A fully-screen printed, multi-layer process for bendable mm-wave antennas

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***Abstract*—In the era of Internet of Things (IoT) and wearable electronics; printing technique, such as screen printing, is becoming popular because of their lower costs and mass manufacturing abilities. However, most of the previous work has been done on printing metallic patterns and not the printing substrates. In this paper, we introduce a custom screen printable dielectric ink (polymer mixed with ceramics), which provides lower loss even at millimeter-wave (mm-wave) bands. With the help of dielectric ink and custom silver nanowires (AgNW) based metallic ink, a multilayer, fully screen-printed fabrication process has been developed. To demonstrate the efficacy of the proposed inks and the multilayer printing process, a stacked patch antenna with 4-parasitic patches in the superstrate is designed, fabricated, and tested for the mm-wave band (5G band). Despite a new fabrication process, the measured results show a decent antenna performance (both in flat and bent positions) where the input impedance is matched from 26.5-30 GHz and a maximum gain of 7.8 dBi has been attained.**

***Index Terms*— additive manufacturing, antennas, dielectric printing, millimeter-wave antenna, screen printing, measurements.**

I. Introduction

The demand for flexible, conformal, low-cost, and mass manufacturable radio-frequency electronics has risen due to the growing applications of the internet of things (IoT), 5G communication, and wearable electronics [1]. For such applications, it is expected that billions of such devices would be connected to the internet and perform operations such as data acquisition, processing, and transportation and collectively make the world smarter [2]. For wearable applications, printed electronic (PE) components must be mechanically flexible to fulfill the diverse mounting conditions on non-planar or curved surfaces. In order to deal with the forthcoming huge demand for radio-frequency (RF) electronic systems, additive manufacturing technologies are attractive as the conventional subtractive fabrication technologies are expensive, result in material waste, and are not ideal for large areas and mass manufacturing [3, 4].

Additive manufacturing technologies such as 3D printing, screen printing, and inkjet printing are cost-effective solutions for large-scale, high-volume, roll-to-roll (R2R) production. Conventionally, printing has been limited to the patterned metallic layers on commercial substrates [5-8]. In some works, the substrate is also 3D printed using standard 3D printers employing the filaments of acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) material and then patterned metallic structures are printed using conductive inks over 3D printed substrate [9, 10]. However, a true fully printing process where multiple dielectric and conductive layers can be printed alternately, particularly for higher frequencies mm-waves, is missing from the literature. Recently, we have shown a custom dielectric ink that can be screen-printed to realize flexible substrates [11]. In this paper, we further extend that work by demonstrating a fully screen-printed multilayer fabrication process for the mm-wave band of frequencies. As a proof of concept, a bendable multilayer stacked patch antenna with 4-parasitic patches at the superstrate layer has been realized through the proposed fully printed process that demonstrates a large bandwidth and high gain as anticipated from the conventional subtractive printed circuit board (PCB) manufacturing with the standard substrates.

II. Fully Screen Printed Electronics

A. Dielectric and conductive inks

To fabricate fully screen-printed electronics including the dielectric substrate and the metallic patterns, suitable dielectric and conductive inks are needed. The employed dielectric ink is developed here by dispersing ceramic particles into an ABS polymer matrix, as shown in Fig. 1(a). Such formulations can provide a low loss tangent (tanδ) for the printed dielectric layer, making it suitable for RF electronics. To prepare the dielectric ink, a solvent mixture of anisole and tetrahydrofuran with a weight ratio of 6:1 has been used to disperse the polymer and the ceramic particles. The optimized screen-printable dielectric ink has a solid loading of 40%. To prepare the silver nanowires (AgNWs) based conductive ink, we have synthesized AgNWs in our lab using the polyol reduction process. The synthesized AgNWs are then dispersed into a polymer solution (polyvinylpyrrolidone in a solvent mixture of propylene glycol and ethanol with a weight ratio of 4:1) to form a screen-printable ink, as shown in Fig.1 (b). The solid loading of the AgNWs ink is about 10%. The AgNWs ink can provide a high electrical conductivity of about ~1.0×10^6 S/m, as well as mechanical flexibility to maintain its electrical performance under various deformations, such as bending and folding.

To print the substrate and the conductive traces, a semi-automatic printer AUREL 900PA, as shown in Fig. 2, is employed. For printing, a calculated amount of the appropriate ink, i.e. either dielectric or the conductive, is dropped along the side and spread over the patterned screen with the help of a squeegee, as explained in Fig. 3. The inks are transferred to the substrate through the patterned screen under pressure. This fabrication process is fairly straightforward and can be optimized for large-scale, high-volume manufacturing. For large area R2R printing, an industrial scale printer can be employed for mass manufacturing after the optimization of the inks and the printing processes at the laboratory scale.

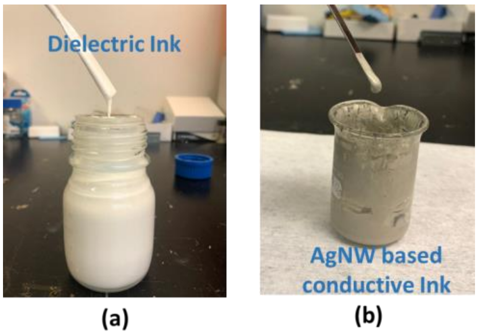

Fig. 1. Screen printable (a) dielectric ink and (b) AgNW based conductive ink

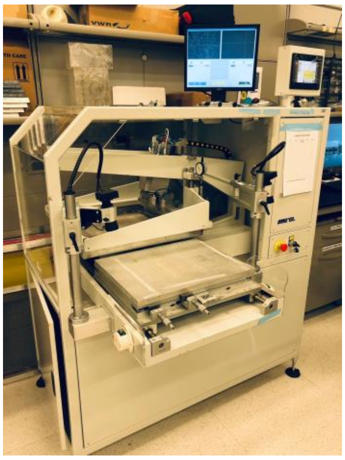

Fig. 2. AUREL screen-printer 900PA

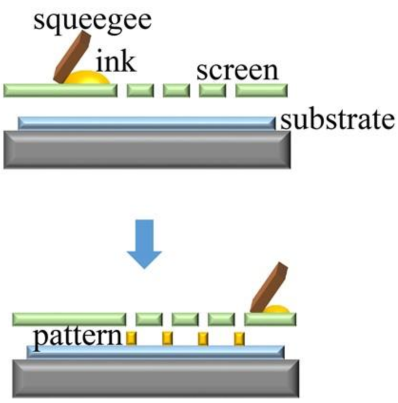

Fig. 3. The standard screen printing process

B. *Design of stacked patch antenna for mm-wave*

For demonstrating the multilayer structure through the fully screen-printed process, a multi-layer stacked patch antenna with 4-parasitic patches at the superstrate layer is considered. It consists of two screen-printed dielectric layers and three-patterned metal (AgNW) layers. The basic antenna configuration is shown in Fig. 4. Since the antenna's metallic and dielectric layers are completely embedded, an additional microstrip-line section (3λ/4) is added to provide the impedance matching and sufficient space for clamping the microstrip edge-launch connector, as shown in Fig. 4 (b).

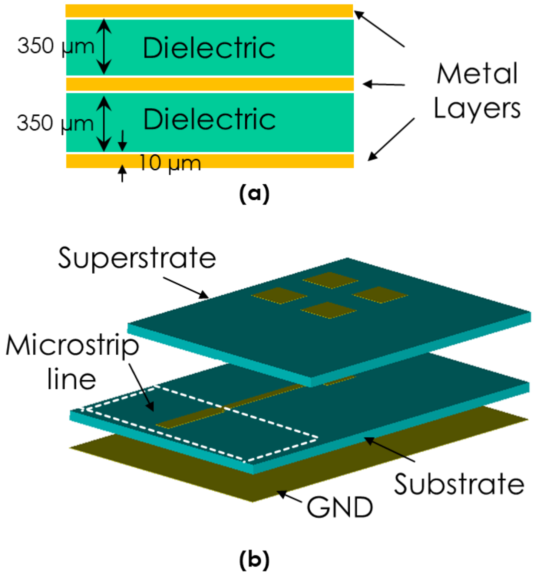

Fig. 4. (a) Antenna stack-up (b) exploded view of antenna layers.

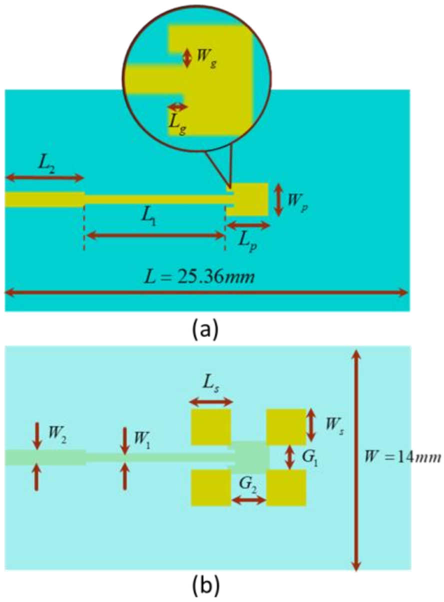

Fig. 5. Detailed design description of the antenna (a) driven patch layer, and (b) superstrate top layer.

TABLE I. ANTENNA DESIGN PARAMETERS (IN MM)

L_1	L_2	L_p	L_s	L_g	W_1	W_2	W_s	W_g	W_p	G_1	G_2
8.77	5.16	2.642	2.471	0.525	0.56	1.0	2.226	0.2	2.113	1.542	2.24

The printed ABS dielectric layers are modeled in the 3D EM simulator with a permittivity ε_r=3.0 and loss tangent tanδ=0.0065 at 28 GHz. The properties of the dielectric substrate are estimated via an independent cavity-based measurement [11]. The AgNW metal layers are modeled as a thin metal sheet with conductivity σ =1.0×10^6 S/m. The detailed antenna structure is shown in Fig. 5 with the design parameters summarized in Table-I. Electromagnetic (EM) simulations have been performed in CST Microwave studio. The simulated reflection coefficient of the antenna is shown in Fig. 6. The simulated -10 dB bandwidth is found to be 6.88 GHz (24%) with center frequency at 28 GHz. The simulated radiation pattern shows 7.65 dBi and 7.45 dBi of realized gain at 25.6 GHz and 30.9 GHz respectively as shown in Fig. 7.

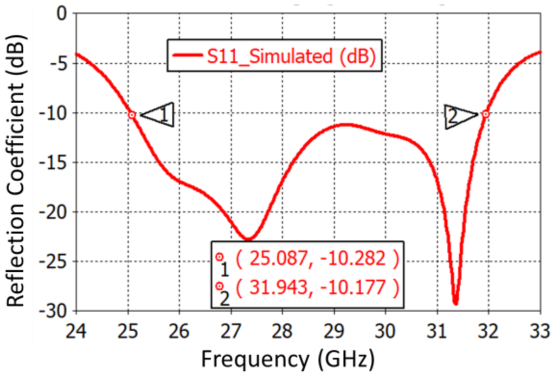

Fig. 6. Simulated reflection coefficient of the antenna

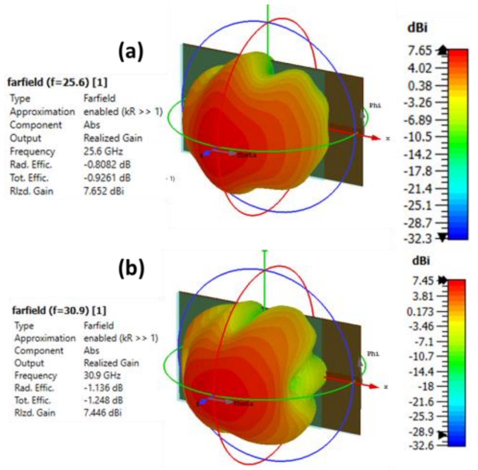

Fig. 7. The simulated 3D radiation pattern of the antenna at (a) 25.6 GHz and, (b) 30.9 GHz.

C. Fabrication process

The antenna is realized through a complete screen-printing process employing the commercial screen-printer. First, the dielectric substrate is fabricated by screen-printing of the dielectric ink [11]. Total 35 printing cycles are performed to obtain the required thickness of 350 µm as one printed layer is approximately 10 µm. Infrared light has been used to dry each layer within 10 seconds. Next, a custom Ag NWs ink has been used to print the metallic traces of the antenna. Then, another dielectric substrate has been printed on top of the metallic pattern, following the same procedures of the printing of the bottom dielectric. Finally, four patches over the superstrate are printed through AgNW conductive inks. Fig. 8 shows the step-by-step fabrication process and the printed layers at each stage. After printing, the fabricated antenna is heated at 110°C in an oven for 10 min. The optical microscope images displayed in Fig. 9 show a clear edge of the printed antenna where Ag NWs patterns can be observed.

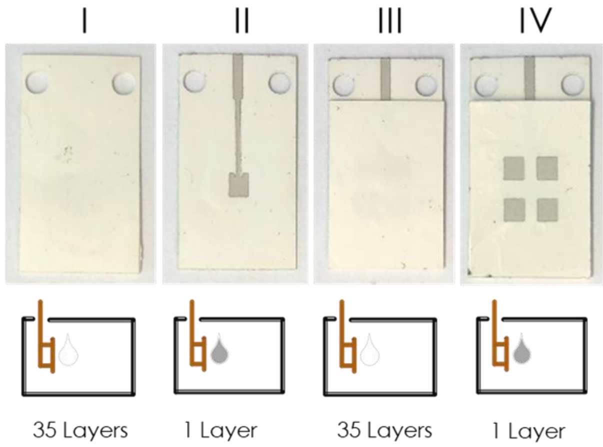

Fig. 8. Fabrication steps for the antenna design.

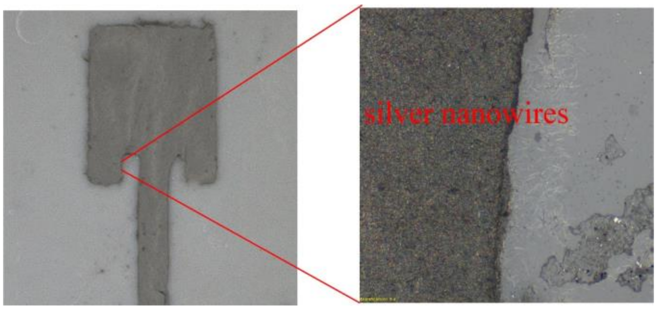

Fig. 9. Microscopic images of the fabricated driven patch using the screen printing.

III. MEASURED PERFORMANCE

Following the fabrication, an edge mount 2.92 mm standard coaxial launcher is integrated with the antenna. The measurement setup consists of a vector network analyzer and associated cables and assemblies, as shown in Fig. 10. The fabricated antenna is measured in various bending conditions and associated reflection coefficients are plotted against the simulated reflection coefficient in Fig. 10. Generally, the antenna is well matched from 26.5 GHz to 30 GHz. The deviation in simulated and measured results are due to the following three reasons i.e. unavoidable air gap between the sandwiched layers, the non-uniform thickness of the printed substrate, alignment of superstrate patches with the driven patch, and the tolerances in fabricated antenna dimensions. A post-simulation is performed for the fabricated prototype with the exact fabricated dimensions and compared with the measured result in Fig. 12. It shows a better match of simulated and measured results, however, the printing process needs to be further optimized.

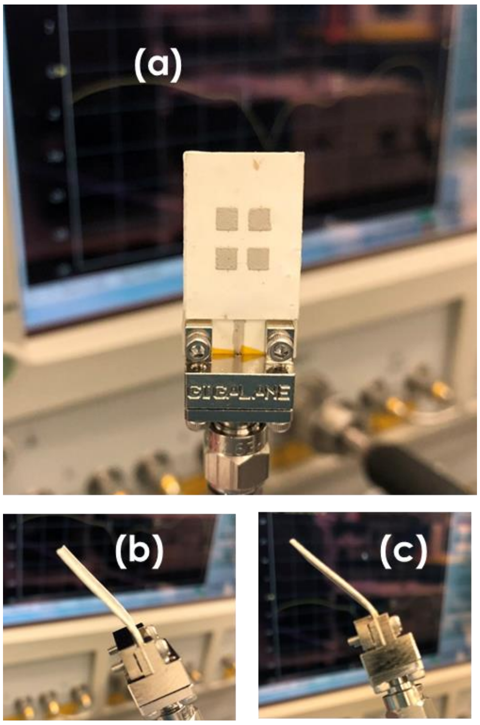

Fig. 10. Measurement setup (a) flat, (b) low bending i.e. Bend_1 and (c) moderate bending i.e. Bend_2 condition.

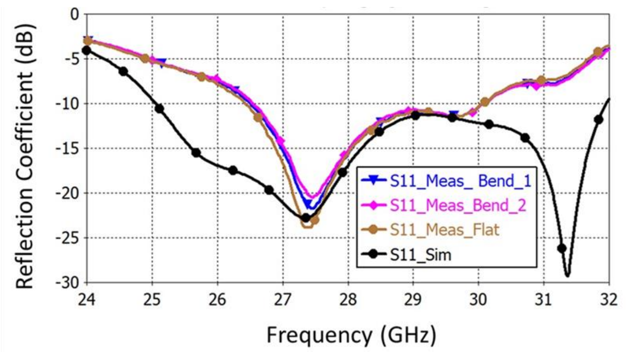

Fig. 11. Measured reflection coefficient for flat and various bending conditions plotted against simulated reflection coefficient in a flat condition.

The fabricated antenna is also characterized for its radiation performance in a high-frequency anechoic chamber, as shown in Fig. 13. A Ka-band standard gain horn antenna is used as a reference antenna to calibrate the chamber from 26.5 to 33 GHz. The measured 2D radiation pattern shown in Fig. 14 shows a broadside radiation pattern in H-plane. The measured HPBW's are 61o and 58o in E-and H-plane respectively and approximated directivity is found to be 9.6 dBi [12]. The measured gain at 27.8 GHz is found to be 7.8 dBi which is pretty close to the simulation result. So the total antenna efficiency is 1.8 dB.

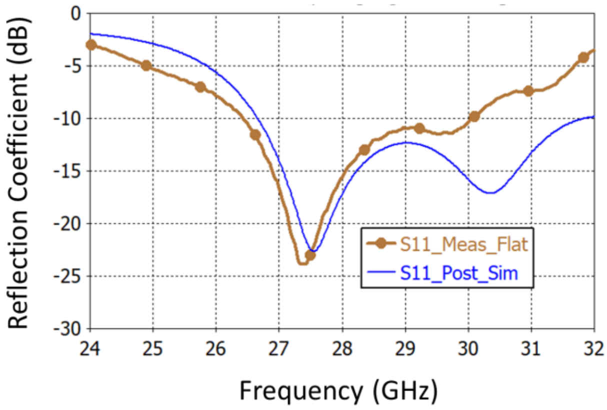

Fig. 12. Comparison of measured and post-simulation reflection coefficients.

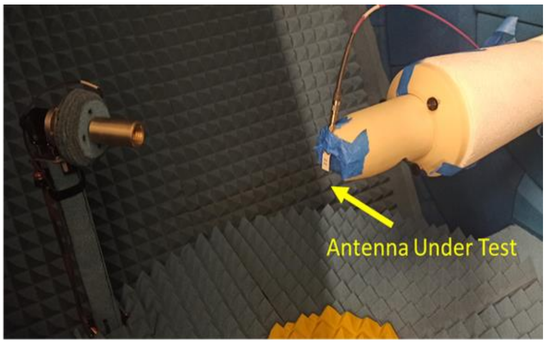

Fig. 13. Antenna radiation pattern measurement setup.

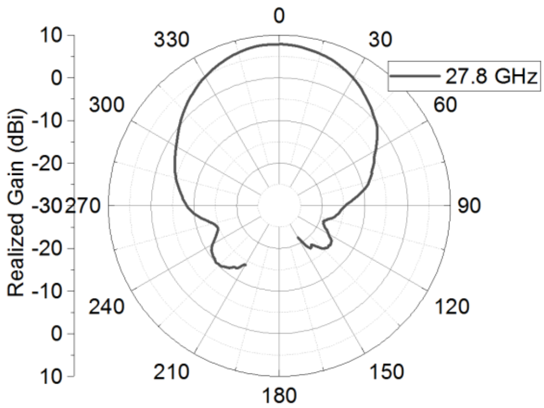

Fig. 14. Measured radiation pattern at 27.8 GHz.

Conclusion

In this paper, we successfully demonstrated a multilayer fully screen-printed antenna operating in mm-wave frequencies fabricated with custom dielectric inks as well as an AgNWs metallic ink. The developed inks and the fully-printing processes make them suitable for the mass production of electronics devices, including IoT devices and mm-wave antennas. The initial measured results of the fully-printed antenna are encouraging, despite minor deviation from the simulations results. Fabrication challenges such as non-uniform thickness and substrate homogeneity as multiple layers are printed intermittently over and over for achieving sufficient dielectric layer thickness. Further optimization in the printing process is required in the future to print dielectric layers with uniform thickness and substrate homogeneity.

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