A Novel Mixed Conventional Microstrip and Composite Right/Left-Handed Backward-Wave Directional Coupler With Broadband and Tight Coupling Characteristics

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***Abstract*—A novel backward directional coupler, composed of a conventional microstrip (CμS) line and composite right/left-handed (CRLH) line, is proposed. This coupler is functionally backward but it is based on a forward-type coupling phenomenon. The coupler is shown to exhibit broad bandwidth and tight coupling characteristics. The theoretical circuit-model results are supported by full-wave and experimental evidence. A quasi 0-dB prototype with more than 50% bandwidth is demonstrated.**

***Index Terms*—Composite right/left-handed transmission lines, coupled-line coupler, metamaterials.**

I. Introduction

LEFT-HANDED (LH) metamaterials [1], [2], which are characterized by anti-parallel phase and group velocities, are promising materials for new types of microwave components and structures.

We present here a novel backward-wave directional coupler based on an LH transmission line initially presented in [3]. This line was later demonstrated to be more generally composite right/left-handed (CRLH), because it includes both LH series C/shunt L *and* parasitic RH series L/shunt C in its circuit model, resulting in a structure which is LH at lower frequencies and RH at higher frequencies [4]. It uses nonresonant reactive elements [5] and is therefore characterized by low loss and broad bandwidth. Several novel concepts and applications for microwave components and antennas have already emerged from the transmission line approach of metamaterials [4], [6]–[9].

The idea of using LH structures in coupled-line couplers configuration was first proposed in [10], 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 [9] and fully explained in [11].

The mixed CμS/CRLH coupler proposed in this paper consists of a conventional microstrip right-handed (RH) line edge-coupled with a CRLH line used in its LH range. A similar type of coupler was discussed theoretically in [12]. We present here a distributed microstrip practical implementation of the coupler, with an accurate circuit model for design, and full-wave/experimental verification of the model.

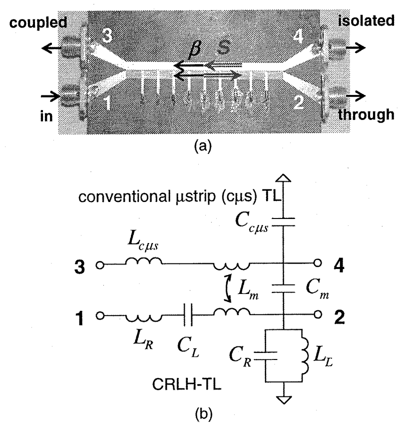

Fig. 1. (a) Picture of a 9-cell prototype of the proposed coupler. The bottom line (ports 1–2) is a CRLH-TL, first introduced in [3], constituted by series interdigital capacitors and shorted stub inductors. The top line (ports 3–4) is a conventional microstrip line (CμS). The substrate used is Rogers RT/Duroid® 5880 with dielectric constant $\varepsilon_r = 2.2$ and thickness $h = 62$ mils $(\text{loss tangent} = 0.0009)$. The spacing between the lines is $s = 0.3$ mm and the length of the coupler is $d = 62$ mm. (b) Circuit model for the unit cell of the coupler. In the CRLH-TL, C_L and L_L represent the interdigital capacitor and stub inductor respectively, while L_R and C_R represent their natural parasitic contributions. In the conventional line, $L_{c\mu s}$ and $C_{c\mu s}$ represent the equivalent series inductance and shunt capacitance, respectively, for one (lumped-implemented) unit cell of the microstrip line. C_m and L_m represent the coupling capacitance and mutual inductance, respectively.

II. Coupler Description and Principle

The proposed mixed CμS/CRLH backward-wave coupled-line directional coupler is shown in Fig. 1(a) and its circuit model is presented in Fig. 1(b). It is an *asymmetric* coupler consisting of a CRLH line and a conventional microstrip line (CμS). Despite the fact the CRLH line will be operating completely in its LH range for the present coupler application, its RH components (L_R and C_R) are essential for an accurate description of the behavior of the coupler. A purely LH model ignoring these RH contributions is incomplete and leads to very inaccurate results.

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As a signal is injected at port 1, power (Poynting vector, $\mathbf{S}$) propagates toward port 2, but phase (propagation constant, β) propagates backward toward port 1 (LH range of the CRLH line). Therefore, since coupling to the other line (3–4) occurs through transverse evanescent waves following the phase direction, phase and power propagate in the same direction toward port 3 in the RH CμS line. Consequently, *backward coupling* is functionally achieved, but the coupling is based on a *forward coupling phenomenon* because the phase velocities in the two lines have the same direction due to weak coupling.

In the case of an asymmetric coupler, we need to consider the c and π normal modes, and the formula for forward coupling in a coupler of length d is given by

$$C_{\text{FWD}} = \frac{2\sqrt{p}}{1+p}\sin\left[\frac{(\beta_c - \beta_\pi)\,d}{2}\right], \quad \text{with} \quad p = -\frac{R_c}{R_\pi} \tag{1}$$

where β_c/β_π are the propagation constants and R_c/R_π are the ratios of voltages on the two lines for the c and π modes, respectively [14]. From (1), maximum coupling is clearly obtained for the coherence length

$$d_{\max} = \frac{\pi}{|\beta_c - \beta_\pi|}. \tag{2}$$

In the conventional case, the coupling factor (1) corresponds to S_{41}; in the case of the CμS/CRLH coupler, because of the reversal of phase direction in the line $1 \rightarrow 2, S_{41}$ has to be replaced by S_{31}, which is the backward coupling of interest ($C_{\text{FWD,conv}} \rightarrow C_{\text{BWD}}$).

In the limit case of very weak coupling between the lines, β_c/β_π become equal to the propagation constants in the different lines $\beta_{1\rightarrow 2}/\beta_{3\rightarrow 4}$, i.e., $\beta_{\text{CRLH}}/\beta_{C\mu S}$, respectively. Since β_{CRLH} is negative in its LH range, (2) can be written in the form

$$d_{\max} = \frac{\pi}{|\beta_{\text{CRLH}}| + \beta_{C\mu S}}. \tag{3}$$

Thus, the negative sign in the denominator of (2) is replaced by a *positive sign*, which suggests that a significantly smaller $d_{\max}$ can be attained in the CμS/CRLH coupler. This expression is based on an excessively crude assumption in practice (Section III and IV), but it provides a useful insight into the possible capability of high coupling in an asymmetric RH/LH coupler.

Complete power coupling, and hence arbitrary level of coupling by reducing the number of cells or increasing the spacing between the lines, will be demonstrated in the next section for the coupler shown in Fig. 1(a). This correspond to the case $p = 1$ in (1), which means that the voltages ratios of the c and π modes are equal.

III. Full-Wave and Measurement Results

Fig. 2 presents the full-wave simulated and measured S-parameters for the coupler of Fig. 1(a). Excellent agreement can be observed between simulated and experimental results.

Quasi 0-dB (around -0.7 dB) backward coupling is achieved over the range from 2.2 to 3.8 GHz (-10 dB bandwidth in measurement), which represents the broad fractional bandwidth of 53%. An excellent directivity of $D = 30$ dB is achieved

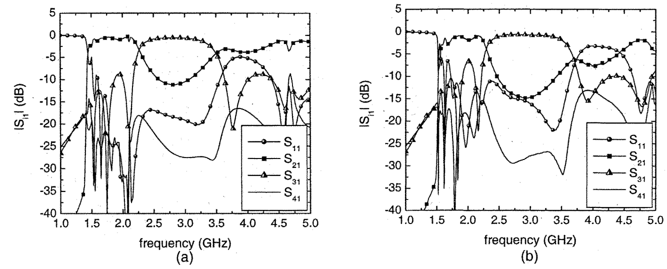

Fig. 2. S-parameters for the coupler of Fig. 1(a). (a) Full-Wave simulation results (Ansoft-Ensemble). (b) Measurement Results.

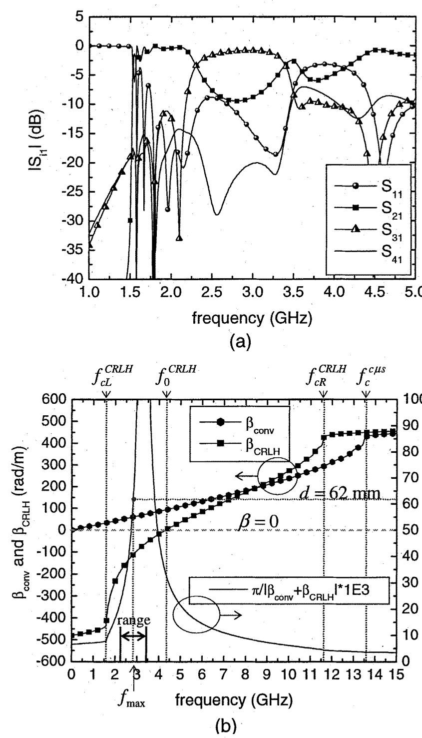

Fig. 3. Results obtained in the circuit model of Fig. 1(b) with extracted parameters $L_{c\mu S} = 1.64$ nH, $C_{c\mu S} = 0.33$ pF, $L_R = 2.21$ nH, $C_R = 0.45$ pF, $L_L = 3.04$ nH, $C_L = 0.61$ pF, $L_m = 0.27$ nH, $C_m = 0.33$ pF. (a) S-parameters. (b) Phase constants in the isolated conventional and CRLH TL's (left-hand axis) and right-hand term of (3) (right-hand axis). The values of the frequencies compted from (4) to (7) are $f_c^{c\mu s} = 13.6$ GHz, $f_{cL}^{\text{CRLH}} = 1.8$ GHz, $f_0^{\text{CRLH}} = 4.3$ GHz, $f_{cR}^{\text{CRLH}} = 10.1$ GHz. The frequency computed with (3) is $f_{\max} = 2.8$ GHz.

in the measured prototype. The asymmetric coupler presented here was built on the same substrate, has the same length and uses two CRLH lines identical to those of the symmetric CRLH-CRLH coupler presented in [8]. However, its operating frequency range is lower (3.3 to 4.7 GHz for the symmetric coupler of [8]), which means that, after rescaling, the asymmetric CμS-CRLH coupler is *more compact* than its symmetric counterpart. On the other hand, due to its asymmetry, the CμS-CRLH *does not exhibit 90 degrees phase balance* in contrast to the symmetric CRLH-CRLH coupler.

IV. Circuit Model Analysis

Fig. 3(a) shows the S-parameters of the coupler obtained from the circuit model depicted in Fig. 1(b). The agreement with full-wave simulations and measurements is remarkable, and the circuit model can therefore be safely used to describe and design such a type of coupler. The parameters of the CRLH lines (L_R, C_R, L_L, C_L) were extracted from separate full-wave simulations of the interdigital capacitor and shorted stub inductor of the unit cell. The parameters of the CμS line were computed from the formulas $L_{c\mu S} = L'(d/N)$ and $C_{c\mu S} = C'(d/N)$, where $C' = \sqrt{\varepsilon_{\rm eff}}/(c_0 Z_0)$ and $L' = Z_0^2 C'$ [13]. Finally, the coupling capacitance C_m and mutual inductance L_m were estimated from curve fitting with the full-wave and measurement results of Fig. 2.

Fig. 3(b) (left-hand axis) shows the propagation constants of the isolated CμS and of CRLH lines constituting the coupler [Fig. 1(b)]. The low-pass cutoff frequency of the CμS [lumped model of Fig. 1(b)] is given by

$$f_c^{c\mu s} = \frac{1}{\pi\sqrt{L_{c\mu s} C_{c\mu s}}}. \tag{4}$$

The LH high-pass cutoff, LH-to-RH transition and RH low-pass cutoff frequencies are given by [4]

$$f_{cL}^{\rm CRLH} = \frac{1}{4\pi\sqrt{L_L C_L}} \tag{5}$$

$$f_0^{\rm CRLH} = \frac{1}{2\pi\sqrt[4]{L_R C_R L_L C_L}} \tag{6}$$

$$f_{cR}^{\rm CRLH} = \frac{1}{\pi\sqrt{L_R C_R}} \tag{7}$$

respectively. Equations (5) and (7) can be shown to be exact in the balanced case defined by the condition $L'_R C'_L = L'_L C'_R$ [11]. In the unbalanced case $(L'_R C'_L \neq L'_L C'_R)$, they are approximate but provide a reasonable estimate of the CRLH cutoffs.

Fig. 3(b) (right-hand axis) also shows the right-handed term of (3). Maximum coupling is expected when this quantity is equal to the length of the coupler, d. The coherence frequency obtained from (3), $f_{\max} = 2.8$ GHz, is consistent with the fact that 2.8 GHz lies in the center of the frequency range of the coupler [Figs. 2 and 3(a)]. However, formula (3) also predicts a maximum coupling at the frequency $f = 3.8$ GHz, which is not verified by experiment. This suggests that the 'weak' coupling assumption in (3) (c and π modes βs are equal to the isolated CRLH and CμS βs) is too crude in reality. Note that a pole of the right-handed term of (3) appears at the frequency where the CμS and CRLH line have same magnitude ($\sim$3.2 GHz) but opposite signs. This pole would suggest that an infinite length is required for complete coupling at this frequency, which contradicts the results. Consequently, the weak coupling assumption giving (3) is clearly inappropriate at this particular frequency.

V. Design Guidelines

The design guidelines of the proposed coupler for a specified coupling level and bandwidth can be summarized as follows: 1) use the circuit model of Fig. 1(b), assuming an initial length d and number of cells N, leading to initial values for $L_{c\mu S}$ and $C_{c\mu S}$ on a given substrate; 2) the CRLH line needs be matched, which can be shown to require the balanced condition $Z_L = Z_R$, where $Z_L = \sqrt{(L_L/C_L)}$ and $Z_R = \sqrt{(L_R/C_R)}$ [11]; in addition, it should conveniently exhibit the same characteristic impedance Z_0 as the CμS line, i.e., $Z_L = Z_R = Z_0$; the last two unknowns among the parameters L_R, C_R, L_L, C_L may be determined by setting the frequency (4) $\sim$50% lower and the frequency (5) $\sim$50% higher than the center of the frequency range of interest; 3) compute the S-parameters of the N-cells resulting lumped-element coupler with starting values for L_m and C_m of the order of 0.5 nH and pF, respectively, check the coupling level, and consequently adjust the number of cells; 4) use approximate formulas to design the interdigital capacitor and stub inductor [15]; 5) full-wave simulate and adjust the spacing for the exact coupling desired; 6) if necessary, extract the exact parameters by the technique exposed in [11] and go back to the circuit model with better starting values of parameters for a second design iteration.

VI. Conclusion

A novel mixed conventional CμS/CRLH coupler with broad bandwidth and tight coupling characteristics has been demonstrated. The working principle has been explained, an accurate circuit model has been proposed for design, and the performances have been demonstrated experimentally.

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