A Compact Enhanced-Bandwidth Hybrid Ring using a Left-Handed Transmission Line Section

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***Abstract* — A novel compact enhanced-bandwidth hybrid ring using a left-handed (LH) transmission line (TL) is proposed. The LH-TL is used in replacement of the 270° TL of the conventional hybrid ring. The proposed hybrid shows a 54-% bandwidth enhancement and 67-% size reduction compared to the conventional hybrid at 2 GHz. The working principle is explained and the performances of the components are demonstrated by measurement results.**

I. INTRODUCTION

Left-handed (LH) materials, which are characterized by simultaneously negative ε and μ, were first investigated theoretically by Veselago in 1968 [1]. From Smith's *et al.* proposal of a practical implementation of in 2000 [2], LH materials have attracted a great deal of attention and start to be integrated into novel microwave and optical applications.

However, the first approaches of LH materials were mainly based on an analogy with plasmas, which naturally resulted in resonant-type structures not suitable for practical microwave applications because of their excessive loss and narrow bandwidth [2,3].

Recently, a transmission line (TL) approach of LH-materials [4,5] and practical implementations of them were proposed in different applications [6,7]. The low insertion loss and broad bandwidth of the LH-TL make it an efficient candidate for new microwave frequencies. Because of their negative β, LH-TLs exhibit phase advance instead of a phase lag, as the conventional right-handed (RH) TL. This phase characteristic leads to new designs for many microwave circuits such as antennas [6,7] and couplers. In this paper, we present a hybrid ring with a LH-TL section, and demonstrate the effectiveness of LH-TL for bandwidth enhancement.

The hybrid ring (or rat-race) is a 180° hybrid which represents a fundamental component in microwave circuits. It can be used as an out-of-phase or in-phase power divider with isolated output ports. Because of these characteristics, the 180° hybrid is widely used in balanced mixers and power amplifiers. The hybrid ring is useful in MIC's or MMIC's because it can easily be constructed in planar form.

The shortcomings of hybrid rings are their narrow bandwidth and large size. There have been many approaches to achieve broad band and small size. Using lumped-elements is one of the major approaches to reduce size [8,9], but it is difficult to achieve a broad bandwidth. L. Fan et al. proposed a broad bandwidth hybrid ring in CPW-slotline configuration [10]. However, CPW and slotline are not suitable for general MIC's. Our hybrid ring, which uses a LH-TL, is one approach realizing acceptably small size and relatively broad bandwidth with conventional radio-frequency circuit processes.

The paper is organized as follows. First, the fundamental characteristics of LH-TL are recalled. Then, the design of the hybrid ring with a LH-TL is explained. Finally, measurement results are presented and discussed in comparison with those of the conventional hybrid ring.

II. CHARACTERISTICS OF LH-TL [6]

Fig. 1 shows the unit-cell equivalent circuit models for a RH-TL (a) and a LH-TL (b). The LH-TL is the electrical dual of the conventional RH-TL, in which the inductance and capacitance have been interchanged. In the LH-TL, the wavenumber β_L, the characteristic impedance Z_{0L}, the cut-off frequency ω_{cL}, and the insertion phase-rotation φ_L are given by equations (1)-(4), respectively. The LH-TL is characterized by a negative β_L and the positive φ_L. These unique features may be exploited in the design of new types of the microwave circuits.

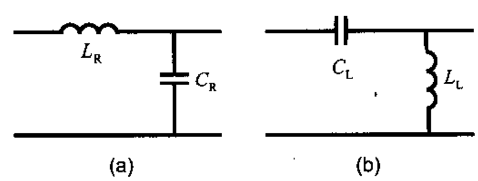

Fig. 1. Unit-cell equivalent circuit model for the RH and LH TL's. (a) RH-TL. (b) LH-TL.

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$$\beta_L = -1/\left(\omega\sqrt{L_L C_L}\right) \tag{1}$$

$$Z_{0L} = \sqrt{L_L / C_L} \tag{2}$$

$$\omega_{cL} = 1/\left(2\sqrt{L_L C_L}\right) \tag{3}$$

$$\varphi_L = -\arctan\left[\frac{\omega(L_L / Z_0 + C_L Z_0)}{1-2(\omega/\omega_{cL})^2}\right] > 0 \tag{4}$$

III. DESIGN OF THE HYBRID RING WITH A LH-TL

The conventional hybrid ring consists of three 90°-RH-TLs and one 270°-RH-TL. The 270°-RH-TL uses half of the area of the component and makes its bandwidth narrow because of the frequency dependence of its insertion phase, which is three times larger than that of a 90°-RH-TL. Since 270° phase rotation is electrically equivalent to -90° phase rotation, we may change the 270°-RH-TL into a -90°-LH-TL. In contrast to the RH-TL, the LH-TL can be made small and has a mild frequency dependence of insertion phase around the frequency of interest. Thus a hybrid ring with a -90°-LH-TL instead of a 270°-RH-TL can exhibit smaller size and broader bandwidth. More interestingly, some amount of parasitic RH contribution is intrinsically included in the practical implementation of a LH-TL, which makes its frequency dependence even milder than that of the ideal LH-TL. In general, a TL which including both LH and RH contributions is called a CRLH (Composite Right/Left Handed) TL.

Fig. 2 shows 3-cells configurations of LH- and CRLH-TLs. To achieve -90° phase rotation, the LH-TL uses three -30°-LH-cells (a) and the CRLH-TL uses three -35°-LH-cells with three 5°-RH-TLs (b). The frequency dependences of insertion phase for these LH- and CLRH-TLs were calculated by using equation (4) and are shown in Fig. 3 with the calculated results for the 90°-RH-TL and 270°-RH-TL. The capacitances C and inductances L in the unit cells were adjusted to make the insertion phase -90° at 2 GHz and the characteristic impedance, given by (2), 70.7 Ω. The resulting values for C and L are (a) 2.2 pF, 11.2 nH, and (b) 1.9 pF, 9.7 nH. It is clearly seen in Fig.3 that the cumulated phase of the LH-TL, thanks to its hyperbolic shape, exhibits a nearly 180° difference with respect to the 90°-RH-TL over a wide frequency range and that the CRLH-TL keeps that 180° difference over an even broader bandwidth, while the phase difference between the 270°-RH-TL and 90°-RH-TL changes linearly with frequency. These phase differences compared to the phase of the 90°-RH-TL are shown in Fig.4. The bandwidths, defined by ±10° phase difference are 11% for the 270°-RH-TL, 60% for the LH-TL, and 70% for the CRLH-TL. The LH- and CRLH-TL show wider bandwidths compared to the 270°-RH-TL as we expected.

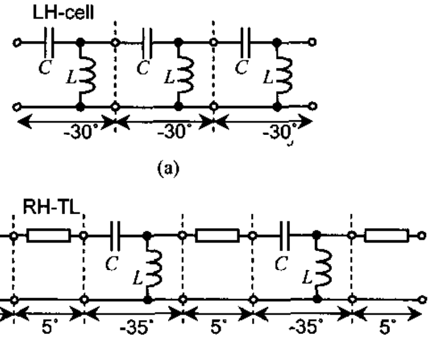


Fig. 2. 3-cells configurations of LH- and CRLH-TLs. (a) LH-TL, (b) CRLH-TL.

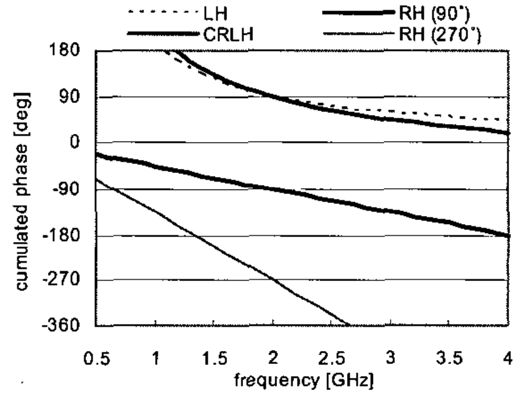


Fig. 3. Insertion phase for LH-, CRLH-, RH (90°)-, and RH (270°)-TLs for the circuits of Fig. 2.

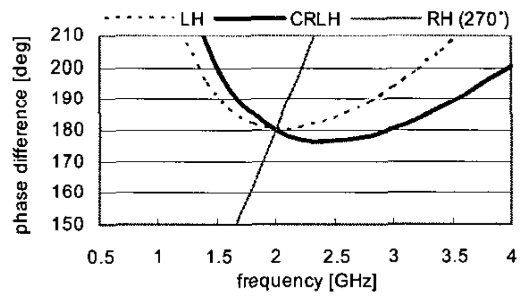
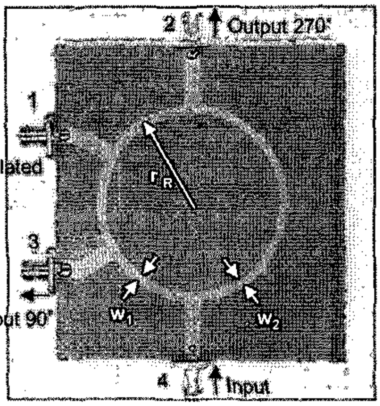


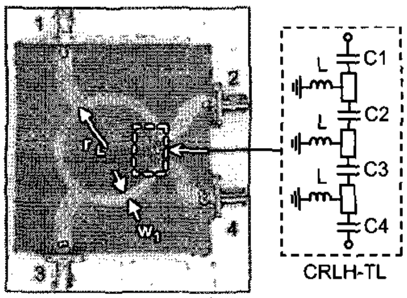
Fig. 4. Insertion phase differences between the LH-, CRLH-, and RH (270°)-TLs, and to 90°-RH-TL, respectively, for the circuits of Fig. 2.

IV. Measurement Results And Discussion

Fig. 5 shows photographs of the fabricated hybrid rings. Fig. 5 (a) is the conventional hybrid ring and Fig. 5 (b) is the proposed hybrid ring including the CRLH-TL (b). The substrate for both hybrids is RT/Duroid5880 (ε_r=2.2, 1.57-mm thickness).



(a)



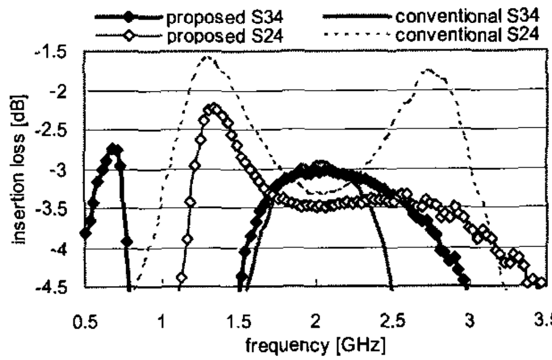
(b)

Fig. 5. Photograph of the fabricated hybrid rings. (a) conventional, (b) with a CRLH-TL.

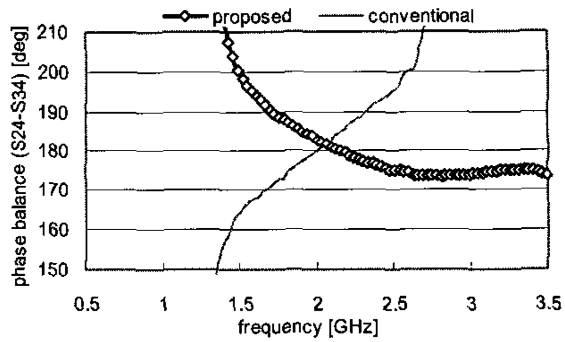
The characteristic impedance of the 270°-RH-TL in the conventional hybrid ring was intentionally slightly shifted from that of the other 90°-RH-TLs for broader bandwidth. The broadest possible bandwidth, defined by ±0.25 dB amplitude balance, was obtained with the width w_2=2.25 mm, corresponding to the characteristic impedance of 79.3 Ω at 2 GHz, while the width of the 90°-RH-TLs w_1 was set to 2.77 mm (70.7 Ω).

The CRLH-TL was implemented in chip components (1.6 x 0.8 mm^2). The values of capacitances and inductances for the CRLH-TL were chosen to have a -90° phase rotation and the same characteristic impedance as that of the 270°-RH-TL at 2 GHz. The resulting values were: C1=1.0+1.2 pF, C2=1.2 pF, C3=1.0 pF, C4=1.0+1.0 pF, L=4.7+4.7 nH. Since these chip components have self-resonant frequencies, parallel and series configuration were used to avoid the limitation by the self-resonance.

The radiuses of the two hybrids were r_R=26.6 mm for the conventional one and r_L =14.6 mm for the proposed one, respectively. Consequently, the outer areas of the rings were 2460 mm^2 and 800 mm^2, respectively. The size of the proposed hybrid was thus reduced by 67 % from that of the conventional one.



(a)



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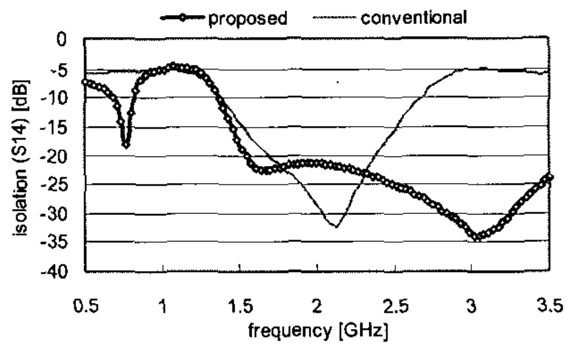

(c)

Fig. 6. Measured characteristics of the fabricated hybrid ring. (a) insertion loss, (b) phase balance, (c) isolation.

Fig. 6 (a) shows the measured insertion-loss characteristics of the fabricated hybrids. The bandwidths of the proposed hybrid and of the conventional one are 1.646-2.615 GHz (45.5 %, -3.28±0.25 dB) and 1.727-2.324 GHz (29.5 %, -3.17±0.25 dB), respectively. The bandwidth of the proposed hybrid was enhanced by 54 % compared to that of the conventional one, while the average magnitude was reduced by only 0.11 dB.

Fig. 6 (b) shows the phase balances of the fabricated hybrids. The phase balances, within the range of 180±10°, are from 1.682 GHz to more than 3.5 GHz for the proposed hybrid compared to from 1.670 GHz to 2.325 GHz for the conventional one.

Fig. 6 (c) shows the isolation characteristics of the fabricated hybrids. Isolations less better than 20 dB were obtained from 1.544 GHz to more than 3.5 GHz for the proposed hybrid while they extended from 1.686 GHz to 2.383 GHz for the conventional one.

The results of Fig. 6 (a)-(c) demonstrate that the proposed hybrid ring exhibits a significant bandwidth enhancement compared with the conventional hybrid ring, in addition to size reduction. This bandwidth enhancement is due to the frequency dependence of the insertion phase in the CRLH-TL, as we explained in the section III.

The characteristics at higher frequencies are influenced by the self-resonance of the chip components. However, using the MMIC process such as MIM capacitors and spiral inductors, the characteristics of LH-TLs in the higher frequency range can be improved.

V. Conclusion

A novel small-size, broad-band hybrid ring including a LH (CRLH)-TL was proposed and its performances were demonstrated by measurement results. Using a LH-TL in replacement of the 270° RH-TL of the conventional hybrid ring, the proposed hybrid showed a 54-% bandwidth enhancement and 67-% size reduction compared to a conventional hybrid ring at 2 GHz.

The interesting features of negative β_L and positive φ_L of the LH- or CRLH-TLs, the usefulness of which was demonstrated in the hybrid ring application in this paper, may be used in several other microwave applications requiring high-compactness and/or broadband characteristics, such as couplers/hybrids, filters, and antennas.

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