# RF Characteristics of Thin Film Liquid Crystal Polymer (LCP) Packages for RF MEMS and MMIC Integration

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***Abstract*— A standard non-metallized liquid crystal polymer (LCP) 4 mil thick microwave substrate with depth-controlled laser-micromachined cavities was investigated as a system-level packaging layer for integrated packaging of monolithic microwave integrated circuits (MMICs) and radio frequency microelectromechanical systems (RF MEMS) switches. The RF characteristics of air/dielectric discontinuities at the cavity interfaces were first simulated and the results show that LCP's low dielectric constant enables cavity dimensions to be arbitrarily chosen without significantly affecting the RF performance. To test this packaging concept a 4 mil LCP sheet with twelve 1 mm x 2.4 mm x 2 mil deep cavities was fabricated. Air-bridge type RF MEMS switches were fabricated on a base LCP substrate and measured before and after introducing the laser-micromachined superstrate layer. The measurements show almost no difference in packaged and unpackaged form for frequencies up to 40 GHz. The concept of a system-level package on a flexible, low-cost, organic substrate has been demonstrated for the first time. The same technique could be used for integrating MMICs all in a near-hermetic low-cost LCP module.**

***Index Terms*— Organic, package, LCP, interconnect, MEMS, laser machining, system-on-package, RF module.**

## I. Introduction

As RF systems' operating frequencies continue to rise, system reliability becomes increasingly reliant on hermetic or near hermetic packaging materials. Higher frequencies lead to smaller circuits, and low material expansion (which is related to water absorption) becomes more important for circuit reliability and to maintain stable dielectric properties. Equally important is the ability to integrate these materials easily and cheaply with different system components. The best packaging materials in terms of hermeticity are metals, ceramics, and glass. However, these materials often give way to cheaper polymer packages such as injection molded plastics or glob top epoxies when cost is a driving factor. Plastic packages are great for cost and ease of fabrication, but they are not very good at keeping out water and water vapor. Ideally, a hermetic polymer would be available that would have an inexpensive material and fabrication cost while still functioning as a good microwave and mm-wave package.

A material called liquid crystal polymer (LCP) nearly satisfies these criterion. LCP has drawn much attention for probably having the best packaging characteristics of all polymers. LCP has been called near-hermetic and has also been compared to glass in terms of water transmission. Previous literature has described the numerous benefits of LCP including [1]-[3]:

- Near-hermeticity
- Low coefficient of thermal expansion (CTE) which may be engineered to match metals or semiconductors
- Natural non-flammability (no need to add halogens, etc.)
- Recyclability
- Flexibility for conformal and/or flex circuit applications
- Excellent high frequency electrical properties

In academia, solid state devices such as pin diodes have been packaged in LCP [4]. In addition, several companies have recently developed injection molded LCP packaging caps [5], [6], which can be used to seal individual components with epoxy or laser sealing. However, these packages can be bulky which may limit the packaging integration density. In addition, these rigid packaging "caps" (LCP becomes rigid when it has sufficient thickness) can take away one of the LCP substrates very unique characteristics – flexibility.

In this paper, the concept of packaging numerous devices with a standard thin-film LCP layer is presented. To accomplish this goal, a 4 mil non-metallized LCP superstrate layer with depth-controlled laser micromachined cavities is investigated as a package. This technique is demonstrated by creating packages for air-bridge RF MEMS switches. The switch membranes are only about 3 $\mu$m above the base substrate which allows a cavity with plenty of clearance to be laser drilled in the LCP superstrate layer. A cavity depth of 2 mils ($\sim$51$\mu$m) [half of the superstrate thickness] was chosen for the MEMS package cavities.

This technique could be extended to include additional layers as necessary. To accommodate devices that require more vertical clearance, multiple LCP layers could have holes or cavities drilled in them and the layers stacked together. The packages can be sealed with thermocompression, ultrasonic, or laser bonding.

The purpose of this paper is to investigate the RF characteristics of the discontinuity introduced by the LCP package cavities. In addition, it presents a new way to package RF MEMS switches or MMICs, where multiple devices may be located across an LCP substrate and the package fitted across both the transmission lines and the devices at once. Several advantages of this technique are: the flexibility of the substrate is maintained for applications such as conformal antennas, the package is light weight, and the LCP packaging layer is a standard inexpensive microwave substrate which can be made into any system-level package configuration. Two primary applications are large-scale antenna arrays with packaged ICs and/or switches inside of a multi-layer antenna substrate, or vertically integrated LCP-based RF modules where switches and/or active devices may be bonded inside of a multi-layer LCP construction.

## II. Simulated Transmission Line Characteristics With Packaging Layer

Since LCP has a low dielectric constant near 3.16 [7] (close to free space $\epsilon_r$=1), impedance mismatches are minimal when an LCP superstrate layer is added on top of a standard transmission line. In addition, if cavities are machined in the superstrate layer, they do not create large impedance mismatches at the cavity interface. Thus, LCP's low dielectric constant could enable package cavities of arbitrary size to be integrated in a superstrate packaging layer to accommodate chips, MEMS, or other devices without concern for the parasitic packaging effects. The LCP superstrate layer would be bonded with a 1 mil thick low melting temperature LCP bond layer to create an all LCP package. The seal would be created by the low melting temperature LCP (290°C) layer, which has the same electrical characteristics as the high melting temperature (315°C) core layers. To determine the utility of such packaging structure we first investigated the RF characteristics of transmission lines with superstrate layers and various packaging cavities.

### A. *Ideal Transmission Line Cross Sections*

Fig. 1 shows three different transmission line cross sections and the impedance difference between them. These cross sections were simulated and the impedance values were calculated with Ansoft HFSS. The first cross section is a standard conductor-backed finite ground coplanar (CB-FGC) line, the second includes a 4 mil superstrate packaging layer, and the third has a 2 mil laser machined cavity in the superstrate layer. The impedance difference of only 4 Ω between a transmission line with a superstrate layer vs. those with a cavity or without a packaging layer creates minimal reflections at the dielectric discontinuity.

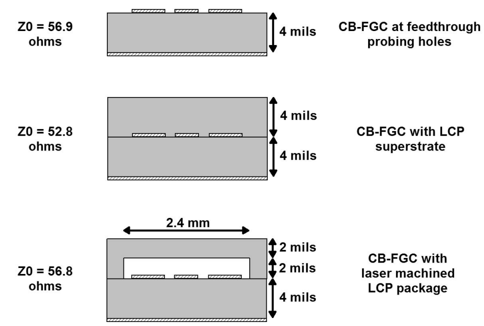


Fig. 1. Three different CB-FGC cross sections present in the measured packaging structures. Impedance values are from HFSS 3D simulator for an CB-FGC with signal width S=200 $\mu$m, gap G=120 $\mu$m, and $\epsilon_r$ = 3.16. $Z_0$ only differs by 4 Ω for the three different cross sections.

### B. *Simulated Signal Reflection with Varying Cavity Size*

To determine the effects of varying the cavity dimensions, the impedance of each cross section of our CB-FGC was found using Ansoft HFSS. Then these impedance values were input to Agilent ADS and a circuit model was simulated for all combinations of transmission lines with these impedance discontinuities. With $Z_0$ = 53 Ω and 57 Ω for our feeding and cavity segments respectively, the worst case value obtained for any combination of feed line lengths and cavity lengths is $S_{11}$ = -17.7 dB. Most combinations yield $S_{11}$ below -20 dB and optimal transmission line length and cavity length combinations yield $S_{11}$ close to -40 dB. Because $S_{11}$ values less than -20 dB correspond to power reflection $< 1\%$, the package cavity size can be chosen almost at random to fit any desired device. Fig. 2 shows an optimal design for 20 GHz operation where the feed lines are $\lambda_G/4$ at 20 GHz and the cavity length is swept from $\lambda_G/24$ to $\lambda_G$.

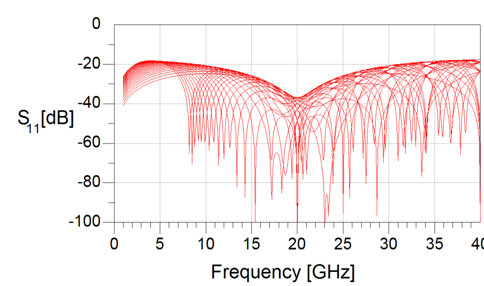


Fig. 2. $S_{11}$ for cavities with electrical lengths from 0-360°. The CB-FGC in the cavity has $Z_0$ = 57 Ω and the CB-FGC with superstrate feeding the cavity has $Z_0$ = 53 Ω. The feeding CB-FGC lines are $\lambda_G/4$ at 20 GHz which is an optimal configuration for minimizing the already low reflections.

## III. Package Fabrication

### A. *Laser Machining*

A $CO_2$ engraving laser with a 10 $\mu$m wavelength was used to drill holes in the LCP superstrate layer. The $CO_2$

laser was selected for this job due to its high power and the corresponding fast cutting rate. Circles were cut out in the four corners for pin alignment and square or rectangular windows were removed in specified locations for the probe feed-throughs. The alignment holes and feed-through holes were drawn in AutoCAD, programmed into the laser software, and the cuts were made concurrently in a single laser run.

Next, an excimer laser was used to micromachine depth-controlled cavities in the desired locations. The stage was aligned to the already cut holes from the $CO_2$ laser and the laser was again programmed to fire in a predetermined pattern. The optical alignment was limited by the large aperture size, but the accuracy was estimated to be within 100 $\mu$m at the worst case. The lateral cavity dimensions were chosen to be oversized enough that this potential alignment error was not a concern. With smaller apertures, alignment with the excimer laser of better than 10 $\mu$m can be accomplished.

The laser power and the number of pulses were tuned to provide the desired ablation depth into the LCP superstrate. We arbitrarily chose to make cavity depths half of the substrate thickness (2 mil deep cavities). Shallower or deeper cavities are possible by varying the laser power and the number of pulses. A custom brass aperture with a rectangular hole was used to shape the beam to the desired cavity shape and size. This aperture size of 12 mm x 5 mm was demagnified five times to create a cavity 2.4 mm wide x 1 mm long. After machining the cavities, the depth was checked with a microscope connected to a digital z-axis focus readout with accuracy to the nearest tenth of a micron. The depth across the bottom of the cavities was not completely uniform due to some small burn marks on the laser optics, but it was within $\pm$5 microns of the desired depth across the entire cavity.

The completed package layers were made such that the alignment holes corresponded to the same location as those on the through-reflect-line (TRL) calibration lines and also on the MEMS switch samples. The package was aligned and stacked over the MEMS substrate with the assistance of four alignment pins as seen in Fig. 3.

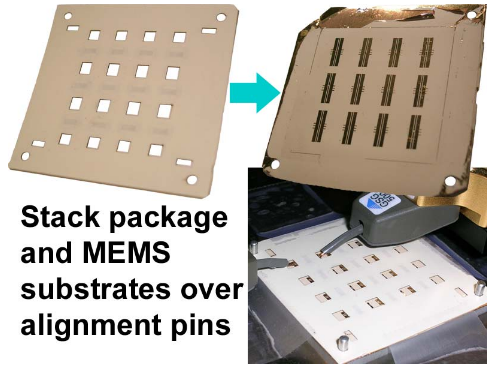


Fig. 3. Top left: LCP superstrate packaging layer with holes for alignment and probe feed-throughs. The packaged cavities between each set of probing holes are visible due to LCP becoming partially transparent at a 2 mil thickness. Top right: CB-FGC transmission lines with air-bridge RF MEMS switches in the center of the transmission lines. Bottom right: Both layers stacked on alignment fixture and probed through the feed-through windows.

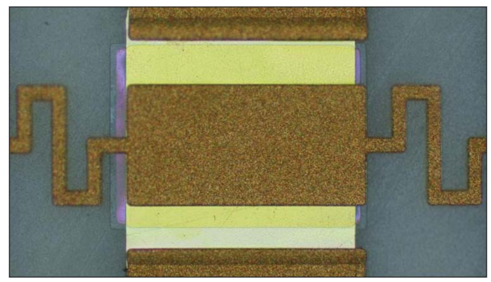

Fig. 4. Fabricated RF MEMS switch.

## IV. Results

### A. *RF MEMS Switch Performance with Package Cavities*

The MEMS switches are comprised of a 2 $\mu$m thick electroplated gold doubly-supported air-bridge layer suspended approximately 3 $\mu$m above the lower metal layer. The 100x200 $\mu$m membrane is suspended over the signal line of a CB-FGC transmission line and anchored to the ground planes on both sides. In the default state, the membrane is up, in which case full signal transmission should take place. When a DC actuation voltage is introduced, the membrane is flexed down into contact with a thin silicon nitride layer between the two metal layers and creates a capacitive short circuit that blocks signal transmission. A picture of a fabricated MEMS switch is shown in Fig. 4.

Because MEMS switches are by nature fragile, an iterative measurement procedure was undertaken. First the switches were measured in air to provide a base measurement case. The second and third measurements were done with the package layer aligned and held into contact with the base substrate. The first packaging iteration was done by gently holding the package layer down over the MEMS substrate with tape. When the switches continued to operate with the package layer in place, this ensured that the alignment of the package cavities was successful. Finally, the top metal plate was placed over the alignment pins and a fifteen pound weight was balanced on top of the samples to simulate the pressure from a bonding process. The plate was removed and the samples were re-measured. Results for these measurements are seen in Figures 5 and 6. The S-parameters of the packaged switch and the non-packaged switch are nearly identical in both the up and down states. For example, the variation between the three measurement cases for $S_{21}$ in the UP state only varies by an average of 0.032 dB across the entire measurement band. The other S-parameter comparisons with and without the package layer are very similar.

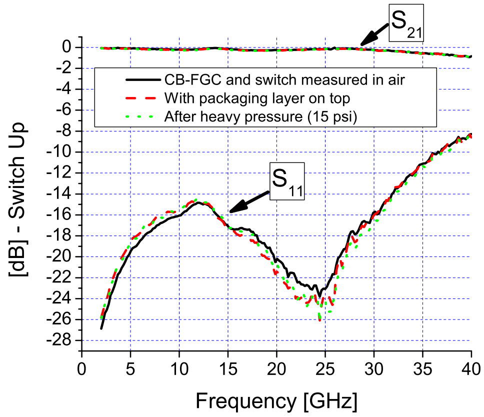


Fig. 5. Comparison of S-parameter measurements of an air-bridge type CB-FGC MEMS switch in the "UP" state. Case 1: The switch is measured in open air. Case 2: The packaging layer is brought down and taped into hard contact and measured. Case 3: A top metal press plate and a fifteen pound weight are put on top of the packaging layer (15psi) to simulate bonding pressure. The weight and the press plate are then removed and the switch is re-measured.

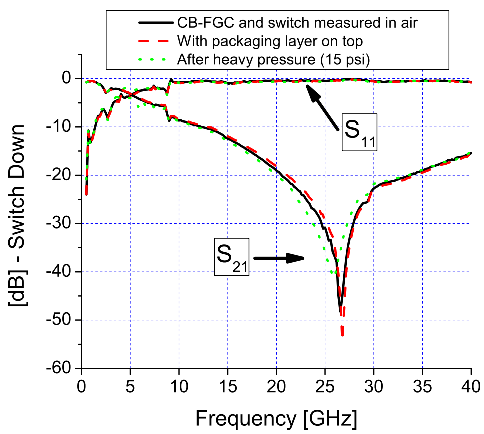


Fig. 6. Comparison of S-parameter measurements of an air-bridge type CB-FGC MEMS switch in the "DOWN" state. The three measurement cases shown are the same as those explained in the caption for Fig. 5.

### B. *Transmission Lines with Package Cavities*

To show the effects of the packaging layer and cavity on a simple transmission line the switch membrane was physically removed and the circuit re-measured. The results of the bare transmission line with and without the packaging layer are shown in Fig. 7. As expected from the simulations, the cases with and without the packaging layer are very similar.

## V. Conclusion

The RF characteristics of thin film LCP packaging layers with laser micromachined cavities have been investigated for frequencies up to 40 GHz. Due to LCP's low dielectric constant, the air/dielectric discontinuities in these packaging structures were found to be insignificant. Thus, the package cavities can be designed with this method almost arbitrarily without concern for their effect on RF performance. To test this packaging structure, RF MEMS switches and plain transmission lines were fabricated and measured with and without an LCP packaging layer. S-parameter measurement results showed little to no difference with or without the package. This technology could pave the way for simple, low-cost, near-hermetic, system-level packaging structures.

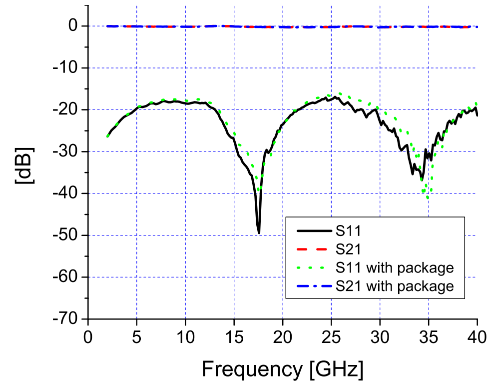


Fig. 7. Comparison of S-parameter measurements of the MEMS switch transmission line after the switch was physically removed. The cases with the package and without the package layer are nearly the same.

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