

# Panel-Size Component Integration (PCI) with Molded Liquid Crystal Polymer (LCP) Substrates

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## Abstract

Future product development in microelectronics requires low-cost, high-speed, high-reliability, good manufacturability, and environmental compatibility. Recently developed DCA techniques, such as flip-chip and CSP on high-density microvia substrates, are believed to be able to satisfy such needs. Further integration of passive devices has been realized recently in the Single Level Integrated Module (SLIM). The integration of active devices into a planar substrate has been focused on planar substrates such Si-wafers, or LTCC or low-temperature smart-card substrate applications. More recently, a novel technology to integrate both active and passive components directly into a low-cost, multi-layer organic substrate has been based on a fully additive process utilizing photoimageable polymers and electroless copper processing on multi-layer polymer substrates, and very thin chips with shallow Cu bumps (a few microns) of very small pitch (100  $\mu\text{m}$  or less).

The objective of the present program is to research and develop a technology using LCP substrates for manufacturing and integration of both passives and actives in a package, to exploit the potential CTE match to silicon. The emphasis is focused on studying the polymer/metal interfaces established between the dissimilar materials used in multi-layer modules. Meanwhile, the research work is also aimed to understand the fundamental thermal, electrical, mechanical and interactions between the different materials. The paper reports on work to date.

## 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. 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.

LCPs are ordered thermoplastic polymers with long stiff molecules, which are much cheaper than Teflon® or LTCC. They also offer an excellent combination of electronic, thermal, mechanical and chemical properties that make them promising substrate materials for electronics packaging. The stability is four times greater than that of polyimide, and they have less expansion forces that cause via misregistration. The key point which has motivated this study, however, is that the low coefficient of thermal expansion of LCP laminates can be matched to that of silicon chips, providing higher reliability

[1, 2]. In addition, high moisture and chemical resistance enhance LCP performance in aggressive operating environments, and the low coefficient of thermal expansion, low dielectric constant, and high dielectric strength make them suitable for applications in circuit board laminates for electronics packaging. The other advantage of LCP is the high moisture barrier, which can be used to seal and protect components. LCP films absorb 50 to 100 times less moisture than polyimide film, resulting in much more stable electrical properties in normal and humid environments..

## Integrated Module Board (IMB)

The LCP IMB concept being developed here is based on the prior IMB technology developed by one of the authors (JK.) Increasing microjoint densities and packaging efficiencies are accompanied by decreasing solder joint volumes and new contact metallurgies, decreasing bump size and I/O pitch, which increase the relative amount of brittle intermetallic compounds and decrease void and impurity tolerance in the solder joint. Concurrently, the small solder joints experience higher strains and stresses from CTE mismatch between the board, chip and solder. Due to this development the reliability has become one of the most important factors in high performance consumer electronics. Future tightening of environmental regulations will put more pressure on the development of new packaging and interconnection technologies, and drive interconnection technologies towards solder-less solutions (Figure 1.)

To meet the requirements for future reliable, ultra high density, environmental friendly and powerful electronic products, a solderless interconnection and packaging technique has been developed in Helsinki University of Technology [3]. In this Integrated Module Board (IMB) technique, active components are embedded inside a substrate using the CIB (Chip-in-Board) technique. After the embedding, chip interconnections and wiring are fabricated with a fully additive printed wiring board (PWB) process. This enables the integration of passive components as well. The passives can be fabricated directly above (the active side of) the chip, which reduces the required line length and therefore enhances packages electrical properties. Further, no solder is used in the IMB manufacturing process, which considerably improves the reliability and the electrical performance of high-density packaging. Furthermore, 3-dimensional packaging can be realized by stacking single IMBs together, as shown in Figure 2(a). For vertical interconnection, through-holes are drilled and metallized between the IMB layers. The 3D-IMB enables packaging,

where the whole volume of the package is used for active and passive components (not only a two-dimensional area). Copper can be used as a substrate or a heat sink, attached directly to the backside of the chip (Figure 2(b)). Moreover, the environmental-friendly fully additive fabrication process produces only a small amount of residuals with very low environmental burden. The IMB technique offers an ideal active/passive component packaging solution. The LCP implementation adds the enhancement of improved thermo-mechanical reliability.

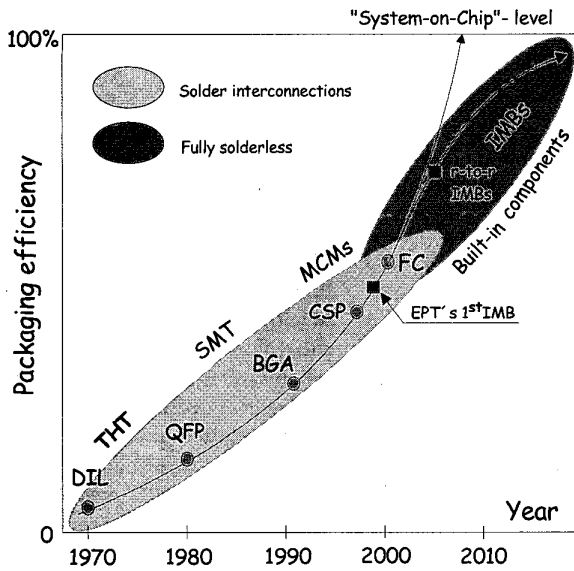


Figure.1 Packaging efficiency development.

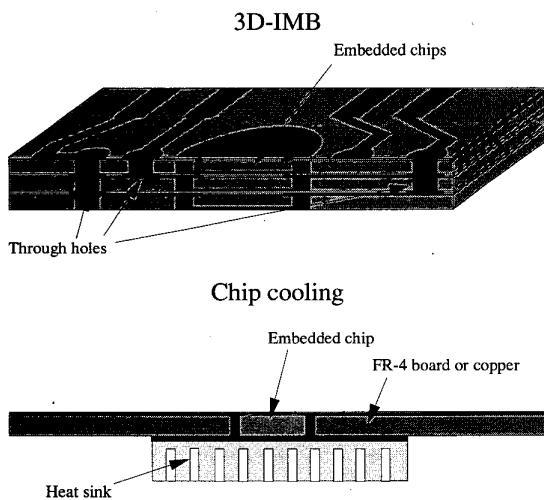


Figure 2. a) 3D-IMB, b) heat sink attached to the backside of an IMB.

## Liquid Crystal Polymers (LCP)

Epoxies, such as FR4, still represent the most common type of polymers used to make circuit laminates. Future generations of electronic devices will increasingly rely on new materials with improved properties such as lower coefficient of thermal expansion (CTE), higher modulus, lower permittivity and loss, lower moisture uptake, better thermal conductivity, good dimensional stability, and more importantly reduced warpage particularly after the build-up process. LCP's are high performance materials that combine the properties of polymers with those of liquids. It is a state of condensed matter between crystalline solids and isotropic liquids. The condensed matter is characterized by a combination of physical properties of a liquid crystalline state and specific polymer properties. LCP's are highly crystalline materials based on aromatic ring-structured compounds that are very stable after polymerizing. The liquid crystalline material can have its molecules realigned using magnetic or electrical fields, and in the process acquire the properties of both solids and liquids. Formulations of LCP's depend on the manufacturer, but they are currently available in a variety of unfilled, glass-filled, mineral-filled, carbon fiber reinforced, and glass fiber-reinforced grades which allow for numerous options in melting points and other key properties. LCP is a promising material because it has exceptional properties that make it well suited for use as a substrate material. LCP technology can replace materials such as ceramics, metals, composites, and other plastics due to outstanding mechanical properties such as: strength, resistance to virtually all chemicals, extreme temperatures, and weathering to name a few. The properties of LCP's discussed are practical/relevant for current packaging concerns. These concerns involve addressing heat removal with a higher thermal conductivity, lower thermal expansion materials to better survive thermal stresses during temperature cycling in a system, and alternatives to solder lead content issues. Currently, polymers are widely used in electronic packaging as adhesives, encapsulants, insulators, dielectrics, molding compounds, and conducting elements for interconnects. These are typical applications requiring resistance to high temperatures and chemicals, and where thin walls, dimensional stability, strength, and rigidity are essential. The thermal analysis data presented will show the importance/need for LCP in future electronic packaging applications.

## Physical LCP Properties

**Moisture Absorption:** LCP samples were cured at 120°C for 30 minutes and then placed in the 85/85 environmental chamber, and observed in the chamber for 312+ hours. The samples experience very little or no weight changes under humid conditions. 5-mil Dupont and Vectran LCPs have a 0% weight change; 10-mil Vectran has a 0.14% weight change, and the Rogers LCP has a 0.50% weight change. The conclusion is that LCP samples are excellent moisture barriers.

**TGA-thermogravimetric analysis:** A thermogravimetric analyzer from TA instruments was used to measure the amount and rate change in sample mass as a function of temperature. The characterization of LCP samples was

determined when weight loss occurred as a result of decomposition. The experiment was done using a heating rate of 10°C/min. The temperature was ramped from 25°C to 800°C using a sample mass not greater than 5mg. Figure 3 shows TGA results in the temperature range of 30-1000°C at a heating rate of 10°C/min under a nitrogen atmosphere. Tests were performed to determine the decomposition temperatures. LCP is a high melt polymer, and the transition temperature is difficult to pinpoint. As seen from Table 1, the samples show relatively high decomposition temperatures at 5-10% weight loss. The LCP materials have excellent thermal stability that may be attributed to the ordered state they maintain below their melting point. Below the melting temperature the polymer is a solid and the polymer chains line up to form crystals. Above the melting temperature the crystals melt to form a fluid with random order.

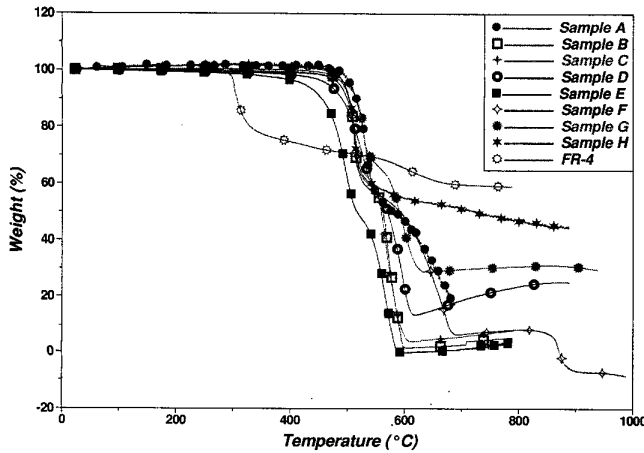


Figure 3. Weight loss curves from TGA data.

Table 1. Decomposition temperatures (as defined by 5% weight loss from Fig. 3) and coefficients of thermal expansion.

Sample	TGA @ 5% (°C)	CTE x (ppm/°C)	CTE y (ppm/°C)
A	501.51	13.6	12.9
B	499.21	48.4	-22.7
C	525.50	47.9	-18.6
D	528.08	18.2	12.7
E	496.30	30.5	32.8
F	495.79	28	35.3
G	510.70	-----	-----
H	494.30	-----	-----
FR-4	295.25	-----	-----

TMA-thermomechanical analysis: The thermomechanical analyzer was used to measure the thermal expansion of the LCP films as a function of force and temperature. The force used was 0.030N with a heating rate of 5°C/min from room temperature to 250°C under a nitrogen

gas atmosphere. From the data collected using the TMA, the CTE is calculated from the change in dimensional area as a function of temperature. LCP materials were chosen due to their high dimensional stability. Currently there is a CTE mismatch between the board and the IC chip. After reflow, during cooling, the substrate wants to shrink but is prevented due to the IC chip holding it flat thus causing stress and warpage for the electronic package. A material with a lower CTE value will aid in eliminating the stress and combat warpage between the substrate and the IC chip.

X and y coefficients of thermal expansion fall into the 12 to 25 x 10<sup>-6</sup> range for Gore materials. For the materials of Table 1, samples B & C expand greatly in one direction and shrink greatly in the other direction. It is believed that the large expansion in one direction causes the shrinkage in the opposite direction. Samples A & D represent the lower CTE values. It was expected that samples E & F would have values similar to if not lower than samples B & C, but since their values are fairly close to each other, this suggests some reliability in the calculated CTE values since they are processed at the same company.

X-direction moduli are higher than the y values for the Gore samples. Vectran (5 & 10 mil) has the highest x-modulus, with a comparable y-value, but the Dupont sample has the more consistent results. The modulus (Dupont) steadily declines with temperature, from 7145Mpa at 25°C to 3802 MPa at 115°C and 1776Mpa at 244°C.

#### LCP-Copper Adhesion

LCP laminates have not been yet widely used for electronics packaging. One of the reasons is the weak interaction between LCP and copper, which will result in low peel strength of the laminates. To improve the peel strength, usually the surface of LCP is roughened and a certain adhesive is used for lamination. However the presence of a rough interface or an adhesive layer between the LCP and the copper pattern is undesirable for high speed circuit boards because of the inferior performance of adhesive materials, difficulties of fine patterning, and the skin effect during high speed signal transmission.

We have attempted to realize a direct bonding between copper foil and LCP film without adhesive. The method adopted is referred to as surface activated bonding (SAB), in which the surfaces of the copper are activated by Ar beam etching and bonded directly in vacuum only by contact. A very smooth interface without any adhesive layer can be achieved.

The SAB method has been applied already successfully to many kind of materials combinations such as Al-Al, Al-Cu, Si-SiO<sub>2</sub>, Si-GaAs, Al-Si<sub>3</sub>N<sub>4</sub>, Al-AlN, Cu-polymers *etc.* Because surfaces of solid materials are originally reactive, it is expected that a strong chemical bond is created between surfaces of two materials if they are contacted closely on an atomic scale. However, there is only weak interaction between the surfaces if they are covered with an inactive layer such as native oxide or any other contaminant. We apply physical fast atom bombardment or Radio Frequency (RF) plasma sputtering to remove these inactive layers. This method is very effective for the material of high surface energy such as metals. In case of a polymer which has a low surface energy,

certain active functional groups are expected to be exposed. The bond strength of polyimide-Cu, however, was not so strong as those of metal-metal bonding. Therefore in the present study, copper is deposited on LCP films prior to the bonding and a heat treatment at a temperature below the transition point of the LCP and after SAB processing.

The following materials are used for the experiments.  
 Copper foil: C1100 rolled copper foil of 35 $\mu$ m thickness.  
 LCP film: Vecstar CTX100 (Kuraray) of 50 $\mu$ m thickness.

They are cut into 175 x 300 mm sheets and put on a stainless plate, and then set to an aluminum cartridge. No special surface treatment was made except wiping with ethyl alcohol.

Bonding is performed in vacuum, of background pressure about 3.0 $\times$ 10<sup>-3</sup> Pa. The copper foil bonding load can be varied up to about 5.0 $\times$ 10<sup>5</sup> N. In this experiment, several parameters were examined to make clear which factor is dominant for improvement in bonding strength. "Normal values" are shown in Table 2 to denote those used in the experiments except for the targeted parameters.

Table 2. Parameters that control bonding conditions. The normal value is applied to each parameter except the targeted parameter.

Parameter	Range	Normal Value
Bonding stress	15 - 50 MPa	25 MPa
RF treatment time (Cu)	30 min (fixed)	30 min
RF treatment time (LCP)	0 - 16 min	8 min
RF intensity (Cu)	720 W (fixed)	720 W
RF intensity (LCP)	20 - 240 W	20 W
Cu deposition time	0 - 90 min	0 min

The relationship between bonding pressure and peel strength is shown in Figure 4. The peel strength of the specimens without heat treatment was very low, whereas after heat treatment it reaches the highest value when the bonding pressure is 25MPa. It is considered that the ultimate contact can be achieved at this point.

Figures 5 and 6 give the relationship between peel strength and RF time/power intensity. The peel strength of the specimens without heat treatment is weak also in those cases. It is observed that the amount of surface removal by the RF plasma etching contributes to improvement in the bond strength. A great improvement in the peel strength is observed in Figure 7, showing that the deposition of copper is quite effective even if the thickness of the deposited copper is as small as several 100nm.

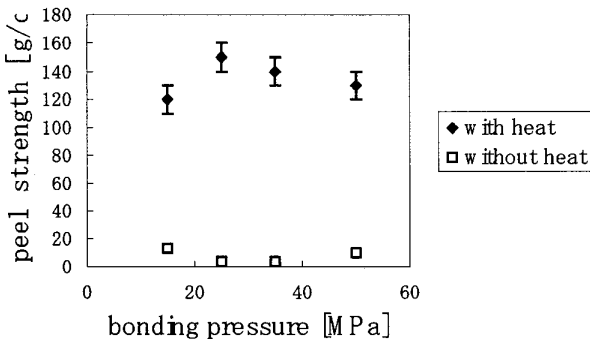


Figure 4. The relationship between bonding pressure and peel strength. Peel strength of the specimen with heat treatment reaches highest value at the point of 25MPa.

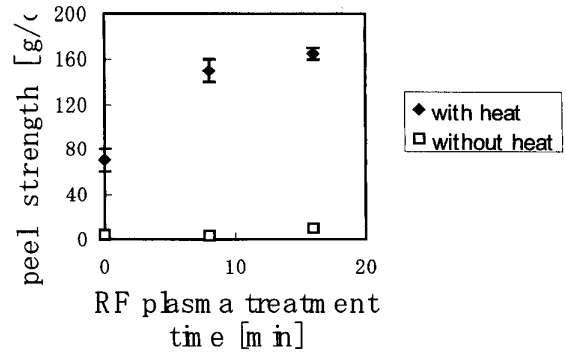


Figure 5. The relationship between RF plasma treatment time and peel strength.

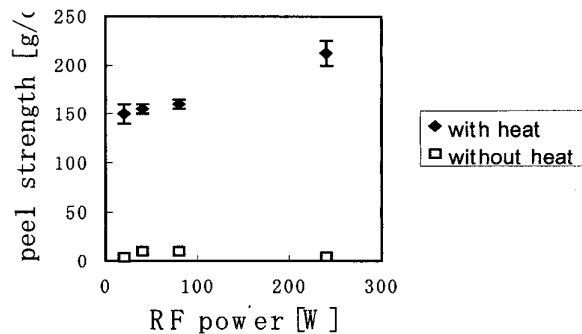


Figure 6. The relationship between RF power and peel strength. Considered with Figure 3, the tendency can be observed that the amount of etching contributes to improvement of the peel strength.

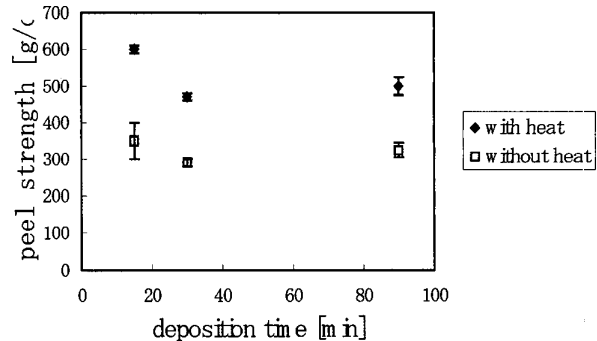


Figure 7. The relationship between copper deposition time and peel strength. Great improvement in peel strength is observed.

The above experimental results indicate that the following factors may contribute to improvement in the peel strength of the laminate. First, the heat treatment is necessary in any case. Secondly, the RF plasma etching of the LCP surfaces is effective to make strong bonding. Thirdly, the deposition of copper on the LCP does work effectively for achievement of a strong bonding.

This means that almost all the deposited copper bonds to the Cu-side. It can be considered that the bonding between deposited copper and LCP is weaker than the bonding between the copper in the copper foil and LCP. This conclusion seems to be opposite to the result of the peel tests. It is probably because the area of real contact of the "copper deposited" specimen is much larger than that of the "as bonded" specimen.

It is presumed from XPS data reported elsewhere [4] that the peeling occurs in the LCP along the bonded interface. Moreover, because in case of no heat treatment, the failure occurs at the bonded interface between the deposited copper and the base copper coil, whereas the deposited copper is detached from the LCP after heat treatment, it is considered that heat treatment leads not only to the stress relaxation effect but also to a certain chemical reaction between copper and LCP.

The results indicate that peeling between LCP and Cu predominantly occurs on the LCP side. One of the possible explanations of this phenomenon is that the strength of the surface layer of the LCP is originally too weak to stand the peeling load. The weakness of the surface layer of LCP might be also due to the damage caused by the RF plasma treatment or by the cold rolling process, however, details of the delamination mechanism have not been made clear.

#### Electrical LCP Properties

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. The loss tangent is of primary importance for high power applications or where carefully balanced circuitry is employed. Low dielectric loss is essential in high power applications, and a precisely controlled and repeatable dielectric constant is necessary for proper circuit performance in higher frequency applications.

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 (<100MHz). 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 within (stripline method) the dielectric. The microstrip ring resonator method was used here [5]. One reason for choosing this method is that the configurations are easier to manufacture because the manufacture involves only etching of copper-clad dielectric material. Another reason is that the current flows predominantly on only one surface of the conductor and the roughness correction is better defined.

The LCP BIAC® Copper Clad Laminate from GoreTex Japan was investigated. The thickness of the substrate is 125µm. The copper foil with thickness of 18µm 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 Figure 8. On the other side, the copper was kept as the ground of the circuit. The radius along the middle line of the ring is 7.9mm. The width of the microstrips on the

LCP surface is 306µm to make sure that the characteristic impedance of the microstrips is 50Ω. There are two 0.12mm 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 it.

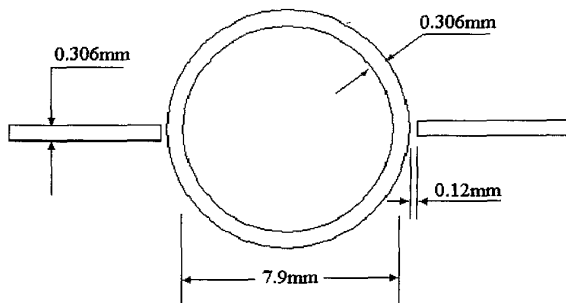


Figure 8. Top layout of the ring resonator on the surface of LCP substrate

Since one of the most important requirements of this experiment is frequency accuracy, the resonator was first measured using a broad frequency sweep to determine the location of resonant peaks (shown in Figure 9). Next *s*-parameters were measured by narrowband frequency sweep near each resonant peak. Then the data were inserted into a computer program developed for this test to calculate the material's dielectric constant and loss tangent as a function of frequency.

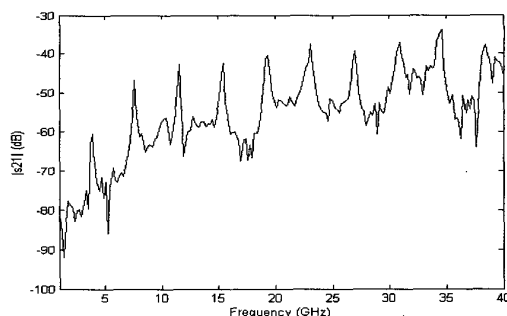


Figure 9. Measured  $|s_{21}|$  of the ring resonator with broad frequency band (1GHz to 40GHz)

**Dielectric constant:** For a ring resonator, the effective dielectric constant is given by

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

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

$$\epsilon_r = \frac{2\epsilon_{r,eff} + M - 1}{M + 1} \quad (2)$$

where  $M = \left(1 + \frac{12h}{W_{eff}}\right)^{\frac{1}{2}}$ ,  $W_{eff}$  is the effective strip width accounting for the nonzero strip thickness  $W_{eff} = W + \frac{1.25t}{\pi} \left[1 + \ln\left(\frac{2h}{t}\right)\right]$ ;  $W$  is the physical width of conductor;  $h$  is the thickness of LCP substrate;  $t$  is the thickness of the copper trace.

Using Equations (1) and (2), the effective dielectric constants and the relative dielectric constants at resonance frequencies were calculated. The results are presented at Table 3 and plotted in Figure 10.

#### Loss tangent

For a ring resonator, the attenuation constant can be determined from the measured insertion loss and its -3dB bandwidth as [4],

$$\alpha = 0.909 * BW [GHz] * \sqrt{\epsilon_{r,eff}} (1 - 10^{-L_A/20}) [dB/cm] \quad (3)$$

where  $L_A$  is the insertion loss of the resonator at resonance;  $BW$  is the frequency width of -3dB insertion loss defined by  $BW = f_H - f_L$ . ( $f_L, f_H$ ) is the -3dB insertion loss frequencies.

Neglect the radiation loss. The attenuation constant includes the conduction attenuation constant ( $\alpha_c$ ) caused by copper conduction loss and the dielectric attenuation constant ( $\alpha_d$ ) caused by dielectric loss. The conduction attenuation constant is given by [1]

$$\alpha_c(f) = 7.02 \times 10^{-6} R_s A Z_0 \epsilon_r \epsilon_{r,eff} F_{SR} \left[ \frac{W_{eff}}{h^2} + \frac{0.667 \left(\frac{W_{eff}}{h^2}\right)}{1.444 + \frac{W_{eff}}{h}} \right] \quad (4)$$

where  $Z_0$  is the characteristics impedance of the trace;  $R_s$  is the surface resistance expressed as  $R_s = \sqrt{\frac{\pi \mu f}{\sigma}}$ ,  $\mu = 4\pi \times 10^{-7} \text{H/m}$ ,

$\sigma$  = bulk conductivity of the metal,  $f$  is frequency.  $A$  is the ratio of the substrate thickness to the microstrip width containing a correction for the finite thickness  $t$  of the trace

$$A = 1 + \left(\frac{h}{W_{eff}}\right) \left(1 + \frac{1.25}{\pi} \ln\left(\frac{2h}{t}\right)\right). \quad F_{SR} \text{ is a correction}$$

factor for the surface roughness of the copper microstrip. It can be approximately defined as

$$F_{SR} = \begin{cases} 1 + 0.285 \left(\frac{\Delta}{\delta_s}\right) & \text{for } \frac{\Delta}{\delta_s} < 1.93 \\ 1.55 & \text{for } \frac{\Delta}{\delta_s} > 1.93 \end{cases} \quad (5)$$

where  $\delta_s$  is the skin depth of copper defined as  $\delta_s = \sqrt{\frac{1}{\pi \mu \sigma f}}$ ;  $\Delta$  is the mean surface roughness of the copper trace.

After correcting the conduction loss and removing the conduction attenuation constant from the total attenuation constant, the dielectric loss tangent of LCP can be determined from the equation (6).

$$\tan \delta = \frac{\alpha_d c \sqrt{\epsilon_{r,eff}} (\epsilon_r - 1)}{\pi f \epsilon_r (\epsilon_{r,eff} - 1)} \quad (6)$$

The measurement and calculation results are shown in Table 3 and Figure 10.

Table 3. Measured high frequency properties of LCP

$f_0$ (GHz)	$\epsilon_{r,eff}$	$\epsilon_r$	$\alpha$ [dB/m]	$\tan \delta (10^{-3})$
3.8531	2.4232	2.9964	8.158	3.4
7.6488	2.4445	3.0585	13.35	3.4
11.5131	2.4426	3.0238	17.80	3.3
15.3560	2.4409	3.0213	21.68	3.1
19.2423	2.4291	3.0047	25.80	3.2
23.0460	2.4385	3.0179	29.26	3.2
26.8866	2.4361	3.0146	32.41	3.2
30.7661	2.4324	3.0094	34.88	3.1
34.4472	2.4526	3.0377	36.10	2.7

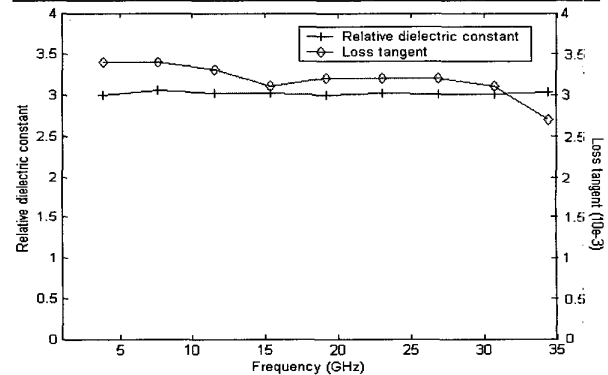


Figure 10. The relative dielectric constant and loss tangent as a function of frequency

#### Conclusions

Thermal stability of the LCP laminates is good. There is significant modulus loss though with temperature. The CTE values are much lower than for FR4, suggesting the possibility of a match to Si chip values. Anomalous results have been observed where high x CTEs lead to negative y readings.

Direct bonding between LCP film and copper foil was examined using the SAB method. The bonding was successfully performed, and the maximum peel strength reached 600 g/cm. The results of peel tests suggested that plasma treatment, heat treatment, and copper deposition process were necessary to obtain strong bonding. The surface analysis by XPS showed that failure of the laminates by the peel test occurs in the bulk of LCP along the bonded interface. Therefore, it is necessary to improve the strength of LCP itself

for applications of circuit board laminates for electronics packaging.

The high frequency characteristics of LCP were investigated. In the frequency range 1GHz to 40GHz, its relative dielectric constant is about 3.0. The value of its loss tangent is below 0.0035. This means that LCP offers Teflon®-like RF performance, and so it is a good substrate for high frequency applications.

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