Improving Density in Microwave Multilayer Printed Circuit Boards for Space Applications

David NÉVO[1]
Olivier VENDIER[1], Jean-Louis CAZAUX[1], Jean-Luc LORTAL[2]
[1]Thales Alenia Space
26 avenue J.-F. Champollion, 31037 Toulouse Cedex 1, France
[2] CNES, 18 av. Edouard Belin, 31401 Toulouse Cedex 9, France

Abstract
The need in complexity for microwave space products such as active BFNs (Beam Forming Networks) is increasing, with a significantly growing number of amplitude / phase control points (number of beams * numbers of radiating elements). As a consequence, the RF component's package topology is evolving (larger number of I/Os, interconnections densification ...) which directly affect the routing and architecture of the multilayer boards they are mounted on. It then becomes necessary to improve the density of these boards. It has already been demonstrated the benefits of non-PTFE (Teflon®) materials for the manufacturing of microwave multilayer PCBs. The Liquid Crystal Polymer (LCP) is a very interesting candidate allowing, among others, to achieve RF and LF flexible interconnections. It has many advantages for packaging applications or manufacturing multilayer structures (low dielectric constant and losses, low water absorption, low CTE in X and Y axis…). Mostly, this material is available in very thin layers, allowing to considerably reduce the total thickness of the board and favoring densification (decrease of via diameter, pads, track width...). However, the use of LCP for printed circuit board is fairly recent and few manufacturers have experience with this material. This paper will present the work performed to achieve LCP-based high density multilayer structures, describing the different electrical and technological breadboards manufactured and tested and presenting the results obtained.

Introduction
Future satellite missions will require more functionality with improved performances, in particular in terms of coverage accuracy offered by the satellite antennas. The equipment allowing to form the radiation pattern of these antennas will be thus more complex : the operating frequency and number of amplitude / phase control points will grow. The number of RF paths to be routed in the circuit being proportional to this number of control points, printed circuit boards that support active function's packages will have to densify in order to reduce the impact on the size and weight of the equipment.
Research aiming at promoting densification then led to introduce a new material with very interesting properties, the Liquid Crystal Polymer (LCP). This material is already well known since many years for packaging applications of active components (RF MMICs, MEMS ...). Its good electrical properties, and especially the fact that it has a very low humidity uptake (see Figure 1), make it an ideal candidate for encapsulation and protection of micro-systems (RF or not) sensitive to external aggressions.

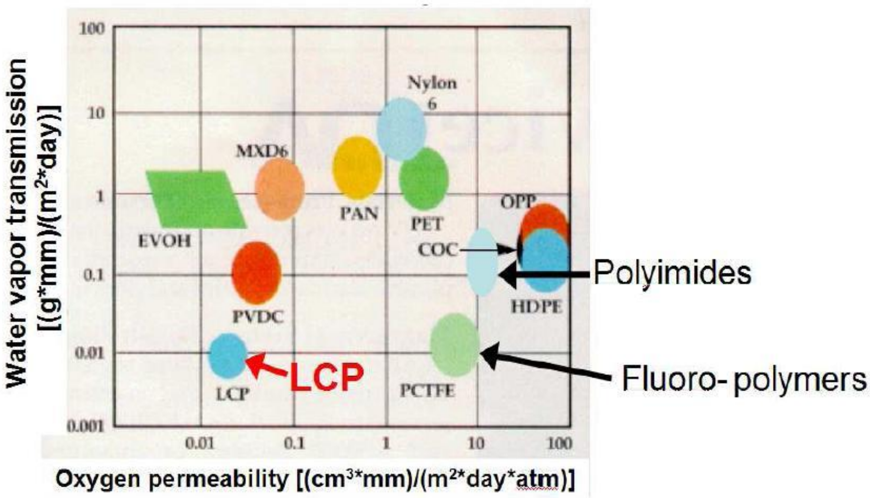


Figure 1 - Permeability to water and oxygen of the different polymer families

Moreover this material has many other advantages allowing to use it as a RF substrate :
- Excellent electrical properties for microwave applications (dielectric constant and low loss tangent),
- Very low humidity uptake (water absorption less than 0.4%),
- Low coefficients of thermal expansion in the X and Y axes,
- Naturally non-flammable (no addition of halogens required),
- Recyclable,

- Flexible for making supple circuits / interconnects,
- Possibility of creating homogeneous multilayer structures,
- Low dielectric constant which is advantageous for antenna applications.

However, the LCP is not a material whose characteristics are close to those of materials commonly used in the PCB industry. Several potential issues have been identified and could complicate the manufacturing or threaten the reliability of the structures :

- A high CTE in the Z axis, generating risks for the integrity of the metallization in the holes,
- A pressing temperature close to 300°C, which is unusual for the PCB industry and implies for the manufacturers to have the adapted facilities,
- A risk linked to the composition of the LCP : this is a material which is not reinforced by a woven glass fabric, which can cause major movements of material during pressing and therefore registration inaccuracies that could be critical for the final stack.
- The LCP is available in very thin layers : this raises potential issues of fragility and flatness of the finished circuit.

Electrical characterization

The first important step consisted in characterizing the electrical properties of the LCP, first according to the frequency and then as a function of temperature. This will allow to confirm the supplier's datas and compare the results with those available in the literature. Several samples of 100 microns thick LCP have been procured and sent to a french laboratory, specialized in this type of electrical characterization by the method of resonant cavity. The two most important electrical parameters were measured : the dielectric constant εr and loss tangent tan δ.

The cavity method is a proven method [1], enabling non-destructive characterization of dielectric materials in the form of thin plates. Even if it is complex, it is the most accurate means of all since it avoids important theoretical approximations mainly due to losses in the conductors, which is not the case for the other methods (resonant rings, transmission lines...). It is also advantageous because it does not require sample preparation by the PCB manufacturer (metallization, etching ...).
The resonant frequency and the quality factor of the cavity are first measured "empty", then the test sample is placed between two cylindrical portions forming the cavity and the measurement is repeated. The dielectric parameters are then obtained from the frequency offset generated by the insertion of the material in the cavity and the new quality factor.

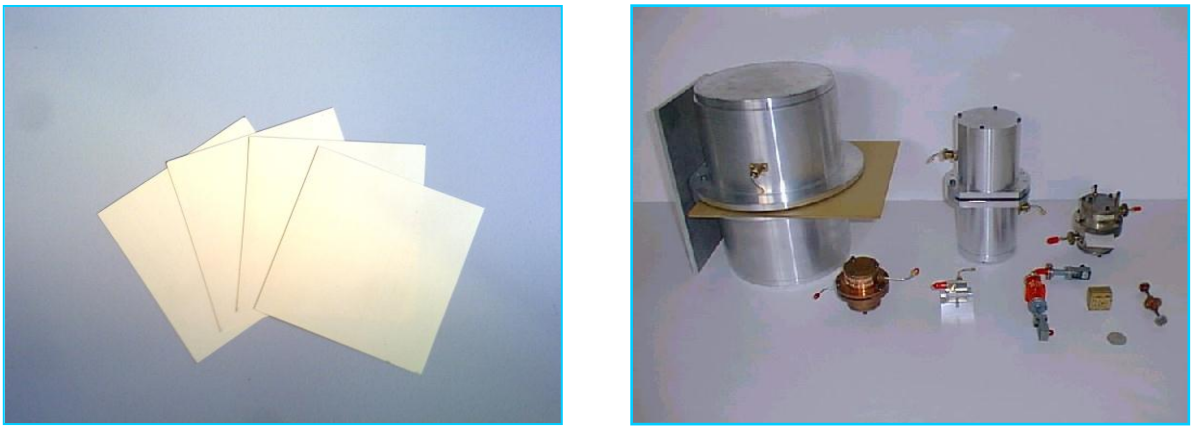


Figure 2 – LCP samples supplied and examples of cavities used for the characterization

For our application iIt was decided to cover the range X-band / Ka-band through three frequency points : 10, 16 and 30GHz. For each frequency two different temperatures will be applied : 20 ° C and 70 ° C, which is representative of what can see the equipment during its life on board a satellite.
A precise measurement of the thickness was performed on each sample before sending them to the laboratory.
Indeed it is important to note that a measurement error on the thickness induces the same order of magnitude uncertainty on the real permittivity of the material. Each measurement was repeated on three different samples in order to assess a possible dispersion between the pieces of substrate.
All samples are 50 × 50 mm ².

The results obtained are summarized by the graphs hereafter :

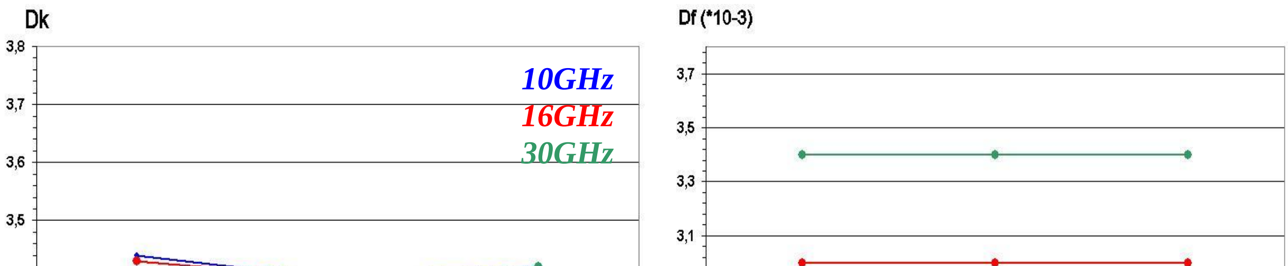


Figure 3 – Dielectric constant (left) and loss tangent (right) at 10, 16 and 30GHz for three different LCP samples at 20°C

The first thing we notice is the very low dispersion values between samples, which is almost zero for the loss tangent. This is important because it shows a good homogeneity of the material in a format and a good reliability of the measurement method.
If we compare the measured values with the datasheet (the values given in the datasheet for Dk and Df at 10GHz / 23 ° C are : Er = 2.9 and tan δ = 0.0025) we observe a significant difference for the dielectric constant, we will come back to this point later. The loss tangent values are slightly higher but still close at $2,9.10^{-3}$ with a measurement tolerance of ± $1,7.10^{-4}$.
The dielectric constant is very stable as a function of frequency. Between 10 and 30 GHz it undergoes a change of only 1.4% with a slight decrease.
Regarding the loss tangent we observe an increase with frequency. Between 10 and 30 GHz tan δ increased by 17% which is not negligible.

Thickness measurements of the samples show a maximum deviation theory / practice of 7.8% (sample n°1), that means we are well within the range of ± 10% announced by suppliers.

Now here is the variation of dielectric parameters as a function of temperature :

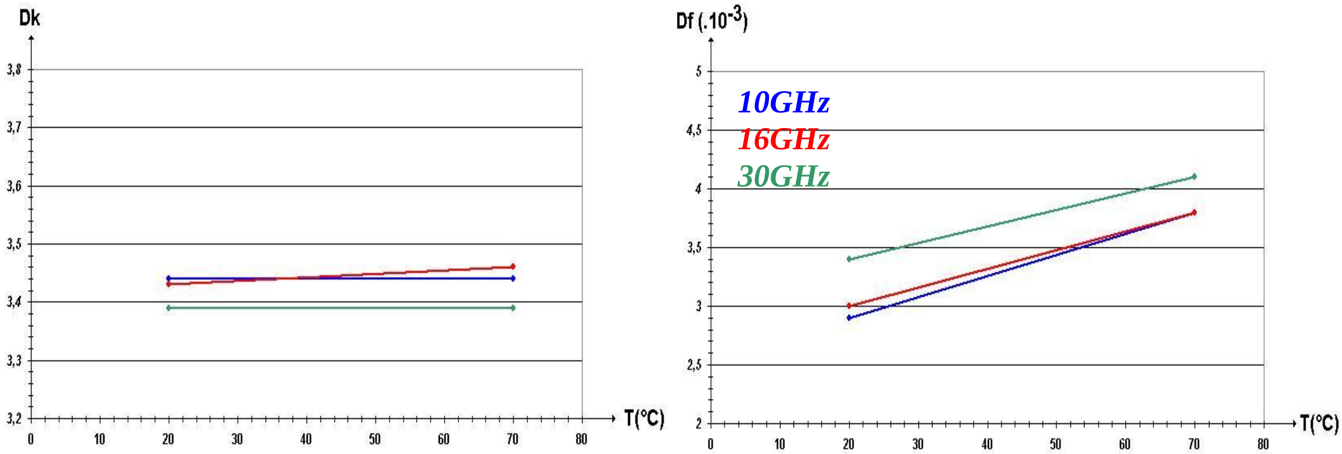


Figure 4 – Dielectric constant (left) and loss tangent (right) as a function of temperature at 10, 16 and 30GHz for one LCP sample

Since the results are identical between two different samples the values above are given for one sample only.

The results are again in line with what we expected : the dielectric constant is very stable when temperature rises.
The loss tangent is much more sensitive, however, and increases with temperature. At 10 and 16GHz, tan δ increases third of its original value between 20 and 70 ° C. At 30GHz, the slope remains almost the same but with an offset value of 17% up.
- At 10 and 16GHz, the tan δ increases by 30% between 20°C and 70°C (from $2,9.10^{-3}$ to $3,8.10^{-3}$),
- At 30GHz, the tan δ increases by 21% between 20°C and 70°C (from $3,4.10^{-3}$ to $4,1.10^{-3}$).

It is therefore important to consider the sensitivity of this parameter when working in high frequency and / or on applications that will be used in environments with high thermal stresses as space.

Regarding the datasheet versus measurement shift observed for the value of the dielectric constant, the first thing we did was to start a new characterization test, using a sample derived from a different batch in order to confirm the first values.

At 10GHz / 22°C, the measured Dk and Df are 3,3 and 3.10^{-3} respectively, which is very close to the first measurements. Then, the laboratory expressed its confidence with respect to the method used and therefore it is very unlikely that the measurements are wrong. They have already performed several characterizations of this type of sample / material that is well suited to a measurement cavity, and there is also the fact that the results are consistent (frequency and temperature behavior) and very reproducible from sample to sample even from different batches.

Our research has led us to focus on the characterization method used. : it is well known that most of the PCB materials are not isotropic (glass fabrics, fibers, loads...). In addition, depending on the characterization method used, the electromagnetic field propagates in a certain direction (XY and / or Z). Therefore, it does not always "see" the same dielectric constant but several contributions, more or less important depending on the path of the wave.
The most commonly used method and from which are given in the supplier's datasheet values, the IPC-TM-650, is based on a stripline resonator operating in X-band (10GHz), excited by two coupling lines. The propagation of electromagnetic fields is therefore mainly in the Z axis. For resonant cavities on the contrary, the field propagates in the X and Y axes into the substrate, which may explain the differences observed in the dielectric parameters.
Furthermore, a 2010 paper on the subject [2], is reporting resonant cavity measurement results on LCP samples that are in line with ours. In this publication, a method for characterizing the substrate in the X and Y axes separately is proposed. They also performed measurements in the Z axis. The dielectric constant values obtained between 5 and 20 GHz are :
- 3.6 for the X axis, the Y axis to 3.3, giving an average at 3.45 for these two axes, very close to what we have been presenting earlier,
- 2.72 for the Z axis, which is close to what is given by the substrate's datasheet (2.9).

The hypothesis of a disparity of the Dk values according to the orientation of the electromagnetic field into the substrate is then pertinent to explain our results.

Breadboards definition and manufacturing

The first breadboard we wanted to design aims at evaluating the copper adhesion on the substrate. This point is important because it ensures that there will be no tracks and/or pads stripping during heat stresses, especially during components report phases.
A peel strength test has been performed according to IPC standard with test coupons etched on a 100 microns thick LCP substrate :

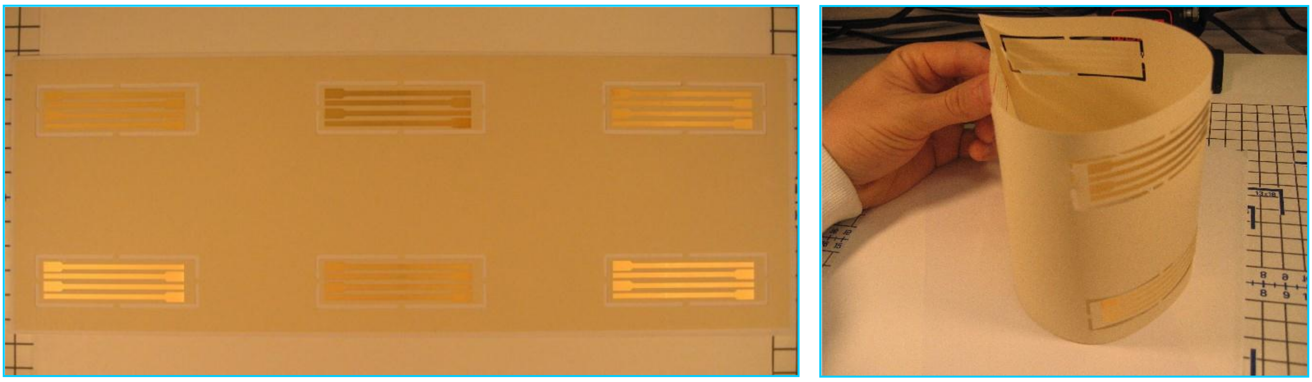


Figure 5 – Breadboard used for the peel strength test

For that the conductor selected is peeled back at one end for a length of about 10 mm. The detached end of the conductor is firmly gripped over its whole width and traction is then applied in a direction perpendicular to the plane of the PCB until the copper starts to peel away. The rate of traction is kept constant at 50 mm/min. The traction direction is kept perpendicular to the plane of the PCB. The conductor width to be taken into account shall be the actual width where the conductor is stuck to the insulation.

Following this test we were not able to deduce some peel strength values : indeed, the adhesion of copper was so good that it is the substrate that has been torn and peeled off from the aluminum soleplate it was glued onto for the test.
The photo below shows the substrate after the test :

Figure 6 – Substrate after the peel strength test

Another test aiming at evaluating the copper adhesion has been performed. We have, using a soldering iron operating at 380°C, brazed and unbrazed a wire on the tracks of the coupon previously used, on both sides of the track in order to test two different widths. This operation has been repeated five times, and no peeling of the tracks or deterioration of the substrate has been observed. This confirms our initial tests and the very good copper adhesion on LCP.
The picture below shows the substrate after the five wire brazing / unbrazing :

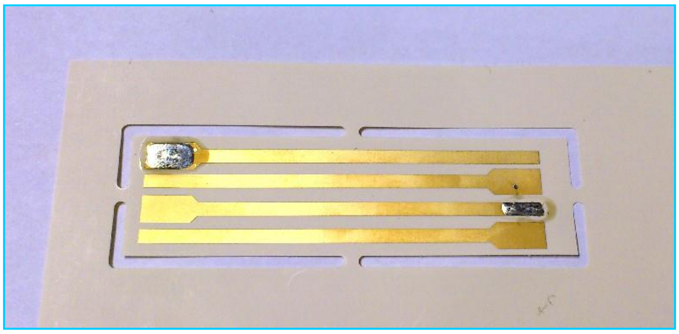


Figure 7 – Substrate after the wire brazing / unbrazing tests

The second breadboard designed and manufactured is a double-sided board of 160×150mm² on 100 microns thick LCP. It contains various types of patterns that allow us to judge the quality of this board on a technological point of view (plating quality, etching accuracy, via hole quality...). Five identical boards have been manufactured. The photos below present this board and each pattern is described just after :

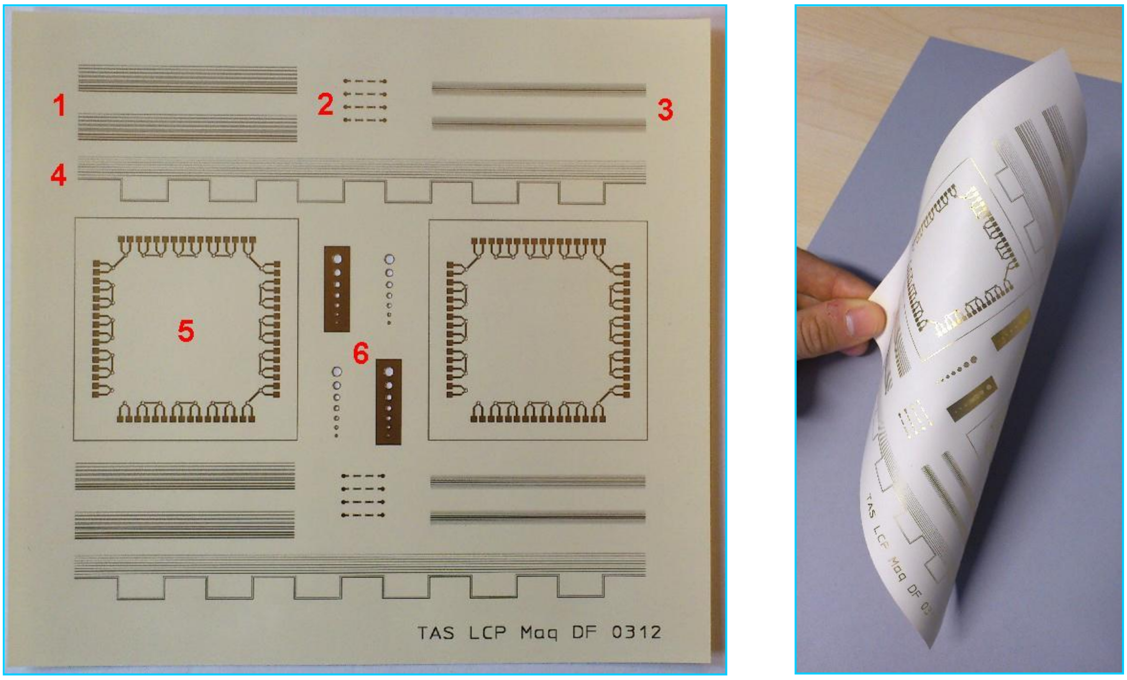


Figure 8 – Second breadboard : double sided board on 100 microns thick LCP

1. Several groups of three tracks, with the same width and same gap for each group (40µm, 60µm, 80µm, 100µm, 150µm and 300µm),
2. Very small vias (100µm and 200µm) connected in daisy chain, made by mechanical and laser drilling (six holes per daisy chain),
3. Short lines (5 cm) of different widths (40µm, 60µm, 80µm, 100µm, 150µm and 300µm) with no critical gaps (200µm),

4. Long straight tracks (13 cm) of different widths (60µm, 80µm, 100µm, 150µm) and two meandered lines of 100µm and 200µm with a 200µm gap,
5. Specific pattern with 32 vias connected in daisy chain, dedicated to a very precise measurement of the overall chain resistance, allowing to detect failures in the metallization,
6. Vias of different diameters (400µm, 600µm, 800µm, 1mm, 1,2mm, 1,5mm and 2mm) made in both pads and metallized areas.

The pictures below detail some of these patterns :

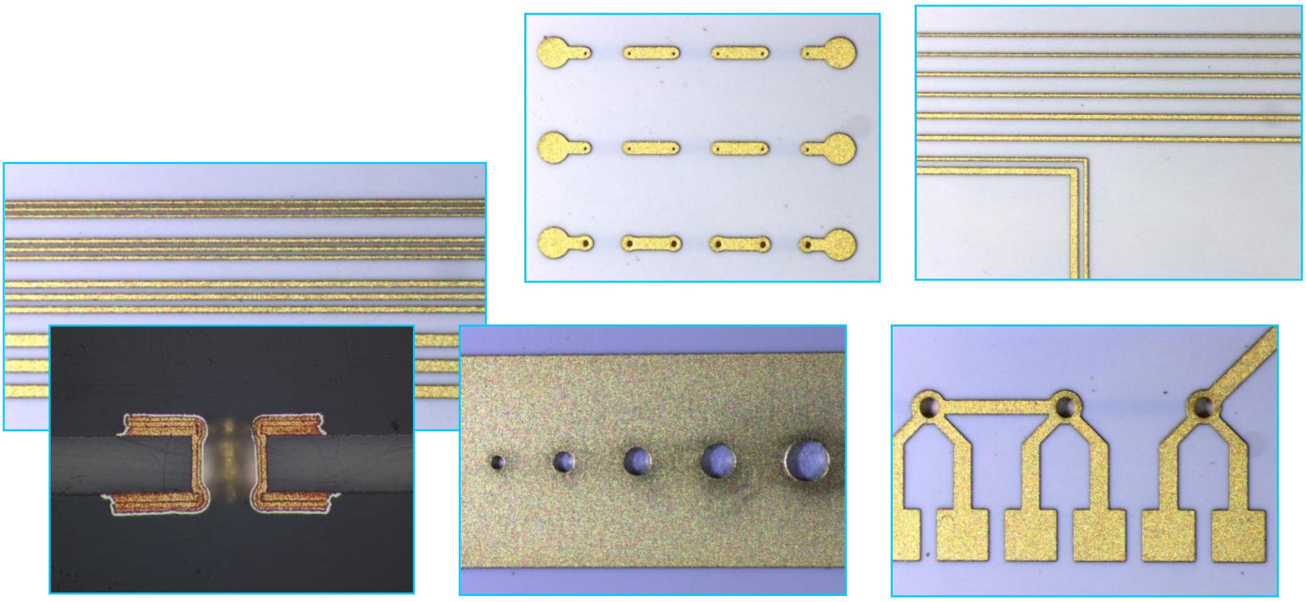


Figure 9 – Second breadboard: detailed views of the board

The conclusions from the complete analysis of three identical boards are the following:
- No visual defects on the substrate or the metallizations, whether on the circuit or in the microsections,
- Vias of good quality, well centered in the pads,
- No cuts or abnormal resistance value in daisy chains,
- For the groups of three tracks with the same widths and gaps (pattern n°1), 54% of measured track widths and gaps (360 measurements have been performed) are within tolerance ±20µm, 41% are within tolerance ±30µm with a majority within ±25µm and 5% are beyond,
- For the short lines of different widths (pattern n°3), 58% of measured track widths (132 measurements have been performed) are within tolerance ±20µm and 42% are within tolerance ±25µm,
- For the long straight tracks of different widths (pattern n°4), 92% of measured track widths (48 measurements performed) are within tolerance ±20µm and 8% are within tolerance ±25µm,
- All the long meandered lines (pattern n°4) are within tolerance ±20µm (12 measurements performed) and half of them are within ±10µm.

Globally we notice an over-etching of the circuit, this is the reason why all tracks are thinner than expected and gaps wider. In spite of this, the values are quite acceptable and regular (no large variations in width for a single line, even the longest), even for thinnest tracks / gaps.

The next breadboard was designed for achieving etched resistors on LCP. Indeed, for some RF functions it is necessary to integrate passive components such as resistors and / or capacitors. This is the case of the application we are focusing on in this paper, the Beam Forming Network, which contains Wilkinson couplers that need a resistor to operate. We have therefore designed a board consisting of a 100µm LCP substrate associated to a thin resistive film deposited on copper, bonded together using a 40µm prepreg.
This single sided 150×100mm² board contains 96 resistors which have two different widths (150µm and 500µm) and values (50Ω and 100Ω).

Pictures of this board are given hereafter:

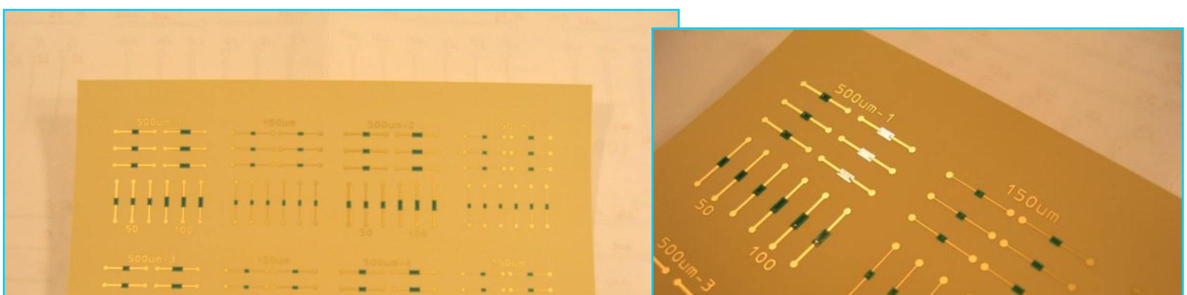


Figure 10 – Single sided board with resistors

Four identical boards have been measured. For each line width (150µm and 500µm) and value (50Ω and 100Ω) the values distribution is given hereafter :

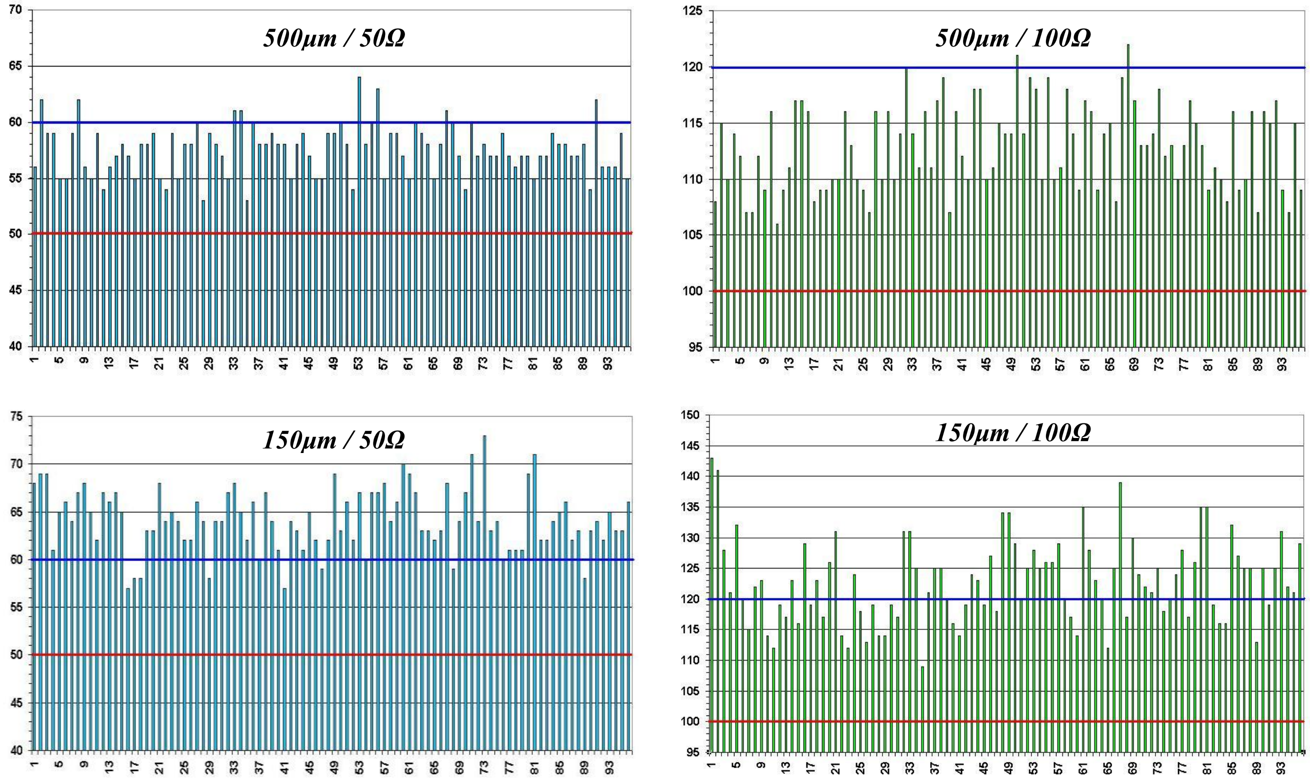


Figure 11 – Resistors values

The specified tolerance is ±20%. The red line represents the expected value and the blue one the upper limit. The number of measured resistors is given on the X axis.

We observe that all the values are higher than expected, probably due to a global over-etching of the copper on the board. Nevertheless the values are very good for resistors of 500µm width : only eight are out of range for 50Ω resistors and only two for 100Ω. The results are not as good for 150µm width resistors as most of them are out of the specified range. This is not surprising because the lines are very thin, the slightest etching inaccuracy has much more impact on the final value. Despite this all the resistors are functional and the majority is within the range ±30% which could be acceptable depending on the application.

The last breadboard was also designed for achieving resistors but buried inside a fully LCP structure. Indeed thin film etched resistors are very sensitive to the external environment and it is better to bury them in circuits to protect them better. We thus designed a similar board to the previous one but in a three layers configuration (stripline).

The structure of this circuit is described hereafter:

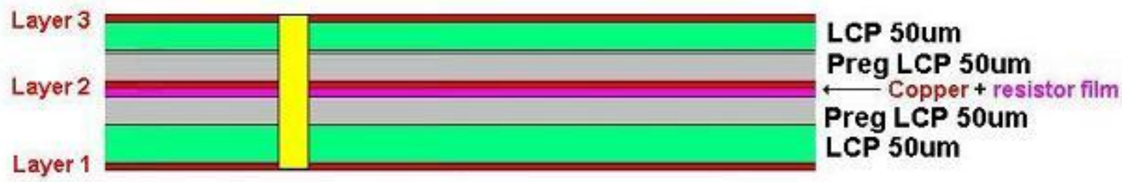


Figure 12 – Three layers LCP structure with buried resistors

Pictures of this board are given hereafter:

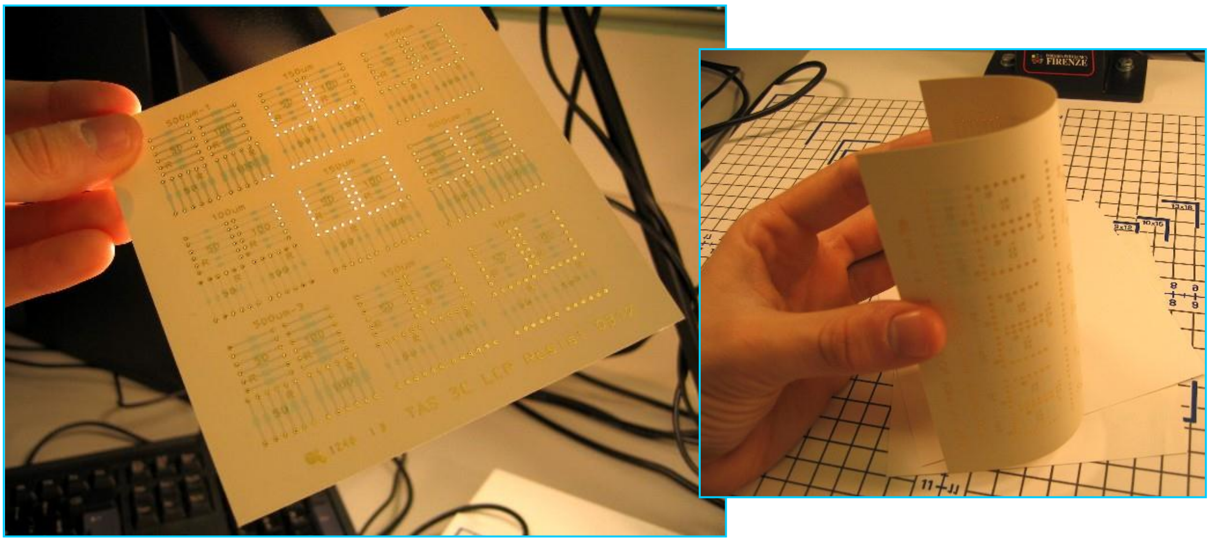
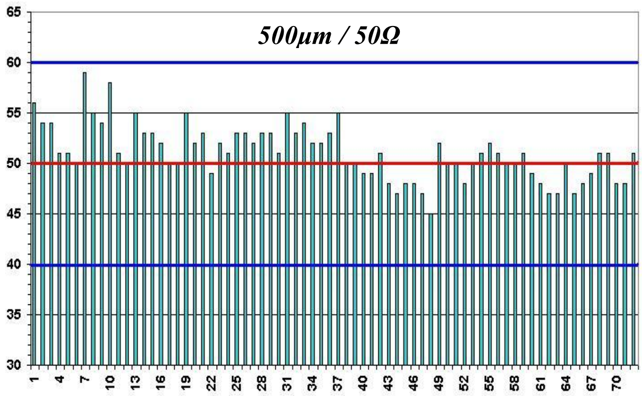
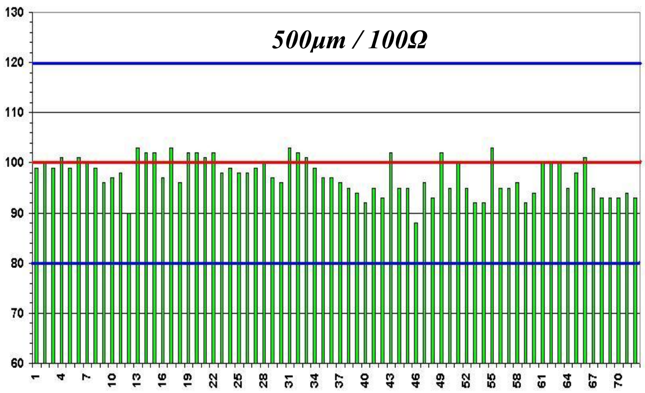


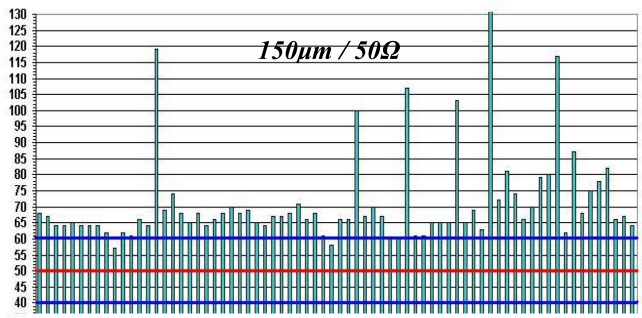
Figure 13 – Three layers board with buried resistors

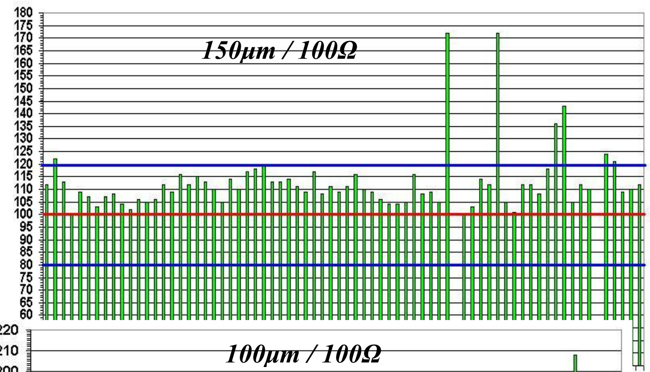
No visual defects have been observed on the substrate or the metallizations, whether on the circuit or in the micro sections.
This 120×120mm² board contains 108 resistors which have three different widths (100µm, 150µm and 500µm) and two different values (50Ω and 100Ω).

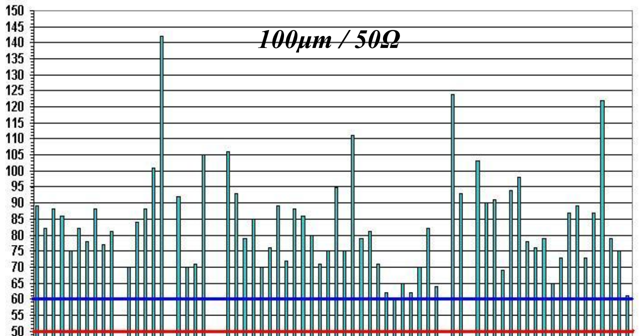
Four identical boards have been measured. For each line width and resistor value the results are given hereafter:











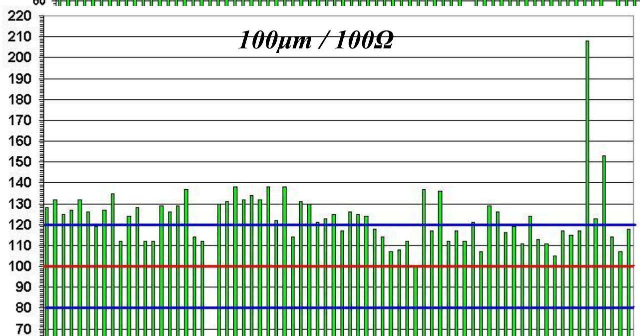


Figure 14 – Resistors values

The specified tolerance is ±20%. The red line represents the expected value and the blue one the limits including the tolerances. The number of measured resistors is given on the X axis.
We observe that all the values are very good for resistors of 500µm width, most of them are even in the range ±10%.
These results deteriorate when the track width decreases, in particular for 50Ω resistors. We also observe resistors with values abnormally very high and even some damaged ones. Nine resistances were lost in total on the four circuits measured, three-quarter of them for a track width of 100µm, the rest for the 150µm tracks. The pressing step has a significant effect on the resistors. Indeed, the pressing temperature of the LCP prepreg is very high, close to 300 ° C, which can degrade resistors if they are too thin. This could be verified because the same breadboard has been tested but using a bonding film requiring a lower pressing temperature : the values dispersion obtained is the same but all the resistors are functional.

Conclusion

The liquid crystal polymer is a very interesting candidate as a printed circuit board substrate and the work presented in this paper confirms this. Its excellent dielectric properties have been first measured up to 30GHz with an accurate characterization of cavity. Very good copper adhesion has been then observed even with high thermal stresses (soldering / desoldering). A double sided breadboard has allowed to know the etching accuracy that can be achieved for high density circuits (small diameters, very fine track widths / isolations). Finally, the possibility to achieve etched resistors on LCP has been demonstrated both in outer layer and buried in the circuit, provided that you comply with a sufficient track width, in order to reduce their sensitivity to etching tolerances and protect them in case of high pressing temperature.

Acknowledgment

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References

1. “Complex permittivity of MIC substrate”, P. Guillon, Y. Garault, AEU, Band 35, Heft 3, 1981, pp. 102-104
2. “Discussions on Microwave Measurement of Permittivity Anisotropy in the Plane of Dielectric Laminate Substrates”, Shuhei WADAYAMA, SAITAMA UNIVERSITY, Asia-Pacific Microwave Conference 2010