A Broadband Left-Handed (LH) Coupled-Line Backward Coupler with Arbitrary Coupling Level

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***Abstract* — A novel broadband left-handed (LH) coupled-line backward coupler with arbitrary coupling level is presented. This coupler is composed of two LH transmission lines (TL) constituted of series interdigital capacitors and shunt shorted-stub inductors. A quasi-0dB implementation of the coupler is demonstrated by simulation and measurement results, and shown to exhibit a bandwidth of 35% despite the relatively wide lines-gap of 0.3mm. An even/odd modes analysis is presented to explain the working principle of the component. A 3dB-quadrature implementation, with 37% bandwidth, is also demonstrated. Finally, parametric results illustrate the versatility of the LH coupler and its strongly enhanced backward coupling compared with the conventional coupled-line coupler.**

I. INTRODUCTION

A well-known problem of conventional microstrip parallel-coupled couplers is their difficulty to achieve tight backward-wave coupling (e.g., 3-dB) because of the excessively small lines-gap required [1]. Alternative components include non-coupled-line couplers such as the branch-line or rat-race; however, these couplers are inherently narrowband (<15% bandwidth) circuits. The Lange coupler [2] is a solution widely used in the MMIC industry for broadband 3-dB coupling, but it has the disadvantage of requiring cumbersome bonding wires.

Recently, there has been a great interest in the emerging field of metamaterials (artificial materials with properties not found in nature) and, more specifically, left-handed (LH) structures (structures in which phase and group velocities exhibit opposite signs, and corresponding to negative refractive index materials) [3]-[5]. A TL approach of LH materials was recently proposed and demonstrated to provide an efficient tool for the design of novel structures and devices, both in 1D and 2D configurations [6]-[8]. The concept of LH-TL has paved the road for a diversity of novel microwave components (couplers, phase shifters, baluns), circuits, reflectors and antennas [9]. In this paper, we combined two LH-TLs introduced in [7] into a novel symmetric coupled-line coupler. This coupler can provide arbitrary loose/tight coupling levels over a broad bandwidth and quadrature through/coupled outputs, without requiring bonding wires like the Lange coupler.

The paper is organized as follows. In section II, the architecture of the coupler is described, and a quasi-0dB implementation is demonstrated by both simulation and measurement results. Section III presents an even/odd mode analysis of the coupler and explains its working principle. A 3-dB implementation, of particular interest for practical applications, is demonstrated in Section IV. Finally, Section IV provides some parametric results, showing the coupling levels achievable for different lines-gaps of the LH-TLs, in comparison with the conventional case.

II. DESCRIPTION OF THE COUPLER AND DEMONSTRATION OF A QUASI-0DB IMPLEMENTATION

Fig. 1 shows a prototype of the proposed coupler. This coupler is composed of two parallel identical LH-TLs, consisting of the periodic repetition of a T-network symmetric microstrip *unit-cell* including two series interdigital capacitors of value *2C* and one shunt shorted-stub inductor of value *L*.

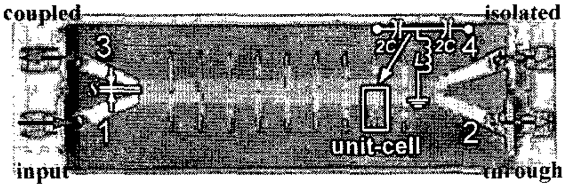

Fig. 1. Picture of a 9-cells LH coupler prototype printed on a RT-Duroid 5880 substrate (h=62mils, ε_r=2.2). The gap between the lines is s=0.3mm (s/h=0.19).The unit-cell of each LH-TL (1-2 and 3-4) consists of a series interdigital capacitor $2C$ ($2C$=2.4pF @ 3GHz) (after series-combination, $2C$ at both ends and C everywhere else) and of a shunt shorted-stub inductor L (L=6.5nF @ 3GHz). $Z_0 = \sqrt{L/C} \simeq 75\Omega$.

The resulting ladder-network for each line is a *high-pass* filter equivalent to an *artificial* (non-existing in nature) *LH-TL* in its pass-band if the electrical length of the unit-cell, given by

$$\phi = -\mathrm{atan}\left\{\omega\left(L/Z_0 + CZ_0\right)\Big/\left[1-2\left(\omega/\omega_0\right)^2\right]\right\}, \quad (1)$$

where $\omega_0 = 1/\sqrt{LC}$, is much smaller than wavelength (ideally $\phi \ll \pi/2$). In the case of Fig. 1, the unit-cell length is about $\lambda_g/10$ at 3 GHz. Under this condition, the structure behaves as a *uniform/homogeneous* TL, and the

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physical unit-cell approximates the infinitesimal model of the *dual* of the conventional TL, in which L and C have been swapped [7]. As a consequence, the line exhibits the *negative-hyperbolic* phase response and the corresponding *anti-parallel phase/group velocities* given by

$$\beta = -1/\left(\omega\sqrt{L'C'}\right) \quad (L' \text{ in } H\cdot m, C' \text{ in } F\cdot m), \tag{2}$$

$$v_\varphi = -\omega^2\sqrt{L'C'}, \quad v_g = +\omega^2\sqrt{L'C'}, \tag{3}$$

respectively, which are characteristic of backward or LH waves [10], while the characteristic impedance is still given by $Z_0 = \sqrt{L'/C'} = \sqrt{L/C}$ in the lossless case. In contrast to most structures described previously in literature, this LH structure can have a low insertion loss over a broad bandwidth with moderate dispersion [7].

The combination of two such LH-TLs into the coupler configuration shown in Fig. 1 leads to strongly enhanced backward-coupling. This is demonstrated in Figs. 2 and 3, showing the simulated and measured S-parameters, respectively, of the quasi-*0*dB backward coupler of Fig. 1. Insertion loss is smaller than *0.6*dB in the frequency range from *3.3* to *4.7* GHz, which corresponds to a -3dB fractional bandwidth of *35%*. In comparison, the conventional λ/4 microstrip coupler provides a coupling of only *-11.8*dB for the same substrate parameters and gap (*s*/*h*=0.19). The results also reflect the high-pass nature of the structure, with a cutoff of around *1.4*GHz, corresponding to the formula

$$f_c = 1/\left(4\pi\sqrt{LC}\right), \tag{4}$$

obtained for the infinitely-periodic LH-TL. The frequency dependence of the shunt shorted-stub inductor, $L(\omega) = (Z_0/\omega)\cdot\tan(\beta d)$ ($L\simeq 2.4$nH @ 1.5GHz) must be taken into account in this calculation. A *through* ($S_{21}\simeq 0$dB) propagation band extending from 1.5 to 2.5 GHz, which may be used in dual-band applications, is also observed in Figs. 2 and 3.

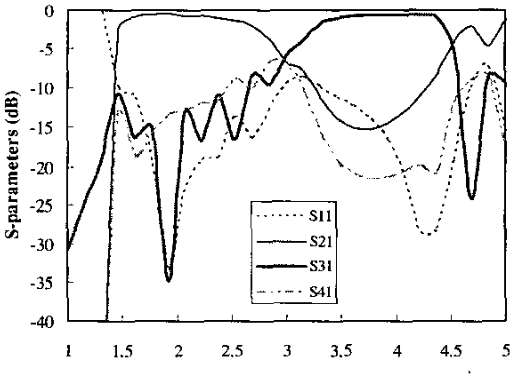

Fig. 2. Magnitude of the S-parameters for the coupler of Fig. 1, obtained by full-wave simulation (Ansoft-Ensemble).

III. EVEN/ODD MODES ANALYSIS

The even and odd modes S-parameters of the coupler of Fig.1 were computed by the Sonnet-EM full-wave simulator, and are shown in Figs. 4 and 5, respectively. In the bandwidth of the backward coupler (*3.3* to *4.7* GHz), the even/odd return losses are very flat and close to *0*dB. This is the reason why through transmission is very small and backward coupling can be close to *0*dB in the coupler.

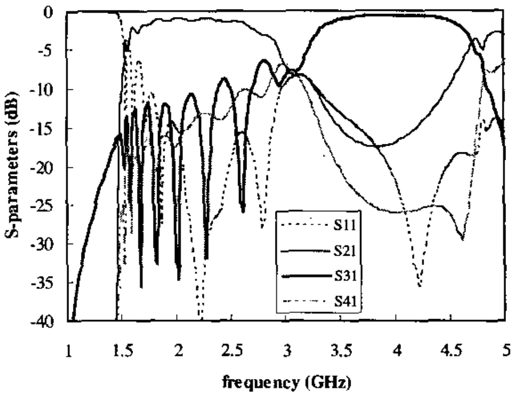

Fig. 3. Magnitude of the S-parameters for the coupler of Fig. 1, obtained by measurement.

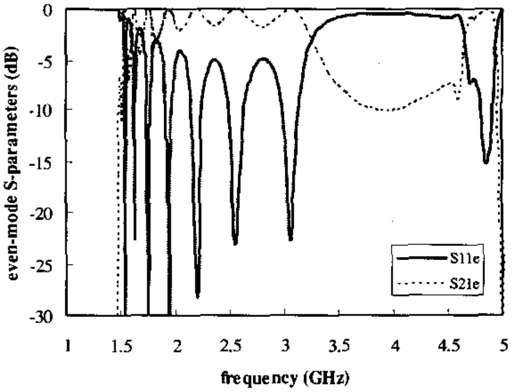

Fig. 4. Magnitude of the even-mode S-parameters (Sonnet-EM) for the design of Fig. 1.

Fig. 6 shows the even/odd characteristic impedances Z_{0e}/Z_{0o} computed from the even/odd S-parameters, using the general formula

$$Z_{0i} = \sqrt{(\Pi_i - 1)/(\Pi_i + 1)}, \quad (i = e, o) \tag{5}$$

$$\text{with } \Pi_i = \left(S_{21i}^2 - S_{11i}^2 - 1\right)/\left(2S_{11i}\right).$$

It can be seen that $Z_{0o} > Z_{0e}$ in the first part of the range, while $Z_{0e} > Z_{0o}$ in the second part of it. In their most general form, also holding for LH lines, the characteristic impedances in a symmetrical coupled-line coupler are given by [1]

$$Z_{0e}=\sqrt{(L'+2L'_m)/C'} \text{ and } Z_{0o}=\sqrt{L'/(C'+2C'_m)}, \qquad (6)$$

where C'_m / L'_m are the per-unit-length mutual capacitance and inductance, respectively, between the two lines, and C'/L' represent here to times-unit-length elements of the LH-TL. In (6), L'_m is a negative quantity since the currents flow in opposite directions in the two lines, but, while it can usually be neglected in the conventional coupler, it appears to be dominant below the Z_{0e}/Z_{0o} crossing frequency f_p=*3.7*GHz in the proposed coupler. This suggests that the operating range of the LH coupler can be divided into two parts delimited by f_p: in the lower part, coupling is essentially of *magnetic* nature with L'_m negative and $|L'_m| > L_{\lim}$ where

$$L_{\lim} = 0.5\cdot\left[L'C'/(C'+2C'_m)-L'\right], \qquad (8)$$

while in the higher part, it is essentially of *electric* nature with $|L'_m| < L_{\lim}$, as in the conventional case. It was verified that the conventional relations

$$S_{11o}=-S_{11e},\quad S_{22o}=-S_{11e},\quad S_{21o}=+S_{21e} \qquad (9)$$

are satisfied above f_p, but not below f_p, which further confirms that the working principle below f_p is very different from that of the conventional case.

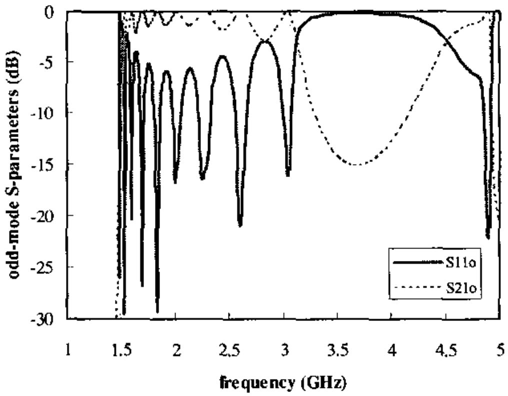

Fig. 5. Magnitude of the odd-mode S-parameters (Sonnet-EM) for the design of Fig. 1.

It should be noted that the usual formula

$$C_{BWD}=\frac{jk\sin\beta l}{\sqrt{1-k^2}\cos\beta l + j\sin\beta l}, \qquad (10)$$
$$\text{with } k=(Z_{0e}-Z_{0o})/(Z_{0e}+Z_{0o}),$$

for backward coupling does *not* apply here, because this formula is based on the relation $Z_{0e}\cdot Z_{0o}=Z_0^2$, which is clearly non satisfied according to Fig. 6. It is therefore not paradoxical that we can have a high level of coupling at f_p=*3.7*GHz despite the fact that $Z_{0e}=Z_{0o}$.

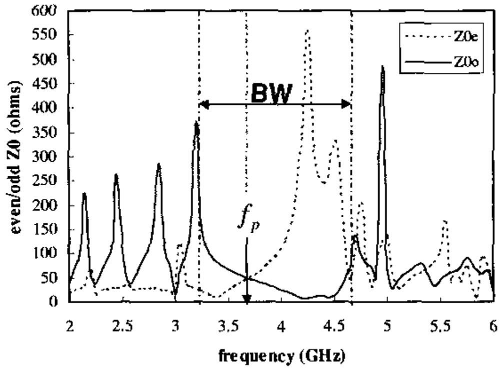

Fig. 6. Even/odd characteristics impedances computed from the even/odd S-parameters of Figs. 4 and 5 with (5).

IV. 3-DB IMPLEMENTATION

Fig. 7 shows the results for a 3-dB implementation of the LH coupler, with a gap of 0.4mm between the lines, which corresponds to a gap of s/h=0.25. For this gap, the coupling level of the conventional coupled-line coupler is around -*12*dB. The physical length of the coupler *25*mm, which represents $0.4\lambda_g$, is the guided wavelength of the corresponding conventional coupler. Note that the 3dB-coupler can be made smaller by reducing the gap. For instance, using only 2 unit-cells results with s=*0.05*mm results in a 3dB coupler of length $0.3\lambda_g$.

The performances of the 3-dB coupler are the following: *-3.3±0.4*dB backward/through coupling, return loss smaller than *18*dB and isolation better than *20*dB over the *3.1* to *4.5* GHz range (*37%* fractional bandwidth). The phase difference between the coupled and through ports is *90.5º±1.5º* across the *3.1* to *4.2* GHz frequency range.

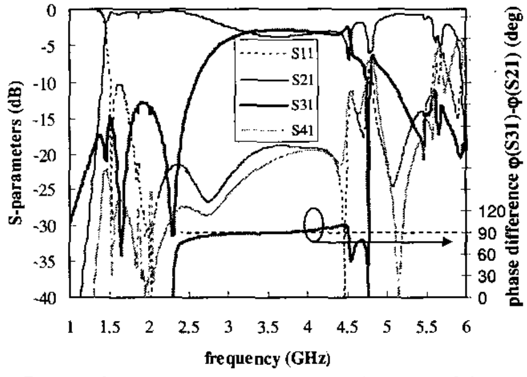

Fig. 7. Magnitude and phase characteristics (Ansoft-Ensemble simulation) for a *3*dB 3-unit-cells backward coupler with gap s=*0.4*mm (s/h=0.25).

V. OTHER COUPLING LEVELS

A quasi-*0*dB LH-coupler was demonstrated in Sec. II, whereas a *3*dB LH-coupler was presented in Sec. IV. In fact, arbitrary coupling level (from around *0.2*dB) can be achieved by varying the gap s between the lines or the number of unit cells N. Some benchmark results for the achievable coupling levels of the LH coupler versus s are shown in Table I, where the coupling levels of the conventional coupled-line coupler with corresponding gaps are also shown for comparison

TABLE I
COUPLING LEVELS VERSUS GAP (S)
FOR THE 9-CELLS LH-COUPLER OF FIG. 1.

LH-C_{BWD} (dB)	s (mm)	conv-C_{BWD} (dB)
-0.5	0.2	-10.2
-3	1.9	-19.5
-6	3.6	-25.2
-10	5.5	-29.3
-20	15.5	< -40

The isolation is typically better than 20dB in all the cases. It can be seen that the proposed LH coupler can achieve arbitrary tight/loose coupling levels with lines-gaps easily realizable even in traditional microstrip implementations.

The strong enhancement of coupling shown here suggests the possibility that, in analogy to what happens in the case of the LH slab presented in [11], the attenuation factor α in the structure may be a *negative* quantity, which would correspond to an enhancement ("amplification" in [14]) of the evanescent waves through which the coupling process occurs. This is still to be demonstrated.

VI. CONCLUSION

A novel LH backward-wave coupler was presented. This coupler was shown to lend itself for arbitrary loose/tight coupling levels despite relatively large lines-gap (typically $s/h>1/5$), which provides a solution to the well-known problem of the impractically small gap required for tight-coupling in conventional coupled-line couplers. The proposed coupler was also shown to exhibit a broad bandwidth, typically larger than *35%*. Both a quasi-0dB and a quadrature 3dB implementations were demonstrated. An even/mode analysis of the coupler was proposed and an explanation based on alternating magnetic and electric coupling in the backward band was suggested.

In addition to providing arbitrary coupling levels over a broad bandwidth, the proposed coupler can be designed for a physical size similar to that of the conventional coupler, and does not require bonding wires in contrast to the Lange coupler.

ACKNOWLEDGEMENT

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