Polarization-Reconfigurable Patch Antenna-on-Package for Millimeter-Wave Operations with DC Bias Circuit Design

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***Abstract*—The proposed polarization-reconfigurable antenna is designed for implementation on IC packaging. For verification, we used Rogers RO4003C boards which closely resembles the material of PCB with packaging. Our prototype swaps out the switchable PIN diode with copper strip and is measured using a styrofoam rotation platform. With DC block and RF choke present in the design, the measurement results show that the design achieves 3-dB axial ratio with sub-−6 dB reflection coefficient at 30 GHz.**

***Index Terms*—polarization-reconfigurable antennas, polarization-agile antennas, patch antennas, 5G antennas, dc bias circuits.**

I. INTRODUCTION

In the world where 5G communication is rapidly developing, implementing antenna design on integrated circuit (IC) packaging has become a prominent technique to reduce the need for additional transmission lines and printed circuit board (PCB) area, and thus lowers cost, enhances compactness, and increases reliability [1], [2]. The versatility of printed patch antennas provides an easy way to integrate the design into such solid-state devices [1]. Combined with polarization reconfigurability, these antenna designs are more compact and lead to simpler and cheaper wireless systems [3].

Since stackup PCBs consist of multiple copper layers, we can use an additional copper layer on top of the packaging molding compound as the patch antenna and choose two copper layers in the substrate for ground and feeding circuit. In an example of an actual stackup PCB, one layer of molding compound ($\varepsilon_r = 3.65$, $\tan\delta = 0.01$) is on top of the substrate, which can be broken down into a mask ($\varepsilon_r = 3.7$, $\tan\delta = 0.031$) on the top, several layers of prepregs and a core ($\varepsilon_r = 3.48$, $\tan\delta = 0.003$) alternating with copper sheets. To verify the design method before using PCBs with molding compound, which requires a more complex fabrication process, we use a single-layer thick (32-mil) and double-layer thin (8-mil) Rogers RO4003C ($\varepsilon_r = 3.55$, $\tan\delta = 0.0027$) boards glued with 2-mil FR4-like substance ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$), as shown in Fig. 1, to imitate the PCB material in terms of permittivity as well as loss tangent.

II. PROPOSED ANTENNA

With a main operating frequency at 28 GHz, our proposed antenna-on-package (AoP) uses similar working mechanisms as our previous stub-loaded patch antenna [4] with a redesign of the feeding method as well as the DC bias circuitry to work with multi-layered boards at millimeter wavelengths.

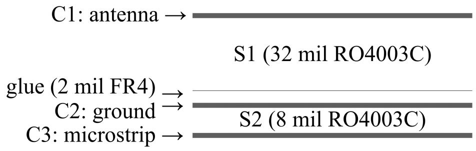


Fig. 1. Structure of PCB for proposed design (not to scale).

The proposed polarization-agile antenna, shown in Fig. 2, has a square ground size of 25 mm × 25 mm. The top layer, C1, consists only of the square patch antenna and its switchable stubs, which are implemented with 2 PIN diodes connected to 2 vias through S1 as depicted in Fig. 3a. A clean top design avoids unnecessary coupling and interference. In ANSYS HFSS, where all simulations in this paper were carried out, we used M/A-COM's MA4AGBLP912 PIN diodes, with one pointing towards the patch and one towards one via, allowing the polarizations to be controlled simply with a voltage inverse from a single DC source. The PIN diode is modeled as a 0.5 nH inductor in series with a 10 kΩ resistor when off and a 0.1 Ω resistor in parallel with a 0.022 pF capacitor when on as in Fig. 4.

In this design, we hoped to achieve all feeding from the backside of the antenna. Since the DC voltage feeds from C3 to C1 through the second layer, C2, to control the PIN diodes, the rectangular 2.5-mil narrow gap in Fig. 3b serves as DC isolation in C2, so that the area outside the rectangle functions as a common ground for both DC and RF. Additionally, there is a hole in C2 for the coaxial feed of the antenna.

The circuitry on the bottom layer, C3, does all of the DC and RF feeding as shown in Fig. 3c and 3d respectively. The voltage source is applied to the DC feed pad, which goes through an RF choke before connecting through a via in S2 to the isolated rectangle in C2. The ground of the DC source is connected to the ground pad, which is shorted to the common ground. In case of undesirable matching after fabrication, additional grounded plates are present along the microstrip feedline for soldering lumped elements on for tuning. There is also a high-pass filter functioning as a DC block before the

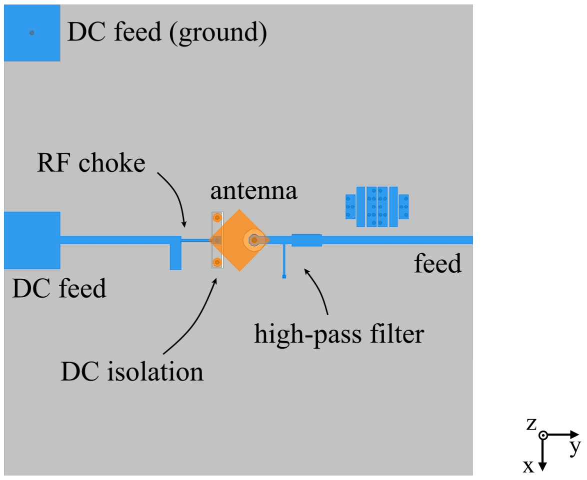
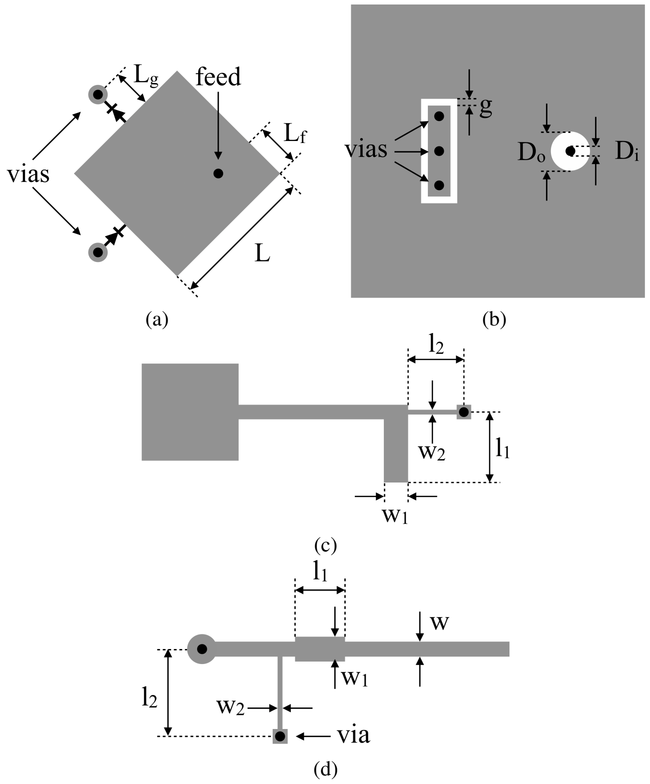


Fig. 2. Top viewed diagram of proposed antenna layout (C1: orange; C2: gray; C3: blue).



(a) (b)

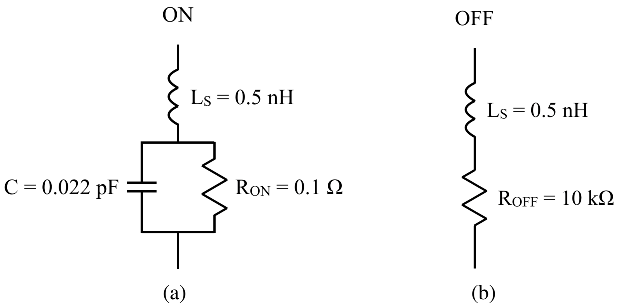
(c)

(d)

Fig. 3. Dimensions of proposed design of layer (a) C1, (b) C2, (c) C3 DC feed, and (d) C3 RF feed ($L = 2.32$ mm, $L_g = 0.5$ mm, $L_f = 0.6$ mm, $D_i = 248$ um, $D_o = 1190$ um, $g = 2.5$ mil, $w_1 = 600$ um, $l_1 = 1577$ um, $w_2 = 100$ um, $l_2 = 1907$ um, $w = 425$ um) (not to scale).

microstrip transitions to a coaxial feed through S2, a hole in C2, and S1 to the antenna.

Our proposed polarization-agile antenna exhibits axial ratio (AR) level of $\leq$ 3 dB between 27.6 GHz and 28.8 GHz, antenna efficiency of 59% and realized circular polarization gain of 3.21 dBic for right-hand circular polarization (RHCP) case at 28 GHz in simulation. The radiation patterns are shown in Fig. 5.



(a) (b)

Fig. 4. PIN diode model for (a) ON and (b) OFF.

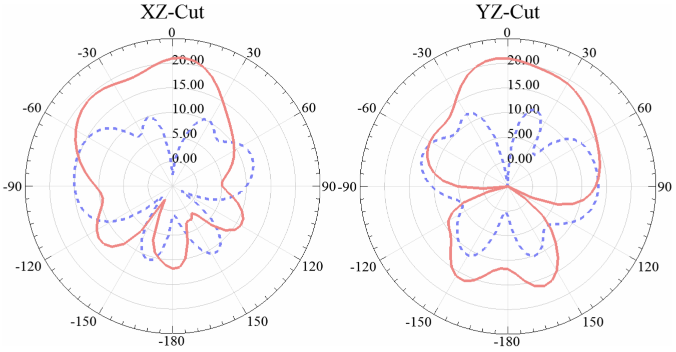


Fig. 5. Simulated results of radiation pattern at 28 GHz (solid: RHCP, dashed: LHCP) for proposed antenna.

III. RESULTS & ERROR ANALYSIS FOR PROTOTYPE MEASUREMENT

For a preliminary verification of the design, we fabricated the proposed antenna with a copper strip replacing the ON diode while removing the OFF diode and adding coplanar waveguide pads for Southwest Microwave's end launch connector for measurement, as shown in Fig. 6. Mounting our prototype antenna and ATH26G40 standard horn antenna 80 cm from each other on a homemade styrofoam rotation platform as pictured in Fig. 7, we measured the reception levels of both horizontal and vertical polarizations using Agilent's E8361A Network Analyzer. To acquire the levels of RHCP, left-hand circular polarization (LHCP), and AR, we import the results to MATLAB with the calculations in [5].

Due to the removal of the PIN diodes, the center frequency for our prototype antenna shifts to around 30 GHz with an increased simulated antenna efficiency of 76%. As shown in Fig. 8, the measured S parameters and AR trend fit those of simulation especially near 30 GHz.

Considering the relative instability of the styrofoam platform, we expect slight difference between simulation and measurement. Currently, we are working on designing a sturdier rotation platform. Also, the screws of the end launch connector might not be sufficient for grounding the coplanar waveguide. We anticipate that the deviation of measurement from simulation results will decrease with more suitable equipment and the prototype will achieve better performance with proper grounding.

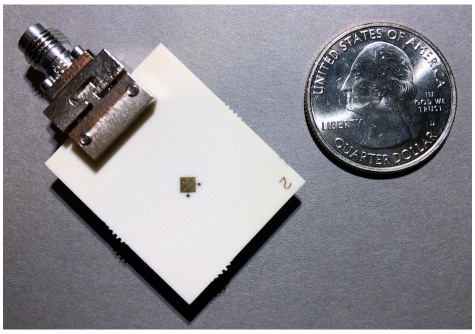
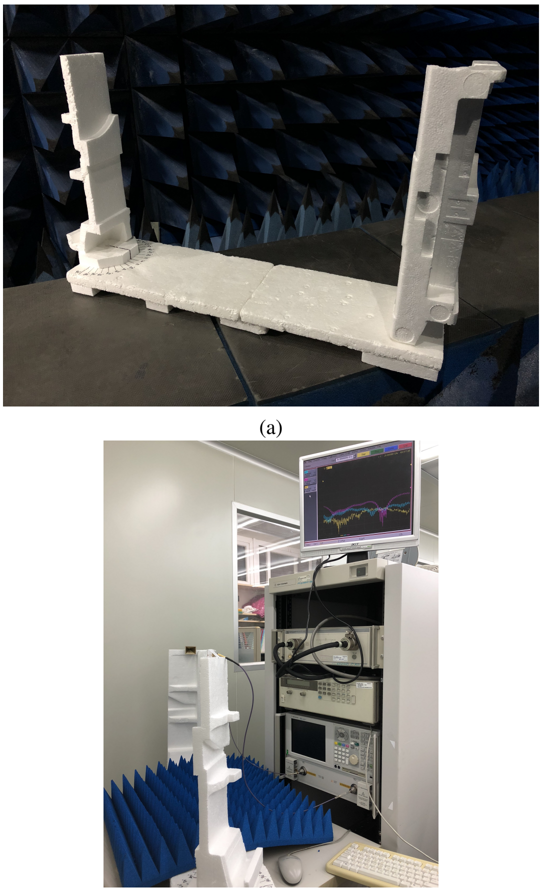


Fig. 6. Picture of antenna prototype with end launch connector.



(a)

(b)

Fig. 7. Pictures of (a) styrofoam rotating platform and (b) measuring environment.

IV. FUTURE WORK

Apart from minimizing the technical errors mentioned in the last section, we can see from Fig. 8 that there is potential for the antenna to be dual-band. The mechanism is yet unknown, but it will be studied and hopefully the design can function as not only a reconfigurable AoP, but also a dual-band one.

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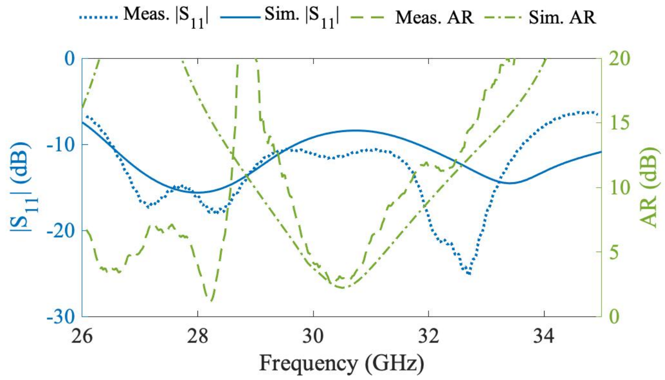

Fig. 8. Measured and simulated AR and $|S_{11}|$ of prototype antenna.