2021 2nd International Conference on Robotics,Electrical and Signal Processing Techniques (ICREST)

2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST) | 978-0-7381-3042-2/20/$31.00 ©2021 IEEE | DOI: 10.1109/ICREST51555.2021.9331208

18.7 GHz 4-Bit PIN Diode Reflection Type Phase Shifter for Radiometer Phased Array Antenna

Kim Tuyen Trinh
Department of ECSE
Monash University
Clayton, Victoria 3800, Australia
kim.trinh@monash.edu

Jiewei Feng
Department of ECSE
Monash University
Clayton, Victoria 3800, Australia
jiewei.feng1@monash.edu

Nemai Chandra Karmakar
Department of ECSE
Monash University
Clayton, Victoria 3800, Australia
nemai.karmakar@monash.edu

***Abstract*—A design of 18.7 GHz PIN diode Reflection Type Phase Shifter (RTPS) for Ku-band soil moisture radiometer phased array antenna is presented. The compact reflective loads are designed using PIN diodes to control phase shifts. The PIN diodes are MACOM's MA4FCP200. The designs sequence is to start with modelling PIN diode equivalent circuits at 18.7 GHz. Then a quadrature hybrid coupler and PIN diode reflective loads are designed. A PIN diode in forward and reverse states is considered as lumped components when designing the reflective loads. This approach offers more freedom when designing loads with high accuracy. The phase shifter is fabricated directly on the same Taconic TLX8 laminate with the feed network, this allows producing a monolithic phased array and reduces the cost of the whole system significantly. The simulated results show that the 4-bit phase shifter can yield 4.7 dB insertion loss (IL) and the input and output return losses (RL) are higher than 15 dB at 18.7 GHz. The phase resolution is 22.5° with the root mean square (RMS) phase error of about 1°. The measured results of the prototypes of $180^{\circ}$and 90° bits show a good agreement between simulation and measurement. The size of the phase shifter is quite compact, just about 2.8 cm x 0.6 cm.**

Keywords*— *PIN diode, hybrid coupler, Ku-band, reflection type phase shifter.

I. Introduction

Phase shifter finds its applications in phased array antennas and many communication systems. There have been a variety of phase shifter topologies reported recently in literature such as switched type [1-3], reflection type [4, 5], vector sum type [6, 7]. All the phase shifters mentioned above are fabricated on chips. To integrate phase shifters into a beamforming network, wire bonding technique is usually adopted, which is a challenging task.

This paper presents a 4-bit PIN diode RTPS operating at 18.7 GHz, which is the design frequency of the proposed soil moisture radiometer, fabricated directly on the Taconic TLX8 microwave laminate with the feed network. This approach is very promising since it eliminates the need for performing interconnections between phase shifters and other components. As a result, the cost of the whole antenna system is reduced significantly. The PIN diodes MACOM's MA4FCP200 are used to construct the reflective loads. We characterize the PIN diode, create the equivalent circuits, and then use the PIN diode as lumped components to design the loads. The prototypes of $180^{\circ}$and 90° bits are fabricated. The measured results of the two bits agree well with the simulated results. The outcomes of this work are: (i) very low IL; (ii) low cost (iii) facilitation of integrating phase shifters into the beamforming network.

This work has been supported by the Australian Research Council (ARC) under the Grant DP160104233: Passive airborne radiometer for high resolution soil moisture monitoring.

II. Phase Shifter Configuration

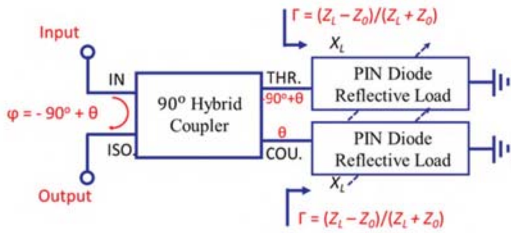

Fig. 1. Configuration of a single bit in the proposed phase shifter.

Figure 1 illustrates the schematic of a single bit PIN diode phase shifter. Here, each bit contains a hybrid quadrature coupler terminated by two identical reflective loads. Theoretically, a coupler is a 4-port device that has one input, two outputs, and one isolation port. The signals at outputs, through and couple ports, have the same amplitude but they are quadrature in phase. There is no signal at an isolation port. However, when the through and couple ports are terminated with reflective loads, the signal goes out at the isolation. Assuming the coupler and the loads are lossless, the signal at the output is delayed with the phase of φ.

$$\varphi = -90^{\circ} + \theta \quad (1)$$

Where θ is the phase of reflection coefficient Γ at the through and couple ports. If θ_f and θ_r are the phase of Γ in forward bias and reverse bias states respectively, the resultant phase shift between the two states is:

$$\Delta\varphi = \theta_f - \theta_r \quad (2)$$

As shown in (2), the phase shift in a single bit is independent of the coupler. Therefore, changing the reflective load impedance only results in the desired phase shift.

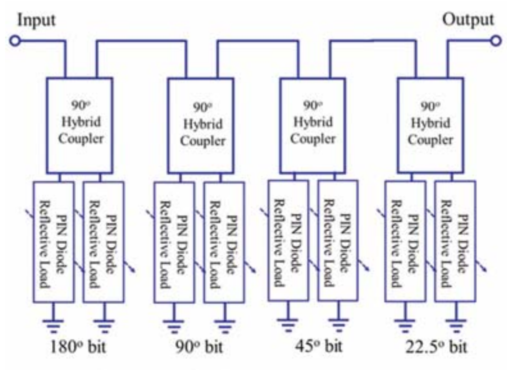

Fig. 2. Complete circuit of the 4-bit Ku-band PIN diode RTPS.

Technically, there are many possible solutions for designing the bits. However, the experiments with switched lines, loaded lines topologies show that they are quite sensitive with process variations. In contrast, the design using a branch-line coupler and reflective loads is very robust. After designing 4 individual bits successfully, the complete arrangement of the 4-bit RTPS is shown in Figure 2.

III. Design of Quadrature Hybrid Coupler

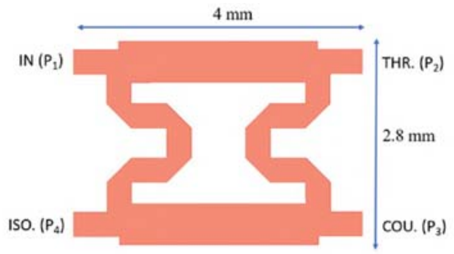

Fig. 3. Layout of 90-degree hybrid coupler.

The coupler is a branch-line type. As mentioned above, the phase shifters are fabricated directly on the same laminate with the feed network of the Ku-band antenna. The layout of 90^o coupler is shown in Figure 3. Port 1 (P_1) is the input; port 2 (P_2) is the through port; port 3 (P_3) is the couple port, and port 4 (P_4) is the isolation port. To reduce the coupler size, the 50 Ω branches are drawn as meander lines. The designed coupler area is 11.2 mm^2 while a normal coupler area is 16 mm^2. Thus, the area reduction is 30%.

IV. Design of Reflection Loads

A. PIN diode characteristics

A PIN diode is known as a current-controlled device. Figure 4 demonstrates the simplified equivalent circuits of a MACOM's MA4FCP200 PIN diode. A PIN diode in a forward bias mode works as an inductor in series with a resistor. On the other hand, in a reverse mode, it behaves like a capacitor in series with a resistor. Ideally, the forward resistance R_F and reverse capacitance C_R should be very small.

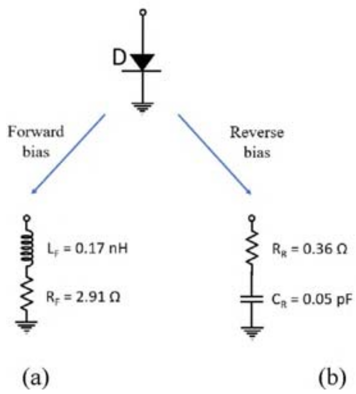

Fig. 4. Simplified equivalent circuits of PIN diode in (a) forward bias and (b) reverse bias.

In this design, the commercial MACOM's MA4FCP200 PIN diodes is a silicon flip-chip type operating up to 40 GHz. By characterizing the PIN diode at 18.7 GHz with bias voltages at 10 V (10 mA)/-10 V for forward and reverse states respectively, the component values in the equivalent circuits are obtained. These circuit models are used to design the reflective loads for phase shifters.

B. Reflection loads

Assuming that the coupler is well designed, the phase shift of an individual bit depends on the phase shift of the reflective loads. Ideally, the loads contain only capacitance and inductance. However, as shown in Figure 4, the resistance exists in the PIN diode equivalent circuits. In terms of loss, the insertion loss of a single bit is the sum of coupler loss and load loss. The parasitic resistance is the contributing loss factor. The resistance in the forward and reverse bias states are different; consequently, the insertion loss variation occurs among 16 phase states. In more details, the IL and IL difference is larger with the larger phase shift bit. For example, in 180^o bit, the IL and IL mismatch in forward and reverse states are largest compared to those of other bits.

The phase response of reflective loads is subject to inductive and capacitive components only. To simplify the calculations, the resistance is not considered. The approach is that the PIN diodes are considered as lumped components and construct the schematic of the loads corresponding to desired phase shifts. Since load schematics are different between 180^obit and others, the load designs are presented in two following groups.

1) For 180^o bit

Figure 5 demonstrates the schematic of 180^oPIN diode reflective load in forward and reverse bias states. To construct the load, the capacitor (C_{P1}) is placed in parallel with the diode. In forward bias state, the load is equivalent to an inductor, this causes a phase delay. In contrast, when the PIN diode is reverse biased, the load is a capacitor, this leads to a phase lead.

In the forward bias state:

$$Z_{FB} = \frac{j\omega L_F}{1 - \omega^2 L_F C_{P1}} \tag{3}$$

$$\Gamma_{FB} = \frac{Z_{FB} - Z_0}{Z_{FB} + Z_0} \tag{4}$$

Where, Z_{FB} is the load impedance and Γ_{FB} is the reflection coefficient in the forward bias state.

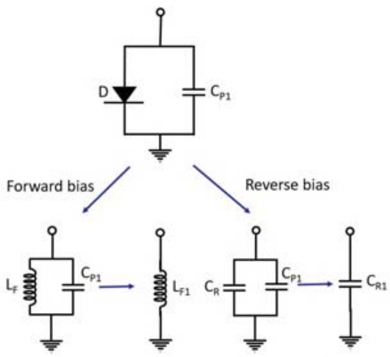

Fig. 5. Schematic of 180^o PIN diode reflective load.

In the reverse bias state:

$$Z_{RB} = \frac{1}{j\omega(C_R + C_{P1})} \tag{5}$$

$$\Gamma_{RB} = \frac{Z_{RB} - Z_0}{Z_{RB} + Z_0} \tag{6}$$

Where, Z_{RB} is the load impedance and Γ_{RB} is the reflection coefficient in the forward bias state.

The resultant phase shift is:

$$\theta_{180} = \angle\Gamma_{FB} - \angle\Gamma_{RB} \tag{7}$$

With L_F = 0.17 nH and C_R = 0.05 pF from the PIN diode model, to obtain 180° phase shift, C_{P1} = 22 fF is the capacitance needed for this load.

2) For 90°, 45°, and 22.5° bits

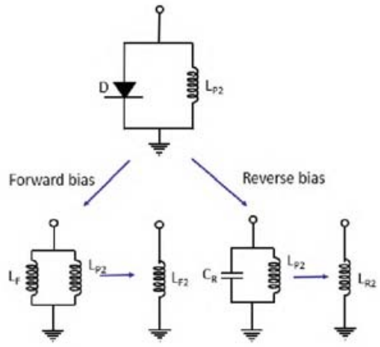

Fig. 6. Schematic of 90° (45°, and 22.5°) PIN diode reflective loads.

For the case of 90°, 45°, and 22.5° PIN diode reflective loads, an inductor is added in parallel with the PIN diode as shown in Figure 6. As can be seen, in the both forward and reverse bias modes, the load acts like an inductor, which causes phase delays with different angles. As a result, the phase shifts are obtained. The values of Z_{FB}, Γ_{FB}, Z_{FB}, and Γ_{FB} are computed as follows.

When the diode is in a forward bias state:

$$Z_{FB} = j\omega\frac{L_F L_{P2}}{L_F + L_{P2}} \tag{8}$$

$$\Gamma_{FB} = \frac{Z_{FB} - Z_0}{Z_{FB} + Z_0} \tag{9}$$

In case of a reverse bias state:

$$Z_{RB} = \frac{j\omega L_{P2}}{1 - \omega^2 L_{P2} C_R} \tag{10}$$

$$\Gamma_{RB} = \frac{Z_{RB} - Z_0}{Z_{RB} + Z_0} \tag{11}$$

Finally, the phase shift is calculated as:

$$\theta_{90\ or\ 45\ or\ 22.5} = \angle\Gamma_{FB} - \angle\Gamma_{RB} \tag{12}$$

Inserting the values of L_F = 0.17 nH, C_R = 0.05 pF, for the loads of 90°, 45°, and 22.5°, the values of the inductor L_{P2} are found as 0.510 nH, 0.255 nH, and 0.153 nH respectively.

V. Phase Shifter Design and Fabrication

A. Design of 180° bit circuit

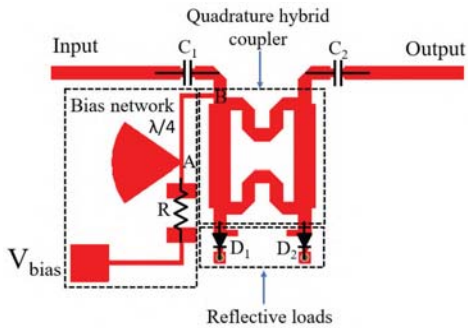

Fig. 7. Complete design of 180° bit.

Figure 7 illustrates the complete design of 180° bit circuit. The circuit comprises one coupler, two identical reflective loads, one bias network, and other parts for connecting to two SMA ports for the use of measurement. The bias network is designed to bias both PIN diodes. In this design, the radial stub is used in conjunction with one quarter-wave impedance transformer and a current limiting resistor R. The radial stub offers low impedance at point A of the quarter-wave impedance transformer, consequently, at point B the high impedance occurs. Therefore, RF/MW signal cannot leak into the DC source while setting the DC bias point of PIN diode in forward and reverse states. The capacitors $C_1 = C_2 = 47$ pF works as DC blocking. D_1 and D_2 are PIN diodes. As calculated, the parallel capacitance (C_{P1}= 22 fF) is very small. Hence, it is realized by a small open stub.

B. Design of 90°, 45°, and 22.5° bit circuits

The complete designs of 90°(45°,22.5°) bits are shown in Figure 8. The details are quite similar to the case of 180°bit. The different part is that each load consists of one PIN diode in parallel with an inductor. The inductor L_{P2} is realized by a microstrip line. To obtain the different inductance for 90°, 45°, 22.5°loads, the lines are selected with different lengths. The capacitors $C_3 = C_4 = 47$ pF act like for DC blocking.

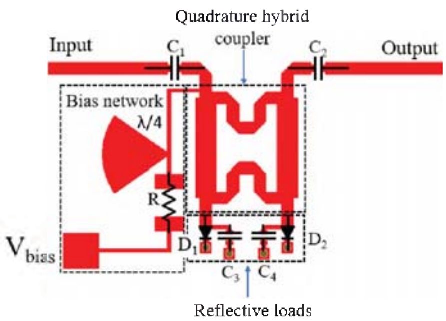

Fig. 8. Complete design of 90°(45°, 22.5°) bits.

C. Circuit fabrication

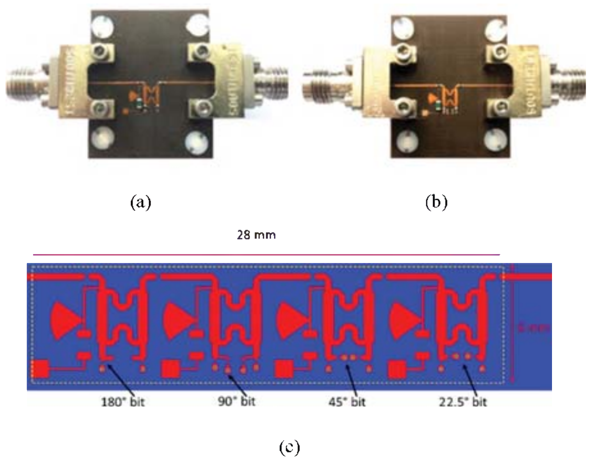

Fig. 9. Individual bit prototypes of (a) 180°, (b) 90°, and 4-bit phase shifter (c).

As stated above, all the individual bit circuits and the phase shifter are designed, simulated, and fabricated on Taconic TLX8 laminate. After computing all the values of components and other parameters, the individual bits and phase shifter circuits are drawn and simulated by ADS 2017 Momentum.

Figure 9 shows the photographs of 180° and 90° bit prototypes and the phase shifter layout. For the ease of measuring the circuits, the input and output microstrip lines of the prototypes are made long enough to accommodate two Southwest SMA End Launch Connectors. The phase shifter size, excluding the connector area, is 28 mm x 6 mm. The designed phase shifter is compact for integrating into the same microwave laminate of the beamforming network.

VI. Results and Discussion

This section presents the EM simulated results on ADS 2017 Momentum software and measured results using Agilent E8361A PNA at Monash University.

A. Individual bits

1) 22.5° bit

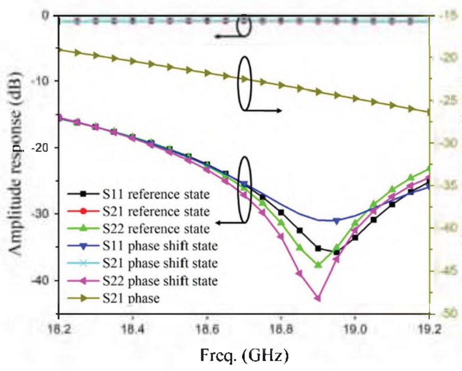

Fig. 10. EM simulated results of 22.5° bit.

The layout of the 22.5° bit is quite similar to the one shown in Figure 8. Only one difference is that the transmission lines connecting with the capacitors C_3 and C_4 are shorter. The EM simulated results are shown in Figure 10. The results show that this bit can achieve the IL of 1 dB in both reference and phase shift states. The RLs are larger than 25 dB at 18.7 GHz. The insertion phase is about 22.5° at center frequency 18.7 GHz.

2) 45° bit

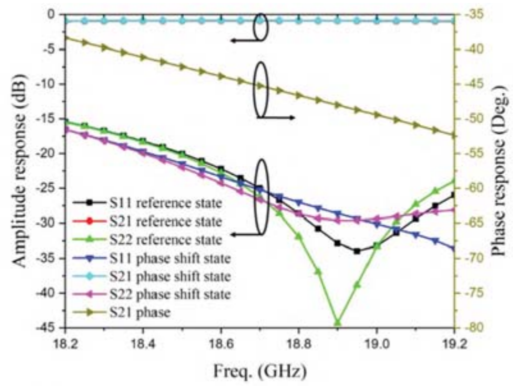

Fig. 11. EM simulated results of 45° bit.

The layout of 45° bit is quite similar to 22.5° bit as shown in Figure 8. The transmission lines connecting with the capacitors C_3 and C_4 are longer than those in 22.5° bit. Figure 11 demonstrates the EM simulated results of 45° bit. The ILs are about 1.2 dB in both reference and phase shift states. The RLs are larger than 15 dB within 18.2-19.2 GHz bandwidth. The phase shift is approximately 45° at 18.7 GHz.

3) 90° bit

Figure 8 illustrates the layout of 90° bit. The photograph 90° bit prototype is shown in Figure 9(b). The simulated results of the 90° bit are shown in Figure 12. As can be seen, the amplitude response shows that the ILs are less than 2 dB in both reference and phase shifter states. The amplitude mismatch between the two states is almost zero. The values of RL are larger than 20 dB at 18.7 GHz. The phase shift is almost 90° at 18.7 GHz.

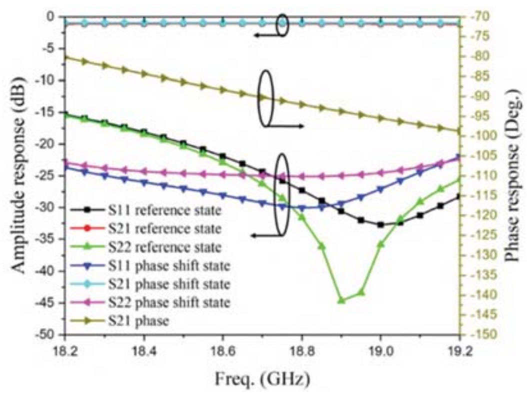

Fig. 12. EM simulated results of 90° bit.

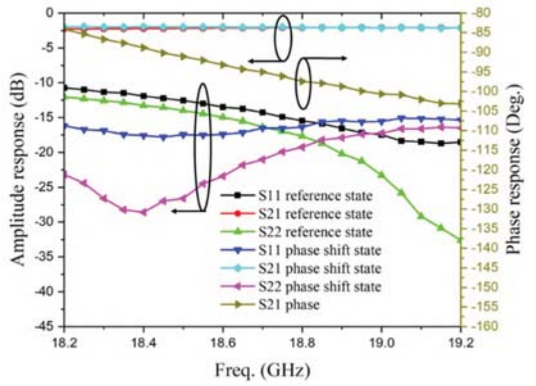

Fig. 13. Measured results of 90° bit.

To validate the design theory, the 90° bit circuit was fabricated. The measured performance of the bit is demonstrated in Figure 13. The measured results include the loss of SMA connectors. In terms of amplitude, the ILs are less than 2.4 dB in both reference and phase shift states within 18.2-19.2 GHz. The amplitude imbalance between the two states is negligible. The RLs are larger than 10 dB within 18.2-19.2 GHz. The phase response shows that the phase shift is 95° at 18.7 GHz. The measured results reveal that the bit achieved very good performance.

4) 180° bit

For the case of 180° bit, as shown in Figure 14, the ILs are less than 2.5 dB in both reference and phase shift states. However, the amplitude mismatch occurs. The IL of the reference state is about 2 dB while the IL of phase shift state is about 1 dB. The RLs are larger than 15 dB within 18.2-19.2 GHz. The phase shift is almost 180° at 18.7 GHz.

The photograph 180° bit prototype is shown in Figure 9 (a). The measured results of 180° bit prototype, which include the loss of SMA connectors, are shown in Figure 15. The ILs are approximately 3 dB and 2 dB in the reference and phase shift states respectively. The amplitude imbalance is about 1 dB. The RLs at input and output in both reference and phase shift states are larger than 10 dB within 18.2-19.2 GHz. The phase shift is 178° at 18.7 GHz. The measured results show that the 180° bit prototype achieved excellent performance.

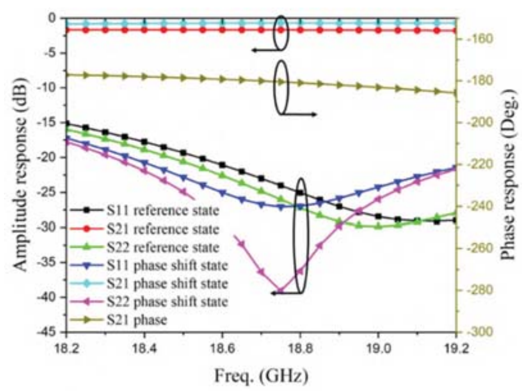

Fig. 14. EM simulated results of 180° bit.

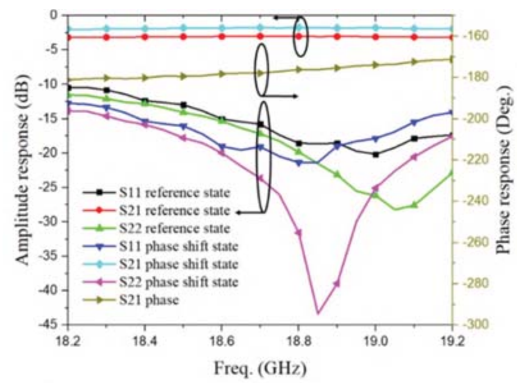

Fig. 15. Measured results of 180° bit.

B. 4-Bit Phase shifter

The simulated results of the 4-bit PIN diode RTPS are presented in Figures 16 to 18. As shown in Figure 16, the RMS phase error is close to zero at 18.7 GHz. Within 200 MHz bandwidth, the RMS phase error is less than 5°. The phase shift patterns are quite consistent from 0° to 157.5°. However, the phase shift trend is changed at 180°. The main cause of this alteration is that among four reflective loads, only in the reverse bias state of 180° load the circuit acts as a capacitor. The simulated ILs for 16 states of the phase shifter are shown in Figure 17. One can see that the IL is ranging from 3.2 to 4.7 dB at 18.7 GHz. The IL variation is only 1.5 dB. Figure 18 reveals that the RLs are larger than 15 dB within the 200 MHz bandwidth in all the 16 phase shift states.

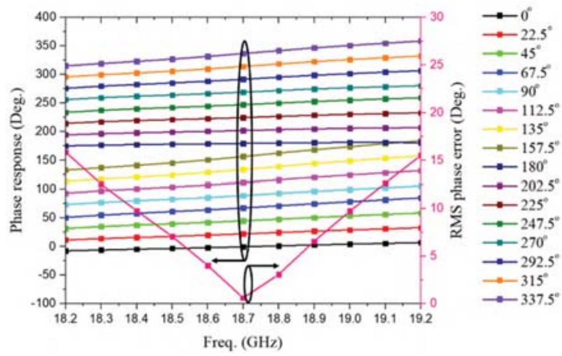

Fig. 16. Simulated phase response for 16 states of the phase shifter.

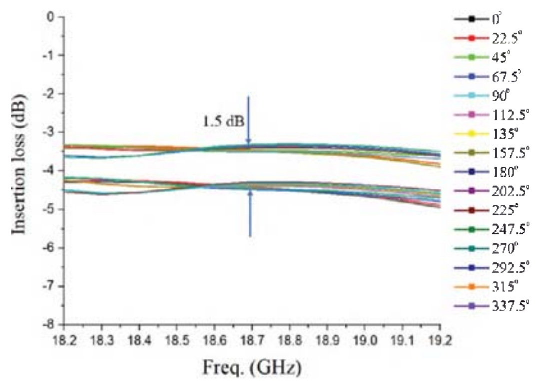

Fig. 17. Simulated insertion loss for 16 states of the phase shifter.

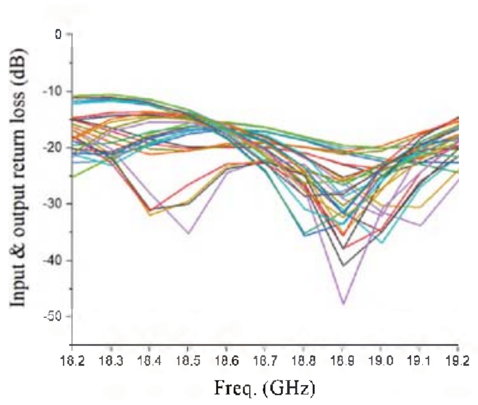

Fig. 18. Simulated return loss for 16 states of the phase shifter.

Table I shows a comparison of this work with other reported works. As can be seen, the designed phase shifter is very well in performance compared to other reported works. The good performance comes in low IL, high RL, and phase shift performance.

TABLE I. PERFORMANCE COMPARISON OF PHASE SHIFTERS

Ref.	[8]	[9]	[10]	**This work***
Technology	CMOS	GaAs	CMOS	**PIN diode PCB**
Freq. (GHz)	26 - 30	33 -35	29 - 37	**18.7**
Bits	5	4	4	**4**
RL (dB)	NA	>12	>11	**>15**
IL (dB)	<16.5	<14.2	<12.8	**4.7**
RMS phase error (°)	<3.3	<5	<8.8	**1@18.7 GHz**

* Simulated results

VII. CONCLUSION

A design of 18.7 GHz 4-bit PIN diode RTPS was analyzed and presented. The PIN diode was characterized, and the compact reflective loads were constructed by PIN diodes with only one component. Fabricating the phase shifters directly on the same Taconic TLX8 laminate with the feed network allows producing a monolithic phased array and reduce the cost significantly. The simulated results show that the phase shifter exhibits maximum 4.7 dB IL with excellent input and output RLs. The RMS phase error is about 1° at 18.7 GHz. The measured results of the two fabricated bit prototypes confirm excellent performance. The proposed phase shifters will be used in the radiometer antenna for soil moisture measurement.

ACKNOWLEDGMENT

The authors would like to thank the Australian Government for providing Endeavour Ph.D. scholarship.

REFERENCES

[1] G. Shin *et al.*, "Low Insertion Loss, Compact 4-bit Phase Shifter in 65 nm CMOS for 5G Applications," *IEEE Microwave and Wireless Components Letters,* vol. 26, no. 1, pp. 37-39, 2016, doi: 10.1109/LMWC.2015.2505624.

[2] L. Wang *et al.*, "Highly Linear Ku-Band SiGe PIN Diode Phase Shifter in Standard SiGe BiCMOS Process," *IEEE Microwave and Wireless Components Letters,* vol. 20, no. 1, pp. 37-39, 2010, doi: 10.1109/LMWC.2009.2035962.

[3] Q. Zheng *et al.*, "Design and Performance of a Wideband Ka-Band 5-b MMIC Phase Shifter," *IEEE Microwave and Wireless Components Letters,* vol. 27, no. 5, pp. 482-484, 2017, doi: 10.1109/LMWC.2017.2690828.

[4] R. Garg and A. S. Natarajan, "A 28-GHz Low-Power Phased-Array Receiver Front-End With 360° RTPS Phase Shift Range," *IEEE Transactions on Microwave Theory and Techniques,* vol. 65, no. 11, pp. 4703-4714, 2017, doi: 10.1109/TMTT.2017.2707414.

[5] T. Li and H. Wang, "A Millimeter-Wave Fully Integrated Passive Reflection-Type Phase Shifter With Transformer-Based Multi-Resonance Loads for 360⁰ Phase Shifting," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 65, no. 4, pp. 1406-1419, 2018, doi: 10.1109/TCSI.2017.2748078.

[6] I. Kalyoncu, E. Ozeren, A. Burak, O. Ceylan, and Y. Gurbuz, "A phase-calibration method for vector-sum phase shifters using a self-generated LUT," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 66, no. 4, pp. 1632-1642, 2019, doi: 10.1109/TCSI.2018.2885172.

[7] B. Cetindogan, E. Ozeren, B. Ustundag, M. Kaynak, and Y. Gurbuz, "A 6 Bit Vector-Sum Phase Shifter With a Decoder Based Control Circuit for X-Band Phased-Arrays," *IEEE Microwave and Wireless Components Letters,* vol. 26, no. 1, pp. 64-66, 2016, doi: 10.1109/LMWC.2015.2505618.

[8] J. Tsai, F. Lin, and H. Xiao, "Low RMS phase error 28 GHz 5-bit switch type phase shifter for 5G applications," *Electronics Letters,* vol. 54, no. 20, pp. 1184-1185, 2018, doi: 10.1049/el.2018.6383.

[9] K. Maruhashi, H. Mizutani, and K. Ohata, "Design and performance of a Ka-band monolithic phase shifter utilizing nonresonant FET switches," *IEEE Transactions on Microwave Theory and Techniques,* vol. 48, no. 8, pp. 1313-1317, 2000, doi: 10.1109/22.859475.

[10] M. Jung and B. Min, "A compact Ka-band 4-bit phase shifter with low group delay deviation," *IEEE Microwave and Wireless Components Letters,* vol. 30, no. 4, pp. 414-416, 2020, doi: 10.1109/LMWC.2020.2975108.