Characterization of Liquid Crystal Polymer for High Frequency System-in-a-Package Applications

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***Abstract*—Liquid crystal polymer (LCP) is a promising substrate for electronics packaging. In this paper, the high frequency characteristics of LCP were investigated using a microstrip ring resonator to verify the possibility of the application of the material in RF packaging. The relative dielectric constant and the loss tangent have been measured. The radiation loss of the ring is considered to accurately determine the loss tangent. A GaAs MMIC switch circuit was fabricated using LCP as substrate to demonstrate an application of this material for system-in-a-package. From the high frequency measurements, it is shown that LCP has low dielectric constant and low loss tangent in the frequency range from 1 GHz to 35 GHz. It is also found that LCP can be used in System-in-a-package applications.**

***Index Terms*—Dielectric constant, liquid crystal polymer, loss tangent, radiation loss, RF packaging, ring resonator, system-in-a-package.**

I. INTRODUCTION

WITH the growth of the personal communication market and the wireless applications, the need for an expanded supply of high frequency packaging materials with high performance has become critical. On the other hand, the requirements of the next generation packaging involve dramatic reduction in size and cost. This can be accomplished with increased integration of passives, RF and optoelectronics within a package, leading to the system-in-a-package (SiP) solution. SiP is a highly integrated technology with all the system-level components including ultra high-density wiring, capacitors, inductors, resistors, RF and optoelectronics, buried into one single board. Due to the embedded RF components in the substrate, the high frequency characteristics of the substrate become important and should be carefully studied.

For many years, the only materials available to microwave engineers were Teflon and ceramics based materials. Both of the materials had one thing in common: they were too expensive. Liquid crystal polymer (LCP) is a thermoplastic polymer much cheaper than Teflon and LTCC. This material also offers an excellent combination of electronic, thermal, mechanical and chemical properties that make it as a promising substrate for electronics packaging. Its mechanical stability is 4 times higher than that of polyimide. It has less expansion forces that cause via misregistration. The coefficient of thermal expansion of LCP laminates and circuit boards can be matched to that of silicon chips and chip packages, providing higher reliability. In addition, high moisture and chemical resistance enhance LCP performance in aggressive operating environments [1]. Since LCP is low-cost, it is also suitable in all applications when FR4 are used today.

For a material used in RF packages, the major considerations include cost, electrical, thermal and mechanical performances. Although LCP was introduced for multiplayer PCBs in 1995, there was no detailed description and tests on its high frequency electrical characteristics [2]. In this paper, the high frequency electrical characteristics of LCP are studied in order to fully exploit its dielectric properties. In Section II, a microstrip ring resonator was fabricated on LCP to measure the dielectric constant and the loss tangent of the substrate. In the calculation of loss tangent, the radiation loss of the ring resonator was considered to reduce the error caused by the electromagnetic radiation. In Section III, an MMIC switch circuit was fabricated using LCP as substrate to demonstrate a simple application of LCP in system-in-a-package. The high frequency performance of the circuit was measured. All the high frequency tests were performed by an HP8510C network analyzer.

II. CHARACTERIZATION OF LCP USING MICROSTRIP RING RESONATOR

The two most important electrical parameters used to characterize an RF substrate are the dielectric constant and the loss tangent. The dielectric constant is important for all RF boards because it determines the characteristic impedance of the circuitry. A precisely controlled and repeatable dielectric constant is necessary for proper circuit performance in higher frequency applications. The loss tangent is of primary importance for high power applications or where carefully balanced circuitry is employed.

There are several standard methods existing for measuring dielectric constant and loss tangent. The impedance or resonator method can be used respectively according to the applicable frequency ranges. The impedance method is usually applied at low frequencies (< 100 MHz). In this method, the dielectric constant and loss tangent are calculated from impedance measurements of a circular capacitor. At higher frequencies, the dielectric properties can be determined from the characteristics of a resonant structure located on (microstrip method) or in (stripline method) the dielectric.

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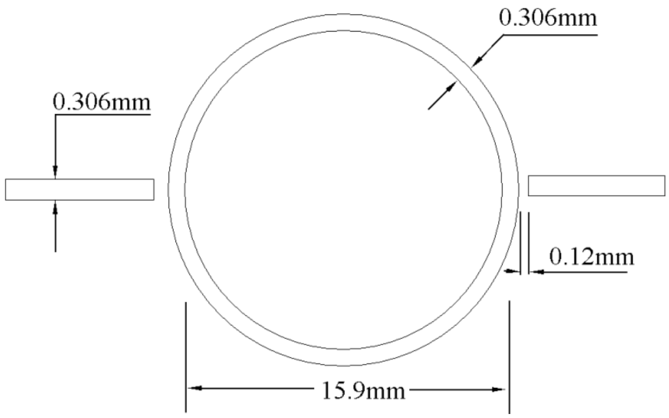

Fig. 1. Top layout of the ring resonator on the surface of LCP substrate.

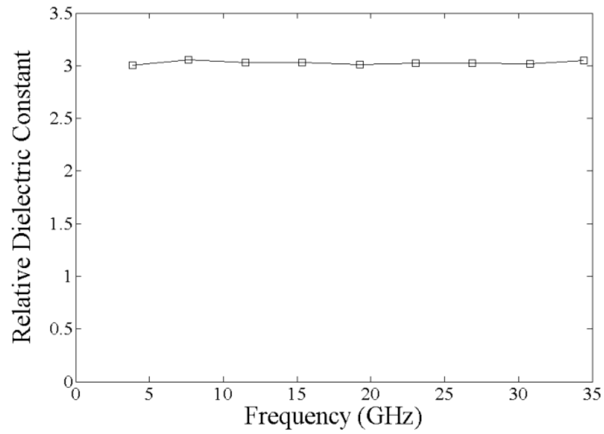

Fig. 2. Relative dielectric constant of LCP as a function of frequency.

In this paper, the microstrip ring resonator method was used. Compared to a microstrip line resonator, a microstrip ring resonator does not suffer from open-ended effects and can be used to give more accurate measurements. The configurations of microstrip ring resonators are easier to manufacture because the manufacture involves only etching of copper-clad dielectric material. In addition, the current flows predominantly only on the surface of the conductor and the roughness correction is better defined [3].

The LCP BIAC Copper Clad Laminate from GoreTex Japan was investigated. The thickness of the substrate is 125 μm. A copper foil with thickness of 18 μm is attached by heat-bonding on both sides of the board. A ring resonant circuit was etched on the surface of the LCP dielectric. The layout is shown in Fig. 1. On the other side, the copper was kept as the ground of the circuit. The radius along the middle line of the ring is 7.95 mm. The width of the microstrips on the LCP surface is 306 μm to make sure that the characteristic impedance of the microstrips is 50 Ω. There are two 0.12 mm gaps at the end of the ring to couple the resonator to the measurement system. This provided sufficiently light coupling to measure the resonators without significantly loading the test equipment.

Since one of the most important requirements of this experiment is frequency accuracy, the resonator was first measured with a broad frequency sweep to determine the location of resonant peaks (shown in Fig. 4). Next s-parameters were measured by a narrowband frequency sweep near each resonant peak. Then the data were inserted into a computer program to calculate the material's dielectric constant and loss tangent as a function of frequency.

A. Dielectric Constant

For a ring resonator, the effective dielectric constant is given by [4]

$$\varepsilon_{r,eff} = \left(\frac{nc}{2\pi r_m f_0}\right)^2 \tag{1}$$

where r_m is the radius along the middle line of the transmission line; f_0 is the resonance frequency; n is the number of half wave lengths; c is the speed of light in vacuum.

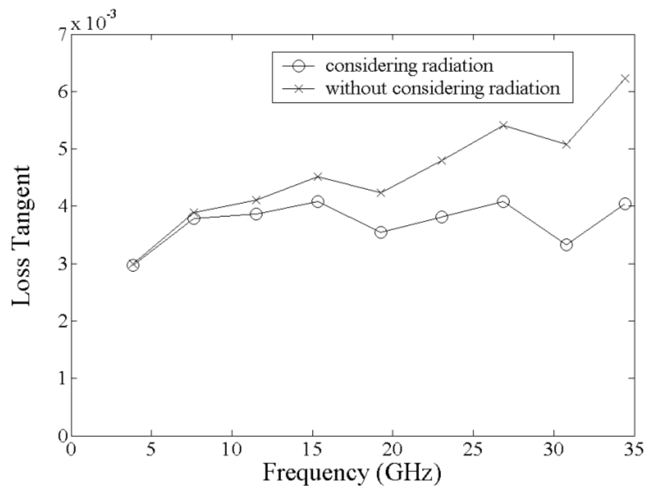

Fig. 3. Value of loss tangent as a function of frequency.

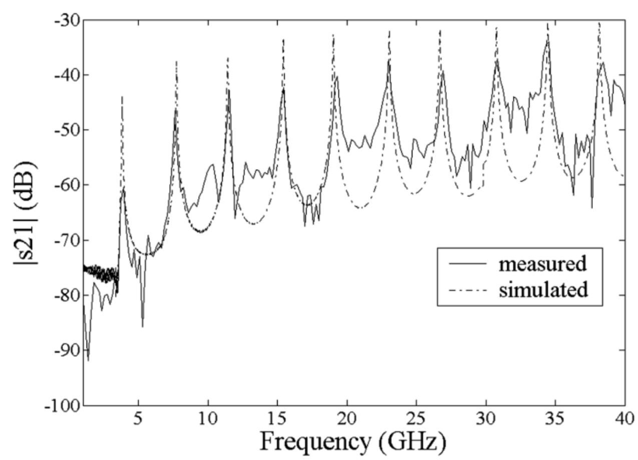

Fig. 4. Measured and simulated $|s21|$ of the ring resonator with broad frequency band (1 GHz to 40 GHz).

Then the relative dielectric constant of LCP can be derived from the effective dielectric constant and the physical dimensions of the microstrip. The expression is

$$\varepsilon_r = \frac{2\varepsilon_{r,eff} + M - 1}{M + 1} \tag{2}$$

where $M = (1 + 12h/W_{eff})^{-1/2}$, W_{eff} is the effective strip width accounting for the nonzero strip thickness $W_{eff} = W + (1.25t/\pi)[1 + \ln(2h/t)]$. W and t are the physical width and thickness of the copper donductor, respectively, h is the thickness of LCP substrate, t is the thickness of the copper trace.

Using (1) and (2), the relative dielectric constant at resonance frequencies was calculated. The result is plotted in Fig. 2.

B. Losses

The measured unloaded Q of a microstrip ring resonator can be obtained by [4]

$$Q_0 = \frac{Q_L}{1 - 10^{-L_A/20}}. \tag{3}$$

Where L_A is the measured insertion loss in decibels of the resonator at resonance. The loaded Q is defined as

$$Q_L = \frac{f_0}{BW_{-3\ dB}} \tag{4}$$

where $BW_{-3\ dB}$ is the 3-dB bandwidth of the resonator. The measured attenuation constant can be given by

$$\alpha_{total} = \frac{\pi}{Q_0 \lambda_g} \left[\frac{\text{Np}}{\text{unit length}}\right] \tag{5}$$

where λ_g is the guided wavelength. It is known that the total attenuation constant (α_{total}) is the sum of the conductor attenuation factor (α_c), the dielectric attenuation factor (α_d) and radiation attenuation factor (α_r)

$$\alpha_{total} = \alpha_c + \alpha_d + \alpha_r. \tag{6}$$

1) Conductor Loss Attenuation Constant: Taking the thickness of the strip into account, we can get the conduction attenuation constant of a microstrip line as [5]

$$\begin{aligned}
\frac{W}{h} \leq& \frac{1}{2\pi} \\
\alpha_c(f) =& \frac{8.68}{2\pi} \frac{R_{s1}}{Z_0 h} \left[1 - \left(\frac{W_{eff}}{4h}\right)^2\right] \left\{1 + \frac{h}{W_{eff}} + \frac{h}{\pi W_{eff}}\right. \\
&\times \left.\left[\ln\left(\frac{4\pi W}{t} + 1\right) - \frac{1 - \frac{t}{W}}{1 + \frac{t}{4\pi W}}\right]\right\} \frac{\text{dB}}{\text{unit length}} \\
\frac{1}{2\pi} <& \frac{W}{h} \leq 2 \\
\alpha_c(f) =& \frac{8.68}{2\pi} \frac{R_{s1}}{Z_0 h} \left[1 - \left(\frac{W_{eff}}{4h}\right)^2\right] \left\{1 + \frac{h}{W_{eff}} + \frac{h}{\pi W_{eff}}\right. \\
&\times \left.\left[\ln\left(\frac{2h}{t} + 1\right) - \frac{1 - \frac{t}{h}}{1 + \frac{t}{2h}}\right]\right\} \frac{\text{dB}}{\text{unit length}} \\
\frac{W}{h} >& 2 \\
\alpha_c(f) =& \frac{R_{s1}}{Z_0 h} \frac{8.68}{\left\{\frac{W_{eff}}{h} + \frac{2}{\pi} \ln\left[2\pi e \left(\frac{W_{eff}}{2h} + 0.94\right)\right]\right\}^2} \\
&\times \left[\frac{W_{eff}}{h} + \frac{\frac{W_{eff}}{\pi h}}{\frac{W_{eff}}{2h} + 0.94}\right] \cdot \left\{1 + \frac{h}{W_{eff}} + \frac{h}{\pi W_{eff}}\right. \\
&\times \left.\left[\ln\left(\frac{2h}{t} + 1\right) - \frac{1 - \frac{t}{h}}{1 + \frac{t}{2h}}\right]\right\} \frac{\text{dB}}{\text{unit length}}
\end{aligned} \tag{7}$$

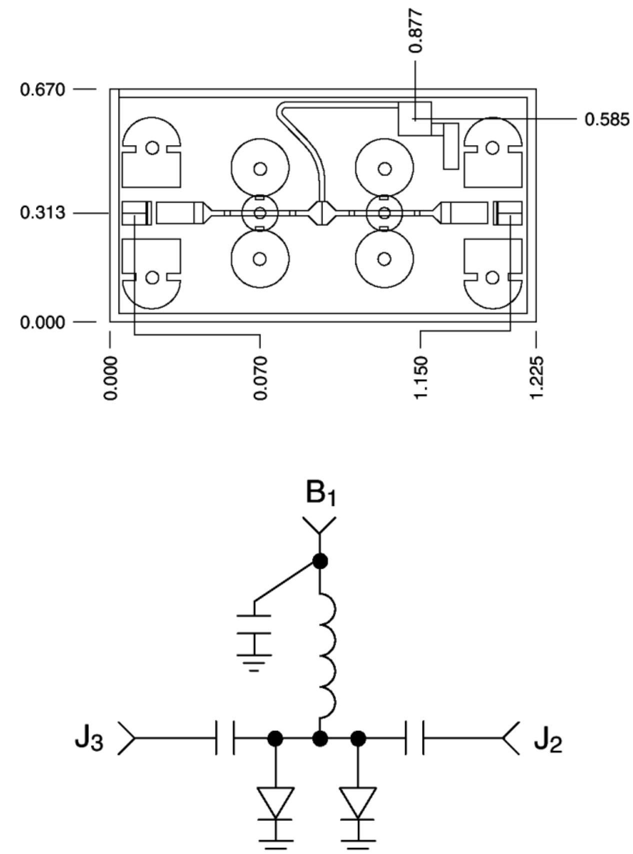

Fig. 5. Outline and schematic of AP640R1-00 (Dimensions indicated in mm; All pads are $\geq$ 0.07 mm wide; Chip thickness $= 0.1$ mm. J1 and J2 are two input/output ports; B1 is the dc bias port.).

where

$$\begin{aligned}
R_{s1} =& R_s \left\{1 + \frac{2}{\pi} \tan^{-1}\left[1.4\left(\frac{\Delta}{\delta_s}\right)^2\right]\right\}, \\
R_s =& \sqrt{\frac{\pi \mu f}{\sigma}} \\
\delta_s =& \sqrt{\frac{1}{\pi \mu \sigma f}}
\end{aligned}$$

R_{s1} is the surface-roughness resistance of the microstrip. R_s is the surface resistance of the microstrip. Z_0 is the characteristics impedance of the microstrip. δ_s is the skin depth of copper. $\mu = 4\pi \bullet 10^{-7}$ H/m, $\sigma =$ bulk conductivity of the metal, f is frequency. Δ is the mean surface roughness of the copper trace.

2) Radiation Loss Attenuation Constant: In the previous works on the measurement of dielectric loss of the microstrip ring resonator, the radiation loss is always neglected due to its complexity [6]–[8]. But the radiation becomes significant at high frequencies because radiation increases rapidly with the ratio of substrate thickness to free-space wavelength. In this paper, only the radiation from the ring resonator is considered. The radiation from other parts was neglected. From Van der Pauw's work [9], we can get the radiation quality factor Q_r of a microstrip circular resonator

$$Q_r \approx \frac{4Z_0}{\omega^2 \mu^2 {v_g}^2 \left(1 - \frac{4}{3}\varepsilon\mu + \frac{8}{15}\varepsilon^2\mu^2\right)} \tag{8}$$

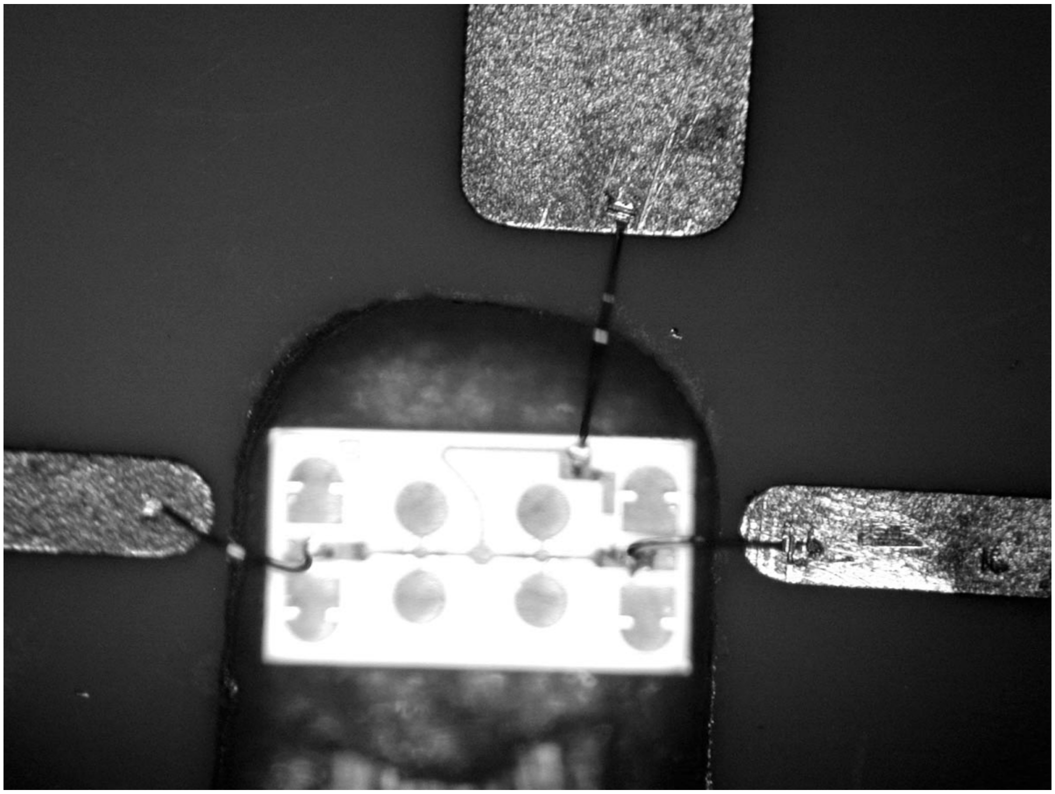

Fig. 6. View of top layer of the MMIC switch circuit.

where ε and μ are the permittivity and permeabiligy of the dielectric substrate respectively. Z_0 is the characteristic impedance. v_g is the propagation velocity of the resonance signal. ω is the operation frequency. Note ω, ε, μ, Z_0 and v_g are dimensionless parameters. After restoring dimension of the above dimensionless expression, we can derive the following equation of Q_r:

$$Q_r \approx \frac{\varepsilon_{r,eff} Z_0}{120\pi^3 \left(\frac{h}{\lambda_0}\right)^2 \left(1 - \frac{4}{3}\varepsilon_r + \frac{8}{15}\varepsilon_r^2\right)} \tag{9}$$

where h is the thickness of the substrate. λ_0 is the wavelength of the resonance signal in the free space. Z_0 is the characteristic impedance of the microstrip. The radiation attenuation constant of the ring can be given as

$$\alpha_r = \frac{\pi}{Q_r \lambda_g} \left[\frac{\text{Np}}{\text{unit length}}\right] \tag{10}$$

where λ_g is the guided wavelength.

3) Loss Tangent: Removing the conductor attenuation constant and the radiation attenuation constant from the total attenuation constant, the dielectric loss tangent of LCP can be determined from the dielectric attenuation constant, showed as

$$\tan\delta = \frac{\alpha_d \lambda_0}{27.3} \frac{(\varepsilon_r - 1)\sqrt{\varepsilon_{r,eff}}}{\varepsilon_r (\varepsilon_{r,eff} - 1)}. \tag{11}$$

The measured values of loss tangent are shown in Fig. 3. The measurement results without considering of the radiation loss are also plotted. We can see that the radiation loss has pronounced effect on the measured value of the loss tangent, especially at high frequencies. To testify the accuracy of the measured values, the FDTD simulation software, QuickWave 3D, was used to model the operation of the ring resonator. The average values of the measured relative dielectric constant (3.0) and the loss tangent ($3.7 * 10^{-3}$) were adopted in the simulation. The simulated and the measured $|s21|$ shown in Fig. 4 agree well.

From the measurement results, it is seen that LCP has low relative dielectric constant and low loss tangent over the frequency range 1 GHz to 35 GHz. So it is a good substrate for high frequency applications.

III. MMIC Switch Circuit

In this section, a switch circuit was fabricated using LCP as substrate to demonstrate the concept of system-in-a-package. A 3-terminal active nonlinear packaged GaAs MMIC switch chip (AP640R1-00) was used. This chip is a single pole, and single throw PIN diode switch with fast switching speed (less than 2 ns) and broad bandwidth (18–40 GHz). Its outline with bias and circuit schematic is shown in Fig. 5.

The chip was embedded into a cavity drilled through the LCP substrate and attached to the ground of the circuit by an Ag-filled conductive adhesive. 50 Ω standard microstrip transmission lines were designed as signal input/output lines. Gold bonding wires were used to connect the chip to these microstrips and dc bias strip. Fig. 6 shows the top view of the embedded chip and the bonding wires. A 300 Ω resistor was chosen as the bias resistor. When the chip is biased by

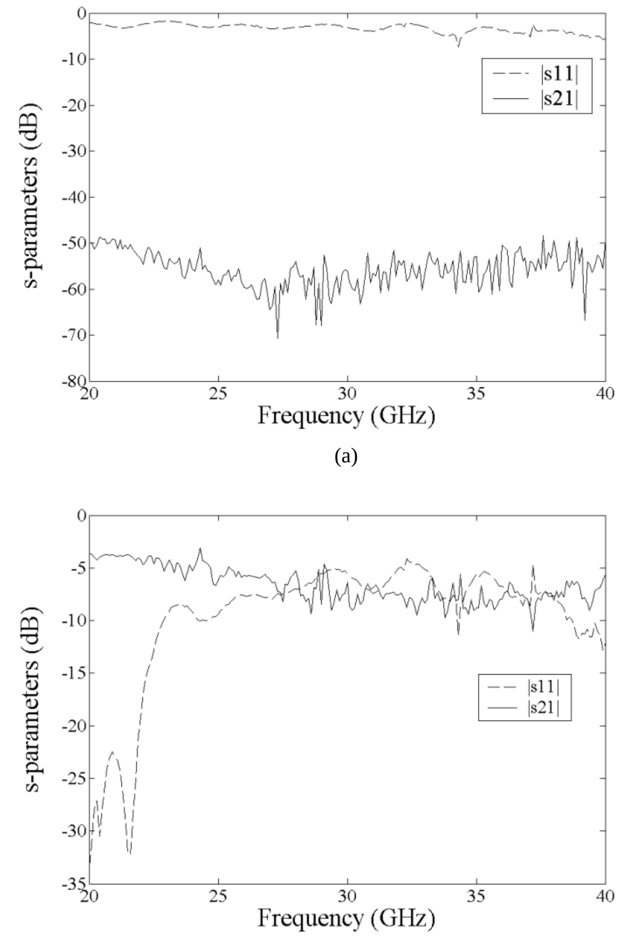

Fig. 7. Measured performance versus frequency of MMIC switch: (a) isolation state and (b) insertion loss state.

dc voltage +7 V, a 20 mA current was applied to the chip. The chip will operate in isolation state. When it is biased by −3 V dc voltage, the chip will work in insertion loss state. The scattering parameters were measured across the input and output ports for both bias conditions. The measurement results are shown in Fig. 7. From the high frequency measurement results, it is shown that the embedded MMIC switch chip works well. The substrate, LCP, has good capability for high frequency signal transmission. It can be used as a substrate for high frequency SiP modules.

IV. CONCLUSION

The high frequency characteristics of LCP were investigated. The radiation loss was considered in the measurement of the value of loss tangent. It was found that in the frequency range 1 GHz to 35 GHz, the relative dielectric constant of LCP is about 3.0. The value of loss tangent of LCP is below 0.0045. This means that LCP offers Teflon-like RF performance, it is a good substrate for high frequency packaging. The GaAs MMIC switch circuit fabricated in the LCP substrate works well in the frequency range 20 GHz to 40 GHz. It is shown that LCP can be used as substrate for system-in-a-package applications.

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