Miniaturized Ring Coupler with Arbitrary Power Divisions Based on the Composite Right/Left-Handed Transmission Lines

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***Abstract*—A novel and miniaturized ring coupler capable of presenting arbitrary power divisions is proposed using the composite right/left-handed (CRLH) transmission lines. The unbalanced CRLH transmission lines that can be easily tailored to implement transmission lines of high or low Bloch impedance are applied to enhance the coupler's capability of arbitrary power divisions. To support our idea, a ring coupler that offers a 6 dB power division ratio and occupies only 44% of the conventional footprint was experimentally realized. Experimental results agree well with the simulation data. The proposed CRLH configuration demonstrates an alternative for implementing a compact ring coupler with arbitrary power division ratios.**

***Index Terms*—Arbitrary power divisions, composite right/left-handed transmission lines, miniaturization, ring couplers, unbalanced structures.**

I. Introduction

RING couplers that create anti-phase signals at two isolated ports find many applications in modern microwave and millimeter-wave circuits, such as the balanced mixers, push-pull amplifiers, and antenna beamforming networks. As a critical element in the integrated systems, studies on the 3 dB ring couplers to reduce the footprint size [1]–[3] or/and to enhance the operating bandwidth [4], [5] were therefore extensively conducted. In the situation when unequal power distribution is preferred, the ring couplers that are capable of arbitrary power divisions are of particular interest. Such a coupler can be realized by connecting the $\lambda/4$ transmission lines of high and low characteristic impedances, alternatingly, to form the ring [6]. Based on this scheme, the $\lambda/4$ line elements in the proposed couplers [7] were implemented on a basis of stepped-impedance microstrip lines with open stubs at both ends. It is found that, however, the maximum attainable power division ratio is limited by the realizable line impedance that increases with the power division ratio. Using the defected ground plane [8] or the offset parallel-strip line [9] enables us to implement a line of higher characteristic impedance but at the expense of increased circuit complexity.

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The unique features of the composite right/left-handed (CRLH) transmission lines have lent themselves to novel applications in the microwave engineering field. Specifically, the dispersion engineering by means of the four lumped-element parameters in the equivalent circuit model demonstrates great potential for miniaturization and dual-band or broadband implementation of the 3 dB hybrid rings [10], [11]. However, less effort has been made on a compact ring coupler with arbitrary power divisions using the CRLH transmission lines, by which the difficulty in realizing high impedance lines can be easily overcome.

In this work, the unbalanced CRLH transmission lines are applied to implement the $\lambda/4$ line elements in the coupler with arbitrary power divisions. The Bloch impedance of the unbalanced transmission line is a function of the frequency and four circuit parameters, which is very useful to realize high-impedance lines in the case of a high division ratio. The proposed design procedure starts by solving the equivalent lumped elements of a $\lambda/4$ CRLH line of prescribed Bloch impedance at a frequency of interest. For the single-band coupler, two degrees of freedom are available to facilitate the implementation of the equivalent parameters and thus the physical dimensions. A ring coupler that demonstrates 56% size reduction and provides 6 dB power division ratio was carried out to validate our idea. Experimental results are given and agree well with simulation data.

II. Design Approach Based on the Unbalanced CRLH Transmission Lines

In general, the CRLH transmission lines are unbalanced structures [12]. In other words, in the dispersion diagram a stop-band gap exists in between the left-handed (LH) and the right-handed (RH) regions and is delimited by the series resonance frequency $\omega_{\rm se}$ and the shunt resonance frequency $\omega_{\rm sh}$ as illustrated in Fig. 1(a). These two frequencies are determined by the equivalent circuit parameters $L_{\rm R}$, $C_{\rm R}$, $L_{\rm L}$, and $C_{\rm L}$ in Fig. 1(b), and are given as follows:

$$\omega_{se} = \frac{1}{\sqrt{L_R C_L}}, \quad \omega_{sh} = \frac{1}{\sqrt{L_L C_R}}. \qquad (1)$$

Furthermore, in the passband region ($\omega > \omega_{\rm se}$ or $\omega < \omega_{\rm sh}$), the Bloch impedance $Z_{\rm B}$ and unit-cell phase response $\Delta\varphi_{\rm c}$ are characterized as follows:

$$Z_B = \sqrt{\frac{L_L}{C_L}} \sqrt{\frac{\left(\frac{\omega}{\omega_{se}}\right)^2 - 1}{\left(\frac{\omega}{\omega_{sh}}\right)^2 - 1} - \frac{\left(\left(\frac{\omega}{\omega_{se}}\right)^2 - 1\right)^2}{4 L_L C_L \omega^2}} \qquad (2)$$

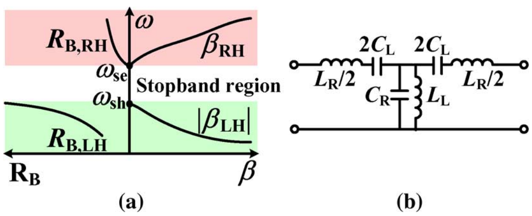

Fig. 1. (a) Illustration of the propagation constant β (to the right of the ω-axis) and Bloch impedance Z_{B} (to the left of the ω-axis) of the unbalanced CRLH transmission lines where $R_{\mathrm{B}} = Real(Z_{\mathrm{B}})$. (b) The equivalent circuit model of the CRLH transmission lines.

TABLE I
LUMPED-ELEMENT SOLUTIONS TO (2) AND (3) FOR THE $\lambda/4$ CRLH TRANSMISSION LINE OF BLOCH IMPEDANCE Z_{B} AT 2.4 GHz

Solutions	L_{R}(nH)	C_{R}(pF)	L_{L}(nH)	C_{L}(pF)	$Z_{\mathrm{B}}(\Omega)$	N
#1	1.831	1.525	2.5	0.9	111.8	3
#2	1.689	1.169	2.5	1.2	55.9	3
#3	1.9	1.282	2.5	0.7	89.9	2
#4	1.356	1.358	2	1	55.6	2

$$\Delta\varphi_c = \varphi(S_{21}) = -\tan^{-1}\left(\frac{1}{\omega}\,\frac{\frac{\left(\frac{\omega^2}{\omega_{se}^2}-1\right)}{C_L Z_0}\left(1-\frac{\left(\frac{\omega^2}{\omega_{se}^2}-1\right)\left(\frac{\omega^2}{\omega_{sh}^2}-1\right)}{4L_L C_L\omega^2}\right)+\frac{Z_0}{L_L}\left(\frac{\omega^2}{\omega_{sh}^2}-1\right)}{2-\frac{\left(\frac{\omega^2}{\omega_{se}^2}-1\right)\left(\frac{\omega^2}{\omega_{sh}^2}-1\right)}{L_L C_L\omega^2}}\right) \quad (3)$$

where ω is the angular frequency and Z_0 is the port impedance. According to (2) and (3), Fig. 1 depicts the passband frequency behavior of the Bloch impedance and propagation constant β of the unbalanced CRLH transmission lines. Note that in the passband regions Z_{B} is a real number and $Z_{\mathrm{B}} = R_{\mathrm{B}}$. In the case when $\omega_{\mathrm{sh}} < \omega_{\mathrm{se}}$, the Bloch impedance in the left-handed region increases rapidly as the frequency approaches its pole frequency ω_{sh}, which enables the fulfillment of a high-impedance transmission line at a prescribed frequency in proximity to ω_{sh}. Furthermore, as observed in (2), the Bloch impedance of the unbalanced CRLH transmission line is a function involving the four circuit parameters, which provides higher degrees of freedom for flexible engineering of the equivalent lumped elements that determine the feasibility of the corresponding physical dimensions. The unbalanced CRLH lines show superior features to the balanced structures where $Z_{\mathrm{B}} = (L_{\mathrm{R}}/C_{\mathrm{R}})^{1/2} = (L_{\mathrm{L}}/C_{\mathrm{L}})^{1/2}$ [12], which makes implementation of high-impedance lines much difficult.

The design procedure of a $\lambda/4$ unbalanced CRLH transmission-line element of specific Bloch impedance starts by solving (2) and (3) to determine the four circuit parameters. In the case of the single-band operation, two parameters can be chosen for implementation convenience. Depending on the chosen substrate and implementation schemes, in our case, the series capacitance C_{L} and shunt inductance L_{L} are assigned two values that can be easily realized from using the interdigital capacitor and shorted stub, respectively. Table I lists sets of parameter solutions to (2) and (3) for implementing $\lambda/4$ unbalanced CRLH transmission lines with N unit cells and of given Bloch impedances. It can be shown that the equivalent lumped-element values in Table I can be easily achieved in a microstrip unit cell that makes use of the series interdigital capacitor and the shunt stub inductor [12]. Upon acquisition of the four parameters, the physical prototype of the $\lambda/4$ CRLH line is developed in a manner so as to have equivalent circuit parameters the same as acquired, which ensures simultaneous fulfillment of the desired Bloch impedance and phase response at a frequency. An example of the $\lambda/4$ CRLH transmission line, shown in the inset of Fig. 2, was developed and calculated in HFSS. Considering the coupler's port placement on the connection between the $\lambda/4$ line elements, it should be noted that, the $\lambda/4$ CRLH line has microstrip lines at both ends in addition to the two pairs of shunt stubs and series interdigital capacitors. At 2.4 GHz, the $\lambda/4$ line was designed based on the lumped parameters in Solution #3 and has calculated Bloch impedance 89.19 Ω and phase response 90.96°, showing good agreement with the corresponding theoretical results from (2) and (3) as observed in Fig. 2.

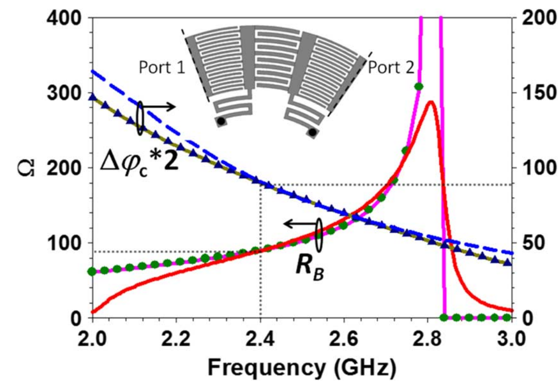

Fig. 2. HFSS-calculated Bloch impedance (solid line) and phase response (dashed line) of the $\lambda/4$ CRLH transmission line element. The corresponding theoretical results from (2) and (3) are represented by the line with circle symbol and the line with triangle symbol, respectively.

III. PROPOSED CONFIGURATION OF THE COMPACT RING COUPLER WITH ARBITRARY POWER DIVISIONS

Based on the aforementioned configuration and proposed design procedure for the $\lambda/4$ unbalanced CRLH transmission line of arbitrary Bloch impedance, a ring coupler that is able to provide a 6 dB power division ratio at 2.4 GHz was carried out by alternatingly connecting two $\lambda/4$ CRLH transmission lines of Bloch impedances 89.9 Ω and 55.6 Ω [6] as shown in Fig. 3. Although not being implemented experimentally, a high-impedance line that produces a higher division ratio, as the first case investigated in Table I for a 111.8 Ω CRLH line, is readily realized with similar structures according to equivalent lumped parameters obtained. This coupler is developed on a Duroid/RT 5880 substrate with dielectric constant $\varepsilon_{\mathrm{r}} = 2.2$ and thickness $h = 62$ mil. Each $\lambda/4$ transmission line makes use of two pairs of series interdigital capacitors and shunt stub inductors to implement the equivalent series capacitance C_{L} and the shunt inductance L_{L}, respectively. Note that the shorted stubs in the CRLH line sections of 55.6 Ω are placed outside the ring simply for implementation convenience. The ring

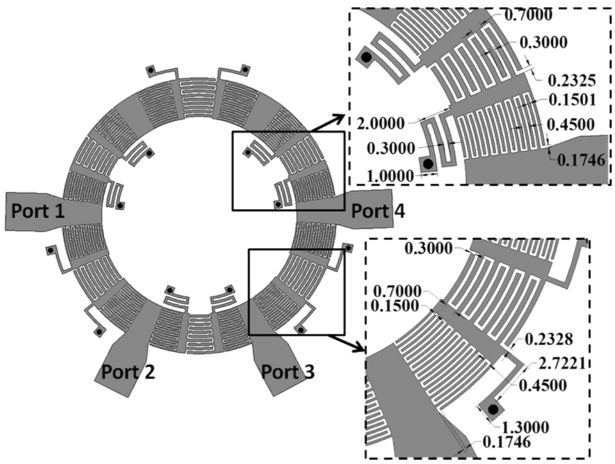

Fig. 3. Proposed compact ring coupler with a 6 dB power division ratio based on the unbalanced CRLH transmission lines. The physical parameters are indicated in the close-up insets. All dimensions are in mm.

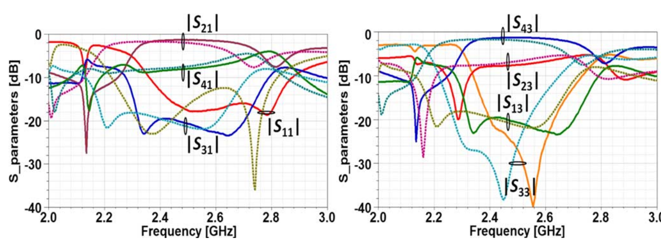

Fig. 4. Measured (solid curves) and simulated (dashed curves) S-parameters for the proposed compact ring coupler with a 6 dB power division ratio. The left and right figures plot the results obtained at port 1 ($\Delta - \mathrm{port}$) and at port 3 ($\Sigma - \mathrm{port}$), respectively.

coupler has a uniform arm width of 4.95 mm and a mean radius of 14.66 mm, which demonstrates a 56% footprint reduction compared to the 2.4 GHz microstrip coupler with the same power split ratio.

The measured S-parameters of the proposed CRLH ring coupler are shown in Fig. 4 along with the simulated results. Good agreement is obtained. The operating band is shifted upward by 80 MHz (3%), and this can be attributed to the fabrication error and the experimental deviation in the dielectric constant. The overall performances of the proposed ring coupler are detailed in Table II where the characteristics of the ring coupler having a 6 dB power division ratio are clearly exhibited and confirmed. Compared to the conventional coupler [6], bandwidth reductions on the measured return losses and phase differences are observed and are attributed to the highly frequency-variant characteristics of both the Bloch impedance and phase constant of the unbalanced CRLH lines. Measured insertion losses show close results as those of the conventional coupler except that more loss is observed in the measurement of $|S_{4\Delta}|$ owing to the increased conductor loss introduced by interdigital capacitors in the path.

TABLE II
MEASURED PERFORMANCES OF THE PROPOSED RING COUPLER WITH A 6 dB POWER DIVISION RATIO (CENTER FREQUENCY AT 2.48 GHz)

	Σ – Port (Port 3)	Δ – Port (Port 1)
Return Losses		
$\lvert S_{\Sigma\Sigma}\rvert$, $\lvert S_{\Delta\Delta}\rvert$	-25.16 (dB)	-16.99 (dB)
$BW_{<-15dB}$	12.3%	15.7%
Isolation $\lvert S_{\Sigma\Delta}\rvert$	-20.33 (dB)	
$BW_{<-15dB}$	17.7%	
Insertion Losses		
$\lvert S_{4\Sigma}\rvert$, $\lvert S_{2\Delta}\rvert$	-1.33 (dB)	-1.38 (dB)
$\lvert S_{2\Sigma}\rvert$, $\lvert S_{4\Delta}\rvert$	-7.65 (dB)	-8.11 (dB)
Magnitude Differences		
$\lvert S_{4\Sigma}\rvert$-$\lvert S_{2\Sigma}\rvert$, $\lvert S_{2\Delta}\rvert$-$\lvert S_{4\Delta}\rvert$	6.33 (dB)	6.73 (dB)
$BW_{6dB\pm1dB}$	11.1%	13.1%
Phase Differences		
$\lvert\angle S_{4\Sigma}$-$\angle S_{2\Sigma}\rvert$, $\lvert\angle S_{4\Delta}$-$\angle S_{2\Delta}\rvert$	7.2°	187.1°
$BW_{\pm10^{\circ}}$, $BW_{180^{\circ}\pm10^{\circ}}$	7.7%	7.9%

IV. CONCLUSION

The unbalanced CRLH transmission lines are applied to realization of the compact ring couplers with arbitrary power divisions. Based on the proposed design procedure, an example of a miniaturized ring coupler capable of the 6 dB output power split ratio is carried out and demonstrated experimentally.

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