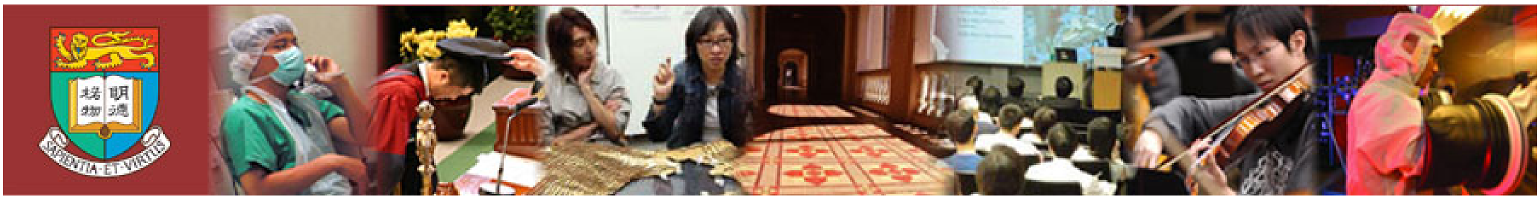

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A Compact 6-bit Phase Shifter with High-Power Capacity Based on Composite Right/Left-Handed Transmission Line

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***Abstract*— A compact 6-bit phase shifter with high power-handling capacity is designed based on the use of metamaterial, composite right/left-handed transmission line (CRLH-TL). Eight PIN diodes mounted on the fingers of the CRLH-TL are used as switches to control the phase incursion of the input signal. Different phase shifts are achieved by using different states of the switches (PIN diodes) determined by 6 controlling bits. Since the surface current flowing through each of the switches is only a fraction of the total current through the device, the power handled by each of the PIN diodes is much smaller than the total power through the device; thus the power-handling capacity of the phase shifter can be greatly improved. The phase shifter is designed to provide a phase-shift range from 0^0 to 360^0 at a step of 5.625^0 and operate in the frequency band from 9.2 to 9.8 GHz. Simulation results and measurement results of the prototype agree closely and show that the phase shifter has a much higher power-handling capacity than that of the PIN diode and low insertion losses across the operating frequency band.**

***Index terms*— Microwave Phase Shifter, Composite Right/Left-Handed Transmission Line (CRLH-TL), High Power-Handling Capacity**

I. INTRODUCTION

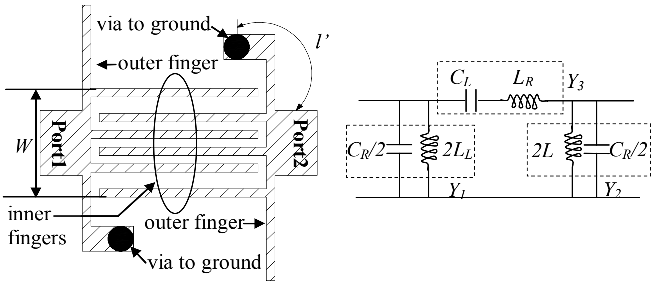
Power-handling capacity, insertion loss and size are major concerns in the design of phase shifters. Phase shifters can be classified as passive and active types. Passive phase shifters can be implemented using the ferrite technology [1] to achieve higher power-handling capacities, but they are large and heavy. Active phase shifters can be implemented using solid-state devices such as FET and CMOS technologies to reduce the sizes. However, their low power-handling capacities and nonreciprocal characteristics limit their applications.

In digital phase shifters, phase shift is usually obtained by switching between two transmission lines of different lengths or between lumped-element low-pass and high-pass filters [2]. Normally, the switches used are implemented using solid-state devices such as PIN diodes which typically have power-handling capacities of just a few Watts. Thus the power-handling capacities of the phase shifters are limited by the power-handling capacities of the switches. To construct an n-bit phase shifter, phase shifters providing different phase shifts can be cascaded together to provide the required phase shifts. This undoubtedly increases the physical size and insertion loss of the design.

In this paper, the design of a 6-bit phase shifter based on the use of the metamaterial, composite right/left-handed transmission line (CRLH-TL) [3] is presented. The major advantages of the design are compact size, high power-handling capacity and low insertion loss. Eight PIN diodes mounted on the fingers of the CRLH-TL unit cell are used as switches to control the phase incursion of the input signal going through the device. Different phase shifts are achieved by using different states of the switches and 6 controlling bits are used to select one of the sixty-four states for the required phase shift. Since the surface current flowing through each finger (and the switch mounted on it) is only a fraction of the total current flowing through the phase shifter, the proposed phase shifter can handle a much higher power than a single PIN diode. The proposed 6-bit phase shifter is designed to have a phase-shift range from 0^0 up to 360^0 at a step size of 5.625^0 and operating frequency range from 9.2 to 9.8 GHz. Computer simulation and experimental measurements are used to study the performance of the phase shifter and both results show good agreements and performances. A chassis has been used to enclose the phase shift to form a phase-shifter module which has a small size of only 60 mm×40 mm×2mm.

II. THEORY

A. Model of CRLH-TL unit cell



(a) (b)

Fig. 1 (a) Schematic and (b) equivalent π-model of CRLH-TL unit cell

The general schematic and equivalent π-model of a CRLH-TL unit cell are shown in Fig. 1, where L_R is the right-handed (RH) series inductance, C_R is the RH shunt capacitance, L_L is the left-handed (LH) shunt inductance and C_L is the LH series capacitance. The expressions for L_R, C_R, L_L and C_L are, respectively, given by [4,5]

$$L_R=\frac{Z_0\sqrt{\varepsilon_{re}}}{c}l \quad , \quad C_R=\frac{\sqrt{\varepsilon_{re}}}{Z_0 c}l \tag{1}$$

$$\begin{aligned}C_L=(\varepsilon_r+1)l\Bigg\{&4.409(N-3)\tanh\left[0.55\left(\frac{h}{W}\right)^{0.45}\right]\\&+9.92\tanh\left[0.52\left(\frac{h}{W}\right)^{0.5}\right]\Bigg\}\times 10^{-12}\end{aligned} \tag{2}$$

and

$$\begin{aligned}L_L=\frac{\mu_0}{2\pi}&\left[h\cdot\ln\left(\frac{h+\sqrt{r^2+h^2}}{r}\right)+\frac{3}{2}(r-\sqrt{r^2+h^2})\right]\\&+\frac{Z_0\sqrt{\varepsilon_{re}}}{c}l'\end{aligned} \tag{3}$$

where h is the thickness of the substrate, r is the radius of the ground pin, ε_r is the relative dielectric constant, ε_{re} is effective dielectric constant, l' is the distance from the ground hole to the port, l is the length of the finger, N is the number of the fingers, W is the width of all the fingers and Z_0 is the characteristic impedance of the fingers.

The phase constant β of the CRLH-TL unit cell can be expressed as [3]:

$$\beta=\omega\sqrt{L_R C_R}-\frac{1}{\omega\sqrt{L_L C_L}} \tag{4}$$

An electromagnetic wave traveling through the CRLH-TL unit cell will have a phase incursion:

$$\theta=\beta\times L \tag{5}$$

where L is the length of the CRLH-TL unit cell. From (1)–(3), it can be seen that the structural parameters of the CRLH-TL unit cell determine the values of L_R, C_R, L_L and C_L which in turn determine the phase incursion through (4) and (5).

B. Phase Shifter based on CRLH-TL

To illustrate the principle of the proposed phase shifter, we use a single CRLH-TL unit cell with four switches (diodes) mounted on the fingers as shown in Fig. 2. The "closed" or "open" state in each of the switches will determine the values L_R, C_R, L_L and C_L through (1)-(3) and, in turn, the phase incursion θ in (5), thus each switch state can be used to provide a particular phase shift:

$$\Delta\theta_m=(\beta_m-\beta_0)\times L \tag{6}$$

where m is the index (from 0 to 2^n-1) for switch state, β_m is the phase constant in the mth-switch state and β_0 is the phase constant in the zeroth-switch state. For convenience and without lost of generality, the zeroth-switch state can be taken as the state when all switches are close. With the use of four switches, there are sixteen possible switch states (from 0 to 15) determined by "closed" or "open" state in each of the four switches and controlled by using 4 controlling bits to have sixteen phase shifts.

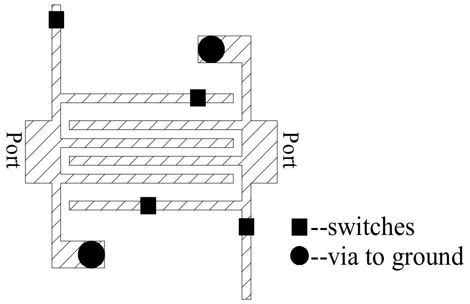
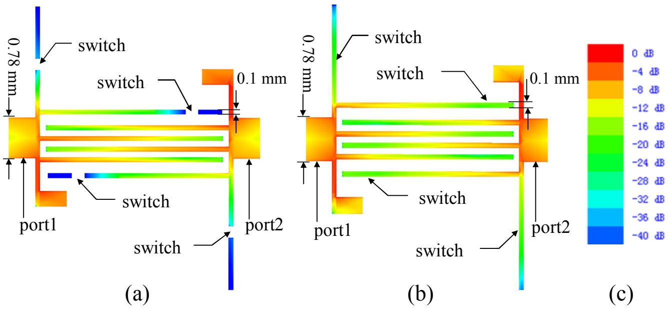


Fig. 2 CRLH-TL unit cell mounted with four switches for 16 phase shifts

The simulation tool IE3D has been used to design the dimensions of a CRLH-TL unit cell with eight fingers, as shown in Fig. 2, with finger width and spacing between them of 0.1 mm, input and output impedance of 50 Ω and the criteria of $|S_{11}| < -15$ dB and $|S_{21}| > -0.5$ dB at 9.5 GHz. The substrate used in the design had a thickness of 0.28 mm and permittivity of 2.55. Results have shown that the required widths for the input and output ports were 0.78 mm and the lengths for the inner fingers and outer fingers were 3.5 mm and 2.5 mm, respectively.



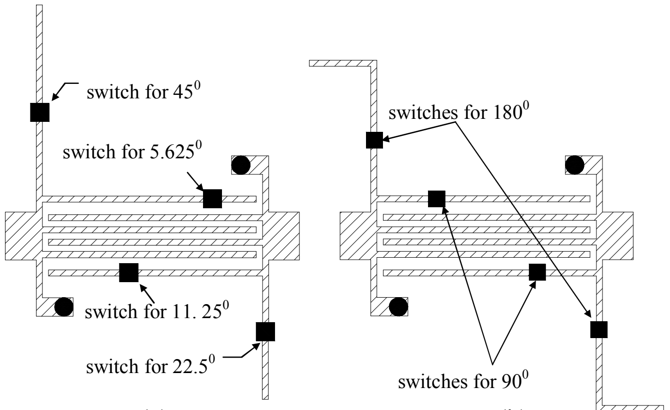
(a) (b) (c)

Fig. 3 Simulated surface-current density distribution on CRLH-TL unit cell (a) all switches "opened" (b) all switches "closed" (c) color scale of surface-current density

Surface-current density distribution has been used to study the power handled by the switches (PIN diodes) in the CRLH-TL unit cell. Figures 3(a) and 3(b) show the simulated surface-current density distributions with all four switches "opened" or "closed", respectively, at 9.5 GHz. The arrowheads indicate the positions of the switches on the fingers of the CRLH-TL unit cell. With all switches "opened",

Fig. 3(a) shows that the largest surface-current density through the switches is about 1/25.1 (-28 dB) of that through the ports. While with all switches "closed", Fig. 3(b) shows that the largest surface-current density through the switches is about 1/6.3 (-16 dB) of that through the ports. Since the width of the finger is 0.1 mm, only 1/7.8 of the width for the input and output ports, the largest surface-current through the switches is 1/49 of that through the ports. Thus the power-handling capacity of the phase shifter is about 49 times higher than the power-handling capacity of the switches (PIN diodes).

III. DESIGN OF 6-BIT PHASE SHIFTER



(a) (b)

Fig. 4 Design of 6-bit phase shifter with two CRLH-TL unit cells (a) the first CRLH-TL unit cell (b) the second CRLH-TL unit cell

Our design for a 6-bit phase shifter based on the use of the matematerial, CRLH-TL, is shown in Fig. 4. As can be seen from (1) - (6), the structural parameters of the CRLH-TL unit cell can be selected to provide the required phase shift. In Fig. 4(a), four switches are used to achieve sixteen different switch states and sixteen different phase shifts (including 0^0). The two switches on the inner fingers are used to provide the phase shifts of 5.625^0 and 11.25^0, while the two switches on the outer fingers are used to provide the phase shift of 22.5^0 and 45^0. The positions of the switches on the fingers affect the phase shift. In Fig. 4(a), the positions of the four switches producing the four corresponding phase shifts were obtained one-by-one through computer simulation. In the simulation, when the position of an open switch was being determined, all other switches were closed. When all positions had been determined, different switch states were then used to provide the other eleven phase shifts. There were interactions between switches, i.e., the total phase shift caused by two switches might not be exactly the same as the sum of the phase shifts caused by the two switches, but simulation has shown that this interaction was insignificant. Moreover, the interaction was minimised by manual tuning the positions of the switches.

In Fig. 4(b), the two pairs of switches are used to produce the larger phase shifts of 90^0 or 180^0. The pair of switches on the inner fingers is used to produce a phase shift of 90^0, while the pair of switches on the outer fingers is used to achieve a phase shift of 180^0. The phase shift of 270^0 is realized by "opening" all the four switches. The positions of the switches were determined as described previously.

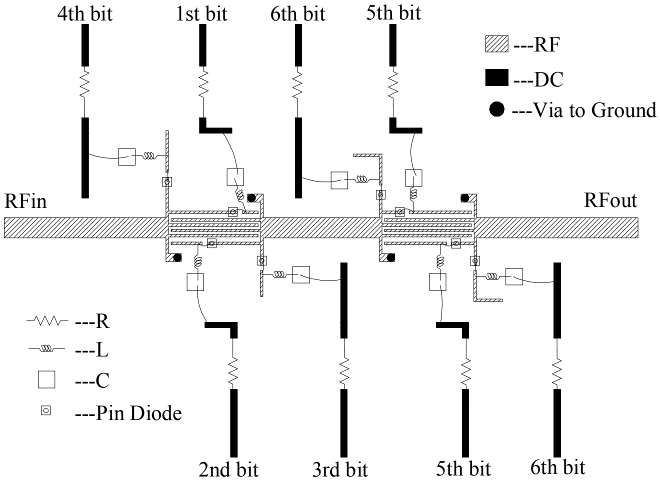


Fig. 5 Layout of 6-bit phase-shifter module

By cascading the designs of the two CRLH-TL unit cells in Figs. 4(a) and 4(b), we can have a design for a phase shifter with a phase-shift range from 0^0 to 360^0 at a step of 5.625^0. The layout of such 6-bit phase shifter is shown in Fig. 5. It consists of two CRLH-TL unit cells, one realizing the phase shifts from 5.625^0 up to 84.375^0 and the other one realizing the phase shifts from 90^0 up to 270^0. Any phase shifts at multiple numbers of 5.625^0 can be achieved by using the 6 controlling bits according to (6).

IV. SIMULATION AND MEASUREMENT RESULTS

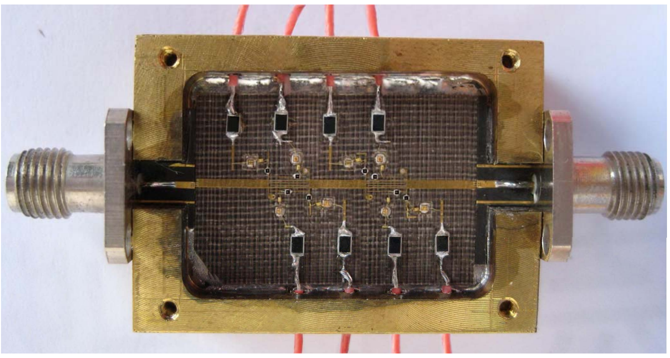


Fig. 6 Photograph of 6-bit phase-shifter module

The 6-bit phase shifter in Fig. 5 has been designed as described previously to operate in an operating frequency band of 9.2-9.8 GHz and fabricated using a polytetrafluoroethylen (PTFE) substrate with thickness of 0.28 mm and permittivity of 2.55. The photograph of the fabricated 6-bit phase-shifter module, as shown in Fig. 6, has a dimension of 60 mm×40 mm×2 mm. The PIN diodes used are from SKYWORKS Co. Ltd and have a dimension of 0.35 mm×0.35 mm×0.15 mm, operating frequency range of 100

MHz-18 GHz and instantaneous power-handling capacity of 2.5W (34 dBm). Surface-mount-technology components such as resistors, capacitors and inductors are used to construct the bias circuits for the PIN diodes and also the circuits to isolate the RF signal from DC.

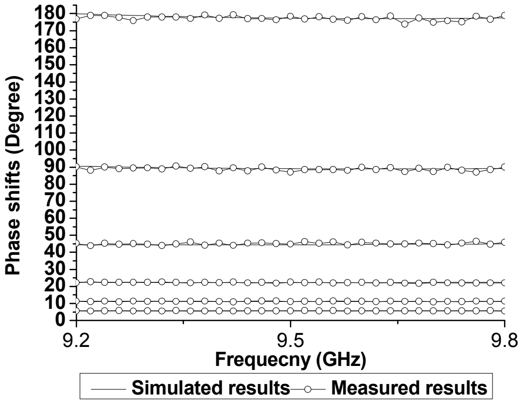


Fig. 7 Simulated and measured phase shifts of 5.625^0, 11.25^0, 22.5^0 45^0, 90^0 and 180^0

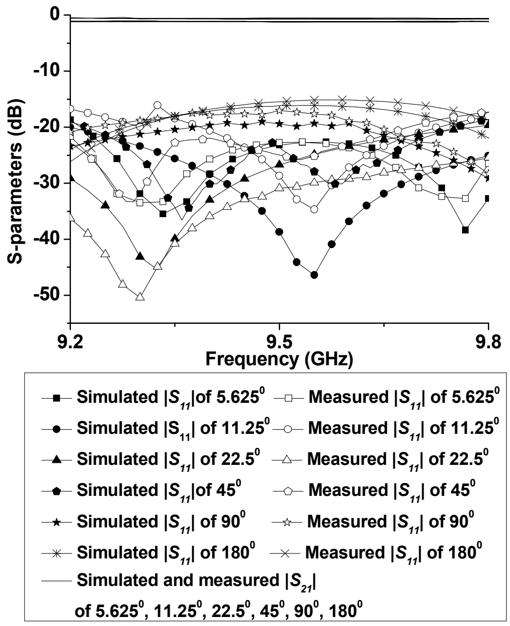


Fig. 8 Simulated and measured $|S_{11}|$ and $|S_{21}|$ for phase shifts 5.625^0, 11.25^0, 22.5^0 45^0, 90^0 and 180^0

Computer simulation and measurements have been carried out to assess the phase shifts, phase errors, insertion loss and return loss of our proposed phase shifter. Results have shown that the phase shifter can provide a phase-shift ranges from 0^0 to 360^0 at a step 5.625^0, i.e., sixty-four phase shifts (including 0^0), in the frequency band from 9.2 to 9.8 GHz by using the sixty-four switch states. The phase shifts errors are within ±4% across the operating frequency band. The simulated and measured results on different phase shifts of 5.625^0, 11.25^0, 22.5^0 45^0, 90^0 and 180^0 across the frequency band from 9.2 to 9.8 GHz are shown in Fig. 7.

To study the return loss and insertion loss, the S-parameters, $|S_{11}|$and $|S_{21}|$, of the phase shifter for different phase shifts across the frequency band from 9.2 to 9.8 GHz have been simulated and measured. Both simulated and measured results show good agreements. The measurement results have shown that the insertion loss is less than 1.3 dB (i.e., $|S_{21}| > -1.3$ dB) and the return loss is more than 15 dB ($|S_{11}| < -15$ dB) across the whole frequency band studied. The simulated and measured results on $|S_{11}|$ and $|S_{21}|$ for phase shifts of 5.625^0, 11.25^0, 22.5^0 45^0, 90^0 and 180^0 are shown in Fig. 8.

The power-handling capacity of the phase shifter has also been measured. In the measurement, the maximum transmitted peak power which caused a PIN diode to blow up was taken as the power-handling capacity of the phase shifter. The PIN diodes used in our design had an instantaneous power-handling capacity of 34 dBm. By analysing the surface-current density distribution of the two CRLH-TL unit cells in Fig. 4 at 9.5 GHz, the expected power-handling capacity of our proposed phase shifter was about 50.2 dBm, i.e. 42 times of the PIN diodes. The measured results have shown that our proposed phase shifter has a power-handling capacity of over 50.5 dBm in the frequency range studied, which is about 45 times of the power-handling capacity of the PIN diodes.

V. CONCLUSIONS

The design of a 6-bit phase shifter based on the use of metamaterial, CRLH-TL, has been presented. The phase shifter has a compact size and high power-handling capacity. It can provide a phase-shift range from 0^0 to 360^0 at a step 5.625^0 and operate in the frequency band from 9.2 to 9.8 GHz. Measurement results have shown that the phase shifter has a low insertion loss of less than 1.3 dB, a high return loss of more than 15 dB and a small phase shift error of ±4% across the operating frequency band. The power level that it can handle is 45 times higher than that of the PIN diodes used as switches in our design.

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