Fully Inkjet-Printed Ramp Interconnects for Wireless Ka-Band MMIC Devices and Multi-Chip Module Packaging

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***Abstract*— This work outlines for the first time the development and demonstration of fully inkjet-printed mm-wave 3D ramp interconnects for Ka-band active wireless devices and MCM packaging solutions. Details of the inkjet printing processes are outlined to realize printed RF and DC interconnects for active MMIC dies. Printed ramp interconnects are demonstrated first with an attenuator die to evaluate the multi-material fabrication process, yielding an interconnect insertion loss of approximately 0.45 dB/mm at 24.5 GHz. The process is then applied to a Ka-band LNA MMIC where ramp interconnects for the RF and DC are inkjet-printed, yielding a maximum aggregate gain of 24.2 dB and interconnect insertion loss of approximately 0.57 dB/mm. The fabrication processes and evaluative demonstrations presented in this work highlight the effectiveness of utilizing fully-additive inkjet printing technology for the realization of highly application-specific wireless MCM systems in a low-cost and efficient fashion up to the mm-wave frequency range.**

***Keywords*— millimeter-wave, packaging, MMIC, inkjet printing, interconnects, Ka-band.**

I. Introduction

The growing field of wireless millimeter-wave (mm-wave) technology has established itself in an increasing number of commercial areas including 5G mobile networking and automotive radar sensing. Along with the development of highly-integrated monolithic microwave integrated circuit (MMIC) design and fabrication, attention is being placed on the development of highly efficient wireless packages and interconnects operating in the frequency range of tens to hundreds gigahertz. These stringent considerations significantly affect the realization of system-on-package (SoP) and multi-chip module (MCM) design schemes, where multiple active and passive devices are packaged within a single system. SoP and MCM packaging approaches allow for systems to be miniaturized from a layout perspective, reducing system size and loss from extraneous interconnect lengths, while proving to be a highly reconfigurable platform from a design-to-product standpoint compared to highly-integrated system-on-chip (SoC) solutions.

Additive printing technologies, such as inkjet and 3D printing, are currently emerging as efficient means to fabricate a variety of wireless components, including antennas, passives, interconnects, and fully-integrated packages [1]. Specifically, the use of additive manufacturing is of interest within the field of mm-wave packaging for the development of robust and efficient wireless systems and SoP schemes [2], [3]. These printing technologies have begun to explore integration with active mm-wave devices with topologies similar to low temperature co-fired ceramic (LTCC) MMIC packages, however interconnection has only been achieved through cavity-embedded methods which limit design capabilities and restrict the realization of 3D interconnections and device integration [4], [5]. The further development of printed ramp-based interconnects allows for the integration of mm-wave MMIC devices on virtually any host substrate, removing the need for milling or designing a substrate around a recessed cavity.

This work outlines for the first time the development of fully inkjet-printed mm-wave 3D ramp interconnects for Ka-band active wireless devices at the discrete IC level for wireless mm-wave MCM packaging solutions. An inkjet printing process is outlined utilizing conductive and dielectric inks to realize printed RF and DC interconnects for MMIC dies, including a 0 dB attenuator for verification and a Ka-band low-noise amplifier (LNA) for further evaluation. Measurements are performed to extract the insertion loss of the printed ramp interconnects where performance is compared to traditional wire bond interconnection methods.

II. Fabrication Materials and Processes

Printed ramp interconnects are realized using a Dimatix DMP-2831 materials inkjet printer with 10 pL drop-volume cartridges. Two ink materials are used to pattern conductive and dielectric features. Metallic features are realized with Sun Chemical EMD5730, a silver nanoparticle-based ink with 40 wt% content loading capable of achieving a volume resistivity of 5–30 $\mu\Omega$ cm after thermal sintering. For this effort, sintering is performed in an oven at 180 °C for 2 h to achieve the desired conductivity. Dielectric features are realized with a MicroChem SU-8 polymer-based ink formulated to achieve a viscosity in the printable range of the DMP-2831. The processing of this dielectric ink includes a thermal soft bake ramping from 60–110 °C over 10 min on a hotplate, a film thickness-dependent exposure to 365 nm ultraviolet (UV) light, and finally a thermal hard bake at 100 °C for 7 min on a hotplate. This dielectric ink is used to pattern 3D features ranging from tens to hundreds of microns in thickness, controlled by the number of printed layers where a single

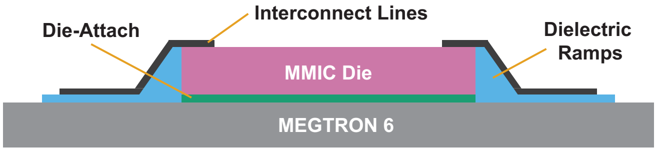

Fig. 1. 2D cross-section schematic of inkjet-printed ramp interconnects for a MMIC die on a MEG 6 substrate.

layer yields a thickness of 4–6 µm with a 20 µm drop spacing resolution. Once deposited and cured, these dielectric features exhibit a relative permittivity (ϵ_r) of approximately 3.2 and a loss tangent (tanδ) of 0.04 at 24.5 GHz.

A 250 µm thick low-loss Matrix R5775KM MEGTRON (MEG) 6 laminate substrate is used as the host substrate for the printed interconnects, exhibiting a ϵ_r of 3.34 and tanδ of 0.004 at 29 GHz. The copper cladding of the MEG 6 laminate is removed using a $FeCl_3$ solution and cleaned with isopropyl alcohol to allow for selective inkjet-printed interconnect patterning.

III. Printed Interconnects with Ka-Band Attenuator

As an initial demonstration, a TriQuint TGL4201-00 GaAs 0 dB attenuator is chosen to evaluate the feasibility of inkjet printing ramp interconnects to Ka-Band MMICs. The 500×500×100 µm TGL4201-00 essentially acts as an RF *through* and exhibits an insertion loss of approximately 0–0.2 dB from DC–30 GHz and a return loss of approximately 15 dB from DC–40 GHz. Bare die measurements for the TGL4201-00 are not included in this work do to its listed specifications and the sensitivity limitations of the measurement equipment used.

A 2D cross-section schematic of the printed ramp stack-up is shown in Fig. 1. First, a die attach is printed onto the MEG 6 substrate with 1 layer of SU-8 ink. After the die is placed, the curing profile outlined in Section II is performed with a 300 mJ/cm^2 UV exposure. Once attached, 4 layers of SU-8 ink are printed and cured with a 400 mJ/cm^2 UV exposure to deposit ramps interfacing the MEG 6 with the top of the attenuator die, where the pattern of the ramp is chosen to overlap 40 µm onto the die to ensure ramp connectivity to the top of the die. The SU-8 pattern also behaves as an adhesion film to promote the subsequent metallic patterning on the MEG 6 substrate. The sample then undergoes a 2.5 min UV-O_3 treatment to ensure proper wetting of the silver nanoparticle (SNP) ink on the printed ramps. Finally, coplanar waveguide (CPW) interconnects are patterned with 4 layers of SNP and then thermally sintered as outlined in Section II. Fig 2 shows a micrograph of the TGL4201-00 die with printed ramp interconnects. The maximum slope of the printed dielectric ramps is measured to reach approximately 35°, which has been demonstrated as a suitable slope for multilayer inkjet printing [3].

As seen in Fig. 2, a taper is included in the printed CPW interconnects to transition from the 15 µm pitch of the RF pads on the die to a 250 µm pitch to faciliate measurement.

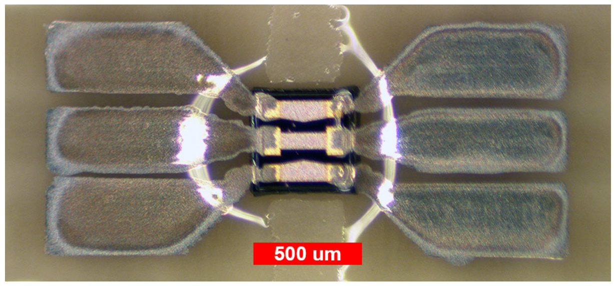

Fig. 2. Inkjet-printed ramp interconnects interfacing a Ka-band GaAs attenuator die.

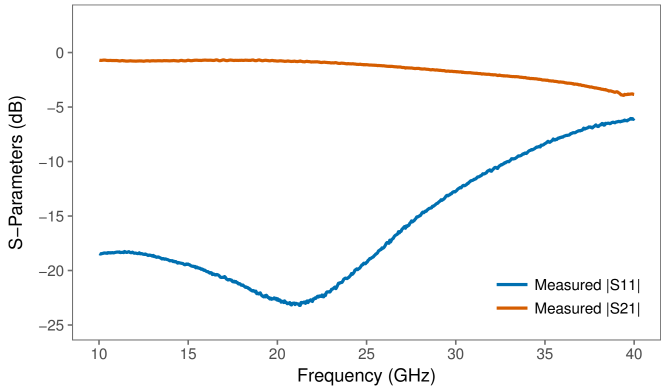

Fig. 3. Measured S-parameters for back-to-back inkjet-printed ramp interconnects with a 0 dB GaAs attenuator die on a MEG 6 laminate.

The interconnected attenuator sample is measured from 10–40 GHz using an Anritsu 37369A VNA with Cascade Microtech ACP40-GSG-250 probes. Measured S-parameters of the interconnected device are shown in Fig. 3. The insertion loss of two back-to-back printed ramp interconnects with the attenuator die is measured to be 1.08 dB at 24.5 GHz, yielding an insertion loss of approximately 0.5 dB per ramp interconnect, or approximately 0.45 dB/mm for a single interconnect. The return loss is measured to be to be greater than 10 dB up to 33 GHz, demonstrating adequate matching throughout the bottom half of the Ka-band where further improvements can be achieved through the optimization of the 250–150 µm pitch CPW taper dimensions.

IV. Printed Interconnects with Ka-Band LNA

With the process of printed ramp interconnection verified with an attenuator die in Section III, focus is shifted to the integration with active devices in the Ka-band. A Hittite HMC-ALH369 GaAs high-electron-mobility transfer (HEMT) MMIC LNA is chosen for the evaluation of these printed ramp interconnects, exhibiting a nominal gain of 22 dB over the range of 24–40 GHz. In addition to the two RF input/output ports of the die, interconnects must also be printed at the Vdd and GND pads with the inclusion of bypass capacitors to ensure proper biasing.

The fabrication process begins with the attaching of the 2.10×1.37×0.10 mm HMC-ALH369 MMIC, where 2 layers of SU-8 ink are printed as a die attach and cured. Next, 5 layers of SU-8 ink are inkjet-printed and cured to form dielectric

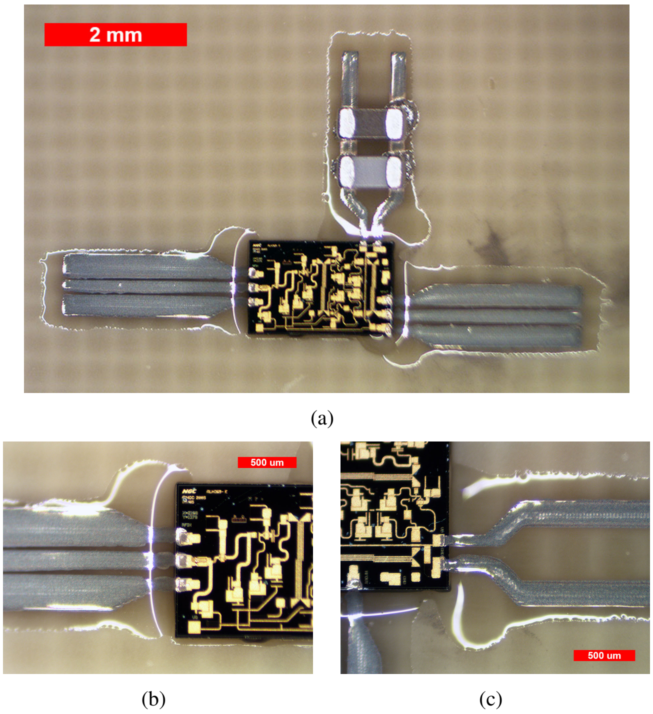

Fig. 4. Inkjet-printed RF and DC ramp interconnects interfacing a Ka-band GaAs HEMT LNA MMIC on a MEG 6 laminate: (a) full device, (b) RF input detail, (c) DC bias detail.

ramps from the MEG 6 to the top surface of the LNA die as well as an adhesion film for metallic patterning. After a 2.75 min UV-O_3 exposure, tapered RF and DC interconnects are patterned with 6 layers of SNP ink which are then thermally sintered. As a final step, 100 pF and 0.1 µF 0402-size surface mount capacitors are placed using conductive silver epoxy to behave as bypass capacitors for the Vdd and GND lines. Fig. 4 shows a micrograph of the LNA MMIC with printed RF and DC interconnects, including bypass capacitors. The first 100 pF capacitor is located approximately 700 µm from the DC pads on the die, staying within the recommended specification of a maximum 750 µm distance.

The LNA MMIC with fully inkjet-printed ramp interconnects is measured from 10–40 GHz with a 5 V DC bias and −20 dBm input power. The measured S-parameters of the device including the printed interconnects along with bare die comparison are shown in Fig. 5. The gain of the device with printed interconnects is measured to be 24.2 dB at 24.5 GHz. Comparing with the specification of 27.1 dB gain at 24.5 GHz for the case of a bare un-packaged die, the insertion loss of the printed ramp interconnects can be observed to be approximately 1.5 dB per interconnect, or 0.57 dB/mm at 24.5 GHz, demonstrating a very effective low-loss interconnect to a Ka-band LNA through the use of multi-material inkjet printing.

V. Comparison with Wire Bond Interconnects

A direct comparison between the performance of the presented inkjet-printed ramp interconnects and traditional

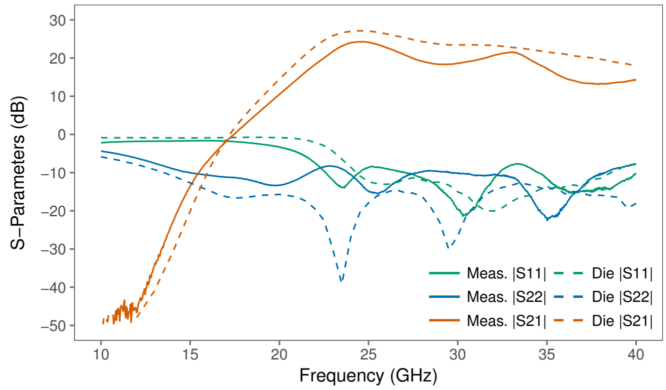

Fig. 5. Measured S-parameters for inkjet-printed ramp interconnects with a Ka-band LNA MMIC on a MEG 6 laminate compared with bare die probing.

wire bonding techniques is a complicated task as there are many factors involved with determining the loss of a wire bond interconnect, including: (1) the package configuration (surface mount or cavity-embedded) and (2) the wire bond height above the die/substrate and position of the pads, contributing to the total *loop length*. For example, G. Baumann et al. presented a cavity-embedded structure featuring an optimized 200 µm wire bond loop length yielding an insertion loss of 0.2 dB at 30 GHz [6]. A more appropriate comparison for the inkjet-printed ramp interconnect configuration would be in [7], where Lim et al. present three 500 µm-length wirebonds in a ground-signal-ground (GSG) configuration yielding an insertion loss of approximately 1.5 dB at 20 GHz. Ultimately, further characterization and specifically designed test vehicles for accurate comparison between the two technologies are reserved as an extension to the efforts presented in this work.

VI. Conclusion

This work outlines for the first time the development of fully inkjet-printed mm-wave 3D ramp interconnects for Ka-band active wireless devices at the discrete IC level for wireless mm-wave MCM packaging solutions. An effective inkjet printing process is outlined utilizing conductive SNP and dielectric polymer-based inks to realize printed RF and DC interconnects for active MMIC dies. Printed ramp interconnects are first demonstrated with a 0 dB attenuator die to evaluate the process, yielding an interconnect insertion loss of approximately 0.45 dB/mm at 24.5 GHz. Inkjet printing is then used to fabricate ramp interconnects for the RF and DC terminals of a Ka-band LNA MMIC, where the insertion loss of the interconnects are measured to be approximately 0.57 dB/mm. The processes and demonstrations presented in this work highlight the effectiveness of utilizing additive inkjet printing technology for the fabrication of highly application-specific wireless mm-wave MCM systems in a low-cost and efficient fashion.

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