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A new broadband differential phase shifter fabricated using a novel CRLH structure*

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Abstract: Broadband phase shifters are mostly proposed and fabricated based on the scheme proposed by Shiffman, which uses a coupled line with far ends connected together and a uniform transmission line to give a differential phase shift. Based on the unique dispersion property of the composite right/left-handed (CRLH) metamaterial structure, a new configuration is presented in this paper for fabricating the broadband differential phase shifter, which employs a novel CRLH metamaterial structure as one of the differential phase-shift arms, instead of the conventional coupled line. The new circuit can achieve a phase shift of 90° in an operational bandwidth as broad as one octave and its phase deviations are quite small. An original design of the novel broadband phase shifter is presented, in which the artificial CRLH structure was implemented by microstrip quasi-lumped elements. Both the simulated and measured results of the 90° broadband differential phase shifter are presented.

Key words: Broadband, Differential phase shifter, Composite right/left-handed (CRLH) metamaterial structure, Quasi-lumped elements
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INTRODUCTION

Differential phase shifters are key passive components widely used in microwave and RF systems, such as hybrid circuits and phase array antennas. Usually broadband phase and amplitude balance can be obtained by the Shiffman phase shifter (Schiffman, 1958), which is conveniently constructed from two separated transmission lines, one of which is folded (parallel-coupled) to be dispersive (Fig.1a). A general synthesis procedure of the basic Shiffman phase shifter was described by Ramos Quirarte and Starski (1991). Ramos Quirarte and Starski (1993) also developed the novel configurations of this kind of shifters with a larger range of feasibility compared to the standard ones. Recently, Guo *et al.*(2006) presented an improved wide-band Shiffman phase shifter using a novel patterned ground plane technology, which achieved good performance in compact size.

Generally, broadband differential phase shifter is mainly operated based on the parallel phase response curves of its two arms. The phase deviation can be very small if the two curves are well paralleled in the wide work band. In order to improve the performance of differential phase shifters, new configurations are proposed for constructing this kind of devices, in which the novel metamaterial structure is used to substitute for the conventional folded coupled-line in the basic Shiffman phase shifter (Kholodnyak *et al.*, 2006). Metamaterials are broadly defined as effectively homogeneous artificial structures with unusual properties. Left-handed metamaterials (LH MMs) represent an interesting example of metamaterials, which is inspiring significant interests in both physics and microwave communities. LH MMs were first

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investigated theoretically by Veselago (1968). Shelby *et al.*(2001) fabricated the first bulk of LH MMs using the so-called SRR structures to demonstrate the negative refraction phenomenon. Most recently, LH MMs formed by L-C loaded microstrip transmission line (TL) have also been studied at microwave frequencies both in theories and experiments (Eleftheriades *et al.*, 2003). Specially, the metamaterial structures having right-handed and left-handed dispersive properties in two different operational frequency bands, respectively, were first presented by Caloz and Itoh (2004). These structures are usually referred to as CRLH metamaterials (Caloz, 2006; Hu *et al.*, 2006). The CRLH structures are very suitable for designing the differential phase shifter due to their unique dispersive property. In this paper, a new differential phase shifter using a novel CRLH structure is newly fabricated. The simulation and measured results illustrate that the new scheme can achieve broadband phase shift and relatively small insertion loss.

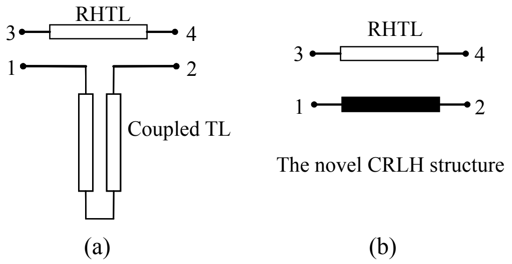

Fig.1 The circuit schemes for (a) standard Shiffman phase shifter and (b) new differential phase shifter based on the uniform RHTL and novel CRLH structure

DESIGN OF NOVEL PHASE SHIFTERS

The basic configuration of the novel phase shifters is shown in Fig.1b, which has two differential arms, the uniform right-handed transmission line (RHTL) arm and the proposed novel CRLH structure arm. The equivalent circuit mode of the proposed lossless CRLH metamaterial unit cell is depicted in Fig.2a, which consists of a per-unit-length impedance (*Z*) constituted by the inductor L_R in series with the capacitor C_L and a per-unit-length admittance (*Y*) by the inductor L_L in series with the capacitor C_g and the paralleled capacitor C_R. The whole circuit can be implemented on quasi-lumped elements in Fig.2b, as presented in (Casares-Miranda *et al.*, 2006). The horizontal interdigital fingers and the right wide wire are used to form the series inductor L_R and capacitor C_L while the vertical interdigital fingers and the right thin wire are used to form the series inductor L_L and capacitor C_g in Fig.2a. The bottom via hole, in a radius of *R*, is used to connect the vertical interdigital fingers to the ground plane. All the microstrip conductor edges and the ground plane form the parallel capacitor C_R. The detailed parameters of the horizontal interdigital fingers are illustrated in Fig.2b and their notations are indexed by subscript ‘1’ (such as S_1, G_1). Similarly, the parameters of the vertical interdigital fingers are defined in the same fashion but indexed by subscript ‘2’ (such as S_2, G_2, not shown herein). The width and length of the right wires connecting the two groups of fingers are defined as W_{s1}, L_{s1}, W_{s2} and L_{s2}, respectively.

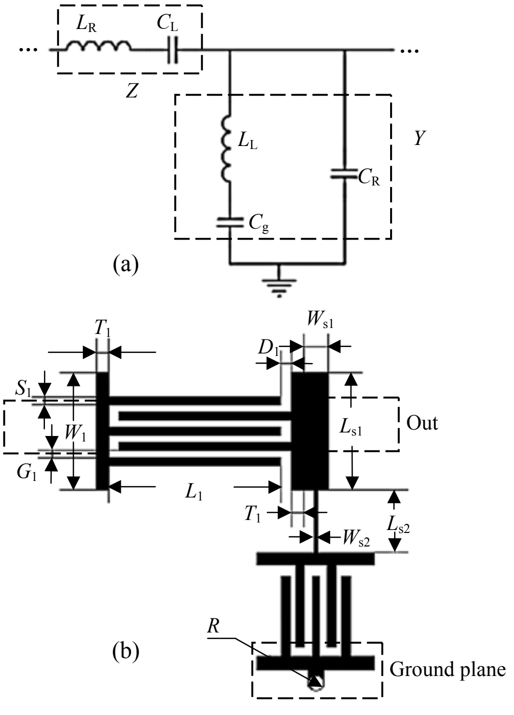

Fig.2 (a) Equivalent circuit mode for the ideal TL unit cell of CRLH structure; (b) The CRLH structure implemented on quasi-lumped elements

As shown in Fig.2a, *Z* and *Y* can be easily written as

$$Z = \mathrm{j}\omega L_R + 1/(\mathrm{j}\omega C_L),$$
$$Y = 1/[\mathrm{j}\omega L_L + (\mathrm{j}\omega C_g)^{-1}] + \mathrm{j}\omega C_R.$$

The propagation constant β and characteristic impedance Z_C of the proposed CRLH metamaterial can be straightforwardly derived by elementary TL theory (Caloz and Itoh, 2006):

$$\gamma p = \mathrm{j}\beta p = \sqrt{ZY}, \quad \Phi_{\mathrm{CRLH}} = \beta p,$$

$$\Phi_{\mathrm{CRLH}} = \sqrt{-\left[\mathrm{j}\omega L_{\mathrm{R}} + (\mathrm{j}\omega C_{\mathrm{L}})^{-1}\right]\left[\frac{1}{\mathrm{j}\omega L_{\mathrm{L}} + (\mathrm{j}\omega C_{\mathrm{g}})^{-1}} + \mathrm{j}\omega C_{\mathrm{R}}\right]}, \tag{1}$$

$$Z_{\mathrm{C}} = \sqrt{Z/Y},$$

$$Z_{\mathrm{C}} = \sqrt{\left[\mathrm{j}\omega L_{\mathrm{R}} + (\mathrm{j}\omega C_{\mathrm{L}})^{-1}\right] \Big/ \left[\frac{1}{\mathrm{j}\omega L_{\mathrm{L}} + (\mathrm{j}\omega C_{\mathrm{g}})^{-1}} + \mathrm{j}\omega C_{\mathrm{R}}\right]}. \tag{2}$$

On the other hand, the conventional uniform RHTL has a linear phase response of

$$\Phi_{\mathrm{RHTL}} = \beta' l, \text{ or } \Phi_{\mathrm{RHTL}} = \theta_0 f / f_0. \tag{3}$$

Here l and β' are physical length and propagation constant of the RHTL, respectively; f denotes the frequency (in Hz) and θ_0 is the electrical length of the RHTL at the frequency f_0. According to Eqs.(1) and (3), the phase responses of the conventional RHTL and the novel CRLH structures can be approximately depicted as in Fig.3, which indicates that the CRLH structures have a primary phase (not zero) at zero frequency, however, they also have almost linear phase response in high-frequency bands. That is the unique dispersive property of the CRLH structure, which makes the CRLH structure and the RHTL can have parallel dispersion curves and phase responses.

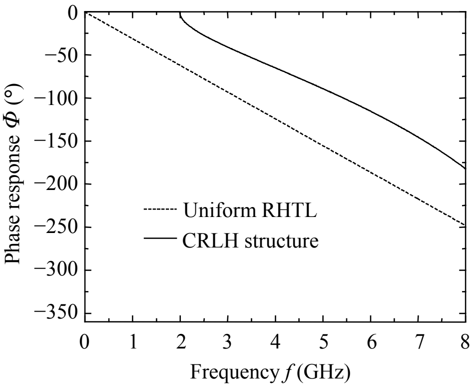

Fig.3 The schematic diagram of phase response (Φ: °). For the RHTL, Φ=−31.3f (f in GHz); for the CRLH structure, L_R=0.1459 nH, C_L=10.8510 pF, L_L=0.7639 nH, C_R= 0.0633 fF, C_g=0.2303 pF, and p=6

As shown in Fig.3, in the wide frequency range, the phase responses of the CRLH structures and the RHTL are almost paralleled, on which a novel broadband differential phase shifter can be constructed as shown in Fig.1b. The differential phase shift is defined as

$$\Delta\Phi = \Phi_{\mathrm{RHTL}} - \Phi_{\mathrm{CRLH}}. \tag{4}$$

SIMULATION AND MEASURED RESULTS

To demonstrate the availability of the new scheme, a broadband 90° differential phase shifter is designed and fabricated as shown in Fig.4. For the RHTL arm, the width of the uniform microstrip is 4.57 mm and the length is 29.3 mm; for the proposed CRLH structure, the length L_1 of the horizontal fingers is 7 mm and the length L_2 of the vertical fingers is 6 mm. The widths of all the fingers and their gaps (S_1, S_2, G_1, G_2, T_1, T_2, D_1 and D_2) are 0.1 mm. The horizontal interdigital strips have 6 pairs of fingers and the vertical ones have 11 pairs. The radius of via hole is 0.15 mm. For the wires connecting the two groups of fingers, the width and length are W_{s1}=1 mm, L_{s1}=4.57 mm, W_{s2}=0.2 mm and L_{s2}=5 mm, respectively. Both the input and output microstrips are designed in the 50-Ω characteristic impedance and physical length of 5 mm. The whole device is fabricated on a substrate of F4B material with permittivity of 2.2 and height of 1.5 mm. The phase responses of two arms are simulated by the fullwave EM software, IE3D and measured by the network analyzer, Advantest R3765C. All the simulations and measured results are shown in Fig.5.

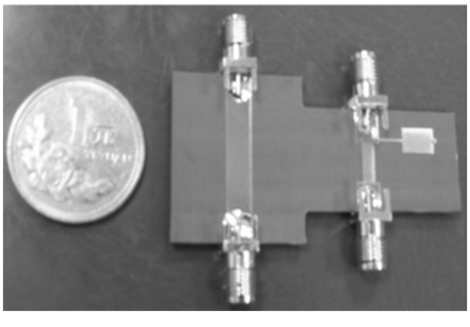

Fig.4 The fabricated device of the proposed differential phase shifter

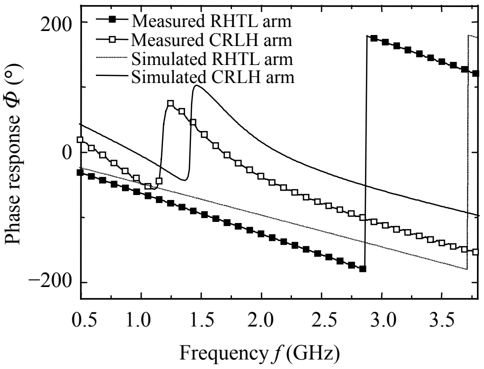

Fig.5 Simulated and measured phase responses of the proposed CRLH and RHTL arms for the novel 90° differential phase shifter

As shown in Fig.5, the simulated phase responses of the two arms are well paralleled at about 2.3~3.8 GHz, while the measured phase responses of the two arms are well paralleled at about 2.1~3.8 GHz. That means the arms of the fabricated device have relatively large phase shifts and electrical lengths than the simulation. It might be caused by the practical substrate material, which had a higher permittivity than the simulated one, 2.2 GHz.

The differential phase shifts of both the simulated and measured results are depicted in detail in Fig.6. The simulation results show that the phase shift is about −90° in the frequency range of 2.3~3.8 GHz. The phase deviation is less than 5° in the whole pass band and in the major pass band it is even less than 2.5°. Actually, in the frequency range of 1.9~3.8 GHz (one octave), the measured phase shift is about −85° and the phase deviation is also small. The simulation and measured results are close. Obviously, the −90° differential phase shift can be easily achieved if the RHTL electrical length is increased.

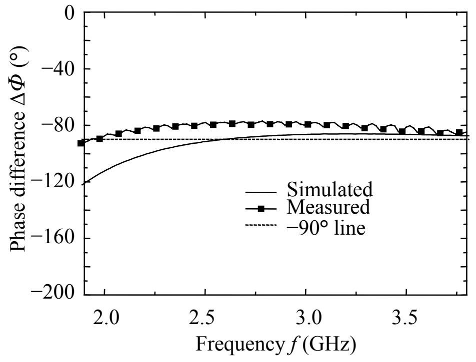

Fig.6 Simulated and measured phase shift ($\Delta\Phi$) vs the frequency (f) for the novel 90° differential phase shifter

Specially, the transmission performance of the proposed CRLH structure arm is simulated and measured, as shown in Fig.7. Compared with the simulated results, the measured S-parameters curves are shifted to low frequency perhaps because of a high permittivity substrate. In the measured frequency range of 1.9~3.8 GHz, $S11$ is less than −15.0 dB and $S21$ is more than −1.0 dB, which means the fabricated device has a relatively small insertion loss.

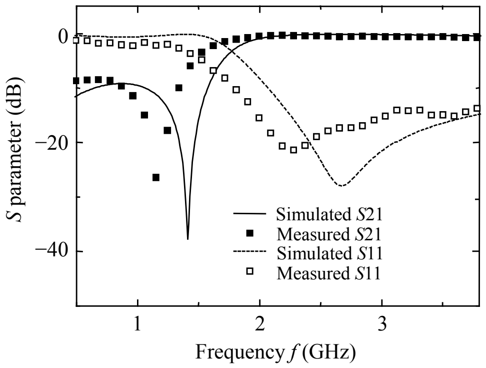

Fig.7 Simulated and measured S results of the proposed CRLH arm for the novel 90° differential phase shifter

CONCLUSION

A novel CRLH structure is presented and investigated in this paper. By using the novel CRLH structure to replace the conventional coupled TL in the standard Schiffman phase, a new scheme of the differential phase shifter has been proposed and implemented. For instance, a broadband 90° differential phase shifter is designed and fabricated. The simulation and measured results indicate that the novel device can lead to a constant differential phase shift with a small phase deviation of about one-octave bandwidth in S-band frequency range. In the whole pass band, the device has relatively low insertion loss. In the future, there will be more efficient and flexible metamaterial structures which will be exploited and designed for microwave circuit applications. These novel metamaterial structures will exhibit a good prospect in microwave and RF engineering.

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