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DESIGN OF A KU BAND SIX BIT PHASE SHIFTER USING PERIODICALLY LOADED-LINE AND SWITCHED-LINE WITH LOADED-LINE

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Abstract—A Ku band six-bit phase shifter is presented in this work. The developed phase shifter consists of four bits realized as periodically loaded-line and two bits based on novel switched-line with loaded-line. A 71Ω line impedance is chosen for the main transmission line in order to reduce the diode loss. Every bit has special tuning elements for the fine tuning of the required phase shift. The phase error for the 64 phase states is not greater than 3.4 degrees at the designed center frequency of 15 GHz, and the insertion loss for the 64 phase states is 5.2 dB±1.1 dB over the operating bandwidth of 14.9–15.1 GHz.

1. INTRODUCTION

Phase shifter is a key component of phased array antenna [11, 12]. Microwave phase array technique is one of essential techniques in the fields of microwave radar [13, 14], communication and navigation. As the two-port key element of a phased array antenna system, the phase shifter gives the role to change the phase of the input signal ideally without the insertion loss, but practically it has the insertion loss variation according to each phase state. The planar integrated digital phase shifter can be roughly classified into three groups: the MEMS (Micro Electro Mechanical System) phase shifter, the FET phase shifter, and the PIN diode phase shifter.

MEMS phase shifter [1–4] has the advantages of small volume, small current, wide frequency band, low insertion loss, and so on, while issues regarding their yield and packaging still remain unexplored. Even though silicon technology has matured, MEMS devices [10] with complex structure are prone to high production cost and limited yield

[5]. On the other hand, FET phase shifter [6], despite of its small size and negligible current, has high insertion loss and cost.

Although it requires more current to drive, PIN diode exhibits the excellent performance of $f_{\max}$ compared with FET and MEMS [7]. For most important, it is commercially available and easy to fabricate in Ku-band. Thus, it is often used for microwave phase shifter in practice.

In this paper, considering the disadvantage of switched-line phase shifter, a new type of switched-line with loaded-line phase shifter is proposed. This design not only make advantageous debugging of circuit, but also minimize phase error in a given frequency band. Four-cell circuits are designed, fabricated and tested including bit 5.625 degree and 45 degree using a concept of periodically loaded-line [8, 9], bit 90 degree and 180 degree using switched-line with loaded-line phase shifter. Finally, according to the testing result of cell circuit, a Ku-band six-bit PIN diode phase shifter is fabricated, which exhibits good microwave performance.

2. CIRCUITS DESIGN

The considered phase shifter has to realize 64 states of the phase shift of a microwave signal with a 5.625 degree step. For this purpose six two state bits (5.625, 11.25, 22.5, 45, 90 and 180 degrees) are necessary. Each bit has to be controlled independently by streams of pulses from a proper driver. To realize four first bits, a concept of periodically loaded-line, has been applied. The structure is very simple and it exhibits quite good frequency behavior concerning the phase shift and matching. The last two bits (90 and 180 degrees) are based on a novel structure of switched-line with loaded-line. The circuit combines the advantages of switched-line and loaded-line, exhibits good microwave performance as well as advantageous debugging of circuit. The complete circuit is shown in Fig. 1. A 71Ω line impedance is chosen for the main transmission line in order to reduce the diode

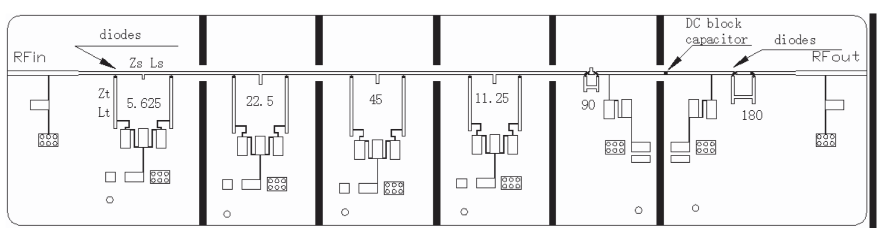


Figure 1. Complete circuit of the six bit phase shifter.

loss by increasing the ratio between the line impedance and the diode series resistance. A $\lambda/4$ transformer was added at each end of the circuit to bring the input and output impedances back to 50Ω.

The structure of periodically loaded-line is shown in Fig. 1, such as bits 5.625, 11.25, 22.5 and 45 degrees. The bottom of loaded-line is open and the phase shift is mainly decided by the length of loaded-line. Thus, this type of phase shifter has advantageous debugging of phase shift. Table 1 displays the simulation results of bit 5.625 degree to different length of loaded-line by means of full-wave simulation using commercial software (Ansoft HFSS). From Table 1, it is easily seen that the phase shift becomes larger as the length of loaded-line varies longer while other performance keep steady. For debugging of practical circuit, it is very convenient to tune phase shift based practical demand.

Table 1. Simulation results of bit 5.625 degree to length of Lt by HFSS.

Lt (mm)	VSWR state one	S21 (dB) state one	VSWR state two	S21 (dB) state two	Phase shift degree
Lt=7.8	1.14	-0.12	1.06	-0.18	2.68
Lt=7.9	1.06	-0.1	1.04	-0.18	3.41
Lt=8	1.07	-0.1	1.11	-0.186	5.74
Lt=8.1	1.04	-0.09	1.15	-0.226	8.97
Lt=8.2	1.03	-0.09	1.2	-0.248	9.44

In the structure, there is a tuning block between two loaded-lines. Therefore, this structure is actually a loaded-line phase shifter with branches. Primary function of the tuning block is improving matching, sometimes is useful for tuning of phase shift. According to results of simulations, bit 5.625 and 45 degree are designed, fabricated and tested using this structure. Fig. 2 and Fig. 3 show the experimental results and photograph of bit 5.625 degree and 45 degree, respectively.

From the Figs. 2 and 3, it can be found that over the operating bandwidth of 14.9–15.1 GHz the insertion loss is smaller than 0.4 dB (wiping off loss of connectors and impedance transformers, about 0.6 dB), the amplitude imbalance is smaller than ± 0.08 dB, the VSWR is lower than 1.3, the phase error is smaller than ± 1.1 degree for bit 5.625 degree, and for bit 45 degree, the insertion loss is smaller than 1.5 dB, the amplitude imbalance is smaller than ± 0.3 dB, the VSWR is lower than 1.5, and the phase shift is 45.01 degree at the designed center frequency of 15 GHz. Experiment also show that phase shift can be easily tuned by changing the length of branches. The experimental results of the cell circuits illuminate that the structure of periodically

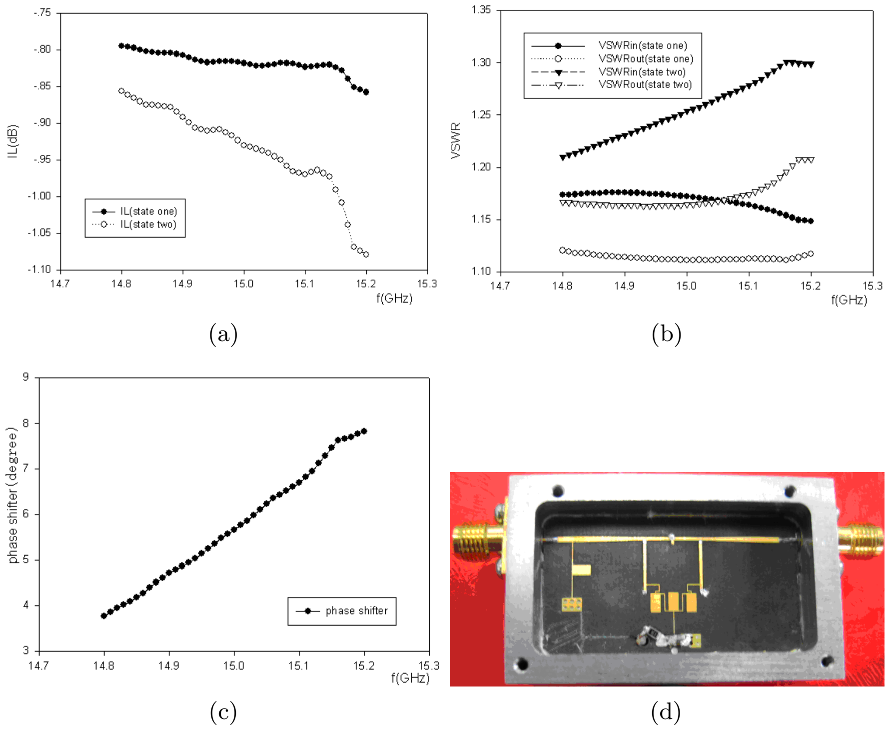


Figure 2. Experimental results and photograph of bit 5.625 degree (a) insertion loss (b) VSWR (c) phase shifter (d) photograph.

loaded-line has good microwave performance and is very suitable for little phase shift smaller than 90 degree.

The simulation model of switched-line with loaded-line is shown in Fig. 4. There are two tuning stubs (equal with loaded-line) at the corner of the long path, and a tuning stub at the middle of the short path. The phase shift can be easily tuning by changing the length of stubs. Tables 2 and 3 show the simulation results of bit 90 degree to different length of tuning stubs, L_1 and L_2, by Ansoft HFSS, respectively. From the Tables 2 and 3, it is easily seen that the phase shift becomes larger as the length of stubs L_1 varies longer, and becomes smaller as the length of stub L_2 varies shorter while other performance keep steady. Therefore, to tune phase shift based on practical demand is very convenient for debugging of practical circuits.

According to results of simulation, bit 90 and 180 degree are designed, fabricated, and tested using the novel structure of switched-line with loaded-line. Figs. 5 and 6 show the experimental results and

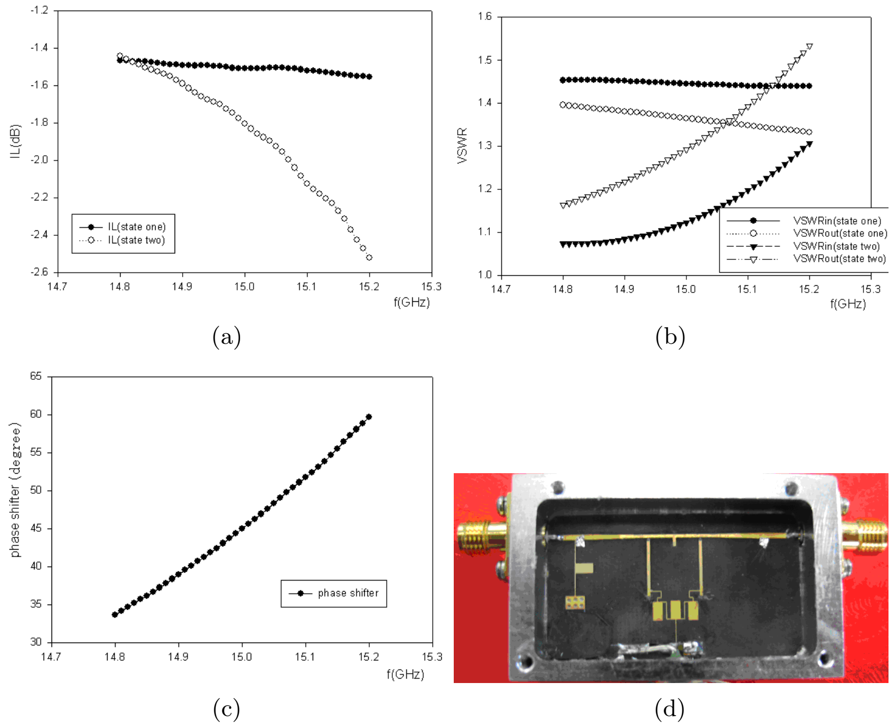


Figure 3. Experimental results and photograph of bit 45 degree (a) insertion loss (b) VSWR (c) phase shifter (d) photograph.

photograph of bit 90 degree and 180 degree, respectively.

From the Figs. 5 and 6, it is easily seen that over the operating bandwidth of 14.9–15.1 GHz the insertion loss is smaller than 1.5 dB (wiping off loss of connectors and impedance transformers, about 0.6 dB), the amplitude imbalance is smaller than ±0.1 dB, the VSWR is lower than 1.46, the phase error is smaller than ±1.1 degree for bit 90 degree, and for bit 180 degree, the insertion loss is smaller than 1.3 dB, the amplitude imbalance is smaller than ±0.12 dB, the VSWR is lower than 1.7, the phase error is smaller than ±1.35 degree. Obviously, the new structure exhibits good performance, especially in aspects of amplitude imbalance and phase error. Practical experiments also show that phase shift can be easily tuned by changing the length of stubs, according to the designed demand. The experimental results of the cell circuits illuminate that the novel structure of switched-line with loaded-line has good microwave performance, and is very suitable for bit 90 and 180 degree.

Table 2. Simulation results of bit 90 degree to length of stubs L_1 by HFSS.

L_1 (mm)	VSWR state one	S21 (dB) state one	VSWR state two	S21 (dB) state two	Phase shift degree
L_1=0.4	1.23	-0.58	1.1	-0.56	89.19
L_1=0.5	1.11	-0.56	1.19	-0.56	90.97
L_1=0.6	1.14	-0.56	1.25	-0.63	93.57
L_1=0.7	1.21	-0.57	1.4	-0.7	95.66
L_1=0.8	1.21	-0.57	1.44	-0.8	98.58

Table 3. Simulation results of bit 90 degree to length of stub L_2 by HFSS.

L_2 (mm)	VSWR state one	S21 (dB) state one	VSWR state two	S21 (dB) state two	Phase shift degree
L_2=0.5	1.11	-0.5	1.18	-0.57	91.9
L_2=0.6	1.11	-0.56	1.19	-0.56	90.97
L_2=0.7	1.1	-0.54	1.18	-0.57	89.81
L_2=0.8	1.16	-0.6	1.18	-0.58	88.62
L_2=0.9	1.16	-0.6	1.19	-0.55	86.47

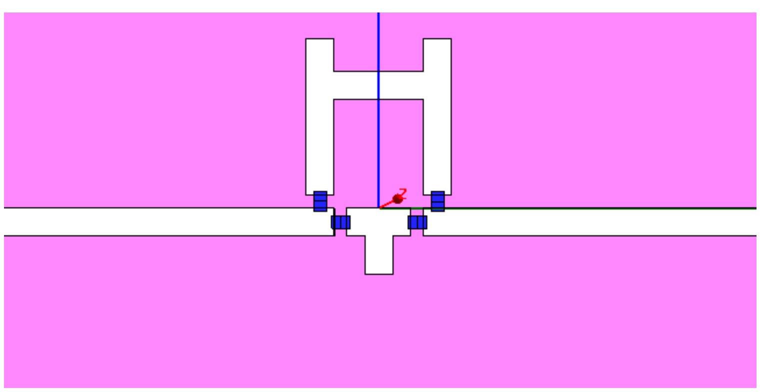


Figure 4. Simulation model of switched-line with loaded-line.

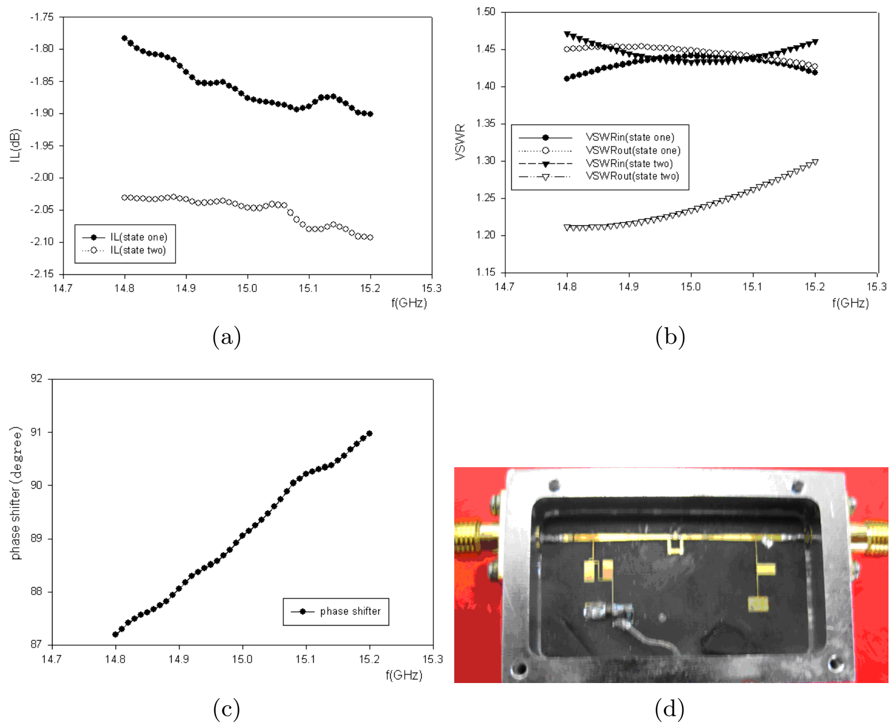


Figure 5. Experimental results and photograph of bit 90 degree (a) insertion loss (b) VSWR (c) phase shifter (d) photograph.

3. KU-BAND SIX-BIT PHASE SHIFTER AND EXPERIMENTAL RESULTS

According to the experimental results of cell circuits, a Ku-band six-bit PIN diode phase shifter is designed, fabricated and tested. The PIN diode DSG6474-000 with capacitance of about 0.02 pF at -10 V and a series resistance of 4Ω at 10 mA is chose as switching element. The photograph of the Ku-band six-bit digital phase shifter is shown in Fig. 7, the driver circuit is enclosed on the opposite side.

The circuit consists of six microstrip cells in cascade. The six cells are designed to provide phase shift of 5.625, 22.5, 45, 11.25, 90 and 180 degree in the order shown in the figure starting from the bottom of the circuit. The four first cells are realized using the structure of periodically loaded-line, and the two last cells are completed by the novel configuration of switched-line with loaded-line. Fine phase shift tuning is achieved by means of stubs as shown in Fig. 7.

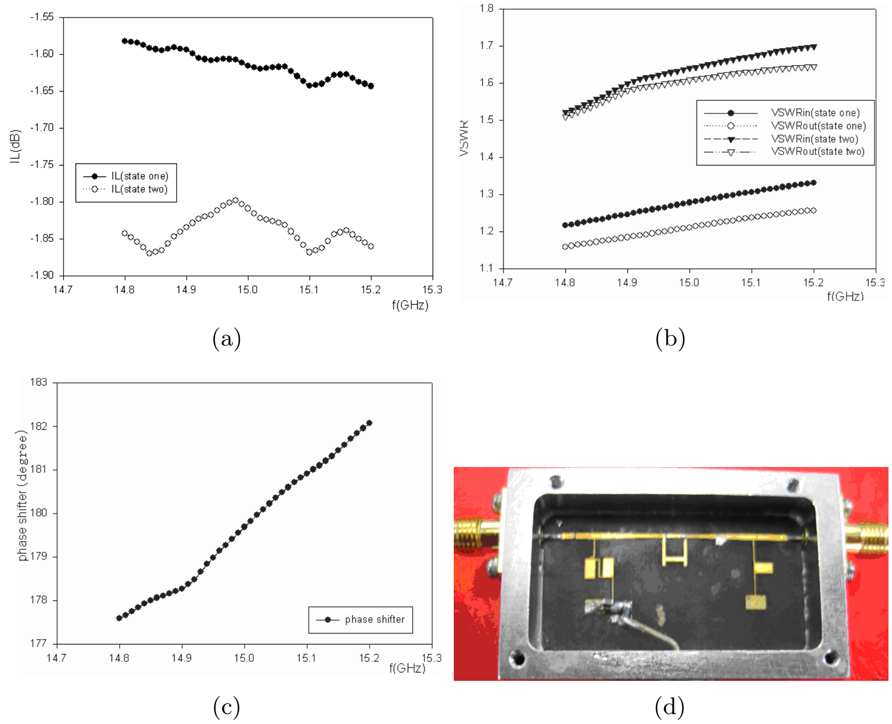


Figure 6. Experimental results and photograph of bit 180 degree (a) insertion loss (b) VSWR (c) phase shifter (d) photograph.

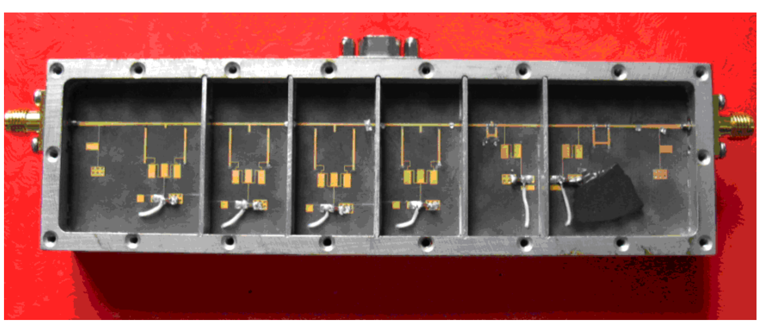
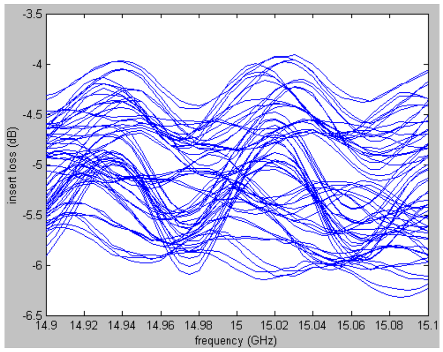
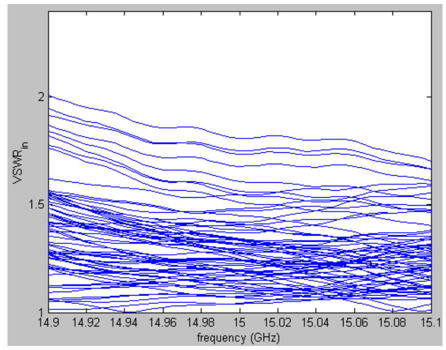


Figure 7. Photograph of the Ku-band six-bit digital phase shifter.



(a)



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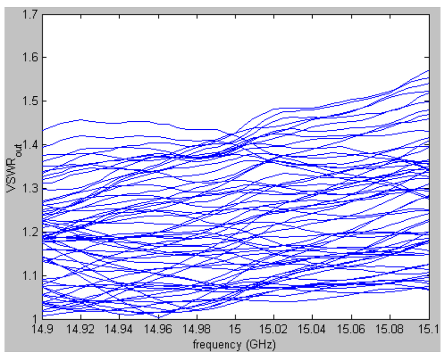
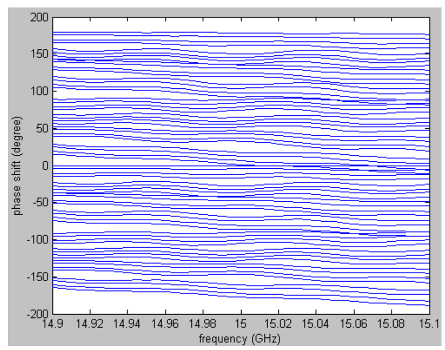


(c)



(d)

Figure 8. Experimental results of the Ku-band six-bit digital phase shifter (a) insertion loss (b) VSWRin (c) VSWRout (d) phase shifter.

Fig. 8 shows the insertion loss, VSWR and phase shift of the 64 phase states measured over the operating bandwidth. For the 64 phase states, over the operating bandwidth of 14.9–15.1 GHz, the insertion loss is smaller than 6.3 dB, the amplitude imbalance is smaller than ±1.1 dB, the VSWR is lower than 1.92. The phase error for the 64 phase states is not greater than 3.4 degree at the designed center frequency of 15 GHz.

4. CONCLUSION

In this paper, we have presented a novel switched-line with loaded-line phase shifter. Compared with conventional switched-line phase shifter, this kind of phase shifter has excellent tuning of phase shifting. Bit 5.625, 45, 90 and 180 degree cell circuits, and a Ku-band six-bit digital phase shifter have been successfully demonstrated. Due to tuning element provided, the required phase shifter can be easily obtained despite the PIN diode reactive elements are not identical to those taken into design.

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