Short Papers

Development of a Millimeter-Wave System-on-a-Package Utilizing MCM Integration

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Abstract—**We present the development of a system-on-a-package at millimeter-wave frequencies utilizing a commercially available multichip-module process. This technology has established a platform for integrating multiple components of different material systems to combine digital application-specific integrated circuits (ASICs), radio-frequency integrated circuits, and microelectromechanical devices onto a package. The multilayer polymer thin films also empower the design and fabrication of integral passive devices, including thin-film resistors, filters, and Wilkinson power combiners.**

Index Terms—**Heterogeneous, integration, millimeter wave, organic, SOP.**

I. INTRODUCTION

Dramatic changes have been underway in wireless communications and consumer electronics industries. Good representations of these are handheld devices that have real-time Internet access, video, voice, and sensing capabilities. All of these advanced features require paradigm shifts in packaging technologies that can address the integration of a system-on-a-package (SOP)[1] [1]. In general, the development of a wireless subsystem requires devices of several material systems to provide, for example, digital processing power, high-frequency transceivers, and even microelectromechanical system (MEMS) sensors. Microwave transceivers are composed of both integrated circuits (ICs) and passive devices including filters and power combiners that are not integrated on semiconductor substrates. Further, these passive components must have low loss in the gigahertz wireless frequency bands. Therefore, a SOP technology must address both the heterogeneous integration and frequency operation (above 1 GHz). The aim of this paper is to review the commercially available organic multichip-module (MCM) process and to demonstrate its feasibility for integrating an SOP at microwave and millimeter-wave frequencies. This technology provides a SOP paradigm that will address the need for future heterogeneous integration of electronics systems. In particular, this paper will present the direct integration of passive devices onto a multilayer package to provide necessary functionality for a wireless system at microwave and millimeter-wave frequencies.

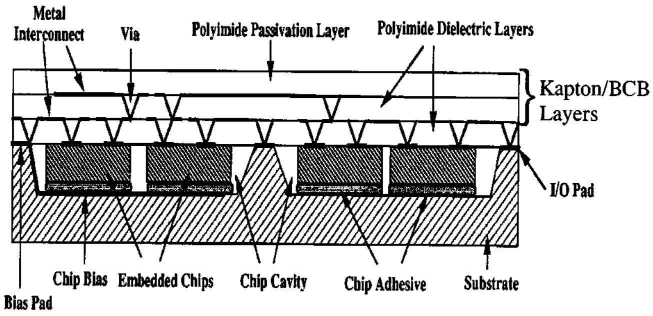
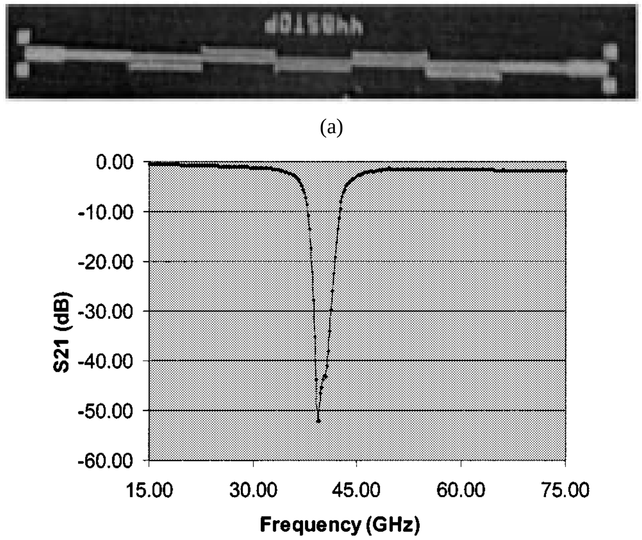


Fig. 1. Cross section of the multilayer organic MCM.



(a)

(b)

Fig. 2. (a) Integral bandstop filter on Kapton flex. (b) Measured results of the integral bandstop filter on Kapton flex.

II. MULTILAYER ORGANIC MCM TECHNOLOGY

The multilayer organic MCM is a potential candidate for integrating an SOP at microwave and millimeter-wave frequencies. This technology has been utilized to package high-speed memory ICs and transceiver modules for communications [2]–[4]. Recently, Butler *et al.* have demonstrated the use of this MCM to package MEMS devices [5]. Fig. 1 reviews the architecture of the organic MCM technology. In this platform, packaged devices can be encapsulated in molding plastic that forms a substrate [2] or can be placed in a cavity recess that is laser drilled in ceramic materials. Therefore, a variety of devices including digital application-specific integrated circuits (ASICs), RF ICs, and MEMS can be combined with high wall-to-wall isolation. Multilayer interconnects are integrated onto the based-substrate using Kapton thin films and benzocyclobutene (BCB) adhesive. Vertically stacked vias are used to provide the first level interconnects for packaged devices. Both the stacked via and thin-film interconnects have ultra-low loss and parasitic that make this MCM attractive for

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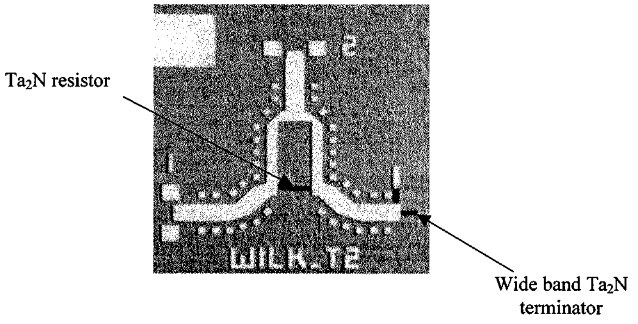

Fig. 3. Integral Wilkinson power combiner/divider on Kapton flex.

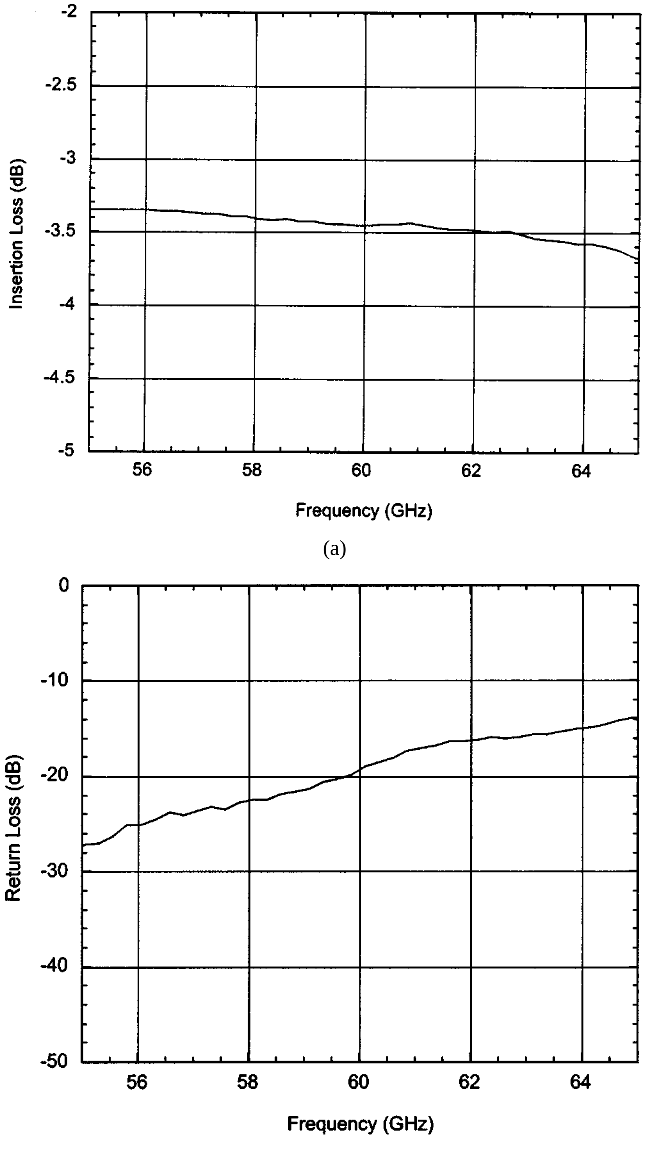

Fig. 4. (a) Measured insertion loss of the integral power combiner/divider on Kapton flex. (b) Measured return loss of the integral power combiner/divider on Kapton flex.

millimeter-wave applications. We have reported that a 50-Ω microstrip line Kapton/BCB achieves a measured insertion of 0.12 dB/mm at 110 GHz [6]. The vertically stacked vias have negligible parasitic effects in a 50-Ω interconnect system [6]. Within the Kapton/BCB multilayer structures, integral passive components can be embedded to increase the packaging density and to eliminate parasitic from surface mount components. Recently, a Ta_2N thin-film resistor process [7], [8] has been developed for the design of terminators, Wilkinson power combiners, and dividers [9] on Kapton flex. In general, the attributions that enable this technology for millimeter-wave SOP applications include: 1) ultra-low loss and parasitic interconnects; 2) housing various devices of different materials; and 3) integral passive components on multilayer organic thin films.

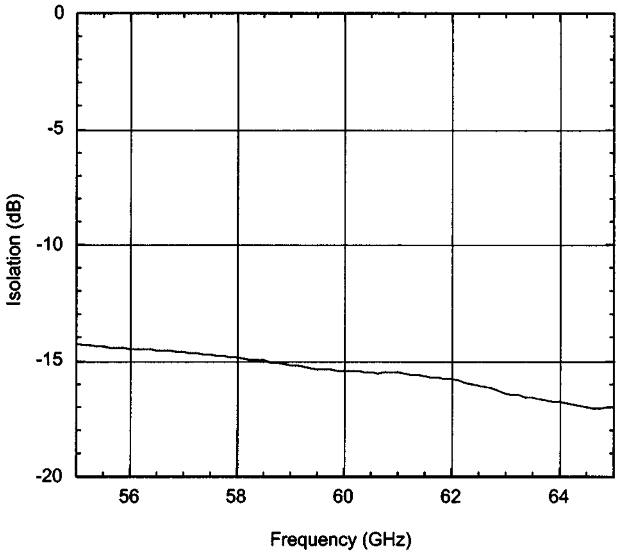

Fig. 5. Measured isolation of the integral power combiner/divider on Kapton flex.

III. PASSIVE-CIRCUIT INTEGRATION

Several passive circuits have been designed and fabricated on multilayer Kapton films to demonstrate integral components on a package. One circuit is a parallel coupled-line bandstop filter that is integrated onto three-layer Kapton films with a total thickness of 110 μm. The schematic representation of the bandstop filter is shown in Fig. 2(a). This fifth-order filter has five parallel coupled lines that constitute a total length of 5.6 mm and a width of 0.5 mm. Each coupled line has a connecting line and a stub that is open circuited on one end and shorted circuit on the other [10]. A vertically stacked via is used to provide shorted circuits for the stubs. On-wafer measurements using off-chip line-reflect-line calibration [11] have been conducted to characterize the filter from 15 to 75 GHz. Two measurements have been performed separately to cover from 50 to 75 GHz and below 50 GHz using a millimeter-wave network analyzer (HP 85109C). Fig. 2(b) demonstrates the measured results of the bandstop filter to 75 GHz. Within the passband, the measured insertion loss is 0.5 dB at 15 GHz and is 1.8 dB at 75 GHz. The 3-dB stopband is measured to be nominally from 36.5 to 44.5 GHz. This result demonstrates the viability of printing high-order filters and passive devices directly onto multilayer Kapton films.

Other types of passive circuits that are critical to millimeter-wave applications include Wilkinson power combiners and dividers [9]. Since power at these frequencies is difficult to achieve, low-loss integral combiners are used to combine power from several monolithic microwave integrated circuits (MMICs). The integral Wilkinson power combiners require the use of resistors to realize the combining or dividing functionality. The Ta_2N thin-film resistor is an enabling technology to design integral Wilkinson power combiners and dividers on Kapton films. Fig. 3 demonstrates an integral Wilkinson power combiner/divider that occupies 2 mm^2 on Kapton flex at the V-band. Three topologies of the Wilkinson power combiners have been designed to characterize this

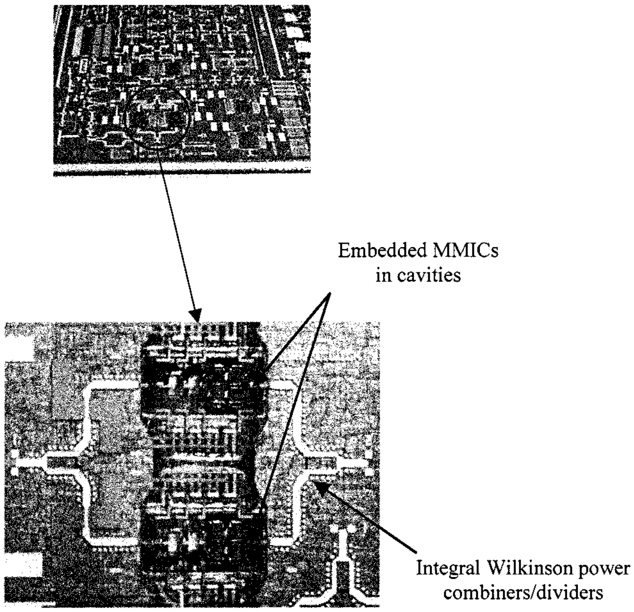

Fig. 6. V-band power-combining subsystem. MMICs are embedded in recess cavities and Wilkinson power combiners are integrated directly on Kapton flex.

three-port device. In each configuration, the third port is terminated with a 50-Ω Ta$_2$N thin-film terminator [8]. Two-port on-wafer measurements have been conducted using 1-mm to WR-15 adapters. The 1-mm coaxial cables provide flexibility to perform an on-wafer calibration then change the probe positions, which enable orthogonal probe contacts. These measurements are to determine insertion loss, return loss, and isolation.

We have achieved a measured insertion loss of less than 0.5 dB for the 3-dB Wilkinson power combiner/divider at 60 GHz, as shown in Fig. 4(a). This result demonstrates the state-of-the-art integral Wilkinson devices on Kapton flex at the V-band (60 GHz). In addition, the measured return loss is within 20 dB at the V-band, which provides a good input match [see Fig. 4(b)]. In addition, we have fabricated two back-to-back Wilkinson power circuits. The measured insertion and return losses of the back-to-back configuration is 0.9 and 15 dB, respectively. These measurements confirm excellent performance of integral passive devices on multilayer Kapton films. Fig. 5 shows the isolation between the two inputs or outputs of the device. The third port is terminated with a 50-Ω wide-band terminator using a thin-film Ta$_2$N resistor. Further refinement in the design of the junction is needed to improve the 15-dB isolation. Electromagnetic simulations have been conducted to demonstrate that more than 20-dB isolation can be achieved by redesigning the junction of the combiner circuit on Kapton flex.[2]

To further demonstrate the millimeter-wave system on a package, two V-band MMICs have been packaged and interconnected with integral Wilkinson power combiners/dividers. These two MMICs are placed in cavities and are interconnected at the first level to the integral Wilkinson power combiners and dividers using a stacked via. The size of this configuration is 90 mm^2, as shown in Fig. 6. On-wafer measurements have been conducted to ensure this system functional. The measured results using a millimeter-wave network analyzer demonstrate a gain of 7 dB and a return loss of 15 dB at the V-band (60 GHz).

IV. CONCLUSION

This paper has reviewed the commercially available organic MCM process and demonstrates its feasibility for implementing an SOP. This MCM technology is capable of integrating digital ASICs, microwave and millimeter-wave transceivers, and MEMS onto the package. In addition, this paper has reported the direct integration of passive devices on multilayer organic packages. The experimental results demonstrate the feasibility of integrating low-loss filters and Wilkinson power combiners/dividers on Kapton flex to 60 GHz.

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