3D-Printed Low-Profile X-Band Tunable Phase Shifter

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***Abstract*— A novel 3D printed X-band tunable phase shifter is presented in this paper. By using the low temperature (140 °C) additively manufactured (AM) method, a multilayer conductive structure within a single dielectric substrate is realized by simultaneously jetting both dielectric and conductive inks. Taking advantage of this inkjet printing technology, a tunable phase shifter operating at X - band is proposed and designed. Within 90° continuous phase tuning range, a low insertion loss variation can be achieved with very compact size 0.22 × 0.12 × 0.1 (λ_g^3). To verify proposed design concept, a prototype parallel strip line tunable phase shifter working at 9 GHz is designed, fabricated, and measured, where the measurement results agree well with EM simulations and design theory.**

***Keywords* — 3D inkjet printing, additively manufactured electronics (AME), X - band tunable phase shifter, transmission line, microwave circuits.**

I. Introduction

With emerging 5G and coming NextG wireless communication technology, phase array antenna system [1]-[4] is playing essential role to support high data rate, wide coverage with multiple user accesses, and large channel capacity in applications of radar [5], communication, IoT, and autonomous driving etc. The direction of wireless link is configured by magnitude and phase control of signal radiated by massive antenna element in phased array, where the phase control is realized by tunable phase shifter.

In the past decades, a variety of phase shifters have been studied and designed at different frequencies to achieve large phase shifting range with low insertion loss variation. As in Fig. 1 (a), most designs focus on low frequency where the maximum phase tuning range 360° can be realized with reasonable insertion loss. For example, a coupler-based reflection-type phase shifters have been presented in [6], and a reconfigurable phase shifter have been designed in [7] for base - station antenna. Different transmission line circuit topologies have been investigated in [8] - [9] to realize tunable phase shifters. From the summary plot in Fig. 1 (a), it is found that the transmission loss is increasing when the frequency moves up so as the phase tuning range is also getting smaller. To be more specific, at X-band, many different tunable phase shifters have been investigated using substrate integrated waveguide (SIW), CMOS, MMIC, and RF superconducting quantum interference devices (SQUID), and their performance (transmission loss vs phase shifting range) is summarized in Fig. 1 (b). All these efforts are trying to achieve 360° progress phase tuning range for full phase array scanning angle, which

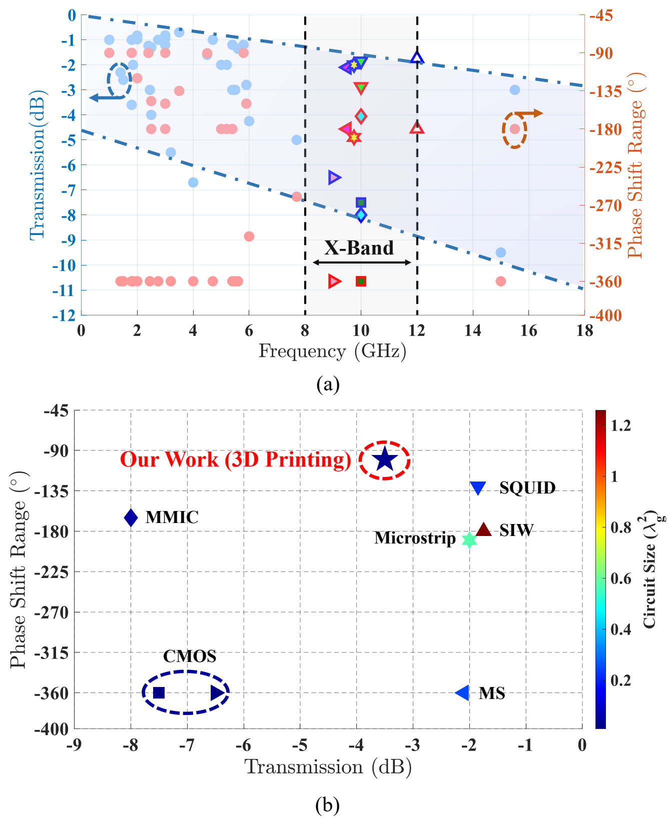

Fig. 1 Summary of tunable phase shifters in the past decade. (a) Compare of magnitude and phase response (b) Evaluation of X -band tunable phase shifter including transmission, phase shift and circuit size (λ_g^2).

results in significant signal transmission loss. In recent, a novel matrix based phased array [10] is presented to achieve full scanning angle using tunable phase shifters with only 90° phase tuning range, which highly releases the loss effect of large phase tuning range.

From fabrication perspective, additive manufacturing electronic (AME) features advantages in fast prototyping, lower cost, and freedom of full customized 3D implementation, which may overset the manufacturing value chain in industry 4.0 and become an alternative method beyond the traditional fabrication methodology. Up to now, various type of RF devices and components such as transmission lines [11], filters [12], antennas, and arrays [13] - [15] are printed using different printing technologies. Most of these techniques are printing entire structure with a single material either metal or dielectric. In recent, a new 3D printing technology [16] is

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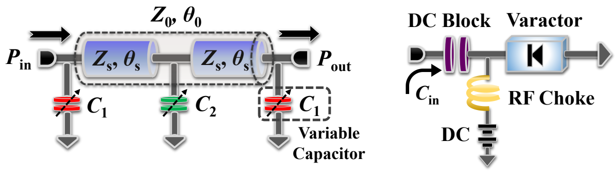
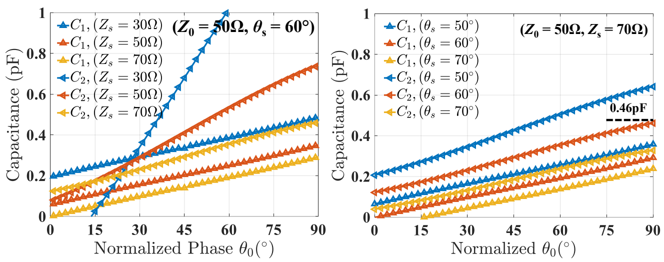


(a) (b)

Fig. 2 Schematic diagram: (a) Proposed tunable phase shifter (b) Equivalent circuit module of variable capacitor.



(a) (b)

Fig. 3 Capacitance range analysis based on required phase shift at 9 GHz ($Z_0 = 50\Omega$, $\theta_0 = 0° \sim 90°$): (a) Fixed $\theta_s = 60°$ (b) Fixed $Z_s = 70\Omega$.

developed to enable printing conductor and dielectric simultaneously.

Leveraging both small phase tuning phased array and advanced 3D printing technology, in this paper, a tunable phase shifter using novel 3D inkjet-printing technology is presented to provide an alternative solution for high performance X-band phase shifter implementation, which can be applied for X-band phased array design. The paper is organized as: section II explains the design theory of proposed tunable phase shifter and novel 3D printing process. Section III provides the experimental validation of proposed design, and the conclusion is given in section V.

II. Prepare Your Paper Before Styling

A. Design Theory of Proposed X-Band Tunable Phase Shifter

The schematic diagram of proposed tunable phase shifter is shown in Fig. 2 (a), where it consists of two identical transmission lines and three shunt variable capacitors at the input port (P_{in}), center, and output port (P_{out}), respectively. The characteristic impedance and electrical length of transmission lines are denoted as Z_s and θ_s. The detail of shunt variable capacitors is given in Fig. 2 (b), where it is composed of varactor, a DC block, and a RF choke. By tuning DC control voltage, the capacitance of varactor (C_{in}) can be tuned such that phase delay from Pin to Pout can be manipulated. In specific, the desired capacitance C_1 and C_2 can be derived in form of Z_0, θ_0, Z_s, and θ_s using ABCD-matrix analysis in [17] - [18]:

$$C_1 = \frac{Z_s \cdot (\cos 2\theta_s - \cos\theta_0) + \cot\theta_s (Z_0 \cdot \sin\theta_0 - Z_s \cdot \sin 2\theta_s)}{\omega \cdot Z_0 \cdot Z_s \cdot \sin\theta_0} \quad (1)$$

$$C_2 = \frac{Z_s \cdot \sin 2\theta_s - Z_0 \cdot \sin\theta_0}{\omega \cdot Z_s^2 \cdot \sin^2\theta_s} \quad (2)$$

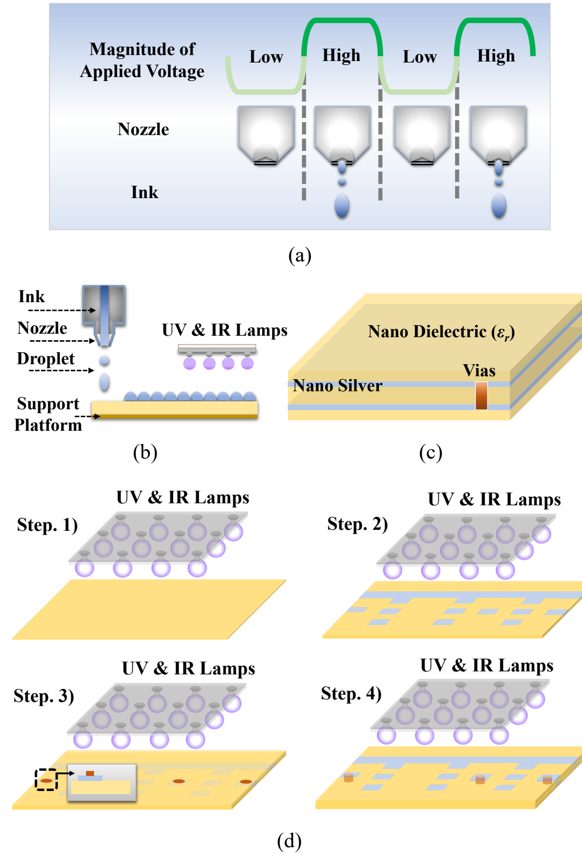


Fig. 4 Inkjet printing technology with fully integrated AME system: (a) Working diagram of piezoelectric inkjet (b) Fully integrated dielectric and conductive inks (Nano particle of dielectric and silver) (c) Material stack-up (d) Flow chart of circuit fabrication process.

Based on equations (1) and (2), the graphic analysis for Z_s and θ_s is shown in Fig. 3 for optimal capacitance tuning range of C_1 and C_2, where phase shifting θ_0 versus individual capacitances (C_1 and C_2) for various Z_s and θ_s are studied at fixed operating frequency $f_0 = 9$ GHz. With $Z_0 = 50\Omega$ and phase tuning range $\theta_0 = 0° \sim 90°$, there are multiple solutions for Z_s and θ_s. In specific, Fig. 3 (a) shows tuning range of C_1 and C_2 to realize 90° phase tuning with different impedance: $Z_s = 30\Omega$, 50Ω, and 70Ω (assume $\theta_s = 60°$ here), and Fig. 3 (b) explains the capacitance tuning range with fixed $Z_s = 70\Omega$. From Fig. 3, the range of required capacitance tuning is about 0.46pF, and varactor MA46H120 with capacitance range 0.18 ~ 1.17pF is applied in our design. Here, DC block and RF choke are designed carefully to realize low insertion loss and required phase tuning range.

B. 3D Printing Proposed Tunable Phase Shifter

The proposed tunable phase shifter is fabricated using additive manufacturing electronic technology (AME), where multi-layer circuit is seamlessly printed in a single substrate. In this printing process, conductive and dielectric layers are printed simultaneously. The conductive ink (AgCite[TM] nano-silver) and dielectric ink (acrylate: $\varepsilon_r = 2.75$, $\tan\delta = 0.02$) are prepared by tightly controlling particle sizes with great stability for precise printing.

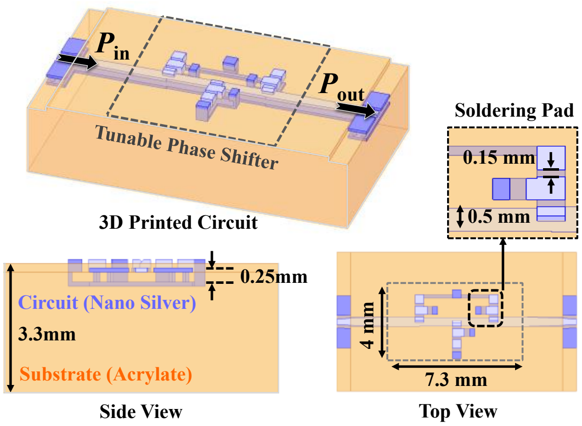


Fig. 5 Layout model of proposed 3D printed X-band tunable phase shifter, and the circuit volume occupation is 4 × 7.3 × 3.3mm^3.

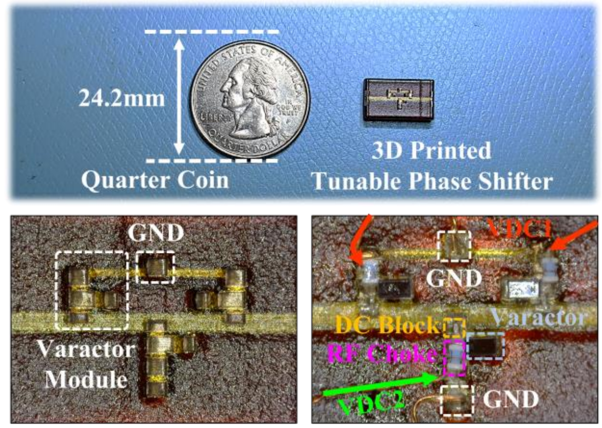
The printing setup and process are shown in Fig. 4, where piezoelectric based nozzles with deposition of liquid ink is applied. A control voltage generates pressure pulse in the fluid to force a droplet of ink from the nozzle as shown in Fig. 4 (a), and the ink will be pressed from the nozzles when the magnitude of applied voltage raised over a threshold voltage. Fig. 4 (b) and (c) show the printing process and substrate stack-up, where an ultraviolet (UV) lamp or an infrared radiation (IR) lamp is used for curing the nanoparticles after the dielectric or metal inks are ejected out from the nozzles. Fig. 4 (d) depicts the fabrication steps for proposed 3D printing circuit:

1) Step 1: the bottom dielectric layer is printed as a support platform.
2) Step 2: the designed circuit, including the conductor and dielectric, is built on top of the bottom dielectric with designed thickness of each printing slice.
3) Step 3: a layer consisting of dielectric layer and conductor vias is built on, in which the vias link the top and bottom layer for grounding.
4) Step 4: another circuit layer is printed in both conductor and dielectric inks.

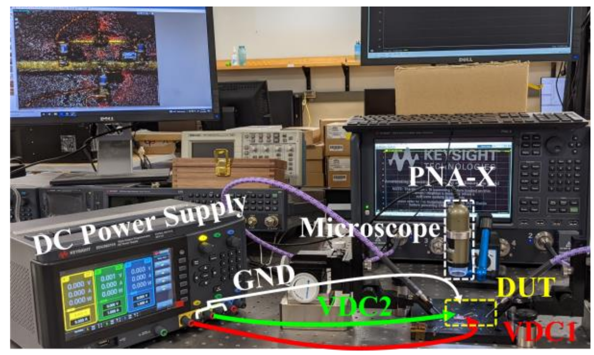
This fully integrated printing solution shows advantages in printing a complex 3D structure seamlessly consisting of both dielectric and conductive materials, including multi-layer RF circuits with high performance.

III. Experimental Results and Analysis

The proposed tunable phase shifter is designed using parallel strip line at 9 GHz, and the corresponding 3D model is shown in Fig. 5. The size of design is 4 × 7.3 × 3.3 mm^3, and GSG pads are added for experimental validation. The parallel strip lines are printing and covered by dielectric material except the lumped component footprint and GSG pads. To be specific, the width of transmission line is about 0.5mm, while the distance between signal and reference lines is 0.25mm. Nano Dimension's DragonFly LDM system is applied to print proposed tunable phase shifter, and the printed prototype including varactors (MACOM), DC blocks (Murata), and RF chokes (CoilCraft) is shown in Fig. 6 (a). Testing setup for proposed tunable phase shifter is shown in Fig. 6 (b), where the circuit is connected to PNA - X through GSG probe. Here the varactors are controlled by two - channel digital DC power supply.



(a)



(b)

Fig. 6 Fabrication and testing of the proposed 3D printed tunable phase shifter: (a) The prototype compared to the size of a quarter coin (Diameter = 24.2mm) and the zoom-in view with details (b) Measurement setup.

The measured experimental results are shown in Fig. 7. Specifically, the magnitude and phase responses are plotted by varying the DC control voltage. In Fig. 7 (a), the insertion loss is better than 4 dB with variation of 1.75 dB around 9 GHz. The return loss shown in Fig. 7 (b) is better than 12 dB. With the selected combinations of VDC1 and VDC2, more than 90° phase shifting is measured as in Fig. 7 (c). Fig. 7 (d) compares the simulated and measured insertion loss variation across the phase delay. The dash line with green dots is envelope of optimal insertion loss when phase is tuning. Within 90° phase tuning, the simulated insertion loss achieves 1.3 dB variation at working frequency. In the measurement, the variation of the insertion loss is around 1.75 dB. The slight difference is from fabrication tolerance and components soldering etc.

IV. Conclusion

In this paper, for the first time, a X-band tunable phase shifter is printed using 3D additive manufacturing (AM) technology. By controlling varactors, the proposed phase shifter can realize 90° continuous phase tuning. The design theory and printing process has been discussed. The measurement results agree well with simulation results, which verifies the design theory and proves that the 3D printing can

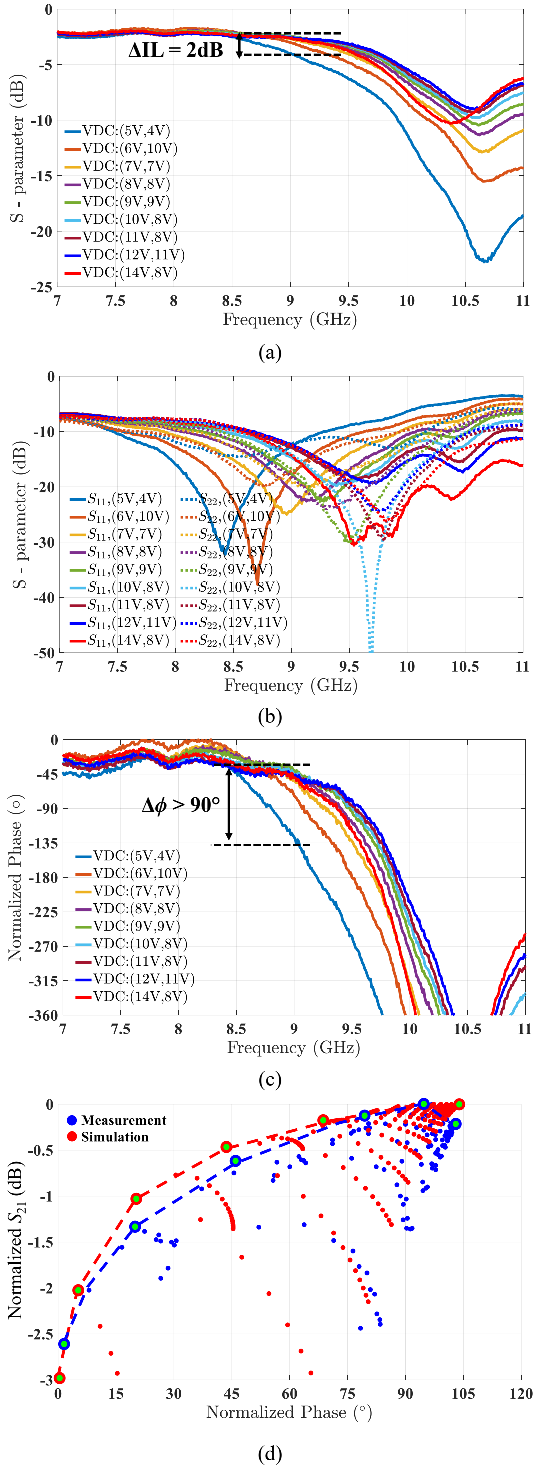


Fig. 7 Measurement results of 3D printed tunable phase shifter by varying DC bias: (a) Insertion loss (b) Return loss (c) Phase difference (d) Variation of insertion loss with the phase tuning range.

be alternative manufacturing process to design high performance RF/microwave circuits. In our future work, the comprehensive phased array system will be proposed and designed using 3D printing technology.

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