Development of Multi-Layer Liquid Crystal Polymer Ka-band Receiver Modules

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***Abstract*-We present the development of a Ka-band receiver module using liquid crystal polymer (LCP) thin-film surface mount packages. The packages are constructed using multi-layer LCP films and can be surface mounted on a printed circuit board (PCB). The package utilizes vias to connect the RF input from the PCB signal launch onto the package substrate. The use of an LCP enclosure provides near-hermetic capabilities in a compact structure. The receiver module consists of a low-noise amplifier (LNA), an image-rejection mixer and a driver amplifier. The surface mount package feedthrough simulation predicts better than 20 dB return loss up to 42 GHz. We show the conversion gain measurement of the receiver and derive a chart that explains sources of loss in the module. From the chart we discern that the package feedthrough loss is approximately 0.7 dB at 38.4 GHz.**

I. INTRODUCTION

Emerging microwave and millimeter-wave applications require effective and low-cost approaches to high-frequency electronic packaging to fulfill the industry demand [2]-[3]. At millimeter-wave frequencies, ceramic packages [4]-[9] are frequently used to provide low loss transitions and hermeticity. High cost and poor thermal dissipation are the disadvantages of ceramic packages. At lower frequency ranges, plastic packages [10]-[12] are used for cost effectiveness. However, their electrical performance is limited, and plastic does not serve as a moisture barrier. Recently, Quad Flat No-Lead (QFN) packages molded with liquid crystal polymer (LCP) have emerged as an organic package platform for high frequency applications [13]-[16]. The LCP QFN packages are formed by injection molding of liquid crystal polymer around a conventional lead frame [16]. The lead frame thickness is on the order of 15 mils (375μm), and the width and gap feature sizes are at least ~8 mils (200μm) to ensure successful molding and lead frame metal etching. These large feature sizes of the lead frame limit the design of package feed-through transitions to achieve low loss and low parasitics at millimeter-wave frequencies. Another drawback of the LCP QFN is the use of epoxy to mount a cap onto the package base [15]. The epoxy is the interface through which moisture will be penetrating into the package.

In this paper, we present the development of thin-film liquid crystal polymer surface-mount packages for Ka-band receiver down-converter modules. The LCP films have the ability to act as both the substrate and package for multilayer construction [17]-[18]. The use of multilayer LCP films provides us added flexibility to design the package feedthrough with smaller feature sizes. The height of the vertical transition can be altered through the use different film thicknesses starting from 1 mil. Furthermore, the multi-layer LCP structures will provide a hermetic environment for packaged MMICs [19] and embedded passive devices. Using our technology, a near-hermetic package can be constructed in a compact and light-weight format. Our packages are constructed using multilayer LCP films and can be surface mounted onto a printed circuit board. The package uses vias to provide electrical connection between the PCB and the package substrate. Our via and surface mount concepts applied to the package using LCP demonstrate exceptional performance in the Ka-band downconverter module, as will be shown later.

II. LIQUID CRYSTAL POLYMER

Liquid crystal polymer (LCP) is a thermoplastic material that has low moisture absorption and low hydroscopic expansion. The low loss ($\tan\delta = 0.002\text{-}0.004$ up to 100GHz) [1], [20]-[22], near-hermetic characteristic (water absorption <0.004%) [19], [23], and low material cost [24] make LCP appealing for high-frequency designs where excellent mm-wave performance is required at cost lower than that of ceramic. LCP's low water absorption makes it stable across a wide range of environments by preventing changes in the relative dielectric constant (ε_r) and loss tangent ($\tan\delta$) [1]. Fig. 1 shows an S21 (dB/mm) plot of microstrip line fabricated on an LCP substrate of 50 μm thickness. The conductor width is 108 μm. The measurement shows microstrip line insertion loss of 0.1 dB or less per 1-mm length up to 40 GHz. The low dielectric constant of LCP allows fabrication of transmission lines on ultra-thin substrates (i.e. 20 μm) with low attenuation loss compared to a ceramic counterpart with high dielectric constant forcing its 50-Ω lines to be very thin and have higher attenuation loss. In addition, the material's flexibility and relatively low processing temperatures, compared to ceramic counterparts, enable applications such as integration of microelectromechanical systems (MEMS) low-loss RF switches [19]. Finally, development of high-density multilayer packaging is possible due to the availability of many types of LCP material with various melting temperatures from 240 °C to 320 °C, allowing many sequences of lamination steps in the fabrication multilayer structures.

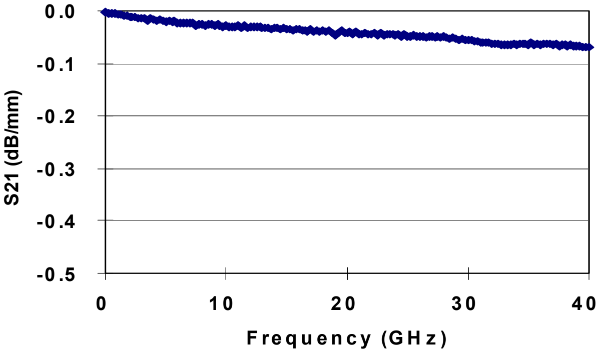

Figure 1.Measured return loss of a microstrip line on 50-µm-thick LCP (width 108 µm)

III. Design Of Package and Package Feed-Through

Fig. 2 shows a schematic diagram of the thin-film LCP surface mount packages developed at the University of California at Davis [25]. The substrate layer can be as thin as 1 mil (25.4 µm) to shorten the vertical interconnect transition. Electrical signals enter the package through a bottom metal trace and connect to the top of the package substrate through a plated via. The LNA, mixer and driver amplifier are mounted on the top metal layer of the package substrate. Once proper electrical connections are provided to the MMICs by bond wires, a multi-layered LCP lid is laminated on top of the package to produce a near-hermetic cavity. Note that the ground pads from the top metal layer are connected to the bottom ground plane of the package by blind vias instead of through vias. The main purpose of using blind vias from above and below the package substrate and electrically connecting them at an intermediate ground metal layer is to prevent moisture from entering the package cavity through the ground vias. Also, the RF signal vias are through vias but are covered by the laminated LCP lid on the package surface, Fig 1d. Therefore, moisture will be blocked by the lid from entering the package.

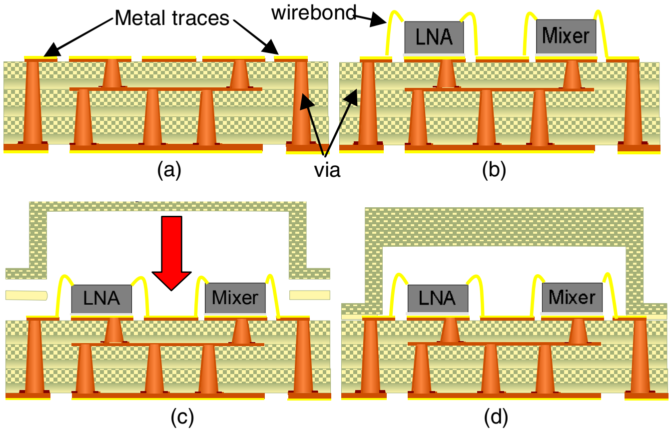

Figure 2. Schematic diagram of the multi-layer thin-film LCP package: (a) cross section view, (b) after MMICs are mounted, (c) before lid lamination and (d) after lid lamination.

We have designed the vertical feedthrough transition of the thin-film LCP surface-mount packages with the aid of an Ansoft HFSS (High Frequency Structure Simulator) and Q3D Extractor. Our design starts out with a 9-mil (228.6-µm) thick LCP multilayer substrate with a 10-mil (254-µm) diameter via process. We have chosen the via diameter to be 10 mils, which is mechanically drillable, to minimize the production cost by avoiding laser machining. The via and via pad dimensions were designed using a first-level approximation of dividing the inductance of the via by the capacitance of the via pads, taking the square root of the quotient and setting it to equal approximately 50 Ω. Since the height of the via is fixed at 9 mils, the sizes of the via pads were varied to achieve 50 Ω. This design was performed using the Q3D Extractor that calculates the inductance and capacitance of the via. Then, the complete feedthrough was simulated and optimized on HFSS. Fig. 3 shows the simulated S-parameters of the complete package feedthrough design. The simulation shows a return loss of better than 20 dB and an insertion loss of less than 0.45 dB up to 40 GHz.

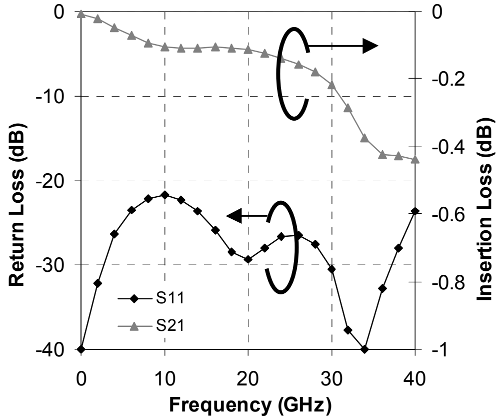

Figure 3. Simulated result of the thin-film LCP package feedthrough transition design on HFSS

The fabrication of the design was carried out at Microconnex on multi-layer LCP films. Six layers of LCP film with thicknesses alternating between 2mils (50.8 µm) and 1mil (25.4 µm) were laminated to produce a total substrate thickness of 9 mils (228.6 µm). High- and low-melting-temperature LCP layers were staggered to allow lamination by sandwiching the melted low-melting-temperature LCP layers with the high-melting-temperature LCP layers. The metal traces are located above, below, and in two layers within the multi-layer LCP stack to allow blind vias to electrically connect the ground planes on the package substrate surface to the bottom ground of the package while preventing moisture from entering the package cavity, as well as to route DC input and IF signal traces. The bottom ground metal has a thickness of 18 µm to provide mechanical support, and all visible copper traces and planes are gold plated to prevent oxidation.

IV. RECEIVER LAYOUT AND MMIC COMPONENTS

The schematic diagram of the Ka-band receiver module is shown below in Fig 4. The package requires two Ka-band signal inputs, for input RF and LO, and two IF outputs from the mixer. There are three DC inputs for powering the LNA and the driver amplifier. Fig. 5 shows the layout of the module. As can be seen the RF signal enters the package on the left hand side and is amplified through the LNA. The amplified signal then enters the mixer to be downconverted to two IF signals, which exit at the top right region of the package. The LO signal enters the package from the bottom right, is amplified through a driver amplifier, and enters the mixer.

V. CONVERSION GAIN MEASUREMENT

The package was mounted onto a 20-mil-thick Rogers RO4350B [26] printed circuit board using epoxy. The CPW launches on the PCB test board were probed for measurement. The receiver RF input power was varied from -39 dBm to -12 dBm, the RF frequency was varied from 37 to 39.4 GHz, the LO frequency was varied from 35.8 to 38.2 GHz, and the IF output power was measured at 1.2 GHz. The RF signal was generated by Agilent's Performance Network Analyzer 8364B, the LO was supplied by an HP8350A Sweep Oscillator, and the IF output was picked up by the E4440A PSA Series Spectrμm Analyzer. The LO input power entering the package was 2 dBm, and the driver amplifier provided enough gain, ~24dB, to supply the mixer with greater than 17dBm of power. Fig. 6 shows the conversion gain of the packaged receiver. The x axis gives the input RF signal frequency, and the y-axis gives the conversion gain achieved at 1.2 GHz. The legend shows the input RF power. As can be seen, up to ~38.4 GHz the conversion gain is maintained at 2.5~3.5 dB. The conversion gain above 38.4 GHz drops off due to degradation of the package feedthrough performance. Table I shows the gain/loss distribution seen throughout the package by the RF input signal until it leaves the package after being downconverted, assuming a 3-dB conversion gain is achieved, i.e. at 38.4GHz. Also, the chart assumes a power level of -18 dBm presented to the RF input of the package. From the table it can be seen that the package feedthrough loss was approximately 0.7 dB.

Fig 7 shows the assembled receiver module on the LCP package mounted on the PCB board for measurement.

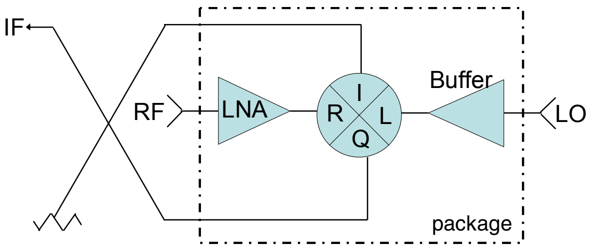

Figure 4. Block diagram of the Ka-band receiver module

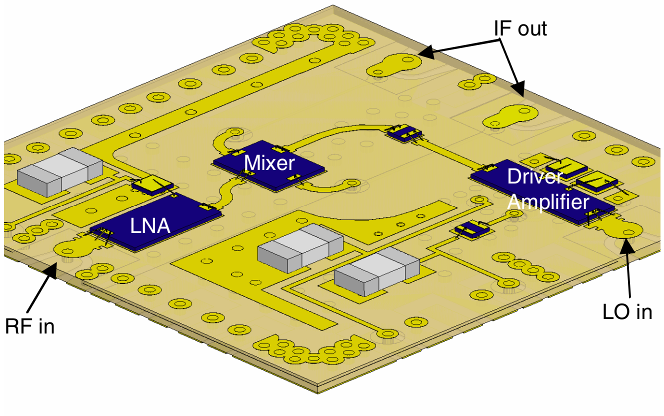

Figure 5. Module layout

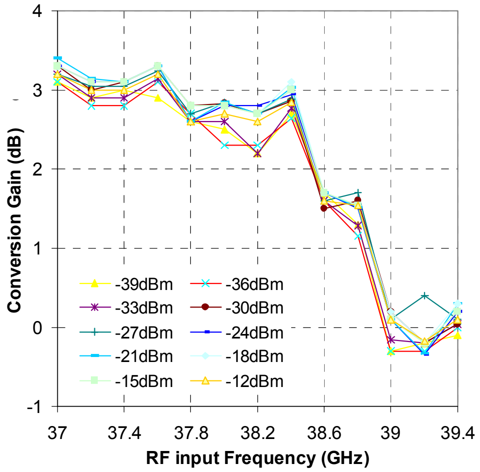

Figure 6. Conversion gain measurement of the Ka-band receiver module

Table I Loss distribution throughout the package at 38.4GHz

Description	Loss (dB)	Gain (dB)	Power (dBm)
Receiver Package RF Input			-18dBm
Package feed-through	0.7dB		-18.7dBm
LNA Gain		16.5dB	-2.2dBm
Bond wires connecting LNA and microstrip on package	0.3dB		-2.5dBm
Microstrip between LNA and Mixer (~2mm)	0.2dB		-2.7dBm
Bond wires connecting microstrip to Mixer	0.3dB		-3dBm
Mixer Conversion Loss	11dB		-14dBm
Loss from mixer wirebonds, stripline, package feedthrough, probe and cable connecting to PSA at IF frequency output	1dB (estimate)		-15dBm
Conversion gain		3dB	

VI. LID CONSTRUCTION AND LAMINATION

We have investigated the multi-layer lid construction, the lid-to-substrate lamination method, and the cavity leak rates for the laminated cavity. We laminated a 2-mm-thick LCP sample and drilled a cavity. Ninety-five percent of the cavity depth was drilled mechanically for the purpose of saving cost and time, and the remaining five percent was drilled with a laser for precision. The thick lid cover provides rigidness to the package, and the cavity allows room for wire bonds. In laminating the lid to the package substrate we applied heat locally to avoid heating and damaging of the packaged components. Currently, our cavity achieves a $5x10^{-8}$ atm-cc/sec leak rate according to measurements taken at Sixsigma Services [27].

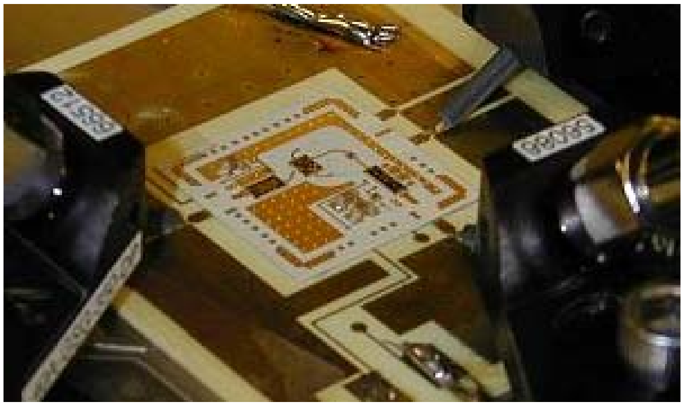

Figure 7 Thin film LCP surface-mount receiver package module mounted on the PCB test board

VII. CONCLUSION

We have presented the development of a Ka-band receiver module in a thin-film LCP surface-mount package. We have described the LCP material and the design of the surface-mount package feedthrough. We showed that our feedthrough simulation indicates better than 20 dB return loss up to 42 GHz. We showed the conversion gain measurement of the receiver and a gain/loss chart that lists sources of loss in the module. From the chart we showed that the package feedthrough loss is approximately 0.7 dB at 38.4 GHz. We have also described the lamination of a multi-layer LCP lid onto the package substrate.

ACKNOWLEDGMENT

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