High Temperature Dielectric Stability of Liquid Crystal Polymer at mm-Wave Frequencies

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***Abstract*— The temperature dependent dielectric stability and transmission line losses of liquid crystal polymer (LCP) are determined from 11–105 GHz. Across this frequency range, LCP's temperature coefficient of dielectric constant, τ_{ϵ_r}, has an average value of -42 ppm/°C. At 11 GHz the τ_{ϵ_r} is the best (-3 ppm/°C), but this value degrades slightly with increasing frequency. This τ_{ϵ_r} average value compares well with the better commercially available microwave substrates. In addition, it includes information for mm-wave frequencies whereas standard values for τ_{ϵ_r} are usually only given at 10 GHz or below. Transmission line losses on 3- and 5-mil LCP substrates increase by approximately 20% at 75 °C and 50% or more at 125 °C. These insertion loss increases can be used as a design guide for LCP circuits expected to be exposed to elevated operating temperatures.**

***Index Terms*— coefficient, dielectric, LCP, resonance, resonator, temperature, mm-wave.**

I. INTRODUCTION

LIQUID crystal polymer (LCP) is a relatively new, flexible thin film material with excellent properties for mm-wave passive circuits and printed antennas. The material's light weight and mechanically flexible nature makes it suitable for rolled, conformal, or other deployable antenna arrays and RF circuits. LCP has been shown to have promising electrical properties for applications above 10 GHz [1], but temperature testing on it has only been done up to 8 GHz [2]. Since many of the desired LCP applications are at mm-wave frequencies, the material's dielectric characteristics under thermal variations are important to identify across the mm-wave range.

The thermal stability of LCP's dielectric constant is investigated for the first time up to 105 GHz with the temperature varying between room temperature (25 °C) and 125 °C. A variable denoted τ_{ϵ_r}, the thermal coefficient of dielectric constant, is commonly given on material data sheets to specify dielectric temperature stability. To determine LCP's thermal characteristics at mm-wave frequencies, its τ_{ϵ_r} is investigated here at 10 frequency points between roughly 11 and 105 GHz. In addition, the temperature dependent microstrip transmission line losses in dB/cm are measured from 10–110 GHz. The goal is to determine how significantly temperature affects LCP's dielectric constant and loss for frequencies greater than 10 GHz.

Manuscript received October 1, 2004; revised November 18, 2004. This work was supported by the National Aeronautics and Space Administration under Contract NCC3-1015, by the National Science Foundation (NSF) under CAREER Award ECS 9984761, by the Georgia Electronic Design Center, and by the Georgia Institute of Technology NSF Packaging Research Center.

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II. METHOD OF IDENTIFYING DIELECTRIC STABILITY

A. Temperature Coefficient of Dielectric Constant

The temperature coefficient of dielectric constant describes how much a material's dielectric constant changes with a given temperature change. This variable is usually given as a constant over some temperature range, although it often changes slightly depending on the specific temperature. Typical absolute values for τ_{ϵ_r} based on a random sampling of material data sheets are from 11 - 280 [ppm/°C]. Values of τ_{ϵ_r} can be positive or negative, indicating an increasing or decreasing dielectric constant, respectively, with an increasing temperature. To extract τ_{ϵ_r}, the measured dielectric constant at some reference temperature, T_{ref} (usually 25 °C), is compared with that obtained at some lower, $T_{initial}$, and higher, T_{final}, temperature. Equation (1) is then used to find τ_{ϵ_r}.

$$\tau_{\epsilon_r} = \frac{\frac{\epsilon_r(T_{final})}{\epsilon_r(T_{ref})} - \frac{\epsilon_r(T_{initial})}{\epsilon_r(T_{ref})}}{T_{final} - T_{initial}} * 10^6 \left[\frac{\text{ppm}}{°\text{C}}\right] \qquad (1)$$

The τ_{ϵ_r} value has units of parts per million per degree Celsius [ppm/°C]. As an example, a material with ϵ_r=3, τ_{ϵ_r}=-50, and a temperature increase of 100 °C would be expected to change to $\epsilon_{r\ at\ temp}$ = 3+3(-50e-6)100 = 2.985.

B. Measurement Structures

Traditional mm-wave high-temperature dielectric characterization methods such as using split-cylinder, split-post, or Fabry-Perot resonators [4] inside of an environmental chamber can become prohibitive past 50 GHz. This and other resonant cavities have excellent measurement fidelity but they become problematic when attempting to integrate 1.85 mm or 1 mm coaxial connectors feeding into an environmental chamber. These connectors are expensive, fragile, usually short in length, and difficult to connect with precision. In addition, the design of coupling loops at the ends of very small diameter coaxial conductors is not a trivial matter, especially for mm-wave measurements. These loops are used to transfer the signal from coaxial to resonant cavity modes. Finally, 1 mm cables capable of 110 GHz measurements are almost exclusively used for measurements with ground-signal-ground (GSG) on-wafer probes.

Another measurement complexity arises from 50 GHz and higher signal generators. Bulky mm-wave mixing modules typically upconvert the signal very close to the measurement area. This makes for a cramped space for a temperature controlled measurement.

The numerous limitations of cavity resonators restricted the mm-wave temperature measurements to printed resonant circuits with GSG feeding structures. The solution was to mount a Temptronic digitally controlled hot chuck (with 0.1 °C accuracy) onto the Agilent 8510XF chuck and to custom build 2" thick aluminum spacers for elevating the mm-wave mixing modules and the attached GSG probes to the same level as the hot chuck. Microstrip ring resonators with conductor-backed coplanar waveguide (CBCPW)-to-microstrip transitions were then measured on the hot chuck for 3- and 5-mil LCP substrate thicknesses. The ring resonators were designed to provide resonances approximately every 10 GHz. Each resonance provided a frequency where τ_{ϵ_r} was measured.

III. FABRICATION

LCP (R/flex 3850) material was provided by Rogers Corporation with double copper cladding in 2- and 4- mil thicknesses. In addition, 1 mil low melt bare LCP (R/flex 3908) bond layers were provided. Copper was etched from one side of the substrates by masking the bottom with polyester tape and using piranha etch to remove the copper on the top. Olin Copper Bond 5 μm copper foil was then bonded to the 2- and 4- mil single copper clad LCP core layers with the 1 mil LCP bond layer. The smooth 5μm copper was used for minimizing skin effect losses at high frequencies. The result was 3- and 5-mil LCP substrate heights. The bond was done in a Karl Suss SB-6 computer controlled silicon wafer bonder with a recipe developed at Georgia Tech. The 5 μm copper was then patterned using a standard photolithography process. Shipley 1827 photoresist was used to define the pattern and ferric chloride was used to chemically etch the copper pattern. Acetone was used to strip the photoresist.

IV. MEASUREMENTS

A. Measurement Procedure

CBCPW-to-microstrip transitions fed the microstrip ring resonator configuration D found in [1]. Cascade 250 μm pitch 110 GHz probes were used with the Agilent 8510XF network analyzer. First, a through-reflect-line (TRL) calibration was done with a set of CBCPW-to-microstrip transmission lines to calibrate out the transitions and set a reference plane on the microstrip feed line. The ring resonators were then measured to identify the locations of the resonant peaks. Once the resonant frequencies were established, a second TRL calibration was done with much finer frequency resolution around each peak. The peaks were calibrated with frequency resolutions varying between 1.25 MHz and 3.75 MHz. The hot chuck was initially set to 25 °C. Calibrated S-parameters were then taken at 25, 50, 75, 100, and 125 °C. Once the hot chuck reached each desired temperature, 10 minutes were given for the probes and attached coaxial cable to heat evenly and for the temperature to settle.

An averaging factor of 256 was used for all measurements to reduce measurement noise. However, noise was still present in the measured data. Postprocessing using MATLAB was used to perform least-squares fits with each resonant peak to an analytical gaussian distribution. The residuals were then checked to verify an acceptable fit. Using the fitted gaussian equation, the maximum amplitude point for resonant peak was then identified to the nearest 1 KHz. This value was used as the resonant frequency for each peak. One exception was made near the 21 GHz resonance where the resonant peaks were strongly distorted and did not fit the expected gaussian distribution. This resonance frequency was thus left out of the analysis.

B. Measurement Accuracy

The most important consideration in taking a measurement with varying temperature is accounting for the expansion of the materials under test. The $xy-$CTE of LCP and the CTE of copper are matched at 17 [ppm/°C]. The $z-$CTE of LCP is higher at 150 [ppm/°C]. The measured resonant frequencies are thus a combination of both dielectric/metal dimension changes and changes in the dielectric constant. To separate these contributions, the equations from [1] for converting the measured resonant frequencies to ϵ_{eff} and ϵ_r were carried out with the corrected expanded dimensions for the mean ring radius r_m, the substrate height h, and the strip width W at each temperature. These dimensional uncertainties as well as the uncertainty in the LCP $xy-$CTE (± 3) [2] were taken into account as shown by the error bars in Fig. 1.

V. RESULTS

A. Temperature Coefficient of Dielectric Constant

Two changes occur when the resonant structures under test are heated. A frequency shift of the resonant peak corresponds to a combination of the change in structure size and the change in the dielectric constant. Second, a decreasing Q-factor of the peaks with increasing temperature indicates an increase in dielectric loss.

Frequency shifts at each of the four ΔT values (25, 50, 75, and 100 °C) were recorded for each resonance. Calculating the dielectric constant (while accounting for the dimension changes at each temperature) provided four τ_{ϵ_r} values for each set of resonant peaks. The τ_{ϵ_r} value is known to vary slightly with temperature so the mean value was taken and this is the value given at each resonant frequency shown in Fig. 1.

LCP's temperature stability near 11 GHz is excellent. However, it slowly degrades with increasing frequency and it seems to converge to a nearly constant τ_{ϵ_r} value between 53 and 105 GHz. Overall, LCP's temperature stability is as good or better than the 10 GHz PTFE/glass and alumina temperature stability values. This is comparing LCP's stability over a nearly 100 GHz range while the others are for a τ_{ϵ_r} only at 10 GHz. Thus, the values measured for LCP show that it has attractive temperature stability properties for mm-wave applications.

Fig. 2 shows the data in a different representation as normalized dielectric constant vs. temperature. This shows that the dielectric constant of LCP drops more sharply with increasing temperature at high frequencies. Finally, Fig. 3 shows the

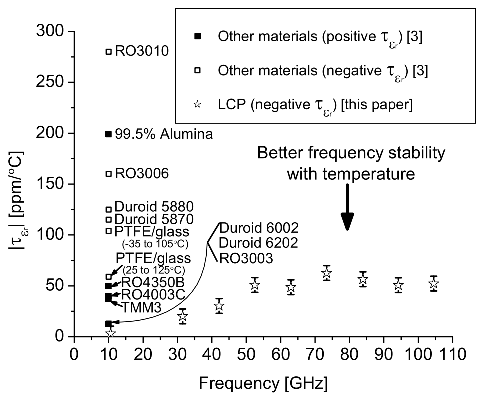

Fig. 1. Absolute value of the thermal coefficient of dielectric constant, τ_{ϵ_r}, vs. frequency of several standard materials and of the broadband τ_{ϵ_r} for LCP. The closer $|\tau_{\epsilon_r}|$ is to zero, the more stable the dielectric constant is with respect to temperature.

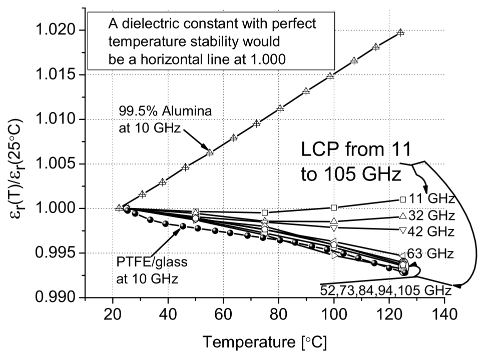

Fig. 2. The ratio of LCP's heated dielectric constant and the dielectric constant at 25 °C vs. temperature. The values for LCP are for measurements from 11–105 GHz from this paper. As a comparison, 99.5% alumina and PTFE/glass have been included. Notice that the values for 99.5% alumina and for PTFE/glass are for measurements at 10 GHz [3].

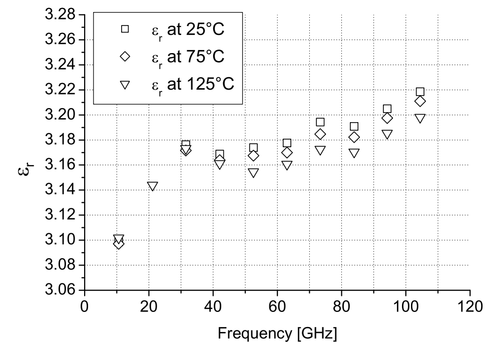

Fig. 3. LCP's dielectric constant vs. frequency and temperature. The dielectric constant increases with increasing frequency and decreases with increasing temperature. Note that the peak at 21 GHz did not have a well shaped gaussian distribution and thus the resonant frequency could not be accurately calculated. However, the 21 GHz measurement at 125 °C was the best fit at that frequency and so only it is included for an estimate of the dielectric constant.

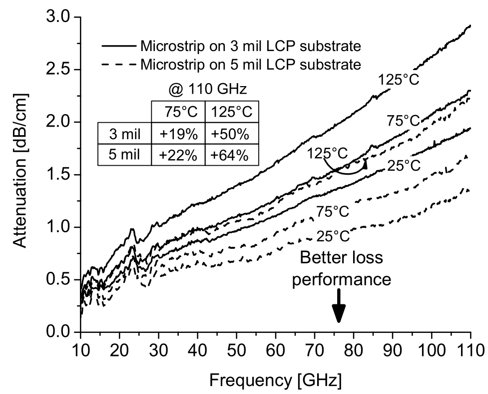

Fig. 4. Attenuation of 3- and 5-mil LCP substrate microstrip transmission lines as a function of temperature. Line width, W, was $104\mu m$ for both lines which gave Z_0 = 68 Ω and 88 Ω for the 3- and 5-mil thicknesses, respectively.

actual values of LCP's dielectric constant vs. frequency and temperature.

B. Microstrip Transmission Line Losses vs. Temperature

At mm-wave frequencies, power becomes scarce and low insertion loss for transmission lines is important. Therefore, temperature dependent loss variations need to be taken into account. Microstrip losses in dB/cm were extracted from the TRL calibration previously mentioned using Multical software [5]. Losses are shown in Fig. 4 for 3- and 5- mil LCP substrate microstrip lines.

Microstrips on both substrate thicknesses experience increases in loss of approximately 20% for ΔT=50°C and 50% or more for ΔT=100°C at 110 GHz. The specific percentage values are shown in Fig. 4. These loss increases should be accounted for in LCP circuits used at high temperatures.

VI. Conclusion

LCP has shown to be an excellent material for high temperature dielectric stability up to mm-wave frequencies for the first time. The average of the absolute values of τ_{ϵ_r} from 11–105 GHz is approximately -42 [ppm/°C]. This is comparatively better than a majority of other standard microwave substrate materials in this parameter. The microstrip transmission line losses on LCP increased steadily with increasing temperature. Loss increases of approximately 20% and 50% or more were observed for temperature increases to 75 °C and 125 °C, respectively. These loss increases should be considered for LCP transmission lines exposed to significantly elevated temperatures.

Acknowledgment

This work was supported by NASA under grant #NCC3-1057.

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