A Wideband Time-delay Line Inspired by CRLH TL Unit Cell

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***Abstract*— This paper presents the design of ultra-wideband time-delay lines in microwave frequency inspired by the composite right/left-handed transmission line (CRLH TL) unit cell. A rotated version of the conventional CRLH TL unit cell is used to achieve an ultrawide bandwidth. For comparison, the time-delay lines using the conventional CRLH TL unit cells, right-handed transmission line (RH TL) and periodic microstrip line (PML) are also designed, optimized and fabricated. Simulation and measurement results show that, for the same length of 60 mm, our proposed time-delay line has an ultrawide bandwidth and much longer time delay than those of the RH TL and PML ones. It also has the advantages of high return loss and low insertion loss.**

I. Introduction

Time-delay lines have found applications in different areas, such as signal processing systems, telecommunications systems and phased array systems. In the design of time-delay lines for microwave applications, the size, return loss, insertion loss and bandwidth are major concerns. Time-delay lines based on waveguides are low loss, but bulky and expensive, while time-delay lines based on transmission lines are of smaller sizes and losses.

The concept of metamaterials, commonly known as left-handed materials (LHMs), was first investigated by Veselago in 1968 [1]. 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 transmission line (TL) approach [2]. Practical LH TLs also have the right-handed (RH) effects, so LHMs realized using TLs are called composite right/left handed transmission lines (CRLH TLs). CRLH TL can be used to design many different microwave components such as phase shifters, antennas and bandpass filters, etc. Recently, different design approaches of time-delay lines based on using the CRLH TL have been proposed and studied [3-6]. However, these designs share one of the major drawbacks, i.e., the bandwidth is relatively narrow.

In this paper, we propose to use conventional CRLH TL unit cells [3] to design a narrowband time-delay line and a rotated version to design a time-delay line for ultra-wide band (UWB) applications. Simulation and measurement results show that our proposed time-delay line can provide a much longer time delay than those of the time- delay lines based on the periodic microstrip line (PML) [3] and the traditional right-handed transmission line (RH TL). Moreover, our proposed time-delay line has a much wider operation bandwidth of 0.1–10 GHz than that of using the conventional CRLH TL unit cells, a high return loss of more than 15 dB and a low insertion loss of less than 1 dB.

II. Time Delay of Transmission Line

The time delay of a transmission line is the time it takes for a signal to travel from one end to the other end of it. This time-delay property can be used to design time-delay lines. For a transmission line with a length of L, the time-delay for a signal to travel through is given by:

$$t_{delay} = \frac{L}{\lambda f} = \frac{L \times \beta}{2\pi f} \tag{1}$$

where f is the signal frequency and $\beta=2\pi/\lambda$ is the phase constant. Equation (1) shows that the time delay is proportional to the length of the transmission line. However, the equation also shows the time delay is proportional to the phase constant β. Thus, for a fixed length of transmission line, a larger time delay can be obtained by using a larger phase constant β. A transmission line (which can be called RH TL) has a wide bandwidth but a small phase constant β. If it is used to implement a delay line with a large time delay, the total of length of the time-delay line will be very long, leading to a high insertion loss. A periodic microstrip line (PML) can be realized by making periodic defection on RH TL. It has a large bandwidth and, at the same time, a larger phase constant β than that of the RH TL due to the slow-wave characteristic [7].

III. Time-Delay Lines Using CRLH TL Unit Cells

A. Model of CRLH TL Unit Cell

The general schematic figure and the equivalent circuit of a conventional CRLH TL unit cell [3] with six fingers are shown in Fig. 1, where in Fig. 1(b) the series inductance L_R and capacitance C_L are the inductance along the fingers and the coupling capacitance between the fingers, respectively, the shunt inductance L_L is realized by the two fingers each having a via at the end to the ground, and the shunt capacitance C_R is the stray capacitance of the fingers.

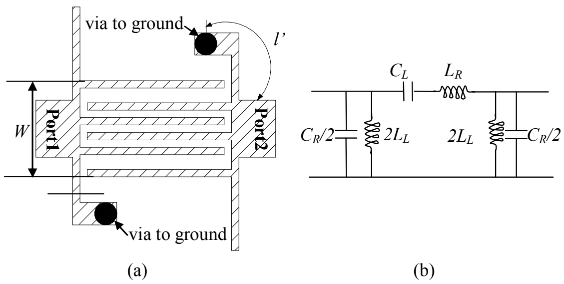


Figure 1 (a) Structure and (b) equivalent circuit of conventional CRLH TL unit cell

The expressions for L_R, C_R, L_L and C_L are, respectively, given by [8,9]:

$$L_R = \frac{Z_0\sqrt{\varepsilon_{re}}}{c} l \tag{2}$$

$$C_R = \frac{\sqrt{\varepsilon_{re}}}{Z_0 c} l \tag{3}$$

$$C_L = (\varepsilon_r + 1) l \left\{ 4.409(N-3)\tanh\left[0.55\left(\frac{h}{W}\right)^{0.45}\right] + 9.92\tanh\left[0.52\left(\frac{h}{W}\right)^{0.5}\right]\right\} \times 10^{-12} \tag{4}$$

$$L_L = \frac{\mu_0}{2\pi}\left[h \cdot \ln\left(\frac{h+\sqrt{r^2+h^2}}{r}\right) + \frac{3}{2}(r - \sqrt{r^2+h^2})\right] + \frac{Z_0\sqrt{\varepsilon_{re}}}{c} l' \tag{5}$$

where h is the thickness of the substrate, r is the radius of the ground via, ε_r is the relative dielectric constant, ε_{re} is the effective dielectric constant, l' is the distance from the ground via to the port, l is the length of the finger, N is the number of fingers, W is the width of all the fingers together and Z_0 is the characteristic impedance of each of the fingers. The phase constant β of such CRLH TL unit cell is [10]:

$$\beta = \omega\sqrt{L_R C_R} - \frac{1}{\omega\sqrt{L_L C_L}} \tag{6}$$

(2) - (6) show that the structural parameters L_R, C_R, L_L and C_L determine β and hence the times delay of the unit cell through (1).

B. Narrowband Time-delay Line

Here we propose to use the conventional CRLH TL unit cells to design time-delay lines. To provide a long delay time, we can use the structural parameters L_R, C_R, L_L and C_L through (1)-(6) to control the value of β for the unit cell and cascade a number of the unit cells together. Although we can design a time-delay line with a large delay using the CRLH TL unit cells, computer simulation results have shown that using the larger values of β in the CRLH TL unit cells results in the time-delay line having a narrower bandwidth.

C. Wideband Time-delay Line

To extend the bandwidth of the time-delay line, we propose to rotate the CRLH TL cell by 90-degree and reduce the number of fingers to five, as shown in Fig. 2(a), with the equivalent circuit shown in Fig. 2(b). The reason to reduce the number of fingers to five is to make the unit cell having a symmetrical structure so that the two S-parameters, S_{11} and S_{22} are equal. One of the main advantages of using such symmetrical structure is that we can use identical unit cells in cascade to provide a long time delay. Since the two S-parameters, S_{11} and S_{22}, in each unit cell are equal, so there is no need to perform any matching process between the unit cells. Simulation studies have shown that it has a much wider bandwidth, so we use this to design the time-delay line.

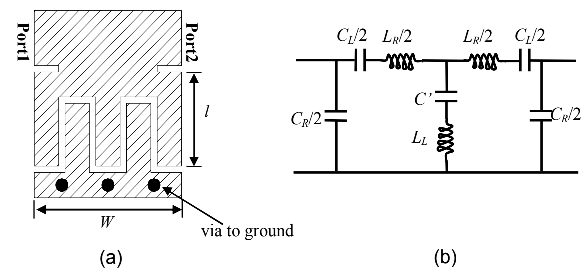


Figure 2 (a) Rotated structure and (b) equivalent circuit of the unit cell

IV. SIMULATION, MEASUREMENTS AND DISSCUSSIONS

A time-delay line employing 16 rotated unit cells in cascade, leading to a total length of 60 mm, has been designed and optimized using the EM simulation tool CST MWS. In the optimization process, the number of fingers used in each unit cell was five as shown in Fig. 2(a) and the width of each finger was set to 0.2 mm (which is the smallest dimension we could make in our lab). The dimensions of the unit cell were optimized with the criteria of having (1) $|S_{11}| < -15$ dB, and (2) the largest phase constant β. The final optimization results were used for fabrication on a F4B-2 PCB with a thickness of 0.8 mm and permittivity of 2.65. For comparison, the time-delay lines using the conventional CRLH unit cells (denoted as the narrowband time-delay line here), PML and RH TL with the same length of 60 mm have also been designed, optimized and fabricated using the same substrate. The layouts and photographs of the four time-delay lines are shown in Figs. 3 and 4. To further increase the phase constant β, hence the time delay, of the rotated unit cell, we use a periodic rectangular shape on the top edge of the time-delay line as shown in Figs. 3(a) and 4(a).

Simulation studies have indicated that the length of the fingers in the rotated unit cells has significant effects on $|S_{11}|$, so the optimization process mainly optimizes the length of the fingers. Simulation and measurement results on the two S-parameters, $|S_{11}|$ and $|S_{21}|$, and the time delay of these time-delay lines are shown in Figs. 5 and 6, respectively. It can be seen that the simulated and measured results show good agreements. For the proposed time-delay line, Fig. 5(a) shows that the measured return loss is more than 15 dB ($|S_{11}|$<-15 dB) across the whole frequency band tested. The insertion loss is less than 1 dB (i.e., $|S_{21}|$>-1dB) across the frequency band tested. Among these time-delay lines, the proposed time-delay line achieves the largest time delay of 2000 ps across the whole frequency band tested, i.e. 0.1 – 10 GHz, as can be seen in Fig. 6.

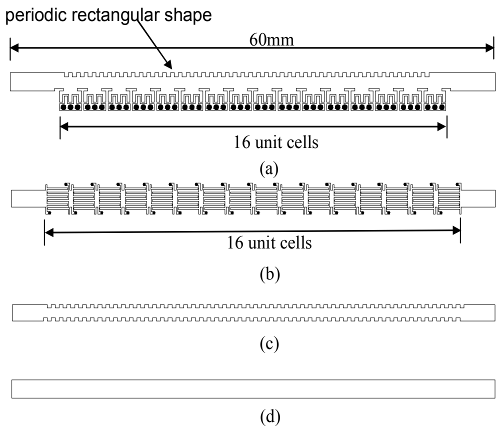


Figure 3 Layouts of time-delay lines using
(a) rortaed wideband unit cells, (b) conventional CRLH TL unit cells,
(c) PML and (d) RH TL

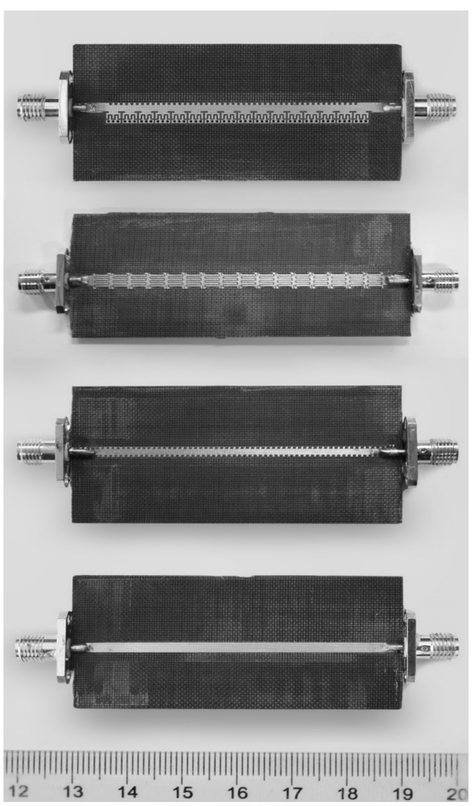
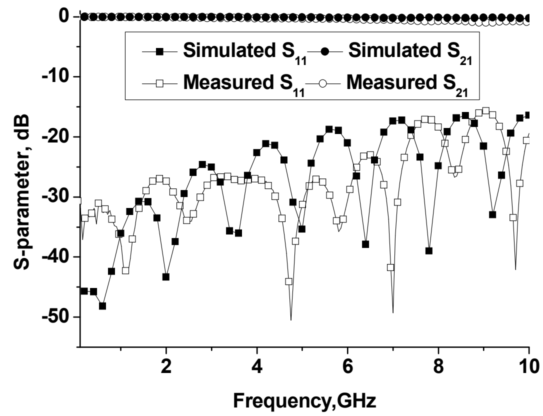
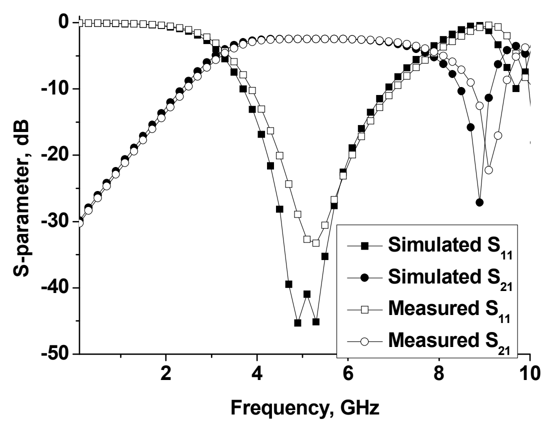


Figure 4 Photographs of time-delay lines using
(a) rortaed wideband unit cells, (b) conventional CRLH TL unit cells, (c) PML and (d) RH TL

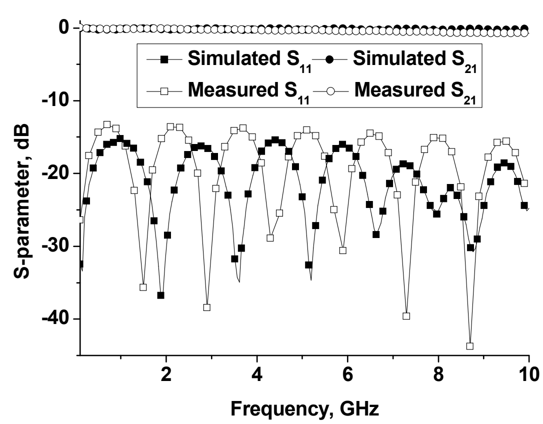
The time-delay line using the conventional CRLH TL unit cells achieves a time delay of 1800 ps, 200 ps less than that using the rotated unit cell. It has a narrower bandwidth of only 4-6 GHz and a larger insertion loss of about 2 dB within the 4-6 GHz pass band as shown in Fig. 5(b)



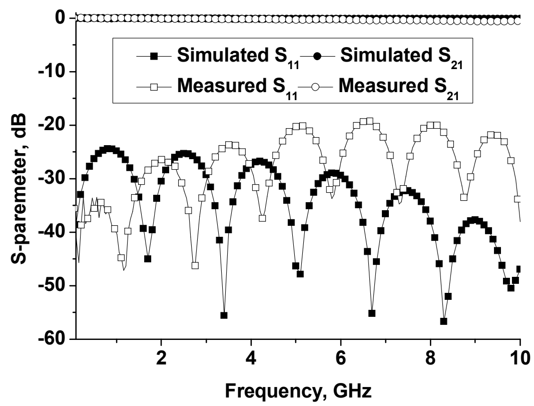
(a)



(b)



(c)



(d)

Figure 5 Simulated and measured $|S_{11}|$ and $|S_{21}|$ of time-delay lines using (a) rotated wideband unit cells, (b) conventional CRLH TL unit cells, (c) PML and (d) RH TL

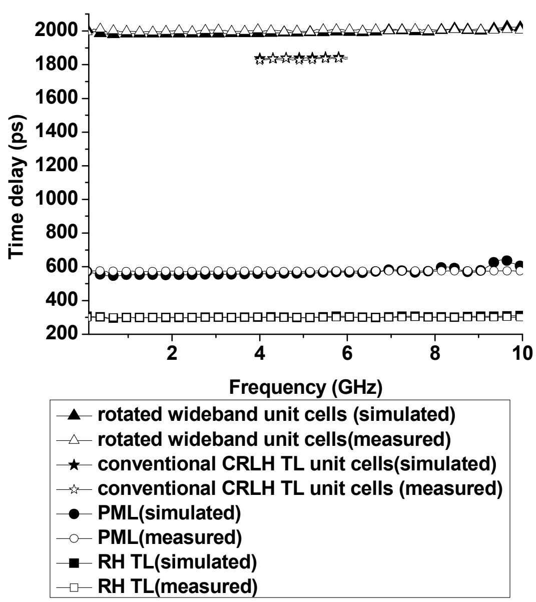


Figure 6 Simulated and measured time delays of different time-delay lines

The time-delay line using the PML also has quite a high return loss as shown in Fig. 5(c), slightly higher than our proposed wideband time-delay line, but it has a very low insertion loss of less than 1 dB. However, the time delay achieved is less than 600 ps, substantially less than that of our proposed wideband time-delay line. Fig. 5(d) shows that the return loss of the time-delay line using the RH TL is even higher than that of our proposed time-delay line and the insertion loss is less than 1 dB, but the time delay achieved is only 300 ps.

V. CONCLUSION

A wideband time-delay lines based on cascading a number of rotated version of the conventional CRLH TL unit cells have been proposed, studied and fabricated. Three other time-delay lines using the conventional CRLH TL unit cells, PML and RH TL have also been designed and optimized for comparison. Simulation and measurement results have demonstrated that, for the length of 60 mm, our proposed wideband time-delay line has a much longer time delay of 2000 ps, more than 3 times and 6 times longer than that of the PML and RH TL, respectively, yet it has a much wider operating bandwidth of 0.1–10 GHz compared with the conventional CRLH TL time-delay line, a high return loss and a low insertion loss.

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