A Novel Phase Shifter Based on Reconfigurable Defected Microstrip Structure (RDMS) for Beam-Steering Antennas

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***Abstract*—A low cost phase shifter based on a cascaded reconfigurable defected microstrip structure (RDMS) is proposed. This RDMS unit is produced by etching a slot to introduce a defect on a microstrip line and then PIN diodes are inserted in the defected area. By switching the PIN diodes, the RDMS unit is able to operate in two different states with a phase shift of 17° at 5.2 GHz. The RDMS units can be cascaded for higher phase shift values that may be determined by array design requirements. Phase shifters cascading three and six RDMS units were designed, fabricated, and measured. The measured results show that the two phase shifters introduce 45° and 90° phase shifts, respectively, with low insertion loss. Finally, a four element patch array is proposed with a beamforming network employing the phase shifters and Wilkinson power dividers. The array is able to switch its main beam direction to 0° and ±20° in the H plane and the impedance bandwidth covers the overlapping wireless local area network (WLAN) bands in the vicinity of 5.2 GHz.**

I. Introduction

Phase shifters are critical components in phased array and beam steering antenna designs. In recent years, novel phase shifters have been proposed based on defected ground structures (DGS) [1], which was originally used in filter, coupler, and oscillator designs. The DGS was employed as a termination load in [2] which increased the phase shift range by 80° compared with the structure using a conventional load. A DGS based 45° phase shifter was proposed in [3], which increased the bandwidth and reduced the size comparing to the structure without a DGS. In [4], thin-film copper membranes were placed in a ground plane. By actuating these membranes, the space between the transmission line and the ground plane was changed, which resulted in a phase shift. In [5], the membranes were replaced by flexible micro-ribbons and significantly lowered the biasing voltage. In [6], the metallized polydimethylsiloxane (PDMS) elastomeric ground plane was selected to reconfigure the air-gap spacing which resulted in reduced cost. However, these phase shifter designs based on DGS or ground plane reconfiguration still suffer from high complexity and cost, which limits their applications in beamforming and phased array designs.

Here we propose phase shifters that based on the defected microstrip structure (DMS) [7] [8] which is the dual structure of DGS. Fig. 1 shows the layout of the proposed DMS unit.

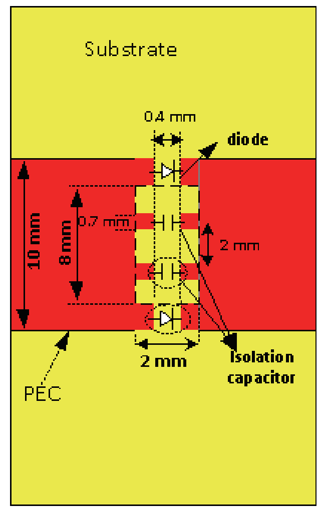


Fig. 1. Geometry of the RDMS unit.

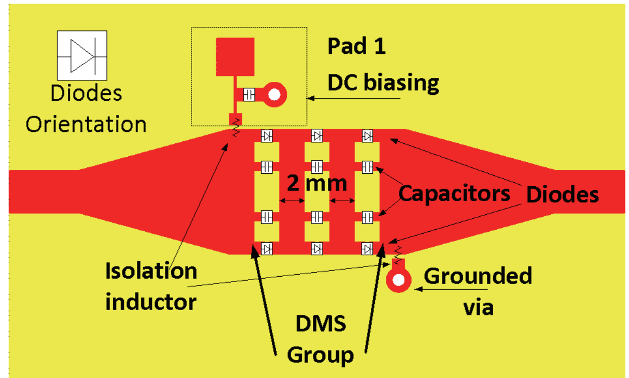
The DMS unit is made by etching a slot in a microstrip line printed on a Rogers4003 substrate with the dielectric constant of 3.55 and substrate thickness of 1.524 mm. By inserting controllable PIN diodes into the defected area, the DMS unit is endowed with structural reconfiguration and can be turned into a reconfigurable DMS (RDMS). By turning the diodes "on" and "off", a phase shift is introduced. This is due to the current path flowing across the RDMS unit has been changed. Specifically, the surface current on a microstrip line is concentrated at the edges. As a consequence, the etched slot on the microstrip line has little effect on the current flow concentrating at the edges when the diodes are "on". When the diodes are "off", the diodes behave as an open circuit and the current mainly flows across the capacitors, which results in current path change and introduces phase shift. The dimensions of the RDMS unit are optimized by considering both the insertion loss and phase shift together. With the dimensions shown in Fig. 1, an RDMS unit is able to introduce a phase shift of 17° with 0.8 dB insertion loss at 5.2 GHz. When the RDMS units are cascaded, the insertion losses increase slightly, but the phase shift value is significantly increased, almost linearly with the number of the RDMS units cascaded. Using this approach, phase shifters with variable and significant phase shifts can be obtained for different requirements. The phase shifter design using this method has advantages of low cost, easy to control, easy to integrate, and low insertion losses, which makes it suitable for low cost phased array feed network.

II. Phase Shifter Based on Cascaded RDMS Units

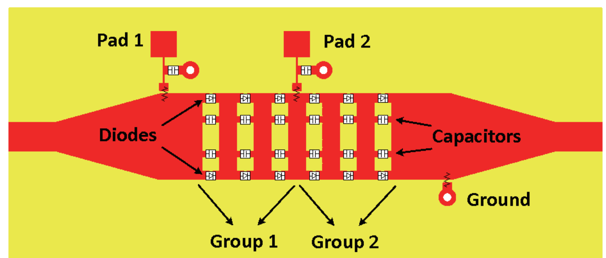
Figs. 2(a) and 2(b) show the phase shifters made by cascading three and six RDMS units, respectively. They are designated as 3-RDMS phase shifter and 6-RDMS phase shifter for simplicity. The phase shifters are composed of cascaded RDMS units for phase shift, tapered microstrip lines for impedance match, and DC bias networks to control the diodes. The 3-RDMS phase shifter has one DC bias network, which allows the phase shifter to work in two states when positive or negative DC voltages are applied on the pad. The two working states of the 3-RDMS phase shifter are defined as "All-on" and "All-off" states when all the diodes of the RDMS units are turned "on" and "off", respectively. For the 6-RDMS phase shifter, two DC bias networks are employed, with each bias network controlling 3 RDMS units. The 6 RDMS units are divided into two RDMS groups as depicted in Fig. 2(b). By applying different DC voltages on the bias pads, the 6-RDMS phase shifter is able to work in 4 possible states when the two RDMS groups are all "on", "on" and "off", "off" and "on", and all "off", respectively. The 4 states are defined as "All-on", "On-off", "Off-on", and "All-off" states. In addition, the "On-off" and "Off-on" states are expected to have the same performance since the configurations of the phase shifter in these two states are symmetric.

The phase shifters were not only simulated but they were also fabricated and measured. Fig. 3 shows the two fabricated phase shifter prototypes. To assess the performance, the insertion loss and phase shift were measured as shown in Figs. 4 and 5. The phase shifts shown in Figs. 4(b) and 5(b) are given by Phase (other states) – Phase (All-on state). The All-on state phase is used as a reference and not presented in the figures. As shown in Figs. 4 and 5, the simulated results agree well with the measured ones. For the 3-RDMS phase shifter, the measured insertion losses of the two states are below 1 dB for a phase shift of 45° at 5.2 GHz. For the 6-RDMS phase shifter, the measured insertion losses are $<$1.8 dB in all the four states. With reference to the phase of the "All-on" state, the measured phase shifts of the "On-off", "Off-on", and "All-off" states are 45°, 45°, and 90°, respectively, at 5.2 GHz.

The proposed 3-RDMS and 6-RDMS phase shifters are suitable for the antenna array design as described in the next section. In addition, there is greater flexibility to obtain different phase shift values and the step sizes for the proposed phase shifters. Various phase shifts are able to be achieved by tuning the dimensions of the RDMS units or by controlling the quantity of the RDMS units cascaded. As well the step-size of the phase shifters is mainly determined by the phase shift of a single RDMS unit and the number of the RDMS units biased simultaneously.



(a)



(b)

Fig. 2. Layout of the (a) 3-RDMS phase shifter and (b) 6-RDMS phase shifter.

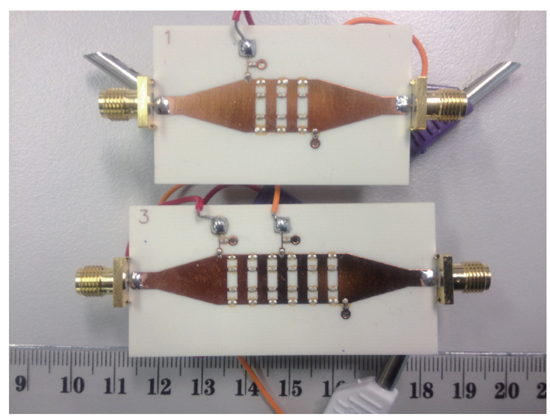
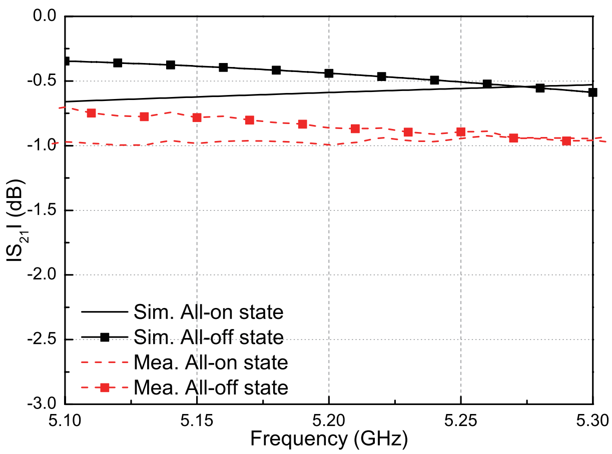


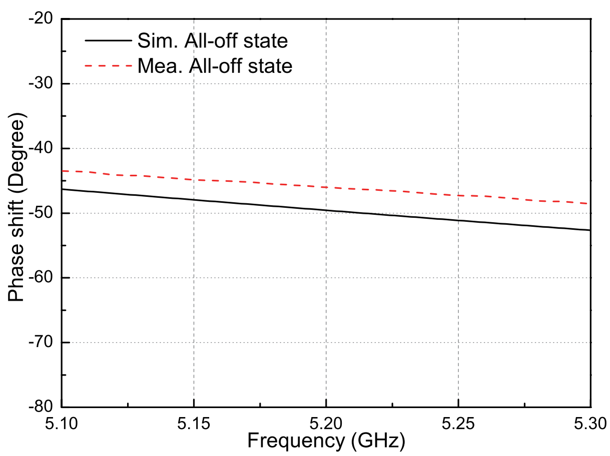
Fig. 3. The phase shifter prototypes.

III. Antenna Array Design

Based on the aforementioned phase shifters, a 4-element patch antenna array for beam steering was designed for the 5.2 GHz WLAN band. The beamforming network of the



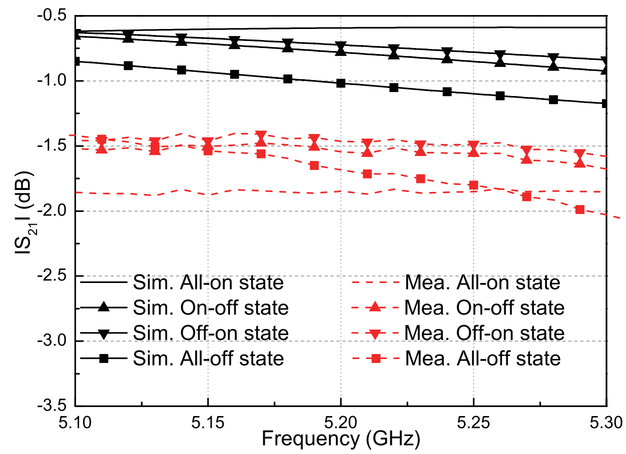
(a)



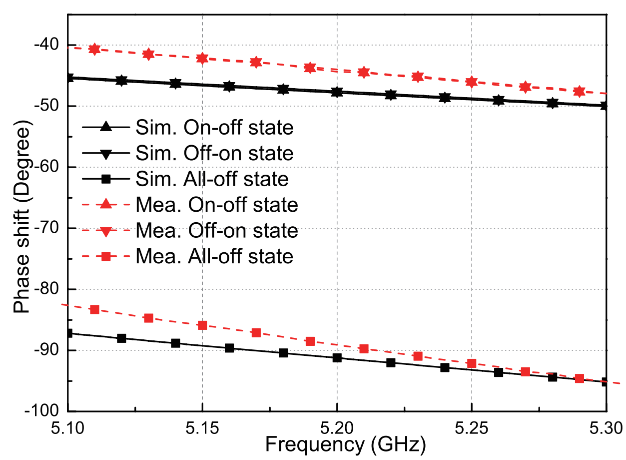
(b)

Fig. 4. Simulated and measured (a) insertion loss and (b) phase shift of the 3 RDMS phase shifter.

phased array consists of three Wilkinson power dividers, two 6-RDMS, and four 3-RDMS phase shifters. The prototype of the antenna array is shown in Fig. 6. With only two DC bias voltages V_1 and V_2 labeled in Fig. 6, the antenna array is able to operate in 4 states. When V_1 and V_2 are all positive or all negative, the two states are defined as “All-on” and “All-off” states, respectively. For these two states, all the phase shifters employed in the array work in the same state, which results in uniform phase excitations of the antenna elements. This leads to a boresight beam direction in the H plane (Z-Y plane). When V_1 is positive and V_2 is negative, the working state is defined as “Left-on-right-off” state with the phase shifters working at different states and results in $45°$ phase advances compared to that of the adjacent elements on the right. Therefore, the main lobe is shifted to $\theta = -20°$ in the H plane. When V_1 is negative and V_2 is positive, the state is defined as “Left-off-right-on” state with $45°$ phase delays



(a)



(b)

Fig. 5. Simulated and measured (a) insertion loss and (b) phase shift of the 6 RDMS phase shifter.

between the adjacent patches. As a consequence, the main lobe in the H plane is shifted to $\theta = 20°$.

Computed results for the reflection coefficient (S_{11}) and the far-field pattern in H plane for the four states are given in Figs. 7(a) and 7(b), respectively. As shown in Fig. 7(a), the overlapping impedance bandwidth for the four states covers the 5.2 GHz WLAN band (e.g. 5.15-5.35 GHz in the USA, 5.15-5.25 GHz in Japan, and 5.15-5.35 GHz in Europe). It is observed from Fig. 7(b) that the main beam of the antenna array is able to be switched in the H plane between $0°$ and $\pm 20°$ by employing only two DC voltage levels. The maximum realized gain is 10 dB and the gain variation between the four states is below 1 dB. In addition, the maximum sidelobe level is less than -8.5 dB below the peak.

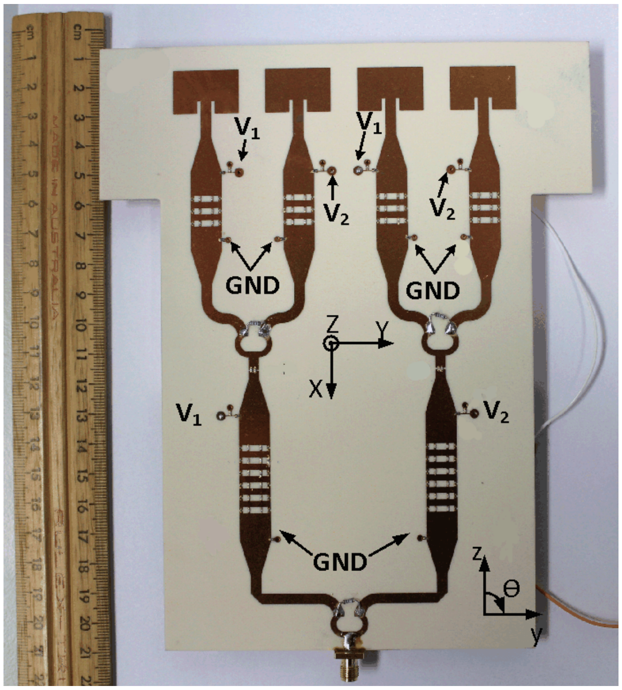
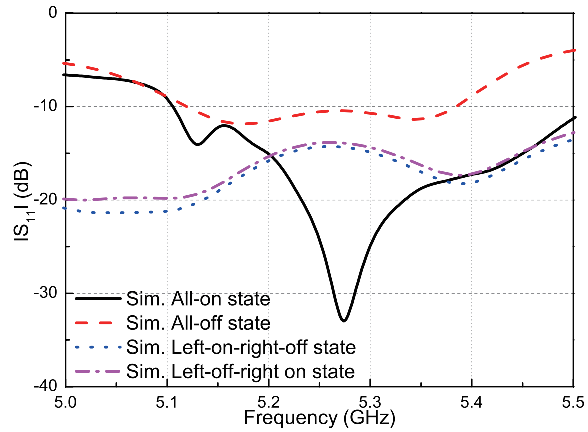


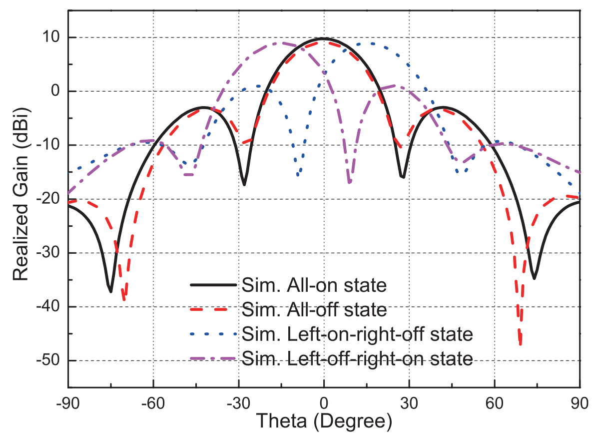
Fig. 6. The antenna array prototype.

IV. CONCLUSIONS

An RDMS unit has been described for low cost phase shifting applications. The RDMS is able to realize a phase shift of 17° by controlling the working states of the PIN diodes. By cascading the RDMS units, the phase shift value increases quasi-linearly with the unit quantity. Phase shifters made by cascading three and six RDMS units were obtained with phase shifts of 45° and 90°, respectively, and these were used in an antenna array beamforming network. Employing the phase shifters and typical Wilkinson power dividers, a 4-element phased array antenna was built. A beam steering characteristic of the antenna array was observed from the simulated results, demonstrating the practicability of the phase shift method based on the RDMS. The RDMS offers a low cost and low complexity phase shifting solution that is suitable for low cost beamforming and phased array antennas.



(a)



(b)

Fig. 7. Simulated (a) reflection coefficient and (b) far-field pattern of the antenna array in the four states.

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