W-Band Characterization of Finite Ground Coplanar Transmission Lines on Liquid Crystal Polymer (LCP) Substrates

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Abstract

Liquid Crystal Polymer (LCP) is a material with properties that suit it well as both a substrate and packaging material. LCP's multi-layer lamination capabilities, excellent electrical properties, and near hermetic nature suit it to a wide range of RF applications. Several frequency bands of interest, such as evolving applications in the 60 GHz band and military use at 94 GHz, could potentially benefit from the use of LCP system on package (SOP) devices. To test the viability of LCP at these frequencies, a conductor-backed coplanar waveguide (CBCPW) on a 50 micron LCP substrate was fabricated and measured from 2 – 110 GHz. For measurement accuracy and substrate characterization, a through, reflect, line, (TRL) calibration was performed according to the National Institute of Standards and Technology (NIST) guidelines. For the first time, LCP is characterized as a mm-wave circuit substrate up to 110 GHz.

Introduction

Liquid Crystal Polymer has recently received much attention as a high frequency circuit substrate and package material. LCP has impressive electrical characteristics that are environmentally invariant due to extremely low water absorption [1], and it provides a nearly static dielectric constant across a very wide frequency range [1, 2]. Thermal expansion characteristics are equally desirable. For circuit applications, the controllable coefficient of thermal expansion (CTE) can be engineered to match either copper or silicon [3]. LCP is flexible, recyclable, impervious to most chemicals, and it is stable up to its high melting temperature (280°C or 335°C). LCP possible applications include use as a substrate for multi-layer antenna arrays capable of being folded or rolled, use as a flexible dielectric in radio frequency micro-electro-mechanical systems (RF-MEMS), or use as a dielectric and/or package for capacitors, inductors, vertically integrated designs and many other microwave components. In addition, LCP is much cheaper than traditional materials such as Kapton, Teflon, and LTCC [3, 4]. These benefits assure LCP to compete favorably in many existing and future markets.

LCP research to date has focused mainly on process related issues. Processes have been developed that allow LCP films to be manufactured consistently with good uniformity and strength. Important issues such as copper-LCP adhesion and via formation/plating have also greatly improved over the course of the last year. These advances have facilitated multilayer lamination and vertical integration capabilities. As a result, fabrication of multilayer LCP-based circuits is now becoming a feasible and repeatable process. However, the potential of LCP in microwave and mm-wave devices and circuits has not been fully explored from a materials characterization standpoint.

The design, fabrication, and measurement of transmission lines on LCP using the TRL calibration technique is performed in order to provide the frequency dependent attenuation, effective dielectric constant, and propagation constant through W-band frequencies.

Design

The CBCPW design was selected to accomplish several goals. The first consideration was to ensure compatibility with 150 micron pitch ground-signal-ground (GSG) 110 GHz RF probes. The CPW probe contacts are excellent for high frequency measurements, but they require relatively small circuits for proper contact. The ground contacts from the probe should have a minimum spacing of 50 μm between the contact point on the ground plane and edge of the gap. To meet these requirements, and to make a 50 Ω line that would closely match the vector network analyzer (VNA), the structure in figure 1 was devised. Note that the conductor backing and LCP substrate extend at least 3 mm in all directions beyond the edges of the CPW structure. This dimension is too large to include in this scale.

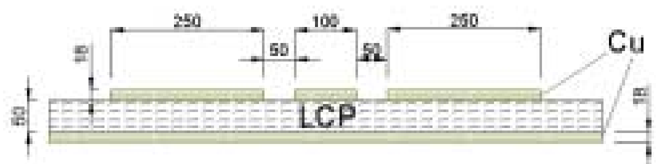

Figure 1. CBCPW designed for optimal W-band TRL measurement.

LCP substrates of 50 microns, 100 microns, and 200 microns from Rogers Corporation were available for selection. The material parameters for the Rogers LCP are as follows:

Cu clad	Cu Thickness	ε_r	tan δ
Double	18 μm	2.9	0.002

Table 1. Rogers Corporation LCP Parameters

Based on these material parameters and the previous dimensional restrictions, simulations were carried out to determine the final CPW design. HP Advanced Design System was used to find the expected characteristic impedance for CBCPW lines for each substrate thickness. The 50 micron substrate provided the closest match to 50 ohms, while still meeting our dimensional requirements. Although 50 ohms is not necessary, it does allow for much less reflection at the probing discontinuities.

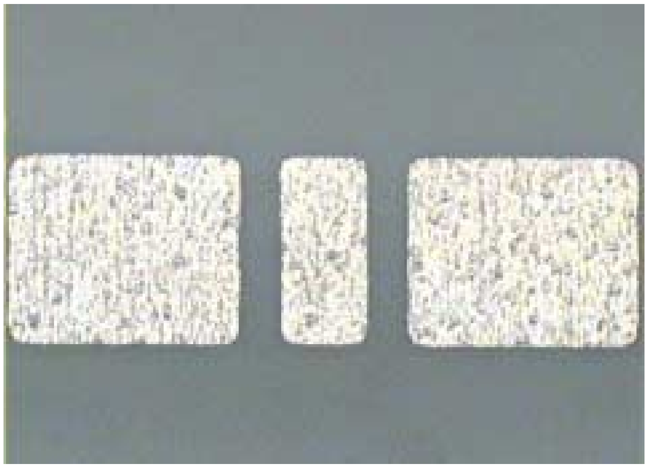

Figure 2. Photo of CBCPW transmission line on LCP.

In addition to the finalized dimensions for the transmission line, TRL line lengths were calculated to be consistent with the NIST protocol. Starting with the ε_{eff} value given by HP-ADS for the selected transmission line, and choosing 500 µm for the thru line length, equations (1)-(3) were used to ensure proper overlap of the delay calibration lines. First, the physical length of each delay line was estimated and plugged into the equations along with the other pertinent information. The result produces the lower, F1, and upper, F2, cutoff frequencies. Between these frequencies the designated delay line will provide adequate calibration coverage. An ideally calibrated frequency will be at F90, which is the center of the valid frequency range for a given delay line. The delay lines selected for the CBCPW in this experiment gave a liberal overlap of these covered frequency ranges.

Below, the n subscript is for the nth delay line and T subscript corresponds to the through length.

$$F1 = \frac{c \times 20}{\left(PhyLength_n - PhyLength_T\right) 360 \sqrt{\varepsilon_{eff}}} \quad (1)$$

$$F90 = \frac{c \times 90}{\left(PhyLength_n - PhyLength_T\right) 360 \sqrt{\varepsilon_{eff}}} \quad (2)$$

$$F2 = \frac{c \times 160}{\left(PhyLength_n - PhyLength_T\right) 360 \sqrt{\varepsilon_{eff}}} \quad (3)$$

Table 2 shows the final TRL line lengths and types used for the LCP characterization sweep.

Line Type	Line Length
Delay 1	1.50 cm
Delay 2	0.40 cm
Delay 3	0.24 cm
Delay 4	0.10 cm
Reflect/Open	0.025 cm
Thru	0.050 cm

Table 2. TRL lengths.

Fabrication

The patterning of the completed design was carried out using a standard photolithographic process and a wet chemical etch. The fabrication was optimized by completing fifteen 4” x 4” boards, each with forty-eight complete sets of TRL lines. As might be expected, the last board produced the best transmission lines for measurement. These lines were used in the measurement.

Measurement

An Agilent 8510XF VNA fitted with Cascade Microtech 150 micron pitch probes was used to carry out the measurement. Multical and HP BASIC Version 6.32 were used to collect the calibration data from the VNA and de-embed the error terms. 401 data points (maximum) were taken across the valid sweep range from 2 – 110 GHz. 20 samples were taken at each frequency and averaged to achieve stable results. HP BASIC was then used to view and output the data. From the complete set of measurements the following data was retrieved:

1) Twelve term error model
2) Attenuation vs. Frequency
3) Real and Imaginary Parts of the Effective Dielectric Constant
4) Relative Phase Constant vs. Frequency

The twelve term error model is fed electronically back into the VNA. Items (2) through (4) are included in the plots below.

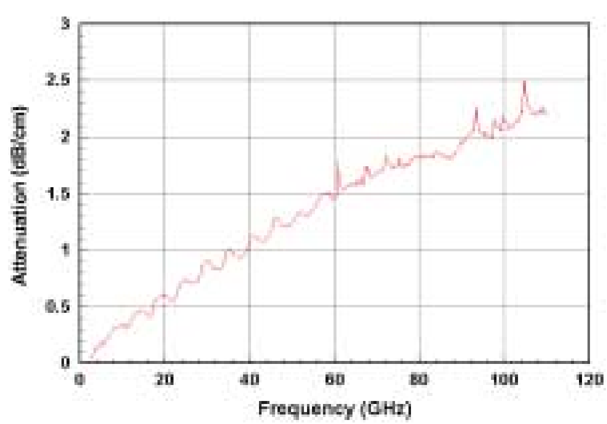

Figure 3. Attenuation vs. Frequency for 50 µm LCP substrate CBCPW

Figure 3 shows the attenuation in dB/cm to be almost linear vs. frequency. The slope appears to decrease slightly as frequency increases. Some notable frequencies and their measured attenuation values are listed in Table 3.

Frequency (GHz)	Attenuation (dB/cm)	Applications
5.78 GHz	0.178	802.11a, cordless phones
13.88 GHz	0.461	Precipitation sensing
34.94 GHz	1.008	Precipitation sensing
60.05 GHz	1.469	High BW short range wireless
94.07 GHz	2.068	Military
104.60 GHz	2.51	Highest attn. observed
110 GHz	2.235	Highest frequency measured

Table 3. Selected application frequency values of attenuation constant

The frequency values listed above correspond closely to several practical applications bands. The exceptions are the attenuation value at 104.6 GHz, which is the maximum attenuation observed across the entire measured range, and the attenuation at 110 GHz, which is the highest frequency measured. Due to the non-infinite number of data points taken, the frequencies listed are the closest approximations to familiar bands rather than exact values.

Comparing LCP with other traditional mm-wave substrates, such as GaAs, over the same frequency range reveals a surprising similarity. LCP and GaAs have a very similar attenuation response in the 2 – 110 GHz range. For potential integration at higher frequencies, this gives LCP good initial implications.

The next characteristic measured is the effective dielectric constant versus frequency. Figure 4 includes both the real and imaginary values for ε_{eff}.

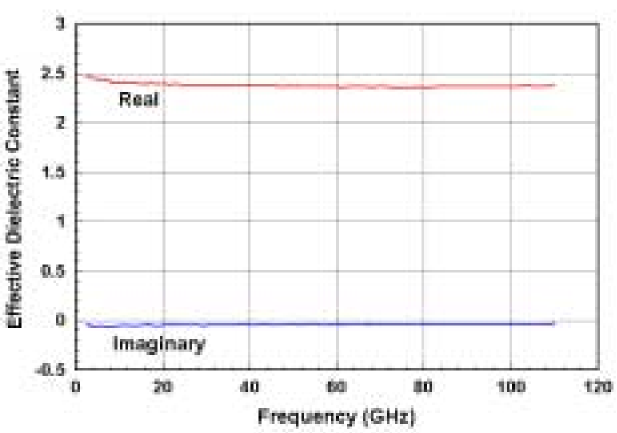

Figure 4. Real and imaginary effective dielectric constant versus frequency

The real part of ε_{eff} value has a minimum value of 2.355 and a maximum of 2.474. However, for a large majority of the frequency range, the value stays very steady somewhere between 2.36 and 2.37. This reveals an almost pure TEM mode of propagation over the entire frequency range. The imaginary part of ε_{eff} is a very small negative value close to zero. The plot in Figure 4 shows that Rogers LCP has an almost constant dielectric performance from 2 – 110 GHz.

Figure 5 is the relative phase constant versus frequency. The relative phase constant varies from 1.5346 to 1.5729. However, again a nominal value is dominant over a wide frequency range. The value of 1.54 is almost constant from 20 GHz to 110 GHz.

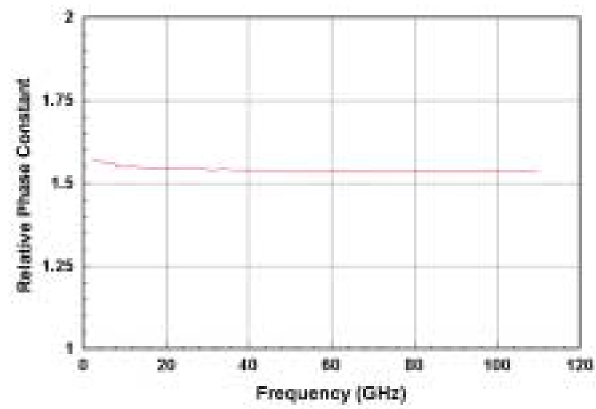

Figure 5. Relative phase constant versus frequency

As a verification step, after uploading the 12 term error model back into the VNA, an S-parameter measurement was performed to observe the characteristics of the 0.24 cm long delay line. Since the through line length was 500 µm, a reference plane 250 µm from the end of each line is implied. Thus, the 0.24 cm line would then be expected to measure like a 0.19 cm line. S-parameter results are as follows.

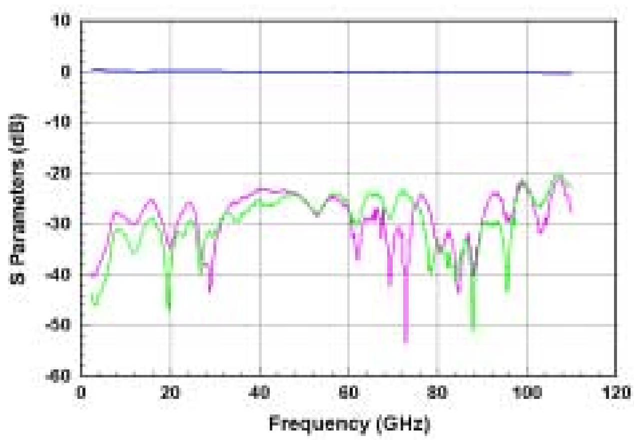

Figure 6. S-Parameter Measurement Data of the 0.24 cm line after calibration

S_{11} and S_{22} are below -20 dB everywhere and below -30 dB many in many places. These input and output reflection values are larger than desired, but they could be due to line imperfections, uneven etching, or oxidation on the bare copper line surface.

S_{21} and S_{12} are both lined up right on the 0 dB line as they should be after calibration. At 110 GHz, the 0.24 cm line was expected to register the attenuation that a 0.19 cm line would see. Looking to the attenuation chart, this is (2.235 dB/cm) * (0.19 cm) = -0.42465 dB. The S_{21} value read from the data of Figure 6 at 110 GHz is -0.41207 dB. These numbers are in agreement within 0.0126 dB, which shows the calibration is accurate.

Future Steps

Future work will include more intensive characterization of LCP as a versatile material for many applications. Further characterization of LCP transmission lines with different substrate thicknesses, and laminated structures such as antennas with several LCP layers will be explored in the near future. Several process related issues are also being investigated in order to optimize feature sizes, yield, and potential for greater emphasis on vertically integrated systems on package. Now that LCP has been characterized across the entire practical frequency range, and has performed very well, it should prove attractive for an even greater variety of applications.

Conclusion

Transmission lines utilizing the NIST calibration technique have been designed, fabricated, and measured on LCP to 110 GHz. 150 micron pitch probes and fine line features were utilized to ensure measurement accuracy. Measured attenuation is approximately 1.5 dB/cm at 60 GHz, 2 dB/cm at 94 GHz, and 2.25 dB/cm at 110 GHz. Also reported was a steady effective dielectric constant of about 2.365 and a relative phase constant of 1.54. S-parameter testing of delay lines after calibration enabled verification of the calibration accuracy and thus the validity of the results.

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