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A NOVEL BROAD BANDWIDTH AND COMPACT BACKWARD COUPLER WITH HIGH COUPLING-LEVEL

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Abstract—A novel backward microstrip coupled-line coupler which has been designed based on the metamaterial and composite right/left handed (CRLH) transmission line (TL) concepts is proposed. Coupling coefficient, bandwidth and size of proposed microstrip coupler are improved by coupled interdigital TLs which have been realized only by one interdigital capacitor. The design procedure to reach the coupler with predefined coupling coefficient and characteristic impedance of its ports is clearly presented. The designed and fabricated prototype is a 3-dB microstrip coupler with 0.2 mm spacing between its coupled lines over a wide bandwidth of 60% from $2.3 \sim 4$ GHz centered at 3.2 GHz. The coupled-line length and the width of the proposed structure are approximately $\lambda_g/4$ and $\lambda_g/36$, respectively, which makes it more compact than the conventional cascaded CRLH microstrip coupled-line couplers.

1. INTRODUCTION

When two unshielded transmission lines (TLs) are close together, power can be coupled between the lines due to the interaction of the electromagnetic fields of the lines. A coupled-line coupler (CLC) is a four-port network comprised from such lines that its specifications can be controlled with design parameters such as the interspacing between

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the two lines and the length of the overall structure [1]. Conventional CLCs exhibit the advantage of broad bandwidth (more than 25%) but can achieve loose coupling level (typically $< 10\,\text{dB}$) and cost a large circuit area [1]. Most of them utilize the edge-coupling between two parallel coupled lines. In order to get the tight coupling-level, the space between the two lines must be very small, and it is very difficult to obtain due to the fabrication constrains [1]. All these drawbacks limit their broad applications to wideband microwave systems as well as the systems requiring small size devices.

In the past few years, there has been a great interest in the field of metamaterials (MTMs), especially composite right/left-handed (CRLH) structures and the microwave circuits based on the unusual properties of them. Numerous novel MTM-based microwave components have been proposed to control amplitudes, frequencies, and wave numbers of propagating and non-propagating electromagnetic modes [2–8]. Advances in MTMs have also stimulated the development of new couplers with unique coupling mechanisms. Recently, CLCs using CRLH TLs with broad bandwidth and arbitrary loose/tight coupling levels have been developed [9–14]. In these couplers, backward coupling occurs in a frequency band where the even and odd modes have the bandgap characteristics of the CRLH TLs. In the bandgap, the impedances of the even and odd modes become pure imaginary numbers with opposite signs, and there is a large impedance difference between them. The backward coupling depends on this difference between the even/odd-mode impedances and length of the coupled lines. In most cases, to obtain tight coupling couplers that use the cascaded left-handed microstrip coupled-line sections, a large coupled-line length is required [11–14]. It is considerable that the microstrip CRLH TL structures have been mostly implemented in the form of interdigital capacitors and stub inductors. So, using shorted stub inductors with large sizes to achieve the required inductances can cause the structure width to be also enlarged. For instance, the length and width of 3-dB microstrip coupled-line coupler proposed in [11] are approximately $\lambda_g/3$ and $\lambda_g/6$, respectively.

In this paper, a novel compact microstrip CLC with very wide bandwidth and tight coupling level is presented. The proposed operating and design principles are based on the interdigital TLs to improve the bandwidth and size of the conventional microstrip CRLH backward coupler. Each interdigital TL of the proposed coupler consists of only one interdigital capacitor without short-circuited stub inductors. In the propounded structure, used interdigital TLs operate in the right-handed mode. Therefore, its coupling mechanism is similar to the conventional couplers. This leads to a structure with a fixedlength $\lambda_g/4$ for different coupling levels, unlike the conventional CRLH couplers. Moreover, removing the shorted stubs leads to decrease in the structure width, considerably. Compared with the tight coupling conventional edge-coupled microstrip coupler, the proposed structure has more attainable size and wider bandwidth.

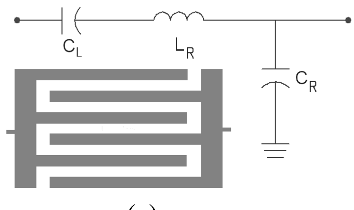
The organization of this paper is as the following. At first, theoretical description and principle of proposed microstrip coupled-line coupler is presented. Afterward a design example of a 3-dB coupler with flat coupling has been shown. Simulation results of the proposed interdigital TLs coupler are demonstrated by using an electromagnetic simulator (Agilent ADS) and finally, experimental verification is presented.

2. COUPLER DESCRIPTION AND PRINCIPLE

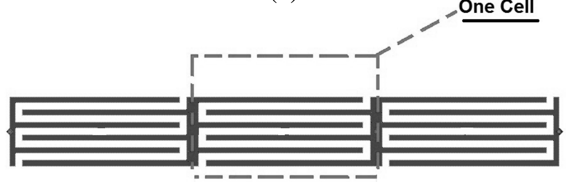
Interdigital capacitor is a multifinger periodic structure which can be used as a series capacitor in high frequency circuits. Figure 1(a) shows the physical structure of an interdigital capacitor and its equivalent circuit model. Series capacitor, C_L, is the main element of the model and its capacitance value is given by [15]:

$$C_L = \frac{\epsilon_{r_{\mathit{eff}}}}{18\pi}(N-1)\frac{K(\kappa)}{K'(\kappa)}l\,(\mathrm{pF}) \tag{1}$$

where $\epsilon_{r_{\mathit{eff}}}$ is effective permittivity of a microstrip TL whose strip width is W (W is the width of a finger), N is the number of fingers, l is the



(a)



(b)

Figure 1. (a) Interdigital capacitor and its equivalent circuit model. (b) Interdigital transmission line (TL).

length of interdigital capacitor in mm and $\frac{K(\kappa)}{K'(\kappa)}$ is a constant that its value has been presented in [15]. L_R and C_R are parasitic elements of the interdigital capacitor, which their closed-form expressions has been also given in [15].

If some interdigital capacitors are cascaded to each other, the interdigital TL will be realized (Figure 1(b)). As seen in Figure 1, equivalent circuit of an interdigital capacitor, one cell of the interdigital TL, is similar to one cell equivalent circuit model of a CRLH TL with $L_L \to \infty$ (L_L is shunt inductance of CRLH). As is well-known, the characteristic impedance of a CRLH TL (Z_c) is given by [3]:

$$Z_c = Z_L \sqrt{\frac{\left(\frac{\omega}{\omega_{se}}\right)^2 - 1}{\left(\frac{\omega}{\omega_{sh}}\right)^2 - 1}} \tag{2}$$

where

$$Z_L = \sqrt{\frac{L_L}{C_L}}, \quad \omega_{se} = \frac{1}{\sqrt{L_R C_L}}, \quad \omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \tag{3}$$

Substituting $L_L = \infty$ into (2) results the characteristic impedance of an interdigital TL, (Z_c^{int}), as:

$$Z_c^{\text{int}} = \sqrt{\frac{\left(\frac{\omega}{\omega_{se}}\right)^2 - 1}{\omega^2 C_L C_R}} = \sqrt{\frac{L_R}{C_R} - \frac{1}{\omega^2 C_L C_R}} \tag{4}$$

It is seen from above equation that Z_c^{int} is real for $\omega > \omega_{se}$. From TL theory, it is clear that $\sqrt{\frac{L_R}{C_R}}$ is the characteristic impedance (Z_0) of a microstrip TL consists of a strip with width of $W' = (4N - 1)W$ [15].

Similarly, the propagation constant for this TL is obtained as [3]:

$$\beta^{\text{int}} = \sqrt{\omega^2 L_R C_R - \frac{C_R}{C_L}} \tag{5}$$

So, in an interdigital TL, for $\omega > \omega_{se}$ the propagation constant (β^{int}) is real and positive. Thus, in this frequency interval, the transmission line operates in the right-handed (RH) band and consequently the interdigital TLs and coupled lines using them are not indeed CRLH TLs. However, for simpler driving the interdigital TL equations, we considered the interdigital TL as a special case of CRLH TL.

On the other hand, the proposed interdigital TLs which are capacitively (microstrip gap) loaded lines can be observed as fast-wave structures and analyzed by their concepts [3].

In the coupled-line coupler, input matching condition to terminations of impedance Z_c ($Z_{in} = Z_c$) is obtained under the condition given by [1]:

$$Z_c = \sqrt{Z_{ce} Z_{co}} \tag{6}$$

where Z_{ce} and Z_{co} are even and odd mode characteristic impedances of the coupler, respectively. Above matching condition of the coupler in conventional MTM CLCs, is satisfied in the gap of the even/odd modes of the CRLH TL (gap is an interval between ω_{se} and ω_{sh}, where β is imaginary) [3]. Whereas, in the conventional CLCs such gaps cannot exist because the lines are of pure right handed nature.

The proposed backward-wave directional coupler is shown in Figure 2. It is a coupled-line coupler consisting of an interdigital capacitor with one finger as a CRLH TL in each coupled-line. It is seen that using only one interdigital capacitor to realize the interdigital TLs is more suitable to reach a coupler with better matching and wider bandwidth. As it was mentioned, for $\omega > \omega_{se}$, these interdigital TLs will be operating completely in their RH range for the presented coupler application. So in this coupler, similar to the conventional edge-coupled couplers, the coupling coefficient is [1]:

$$S_{31} = \frac{jk \sin\theta}{\sqrt{1-k^2}\cos\theta + j\sin\theta}, \quad k = \frac{Z_{ce} - Z_{co}}{Z_{ce} + Z_{co}} \tag{7}$$

where, $\theta = (\frac{2\pi}{\lambda_g}\ell)$ is electrical length and ℓ is the length of CLC. Therefore, setting the interdigital capacitor length as $\ell = \frac{\lambda_g}{4}$ or $\theta = \frac{\pi}{2}$ results in maximum coupling level. On the other hand, selection of $\ell = \frac{\lambda_g}{4}$ can preserve the homogeneity condition in CRLH structure (i.e., $p \leqslant \frac{\lambda_g}{4}$, where p is structural cell size) [3].

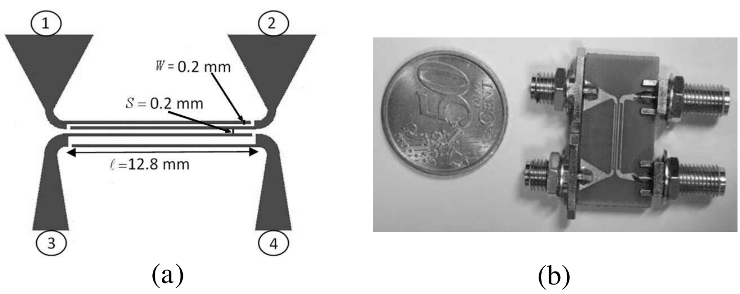


Figure 2. Structure of the proposed microstrip coupled-line backward coupler on FR4 substrate, $\varepsilon_r = 4.7$, thickness of 1.6 mm. (a) Structure layout. (b) Fabricated coupler.

Even and odd mode characteristic impedances (Z_{ce}, Z_{co}) of the coupled-lines composed of interdigital TLs are obtained from [3] with setting $L_L \to \infty$ as:

$$Z_{ce} = \sqrt{\frac{L_{Re}}{C_R} - \frac{1}{\omega^2 C_L C_R}}, \quad Z_{co} = \sqrt{\frac{L_R}{C_{Ro}} - \frac{1}{\omega^2 C_L C_R}} \tag{8}$$

and

$$Z'_{ce} = \sqrt{\frac{L_{Re}}{C_R}}, \quad Z'_{co} = \sqrt{\frac{L_R}{C_{Ro}}} \tag{9}$$

Z'_{ce} and Z'_{co} are even and odd mode characteristic impedances of a conventional microstrip CLC with strips of width W' for each TL, where W' $(= (4N - 1)W)$ is total width of the interdigital capacitor.

In the proposed coupler for given even and odd mode characteristic impedances, according to (8), selection of a small C_L leads to larger values of Z'_{ce} and Z'_{co}. This situation is very suitable for elimination of the fabrication restrictions in CLCs with tight coupling level. Consequently, to decrease the value of C_L in the proposed structure, interdigital capacitors with only one finger (i.e., $N = 1$) are used.

In design procedure, for an indicated coupling-level (c) and characteristic impedance (Z_c^{int}), Z_{ce} and Z_{co} can be obtained from conventional expressions as [1]:

$$Z_{ce} = Z_c^{\text{int}} \sqrt{\frac{1+c}{1-c}}, \quad Z_{co} = Z_c^{\text{int}} \sqrt{\frac{1-c}{1+c}} \tag{10}$$

With setting $N = 1$, $l = \lambda_g/4$ and the substrate profile being determined, C_L and C_R can be calculated using expressions presented in [15] and Z'_{ce} and Z'_{co} are obtained from (8) and (9). Then, W' and

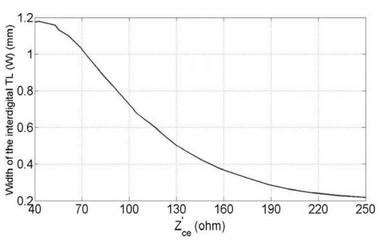


Figure 3. Width of the interdigital TL (W) in the proposed coupler versus Z'_{ce} on FR4 substrate, $\varepsilon_r = 4.7$, thickness of 1.6 mm.

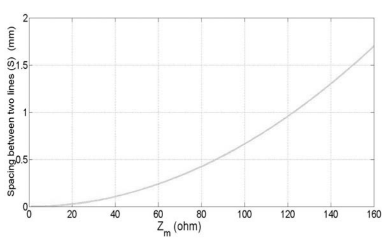


Figure 4. Spacing between two coupled interdigital TLs (S) in the proposed coupler versus Z_m on FR4 substrate, $\varepsilon_r = 4.7$, thickness of 1.6 mm.

S can be determined by using achieved Z'_{ce}, Z'_{co} and relative design graphs for conventional coupled microstrip lines.

For instant, Figure 3 illustrates the required width of the interdigital TL (W) in the proposed coupler realized on FR4 substrate, with $\epsilon_r = 4.7$ and thickness of 1.6 mm, for different values of Z'_{ce}. In addition, the necessary spacing between two coupled interdigital TLs (S) for the presented structure versus Z_m, where $Z_m = \frac{2Z'_{ce}Z'_{c0}}{Z'_{ce}-Z'_{co}}$, has been provided in Figure 4.

As it was mentioned, since Z'_{ce} and Z'_{co} would be larger than Z_{ce} and Z_{co}, for constant coupling-level (c) and characteristic impedance (Z_c^{int}) in comparison with the conventional CLCs, W' decreases and S increases. Therefore in the proposed coupler, the fabrication constrains in conventional edge-coupled couplers to get a tight coupling-level caused very small spacing between two coupled lines (i.e., S) can be removed.

3. SIMULATION AND EXPERIMENTAL RESULTS

To validate the proposed technique, a 3-dB coupled line coupler based on the design procedure and presented expressions has been designed on FR4 substrate with $\epsilon_r = 4.7$, thickness of 1.6 mm and $\tan\delta = 0.021$. Figures 2(a) and 2(b) show the designed coupler layout and the fabricated structure. A 3-dB coupled line coupler with nearly 60% bandwidth (from 2.3 to 4 GHz) around the design frequency $f_c = 3.2\,GHz$ is achieved in the measured prototype. The spacing between two TLs (S) and width of the interdigital capacitor fingers (W) are 0.2 mm. Also, the length of the TLs is 12.8 mm (see Figure 2). For better matching and wider bandwidth, we use only one

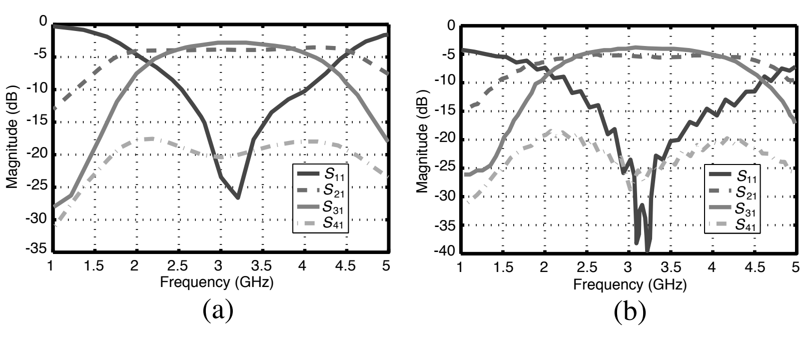


Figure 5. S-parameters of the proposed coupler shown in Figure 2. (a) Full-wave simulation results. (b) Measurement results.

interdigital capacitor, i.e., one cell, in every interdigital TL. Moreover, to reach a large isolation parameter, spacing between the fingers in the lower interdigital capacitor is set larger than the upper one, when ports 1 and 4 are the input and isolated ports, respectively. As shown in the layout of the coupler in Figure 2(a), at the all four ports of the structure, tapered microstrip TLs have been used for the impedance matching to 50 Ω, as well as to fit the ports size to the inner conductors of the coaxial-to-microstrip transitions.

Figures 5(a) and 5(b) present the full-wave simulated (by using Agilent ADS software) and measured S-parameters for the coupler of Figure 2. Excellent agreement can be observed between simulated and experimental results. There is only a small difference between S_{11} parameter of simulated and measurement results. Due to small distance between coupler connectors, we could not connect network analyzer ports to adjacent coupler connectors, directly. Therefore, two interface cables were connected to the coupler connectors and then S-parameters were measured. This drawback shows its bad effect on S_{11} parameter more strongly than other S-parameters.

Using these figures, a amplitude balance of ± 2 dB over a bandwidth of 60% (2.3–4 GHz), a matching (10 dB bandwidth) and an isolation at least -20 dB over a bandwidth of 80% (2.2–4.6 GHz) are observed. Figure 6 illustrates the phase difference between ports 2 and 3 of the coupler. This phase difference is 90° at design frequency and exhibits a phase-balance ($\pm 10°$) bandwidth of 1.3 GHz.

In comparison with the conventional CRLH CLCs, the electrical length of the proposed CLC is more compact than the CRLH CLCs presented in [11–14]. Moreover, due to the elimination of the stubs in the structure, its width is also smaller. For instance, the width of the coupler is nearly 11 times smaller than CRLH CLC reported in [11] and

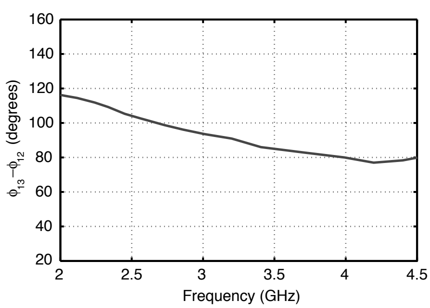


Figure 6. Measured phase difference between the through port and the coupled port for the proposed coupler of Figure 2.

its coupled-line electrical length is shortened to 60% of the 3-dB CRLH coupler electrical length presented in [12]. Moreover, the bandwidth of the proposed CLC is wider than CRLH CLCs presented in [13] and [14]. In comparison with the conventional planar microstrip CLC realized in the same substrate material and similar spacing between coupled TLs, this CLC achieves higher coupling level. The high coupling level (8 dB or higher) is extremely difficult to achieve in the conventional CLC due to the present limit in fabrication [1]. Also, simulation results show that in the proposed structure if the spacing between the coupled lines increases, the bandwidth increases up to 85% for 7-dB coupling factor.

4. CONCLUSION

In this paper, we present a new technique for realizing a compact and tight coupling (3-dB) microstrip coupled-line backward coupler with attainable dimension, broad bandwidth and smaller size than the conventional and CRLH couplers. New coupler structure consists of only one interdigital capacitor in each coupled TL without shorted stubs as the CRLH TL. Designed and fabricated 3-dB microstrip coupler at center frequency about $f_c = 3.2\,\text{GHz}$ exhibits a matching (10 dB) bandwidth of over 2 GHz, a phase-balance ($\pm 10^\circ$) bandwidth of 1.3 GHz and at least 20 dB isolation between adjacent ports. The coupled-line length and the width of the proposed structure are approximately $\lambda_g/4$ and $\lambda_g/36$, respectively, which makes it more compact than the conventional cascaded CRLH microstrip coupled-line couplers. Moreover, This coupler exhibits a much higher design simplicity than the existing CRLH CLCs.

Due to the wide bandwidth and compact size, the proposed coupler is well suitable for microwave and milimeter-wave integrated-circuits, wideband communication systems and many kind of antenna arrays.

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