Environmental Concerns with Liquid Crystal Based Printed Reflectarrays in Space

D. Doyle, C. Woehrle, D. Wellems, and C. G. Christodoulou

***Abstract*—This project documents testing done with Radio Frequency (RF) materials considered for Liquid Crystal (LC) reflectarray elements for potential space applications. It includes studies of the impact of space simulated environmental conditions. Testing focused on thermal vacuum, electron and x-ray radiation, and surface charging. Tests were performed on individual candidate materials and on a final assembled LC RF element. The following paper summarizes the findings of tests performed to identify design obstacles to the transition of printed LC RF elements for space applications.**

***Index Terms*—Liquid Crystal; reconfigurable antenna; Space environment; 3D printing;**

I. Introduction

ADVANCEMENTS in manufacturing techniques and an interest in less complex RF platforms with better performance, created the demand for new reconfigurable apertures. This inspired a variety of low power reconfigurable approaches [1]. The Air Force Research Laboratory (AFRL) expressed interest in the application of Liquid Crystals (LCs) for reconfigurable antennas because of their utilization in optical applications, claims of radiation robustness, and continuously tunable anisotropic permittivity as a function of applied voltage.

The molecular realignment of the LC molecules under an applied electric field makes the LC phase control mechanical. The time needed for the transition of LCs, $\Delta T_{on/off}$, is determined by LC cavity thickness, elastic moduli, viscosity, control voltages and tunable permittivity range ($\Delta\varepsilon = abs|\varepsilon_{\|}-\varepsilon_{\perp}|$). In Fig. 1, a sample cell shows where the LC reservoir resides between the patch and the ground plane. Biasing lines to the ground plane and the patch extend to the edges of the substrate and are soldered to feed pins connecting to a DC voltage source.

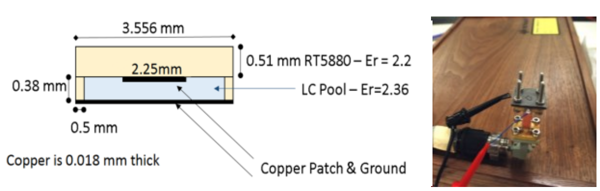

Fig.1 LC unit cell illustration for S-parameter tests under simulated space environmental exposure (left) and actual unit tested (right)

The next figure depicts a two-cell reflector using the profile from Fig. 1 showing a 0-30V charge applied to the patch and the ground connected to the ground plane. Application of voltage between the patch and ground plane with a Merck LC GT3-23002 as the dielectric spacing material, resulted in a loss of resonance and resonant peak shift. This caused a phase shift of 200 degrees. Elements with a greater phase shift potential allow for larger arrays and wider steering angles to be achieved.

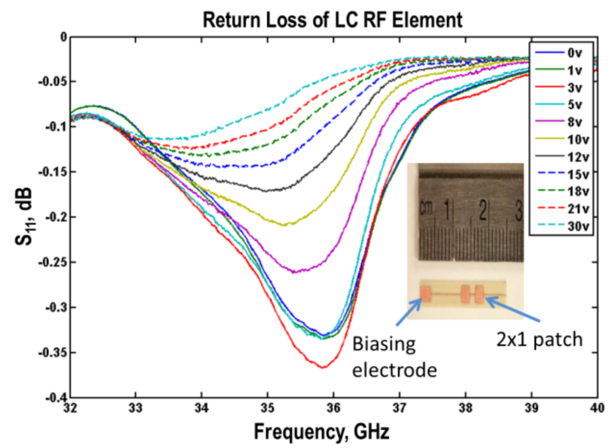

Fig. 2 Reflected power of 2 element LC patch sample designed to 36 GHz as the element is biased with 0-35 V between the patches and groundplane.

The performance of an LC element may be adversly effected by the operational environment. Research and Development (R&D) using LCs for RF applications, focused on antenna theory and performance metrics which allowed researchers to claim space utility [2]. The basis of this claim comes from laser communications [3] which concentrated on performance metrics maintained after neutron irradiation. But this study lacked in-situ measurements to track LC performance under the influence of ionizing particles and merely provided a pre/post test performance degradation assessment.

Many of the proposed concepts for RF applications use simple cavities filled with the LC. This presents a single point of failure if the cavity is compromised. Complex reservoir networks and fluid feed lines might be able to limit this type of vulnerability allowing for graceful degradation. Additive Manufacturing (AM) can address this problem. Today, single stations preform dual processing of dielectric and metallic elements with materials tailored for RF use. An additional printer head feature designed to fill cavities with LC makes printing an entire array without technician handling a possibility for the future. The remainder of this paper shows the impact of what can be expected from a printed LC reflectarray structure when exposed to simulated space environments.

When considering space applications, three operational considerations must be tested that are uncommon for terrestrial architectures:

1. The vacuum of space and the thermal radiative

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environmental extreemes of +/-200C

2. The radiation environment at various orbits encountering charged particles with energies well beyond 1MeV.
3. The charge of spacecraft that build up in dielectrics.

LC RF elements must be exposed as both full assemblies and as individual material components where practical to these environments to assess the possible mechanical and electrical property changes possible of a printed LC RF array.

II. The Thermal-Vacuum (TVAC) Problem

All materials exposed to space must withstand the harsh vacuum of space. The amount of particulates that may outgas from the sample should be minimized as they can condense on colder parts of the system and impact measurements from sensors. Samples are typically exposed to less than 1e-5 torr vacuum and cycled between the expected operational temperature range. For a Low Earth Orbit (LEO) mission, this may be -20C to 80C. Most RF materials meant for space applications, have already been tested and are tailored to survive with minimal change of the material property.

3D printed materials are not as common for space applications. One particular brand of printed filament, Acrylonitrile Butadiene Styrene (ABS) plastic, claimed to meet NASA's outgassing requirements [ASTM E-595-93] of <1% Total Mass Loss (TML) and <0.1% Condensable Volatile Material Loss (CVML). The ABS plastic was 3D printed to make a 5GHz patch antenna substrate. A total of eight samples were made with the ABS plastic.

Four samples utilized copper tape as a conductive patch. Another four samples were coated with MG Chemicals silver epoxy. This layer of painting accommodates traditional AM approaches where printing and conductive ink writing are done concurrently. The copper tape samples focused on temperature effects to the printed dielectric since the tape was vacuum compatible. The painted samples demonstrated a more realistic AM cell but were exposed to vacuum only with no temperature cycling due to concerns with how the paint would outgas at elevated temperatures. All samples were put under 5e-6 torr vacuum for one week. LC was left out of the samples at this point to isolate material effects and reduce test variables expected from degradation.

The painted samples remained at room temperature while the remaining taped samples were attached to a cold plate and driven to temperatures of -25C to 95C to assist outgassing in the ABS. Two of the four heated samples warped at elevated temperatures due to insufficient clamping force on the substrate. The elements were not permanently bonded to a stiffened backing structure, such as a honeycomb composite plate, to maintain stiffness during thermal transitions. However, a more troubling phenomenon is shown in Fig. 3.

Many printing approaches utilize Fused Deposition Modeling (FDM). In this procedure, printable strands are passed through a heater head to soften it for layering and help it adhere to the structure. As the filament becomes heated, then cooled, water vapor collects inside the structure and in the strand. The trapped water escapes under vacuum, creating cracks in the strands and between the bonded layers. For a LC cavity, this risks creating fissures. This allows the LCs to permeate through the material due to strong capillary forces and a high degree of wetting from the LC. Coating methods, like epoxy infiltration, may protect printed strands from this degradation mechanism. However, this method may fill capillary channels and LC reservoir spaces prior to filling. For the printed samples, weight measurements indicated the moisture reabsorbed within a week of being in the atmosphere.

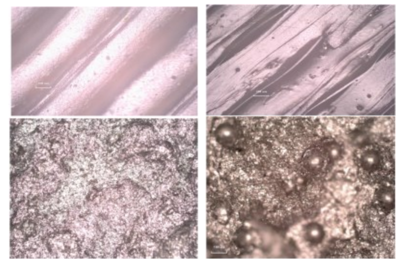

Fig. 3 Optical microscope measurements made before (left) and after (right) thermal-vacuum testing where images show printed (top) and paint (bottom) effects.

The effect of outgassing had a major impact on the conductive paint applied to the samples. The trapped gas came up under the paint causing some spots to bubble and pop. Overall the painted structure was cracked to the point of increasing surface resistivity from 17.4mΩ-cm to effectively >1MΩ as a 4-point surface resistivity meter was unable to consistently find sufficient path conductance. The element was unable to perform as an antenna after exposure. As a result, this type of conductive layer should be avoided to preserve surface conductivity or a more robust material is needed.

For the non-painted samples the outgassing changed the resonance of the copper patch antenna. As water returned to the system, the radiation pattern shifted 40 MHz, returning to the starting resonating frequency. It is believed that as water vapor returns to the sample and replaces the nitrogen backfilled gas residing in the material that a small change in the substrate dielectric properties restores the bulk permittivity of the dielectric.

FDM materials that require higher temperatures like Ultem or PEEK may capture increased levels of moisture, creating larger potential for mechanical change. To avoid this problem, 3D printed RF materials should be manufactured in nitrogen chambers which would remove moisture from the build. Parts should be printed so that cavities are not formed until layers are pressed together. This allows infiltration and coating methods to better hermetically seal the parts without blocking fluid channels. Potting of the final assembly is also advised.

Further research will be needed to understand the role of the coefficient of thermal expansion differences among the assembled materials to assess the likelihood of propagation and crack formation. In terms of the LC material, researchers must understand the relationship temperature has on the viscosity of the LC substrate and the resulting capillary forces. Reduced temperatures, as experienced in space, will certainly increase the viscosity of the material. If researchers wish to mitigate the wetting of a nematic LC, then polymerization may also be an effective approach to mitigate flow through possible

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cracks. However, increasing viscosity will lead to a higher Fréedericksz transition requirement and an increase of the turn off transition time [4].

III. Radiation Concerns

The potential hazards of space weather are well known for causing anomalies [5]. As proton, electron, and heavy ions impact a structure, their kinetic energy allows them to penetrate some distance based on the densities of the substrate and the energy level of the particle. As the energy level of a proton, electron, or ion particle increases from 10s of keV to MeV, the particle penetrates the surface. These particles interact with dielectric materials and can cause damage in certain polymer molecules by separating atomic bonds. The effects may be recoverable with heated annealing or irreversible due to outgassing constituent molecules. Depending upon the reactivity of the broken molecular chain, it may also change the properties in terms of mechanical and electrical parameters. For LCs that contain long molecular chains of phenyl rings, and associated organic bonds consisting of carbon, nitrogen, oxygen, etc., many of the possible constituents are gasses. These may interfere with the LCs anisotropic properties or outgas through permeation of the vessel walls. These effects need to be understood for possible materials to understand the cumulative effects and operational performance degradation from beginning to end of system life.

As LCs have already been shown to hold up to heavy neutron radiation [3], this research focused on an electron source to provide ionizing particles. Given the problems seen in the FDM samples during vacuum, Stereo-lithography (SLA) ABS samples were prepared and exposed to a Strontium-90 (Sr-90) source that provided a spectrum of beta electrons ranging from ~150keV to 2.5 MeV. Samples were spaced from the source to allow propagation from the Sr-90 disk to cover the sample. The equivalent flux equated to about 2-5 days of a Geostationary Orbit (GEO) exposure in terms of the lower energy spectrum around 150keV and closer to 1-2 months in regards to energies greater than 1MeV. This can be obtained by comparing the electron flux emissions of Sr-90 to that of an AE9 model of the GEO fluxes and setting exposure time in the chamber. No sources currently exist which accurately replicate the GEO radiation spectrum on Earth.

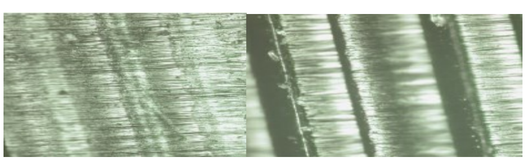

Fig. 4 Printed substrate before (left) and after (right) Sr-90 exposure illustrating the manifestation of defects where top picture shows between printed layers and bottom shows face of a single layer with increasing defects.

Exposure caused visible warping in the printed sheet indicating bond breaking in the polymer substrate. This expansion of the dielectric caused layer interfaces to dislocate and created fissures of up to 35μm wide to form between layers. The previous discussion suggested that outgassing problems could be solved with epoxy or coatings to create hermetic seals. However, this expansion would likely crack parylene coatings or other epoxies traditionally applied to electronics and would allow a fluid cavity to depressurize if housing a fluid nematic LC.

The rate of LC leakage through such a defect would be dependent on how far the defect permeates into the vessel, the pressure differential between the LC cavity and the external vacuum, the temperature of the LC which will affect its viscosity, and the tortuosity of the crack (is it a straight through penetration or are there a lot of curves. While the crack opening in Fig. 4 indicates a 35μm gap, there is layering between the printed channels that may help minimize leakage of the internal fluid channels. While ABS is not a suitable RF dielectric due to its high lossiness [6] and poor space worthiness, it does give an idea of what problems may manifest with an AM approach. In order to monitor an assembled LC RF element, the study moved to more common RF dielectrics that may one day be available for SLA resin-type solutions or filaments for deposition modeling.

Duroid RT 5880 and Rogers TMM3 were selected for a quick evaluation of material worthiness prior to making an LC RF element for further testing. Each was exposed to rapid aging of 200 krad and 1 Mrad total dose X-ray (50 keV) and Cobalt-60 (140 keV) sources. The RT 5880 samples seemed to tolerate the lower dosages. Higher dosages made the TMM3 blend more brittle and showed a 6% reduction in permittivity and change in loss tangent at frequencies above 60 GHz into the E-band range. It should be noted that in an accelerated exposure test, materials are not given the chance to anneal naturally as they would in the environment of space. This means that degradation of materials seen on the ground may not occur in space. The Duroid RT 5880 sample proved to have the least degradation and change after material exposure tests and was used to build a test sample LC reflectarray patch shown in Fig. 1.

IV. Consideration of Surface Charging

As mentioned before, radiated particles in space interact with spacecraft. Penetrating electrons can deposit charge within the dielectric materials in an assembly. It deposits a charge in the structure extending from the surface to the point where it finally stops. At this location, the remaining energy releases. This energy burst becomes larger than the deposited charge left along the trace. For LC structures, these deposited charges may pose problems. The resultant electrons and the subsequent holes they form to offset the deposited charge, can create unintended E-fields in the anisotropic LC.

In electronics, the concerns about these E-fields relate to exceeding transistor or switch limits causing single event effects (SEEs) like latch-ups. But with LC, the field only needs to exceed the Fréedericksz transition limit to create problems. These events can reorient an unbiased LC region, or add to an applied field to change the expected load.

To illustrate this phenomenon, a Duroid 5880 sample was exposed to a 20 keV electron beam gun in a vacuum chamber. This characterized the sample's charging and radiation induced current properties. Dielectric surface voltages developed due to small volume resistivity. Measured values in

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a 20keV e-beam experiment indicated ~ $7x10^{10}$MΩ-cm and a discharge constant of $\varepsilon_0\varepsilon_r/\sigma$ ~ 5000s. These properties can be modeled with the patch configuration from Fig. 1 to show possible resulting fields generated in an unbiased LC RF element.

Fig. 5 shows a calculated 2D field of the layup shown if Fig.1 when exposed to a deposited electron flux associated to just one energy level of a complex orbital environment. In this case the source is 20keV depositing a total surface charge of 6e-8C/cm^2. Without the presence of charging electrons the region under the biased patch would be uniform based on applied charge. When an incident charging flux is applied, LC distortion from charging initiates at the patch edges and propagates toward the center with increasing flux intensity. The effect of deposited charge for this layup is significantly less than the full biasing voltage of 30V resulting in 80kV/m in the LC region. It is therefore expected that the impact of a charged environment will be of concern more for understanding the unbiased state of a particular LC RF element.

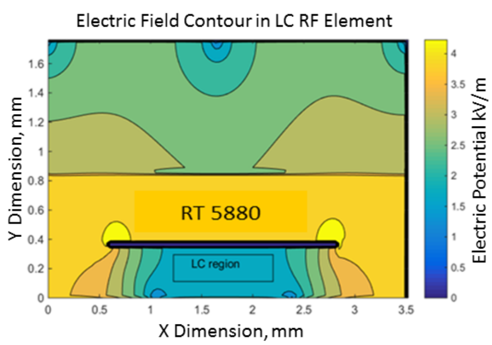

Fig. 5 Simulated Field build up in LC RF element based on 20 keV electron beam tests.

To observe this phenomenon, an open chamber exposure test was performed using Sr-90. A sample distance of 12 inches reduces the 'GEO' simulated intensity to ~1/3 the natural exposure rate. Energies below 150keV are not emitted by the source. But some level of energies down to the 10s of keV, bleed off as particles penetrated the surface. The modeling capability to properly show this non uniform distribution is still under development [7] and as such, empirical analysis is required.

Return loss and phase measurements were taken for the unit cell in a biased state from 0-30V. The cell was returned to an unpowered state and the Sr-90 source was introduced. While no immediate impact was observed during 2 hours of exposure, post analysis of the resulting phase and overlapped reflection loss profiles revealed measurable effect of the Sr-90 exposure, as seen in Fig. 6.

Sr-90 exposure alone does not initially exceed Fréedericksz transition but it helps to provide more biasing force at various charging states up to 30V. This is illustrated in Fig. 6 where the phase was extracted from the return loss measurement for environmental states and the percentage difference between charged states in both environments was calculated. As expected, the fully biased cell deviates little (<5%) over the measured range in a charged environment. However at 18V and at a relaxed 0V state, significant differences exist. Once the cell is unpowered, under a charged environment, it is unable to return to a fully relaxed state due the residual charge counters the anchoring force provided by the LC orientation layer on the 5880 substrate. The effect on return loss appears small, but the resulting percentage difference of compared phase between the irradiated and non-radiated samples can differ by up to 35%. Without knowledge of this increased field influence or mitigation of it, phase of LC RF elements will be difficult to predict in an operational environment complicating array beamforming.

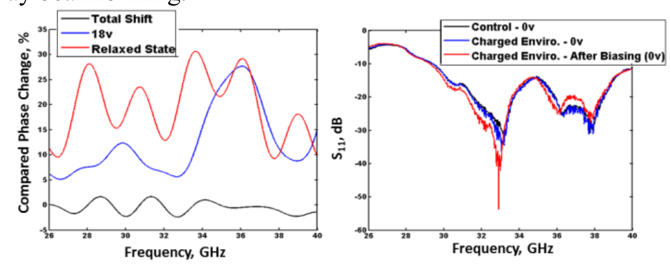

Fig. 6 Phase difference between exposed and unexposed samples(left) and the return loss for the LC cell with and without the Sr-90 source(right).

V. Conclusions

This study provided insight into challenges facing the transition of printed LC RF elements to space applications. TVAC creates loss of material through outgassing, warping, crack propagation. Radiation exposure can cause bond dislocation, constituent gasses from damaged molecules, and deposit charge. Charging induces electrostatic potentials augmenting expected bias states complicating phase control. While AM may aid in producing complex dielectric bodies to accommodate reconfigurable LC RF elements, the identified issues must be addressed.

LC RF element layups need to be designed to minimize the influence of deposited charges on LC reservoirs. Future designs should minimize the volume of LC considered and isolate it from radiation induced charge. Charging effects near the biasing interfaces may be mitigated by leaving no LC regions uncovered by a grounded structure.

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