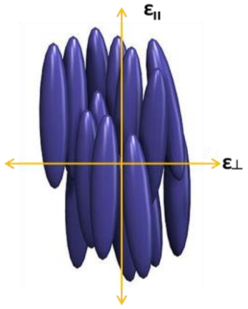


Figure 3. Schematic illustration of one antenna “pixel” with LC disposed between two RF substrates.

The microwave feed structure sits below the lower electrode; the slot in this metal layer couples energy from the feed to excite the patch, which comprises the other LC driving electrode. A low frequency (typically 100 Hz to 1 KHz) voltage is placed across these electrodes to drive the LC.



$$\begin{pmatrix} D_z \\ D_y \\ D_x \end{pmatrix} = \begin{pmatrix} \varepsilon_{\parallel} & 0 & 0 \\ 0 & \varepsilon_{\perp} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{pmatrix} \begin{pmatrix} E_z \\ E_y \\ E_x \end{pmatrix} = \begin{pmatrix} \varepsilon_{\parallel} \cdot E_z \\ \varepsilon_{\perp} \cdot E_y \\ \varepsilon_{\perp} \cdot E_x \end{pmatrix}$$

Figure 4. LC molecular arrangement and corresponding dielectric tensor.

The requirements for RF liquid crystals (RFLC) in the MSAT approach are significantly different than with LC-based phase shifters. The FoM for LC phase shifters is heavily weighted towards reduced microwave losses, rather than large birefringence [3]. MSAT requires much larger changes in the relative permittivity with a tunability of roughly 35%-40%, where the tunability is defined as:

$$\tau = \frac{\varepsilon_{\parallel} - \varepsilon_{\perp}}{\varepsilon_{\perp}} \tag{4}$$

The phase shifter approach, in contrast, sees tunabilities of typically ~20%. The evolution of RFLCs to higher birefringence has significantly improved MSAT performance by improving the contrast ratio between on and off states, which relates directly to antenna beam gain and side lobe levels.

4. Radio Frequency LC Modeling

Kymeta’s antenna design process begins first at the antenna element level, where the DC and RF properties of the LC are modeled to produce an RF structure that radiates efficiently, yet also obtains large tunability and fast switching speed. The authors have developed, from first principles free energy considerations, a COMSOL multiphysics model that couples the field-dependent electrostatic behavior of the LC director with an RF model of the antenna element. Time dependency has also been developed for this model so that both material and physical device parameters, i.e. electrode gap and LC material coefficients, can be assessed for LC relaxation speed.

Figure 5 shows the geometry and solid model for this simulation. In this example, a solid square patch is modeled above a metal sheet with a slot placed in it, with the LC disposed between these two structures as depicted in Figure 3. This structure is coupled to a microwave waveguide, where the input and output ports to this structure are labelled on the figure.

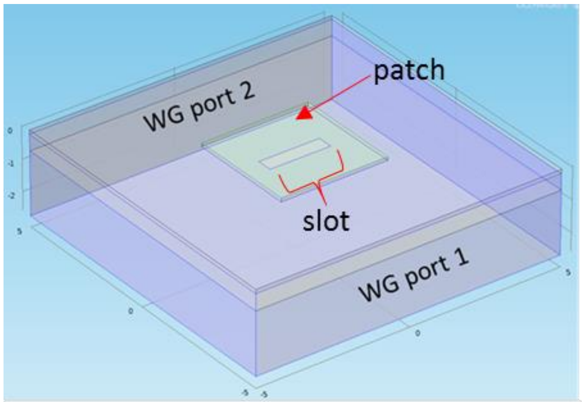


Figure 5. Solid model geometry for the coupled electrostatic and RF LC model.

Using the Oseen-Frank expression for the elastic energy and minimizing the free energy of the system yields a calculation of the LC director for the electrode configuration, based on a calculation of the electrostatic potential, as shown in Figure 6. The three slices in Figure 6 show an intensity representation of the electrostatic field across the electrode geometry, with the middle slice showing the area immediately around the slot.

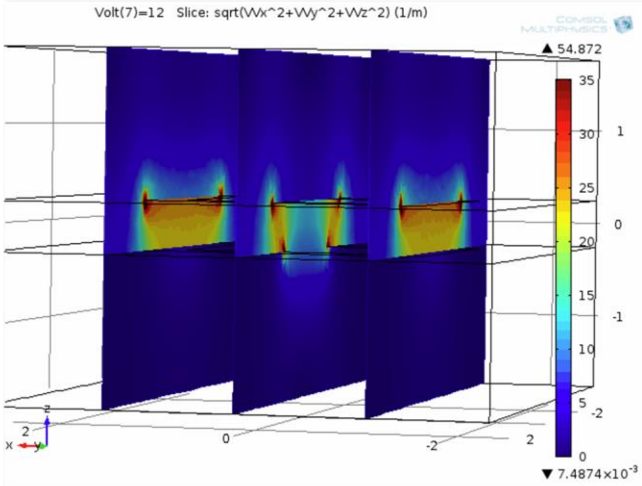


Figure 6. Intensity map showing the electrostatic field intensity for the patch/slot electrode configuration.

The LC director orientation is shown in Figure 7 for this electrode configuration. Around the slot and beyond the edges of the patch electrode, no deformation of the LC director can be observed.

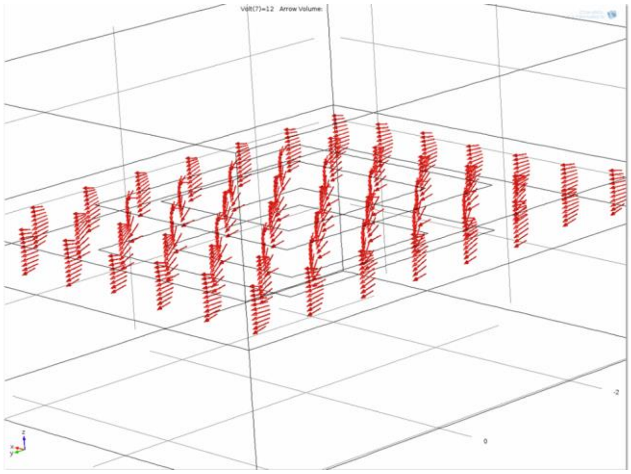


Figure 7. LC director calculation for the patch/slot geometry.

Once the LC director orientation has been determined, RF permittivity values can be assigned throughout the volume of the simulation as a function of voltage. Next, the RF resonance of the system can be calculated by solving Maxwell's equations throughout the volume using the RF permittivity at each voltage step, as shown in Figure 8.

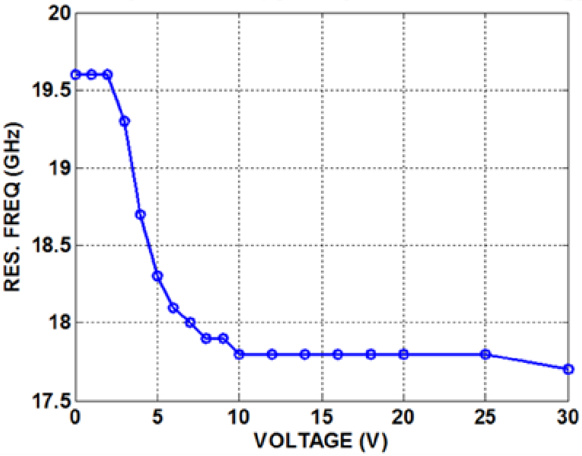


Figure 8. Resonant frequency of an MSAT antenna element as a function of voltage

From this basic unit cell design, full wave electromagnetic modeling tools are used to simulate larger portions of the antenna structure so that antenna radiation patterns can be modeled. LC blocks with effective permittivities and loss tangents are derived from the output of the COMSOL tool and passed on to the full wave tools.

Figure 9 depicts a solid model for an antenna segment and the simulated far field radiation pattern from one of Kymeta's designs. In the solid model, LC blocks of varying permittivity are shown as the blocks of material ranging in color from red to white. These calculations were performed with CST Microwave Studio.

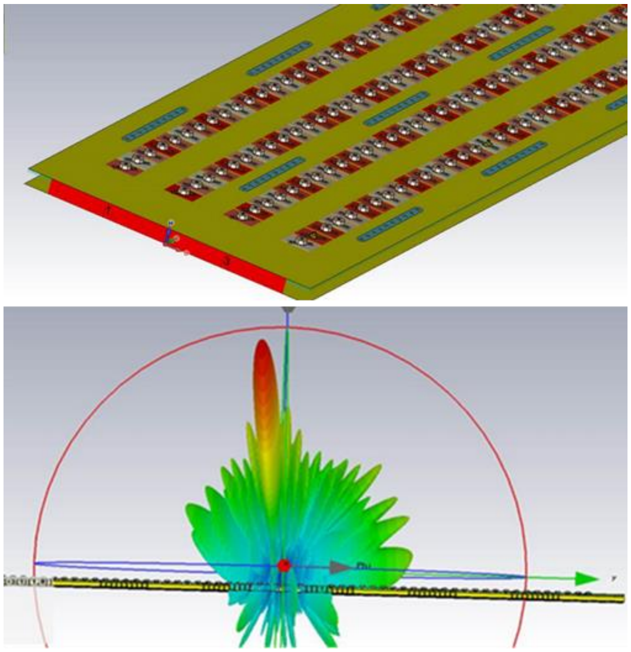


Figure 9. Full wave solid model and simulated radiation pattern for an MSAT antenna segment.

5. Results

With the approach described in this report, Kymeta has built several generations of prototypes (see Figure 10) and has completed a number of critical communications demonstrations across various satellite links. These include:

- Receive-only demonstration on the DirecTV constellation—April 2013
- Full duplex transmit and receive demonstration on Telesat's Anik F2 satellite—Dec 2013
- Full duplex transmit and receive on a non-geostationary constellation—October 2014

These tests demonstrated several key MSAT performance targets, namely automatic acquisition and tracking, conformance of the transmit beam to international regulatory interference requirements, and 10 Mbit/s data rates, both up and down.

Kymeta's latest prototypes have yielded exceptional beam performance and agility, such as:

- > 80% aperture efficiency
- Fully dynamic polarization control
- Cross-polarization discrimination better than 30 dB
- Scan angles to > 60 degrees.
- Axial ratio of 1.2 dB at 60 degree scan angle

6. Conclusions and Impact

Kymeta has demonstrated a novel approach to electronically scanned antenna arrays that offers to fundamentally change the way the satellite communications industry has operated over the last 70 years. The power consumption and cost of Kymeta's approach are roughly 1% that of a phased array, and 10% that of gimbaled dish solutions.

To achieve equivalent scan angle and polarization purity with a phased array, additional wide angle impedance matching layers and active impedance control circuits are required. In addition, dish solutions typically do not achieve such high polarization purity, which impacts the signal-to-noise ratio in the receiver for systems that provide data streams on orthogonal polarizations. Furthermore the aperture efficiency of a dish is typically ~65%, meaning that a larger aperture is required, as compared to MSAT, to produce the same directivity.

Kymeta's latest prototypes, achieved with the use of TFT active matrix addressing schemes, are now aligned with LC display industry components, materials, and manufacturing process. This will allow Kymeta to leverage the LCD industry's manufacturing base and ultimately bring broadband satellite connectivity to high-volume consumer markets.

7. References

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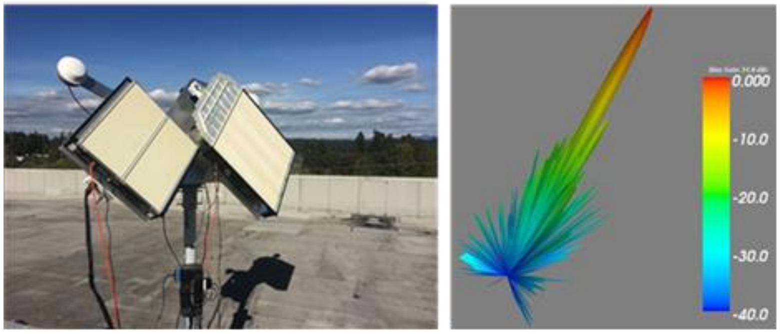

Figure 10. Transmit and Receive antenna assemblies and the measured far field radiation pattern of the transmit array.