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Discussion on coupling mechanism of asymmetric CRLH/RH TL coupler*

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Abstract: A quasi 0-dB coupler composed of a composite right-/left-handed transmission line (CRLH TL) and a conventional right-handed transmission line (RH TL) is presented. This coupler is shown to exhibit broad bandwidth and tight coupling characteristics. The circuit model and *S*-parameter results are also demonstrated. Another coupler with properly chosen loaded lumped-elements L_L and C_L in the CRLH TL is proposed to gain further understanding of the coupling mechanism. By adjusting the spacing between the CRLH TL and RH TL from 8 mm to 0.2 mm, it can be shown that backward coupling occurs in the left-handed region.

Key words: Asymmetric coupler, Coupling mechanism, Composite right-/left-handed transmission line (CRLH TL)
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INTRODUCTION

In recent years metamaterials, more commonly referred to as left-handed materials, have stimulated great interests in the scientific and engineering field. These artificial materials, which were first theorized by Veselago (1968) and experimentally realized by Shelby *et al*.(2001), can exhibit specific electromagnetic properties not commonly found in nature. The approach of using transmission line theory was verified to be an efficient design tool for metamaterials applications. Many novel microwave devices have been developed based on this approach. For example, asymmetric backward directional coupler composed of a conventional microstrip line and composite right-/left-handed transmission line (CRLH TL) have been introduced and studied (Caloz and Itoh, 2004; Islam and Eleftheriades, 2003). Zhang *et al*.(2004) in our group also studied the unique characteristics of this asymmetric CRLH/RH backward directional coupler which could present arbitrary coupling level and broad bandwidth. These very unusual characteristics induce us to explore the coupling mechanism of such type of couplers.

In this paper, the circuit model and *S*-parameters results of quasi 0-dB CRLH/RH TL coupler are demonstrated. It exhibits the unique characteristics of broad bandwidth and tight coupling. Then, another specific CRLH/RH TL coupler composed of conventional RH TL and matched CRLH TL was designed. The coupling mechanism was deduced by adjusting the spacing between the RH TL and CRLH TL. The possible mechanism for the coupler was also discussed.

CHARACTERISTICS AND CIRCUIT MODE

The prototype of the proposed asymmetric

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CRLH/RH TL coupler and the circuit model for unit cell of the coupler are shown in Fig.1. It is an asymmetric coupler consisting of a pure right-handed microstrip (Ports 1~2) and a CRLH TL (Ports 3~4) with loaded lumped-elements L_L=3.9 nH and C_L=2.0 pF. The length of a unit cell is d=4 mm and the coupler consists of 20 cells. A separation of 0.16 mm is used between the two lines. The substrate used is a 1.6 mm FR-4 substrate with permittivity 4.75. The width of microstrip TL is 2.945 mm and terminated impedance is 50 Ω.

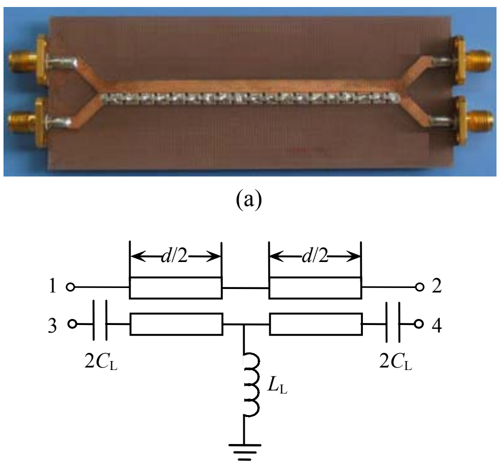

Fig.1 (a) Prototype of the asymmetric CRLH/RH TL coupler; (b) Circuit model for a unit cell of the coupler, L_L and C_L are loaded lumped-elements

Figs.2 and 3 show the measuring and ADS (Advanced Design System, Agilent economic software) simulating S-parameters for the coupler in Fig.1. The signal is put into Port 3. Quasi-0 dB backward coupling is achieved over the range from 2.1 GHz to 2.8 GHz. The excellent agreement between simulation and experimental results is remarkable. Therefore the circuit model and ADS simulation can confidently be used to describe other couplers of the same type.

DISCUSSION

Another coupler, with circuit model shown in Fig.1, is designed for gaining understanding of the coupling mechanism. This coupler is composed of a conventional microstrip and a CRLH TL with loaded lumped-elements L_L=5 nH and C_L=2 pF.

Caloz *et al*.(2004) provided detailed formulae for the eigenfrequencies of the stopband for artificial CRLH TLs, which are written as

$$f_1 = \frac{1}{2\pi\sqrt{L_R C_L}}, \quad (1)$$

$$f_2 = \frac{1}{2\pi\sqrt{L_L C_R}}, \quad (2)$$

here L_L is 5 nH and C_L is 2 pF. The distributed capacitance C_R' and inductance L_R' of the microstrip segment, which can be extracted based on the parameters of the microstrip, are 127.89 pF/m and 319.72 nH/m respectively. Since each unit's length d is 7 mm, so

$$C_R = C_R' d = 0.895 \text{ pF},$$
$$L_R = L_R' d = 2.238 \text{ nH}.$$

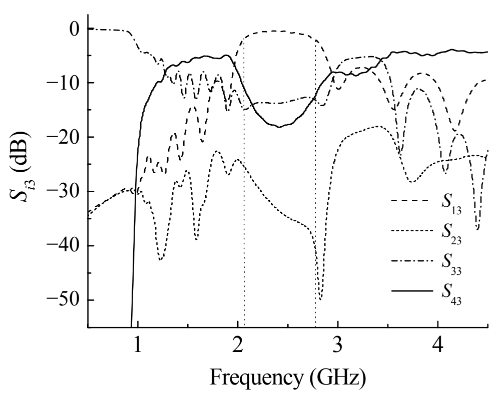

Fig.2 Measuring *S*-parameters for the quasi 0-dB coupler

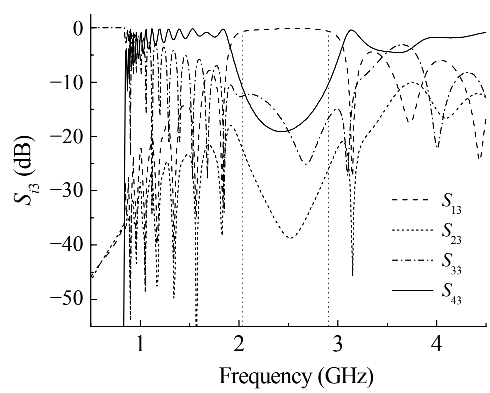

Fig.3 Simulating *S*-parameters for the quasi 0-dB coupler

The eigenfrequencies f_1, f_2 for the stopband of the CRLH TL, which can be defined by Eqs.(1) and (2), are f_1=f_2=2.37 GHz. This is the balanced condition which shows the absence of gap. This CRLH TL is called matched CRLH TL.

Then, a conventional microstrip line of the same length and width is put nearer to the matched CRLH TL. Fig.4 shows the changes of the *S*-parameters when the RH TL is put nearer and nearer towards the CRLH TL. The original spacing between the two lines is very large. Taking 8 mm as an example, there is only very weak coupling as shown in Fig.4b, and the RH TL has single microstrip line properties shown in Fig.4a. Because the CRLH TL is matched, the gap of the CRLH TL is absent as shown in Fig.4c. During decreasing of the spacing between the two lines, two gaps appear on S_{43} (through coupling parameter of the CRLH TL), but only one gap appears on S_{21} (through coupling parameter of RH TL). By using the coupling mode theory, when the spacing becomes small, the coupling capacitance C_m and mutual inductance L_m become large. Therefore, L_R should be substituted for L_R+2L_m and C_R for C_R+2C_m, so the balanced condition is broken. The CRLH TL in the coupler presents a stopband from 2.1 GHz to 2.8 GHz in the S_{43}, while the RH TL does not present the same properties. The reflection S_{33} is very strong during this range shown in Fig.4d. Another gap from 1.4 GHz to 2.1 GHz, which appears both in S_{21} and S_{43}, occurs because of the backward coupling in the left-handed region. This shows backward coupling operates in the left-handed region.

The dispersion diagram for a single CRLH TL at the matched condition is shown in Fig.5. It shows no gap as we have mentioned before. Fig.6 shows the dispersion relation of both the CRLH TL and the RH TL of the coupler. Results are obtained from ADS simulation when the spacing between the CRLH TL and RH TL is 0.2 mm. Homogeneous RH TL's dispersion relationship is linear, while the RH TL of the

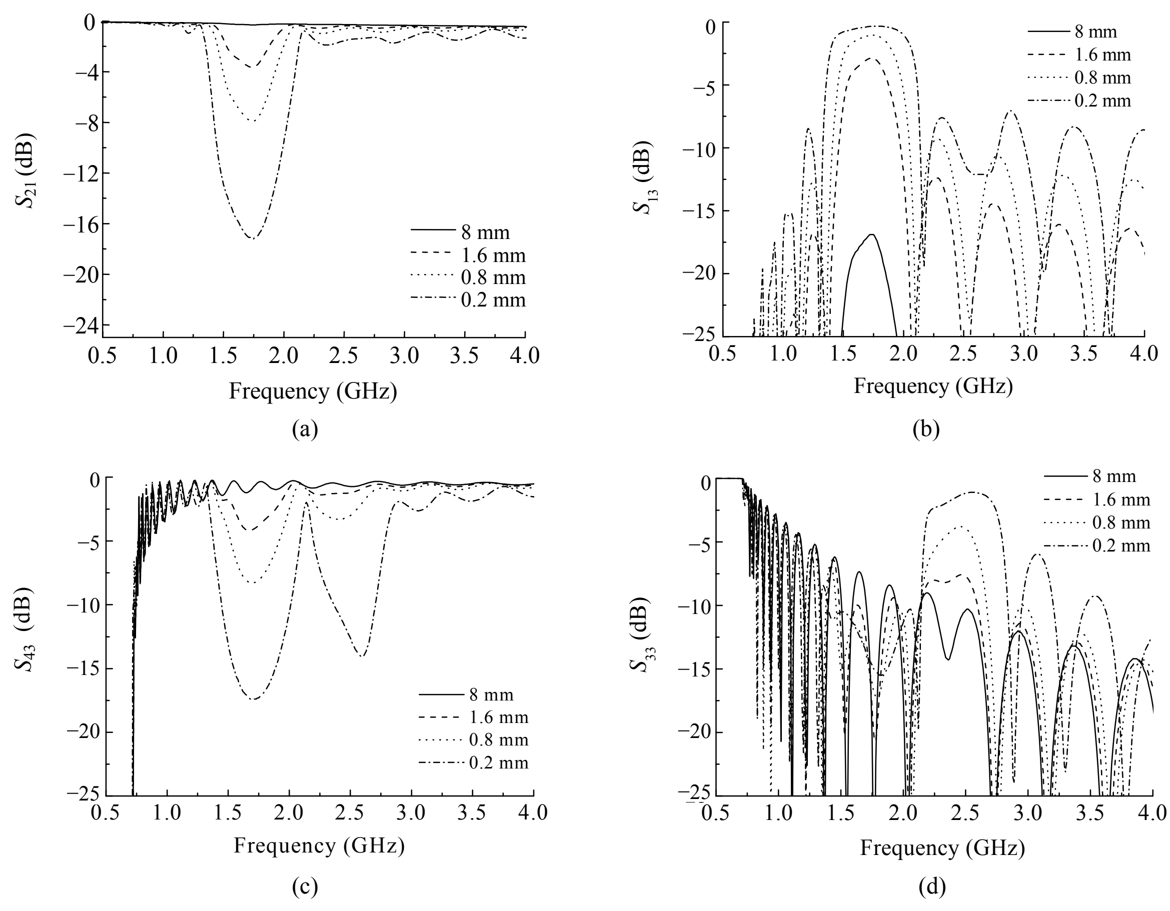

Fig.4 *S*-parameters for the asymmetric CRLH/RH TL coupler when the spacing between the lines is changing. Spacing between CRLH TL and RH TL is from 0.2 mm to 8 mm. (a) S_{21}; (b) S_{13}; (c) S_{43}; (d) S_{33}

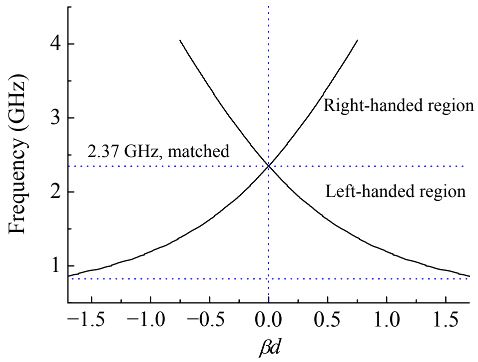

Fig.5 Dispersion diagrams for the single CRLH TL at the matched condition

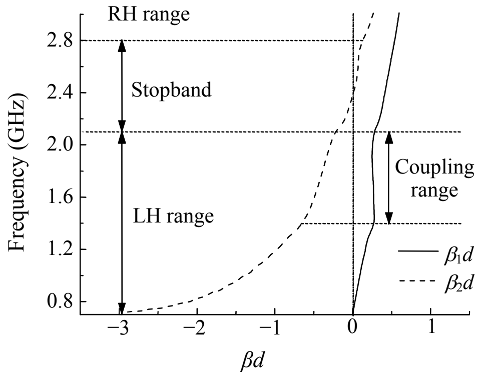

Fig.6 Dispersion diagrams for the CRLH TL and RH TL of the coupler. Spacing between the two lines is 0.2 mm. $\beta_1 d$ and $\beta_2 d$ represent the phase relationship for RH TL and for LH TL respectively

coupler presents a fast wave velocity in the region from 1.4 GHz to 2.1 GHz because of the coupling between the lines. This is the coupling region. Fig.6 also shows the stopband of the CRLH TL, in which the phase is close to zero.

Comparison with the traditional microstrip coupler showed that the asymmetric CRLH/RH TL coupler has relatively high coupling and broad bandwidth, probably because the group velocity in CRLH TL and the RH TL is much slower than in conventional coupler. Shadrivov *et al*.(2003) supposed that there are vortexes between CRLH TL and RH TL resulting in the lower effective coupling length and lower group velocity. In this case more energy can be transfered between CRLH TL and RH TL, so that it shows tighter coupling than a conventional coupler.

CONCLUSION

An asymmetric CRLH/RH TL coupler with broad bandwidth and tight coupling characteristics is demonstrated. Another coupler with matched CRLH TL was studied. This coupler gave us useful understanding of the coupling mechanism. Adjusting the space between the CRLH TL and RH TL showed that backward coupling operates in the left-handed region.

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