Substrate-Independent System-on-Package Antenna Integration with Inkjet Printing

Bijan K. Tehrani, Manos M. Tentzeris
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA, USA

***Abstract*—This work outlines the design and simulation of a multilayer inkjet-printed mm-wave on-package antenna with a focus on electrical isolation from the packaging substrate. For the first time, a fully-printed SoP solution is outlined for the attach, 3D interconnection, and integration of an IC die with a peripheral 30 GHz microstrip-fed antenna. A CPW to microstrip feed transition is simulated to interface the microstrip-fed antenna with the CPW feed from the IC die. Return loss and radiation patterns are simulated with varying packaging substrate ϵ_r values in order to demonstrate electrical isolation and independence from the host packaging substrate material.**

I. Introduction

The next generation of wireless technology is focusing on the millimeter-wave (mm-wave) regime, promising higher bandwidth for gigabit wireless networks and greater resolution for consumer radar applications. In order to drive device miniaturization and increase system efficiency, the packaging of these mm-wave systems is a very active area of research. System-on-package (SoP) solutions are packaging schemes that integrate multiple discrete components into a single package, such as a wireless transceiver die with an antenna and other peripherals, eliminating the need for any high-frequency external connections. Mm-wave SoP design schemes with integrated antennas are very effective, however cost and process compatibility are present issues [1]. In order to reduce fabrication costs and increase design versatility, fully-additive inkjet printing processes are of interest for integration with SoP solutions.

This work presents for the first time a method of integrating a multilayer antenna structure with an integrated-circuit (IC) die using additive inkjet printing technology. A fully-printable on-package 30 GHz microstrip patch antenna is designed and simulated to interface with an on-die coplanar waveguide (CPW) feed line through the integration of a 3D CPW to microstrip feed converter. The return loss and radiation patterns of the antenna are simulated when the relative permittivity of the packaging substrate is altered in order to investigate the robustness of this method of SoP integration with various packaging substrate options.

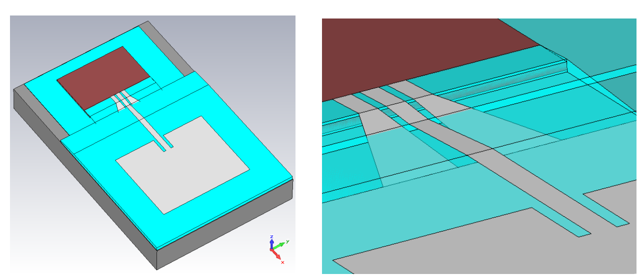
II. Simulation Model Parameters

The simulation model of the SoP antenna consists of the following materials: a glass packaging substrate, a silicon IC die, an inkjet-printed metal, and an inkjet-printed dielectric. The glass substrate is a lossy Pyrex model with a dielectric constant (ϵ_r) of 4.82 and a loss tangent (tan δ) of 0.0054. The silicon die is a lossy model with a resistivity of 10 ohm·cm and a ϵ_r of 11.9. The inkjet-printed metal is based off of a silver nanoparticle-based ink that yields a conductivity of 1.1×10^7 S/m [2]. The inkjet-printed dielectric is based off of an SU-8 polymer-based ink that yields a ϵ_r of 3 and a tan δ of 0.04 at 30 GHz [3].

The physical model of the wireless SoP solution consists of several printed elements: a die attach, a dielectric ramp, and a multilayer antenna structure. The die attach is modeled with the SU-8 dielectric and is used to mechanically attach the $2\times2.7\times0.05$ mm silicon IC die to the glass packaging substrate. The dielectric ramp is also modeled with the SU-8 dielectric and is used to interface the top of the IC die with the peripheral antenna structure. Finally, the 30 GHz multilayer microstrip patch antenna with a 120 μm thick dielectric substrate is realized with the SU-8 dielectric and silver metal patterns. A CPW to microstrip feed transition is included in the model in order to interface the patch antenna with the silicon die, demonstrating a fully-printed SoP antenna integrated with an IC die. Several measures are used in modeling in order to account for morphological phenomena typically present in thick inkjet-printed dielectric films. Simulation models of the SoP solution are presented in Fig. 1. All simulations are performed in CST Microwave Studio.

III. CPW to Microstrip Feed Transition

The inclusion of a CPW to microstrip feed transition is necessary to interface the output feed on the top of the IC



(a) (b)

Fig. 1. Simulation model for inkjet-printed SoP patch antenna: (a) full 3D model and (b) detail of CPW to microstrip feed transition.

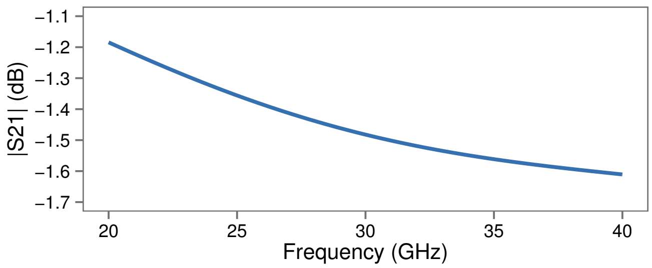


Fig. 2. Simulated S21 insertion loss for inkjet-printed CPW to microstrip feed transition.

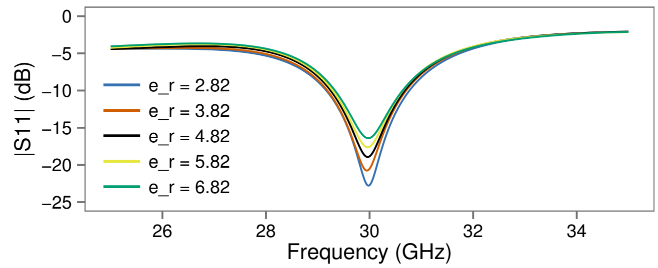


Fig. 3. Simulated S11 return loss for inkjet-printed patch antenna with ϵ_r variations in host packaging substrate.

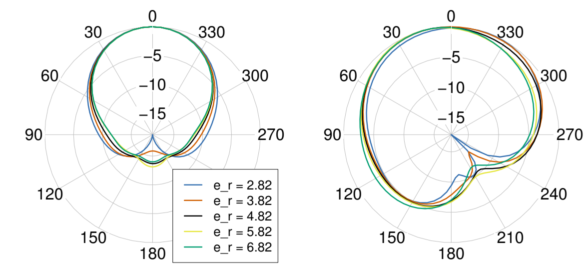
die with the peripheral multilayer patch antenna. In order to optimize this transition, the ground traces of the CPW line are tapered out to the ground plane of the microstrip line. As the signal trace increases in height relative to the ground traces due to the positively-ramping edge of the patch substrate, the ground lines slightly taper inwards in order to improve the efficiency of the transition. Finally, the signal trace of the CPW feed is widened to 200 μm to create a 50 Ω microstrip line.

Simulations are performed over 20–40 GHz in order to assess the efficiency of the transition for the proposed 30 GHz antenna. S-parameter results are presented in Fig. 2. The simulated results demonstrate a low S21 insertion loss ranging from -1.2 dB to -1.6 dB and a suitable S11 return loss below -15 dB throughout the simulated range.

IV. Multilayer SoP Patch Antenna

With the design and simulation of the CPW to mirostrip feed transition established, a fully-printed rectangular patch antenna is designed to operate at 30 GHz. The dimensions of the patch antenna are 2.85$\times$3.5 mm with a 120 μm thick SU-8 dielectric substrate. An inset feed with a length of 0.6 mm and a gap width of 0.1 mm is used in order to improve the impedance matching between the 50 Ω microstrip feed line and the edge of the patch antenna.

The purpose of choosing a microstrip-fed antenna for this printed SoP scenario is to demonstrate the electrical independence of the the antenna structure to the host packaging substrate. To investigate the benefits of this isolated antenna, parametric simulations are performed on the inkjet-printed multilayer patch structure with variations in ϵ_r ranging 2.82–6.82 for the glass packaging substrate. Return loss measurements of the simulated patch antenna with these parametric conditions are presented in Fig. 3. When the ϵ_r of a material in close proximity to a resonant structure such as a patch antenna changes, it is expected that the resonance of the antenna will shift inversely with with magnitude of ϵ_r. However, simulations show virtually no shift in resonant frequency with variable packaging substrate ϵ_r, highlighting the electrical isolation between the printed antenna structure and the host packaging substrate. The variation in return loss magnitude between ϵ_r values is likely the result of the feed transition that takes place over the packaging substrate.



(a) (b)

Fig. 4. Simulated (a) YZ and (b) XZ normalized radiation pattern cuts.

In order to investigate the farfield characteristics of the printed patch antenna, radiation patterns are simulated with the same ϵ_r variation for the packaging substrate. Simulated θ-sweep normalized radiation patterns in the XZ and YZ planes are presented in Fig. 4, further demonstrating the electrical isolation of the inkjet-printed patch antenna model.

V. Conclusion

This work presents for the first time the design and simulation of an inkjet-printed mm-wave multilayer microstrip patch antenna integrated on-package with a silicon IC die. A 3D mm-wave CPW to microstrip feed transition is presented to interface a die with an on-package antenna with low insertion loss. The electrical isolation of the antenna from the packaging substrate is investigated through parametric simulations varying the ϵ_r of the packaging substrate, demonstrating host material independence. The integration of inkjet printing technology with SoP solutions has the potential to improve the versatility of wireless mm-wave systems while offering reductions in fabrication costs and extraneous material waste.

References

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