New Liquid Crystal Polymer Substrate For High Frequency Applications

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Abstract
Novel LCP films have been developed by iQLP, LLC in a Joint Development effort with Dupont, for commercialization in the Printed Circuit Board (PCB) industry, for high frequency applications. The films will be commercialized as Copper Clad Laminate (CCL), and thermoplastic bond ply. Prototype PCB's have been built to evaluate integrity during processing, and tested for mechanical reliability. The films/laminates were well suited for PCB manufacture, and the resulting board's surpassed reliability testing requirements. Of particular note, is the low Z axis coefficient of expansion of the LCP which allows for multilayer reliability and the large difference in melting temperature between the bond and circuit layer which allows for ease of manufacture. In addition RF test vehicles were established that demonstrated that the material supports very low loss signal transmission in Millimeter wave frequencies in the range 40 to 110 GHz, making this material system one of the best circuit laminates available for Millimeter wave applications today.

Key words
High frequency materials, LCP Clad Films, Printed Circuit Boards, and Reliability.

I. Introduction
Liquid crystal polymer (LCP) materials have been available to the electronics industry for over 20 years. Thin films made from these materials have held great promise with respect to high frequency applications, because of their inherent low moisture absorption, low dielectric constant, and loss tangent. The promise for LCPs has been to satisfy a wide variety of applications, where a range of materials has been used, each satisfying a specific niche. The incumbent materials include PTFE polymers filled with ceramics and glass weaves, hydrocarbon/ceramic composites, various thermoset materials, and low temperature co-fired ceramics [1]. In particular, LCP has been thought to be able to satisfy all requirements for millimeter and microwave organic materials, at a lower cost. Until now LCPs have only satisfied niche applications in these markets. One of the major reasons is due to the fact that there are very specialized processes to make a uniform LCP film, which are not very cost effective and are volume limited. In addition, these processes can only provide for thin films which are appropriate for flex applications, and not for the mainstream rigid board specifications of major high frequency applications. Other problems with the incumbent technology include high variation of layer thickness, due to the requirement for post processing in the film manufacturing process, multilayer via reliability issues due to high coefficient of thermal expansion in Z axis(> 100 ppm/ ºC), and manufacturability issues for multilayers due to limitations on current LCP "bond ply".
iQLP and DuPont are jointly developing liquid crystal polymer film and laminates which solve the previous limitations with respect to this technology, which will be positioned to be the first LCP material to meet organic rigid board high frequency requirements. Also, this material has the promise to meet a wide variety of applications, which currently require multiple material sets. The innovation is

based on new materials science which overcomes previous limitations with respect to properties and manufacturability. In particular these materials can be easily processed to achieve a wide variety of thicknesses and very tight thickness specifications, while also meeting the rigid board requirements. Bond plies have been developed with characteristics to allow for ease of multilayer PCB assembly, and mechanical properties for both dielectric layers have been tailored to minimize stresses on vias in multilayer systems for high reliability. In this work, we present our initial findings with this new material system. With our new set of properties we will show reliability data on multilayer LCP PCBs with various sizes of vias, establishing a promising threshold of reliability, using a new LCP bond ply material. In addition we are presenting insertion loss data at frequencies between 40 and 110 GHz, on circuits showing that this material has better loss properties than much more expensive premium material such as low temperature co-fired ceramics.

II. New materials science

Premium high frequency laminate technology has been centered on several categories of materials (previously mentioned) which have controlled, stable dielectrics and low loss properties. Each material has very specialized manufacturing technologies which provide challenges in higher volume.
Our technology takes advantage of materials science where the key properties (Table 1) can be tailored to specific levels. In addition, the material is formulated to be manufactured and scaled to high volume processes.

Table 1: Key properties of the material

Gen 1 Product Properties	
Dielectric Constant	3.8 +/- 5%
Loss tangent	< .003
XY CTE	17+/- 10 ppm/ ºC
Z axis CTE	< 80 ppm/ ºC
Film Properties	Initially 4 and 8 mil plus LCP bond ply. Thickness variation +/- 5%.
LCP Bond ply	ΔT (Melting Temperature) difference Bond Ply and circuit layer. (30 ºC)
Insertion loss (clad material)	1.4 db/cm HTE Cu --1.0 dB/cm RA

Our materials science allows for breakthroughs in several areas: Low Z axis CTE which allows for multilayer PCB reliability; low electrical loss which provides for extremely low insertion loss in circuits; bond ply with > 30C temperature difference between bond ply and circuit layer; and tailored molecular weight/viscosity which allows for a unique and high volume controlled gauge manufacturing process. In addition the material science allows for tailoring of properties which will result in a roadmap of products.

III. Rigid circuit board applications

As part of the Joint Development effort between DuPont and iQLP, specialized LCP films have been developed by iQLP for use in printed circuit boards (PCB's), primarily for use in high speed radar circuit applications and the like. Specifically the two types of films are a circuit clad material (CCL, a layer of film, clad on each side with copper foil) and a thermoplastic bond ply material, having a lower processing temperature such that previously printed/etched layers are not affected by the layer joining process. Further, the Z-axis CTE is much lower than competitive products, which will prevent via cracks under thermal stresses.

Part of the development effort has been to test these materials for application suitability by using them in rigid PCB prototypes. To this end, several iterations of builds have been done by different shops, using different revisions of the materials as they were being developed.
The intent of these builds was to demonstrate the suitability of use in a customary printed board shop operation for similar applications (PCB's made from Teflon®, Kapton®, LTCC, and hybrids), without difficult adaptations of the normal process. Additionally, it was necessary to show that PCB's made with these materials would sustain integrity and full functionality after being subjected to the same reliability testing as rigid PCB's that are currently commercially available.

IV. Multilayer Processing (PCB)

A. *Suitability for Processing*

Press requirement: due to the high melting points of these materials, a lamination press capable of reaching 600°F (315°C) is needed. A vacuum press is beneficial, but not an absolute requirement. Aside from this, any shop equipped to build PCB's with Teflon®, Kapton®, etc. is equipped to use the Dupont/iQLP materials.

Prior to building the boards, some preliminary process testing was performed for via metallization, and it was found that there were no issues doing this. In particular, for the second material revision, it was found that the materials allow processing without any special effort or adaptation, aside from adding leaders for thin structures in the etcher.

B. Build #1

Fig. 1 shows a 4-layer board made up of various microwave test circuits (including stripline antennae, ring resonators, , flip chip, and daisy chains), using all CCL (original revision), and done in foil design using sequential lamination:

- Layers 2 and 3 printed/etched.
- Layer 1 pressed, printed/etched, then layers 1-3 drilled (to become blind vias).
- Layer 4 pressed, printed/etched, drilled with thru vias, metalized, plated, and solder masked.

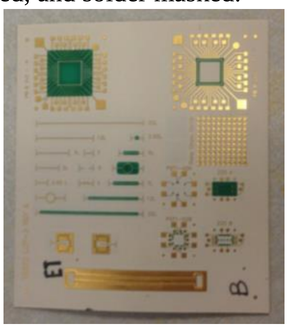

Fig. 1 4-Layer Circuit

C. Builds #2, #3, and #4

Fig. 2 shows a 4-layer daisy chain circuit for mechanical testing. These builds were made with original material revision, and second material revision, by two different shops.

This was done in cap design using CCL outer layers, and bond ply for inner layers:

- Inner layers 2 and 3 printed/etched.
- Inner layers joined with bond ply.
- Layers 1 and 4 printed/etched, drilled with thru vias, metalized, and plated.

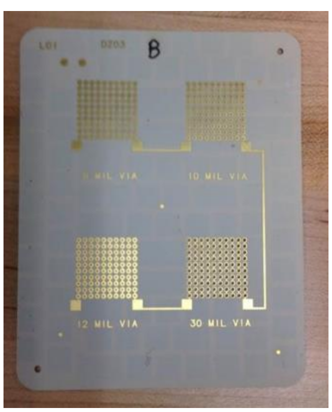

Fig. 2 4-Layer Daisy Chain PCB

V. Results and Discussion

A. Mechanical Measurements

Fig. 3 shows the flatness of a PCB from build #2, which is done by Thermoire analysis. The result being, the board is flat within .013", over 3.5" length, which is within the allowable limit of .008 in/in (.026" over 3.5" length). 3 PCB's from this panel were measured, with similar results.

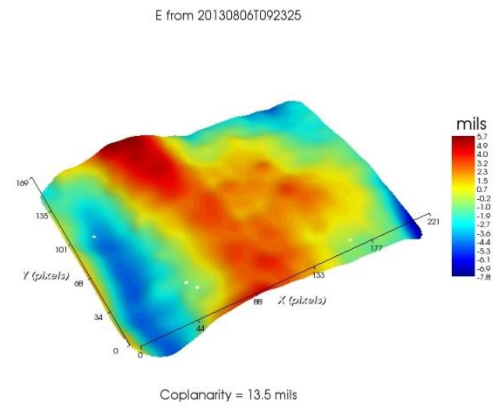

Fig. 3 Thermoire Analysis of PCB

Fig. 4 shows the results of wirebond testing: .001" diameter gold wires bonded to pads plated with soft gold, using ball-stitch wire bonds. Measure the wire-pull force to break bond (minimum 3 gm). Results are 5-16 gm pull force with no bond failures or trace lifts. Post pull examination of lower strength bonds (5-8 gm) revealed traces of residue from PCB fabrication process that were not fully cleaned. Higher bond strength areas had no residue.

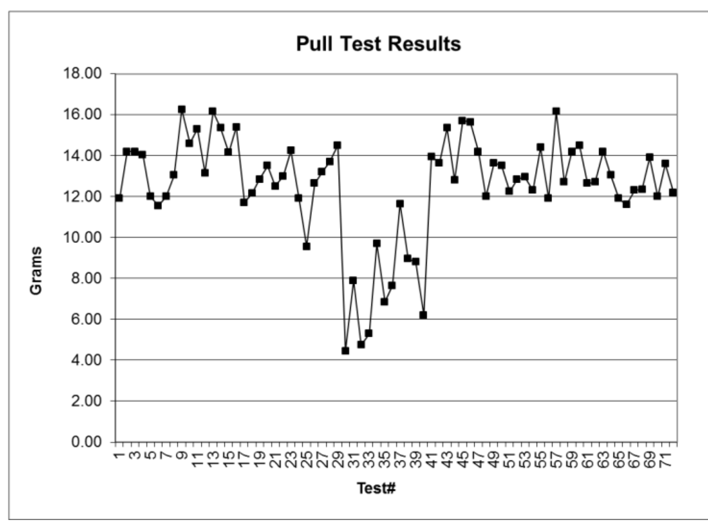

Fig. 4 Wire Bond Pull Test

Fig. 5 shows a cross section of a typical via after exposure to 260°C solder reflow. No via barrel cracks or delamination observed.

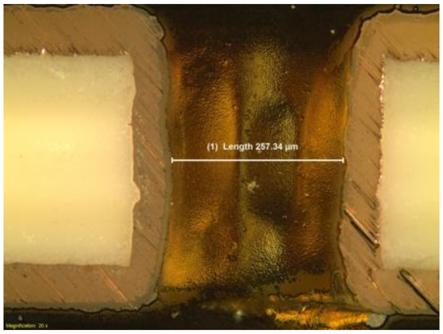

Fig. 5 10 mil via cross sec after solder reflow

Fig. 6 depicts a mechanical stress test of wrapping an etched circuit around a mandrel (1" PVC pipe), and inspecting for loss of adhesion between the copper trace and the film, while under stress. No loss of adhesion observed. Fig. 7 shows an SEM photograph of the trace area at 1020X magnification, showing no indication of trace separation from film.

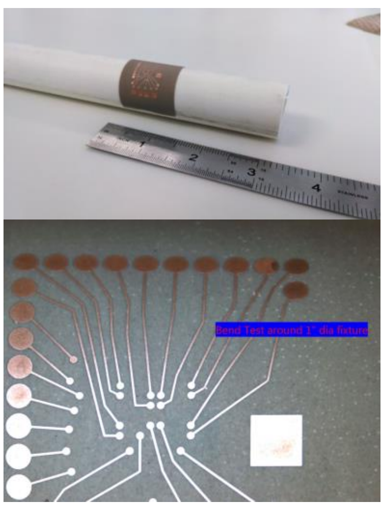

Fig. 6 Traces well bonded to film after mechanical stress

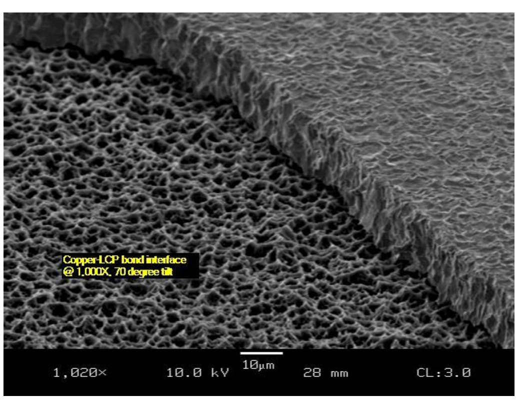

Fig. 7 SEM photo of trace/film

B. Reliability Testing

Fig. 8 shows < 2% increase in resistance through the daisy chains after over 2000 cycles of air-to-air temperature excursions (-45°C to +125°C). Limit is 10% increase over 500 cycles. Further exposure to an additional 200 cycles of liquid-to-liquid shocks at the same temperatures produced no additional increase in resistance. No delamination or blisters were present in the PCB after exposure. Additional PCB's were exposed to 85°C at 85% relative humidity for 168 hours also resulting in no delamination, wicking, or blisters.

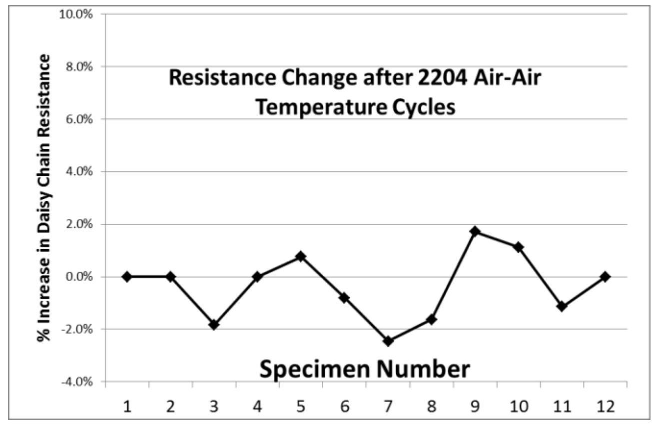

Fig. 8 Resistance Change after Temp Cycles

Fig. 9 shows a cross section of a typical via after exposure to air-to-air and liquid shock tests. No cracks were observed in the via barrel after exposure.

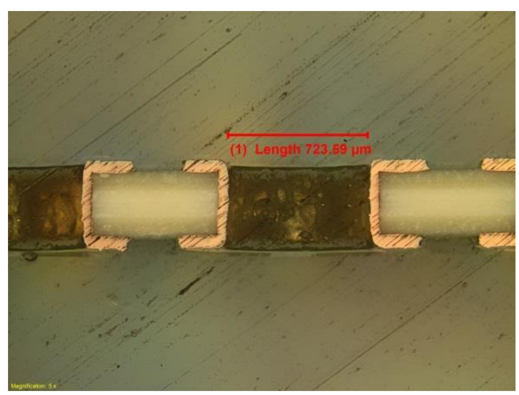

Fig. 9 30 mil via cross section after temperature shocks

VI. RF Test Coupon Description

A test coupon was developed with two metal layers on 4 mil thick LCP dielectric, as shown in Fig. 10. Two different types of copper foils were used –IPC Grade 3 High

Temperature Elongation Electro-deposited copper foil (HTE) and Rolled-Annealed (RA) copper foil for fabricating the test coupon samples. HTE copper has a higher surface roughness compared to RA copper which is one of the smoothest copper foils available for laminate applications. RA copper provides a lower conductor loss thereby reducing overall signal transmission loss. The top metal layer was patterned to form various Microstrip test structures. These test features include Microstrip lines of various lengths, TRL calibration lines, ring resonators and T resonators for extracting dielectric properties. All designs were simulated using Ansys HFSS electromagnetic simulator. Design parameters were optimized for best performance for a 50 ohm test environment. A broadband coplanar waveguide (CPW) to Microstrip transmission lines was used for probing the test structures using Ground-Signal-Ground probes with 150 micron pitch using a Cascade Microtech probe station. Measured S parameter data was recorded using an Anritsu ME 7828 A Vectorstar VNA with millimeter wave test heads in the frequency band 40 GHz to 110 GHz.

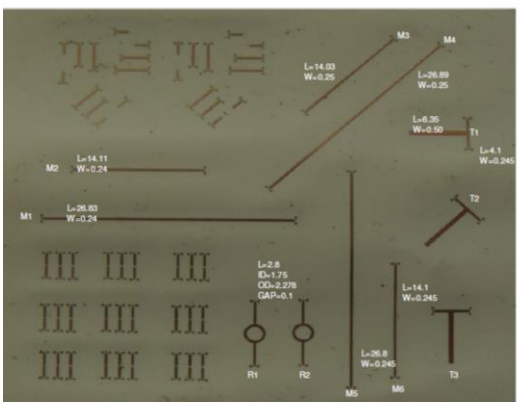

Fig. 10 RF Test Coupon for mm Wave Tests

VII. Millimeter wave Test Results and Discussion

S parameters were measured as a function of frequency and are shown in Fig. 11 and Fig. 12. Fig. 11 shows the measured insertion loss (S21) for two lengths of Microstrip transmission lines; a shorter 0.5 in. line and a longer 1 in. line.

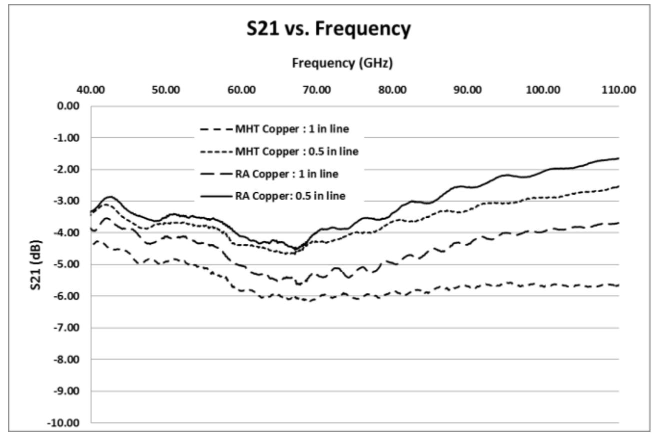

Fig. 11 Measured Insertion Loss (S21) vs. Frequency

As expected longer lines shows nearly twice the insertion loss of the shorter lines. Moreover, smoother RA copper shows a lower insertion loss through the measurement frequency band for both short and long lines indicating better loss performance due to lower surface roughness.

Fig. 12 shows the measured return loss (S11) for both short and long lines using RA and HTE copper foils. As anticipated the copper selection does not significantly affect the impedance match and hence the return loss. All cases show a better than -10 dB return loss with better match (-15 dB) around 80 GHz. This is due to the fact that the CPW to MS transitions used for probing was optimized for 77 GHz considering automotive radar application. However, the matching is good through the entire 40 to 110 GHz frequency band. Mismatch loss due to reflection was removed from the insertion loss of both short and long transmission lines to calculate transmission loss per unit length (unit of dB/inch) for a more objective representation of the transmission line performance.

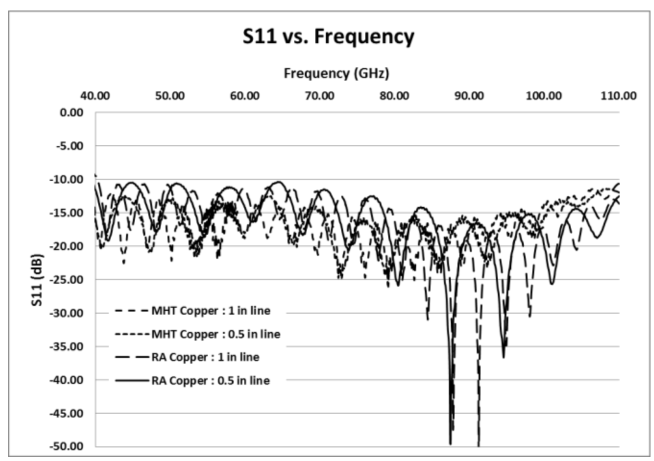

Fig. 12 Measured Return Loss (S11) vs. Frequency

In addition, this method will also remove systematic error components such as influence of probe transitions, asymmetries in measurement setup, spurious reflections, unwanted coupling etc. which are common to both the long and short transmission lines. The calculation method used is explained below followed by results.

Mismatch loss $= -abs[10.\log(1 - |\Gamma|^2)]$ (1)

Where Γ is the frequency dependent reflection coefficient calculated from S11 using,

$\Gamma = 10^{S11/20}$ (2)

True insertion loss as a frequency can then be calculated from;

Insertion Loss = S21 – Mismatch Loss (3)

Transmission Loss/Unit Length (dB/inch) is given by;

Insertion Loss/(L_{long} – L_{short}) (4)

Where: L_{long} and L_{short} are the lengths of long and short lines in inches.

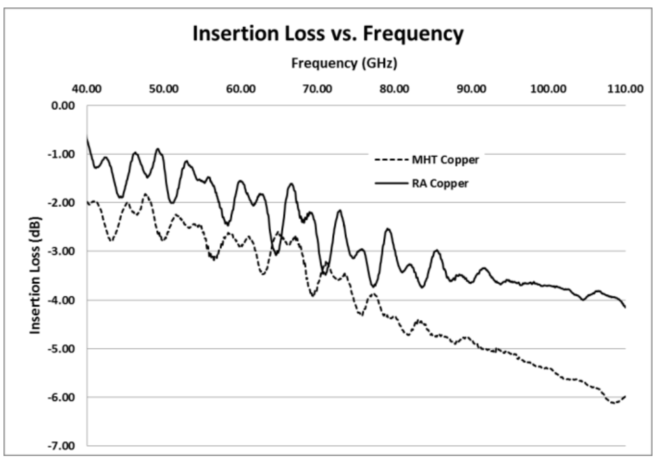

Fig. 13 Transmission Loss/unit length (dB/in) vs. Frequency

Calculated results of Insertion loss per unit length are shown in Fig 13. It is clear from the graphs that smoother RA copper has significantly lower transmission loss compared to relatively rougher HTE copper.

Based on the measurement data and transmission loss data presented in this paper it is very clear that the LCP dielectric laminate supports very low loss signal transmission in Millimeterwave frequencies in the range 40 to 110 GHz making this material system one of the best circuit laminates available for Millimeterwave applications today.

VIII. Conclusions

iQLP/Dupont clad and bondply film materials were tested for suitability of processing for PCB applications in the high-speed radar market. Additionally, several prototype printed circuit boards were built. The films were found to be suitable for processing without difficult adaptations, particularly in later revisions of the materials. The resulting boards were flat within specifications, with well aligned layers, and had good quality vias. Vias continued to have good integrity following solder reflow simulations, and temperature cycles. Testing showed that these boards surpassed reliability requirements. Further work is underway to build boards having BGA components attached for mechanical reliability testing. Also, work is underway to build prototype passive boards that can be used in an actual functioning product.

RF test circuits were built in order to characterize the LCP/copper insertion loss properties. Testing was performed at Dupont RTP and also at an OEM. Insertion measured in the 40-110 GHz range indicates that this material system is one of the best circuit laminates available for millimeter wave applications today.

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References

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