

Development of Microwave Multilayer Plastic-Based Multichip Modules

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Abstract—We present the design and development of multilayer plastic-based multichip modules (MCM) at microwave frequencies. A vertical feed-through interconnect, which consists of embedded copper wires in plastic, has been developed to transport RF/microwave and dc signals from the first to the second packaging level. The development of this vertical feed-through enables plastic modules to be configured in a surface mount topology that can be interfaced with low cost FR-4 boards using ball grid arrays (BGA). The experimental analysis results demonstrate that this vertical feed-through used with BGAs has ultra-low parasitics and achieves a return loss of greater than 20-dB at 4-GHz. In addition, we demonstrate a number of packaged active microwave circuits including a switch, a low noise amplifier (LNA) and a power amplifier using the plastic module technology at microwave frequencies.

Index Terms—BGA, MCM, microwave, package, plastic, vertical interconnects.

I. INTRODUCTION

THE CONTINUED growth of personal communications with wireless applications has generated a great demand for portable and highly integrated components and subsystems. As a consequence, these applications challenge electronics packaging technologies to integrate smaller, lighter, high-density, mixed integrated circuits (ICs), reproducible, and low-cost packages or modules [1]. Three-dimensional (3-D) integration has been the primary approach to achieve high-density packaging by utilizing the vertical dimension. The multilayer thin-film interconnect with embedded ICs in a cavity recess is one of the 3-D architectures that enable high-density packaging [2]–[5]. This technology utilizes a supporting ceramic substrate that is laser drilled to form a cavity recess for housing ICs. In 1996, the chip-on-flex (COF) technology was introduced to replace the ceramic substrate and laser drills with plastic encapsulation [5]. In the COF technology, ICs are encapsulated in plastics and followed by the same multilayer interconnect processing. Recently, a vertical feed-through consisting of copper wires integrated in plastic encapsulation has been developed to construct the module in surface mount configurations using BGAs. The use of BGAs allows the microwave plastic modules

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to interface with low cost FR-4 boards at the second level using industry standard assembly. These recent developments of the multilayer organic based MCMs have made significant progress and geared this technology to meet the demand for high-volume wireless communications applications.

In this paper, we present the design and development of surface mount plastic MCMs at microwave frequencies. We demonstrate the design and development of the vertical feed-through that enables the microwave plastic module to be mounted on an FR-4 board using BGAs. The experimental analysis demonstrates that this feed-through achieves a return loss of greater than 20-dB at 4 GHz. In addition, we demonstrate several packaged microwave circuits including a low noise amplifier, a switch, and a power amplifier using this plastic module technology.

II. PLASTIC MCM TECHNOLOGY

The multilayer plastic-based MCM maintains the same basic processing and structures that provide this technology high-density integration, excellent electrical and mechanical performance [2], [5]. Fig. 1 shows a typical cross section of the multilayer MCMs with ICs embedded under thin-film interconnects. In the COF technology, bare chips and feed-throughs are mounted face down onto an adhesive coated polymer film that is held to a flat platen. The feed-throughs are pre-fabricated components, which consist of an array of solid copper wires embedded in a rectangular shaped plastic assembly. A molding material is poured or injected into a mold form that is placed around the chips and the feed-throughs. The molding material is cured to form the substrate around the ICs and feed-throughs. The structure is then removed from the platen and flipped over for thin-film interconnect integration as reported in [2]–[5]. A thermal plug using high thermal conductance material such as AlN or copper can be attached directly to the exposed backside of high power ICs, either prior to the placement onto the film or just prior to molding the substrate. After the encapsulation process and thin-film integration, the plastic encapsulant at the backside of the package is ground until the feed-throughs are exposed. This backside will be interfaced with the second level FR-4 board using BGAs.

The thin-film polyimide overlay plastic MCMs offer a number of advantages for manufacturability of microwave and millimeter wave systems. These benefits include

- 1) mechanical protection, especially of air bridges on MMICs;
- 2) environmental protection;
- 3) wide variety of low loss second level interconnects.

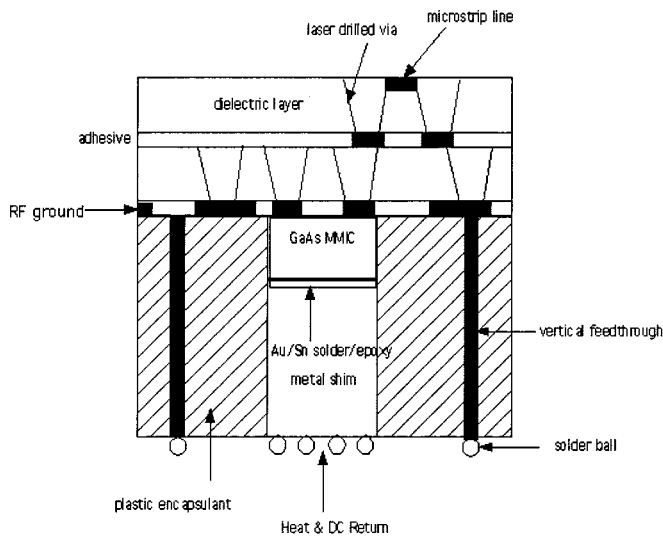


Fig. 1. Cross section of a "chips on flex" (COF) plastic module with vertical feed-throughs.

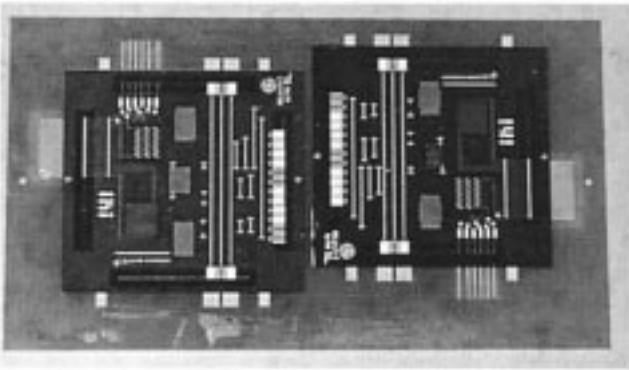


Fig. 2. Actual multilayer plastic-based MCMs fabricated at GE/Lockheed Martin. The two plastic modules are mounted on a FR-4 board using solder balls.

As an example of plastic package reliability, the GE/Lockheed Martin COF plastic packages have withstood 950 thermal cycles from -40°C to 125°C and 1000 h at 85% relative humidity at 85°C . For insertion into wireless applications, which are used in widely varying environments, reliability of plastic packaging will be of paramount importance.

III. VERTICAL FEED-THROUGH

Fig. 2 demonstrates a plastic module fabricated at GE/Lockheed Martin for microwave applications. The vertical interconnection structures fabricated in this plastic module consist of several parts as shown in Fig. 3(a)–(c). The conventional $50\text{-}\mu\text{m} \times 50\text{-}\mu\text{m}$ stacked via technology is used to provide the transition for RF/microwave signals from organic interconnect layers to a plastic base carrier [6]. These stacked vias are fabricated in a coplanar waveguide (CPW) configuration with the gaps determined by the vertical copper wires. The feed-through transports both RF and dc signals through the plastic carrier to the second packaging level using solder balls. This vertical feed-through is developed using a CPW configuration with a $250\text{-}\mu\text{m}$ center conductor separated from the grounds by $400\text{-}\mu\text{m}$ gaps. These dimensions have been optimized to achieve a $50\text{-}\Omega$ characteristic impedance. Solder balls, which have a diameter and height

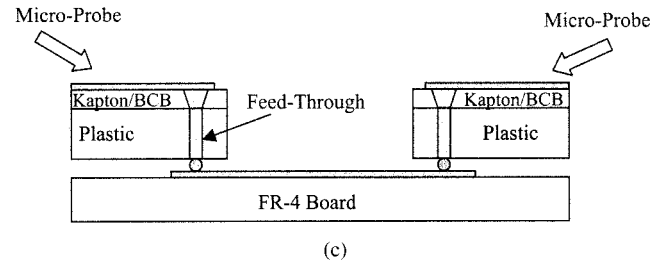
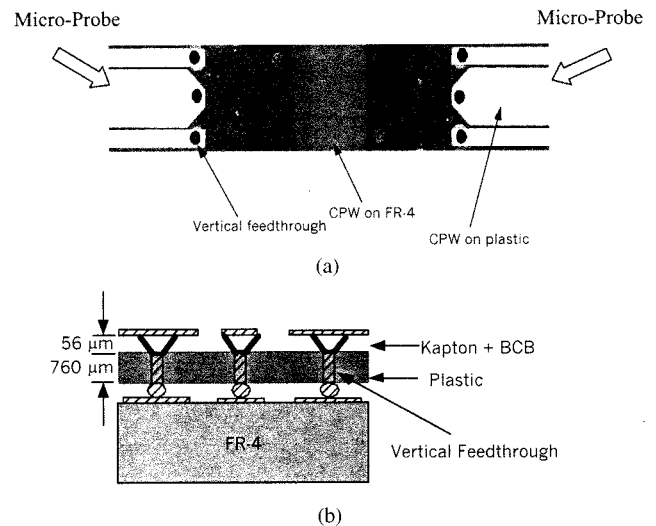


Fig. 3. (a) Schematic representation of the actual test structure including two vertical feed-throughs and an FR-4 CPW line. The CPW on plastic is $900\text{-}\mu\text{m}$ wide center conductor separated from $250\text{-}\mu\text{m}$ wide ground planes by $60\text{-}\mu\text{m}$ gaps. The CPW on the FR-4 board is $700\text{-}\mu\text{m}$ wide center conductor separated from $900\text{-}\mu\text{m}$ wide ground planes by $90\text{-}\mu\text{m}$ gaps. (b) Cross section of the vertical feed-through connecting the plastic module to an FR-4 board. The diameter of the vertical feed-through is $250\text{-}\mu\text{m}$. The signal is separated from the two vertical grounds of the feed-through by $420\text{-}\mu\text{m}$. The diameter and height of the solder balls are $250\text{-}\mu\text{m}$ and $380\text{-}\mu\text{m}$. (c) Side view of the vertical interconnect structure.

of $250\text{-}\mu\text{m}$ and $380\text{-}\mu\text{m}$, respectively, are used to interface the plastic module with an FR-4 board in a coplanar waveguide topology. For testing purposes, $50\text{-}\Omega$ CPW lines are designed on $56\text{-}\mu\text{m}$ Kapton/BCB interconnect layers to launch RF/Microwave signals from microprobes. In addition, a $50\text{-}\Omega$ CPW line has been fabricated on an FR-4 to investigate several discontinuities in the transition.

The test structure is measured using a network analyzer HP 8510C and an on-wafer probe station. Prior to measurements, thru-reflect-match (LRM) on-wafer calibration is performed using microprobes and an impedance standard substrate (ISS). The measurement reference planes result at the probe tips after calibration. Fig. 4(a) and (b) demonstrate the measured S-parameters of the test structure, which includes CPWs on Kapton/BCB, stacked vias, feed-throughs, solder balls, and a CPW on the FR-4 board. The measured return loss of greater than 20-dB up to 4-GHz indicates a good matching for a $50\text{-}\Omega$ microwave system. Since each component has been optimized to have a $50\text{-}\Omega$ match, the measured 20-dB return loss demonstrates that the parasitic induced in the entire vertical interconnection is minimal up to 4-GHz .

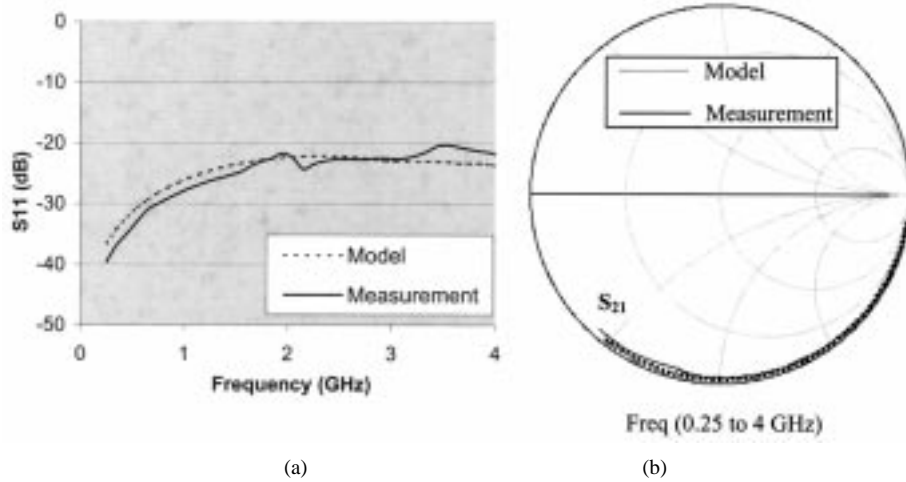


Fig. 4. (a) Measured and modeled return loss of the test structure which includes a 50-Ω FR-4 CPW line and two vertical interconnects. (b) Measured and modeled S_{21} of the test structures.

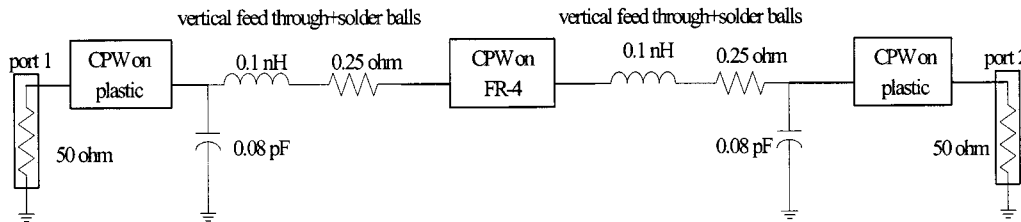


Fig. 5. Equivalent circuit model for the feed-through and solder bumps.

An equivalent circuit, shown in Fig. 5, has been developed to investigate the vertical transition. The Kapton/BCB and FR-4 CPW transmission lines are modeled using an electromagnetics simulator, which outputs the results in S -parameter format [7]. The lumped elements are used to model the general behavior of the vertical interconnect including stacked vias, copper wires, and solder balls. The equivalent circuit is developed based upon the concept of excess charges in a vertical transition [8]. In our test structure, there are two primary vertical discontinuities:

- 1) Kapton/BCB CPWs to stacked vias;
- 2) solder balls to FR-4 CPWs.

The lumped capacitors in the circuit characterize charge densities that are nonuniformly distributed, resulted from the vertical transition. The inductor represents the inductance induced from high-frequency currents traveling through the vertical structures. The lumped elements are tuned using a microwave CAD tool [9] until the modeled and measured S -parameters are correlated as shown in Fig. 4(a) and (b). The lumped circuit model then represents the discontinuities of the signal transition through a vertical feed-through. In addition, the behavior of this lumped circuit represents capacitive characteristics, which indicate the excess charges at the transition. The model demonstrates minimal induced parasitic from the transition, which is key to transport microwave signal and preserve its integrity.

IV. DEMONSTRATION OF PACKAGED MMICs USING PLASTIC MCM

Several MMICs including a single stage dual gate low noise amplifier, a switch, and a power amplifier have been packaged

TABLE I
PERFORMANCE OF AN LNA

Frequency (GHz)	Gain (dB) Packaged	Gain (dB) Un-packaged	NF (dB) Packaged	NF (dB) Un-packaged
1.6	14.6	13	3.7	3.1
1.7	15.4	14.5	3.4	3.1
1.8	14.9	15.5	3.4	3.1
1.9	13.3	15.5	3.1	3.1
2.0	11.1	14.5	3.1	3.1

and integrated in the plastic module. The plastic module size is 25 mm by 0.76 mm, which includes a number of calibration structures. The microstrip MMICs were fabricated at Lockheed Sanders with a 0.5- μm gate MESFET technology on a 125- μm thick GaAs substrate. These packaged MMICs have been characterized in the frequency band of 1.60 GHz to 2.0 GHz. Table I demonstrates measured results of the LNA. We observed some degradation in the performance of the packaged devices. For the switch and LNA, the gain versus frequencies is shifted lower by about 0.2 GHz and the peak gain is reduced by approximately 1 dB as shown in Fig. 6. However, the noise figure maintains within the specifications compared to bare MMICs. The drop-off is caused by the polyimide coating/interconnect above the MMICs. The polyimide coating in this case is approximately 12- μm thick. Above this coating is approximately 70- μm of polyimide interconnect. Both layers have a dielectric constant ranging between 3.00 and 3.30. This polyimide overlayer can produce detuning of the matching section, which is reactive, and increases the C_{gs} , C_{gd} , and C_{ds} of the MESFET resulting in reduced gain and roll-off [10]. For the PA and switch path, the power at the one dB compression, $P_{1\text{ dB}}$, was within 1-dB of the

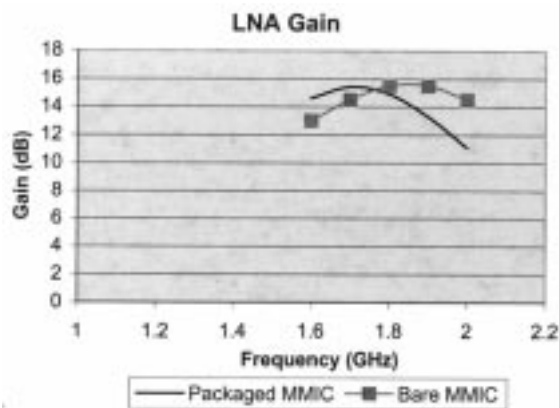


Fig. 6. Measured data of packaged and MMIC LNA.

23-dBm measured from a bare MMIC. The gain of the packaged PA is 2-dB less than that of the bare MMIC.

V. CONCLUSION

We demonstrate the design and development of the multi-layer plastic-based MCM with a new feed-through that enables the use of BGAs at the second level packaging for microwave applications. The vertical feed-through used with BGAs has ultra-low parasitics and achieves 20-dB return loss up to 4-GHz in a 50- Ω electrical connection. This vertical transition allows the plastic modules to interface with low-cost FR-4 boards using industry standard assembly. We also demonstrate the feasibility of this technology by packaging a switch, a low noise amplifier, and a power amplifier. The performance of these active components is preserved within the specifications of bare MMICs.

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V. Krishnamurthy, photograph and biography not available at the time of publication.

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J. Rose, photograph and biography not available at the time of publication.