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NOVEL SYMMETRICAL COUPLED-LINE DIRECTIONAL COUPLER BASED ON RESONANT-TYPE COMPOSITE RIGHT-/LEFT-HANDED TRANSMISSION LINES

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Abstract—A novel kind of symmetrical backward-wave coupled-line coupler with arbitrary coupling level is proposed in this paper which is based on resonant-type composite right-/left-handed transmission lines (CRLH TLs). First, an equivalent circuit model and procedure for circuit parameters extraction are presented to reveal the inherent nature of the unit cell of the CRLH coupler. Then a CRLH TL composed of four cascaded unit cells is demonstrated to point out the way to achieve balanced condition. At last, even/odd modes analysis based on full-wave simulation is employed to explain the operating principle of the coupler. Both quasi 0-dB and 3-dB CRLH couplers are demonstrated experimentally. The quasi 0-dB backward coupling is achieved over the range from 1.69 GHz to 2.19 GHz (-3 dB bandwidth in measurement), which represents the fractional bandwidth 25.8%. The maximum coupling coefficient 0.52 dB is obtained at 1.96 GHz, where the directivity and isolation is 20.8 dB and 21.3 dB, respectively. The 3-dB couplers shows an amplitude balance of 2 dB and quadrature phase balance of 90 ± 5 degree over the fractional bandwidth of around 11.4%, from 1.99 to 2.23 GHz.

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1. INTRODUCTION

The CRLH approach of left-handed (LH) structures, in which phase and group velocities exhibit opposite signs and correspond to negative refractive index materials, was recently proposed and demonstrated to provide an efficient tool for the design of novel structures and devices, such as couplers [1–3], band pass filters [4–6], antennas [7–9], and multi-frequency devices [10, 11]. Generally, the CRLH TLs are classified into two kinds [12]: the transmission-line type which consists of periodic loading a host transmission line with series capacitances and shunt inductances [13], and the resonant-type approach which is alternatively implemented by loading a host transmission line with complementary split rings resonators (CSRRs) [14]. The idea of using transmission-line-type CRLH TLs in coupled-line couplers configuration was first proposed in [15], where a symmetric LH/LH enhanced forward coupler was demonstrated. Using a similar LH/LH configuration, a backward coupler with arbitrary coupling level, broad bandwidth and unique operation principle was later demonstrated in [16] and fully explained in [1]. The resonant-type CRLH TLs firstly applied to coupled-line coupler was introduced in [17], where the coupler is composed of a conventional microstrip line (pure RH) and a LH microstrip line, so the structure is asymmetric.

So far, to the best knowledge of the authors, no literatures about a CRLH coupler which has symmetric structure, can achieve arbitrary coupling level and use resonant-type CRLH TLs simultaneously has been reported yet. Inspired by this motivation, in this paper, we demonstrate a novel symmetric backward directional coupler, which is based on resonant-type CRLH TLs and can also be designed to achieve any arbitrary level of coupling, up to almost complete coupling (0 dB), even with a relatively large spacing between the lines. Due to resonant characteristics, its fractional bandwidth (nearly 25.8%) is relatively narrow compared with [1], but still larger than conventional branch-line or rat-race couplers (typically less than 10%). In practice, the coupling level of conventional couplers is typically lower than 10 dB due to fabrication constraints and this limitation prevents their utilization in many applications such as balanced mixers and amplifiers where 3 dB coupling is usually required. On the contrary, by reducing the number of cells of the CRLH structure or increasing the lines interspacing, the quasi-0 dB CRLH coupler can be easily designed to realize 3-dB coupling level. In addition, the couplers we proposed can take advantage of fully planar fabrication techniques, because no vias are needed in the resonant-type CRLH TLs as compared to the transmission-line-type CRLH TLs.

This paper is organized as follows. In Section 2, the electrical model of the unit cell and the procedure for circuit parameter extraction are given in details, and compared with results of electromagnetic (EM) simulation using the commercial CST Microwave Studio software to verify the validity of the electrical model. Then, in Section 3, a CRLH TL composed of four cascaded unit cells is demonstrated to point out the way to achieve balanced condition. The balanced CRLH TL will be used as one section of the CRLH coupler. In Section 4, an even/odd-mode analysis based on EM simulation is presented. The possibility of complete backward coupling is proved by formula derivation. The prototype of quasi-0 dB coupler has been fabricated and measured in agreement with EM simulation. We also demonstrate a more practical and compact 3-dB CRLH coupler in Section 5. The conclusion is given in Section 6.

2. EQUIVALENT CIRCUIT MODEL AND PARAMETER EXTRACTION

The layout corresponding to the basic cell of the CRLH resonant line, as well as its lumped element of equivalent circuit model [18, 19] is depicted in Figure 1. The structure consists of a microstrip line with a series interdigital capacitor etched in the strip and a square complementary split-rings resonator printed in the ground plane. The series capacitance is modeled by C_g, whereas L models the inductance of the line. CSRRs are described by the resonators formed by the parallel combination of L_c and C_c, and their coupling to the host line is modeled by capacitance C.

The analysis of the structure can be driven through Bloch theory. The phase shift per cell ϕ and the characteristic impedance Z_B can be obtained [19]:

$$\cos\phi = 1+\frac{C\left(1-w^2LC_g\right)\left(1-w^2L_cC_c\right)}{2C_g\left[1-w^2L_c(C_c+C)\right]} \tag{1}$$

$$Z_B = \sqrt{\frac{\left(1-w^2LC_g\right)^2}{-4w^2C_g^2}+\frac{1-w^2LC_g}{w^2CC_g}+\frac{L_c\left(1-w^2LC\right)}{C_g\left(1-w^2L_cC_c\right)}} \tag{2}$$

From Equations (1) and (2), we can find that LH propagation occurs in the region delimited by the following frequencies [20]:

$$f_L = 1/2\pi\sqrt{L_c(C_c+4/(1/C_g+4/C))} \tag{3}$$

$$f_H = 1/2\pi\sqrt{L_cC_c} \tag{4}$$

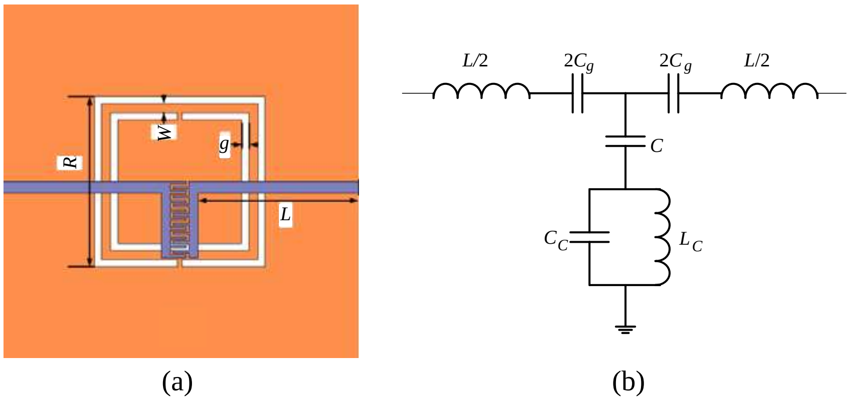


Figure 1. Topology of the unit cell of (a) CSRR-based CRLH transmission line and (b) equivalent circuit model.

There is a transmission zero frequency below f_L given by:

$$f_Z = 1/2\pi\sqrt{L_c(C + C_c)} \tag{5}$$

which can be obtained directly from the EM simulation curve of S_{21}.

RH propagation occurs above the cutoff frequency:

$$f_R = 1/2\pi\sqrt{LC_g} \tag{6}$$

Equations (4) and (5) can be rewritten in the following forms to show the dependence among L_c, C_c and C:

$$L_c = \frac{(f_H/f_Z)^2 - 1}{(2\pi f_H)^2 C}, \quad C_c = \frac{C}{(f_H/f_Z)^2 - 1} \tag{7}$$

If f_H and f_Z are knownby tuning C in the Agilent ADS to fit the response of the electrical model with the full-wave EM simulation, the value of L_c and C_c can be obtained.

Because f_H can also be explained as the resonant frequency of the CSRRs, at f_H, the impedance seen from the input port is given by the impedance of series branch. This means that the admittance of parallel branch is zero. In [18], f_H is considered as the intersection point of measured (or simulated) S_{11} curve and the unit normalized resistance circle if the feed line at the input port is $50\,\Omega$. But in fact, this kind of intersection points is usually more than one as shown in Figure 2(a). Considering that f_H is the cutoff frequency of LH propagation, below it, the phase velocity and group velocity have opposite signs meaning that transmission line is working at LH zone where β is negative. So

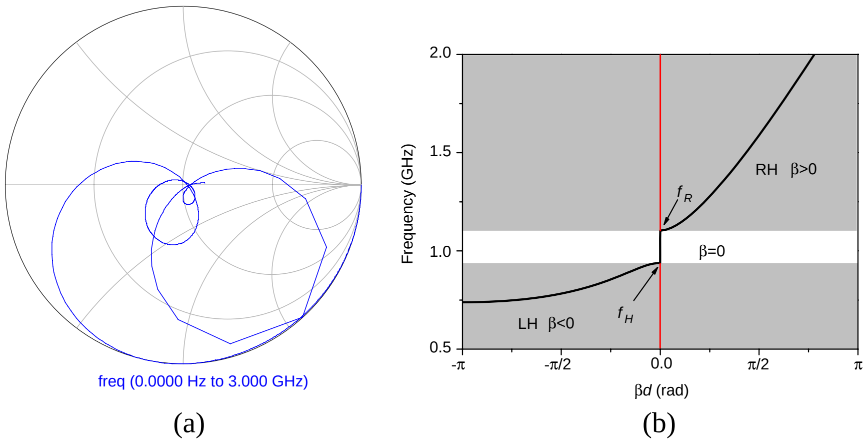


Figure 2. (a) Representation of the simulated reflection coefficient for the structures shown in Figure 1 on Smith Chart. (b) Simulated dispersion diagram obtained by Equation (8) with phase unwrapping.

f_H can be solely determined as the turning point of the LH band as indicated in Figure 2(b), which is computed by

$$\beta d = \mathrm{Im}\left(\cos^{-1}\left((1 - S_{11}S_{22} + S_{12}S_{21})/2S_{21}\right)\right) \tag{8}$$

Comparison of the EM and the circuit simulation are shown in Figure 3. The agreement confirms the validity of the parameter extraction procedure and accuracy of the extracted parameters.

3. BALANCED CRLH TL

Figure 2(b) depicts the presence of the CRLH gap, which is due to the different shunt and series resonances (f_H, f_R); when it occurs, the CRLH TL is said to be unbalanced. When these two frequencies are equal, in which case the TL will be called balanced, the frequency gap closes up.

The meaning of the equivalent circuit model mentioned above is that it reveals the inherent relationship among the structure parameters and provides design guidelines to achieve the balanced condition.

There are several ways to obtain the balanced condition such as increasing C_g or L. Equations (4) and (6) show that increasing C_g can shift the RH band towards lower frequency, whereas decreasing C_c increases LH cutoff frequency f_H. At optimized C_g and C_c, LH and RH bands will overlap and the frequency gap disappears.

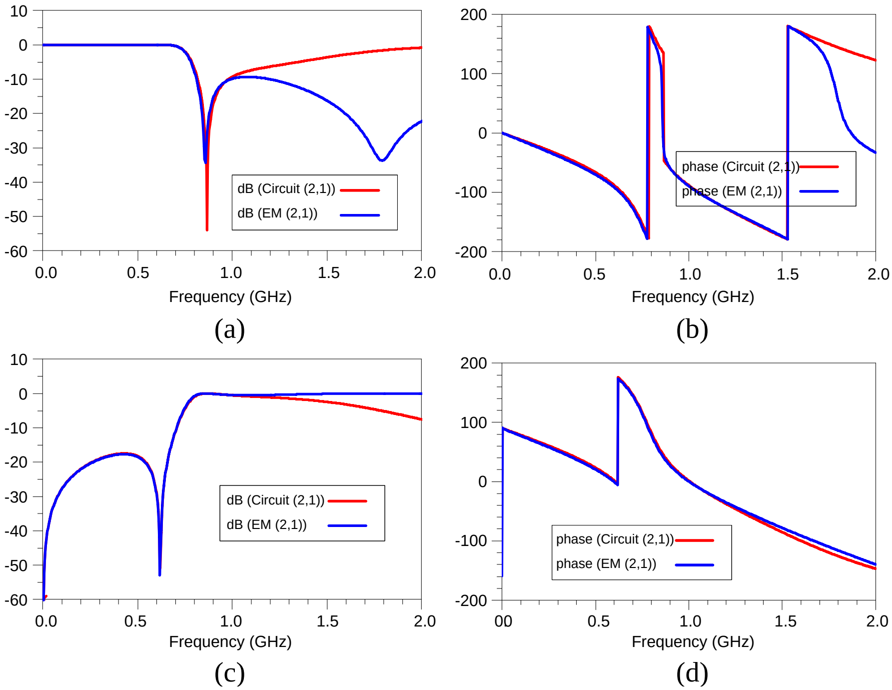


Figure 3. Frequency characteristics of the structure shown in Figure 1 obtained by full-wave simulation and by circuit simulation. Unit cell design with dimensions: the side length of outer square CSRRs $R = 17\,\text{mm}$, the gap between outer square and inner square $w = 0.3\,\text{mm}$, both of the square width $g = 0.5\,\text{mm}$, the width and length of interdigital finger is $w_1 = 0.3\,\text{mm}$ and $L_1 = 1.8\,\text{mm}$ respectively, space between each finger $d = 0.2\,\text{mm}$, the number of fingers $N = 17$, the length of inductance line $L = 18\,\text{mm}$, the substrate used with dielectric constant $\varepsilon_r = 2.65$ and thickness $H = 0.5\,\text{mm}$. Extracted circuit parameters: $L = 10.2\,\text{nH}$, $C_g = 1.92\,\text{pF}$, $C = 14.98\,\text{pF}$, $L_c = 2.52\,\text{nH}$, $C_c = 11.38\,\text{pF}$.

The balanced CRLH TL is widely used in the design of microwave circuits such as wideband filters, power dividers and hybrid ring [21]. Figure 4(a) shows the transmission characteristics of CRLH TL cascaded by four unit cells and a frequency gap (stop band) can be observed between f_H and f_R, in that region $\alpha > 0$ and wave propagation is not allowed because $\beta = 0$ as shown in Figures 4(b) and (c). In addition, the larger the transmission gap, the larger the value of α at the given frequency will be, which means a deeper level of imbalance has been made. As illustrated in Figure 4(c), with the number of the interdigital fingers N increasing, f_R decreases and gradually approaches f_H until the frequency gap between them disappears, so the balanced condition is achieved.

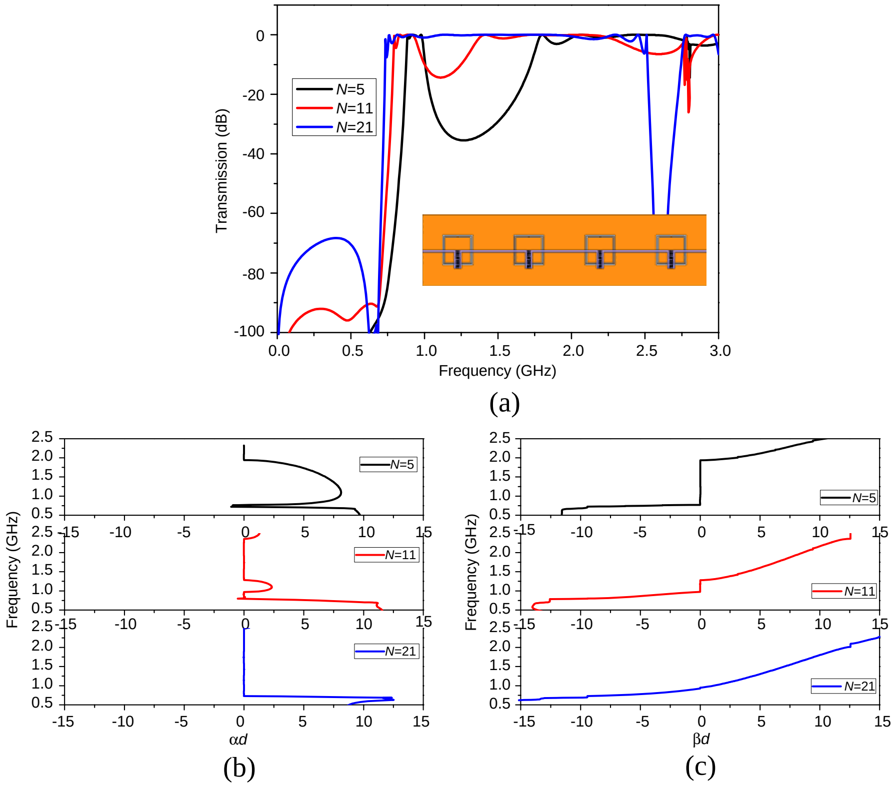


Figure 4. (a) Layout of the CRLH TL cascaded by four unit cells and the transmission response varies with the finger number N changing. (b) Attenuation, (c) dispersion diagrams computed by Equation (8) with phase unwrapping.

4. COUPLER WITH COMPLETE BACKWARD COUPLING

The basic difference in the coupling mechanism between a conventional coupled-line backward coupler and a CRLH coupled-line backward coupler is that, in the former case, coupling is related to electrical length βd, whereas in the latter case, it is related to the attenuation length αd.

The coupling level of coupled-line directional coupler is given by [1]:

$$C_{BWD} = \frac{(Z_{0e} - Z_{0o}) \tanh \gamma d}{2Z_0 + (Z_{0e} + Z_{0o}) \tanh \gamma d} \tag{9}$$

where $\gamma = \alpha + j\beta$, Z_{0e} and Z_{0o} represent the characteristic impedances of the even and odd models of the coupler, respectively. The conventional coupled-line directional coupler is composed of two microstrip lines (pure RH). Its coupling mechanism is related to β and maximum coupling occurs at $\beta d = \pi/2$. Whereas, the metamaterial coupler is constituted by two CRLH TLs, each of which is characterized by the balanced condition when isolated from the other one. When the balanced CRLH TL is used as one section of the coupler, due to the coupling parameters between the two lines, the even/odd mode CRLH TLs are in unbalanced condition now. As shown in Figure 5, both of the even/odd mode S parameters computed by Equation (10) [22] have a stop band, where $\beta = 0$ and $\alpha > 0$.

$$\begin{aligned} S_{11e} &= S_{11} + S_{31}, \quad S_{11O} = S_{11} - S_{31} \\ S_{21e} &= S_{21} + S_{41}, \quad S_{21O} = S_{21} - S_{41} \end{aligned} \tag{10}$$

so Equation (9) can be written as

$$C_{BWD} = \frac{(Z_{0e} - Z_{0o}) \tanh \alpha d}{2Z_0 + (Z_{0e} + Z_{0o}) \tanh \alpha d} \tag{11}$$

if the quantity αd is sufficiently large, $\tanh(\alpha d)$ will tend to 1. Then we can write

$$C_{BWD} \cong \frac{Z_{0e}/Z_0 - Z_{0o}/Z_0}{2 + (Z_{0e}/Z_0 + Z_{0o}/Z_0)} \tag{12}$$

The even/odd characteristic impedances are purely imaginary in the stop band of the even/odd lines computed by Equation (13) as shown in Figure 6

$$Z_{0i} = Z_0 \sqrt{\frac{\Pi_i - 1}{\Pi_i - 1}}, \quad i = e,\, o \quad \text{with} \quad \Pi_i = \frac{S_{21i}^2 - S_{11i}^2 - 1}{2S_{11i}} \tag{13}$$

Equation (12) can be rewritten as:

$$|C_{BWD}| \cong \left| \frac{j\,(\mathrm{Im}\,(Z_{0e})/Z_0 + Z_0/\mathrm{Im}\,(Z_{0e}))}{2 + j\,(\mathrm{Im}\,(Z_{0e})/Z_0 - Z_0/\mathrm{Im}\,(Z_{0e}))} \right| = 1 \tag{14}$$

Thus, complete backward coupling (0 dB) can be achieved in the range of the stop band of the even/odd mode lines. It is clear that if complete coupling can be achieved, any level of coupling can be achieved by reducing attenuation length αd, that is by reducing the number of cells of the CRLH structure or increasing the lines interspacing. This is because αd is clearly directly proportional to the physical length d and the attenuation factor α, which depends on the level of imbalance as shown in Figure 4(a). With decreasing the spacing s of the CRLH coupler, mutual coupling effect between the two balanced CRLH TLs will increase, which causes the level of imbalance increases, i.e., α increases. As to d, which is the physical length of the CRLH coupler, by reducing the number of cells, the whole length of coupler will decrease. So αd will decrease. Of course, the realization process from quasi-0 dB to arbitrary coupling level will not be so simple. Lots of efforts on structure optimization will have to be done. But adjusting α and d are the main two guidelines to obtain the required coupling level.

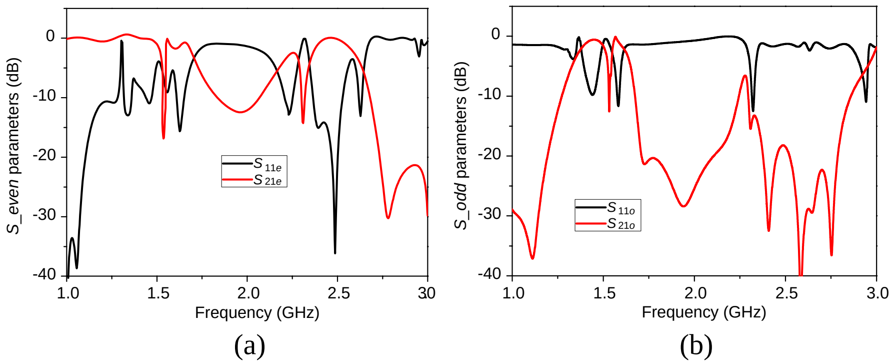


Figure 5. EM simulated S-parameters for the even and odd modes of the coupler shown in Figure 7. (a) Even mode. (b) Odd mode.

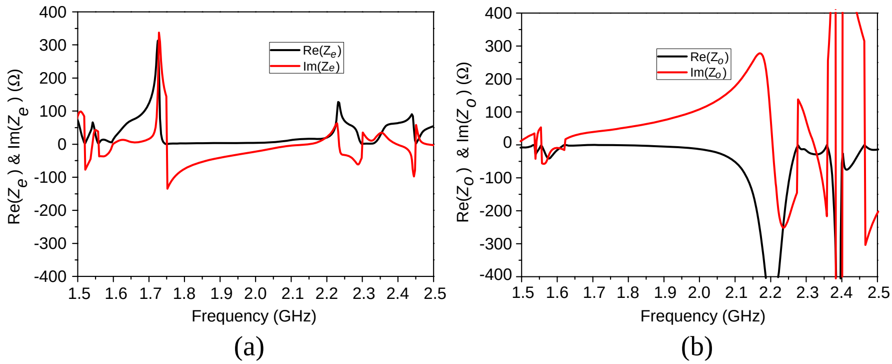


Figure 6. EM simulated even/odd characteristic impedances (real/imaginary parts) for the coupler shown in Figure 7. (a) Even mode. (b) Odd mode.

The prototype of CRLH coupler shown in Figure 7(a) is simulated and optimized using the commercial CST Microwave Studio software to achieve the quasi 0-dB coupling. As depicted in Figures 7(c) and (d), the coupling bandwidth corresponding to -3 dB extends from 1.69 to 2.19 GHz and almost 25.8% fractional bandwidth has been achieved. The maximum coupling coefficient 0.52 dB is obtained at 1.96 GHz, where the directivity and isolation is 20.8 dB and 21.3 dB, respectively. Due to the fabrication inaccuracy and the experimental deviation in the dielectric constant, the measured S_{11} in the passband deteriorates to some extent and the operating band shifts downward slightly. Although the bandwidth of resonant-type CRLH coupler is inferior

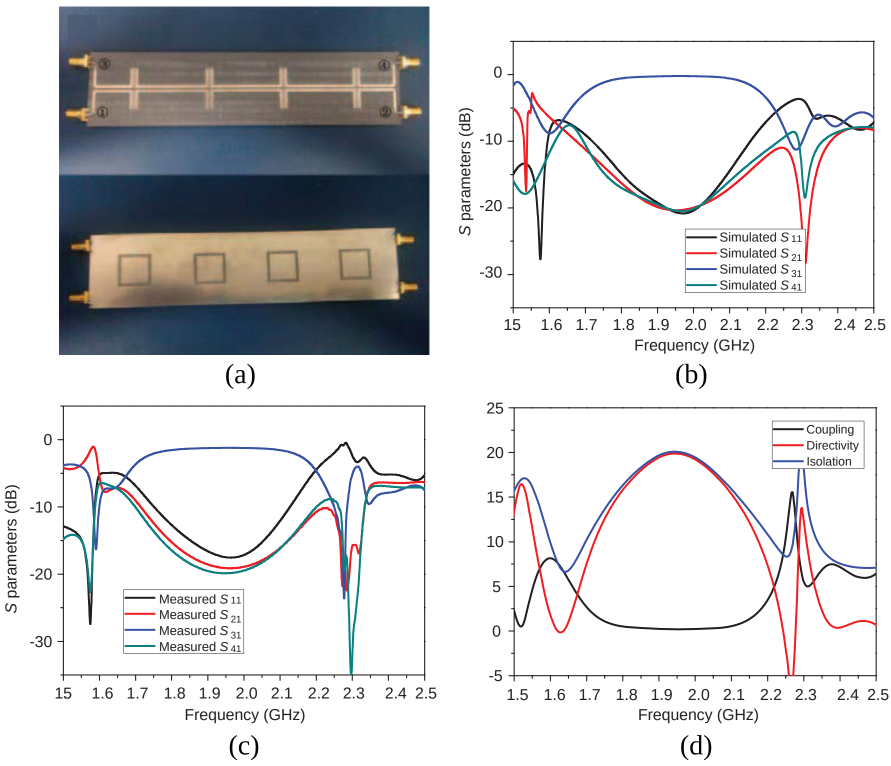
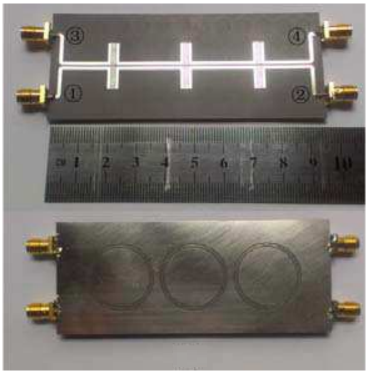


Figure 7. (a) Top (upper) and bottom (lower) sides of the fabricated coupler with parameters: $R = 20$ mm, $w = 1$ mm, $g = 0.5$ mm, $w_1 = 0.3$ mm, $L_1 = 1.8$ mm, $d = 0.2$ mm, $L = 18$ mm, $N = 21$, the spacing between the two CRLH TLs is $s = 1$ mm. (b) Full-wave simulated S parameters. (c) Measured S parameters, and (d) the three quantities characterizing the coupler.

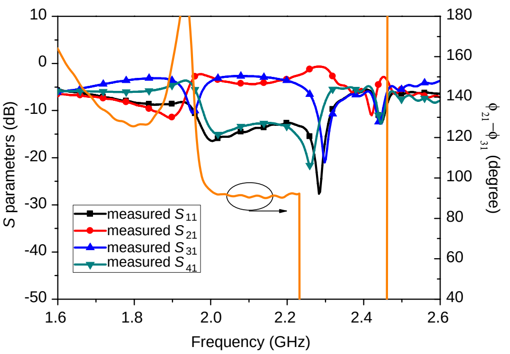
to the transmission-line-type CRLH coupler owing to its intrinsic resonant nature, it provides an alternative way to achieve the quasi 0-dB coupling level and verifies that the resonant-type CRLH TLs can also be employed in the CRLH coupler just as the transmission-line-type CRLH TLs based on the same CRLH theory introduced by Caloz et al. in [23].

5. 3-DB CRLH COUPLER

Although the emphasis of this paper is laid on the realization of the quasi 0-dB coupled-line directional coupler, a 0-dB coupler is not very interesting, except possibly for DC blocks. The motivation for describing a 0-dB coupler was to demonstrate that any coupling level is achievable. A practical more useful 3-dB CRLH coupled-line coupler and corresponding scattering parameters are shown in Figure 8. In order to further reduce the size of the coupler, the square CSRRs are replaced with circular CSRRs, because it has been found that coupling between adjacent CSRR is not significant for circular geometries [20]. The performances of this coupler are as follows: an amplitude balance of 2 dB is achieved over the fractional bandwidth of around 11.4%, from 1.99 to 2.23 GHz. The quadrature phase balance of 90 ± 5 degree can be achieved in the same frequency region.



(a)



(b)

Figure 8. (a) Prototype of the 3-dB backward directional coupler constituted of two CRLH TLs with parameters: $R = 12$ mm, $w = 0.3$ mm, $g = 0.3$ mm, $w_1 = 0.2$ mm, $L_1 = 1.8$ mm, $d = 0.2$ mm, $L = 11$ mm, $N = 17$, the spacing between the two CRLH lines is $s = 0.5$ mm. (b) Measured results.

6. CONCLUSION

In this paper, we demonstrate a novel kind of symmetrical coupled-line directional coupler, which is based on resonant-type CRLH TLs and can also be designed to achieve any arbitrary level of coupling, up to almost complete coupling (0 dB). Besides, in order to reflect the flexibility of the design method, a more practical and compact 3-dB CRLH coupler is also presented.

Our work has verified that transmission-line type CRLH TLs are not exclusive to form the quasi-0 dB coupler, the CSRR-based, resonant-type CRLH TLs can also be used as part of the CRLH coupler to realize the complete coupling. Because both of two types TLs can be tailored to exhibit a continuous transition between the backward and forward transmission bands, i.e., the balanced condition. Compared with the transmission-line type CRLH coupler, the couplers we proposed not only can achieve arbitrary coupling level, but also can take advantage of fully planar fabrication techniques, because no vias are needed in the structure. The prototypes are fabricated with conventional PCB technology and good agreement between measured and simulated results has been achieved.

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