Design of 90°-switched-line Phase Shifter with Constant Phase Shift Using CRLH TL

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Abstract— The design of a 90°-switched-line phase shifter using composite right/left handed transmission line (CRLH TL) is presented in this paper. To achieve a relatively constant phase shift over a large bandwidth, a CRLH TL implemented using lumped elements and a right-handed transmission line (RH TL) are used as the reference and delay arms, respectively, of the phase shifter. Computer simulation is used to study and design the phase shifter. The phase shifter is also fabricated and measured to verify the simulation results. For comparison, a conventional 90°-switched-line phase shifter is also designed and simulated. Simulation and measurement results show that, the proposed phase shifter has a constant phase shift, a high return loss and a low insertion loss across the operating frequency band.

1. INTRODUCTION

Phase shifter is an essential component in the designs of in the radar and phased array systems. Insertion loss, operating bandwidth and constant phase shift within the bandwidth are the major concerns in the design of phase shifters. In a switched-line phase shifter, the phase shift is usually obtained by switching between two transmission lines (TL) of different lengths [1]. To achieve a wide operating bandwidth, the characteristic impedances of the two arms should be designed to match the port impedance in both states. Moreover, the slopes of the phase response versus frequency of the two TLs must be the same. However, this is very difficult to achieve, so it is difficult to have a constant phase shift within the operating frequency band.

The concept of metamaterials, commonely known as left-handed materials (LHMs), was first investigated by Veselago in 1968 [2]. LHMs have negative permittivity and permeability which are not commonly found in nature. Although the properties of LMHs promised for a large diversity of novel applications and devices, LMHs did not attract much attention until it was found that the materials could be realized using a general TL approach [3]. Practical left-handed TL (LH TL) also have the right-handed effects, so LHMs realized using TL are called composite right/left handed transmission line (CRLH TL). CRLH TL can be used to design many different microwave components such as phase shifters, delay lines and bandpass filters, etc..

In this paper, we propose to use CRLH TL to design an 90°-switched-line phase shifter with constant phase shift. The constant phase shift is achieved using CRLH TL as the reference arm and a RH TL as the delay arm. The CRLH TL is implemented using lumped elements. For comparison, a conventional 90°-switched-line phase shifter is also designed and simulated. Simulation and measurement results show that our proposed phase shifter can provide a relatively constant phase shift within the operating bandwidth compared with the conventional switched-line phase shifter.

2. THEORY

A conventional transmission lines (TL), in which the phase and group velocity are codirectional, has a positive phase constant β and is referred as a right-hand transmission line (RH TL). The phase response $\mathrm{Ang}(S_{21})$ of a RH TL is negative and linearly relating to frequency. The slope of the phase response versus frequency varies the length of the TL. A CRLH TL has a negative phase constant β and a positive phase response $\mathrm{Ang}(S_{21})$ in the LH region of the dispersion diagram [4]. The phase response $\mathrm{Ang}(S_{21})$ is not linearly relating to frequency, so the slope of the response versus frequency is not constant but varying with frequency. Thus it is possible to design a RH TL and a CRLH TL to have their phase responses quite parallel to each other across the operating bandwidth.

In a switched-line phase shifter, the difference of phase responses in the arms is the phase shift.

$$\theta = (\mathrm{Ang}(S_{21}))_{\text{reference arm}} - (\mathrm{Ang}(S_{21}))_{\text{delay arm}}$$

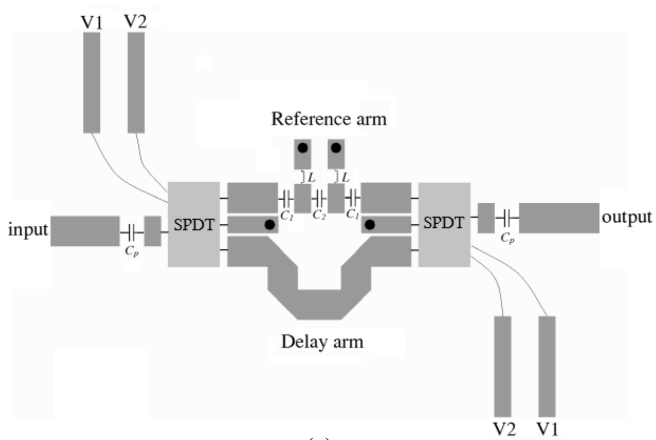
Thus if the RH TL and CRLH TL are used in the two arms of a switched-line phase shifter, the phase shift could be constant. This idea is used in the design of a 90°-phase shifter in this paper.

In the design, we select the parameters of the CRLH TL and the length of the RH TL to satisfy as much as possible the following two criterions:

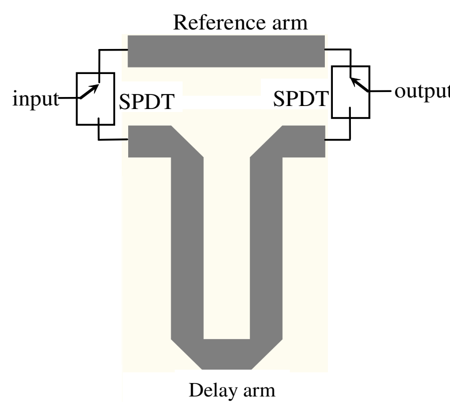
1) the phase responses of the RH TL and CRLH TL are in parallel, and
2) the difference of the phase responses at the operating band is 90°.

3. DESIGN OF PHASE SHIFTER

The design of our proposed 90°-switched-line phase shifter is shown in Fig. 1(a). Two singlepole doublethrow (SPDT) switches are used at the input and output of the phase shifter. A CRLH TL implemented using lumped elements is used as the reference arm and a meander RH TL is used as the delay arm of the phase shifter. The SPDT switches are from SKYWORKS Co. Ltd. Each of the SPDT switches has 2 inputs, V_1 and V_2, which are used to select either the reference arm or delay arm. The reference arm can be selected by setting $V_1 = 0\,\text{V}$ and $V_2 = 4\,\text{V}$, while the delay arm can be selected by setting $V_1 = 4\,\text{V}$ and $V_2 = 0\,\text{V}$. The capacitors are from SAMSUNG Co. Ltd. and the inductors are from MURATA Co. Ltd. The phase shifter has an overall area of $40 \times 12.2\,\text{mm}^2$. The CRLH TL and the meander RH TL together are designed manually using computer simulation to achieve a constant phase shift of 90°. The values in the final design are $C_1 = 10\,\text{pF}$, $C_2 = 5\,\text{pF}$ and $L = 12.1\,\text{nH}$. For comparison, a conventional 90°-switched-line phase shifter using RH TLs for both the reference arm and delay arm as shown in Fig. 1(b) is also designed. A Rogers RO4350B substrate with a relative dielectric constant of 3.48, thickness of 0.762 and a loss tangent of 0.003 is used as the substrate in the designs of the two phase shifters. Fig. 2 shows the proposed prototyped 90°-switched-line phase shifter.



(a)



(b)

Figure 1: Layouts of (a) proposed and (b) conventional 90°-switched-line phase shifters.

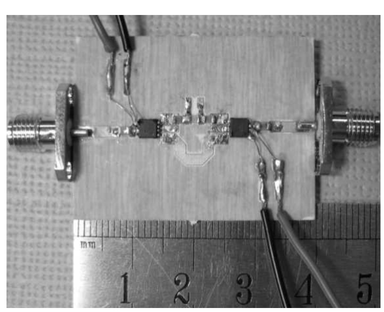


Figure 2: Proposed prototyped 90°-switched-line phase shifter.

4. RESULTS AND DISCUSSIONS

Computer simulation and measurements have been carried out to study the performances of the 90°-switched-line phase shifters. The simulated and measured return losses (RLs), insertion losses (Ils), phase responses and phase shifts are shown in Fig. 3, which show good agreements.

The measured results in Fig. 3(a) show that, with the reference arm switched on, the phase shifter has a operating bandwidth of 0.58–2.7 GHz with RL > 10 dB and IL < 2 dB. When the delay arm is switched on, Fig. 3(b) shows that the phase shifter has a bandwidth of 0.3–2.7 GHz with RL > 20 dB and IL < 2 dB. The differences between the simulated and measured ILs when the

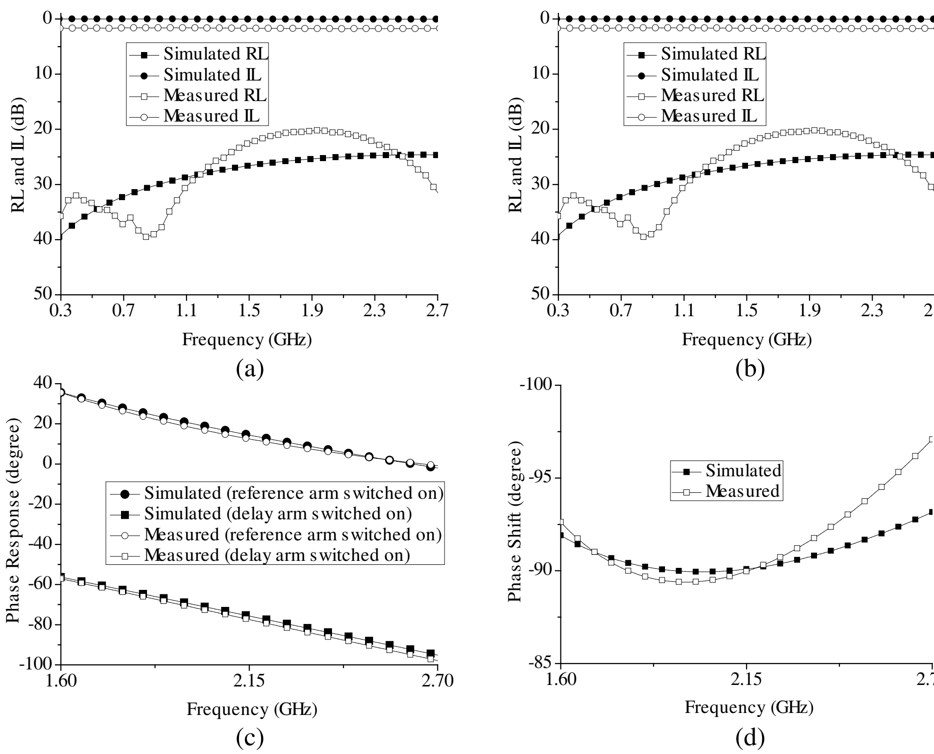


Figure 3: Simulated and measured (a) RLs and ILs with reference arm switched on, (b) RLs and ILs with delay arm switched on, (c) phase responses, and (d) phase shifts of proposed phase shifter.

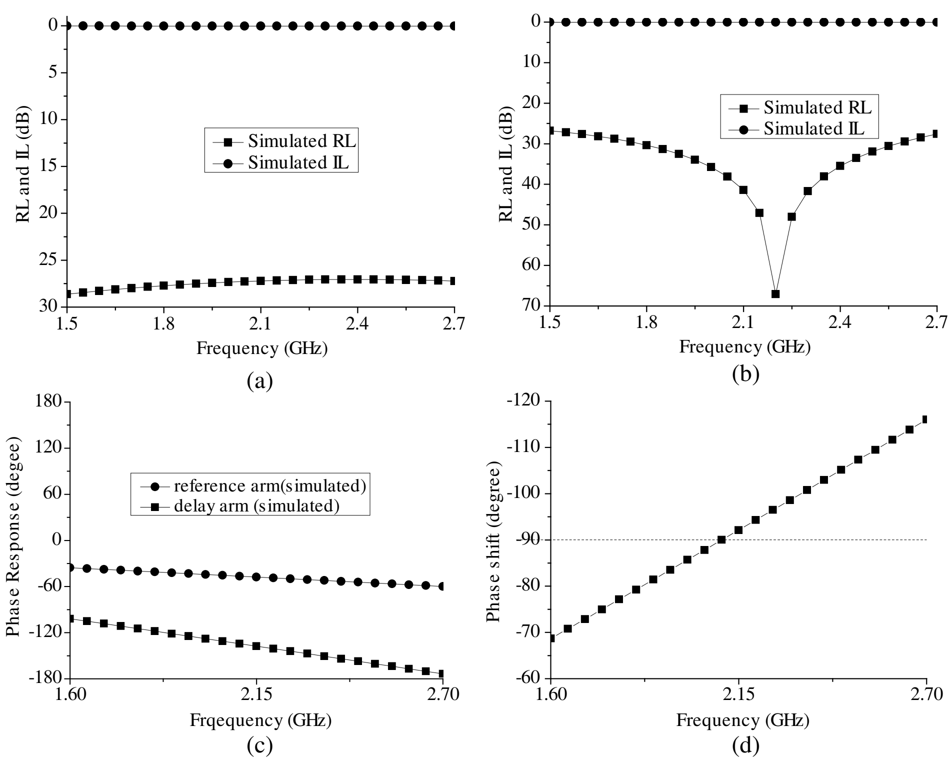


Figure 4: Simulated (a) RL and IL with reference arm switched on, (b) RL and IL with delay arm switched on, (c) phase response, and (d) phase shift of the conventional phase shifter.

reference arm or delay arm is switched on are about 1.6 dB as can be seen in Figs. 3(a) and 3(b). These differences are caused by the IL of the two SPDT switches used in the designs. Fig. 3(c) shows that the simulated and measured phase responses when the reference arm or delay arm is switched on are quite in parallel. Fig. 3(d) shows that the measured phase shift is about $-90°$ with a variation range of $-7°$ to $+0.6°$ in the bandwidth of 1.6–2.7 GHz.

For comparison, the simulated RL, IL, phase response and phase shift of the conventional 90°-switched-line phase shifter in Fig. 1(b) are shown in Fig. 4. Figs. 4(a) and 4(b) show that when the reference arm or delay arm is switched on, good impendence matching in the frequency band of 1.5–2.7 GHz with RL $>$ 20 dB and IL $<$ 1 dB can be achieved. However, the simulated phase responses when the reference arm or delay arm is switched on are not in parallel as shown in Fig. 4(c). The phase shift in the bandwidth of 1.6–2.7 GHz shown in Fig. 4(d) is $-90°$, indicating a large variation range of $-21.3°$ to $+26°$.

5. CONCLUSION

In this paper, a 90°-switched-line phase shifter with constant phase shift using CRLH TL has been designed, fabricated and measured. Results have shown that the proposed phase shifter can provide quite a constant phase shift of $-90°$ with a small variation range of $-7°$ to $+0.6°$. It has a wide operating bandwidth of 1.6–2.7 GHz, a high return loss of more than 10 dB, and a low insertion loss of less than 2 dB.

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