Inkjet Printing of Multilayer Millimeter-Wave Yagi-Uda Antennas on Flexible Substrates

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***Abstract*—This letter presents two high-gain, multidirector Yagi–Uda antennas for use within the 24.5-GHz ISM band, realized through a multilayer, purely additive inkjet printing fabrication process on a flexible substrate. Multilayer material deposition is used to realize these 3-D antenna structures, including a fully printed 120-μm-thick dielectric substrate for microstrip-to-slotline feeding conversion. The antennas are fabricated, measured, and compared to simulated results showing good agreement and highlighting the reliable predictability of the printing process. An endfire realized gain of 8 dBi is achieved within the 24.5-GHz ISM band, presenting the highest-gain inkjet-printed antenna at this end of the millimeter-wave regime. The results of this work further demonstrate the feasibility of utilizing inkjet printing for low-cost, vertically integrated antenna structures for on-chip and on-package integration throughout the emerging field of high-frequency wireless electronics.**

***Index Terms*—Flexible, inkjet printing, inkjet-printed antennas, millimeter-wave, multilayer antenna, on-chip antennas, on-package antennas.**

I. Introduction

THE BROADENING field of wireless electronics is pushing toward the continuous enhancement of functionality, ubiquity, and economic feasibility. Emerging studies of millimeter-wave (mm-wave) wireless communication systems, ranging in operational frequencies from tens to hundreds of gigahertz, are leading to the development of such technologies as gigabit wireless local area networks, automotive collision avoidance and autonomous navigation radar systems, and high-resolution beam-scanning imaging applications. Typical fabrication methods of mm-wave antennas include the lithographic masking, patterning, and etching of materials, which are victim to the utilization of harsh chemicals and a high overall cost. In order for the continued integration and proliferation of these emerging mm-wave technologies, efforts must be made to improve the versatility and cost of antenna fabrication.

Inkjet printing is an additive electronic fabrication method that has been gaining interest for both consumer and industrial applications as a low-cost, highly scalable, and environmentally friendly alternative to typical laminate-based fabrication schemes [1]. Utilizing metallic nanoparticle-based and thin/thick polymer-based inks, multilayer structures have been realized with inkjet printing on flexible substrates for radio frequency (RF) applications, such as fully printed capacitors, inductors, and transformers [2]–[4]. Through the refinement and characterization of these various ink materials, multilayer high-gain antenna structures reaching into the mm-wave regime have been realized through inkjet printing fabrication on both flexible and rigid substrates [5], [6]. However, several recent demonstrations of inkjet-printed mm-wave antennas suffer from limitations present in typical multilayer RF structure design, such as the discrete thicknesses and material properties of common laminate substrates, as well as the difficulties of multilayer laminate substrate processing (e.g., material stacking, bonding, and alignment) [7]–[10]. The vertically integrated, additive nature of inkjet printing is pushing toward high-level integration with areas of high interest, such as system-on-chip (SoC) components, flexible wearable electronics, and conformal/rollable/reconfigurable structures [11], [12]. This integration has the potential to increase the efficiency and versatility of wireless mm-wave systems through the direct post-process deposition of antennas onto any flexible or rigid active circuit topology.

This letter demonstrates two inkjet-printed, multilayer, high-gain Yagi–Uda antennas on flexible substrates for use within the 24.5-GHz ISM band. These multilayer antenna topologies are fabricated using a thick dielectric ink, realizing a purely additive, selectively patterned dielectric substrate exceeding 100 μm in thickness, surpassing previous works while improving printed topology surface uniformity [12]. The technology presented in this work further demonstrates the capabilities of the efficient, low-cost method of inkjet printing for mm-wave antenna fabrication, highlighting the technology's potential for integration with on-chip and on-package fabrication schemes as a post-processed, vertically integrated fabrication method.

II. Inkjet Printing Materials and Processes

In order to realize versatile multilayer antenna structures with inkjet printing, both thin metallic inks and dielectric inks capable of patterning film profiles ranging from thin (< 10 μm) to thick (> 100 μm) must be utilized. Patterning of these materials is achieved with the Dimatix DMP-2831, a piezoelectric drop-on-demand inkjet printing system capable of yielding an accuracy down to 5 μm.

Metallic patterns are achieved with Cabot CCI-300 silver nanoparticle-based ink, composed of a 20 w% suspension of silver nanoparticles within an alcohol-based solution, yielding

Manuscript received April 14, 2015; accepted May 10, 2015. Date of publication May 18, 2015; date of current version February 10, 2016. This work was supported by the National Science Foundation (NSF) and the Defense Threat Reduction Agency (DTRA).

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Digital Object Identifier 10.1109/LAWP.2015.2434823

a viscosity of 11–15 cP and a surface tension of 30–33 mN/m (Cabot Corp., Boston, MA, USA). Once silver layers are printed, solvent evaporation is performed with a thermal ramp from 60°C to 120°C over 10 min. When the alcohol-based solvent is removed, a sintering at 180°C takes place for 1 h, completing the metallic patterning process. Each layer of silver ink is printed with a drop spacing of 20 μm, yielding a thickness of 500 nm and conductivity of 1.1e7 S/m [13].

Dielectric patterns are achieved with an SU-8 polymer-based thick dielectric ink capable of realizing printed structures up to and beyond 500 μm. This dielectric ink is realized through the formulation of 35 w% of the long-chain SU-8 polymer (MicroChem, Newton, MA, USA), a cyclopentanone solvent, and a negative UV-cross-linking agent, yielding a polymer-based ink with a viscosity of 13.4 cP and a surface tension of 30 mN/m [5]. Once a dielectric pattern is printed, an initial thermal bake occurs with a ramp from 60°C to 120°C over 10 min, followed by polymer cross-linking from a 300-mJ/cm^2 exposure of 365 nm UV light, and the printing is concluded with a final thermal bake at 100°C for 7 min. Each layer of the dielectric ink is printed with a drop spacing of 20 μm, yielding a single-pass layer thickness of 4–6 μm. The relative permittivity (ϵ_r) of the printed SU-8 polymer dielectric is approximately 3.2 with a loss tangent ($\tan\delta$) of approximately 0.04 at 24.5 GHz [12].

The host substrate is 100 μm unclad Rogers ULTRALAM 3850 (Rogers Corp., Rogers, CT, USA), a flexible liquid crystalline polymer (LCP) laminate with ϵ_r of 2.9 and $\tan\delta$ of 0.0025.

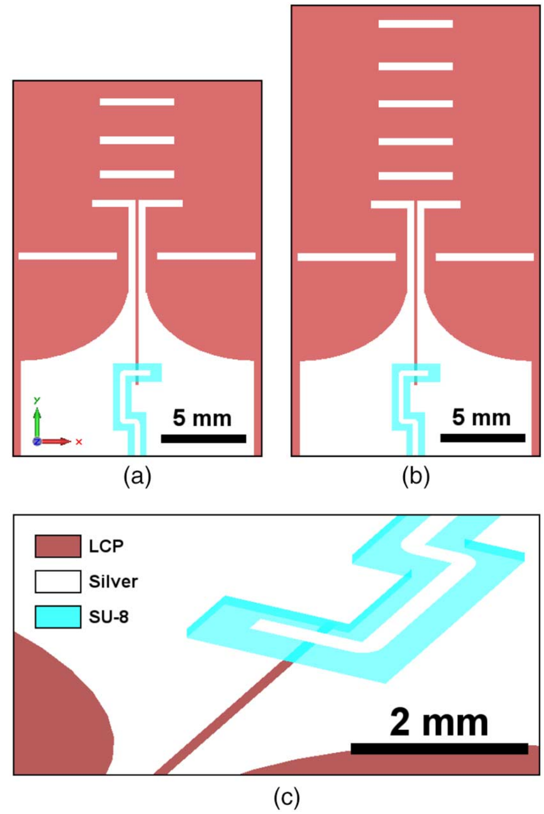

Fig. 1. Simulation models for inkjet-printed (a) 3- and (b) 5-director Yagi–Uda antennas with (c) detail showing a multilayer microstrip-to-slotline transition.

III. Yagi–Uda Antenna Design and Measurements

To demonstrate the inherent capability of the introduced multilayer inkjet printing process for an easy and low-cost integration of printed thick dielectrics, two multilayer Yagi–Uda antenna configurations with 3 and 5 directors are presented for use within the 24.5-GHz ISM band. A microstrip-to-slotline transition is included in the design utilizing a printed dielectric substrate, ensuring the testability of the antennas upon fabrication while enhancing the impedance matching [14]. The antenna topologies are designed, simulated, and optimized for the desired resonant frequency using the 3-D computer-aided design (CAD) tools and time-domain solver in CST Microwave Suite. The simulated geometries of the 3- and 5-director antenna designs and a magnified view of the microstrip-to-slotline transitions are shown in Fig. 1.

A. Multilayer Fabrication Process

The fabrication process of these antennas begins with the printing of 5 layers of a silver nanoparticle ink (2.5 μm thickness) on bare, unclad LCP using the Dimatix DMP-2831 inkjet printing system. Five layers of silver nanoparticle ink is chosen for the antenna topology, while three layers is chosen for the overlying microstrip feedline in accordance with skin depth requirements at 24.5 GHz presented in [5], where the single-sided field confinement of the microstrip feedline metallization only requires tree layers of printed silver compared to the double-sided radiation of the antenna topology. Curing and sintering methods are then performed for the silver ink as previously described, followed by an exposure of the LCP substrate and metallic pattern to 30 s of UV O_3 in order to ensure agreement between the surface energy of the substrate and the surface tension of the next ink deposited. Another printing session of 18 layers of SU-8 dielectric ink is then performed to pattern the desired 120-μm-thick dielectric feeding substrate. After the previously outlined baking and cross-linking techniques for the dielectric ink are performed, another 30 s UV O_3 exposure takes place to ensure ink–substrate material agreement. Next, three layers of silver nanoparticle ink (1.5 μm thickness) are deposited, cured, and sintered, completing the fabrication of the 3- and 5-director Yagi–Uda antenna topologies. Images of the fabricated antennas are shown in Fig. 2, including magnifications of the microstrip-to-slotline feed transition and slight substrate bending.

A profilometer scan of the printed dielectric substrate is shown in Fig. 3. With the deposition of many layers, the printed substrate experiences effects from surface tension and drying, thus creating as a result a convex-shaped profile [12]. Across the 300- μm X-span of the center of the substrate occupied by the microstrip feedline, a profile variation of ± 2 μm is measured, equivalent to 3% of the substrate thickness.

B. Return Loss Measurements

Upon completion of fabrication, end-launch connectors provided by Southwest Microwave (Southwest Microwave, Tempe, AZ, USA) are mounted onto the antennas for RF characterization. S_{11} return loss measurements are then performed from 21 to 27 GHz using an Anritsu 37369 VNA (Anritsu

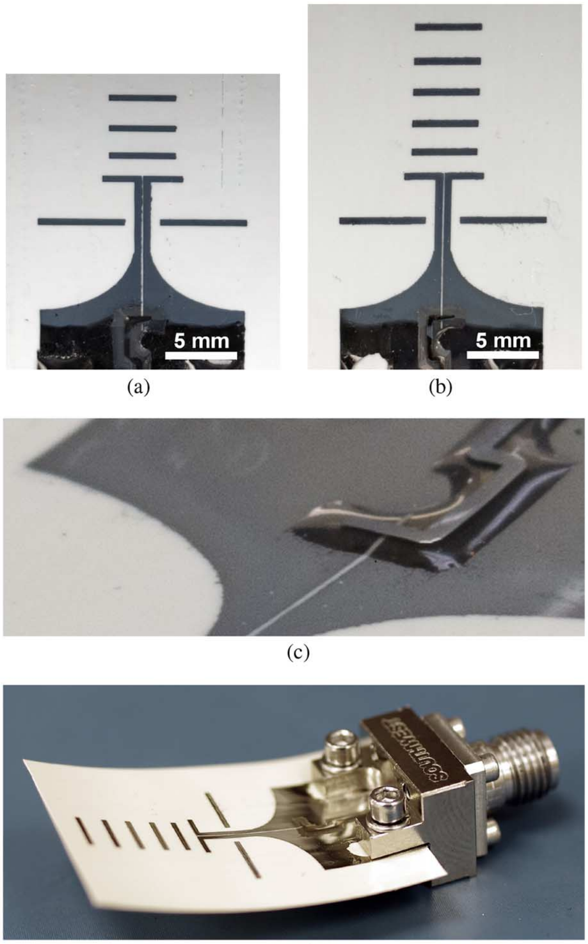

Fig. 2. Inkjet-printed multilayer (a) 3- and (b) 5-director Yagi–Uda antennas with detailed images showing (c) the printed dielectric substrate for the microstrip-to-slotline feeding transition and (d) slight substrate bending.

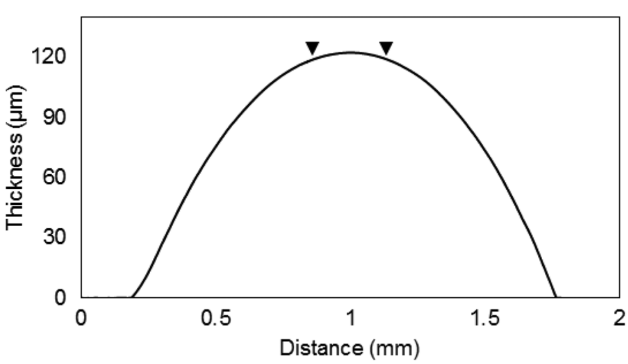

Fig. 3. Profilometer scan of the printed 18-layer (120 μm thick) SU-8 dielectric substrate of the microstrip feedline, identifying the 300 μm area of the printed silver feedline ▼.

Company, Kanagawa, Japan), shown in Fig. 4. Return loss measurements show good agreement with simulated results as well as efficient matching at 24.5 GHz, demonstrating the RF integrity of both the metallic and dielectric ink materials used within the inkjet printing process.

C. Realized Gain Measurements

The realized gain of the fabricated antennas is measured with a mm-wave far-field measurement system utilizing a 20-dB

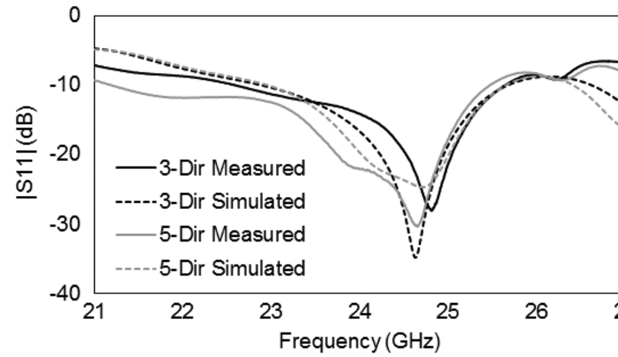

Fig. 4. Simulated and measured return loss values for the inkjet-printed 3- and 5-director Yagi–Uda antennas.

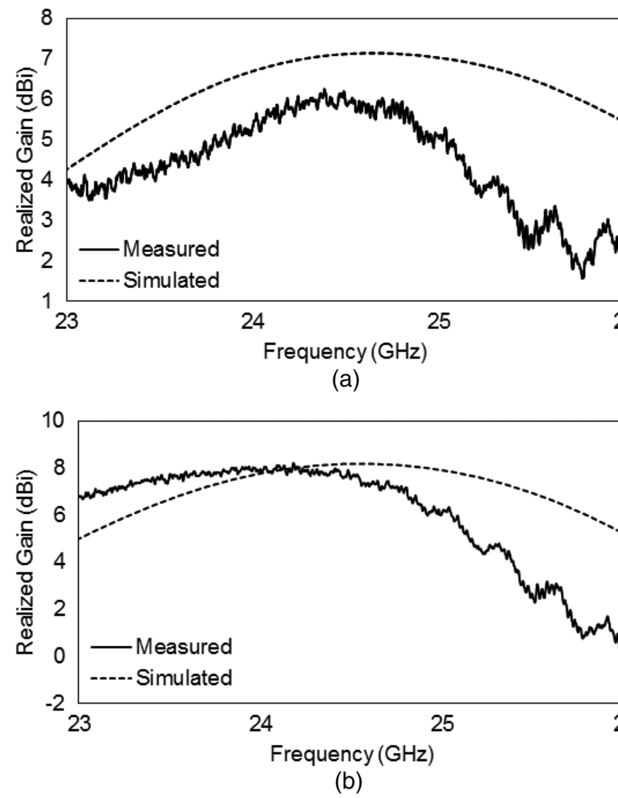

Fig. 5. Simulated and measured realized gain for inkjet-printed (a) 3- and (b) 5-director Yagi–Uda antennas.

standard gain horn antenna provided by Fairview Microwave (Fairview Microwave, Allen, TX, USA) at a distance of 45 cm. A plot of the measured and simulated endfire realized gain for the 3- and 5-director antennas from 23 to 26 GHz is shown in Fig. 5. Maximum endfire realized gains of 6 and 8 dBi for the 3- and 5-director designs, respectively, are achieved within the 24.5-GHz ISM band, improving upon the 7-dBi-gain Vivaldi antenna achieved in [7] and demonstrating the highest-gain inkjet-printed antenna within the outlined frequency band to date.

Though the measured results match well with simulated data in the lower frequencies of the measured range, discrepancies between the two in the higher frequencies are likely the result of substrate deformation during measurement as well as standing waves present in the coaxial feedlines of the measurement system that were unable to be removed from measurements.

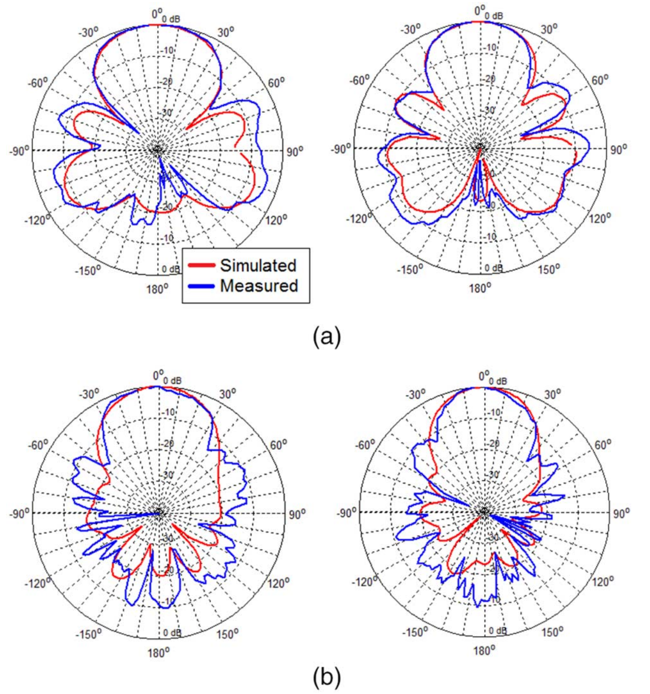

Fig. 6. Simulated and measured normalized (a) yz and (b) xy E-field radiation patterns for inkjet-printed *(left)* 3- and *(right)* 5-director Yagi–Uda antennas.

D. Radiation Pattern Measurements

The radiation patterns of the printed antennas are measured using a mm-wave far-field rotational measurement system setup with a 45-cm distance between interrogating antenna and antenna under testing. Normalized E-field radiation patterns in the xy- (ϕ sweep) and yz- (θ sweep) planes of the antennas are measured and compared to simulated patterns in Fig. 6. The measured yz radiation pattern cuts [Fig. 6(a)] show excellent agreement with simulations for both the 3- and 5-director designs. The measured xy radiation pattern cuts [Fig. 6(b)] exhibit good agreement with simulations in the endfire 0° direction, but experience discrepancies with slightly enlarged sidelobes, specifically in the backside 180° region. These deviations are likely the result of substrate bending during measurement, where a deformation in the xy-plane of the antenna is conducive to a greater degree of error in the xy radiation pattern measurements. A second source of error could result from the modeling of the end-launch connector in simulations, where nonidealities in the feeding structure model have an effect on the radial efficiency of the antenna.

IV. Conclusion

Through the utilization of purely additive inkjet-printing processes, multilayer Yagi–Uda antennas have been realized exhibiting endfire realized gains up to 8 dBi within the 24.5-GHz ISM band. A combination of nanoparticle-based metallic and polymer-based dielectric inks are used to fabricate a fully printed, selectively patterned dielectric substrate exceeding 100 μm in thickness. The additive fabrication process used in this work has the potential to be applied to a variety of applications beyond bulk flexible substrates, including post-processed antenna fabrication for on-package and on-chip wireless systems. Through the continuing advancement of the materials and processes used with inkjet printing, this technology has the potential to greatly impact the field of high-frequency wireless electronics, offering a low-cost, versatile, and environmentally advantageous fabrication methodology.

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