A Novel Reconfigurable Miniaturized Phase Shifter for 2-D Beam Steering 2-Bit Array Applications

Jiadong Hu, Yue Li, *Senior Member*, and Zhijun Zhang, *Fellow, IEEE*

***Abstract*— In this letter, a novel reconfigurable 0°/90° phase shifter is proposed. Compared with the conventional phase shifters, the proposed one uses fewer reconfigurable devices and becomes more compact. Two states of a meander line are used to generate the 90° phase shift, making it suitable for the 2-D beam steering 2-bit array application. A phase shifter prototype on F4B was measured to validate its design theory. Four phase states (i.e., 0°, 90°, 180°, and 270°) are realized through the combination of the phase shifter and the array radiation element. A 2 × 4 array working at 1.5 GHz was fabricated and measured to verify the performance of the proposed phase shifter. When different phase states are switched, the measured peak gain of the array varies from 10.6 to 11.2 dBi.**

***Index Terms*— 2-Bit array, 2-D beam scanning, miniaturized technology, reconfigurable phase shifter.**

I. Introduction

PHASED array antennas have been widely used in radar and other military communications, owing to its superiorities of high gain and fast beam steering. In recent years, phased array antennas begin to be applied in some commercial situations, such as navigation, remote sensing, and automotive radar. However, the high cost of the phased array system usually limits its application.

Many attempts have been made to reduce the system complexity. The discrete phased array (or bit array) can be a good alternative under many circumstances. In general, the discrete phased array can be divided into three categories: space-fed [1], [2], series-fed [3], [4] and shunt-fed bit array [5], [6]. With more array element phase states, the array gets wider scanning range, more accurate beam steering, and lower side lobes.

The main design challenge for shunt-fed bit array is to include the antenna, the phase shifter, and other bias lines in a compact unit cell, limited by the distance between array elements (approximately 0.5 λ_0). Moreover, a unit cell should use few reconfigurable devices as possible to keep certain phase states, which is a common requirement for bits arrays' antenna design. In shunt-fed bit arrays, the digital phase shifter is an important component. The common digital phase shifter are four types: the switchable line type (SLT) [7]–[9], the loaded line type (LLT) [10], the reflection type (RT) [11], and the high-pass low-pass type (HPLPT) [12]. In conventional switchable line phase shifters, two single-pole double throws (SPDTs) are needed to change its phase states, equivalent to use four p-i-n diodes. Other types usually need fewer reconfigurable devices but are still too large to be used in shunt-fed 2-D bit arrays.

Manuscript received December 19, 2020; revised January 27, 2021; accepted February 1, 2021. Date of publication February 15, 2021; date of current version April 8, 2021. This work was supported in part by the National Natural Science Foundation of China under Contract 61971254 and Contract 61525104. *(Corresponding author: Zhijun Zhang.)*

The authors are with the Beijing National Research Center for Information Science and Technology, Tsinghua University, Beijing 100084, China (e-mail: zjzh@tsinghua.edu.cn).

Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LMWC.2021.3057223.

Digital Object Identifier 10.1109/LMWC.2021.3057223

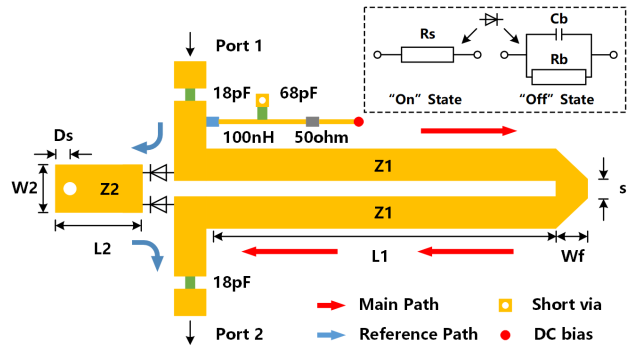

Fig. 1. Schematic of the proposed miniaturized phase shifter.

TABLE I
DETAILED DIMENSIONS OF THE PHASE SHIFTER

Parameter	Value [mm]	Parameter	Value [mm]
L1	19.1	*L2*	5
s	1	*W2*	2
Wf	2.7	*Ds*	1.1

In this letter, a novel reconfigurable miniaturized 0°/90° phase shifter for 2-D shunt-fed 2-bit array applications is proposed. The 90° phase shifting is generated by switching two states of a meander line. The proposed phase shifter uses fewer reconfigurable devices and becomes more compact compared with the conventional ones. A phase shifter prototype at 1.5 GHz is measured for validating the design principle. In array design, the symmetry of the radiation element is used to generate 180° phase reversal, instead of delay circuits. The radiation element is connected with the 0°/90° phase shifter, leading to 2-bit phase states' variation. A 2 × 4 array prototype working at 1.5 GHz was designed and measured to verify the performance of the proposed miniaturized 0°/90° phase shifter.

II. Phase Shifter Design and Analysis

A. Geometry

The whole structure of the phase shifter is laid out on a single-layer F4B substrate ($\varepsilon_r = 2.65$, $\tan\delta = 0.002$) with two panels. The configuration of the proposed 0°/90° phase shifter on the upper surface with the biasing circuit is illustrated in Fig. 1. The proposed phase shifter is composed of a meander line, a shorted stub, and two p-i-n diodes. The type of the p-i-n diodes adopted in this letter is MA4SPS402. The equivalent circuit of the adopted diode ($Rs = 3\ \Omega$, $Rb = 85$ kΩ, and $Cb = 0.025$ pF) is also provided in Fig. 1. The other detailed dimensions of the phase shifter are provided in Table I.

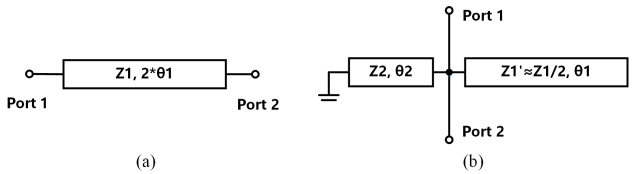

Fig. 2. Equivalent circuits at every phase state. (a) At 0° state (main path). (b) At 90° state (reference path).

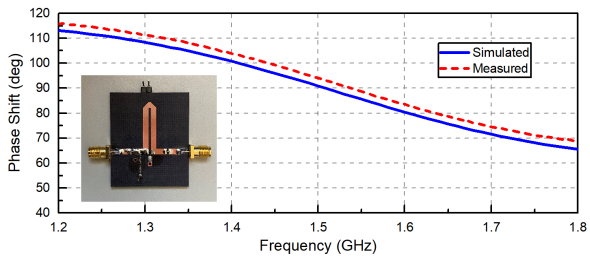

Fig. 3. Simulated and measured phase shifts of the proposed phase shifter.

B. Operating Principle

Generally, a phase shifter has two signal paths, namely, the main path and the reference path. In our design, the signal passes through the main path at the 0° state and the reference path at the 90° state. The equivalent circuits at each phase state are provided in Fig. 2.

In the 0° state, the meander line acts as a transmission line to provide phase delay. The equivalent circuit, as shown in Fig. 2(a), can be represented by a simple transmission line with a length around 2^*L_1 and a characteristic impedance of Z_1.

In the 90° state, two diodes effectively short-circuited the meander line, and thus the input and output ports. In the meanwhile, a short-circuited transmission line is attached to the meander line. The equivalent circuit, as shown in Fig. 2(b), can be represented by two shunt-connected transmission lines. One is an open-circuited transmission line with a length of L_1 and characteristic impedance around $Z_1/2$. The other one is a short-circuited transmission line with a length of L_2 and characteristic impedance of Z2. The open-circuited line, by itself, functions as a capacitive load at the input–output ports. By attaching an extra short-circuited line, which functions as an inductive load, the input–output ports can be rematched.

As is mentioned above, the phase shifter will be matched if the reactance of the two shunted structures is canceled. Therefore, the working frequency f satisfies

$$\tan\left(\frac{2\pi L_1}{v_p} f\right) \tan\left(\frac{2\pi L_2}{v_p} f\right) = \frac{Z_2}{Z_1'} \approx \frac{2Z_2}{Z_1} \tag{1}$$

where v_p is the phase velocity in the substrate.

The phase shift mainly derives from the difference between the main path and the reference path. Assumed that the phase shift of the reference path is P_R, the total phase shift P can be roughly donated as

$$P \approx \frac{2L_1 + 2W_f + s}{v_p} \cdot 2\pi f - P_R \approx \frac{4\pi L_1 f}{v_p} - P_R. \tag{2}$$

C. Results and Comparison

The measured results agree well with the simulated ones, as shown in Figs. 3 and 4. It can be observed that the phase shifter has an impedance bandwidth of 13.3% with a minimum insertion loss of 1.5 dB and a phase shift of 90° ± 5°. It is noted that when the phase shifter is at the 0° state, the simulated and measured $|S_{11}|$ are both below −20 dB. In this case, the return loss is quite small and the waveform is no longer important. A comprehensive comparison between the proposed phase shifter and other relevant works is listed in Table II. It can be found that the proposed phase shifter shrinks its size by at least 50% and needs fewest reconfigurable devices, on condition of the same phase shift. It is noted that for the SLTs [7]–[9], the actual size should include both the main path and the reference path. Moreover, four p-i-n diodes (two SPDTs) are needed to switch phase states in these works.

Although the proposed phase shifter has a compact size, the insertion loss of it is higher than most other works in Table II. In fact, the insertion loss of the proposed phase shifter mainly comes from the ON resistance of p-i-n diodes (*Rs*). When p-i-n diodes are both at the "ON" state, the equivalent shunted inductor and capacitance create a resonance. Therefore, the ON resistance of the p-i-n diode loaded in the loop will lead to considerable insertion loss. As shown in Fig. 5, the insertion loss varies with *Rs*, while the reflection coefficients and phase shifts are not affected. Therefore, the insertion loss can be reduced greatly by replacing other types of p-i-n diodes with lower ON resistances.

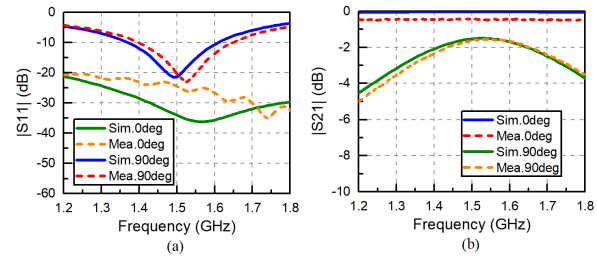

Fig. 4. Simulated and measured S-parameters of the proposed phase shifter. (a) Reflection coefficient. (b) Transmission coefficient.

TABLE II

COMPARISON BETWEEN OTHER RELEVANT RESEARCHES

Ref.	PS(°)	Frequency (GHz)	IL(dB)	Size*($\lambda_g \times \lambda_g$)	No. of Diodes
[6]	90	3.5	0.73	0.47×0.3	2
[7]	90	2.4	1.1	1.2×0.2	4
[8]	90	3	0.7	0.77×0.29	4
[9]	90	3	0.97	0.89×0.12	4
[10]	90	1	0.15	0.75×0.12	2(one state)
[11]	90	1.5	1.9	0.47×0.29	2(one state)
This Work	**90**	**1.5**	**1.5**	**0.24×0.13**	**2**

*: Estimated values.

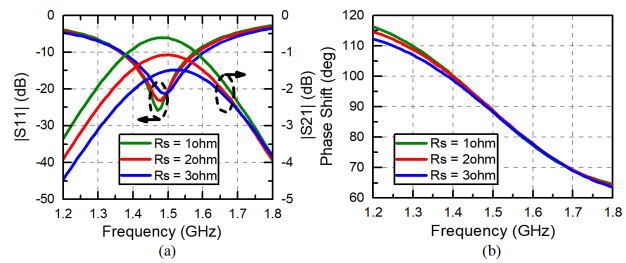

Fig. 5. Phase shifter simulated results with varying *Rs*. (a) S-parameters. (b) Phase shift.

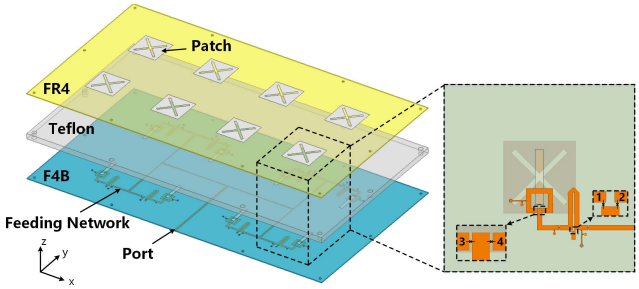

Fig. 6. Perspective geometry of the 2 × 4 array and the bottom view of the unit.

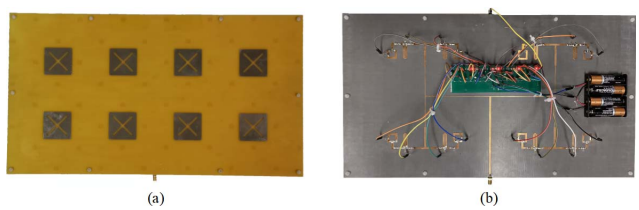

Fig. 7. Photograph of the 2 × 4 2-bit array. (a) Top view. (b) Bottom view.

III. Array Application

In this section, a shunt-fed 2-D 2-bit array at 1.5 GHz is designed, simulated, and measured to validate the performance of the proposed phase shifter in Section II.

As shown in Figs. 6 and 7, the array radiating element is a slot-fed patch on a 1-mm-thick FR4, which is the top layer. A pair of cross slots are etched on the patch to reduce its size and improve isolation between the adjacent units. A piece of 8-mm-thick Teflon ($\varepsilon_r = 2.1$, $\tan\delta = 0.001$) is set as the middle layer. This layer is used to support the radiation aperture and further reduce the patch size. The coupling slot and the phase shifter are placed on the bottom layer, which is a 1-mm-thick F4B.

The symmetry of the feeding style with two loaded p-i-n diodes creates a 180° phase reversal at the radiation patch. Thus, the 2-bit phase states (i.e., 0°, 90°, 180°, and 270°) variation derives from the connection of the phase shifter and the radiation patch.

In array, the distance between the adjacent array units is 0.5 λ_0. Three cases of beams have been selected to validate the 2-D beam steering performance of the array. In Case 1, all units are in-phase and have a broadside beam toward (0°, 0°). In Case 2, there is a phase gradient on the *xoz* plane and the beam direction is toward (0°, 28°). Similarly, the phase gradient of Case 3 is on the *yoz* plane with beam direction toward (90°, 20°).

A comparison between the simulated and measured array reflection coefficients of different cases is presented in Fig. 8(a).

Due to the fabrication and measurement error, the measured working frequency has a slight shift to 1.53 GHz. The array efficiency cannot be measured due to the limited measurement conditions. The simulated array total efficiency is provided in Fig. 8(b). The array total efficiency varies with different phase states, ranging from 70% to 75% at 1.5 GHz among all cases.

The simulated and measured array radiation patterns at 1.53 GHz of Case 1 to Case 3 are illustrated in Fig. 9. It can be observed that the array has the beam steering ability both in the *xoz* plane and the *yoz* plane. The measured main lobes correspond well to the simulated ones at all cases. The simulated peak gain of Cases 1–3 is 13.2, 12.5, and 12.4 dBi, respectively. The measured peak gains are slightly lower than the simulated ones due to some measurement errors. The measured peak gain of Cases 1–3 is 12.1, 11.1, and 10.6 dBi respectively. The cross-polarization level is below −15 dB in the upper radiation space.

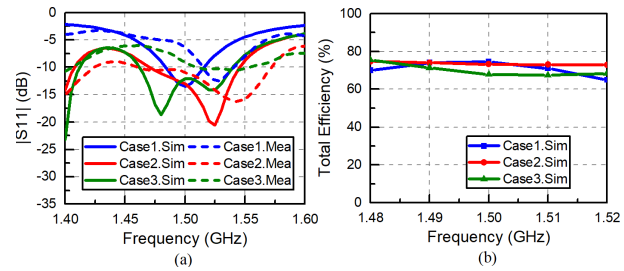

Fig. 8. (a) Simulated and measured array reflection coefficients of Cases 1–3. (b) Simulated array efficiency of Cases 1–3.

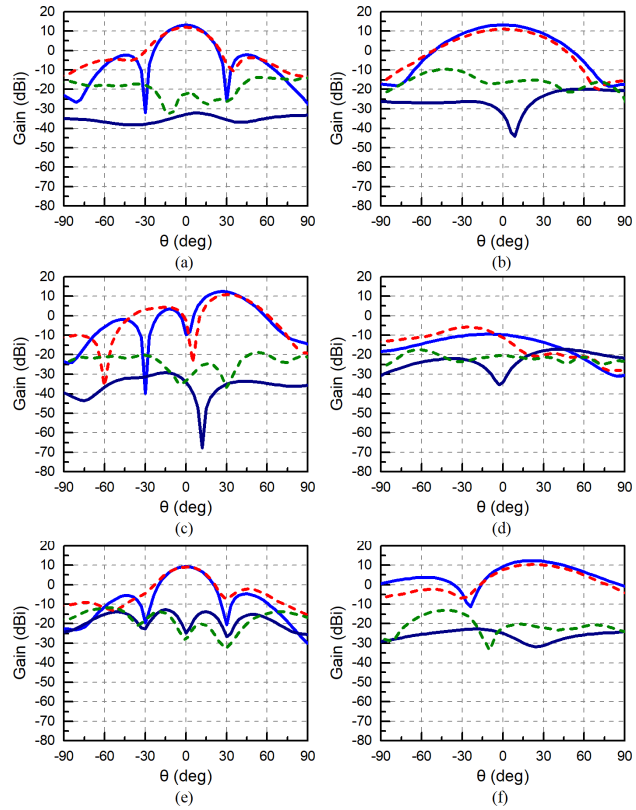

Fig. 9. Simulated and measured array radiation patterns at 1.53 GHz of Cases 1–3. (a) *xoz* Plane of Case 1. (b) *yoz* Plane of Case 1. (c) *xoz* Plane of Case 2. (d) *yoz* Plane of Case 2. (e) *xoz* Plane of Case 3. (f) *yoz* Plane of Case 3.

IV. Conclusion

In this letter, a novel miniaturized 0°/90° phase shifter is proposed. A meander line is used to create the phase difference and realize impedance matching at different phase states. Compared with other relevant works, the proposed phase shifter has the smallest size and uses fewest p-i-n diodes. A 2 × 4 2-bit array prototype working at 1.5 GHz is designed, fabricated, and measured to verify the design theory of the phase shifter. The simulated and measured results prove that the array has the ability of 2-D beam steering.

REFERENCES

[1] M. Wang, S. Xu, F. Yang, and M. Li, "Design and measurement of a 1-bit reconfigurable transmitarray with subwavelength H-shaped coupling slot elements," *IEEE Trans. Antennas Propag.*, vol. 67, no. 5, pp. 3500–3504, May 2019.

[2] H. Yang *et al.*, "A 1-bit 10×10 reconfigurable reflectarray antenna: Design, optimization, and experiment," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 1–9, Jun. 2016.

[3] L. Chang, Y. Li, Z. Zhang, and Z. Feng, "Reconfigurable 2-bit fixed-frequency beam steering array based on microstrip line," *IEEE Trans. Antennas Propag.*, vol. 66, no. 2, pp. 683–691, Feb. 2018.

[4] C. Deng, D. Liu, B. Yektakhah, and K. Sarabandi, "Series-fed beam-steerable millimeter-wave antenna design with wide spatial coverage for 5G mobile terminals," *IEEE Trans. Antennas Propag.*, vol. 68, no. 5, pp. 3366–3376, May 2020.

[5] D. T. Pham, H. Subbaraman, M. Y. Chen, X. Xu, and R. T. Chen, "Light weight and conformal 2-bit, 1×4 phased-array antenna with CNT-TFT-based phase shifter on a flexible substrate," *IEEE Trans. Antennas Propag.*, vol. 59, no. 12, pp. 4553–4558, Dec. 2011.

[6] P. Liu, Y. Li, and Z. Zhang, "Circularly polarized 2 bit reconfigurable beam-steering antenna array," *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 2416–2421, Mar. 2020.

[7] Q. Liu, Y. Liu, J. Shen, S. Li, C. Yu, and Y. Lu, "Wideband single-layer 90° phase shifter using stepped impedance open stub and coupled-line with weak coupling," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 3, pp. 176–178, Mar. 2014.

[8] Y.-P. Lyu, L. Zhu, and C.-H. Cheng, "Single-layer broadband phase shifter using multimode resonator and shunt λ /4 stubs," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 7, no. 7, pp. 1119–1125, Jul. 2017.

[9] L.-L. Qiu, L. Zhu, and Y.-P. Lyu, "Schiffman phase shifters with wide phase shift range under operation of first and second phase periods in a coupled line," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 4, pp. 1423–1430, Apr. 2020.

[10] T. Zhang, W. Che, H. Chen, and Q. Xue, "Reconfigurable impedance matching networks with controllable phase shift," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 65, no. 11, pp. 1514–1518, Nov. 2018.

[11] H. R. Fang, X. Tang, K. Mouthaan, and R. Guinvarc'h, "180° and 90° reflection-type phase shifters using over-coupled lange couplers," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 11, pp. 3440–3448, Nov. 2012.

[12] I. S. Song, G. Yoon, and C. S. Park, "A highly integrated 1-Bit phase shifter based on high-pass/low-pass structure," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 8, pp. 523–525, Aug. 2015.