

Experimental Analysis of the Water Absorption Effects on RF/mm-Wave Active/Passive Circuits Packaged in Multilayer Organic Substrates

Dane C. Thompson, *Member, IEEE*, Manos M. Tentzeris, *Senior Member, IEEE*, and John Papapolymerou, *Senior Member, IEEE*

Abstract—The feasibility of using near-hermetic organic materials for microwave and millimeter-wave packaging is investigated. The effects of moisture on both passive and active components on/inside the nonhermetic materials are tested. Microstrip patch antennas on three low moisture absorption substrates (0.1% or less) are subjected to immersion tests until saturated and the corresponding measured frequency shifts are found to be less than 0.25% for two of the three materials tested. The recovery time from saturation to normal operation is found to occur from natural evaporation at room temperature in 10 min or less. One of the three materials, a promising organic laminate material called liquid crystal polymer (LCP), showed no measurable change in weight or in antenna resonance frequency between the ambient (air) state and that after extended submersion in water. In addition, a novel laminated LCP package for a 13–25 GHz monolithic microwave integrated circuit (MMIC) formed from seven thin layers of laser-machined LCP is subjected to immersion testing. The seal for the embedded chip cavity (formed by the LCP conforming around the feeding transmission lines) is found to be robust for protecting the embedded chip. Standard hermetic materials are suggested to be a potentially unnecessary requirement for reliable, long-lifetime, high-performance RF systems.

Index Terms—Absorption, embedded actives, embedded passives, near-hermeticity, organics, package, water.

I. INTRODUCTION

MICROWAVE and millimeter-wave (mm-wave) radio-frequency (RF) circuits and systems require proper substrate and packaging materials to ensure reliable operation. Depending on the desired operating life of the application, appropriate materials are chosen to meet both the lifetime specification and cost. For example, cellular handsets may be rated to survive for less than ten years, while critical satellite or military devices can have lifetime requirements of several decades [1]. The packaging implementations of these disparate lifetime requirements can make a difference of several orders of magnitude

Manuscript received March 3, 2006; revised December 15, 2006. This work was supported by the National Aeronautics and Space Administration under Contract NCC3-1015, by the National Science Foundation (NSF) under CAREER Award ECS 9984761, by the Georgia Electronic Design Center, and by the Georgia Institute of Technology NSF Packaging Research Center.

D. C. Thompson was with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA. He is now with Ansoft Corporation, Pittsburgh, PA 15219 USA.

M. M. Tentzeris and J. Papapolymerou are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: etentze@ece.gatech.edu; papapol@ece.gatech.edu).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TADVP.2007.898637

in cost. A system consisting of several integrated circuits (ICs) with plastic injection molded packages, which are soldered onto an RF board, may be on the order of a few dollars [2]. In contrast, a hermetically certified/tested laser sealed machined metal package with an enclosed populated RF board can cost several thousand to tens of thousands of dollars [3].

Recently, some have questioned the need for truly hermetic packages and even suggested that the “hermetic” requirement could be an outdated and unnecessary requirement from “what worked” for military projects as far back as the 1960s [4]. Organic materials that have a “near-hermetic” classification could be sufficient to provide acceptable packaging characteristics for intermediate to long lifetimes, and at a fraction of the price, weight, and size of current hermetic packaging solutions [5].

In terms of mm-wave systems, the primary semiconductor technology used for active devices is gallium arsenide (GaAs). Fortunately, GaAs ICs have shown to be nearly unaffected by temperature and humidity testing even with poor packaging materials (epoxies) or no package at all [6], [7]. The function of a GaAs package is then more for a bulk protection layer that disables direct condensation, mechanical contact, and provides a close thermal expansion match. Since GaAs ICs are robust with nonhermetic packaging materials, they may be integrated in or on some of the high-performance organic materials to create new class of “hygienic” [4] packaged RF systems.

Some of the challenges that remain in establishing the viability of robust mm-wave nonhermetic packaged RF systems in organic materials are as follows.

- 1) Determining the quantitative effects of water absorption on passive element performance in the RF/mm-wave frequency range for low water absorption substrates.
- 2) Finding organic materials that can match the thermal expansion coefficient of both metals and semiconductors.
- 3) Establishing methods for creating sealed organic packages for embedded passives *and* embedded ICs.

Previous data from [8] shows changes in dielectric properties of materials with 0.25% and 0.05% water absorption. The conclusion is that 0.25% is not an acceptable water absorption level. Several sources [9], [10] have pointed out that liquid crystal polymer (LCP) is a near-hermetic organic material with excellent electrical properties and the ability to be engineered to match the αy -CTE of both metals and semiconductors. A packaging topology that allows active/passive integration on a multilayer laminated LCP substrate has been demonstrated in [11].

The contribution of this paper is to investigate items 1) and 3) for RF passive and active devices built on/inside low absorption organic substrates. Quantitative testing is performed on ob-

TABLE I
LOW WATER ABSORPTION MATERIALS. TESTED
MATERIALS ARE FROM ROGERS CORPORATION

| Material | Water Absorption [%] | ϵ_r | $\tan \delta$ | Thickness [mils] | CTE (x - y) [ppm/ $^{\circ}$ C] |
|----------|----------------------|--------------|---------------|------------------|---------------------------------------|
| 6202 | 0.1 | 2.94 | 0.0015 | 5 | 15 |
| 3003 | <0.1 | 3.0 | 0.0013 | 5 | 17 |
| LCP | 0.04 | 2.9 | 0.002 | 4 | 17 |

served water absorption and the corresponding frequency shifts of microstrip patch antennas on three different low water absorption substrates (0.1% or less). In addition, an active device embedded in a novel multilayer LCP package from [11] is tested for bulk sealing characteristics. This test is done to prove the concept that the standard thermocompression bonding process for laminating multiple LCP layers can create a seal around feeding transmission lines that pass through the side of the laminated LCP stackup. The findings of this research are important for validating nonhermetic, low water permeability substrates as desirable packaging materials for microwave and mm-wave RF systems.

II. WATER ABSORPTION MEASUREMENT

The first goal of this research is to experimentally find the relationship between water absorption and passive device performance. Although manufacturers provide water absorption percentages for their materials, this number is difficult to directly relate to expected changes in device performance. In addition, the authors did not locate literature that tested passive devices on substrates with varying water retention/permeability characteristics.

The standard technique that microwave materials manufacturers provide for classifying water absorption characteristics is a weight percentage of water absorbed according to IPC-TM-650 2.6.2.1. A range of water absorption characteristics of organic materials is from 0.02% to 0.25% or more. Low water absorption percentages are better for RF circuit stability and reliability. Focusing on low absorption materials, a sampling of three microwave substrates with water absorption of 0.1% or less were selected for testing. These materials are compared in Table I.

All three of the materials tested are from Rogers Corporation, Rogers, CT. The 3003 and 6202 materials are both fluoropolymer composites, or in other words, ceramic-filled polytetrafluoroethylene (PTFE). Both are composed of fluoropolymers loaded with fused silica, and titanium dioxide. The 6202 material also contains fiberglass weave for greater structural stability. The LCP material is an aromatic polyester. All substrate materials were received with double copper cladding with either 9- or 18- μ m-thick copper from the manufacturer. The metallizations are all electrodeposited. No adhesive materials/layers are present between the substrate materials and the copper metallization.

The substrate thicknesses, dielectric constants, and loss tangents of the three materials were chosen to be as close as possible. Any differences in device performance could then be reasonably attributed to variations from absorbed water content. Although the typical water absorption test is performed with

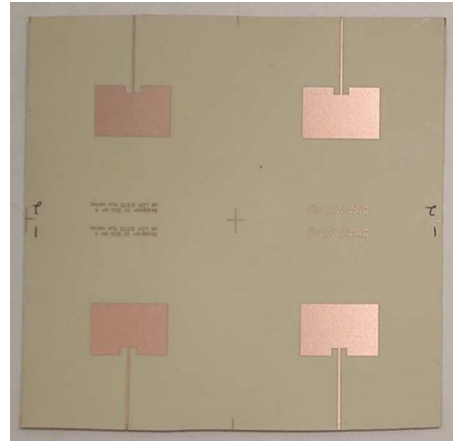


Fig. 1. Water absorption test sample. Each sample is 2 in \times 2 in and contains four 14-GHz microstrip patch antennas. Each of the different substrate materials had the same metallization pattern. The samples were used for both the water weight gain tests and for the passive device sensitivity tests.

bare samples, this experiment required it to be performed with passive devices on the substrate. Each 2 in \times 2 in substrate had four 14-GHz single patch microstrip patch antennas on the top side and full metallization on the back side. One such sample is shown in Fig. 1.

For each substrate material, a control sample and a test sample were used. The control samples were used to establish that samples kept at room temperature with ambient humidity could verify stable weight and resonant frequency characteristics over the time duration of the testing. The control samples indeed maintained identical weight and resonant frequencies at all times during the several week testing period. As a result, the test sample differences were identified as direct results of the conditions administered to them.

A. A Water Weight Gain

The standard IPC water absorption test was performed per specification using a digital scale with precision to the nearest tenth of a milligram to weigh the samples. For comparison purposes, all samples were weighed and measured “as fabricated” prior to the IPC testing. The test samples were then baked in an oven for over 1 h at 110 $^{\circ}$ C. Each sample was removed individually and immediately weighed. The oven was located only a few feet from the scale, which was important in this measurement. The samples were observed gaining weight while on the scale, apparently from taking in water from ambient humidity. This weight increase was observed in real time on the scale’s digital readout over the course of a few minutes until the readings settled at the pre-bake weight values. The actual weights from the “as baked” and “in air” states are shown for each material in Fig. 2. The humidity in the room was around 36%.

The test samples were next submersed on edge in distilled water for 24 h. Each sample was removed independently from the water, the surfaces quickly and completely dried with paper towels, and weighed. The weight was recorded immediately upon placement on the scale and the value compared to that from the baked (dry) weight. The resulting water absorption percentages, shown in Fig. 2, are consistent with those provided by the manufacturer, whose values are listed in Table I. Once again, the

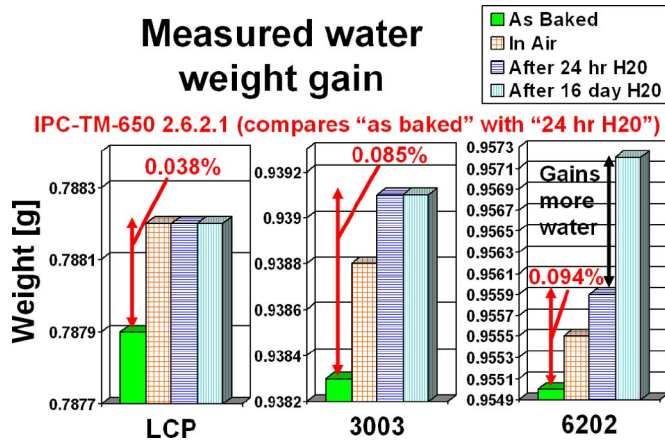


Fig. 2. Measured sample weights to the nearest tenth of a milligram for the following cases: 1) immediately after baking in an oven at 110 °C for 1 h; 2) dry, at room temperature and ambient humidity; 3) after 24 h submerged on edge in distilled water, the surface water dried thoroughly upon removal, and the sample measured immediately; 4) with the same method as 3) except after the samples were submerged for 16 days.

weight was observed to change quickly in real time, this time as the water embedded in the substrate evaporated. Five minutes after removal from the water, all of the substrates had converged from the “after 24 hr H2O” weight to their “in air” weight.

To ensure that the IPC test results are representative for longer submersion times, the samples were dunked in water for 16 days and the same weighing procedures readministered. The LCP and 3003 samples did not show additional water uptake, while the 6202 sample more than doubled its initial water absorption amount. The measured values are displayed in Fig. 2. The two lower water absorption materials could be assumed to be saturated and perhaps could be expected to stay the same with extended water exposure times. However, the 6202 material seemed to accumulate additional water with time. The calculated water absorption percentage for the 6202 sample after 16 days was 0.23%, which is not a desirable level for a packaging material.

A surprise from these tests was the short time needed for the sample weights to revert to the ambient “in air” values from both the baking and submersion tests. For the samples which demonstrated apparent water saturation (3003 and LCP), the most rapid weight changes occurred in the first minute or two after an environment change and the absorption/desorption process could generally be assumed complete within 5–10 min. As an example of the speed of this process, the 3003 sample that had been underwater for 16 days, settled at the original “in air” weight in 1 min. The 6202 sample exhibited the same rapid change to ambient properties when removed from water, but continued to gain water weight slowly after its initial 24-h water uptake.

Another interesting aspect of these tests was that LCP showed zero change (0.0 mg) from the ambient “in air” state to the states after both submersion tests. Similarly, the 3003 material gained only 0.3 mg (0.032%) from the “in air” to the submerged states. In operating environments, the water content of the substrates would realistically be expected to fall between these values since a perfect zero water content (zero humidity) is not likely on Earth. As a result, the authors believe it may

TABLE II
WATER ABSORPTION COMPARED WITH “IN AIR” CONDITIONS

| Material | Measured Water Absorption Using IPC Std. [%] | Water Absorption From “in air” to “after 24 hr H2O” [%] |
|----------|--|---|
| 3003 | 0.085 | 0.032 |
| LCP | 0.038 | 0.000 |

Note: The measured absorption values using the IPC test are provided as a comparison.

make more sense to compare the “in air” state with the saturated state unless the substrates are being evaluated for space applications. A summary of the potentially more useful water gain result comparing the “in air” and “after 24 hr H2O” values is shown in Table II. Note that 6202 is not included in the comparison due to its potential for increasing water uptake with time. A conclusion from these water weight gain tests is that two of the three substrates absorbed little to zero water between the ambient state and the submerged state. The same results held, even when the submersion time was much longer than that for the standard IPC characterization test. Another result is the fast (few minute) acclimation time of the substrates to reach their equilibrium weight (the “in air” weight) from both the baking and submersion test weights.

III. PASSIVE DEVICE SENSITIVITY TO WATER ABSORPTION

Water’s dielectric properties are known to be far different from common materials, which is one of the main reasons its absorption into RF substrates is problematic. At a few gigahertz, the dielectric constant is about 80 and between 10–100 GHz water undergoes a dielectric relaxation effect. The relaxation corresponds to a dielectric constant drop from 80 to about 5 and a drastic increase in loss. In order to pick an operating frequency that is sensitive to both the high dielectric constant and loss of water, 14 GHz was selected, which has $\epsilon_r = 50$ and $\tan \delta = 0.5$ [12]. At 14 GHz, water’s dielectric constant is about 17 times that of our test samples and the loss tangent is at least 250 times greater.

A. Device Selection

A passive device that is sensitive to both dielectric property changes and that is likely to be implemented in these organic materials is a microstrip patch antenna. Changes in the bulk dielectric constant from water absorption are expected to shift the resonant frequency while the loss tangent should increase insertion loss and decrease the depth of the resonance. Ansoft Designer 2.5D planar electromagnetic solver was used to design a 14-GHz microstrip patch antenna on each of the three substrates. Although the dielectric properties and thicknesses of the materials are very similar, an independent design was performed for each material.

B. Fabrication

The antennas were fabricated in the Georgia Tech MiRC cleanroom using photolithography and ferric chloride copper etchant to define the patterns. Each sample had alignment marks on the substrate that formed a 2-in square so that the substrates could be easily cut to the specified 2 in \times 2 in size for the IPC water absorption testing.

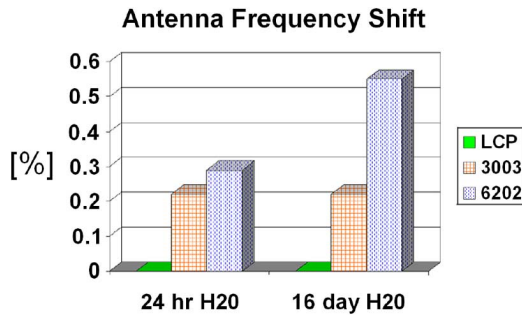


Fig. 3. Measured frequency shift of 14-GHz microstrip patch antennas.

C. Measurement

An important lesson from the water weight gain tests was that a fast connection and measurement would be critical for observing the electrical effects due to water absorption. With this in mind, a special fixture with an adjustable RF signal pin height was used for the measurement. First, 1-port short-open-load-through (SOLT) calibration was performed on an Agilent 8510C network analyzer. Prior to official testing, the pin height was calibrated to the desired substrate thickness with the control samples such that a sample with the same thickness could slide under the pin quickly (with some friction) and to be held in hard mechanical contact. The procedure for placing an antenna on the fixture, positioning the feed line properly in hard contact beneath the signal pin, and beginning a measurement could thus be done in about 10 s. To determine the repeatability of such a measurement method, the control substrate antennas were measured several times by removing/replacing them and remeasuring. The measurement repeatability is estimated to be within ± 5 MHz absolute deviation, which corresponds to $\pm 0.036\%$ at 14 GHz.

Prior to subjecting the test antennas to the baking or water submersion tests, they were all measured. It is important to note that this initial measurement corresponds to the substrate condition which has the “in air” weight. The resonances from these initial measurements were compared with those taken upon removing each substrate from the 24-hour and 16-day submersion tests. The LCP and 3003 results after 16 days were predictably the same since they measured identical water absorption amounts for both time periods. The 6202 results were shifted significantly more after the 16-day submersion. A summary of the results is shown in Fig. 3.

Each of the measurements was performed on four antennas per material and the results averaged. The measured frequency shifts for each of the samples were consistent, demonstrating repeatable results.

As an example of the most extreme frequency shift, the measurements from the 16-day 6202 sample is shown in Fig. 4. Immediately upon removal from the 16-day water submersion, a resonance shift of 0.55% was observed, which is approximately half way out of band. However, these antennas have inherently narrow bandwidths due to the substrate thickness of slightly less than $0.01\lambda_G$ at 14 GHz. More attention should be paid to the magnitude of the shift, which may be insignificant for a 15% bandwidth antenna, but could be critical for an antenna for a

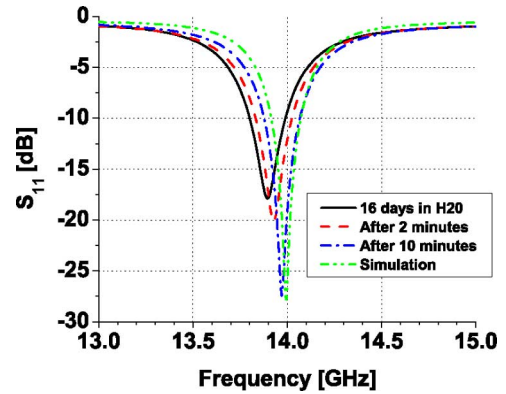


Fig. 4. Frequency shifts of the worst case 14-GHz antenna on the 6202 substrate after the 16-day submersion in water. Successive plots are of the same antenna after waiting 2 and 10 min for the water embedded in the board to evaporate. After 10 min, the response is identical to the dry measurement made before the submersion. The original trace for the dry measurement is not shown to reduce plot clutter. Also shown for comparison is the antenna simulation result.

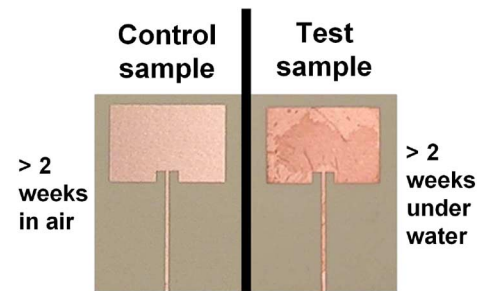


Fig. 5. 14-GHz microstrip patch antennas on a control board which was kept in air at ambient humidity versus an antenna that was submersed in distilled water for 16 days. The submersed antenna demonstrates the corrosion that can occur due to moisture interaction with copper.

bandwidth of a few percent. The worst case shift for the 3003 substrate was only 0.22% and that for LCP was undetectable with the 0.036% measurement resolution.

These antenna tests demonstrate an insignificant effect on two of the three substrates from even the worst case water absorption scenario—full immersion. Even if directly exposed to rain and high humidity, these low-absorption organic materials would not likely reach the same level of water uptake as seen in the tests. In practical applications, the 3003 substrate would not be expected to approach the 0.22% worst case shift and the LCP substrate would be expected to stay extremely stable (no shift) as demonstrated in this testing.

D. Corrosion

A side note about practical implementation of packaged systems using these organic materials is that the standard copper metallization should have some passivation layer to protect the copper from corroding. Some techniques for accomplishing the passivation would be to sputter a thin gold layer on the top of the copper, or in the case of a LCP, a lamination can be carried out to cover/seal the copper metallization inside a multilayer LCP stackup. This technique has been used with the 35-GHz antenna elements in [13]. An example of why a passivation layer is necessary for copper is shown in Fig. 5.

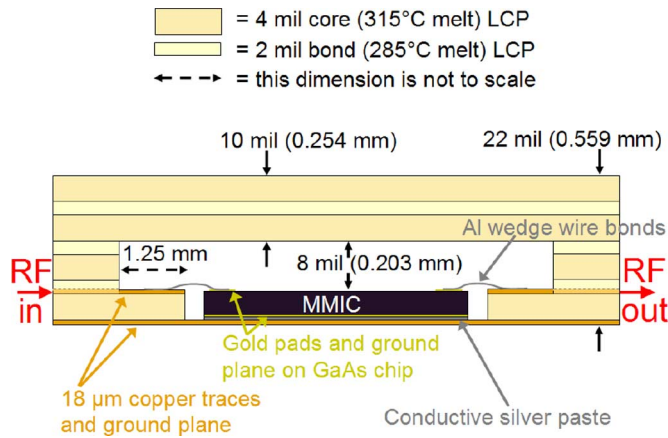


Fig. 6. Pictorial side view of the package stackup.

IV. ACTIVE DEVICE PACKAGING USING MULTILAYER ORGANICS

As mentioned in the introduction, active devices, specifically GaAs MMICs, are robust to humidity and temperature testing. The gold metallization on GaAs chips relieves several of the problems that plague Si MMICs, which have aluminum contacts. However, for reliable long term operation, a substantial sealed package is still desired to protect GaAs MMICs from the environment. In addition, to create compact, inexpensive RF modules, new packaging concepts and convenient integration techniques for combining passive and active devices are required. One such technique, which operates similarly to the low-temperature co-fired ceramic (LTCC) fabrication flow, but whose lamination temperature is low enough for embedding chips, is bonding multiple thin-film LCP substrates into a package with embedded cavities for MEMS or MMICs [11].

A. Embedded MMIC Concept

The idea for embedding a MMIC in a multilayer dielectric substrate/package for creating compact RF modules is not new. LTCC is a material technology that allows the space savings of embedding passive elements on many vertically connected layers. Unfortunately, LTCC has a firing temperature of ~ 850 °C, which means the inclusion of MMICs must be done with some external assembly process after firing. This can involve soldering plastic leaded chips onto the top layer or using other methods to embed chips in cavities between already fired LTCC boards. Since LCP has a lamination temperature of 285 °C, chips can be included directly inside the LCP layer stackup and laminated/package during the same thermocompression bonding process that seals the rest of the passive element layers together.

Two issues that are important for the reliability of active devices are coefficient of thermal expansion (CTE) matching at the semiconductor connection points, and thermal heat dissipation. To prove that concept of a robust multilayer LCP packaged MMIC and to address these issues, the package design in Fig. 6 was devised.

The CTE of the chip's gold ground plane (14.4 [ppm/°C]) is well matched to the special inorganic silver epoxy adhesive and copper layers (both with 17 [ppm/°C]) to which its base is

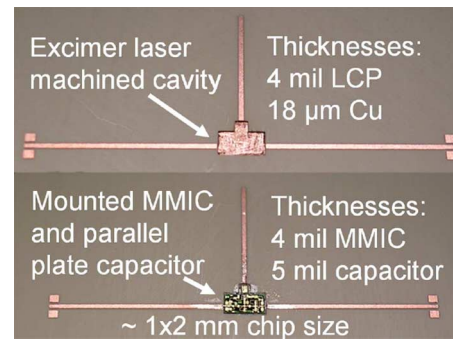


Fig. 7. Comparison of the LCP laser machined base layer before and after the MMIC and parallel plate capacitor were mounted with an inorganic silver paste and wire bonded to the feed lines.

attached. In addition, this contact location is excellent for heat dissipation as the chip is directly connected to the large copper RF ground plane. However, to be realistic about the CTE match, the base of the chip may not be the most sensitive area of concern. It is more likely to be of importance in locations where the chip contacts connect to feed lines. Fortunately, LCP's CTE in the xy -plane can be engineered to match both metals and semiconductors at the expense of slight changes to the z -CTE. LCP with the CTE of 5 [ppm/°C] are used for semiconductor attachment and layers with the CTE of 17 [ppm/°C] are used in layers where matching the copper metallization. For reference, copper has a CTE of 17 [ppm/°C] and GaAs has a CTE of 5.8 [ppm/°C].

B. MMIC Package Fabrication

Several laser micromachining process steps were used to create the multilayer LCP package. First, an excimer laser was used to form the chip cavity in the base substrate layer by ablating LCP down to the 18- μ m copper ground plane. The standard 4-mil GaAs MMIC thickness is the same as an off-the-shelf LCP thickness so that the top of the chip is coplanar with feeding transmission lines on the LCP substrate. A Hittite HMC342 13–25 GHz low-noise amplifier and an off-chip parallel plate bypass capacitor from Presidio Components Inc. were then affixed to the ground plane with an inorganic high-temperature silver paste. These assembly steps are shown graphically in Fig. 7.

The superstrate packaging layers were machined with a CO₂ laser to form square holes in some layers for the chip cavity while leaving other layers solid to create a sealed cavity once laminated. All of the layers, including the base substrate, had laser cut alignment holes in the same relative locations to enable precise stacking on an aluminum bonding fixture. The final laminated package is shown on the fixture with the top press plate removed in Fig. 8.

C. MMIC Package Testing

The important proof-of-concept for the packaging of the MMIC is to show that a seal can be created around the 18- μ m-thick feeding transmission lines. These transmission lines pass directly through the side of the package stackup and require a 2-mil (50- μ m) low melting temperature LCP bond layer to melt and conform around them to create a seal. Fig. 6

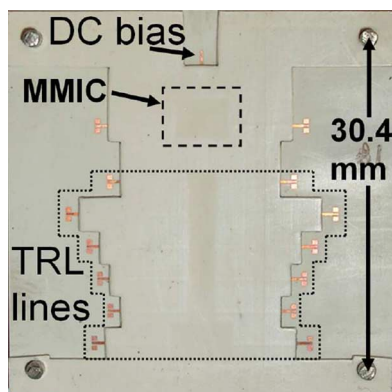


Fig. 8. Top view of the 13–25 GHz GaAs MMIC packaged in multiple thin layers of LCP.

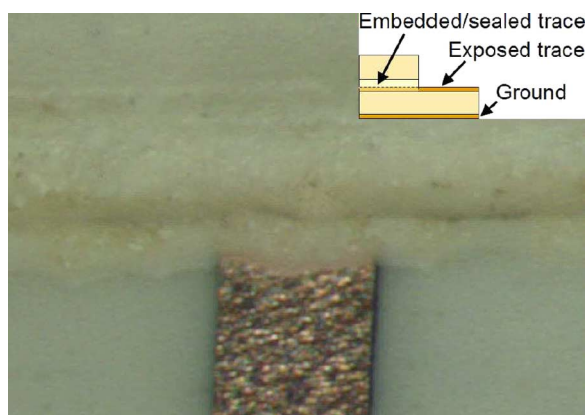


Fig. 9. 18- μ m-thick LCP transmission line passing directly through the side of a bonded superstrate package stackup.

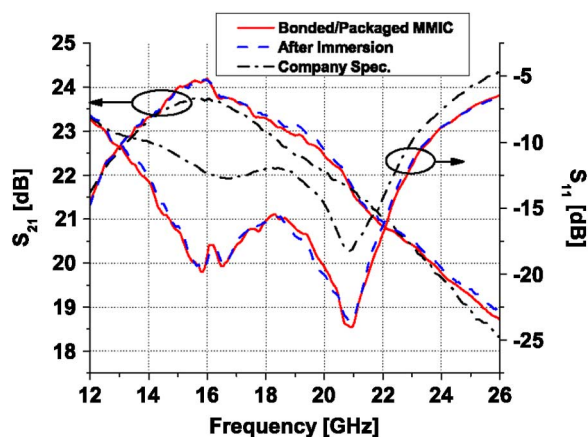


Fig. 10. Gain and S_{11} measurement of the Hittite HMC342 13–25 GHz LNA. The first measurement is of the packaged/bonded MMIC. The second measurement was done immediately after the packaged MMIC was submerged in water on edge for 48 h. The match of the measurements demonstrates a successful seal by the LCP package.

shows a scale representation of the height of LCP's default metallization to the height of the bond ply. A closeup picture of the actual transmission line feedthrough, which demonstrates the ability of the LCP material to conform around the transmission line, is shown in Fig. 9.

To test the package seal, the packaged MMIC was submerged in water for 48 h. The sample was held on edge while underwater to encourage any potential cavity leaks to be breached. A through-reflect-line (TRL) calibration was performed with an identical alternate sample so that the measurement of the packaged chip could be made immediately upon removal from the water. The gain and S_{11} of the packaged MMIC were then measured and compared with the values before the submersion test. The results of this test are shown in Fig. 10.

The gain and S_{11} measurements in the before/after states is nearly identical, indicating that the multilayer LCP MMIC package method can be used successfully for packaging active devices.

V. CONCLUSION

Tests have been performed to determine the water absorption characteristics of three low water absorption organic substrates. The dielectric substrates tested gained and lost water weight, respectively, from submersion and baking processes. The substrate weights returned to ambient weight values from each process in as short as 1 min. Two of the three substrates were found to possess exceptional dielectric stability as demonstrated by minimal (0.22% to 0.0%) frequency shifts by 14-GHz microstrip patch antennas. The small changes in passive device performance indicate that near-hermetic organic materials may be appropriate and practical for both cost and performance in reliable, packaged RF and mm-wave systems.

Active devices packaged in a multilayer organic laminated topology made from thin-film layers of LCP have been demonstrated. The organic chip package has shown the ability to create a water tight seal around feeding transmission lines that pass between the laminated LCP layers. The 13–25 GHz LCP packaged MMIC measurement was unchanged after submersion testing. A conclusion from this research is that both passive and active devices have shown exceptional stability/reliability to water absorption and sealing and that near-hermetic multiplayer organic packaged RF/mm-wave modules could be a robust alternative to other more bulky and expensive packaging implementations.

REFERENCES

- [1] R. Tummala, *Fundamentals of Microsystems Packaging*. New York: McGraw-Hill, 2001, p. 884.
- [2] S. Taylor, Intel Corporation, On-campus presentation, Apr. 2005.
- [3] H. Cunningham, *Thunderline-Z*, Personal Communication at the IMS Exhibition. Jun. 2005.
- [4] G. Riley, Flip Chips Dot Com, Hermeticity: Much to do About Nothing [Online]. Available: <http://www.flipchips.com/tutorial41.html> May 2004
- [5] K. Jayaraj, T. E. Noll, and D. Singh, "RF characterization of a low cost multichip packaging technology for monolithic microwave and millimeter wave integrated circuits," in *URSI Int. Symp. ISSSE*, Oct. 1995, pp. 443–446.
- [6] W. J. Roesch, A. L. Rubalcava, and B. Ingle, "Reliability of plastic packaging for GaAs ICs," in *MANTECH Conf.*, Apr. 1990.
- [7] W. J. Roesch, R. A. Winters, A. L. Rubalcava, and B. Ingle, "Humidity resistance of GaAs ICs," in *IEEE GaAs IC Symp.*, Oct. 1994, pp. 251–254.
- [8] [Online]. Available: <http://www.rogerscorporation.com/mwu/pdf/rt295.pdf>
- [9] K. Jayaraj, T. E. Noll, and D. R. Singh, "A low cost multichip packaging technology for monolithic microwave integrated circuits," *IEEE Trans. Antennas Propag.*, vol. 43, no. 9, pp. 992–997, Sep. 1995.

- [10] D. C. Thompson, O. Tantot, H. Jallageas, G. E. Ponchak, M. M. Tentzeris, and J. Papapolymerou, "Characterization of liquid crystal polymer (LCP) material and transmission lines on LCP substrates from 30–110 GHz," *IEEE Trans. Microw. Theory Tech.*, vol. 52, pp. 1343–1352, Apr. 2004.
- [11] D. Thompson, M. M. Tentzeris, and J. Papapolymerou, "Packaging of MMICs in multilayer LCP substrates," *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 7, pp. 410–412, Jul. 2006.
- [12] R. Buchner, J. Barthel, and J. Stauber, "The dielectric relaxation of water between 0 °C and 35 °C," *Chem. Phys. Lett.*, vol. 306, no. 1–2, pp. 57–63, Jun. 1999.
- [13] R. Bairavasubramanian, D. Thompson, G. DeJean, G. E. Ponchak, M. M. Tentzeris, and J. Papapolymerou, "Development of mm-wave dual-frequency multilayer antenna arrays on liquid crystal polymer (LCP) substrate," in *IEEE Antennas Propag. Symp.*, Jul. 2005, vol. 1B, pp. 393–396.
- [14] D. Thompson, N. Kingsley, G. Wang, J. Papapolymerou, and M. M. Tentzeris, "RF characteristics of thin-film liquid crystal polymer (LCP) packages for RF MEMS and MMIC integration," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Jun. 2005, pp. 857–860.



Dane C. Thompson (M'06) received the B.S and M.S. degrees from Santa Clara University, Santa Clara, CA, in 2001 and 2002, and the Ph.D. degree from the Georgia Institute of Technology, Atlanta, in 2006.

Since February 2006, he has worked as an Application Engineer at Ansoft Corporation, Pittsburgh, PA, a world leading electromagnetic simulation company. His research interests include RF/millimeter-wave packaging and device integration, phased array antennas, medical imaging, and efficient simulation techniques. He has published over 20 refereed journal and conference papers. He is an expert in electromagnetic simulation technologies for signal integrity, RF/microwave, and EMI/EMC analysis.



Manos M. Tentzeris (M'98–SM'03) received the Diploma degree in electrical and computer engineering (*magna cum laude*) from the National Technical University of Athens, Athens, Greece, and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of Michigan, Ann Arbor.

He is currently an Associate Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta. He has published more than 220 papers in refereed journals and conference proceedings and eight book chapters and he is in the process of writing three books. He has helped develop academic programs in Highly Integrated/Multilayer Packaging for RF and Wireless Applications, Microwave MEM's, SOP-integrated antennas, and Adaptive Numerical Electromagnetics (FDTD, MultiResolution Algorithms) and heads the ATHENA research group (15 researchers). He is the Georgia Electronic Design Center Associate Director for RFID/Sensors research, the Georgia Tech NSF-Packaging Research Center Associate Director for RF Research, and the RF Alliance Leader. He is also the leader of the RFID Research Group of the Georgia Electronic Design Center (GEDC) of the State of Georgia.



John Papapolymerou (S'90–M'99–SM'04) received the B.S.E.E. degree from the National Technical University of Athens, Athens, Greece, in 1993, and the M.S.E.E. and Ph.D. degrees from the University of Michigan, Ann Arbor, in 1994 and 1999, respectively.

From 1999 to 2001, he was a faculty member at the Department of Electrical and Computer Engineering, University of Arizona, Tucson, and during the summers of 2000 and 2003 he was a visiting Professor at The University of Limoges, France. From 2001 to 2005, he was an Assistant Professor at the School of Electrical and Computer Engineering, Georgia Institute of Technology (Georgia Tech), Atlanta, where he is currently an Associate Professor. He is the head of the microwave circuit technology group at Georgia Tech. His field of expertise includes the implementation of micromachining techniques and MEMS devices in microwave, millimeter-wave and terahertz circuits and the development of both passive and active planar circuits on semiconductor (Si/SiGe, GaAs) and organic substrates (LCP, LTCC) for system-on-a-chip (SOC)/system-on-a-package (SOP) RF front-ends.