Development of Thin-Film Liquid-Crystal-Polymer Surface-Mount Packages for Ka-Band Applications

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***Abstract*—In this paper, we present the design and development of thin-film liquid-crystal-polymer (LCP) surface-mount packages for Ka-band applications. The packages are constructed using multilayer LCP films and are surface mounted on a printed circuit board (PCB). Our experimental results demonstrate that the package feed-through transition including a PCB launch and bond wires achieve a return loss of better than -20 dB and an insertion loss of less than 0.4 dB around Ka-band. We achieve a measured port-to-port isolation of the package to be more than 45 dB across the Ka-band. We demonstrate the package feed-through circuit model by comparing the simulation of model and bare die measurement data to a packaged amplifier measurement. Finally, we report an LCP cavity that has a measured fine leak rate of 3.6×10^{-8} atm $\cdot$ cc/s.**

***Index Terms*—Hermeticity and Ka-band, liquid crystal polymer (LCP), surface-mount packages.**

I. INTRODUCTION

EMERGING microwave and millimeter-wave applications require effective and low-cost approaches to high-frequency electronic packaging to fulfill industry demands. Organic surface-mount packages are becoming an attractive solution for millimeter-wave frequency applications [1]–[5]. Highly automated assembly processes for surface-mount packages offer low-cost production [6]. Millimeter-wave organic surface-mount packages reported to date are nonhermetic [1]–[3]. The quest for hermetic organic surface-mount packages has led to the investigation of liquid crystal polymer (LCP) for packaging [4], [5], [7]–[10]. LCP has permeation close to glass and can be used to construct potentially hermetic cavities. Researchers have presented surface-mount packages using thin-film LCP at millimeter-wave frequencies [4], [5]. However, the characteristics of a complete package feed-through transition, lid sealing techniques, and hermeticity have not been reported.

Another LCP packaging platform is quad flat no-lead packages molded with LCP alloy [11], [12]. LCP quad flat no-lead packages are formed by injection molding of LCP alloy around a conventional lead frame [11], [12]. However, these packages do not have well-matched low-loss transitions required for millimeter-wave frequencies due to large lead frame feature sizes and limited design flexibility. Another drawback of this LCP quad flat no-lead package is the use of epoxy to seal a lid [11]. The epoxy forms a path for moisture to penetrate into the package. Ultrasonic welding techniques can be a possible solution for hermetic sealing.[1] In ultrasonic welding, a lid interface to the base must be narrow to accumulate enough ultrasonic energy for melting LCP. Molding small feature sizes on LCP present challenges, and the barrier can be insufficient for protection against moisture.

Previously, we presented a preliminary design and measurement of a thin-film LCP surface-mount package transition [13]. The transition included a via from the bottom to the top of a package base and did not take bond wires or a printed circuit board (PCB) launch into consideration. The package transition had a measured return loss from -10 to -15 dB and insertion loss of 1–3 dB at Ka-band.

In this paper, we significantly expand on the design and development of surface-mount hermetic packages to include a new feed-through, sealing processes, packaged amplifiers, and hermeticity evaluation. We report a new package feed-through that incorporates pad capacitance to compensate for bond-wire inductance and a PCB launch transition. The newly designed feed-through provides a matched transition from PCB launch pads through a grounded coplanar waveguide (CPW) below the package, a vertical via to bond wires. We demonstrate that the package feed-through transition, which includes a PCB signal launch and bond wires, achieve a measured return loss of better than -20 dB and an insertion loss of less than 0.4 dB around Ka-band. In addition, we have developed a process to seal a package cavity in an LCP enclosure without using any adhesive material, and demonstrated a packaged amplifier that has negligible degradation at Ka-band. Finally, we have conducted hermeticity evaluation of LCP cavities and have achieved a fine leak rate of $\sim 3.6 \times 10^{-8}$ atm $\cdot$ cc/s, which is less than the 5×10^{-8} atm $\cdot$ cc/s specification required by the MIL-STD-883 Method 1014.[2] Rather than calling quasi-hermeticity, we refer hermeticity as passing a fine leak rate of less than 5×10^{-8} atm $\cdot$ cc/s in this paper.

Section II elaborates on the design and fabrication processes of thin-film LCP packages. Performance sensitivity to variation of copper traces and solder thicknesses is investigated.

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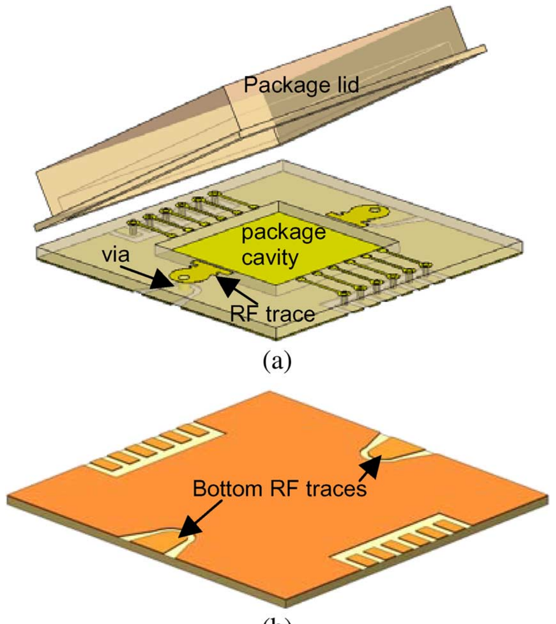
[1] [Online]. Available: http://www.qlpkg.com

[2] [Online]. Available: http://www.dscc.dla.mil/programs/MilSpec/ListDocs.asp?BasicDoc=MIL-STD-883



(a)

(b)

Fig. 1. Schematic diagram of the multilayer thin-film LCP package. (a) Top side and (b) bottom side of the package.

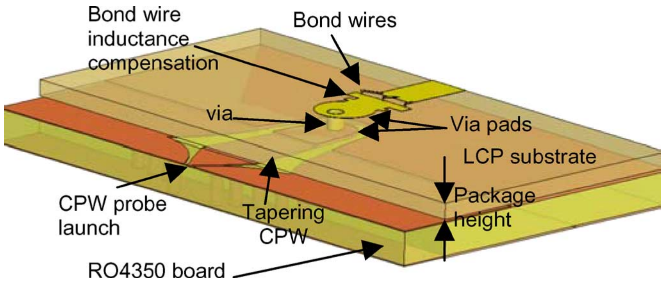


Fig. 2. Ka-band thin-film LCP package feed-through transition design structures on HFSS.

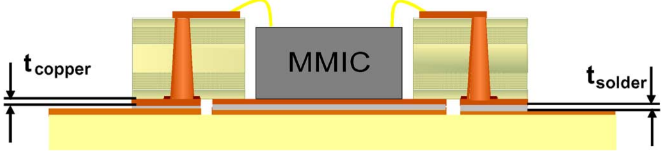


Fig. 3. Cross section of the package showing the package ground copper and solder thicknesses.

Section III introduces LCP lid construction and lamination of a lid onto a package base. Section IV presents measurements and modeling of the package feed-through and port isolation. Section V further supports the package feed-through circuit model by comparing the simulation of model and bare die measurement data to a packaged amplifier measurement. Section VI presents the hermeticity characterization on surface-mount packages fully formed with LCP.

II. DESIGN AND FABRICATION OF THE THIN-FILM LCP PACKAGES

Fig. 1 demonstrates a schematic diagram of our thin-film LCP packages developed at the University of California at Davis. Electrical signals enter the package through underside metal trace and traverse through a plated via to the top of the package base [see Fig. 1(a) and (b)]. Laser ablation drills a cavity through LCP and the cavity bottom consists of package base backside copper. Monolithic microwave integrated circuits (MMICs) are mounted directly on the copper base inside the cavity for thermal dissipation. Die attachment and wire bonding will be followed by a lid lamination that hermetically seals the cavity.

We have designed a vertical feed-through transition for thin-film LCP surface-mount packages using full-wave finite-element-method analysis [Ansoft Corporation's High Frequency Structure Simulator (HFSS)], and quasi-static approaches (Ansoft Corporation's Q3D Parasitic Extractor). We used a 254-μm–thick (10 mil) LCP multilayer substrate and a 254-μm-diameter (10 mil) via process for mechanical drilling compatibility. The dielectric constant and loss tangent of the LCP films we chose are 2.9 and 0.0025, respectively. Fig. 2 shows a package feed-through transition model in HFSS.

Initially, a 50-Ω grounded CPW was designed at the bottom of a package. The grounded CPW extends from the edge of the package to the bottom via pad. The signal trace of the grounded CPW is tapered down toward the bottom via pad while maintaining a 50-Ω characteristic impedance. Since the height of the via is fixed at 254 μm, sizes of the via pads were varied such that the square root of the barrel inductance to pad capacitance ratio maintains 50 Ω. This design was performed using the Q3D Extractor to compute the inductance and capacitance of the via barrel and pads, respectively. A 50-Ω-wide microstrip line was then connected to the via pad on top of the package base. The end of the microstrip line was widened to compensate for bond-wire inductance [14], [15]. The pad size was tuned using HFSS. Three parallel wires were used to minimize parasitic inductance at Ka-band. Three bond wires were connected to another 50-Ω microstrip line to establish a two-port simulation in HFSS. Note that the second microstrip line does not have wide pads.

Once the initial design is optimized, we started investigating the electrical performance sensitivity to package ground copper and solder thicknesses. Fig. 3 illustrates copper and solder thickness parameters. Fig. 4 shows the electrical sensitivity of the package feed-through to the total thickness of ground copper and solder. The total metal thickness varies from 64, 83, and 98 μm to 118 μm, while the solder layer is 30-μm thick in simulations. As can be seen, the thickness of the ground metal does not have dramatic effects on the insertion loss electrical performance. For mechanical support, the copper ground thickness can be chosen up to 72 μm. Fig. 5 shows the simulated electrical performance of the feed-through with changes in bond wire length. While the bond-wire length varies from 180 to 380 μm, the insertion and return losses are maintained to within 0.03 and 8 dB, respectively.

Package bases were fabricated on multilayer LCP films using a PCB process. Five layers of LCP films with thickness of 25.4 μm (1 mil), 50.8 μm (2 mil), 101.6 μm (4 mil), 50.8 μm, and 25.4 μm were laminated to produce a 254-μm-thick (10 mil) substrate. First, a high-temperature (315 °C) LCP film is sandwiched between two outer lower temperature (280 °C) LCP layers and the three-layer structure is laminated. Two

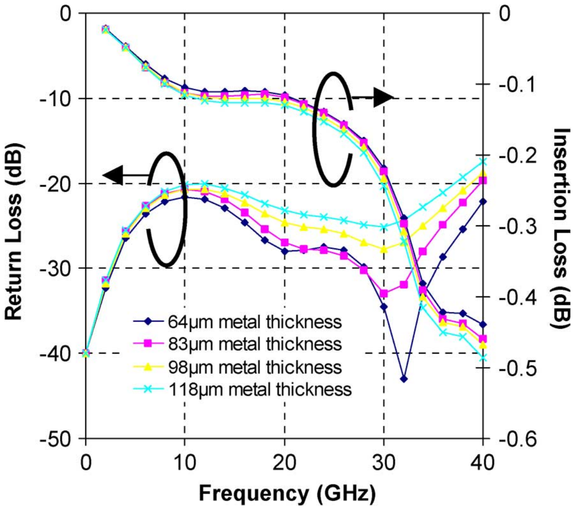


Fig. 4. Simulated S-parameters of the package feed-through with varied metal thickness at package and PCB interface.

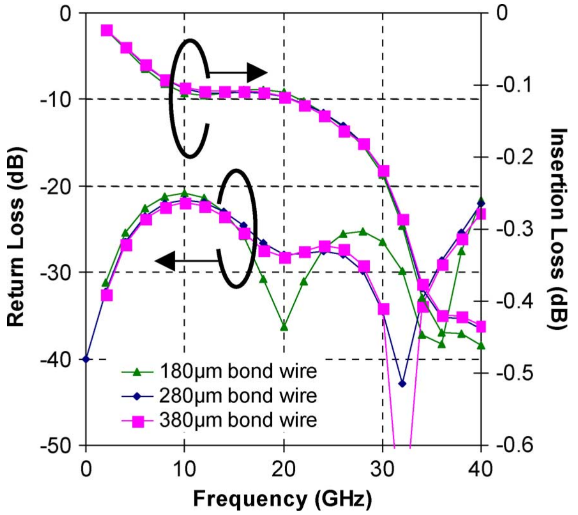


Fig. 5. Simulated S-parameters of the package feed-through with varied bond-wire length.

additional high-temperature LCP films are laminated above and below this three-layer structure to form a five-layer board. The bottom ground is 36-μm thick to provide mechanical support. Top metal traces are 9-μm thick. Once the multilayer LCP package base was fabricated, laser ablation was used to create a cavity [16], as can be seen in Figs. 1 and 6. In a production, LCP films can be made with holes using low-cost machining or punching techniques [17].

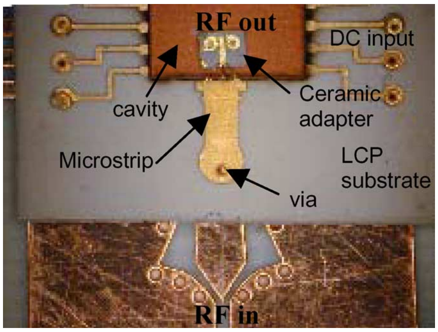
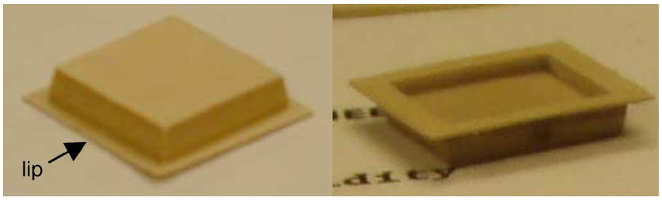


Fig. 6. Thin-film LCP surface-mount package mounted on a PCB.



(a) (b)

Fig. 7. (a) Top view and (b) bottom view of the all-LCP lid.

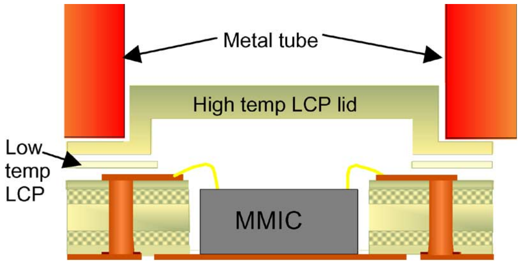


Fig. 8. Cross section of the LCP lid lamination process onto the package base.

III. Lid Construction and Lamination

We have developed a process to laminate a LCP lid directly onto a package base without adhesive materials. Since LCP adheres to itself, MMICs will be enclosed in a moisture-resistant cavity. A lid can be formed by two methods, i.e., multilayer lamination and molding. The multilayer lamination lid consists of 20 layers of 101.6-μm-thick LCP. The molding lid is a molded 2-mm-thick (80 mil) structure. A milling machine drills a cavity into the lid. Fig. 7 demonstrates the prototypes of a molded lid used in this paper. We used a molded lid because of its low cost and repeatability in manufacturing, and uniformity of lid to package interface surface and cavity.

Fig. 8 shows the schematic diagram of the lamination process. Lids and outer layers of the package base are composed with high melting temperature LCP (315 °C–350 °C). A low melting temperature LCP film (260 °C) is used at the interface of the package lid and substrate. A metal tube applies heat and pressure only to the edges of the lid. The temperature applied at the interface layer is roughly 280 °C for 1 h. The lid edges are locally heated to a melting temperature of $\sim$ 260 °C for making adhesion and sealing. Thermal simulations using Ansoft Corporation's ePhysics (Fig. 9) show that the temperature is less than 160 °C inside the package and maintains the integrity of epoxy and interconnect structures.

IV. Results and Model

LCP surface-mount packages were mounted onto a 508-μm-thick (20 mil) Rogers RO4350B PCB using solder. In order to characterize a package feed-through, a 50-Ω CPW to microstrip adapter [18], [19] is mounted in the cavity, approximately 200 μm from the LCP cavity wall, to provide connection from three bond wires to a microprobe. The adaptor is a 50-Ω line fabricated on 127-μm-thick (5 mil) alumina substrate $(\varepsilon_r = 9.6)$ with a ground–signal–ground probe pattern at one

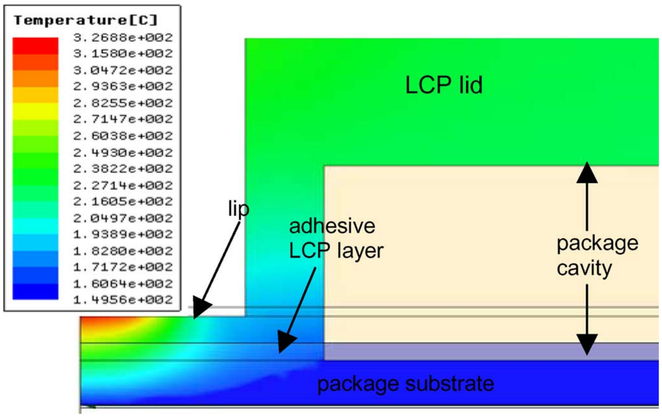
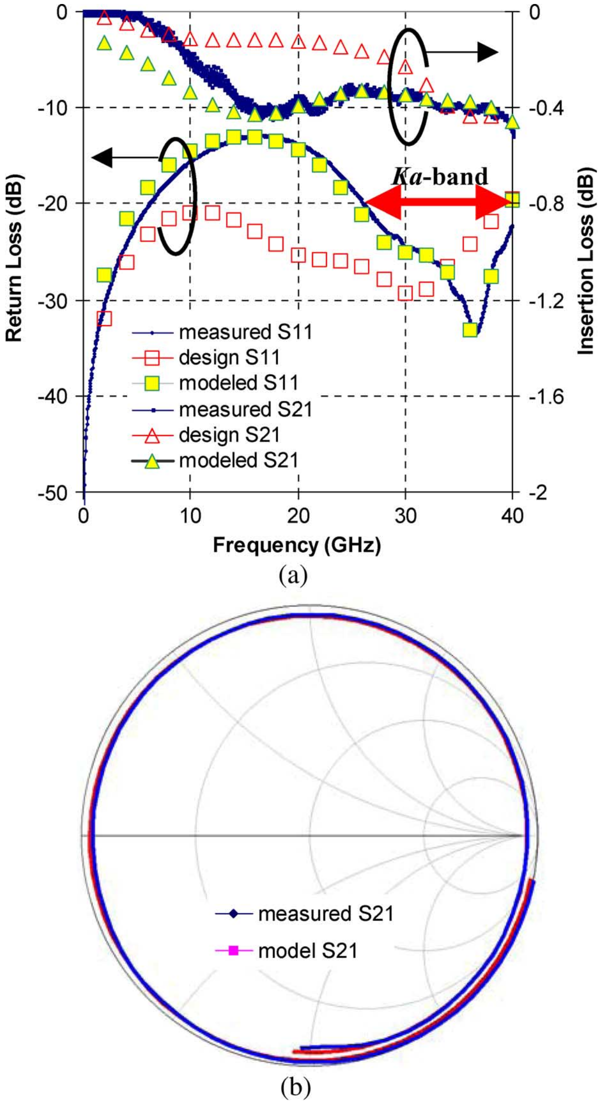


Fig. 9. Cross section of the lid at the edge and temperature distribution of simulated lamination.

end [18]. The 200-μm gap between the adaptor and cavity wall allows bond-wire length to match our design length. This construction will establish a complete package transition from bond wires through a vertical via to a PCB. The input of the package was probed directly on the PCB. The package feed-through transition was measured using a Cascade Microtech probe station, Agilent Technologies' Performance Network Analyzer 8364B (PNA), and 150-μm-pitch CPW probes. The network analyzer was calibrated using a line-reflect-line technique up to 50 GHz. The measurement of the feed-through includes a small grounded CPW signal launch on the PCB, a solder joint between the PCB pad and package, a vertical via transition, a short microstrip line on package substrate, three bond wires, and a ceramic adaptor (Fig. 6).

Fig. 10 shows HFSS-simulated, measured, and lumped-modeled results of the LCP thin-film package feed-through transition. The thickness of the copper ground and solder used in HFSS simulation is 30 and 36 μm, respectively. We optimized the feed-through design for Ka-band operation, but we show the measurement from 0 to 40 GHz for completeness. We have achieved a measured return loss of better than -20 dB and a measured insertion loss of 0.4 dB around Ka-band. HFSS simulation predicted lower insertion loss and better return loss than measurement at the lower half of the Ka-band. This is due to uneven solder thickness used to mount a package to PCB. Recall from the HFSS simulation in Fig. 5 that thicker solder degrades electrical performance at Ka-band. In addition, the length of bond wires was not exactly the same as that used in the simulation. Bond-wire compensation pads were designed to compensate a specific length of bond-wire inductance. Hence, the variation of wire length can cause some mismatches. Overall, the experimental results demonstrate that a well-matched package feed-through can be designed to enable surface-mount packages for millimeter-wave frequencies.



(a)

(b)

Fig. 10. Measured, design, and modeled feed-through data. (a) Return loss and insertion loss. (b) $S21$ phase on Smith chart.

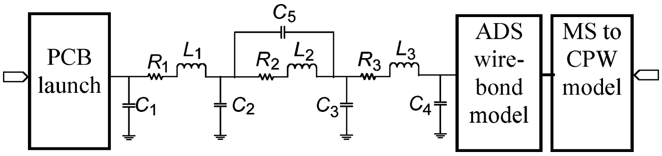


Fig. 11. Lumped circuit model of package feed-through transition.

Fig. 11 shows an equivalent-circuit model of a package feed-through transition with corresponding values shown in Table I. Initially, a simple lumped-element model is generated using the Q3D Extractor. The circuit is then modified using Agilent Technologies' Advanced Design System (ADS) software to correlate the modeled S-parameters to measurement. Resistors $R1$ and $R3$ in Fig. 11 represent the microstrip line conductor losses on the top and at the bottom of the package base. $L1$ and $L3$ model the inductance of the microstrip lines. $C1$ and $C4$ are capacitances between the microstrip lines and grounds. $R2$ and $L2$ model the conductor loss and inductance of the via, respectively. $C2$ and $C3$ represent capacitances of via pads. The circuit also includes a PCB launch, bond wires, and a CPW to microstrip adapter, all modeled using ADS built-in components. The modeled and measured S-parameters are well correlated.

To investigate isolation, each package feed-through is terminated with a 50-Ω resistor and the two resistors are spaced 2 mm apart [see Fig. 12(a)]. The measurement is taken using the same package cavity dimensions as the one that will be used

TABLE I
LUMPED-ELEMENT VALUES OF THE PACKAGE FEED-THROUGH EQUIVALENT-CIRCUIT MODEL

Element	value	Element	value
L_1	0.26 nH	L_3	0.059 nH
R_1,R_2,R_3	0.008 Ohm	C_3	0.078 pF
C_1	0.0653 pF	C_4	0.007 pF
L_2	0.172 nH	C_5	0.049 pF
C_2	0.115 pF		

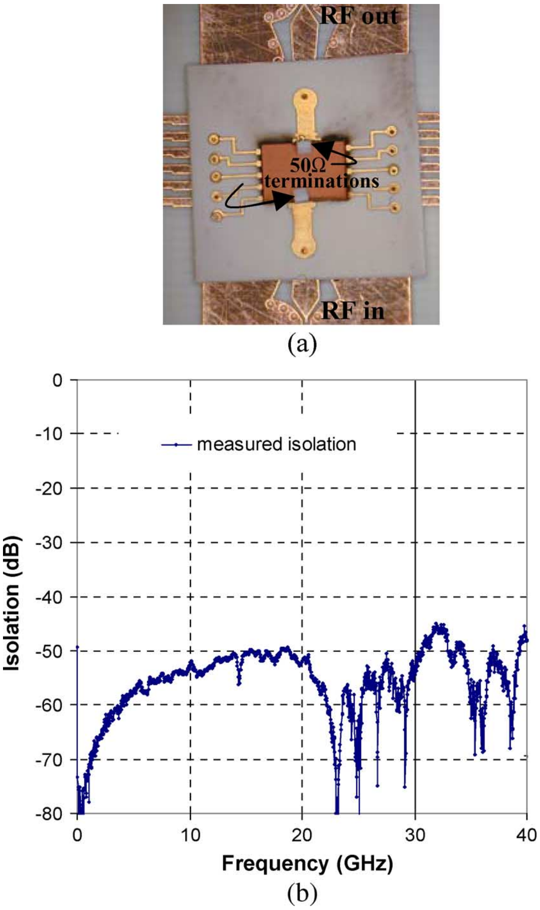


Fig. 12. (a) Demonstration of 50-Ω terminated feed-through for isolation measurement and (b) measured, designed, and modeled isolation.

to package an amplifier in Section V. Microprobes are placed at RF input and RF output on the PCB to measure isolation, as shown in Fig. 12(b). The experimental result shows that the isolation is better than 45 dB for two ports separated by 2 mm.

V. MEASUREMENT OF PACKAGED AMPLIFIER

We have assembled an amplifier from Triquint[3] part number TGA4507-EPU into our LCP surface-mount package. The frequency range of usage for this amplifier is typically from 28 to 36 GHz. The MMIC and bypass capacitors are first mounted inside the package cavity of the package using Diemat silver-loaded polymeric adhesive (DM5030P) that is cured at 200 °C for 30 min. A high-temperature adhesive is used to prevent re-flow during lid lamination. Bond wires are then used to make dc and RF electrical connections. We used triple bond wires between the RF input and output and the package feed-through. Fig 13(a) illustrates an amplifier mounted inside the package cavity. As can be seen, there is a gap between the LCP package wall and amplifier RF input and output. The gap is provided to match the bond wire length to the simulation of the package feed-through. A lid is laminated onto a base to seal the package. The package was surface mounted onto a PCB test board. Fig. 13(b) shows the prototypes of the package.

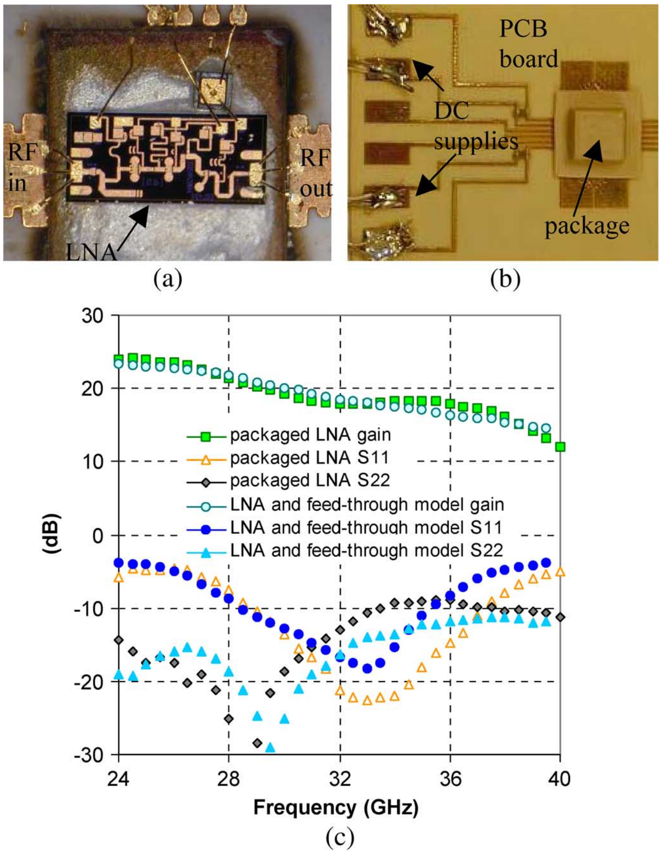


Fig 13. Packaged amplifier on PCB board: (a) with lid and (b) without lid. (c) Comparison of gain, input return loss, and output return loss between packaged amplifier and bare chip data with feed-through model simulation.

The packaged amplifier is measured and compared with simulation of the packaged MMIC. The simulation includes package feed-through model and bare chip data measured at the die level using microprobes. Fig. 13(c) shows the measured gain and input/output return loss of the simulated and packaged amplifiers. From 33 to 38 GHz, the packaged LNA shows up to 7 dB better input return loss, and hence, the gain is up to 1 dB higher than the simulation. Overall, the simulation S-parameters of the packaged LNA show similar trend to measured data of the packaged amplifier. It is reasonable to assume that the extracted model of package feed-through can be simulated in conjunction with the on-wafer measurement of an amplifier to predict the characteristics of a packaged chip because the entire package feed-through is designed to have a 50-Ω characteristic. It can be imagined as a 50-Ω transmission line. The measurement of a packaged chip will show the characteristic of its on-wafer measurement data, plus the phase of the feed-through.

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[3] [Online]. Available: http://www.triquint.com/docs/t/TGA4507

TABLE II
LEAK RATE TEST RESULTS AFTER IMMEDIATE REMOVAL FROM BOMBING AND AFTER A 3-h DWELL

Part #	**Measured Immediate Leak Rate (atm cc/s helium)**	**Measured Leak Rate after 3 hr dwell (atm cc/s helium)**	**Gross Leak (P or F)**
Solid Block	3.2 x 10^{-7}	2.2 x 10^{-8}	P
Package 1	3 x 10^{-7}	3.6 x 10^{-8}	P
Package 2	3 x 10^{-7}	3.6 x 10^{-8}	P
Package 3	3.2 x 10^{-7}	4.0 x 10^{-8}	P

VI. HERMETICITY AND LEAK RATE MEASUREMENT

LCP package parts have been subjected to gross and fine leak testing performed by Six Sigma Services.[4] The package cavity volume under test is $\sim$ 0.3 cm^3. Leak tests are performed on three LCP package parts using Mil-Std-883, Method 1014. Gross leak testing is performed under a 517.1-N/m^2 (75 PSIA) perfluorocarbon fluid bomb for 125 min. Parts are then submerged into a second perfluorocarbon bath, heated to above boiling of the first perfluorocarbon fluid, and inspected for bubbles. Fine leak testing is performed under a 517.1-N/m^2 helium bomb for 125 min. A mass spectrometer is used to measure helium leaking from a cavity to determine leak rates. Equipment is calibrated daily to be accurate to 2×10^{-8} atm $\cdot$ cc/s helium. Since LCP is a thermal plastic material, its solubility is nonzero. In other words, during the helium bomb, helium will be absorbed onto the surface of the LCP packages. When a mass spectrometer measures the helium leaking from a cavity, it also includes any adsorbed helium coming off the surface of the package. This increases the fine leak rate reading since more helium is measured by the mass spectrometer. In order to evaluate artificially high leak rates, a solid LCP block is also tested as a control. The solid block is intended to identify a virtual leak rate of helium desorbing from the surface of LCP.

Leak rate results are shown below in Table II. The results of the LCP packages are compared against the solid LCP block, which does not have a cavity that can be affected by leaks. A further comparison is made between leak rates conducted immediately and after a 3-h dwell. Dwell time is the period defined between the end of the helium bomb and the beginning of mass spectrometer measurements.

The gross leak results indicate that the packages are free from large leaks. For a dwell time of a few minutes, the cavity LCP packages are found to have average fine leak rates of $3.07 \pm 0.2 \times 10^{-7}$ atm $\cdot$ cc/s helium. For comparison, the solid LCP block is found to have $3.2 \pm 0.2 \times 10^{-7}$ atm $\cdot$ cc/s helium. The results indicate that the fine leak rates of $3.07 \pm 0.2 \times 10^{-7}$ atm $\cdot$ cc/s and $3.2 \pm 0.2 \times 10^{-7}$ are measured from the helium desorbing from the LCP surface rather than from helium leaking from the cavity. In fact, the virtual leak rate of the solid block reaches an acceptable leak rate after a 3-h dwell time, as shown in Table II. At this time, all the cavity packages surpass the mil-std requirements.

Optical leak rate testing has also been performed to substantiate these claims. Optical leak tests are performed through measuring lid deflections under dynamically applied pressure. Hence, this optical fine leak rate analysis does not encounter the solubility or the surface absorption issue. Through optical leak rate testing, leak rates have been measured to better than 3.6×10^{-8} atm $\cdot$ cc/s, the mil-std requirements.

VII. CONCLUSION

In this paper, we have reported on the design and development of hermetic LCP packages at Ka-band. We have demonstrated a process to seal cavity LCP packages that pass gross leak and fine leak using Mil-Std-883, Method 1014. The experimental results have showed that the package feed-through can achieve a return loss of better than -20 dB, insertion loss of 0.4 dB, and isolation of better than 45 dB around the Ka-band. We have demonstrated that the package has negligible effects to packaged devices. The package has achieved a leak rate of 3.6×10^{-8} atm $\cdot$ cc/s. We have demonstrated that it is feasible to develop organic surface-mount packages that can achieve moisture resistance for millimeter-wave applications.

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