A Compact and Wideband Coupled-Line Coupler with High Coupling Level Using Shunt Periodic Stubs

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Abstract. *A wideband microstrip forward-wave coupled-line coupler with high coupling value is presented. Compared with the conventional edge-coupled microstrip forward-wave coupler, this symmetrical structure, consisting periodic shunt stubs between the two coupled-lines, achieves wider operating bandwidth and larger coupling level. To characterize this structure, the equivalent circuit model is established and verified by measurement and full-wave results. The designed and fabricated prototype is a 0-dB forward-wave coupler with 0.6 mm stub length. This coupler exhibits a coupled amplitude balance of ±2 dB, good matching (15 dB) and at least 15dB isolation between adjacent ports over a wide bandwidth of 66% from 2 GHz to 4 GHz centered at 3 GHz. The coupled-line length and width of the proposed structure are approximately $\lambda_g/2$ and $\lambda_g/13$, respectively, which makes it more compact than the conventional forward coupled-line couplers.*

Keywords

Coupled-line couplers, periodic structures, forward-wave couplers, shunt stubs, wideband microwave devices.

1. Introduction

A coupled-line coupler (CLC) is a four-port network constituted by the combination of two unshielded transmission lines (TLs) in close proximity to each other. Due to this proximity, the electromagnetic fields of each line interact with each other, which cause to power trade between the two lines, or coupling [1]. Two types of the coupled-line couplers are presented: backward- or forward-wave CLCs. When the output coupling port is in the vicinity of the input port, the CLC is named backward otherwise it is forward. The microstrip implantations of the conventional backward CLCs suffer from poor coupling. But, forward CLC can achieve high coupling level around 0-dB, whereas length of the forward CLCs is larger than backward ones [1].

It is known that if the phase velocities of the two even and odd modes of symmetrical coupled-lines are different, energy can be coupled from one line to another in the forward direction [2]. The backward-wave coupling can be reduced to negligibly small values by choosing a relatively large separation between the lines. On the other hand, appreciable power can be made to couple in the forward direction, if the length of the coupling section is properly chosen [1].

Various forward CLCs have been proposed until now. For example, a size-reduced 3-dB forward coupler loaded with periodic shunt capacitive stubs has been reported in [3]. But, the coupled-line length of this coupler is 0.75 λ_g and it seems that the coupler size is still large and its bandwidth is narrow. Other examples of the forward CLCs have been presented in [4] and [5], which in addition to have low coupling level show narrow bandwidth.

Recently, we have introduced a novel forward-wave CLC by loading with periodic shunt stubs in [6]. This proposed forward CLC shows compact size and wide bandwidth. In this paper, we have presented equivalent circuit model and experimental results and discussed in details about theory and design procedure of the coupler. The design principle is based on increasing the difference between the phase velocities of the even and odd modes and decreasing the coupled lines length. The periodic shunt stubs that have been used between the coupled-lines reach us to this purpose. The coupler is modeled by the equivalent circuit model and its measured and full-wave simulation results are also presented and discussed. Compared with the conventional edge-coupled forward CLCs and composite right/left handed (CRLH) forward CLCs that presented in [7-10], the proposed structure achieve wider bandwidth and its size is smaller.

This paper is organized as follows. In section 2, theoretical description and principle of the proposed microstrip forward coupled-line coupler is presented. Section 3 deals with a design example of a 0-dB coupler with flat coupling based on the proposed approach; and simulation and measurement results of the proposed coupler are demonstrated in this section. Finally, section 4 summarizes the approach and results.

2. Coupler Theory

The scattering parameters of an ideal forward-wave directional coupler, as shown in Fig. 1, are given by [1]:

$$\begin{aligned} &S_{11}=0, \\ &S_{12}=-j\mathrm{e}^{\frac{-j(\beta_e+\beta_o)l}{2}}\cos[\frac{(\beta_e-\beta_o)l}{2}], \\ &S_{13}=0, \\ &S_{14}=-j\mathrm{e}^{\frac{-j(\beta_e+\beta_o)l}{2}}\sin[\frac{(\beta_e-\beta_o)l}{2}] \end{aligned} \tag{1}$$

where β_e and β_o are even and odd mode propagation constants of coupled lines, respectively. Also, l is the length of the coupled line. As it was mentioned, forward-wave directional couplers cannot be realized using TEM mode transmission lines such as coaxial lines. It is due to this fact that for the TEM mode, the propagation constant of the even and odd modes are equal, and as shown in (1), there is no coupling between ports 1 and 4. Therefore, forward-wave coupling mechanism can only be appeared in non-TEM coupled transmission lines such as metallic waveguides, fin lines, dielectric waveguides and also quasi-TEM mode transmission lines like microstrip lines at high operating frequencies. In these transmission line structures, in general, the phase velocities of the even and odd modes are not equal [1].

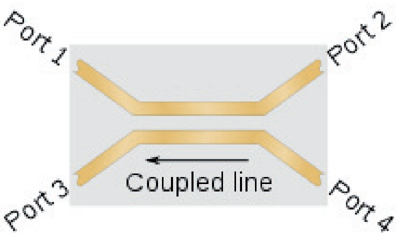


Fig. 1. Typical structure of a coupled-line coupler (CLC).

From (1), it is clear that complete power can be transferred between lines if the length l of the coupled line is chosen as:

$$l=\frac{\pi}{|\beta_e-\beta_o|}. \tag{2}$$

Above result is significant in the sense that even for arbitrarily small values of difference in the propagation constants of even and odd modes, complete power can be transformed between the lines if the length of the coupler is chosen according to (2). In this situation, the directivity and isolation of the coupler are thus infinite. Also, the phase difference between ports 1 and 4 (S_{41} and S_{21}) is 90 degrees. However, in general, situation (2) cannot be completely satisfied. Hence, some finite amount of backward-wave coupling always exists between coupled lines.

Our proposed forward-wave coupled-line coupler is shown in Fig. 2(a), where the coupled-lines have the same width of W and periodic stubs have been loaded between these coupled-lines. In this structure, W_s and l_s are the width and length of the periodic stubs, respectively, and d_s is a period of the stubs. The mid plane (red line in Fig. 2(a)) between the coupled-lines remains two different equivalent circuits for the even and odd modes. The even and odd modes are associated with a magnetic wall (open-circuit) and an electric wall (short-circuit), respectively. These two equivalent circuit models have been presented in Figs. 2(b) and 1(c) for one period. In these circuits, C_e and C_o are even and odd mode capacitances per unit length, respectively, and L is inductance per unit length of the coupled-lines. C_e and C_o are equal to:

$$C_e=C_{11}=C_{22},\quad C_o=C_{11}+2C_{12}+2C_{\mathrm{int}} \tag{3}$$

where C_{11} and C_{22} represent the capacitance between one strip conductor and ground in absence of the other strip conductor, in planar structures. Because of the strip conductors of the coupled lines are identical in size and location relative to the ground conductor, C_{11} will be equal to C_{22} or $C_{11}=C_{22}$. From transmission line theory, it is well known that the value of C_{11} is [1]:

$$C_{11}=\frac{\sqrt{\varepsilon_{re}}\,Z}{c} \tag{4}$$

where ε_{re} is effective permittivity of a microstrip transmission line with a strip with W width, Z is characteristic impedance of the transmission line and c is the speed of light. Also, C_1 represents the capacitance between the two coupled lines without stubs and ground conductor. C_{int} is capacitance per unit length of the interdigital capacitor formed between the two coupled lines. An interdigital capacitor is a multifinger periodic structure which can be used as a series capacitor in microstrip transmission lines technology [11]. This capacitor uses the capacitance that occurs across a narrow gap between thin-film conductors.

The value of capacitance of the structure interdigital capacitor can be expressed as [11]:

$$C_{\mathrm{int}}=\frac{\varepsilon'_{re}}{18\pi}\,(N-1)\,\frac{K(\kappa)}{K'(\kappa)}\,l_s \quad \text{(pF)} \tag{5}$$

where ε'_{re} is effective permittivity of a strip with W_s width, N is the number of fingers and $\frac{K(k)}{K'(k)}$ is a constant [11].

Some extra distributed shunt capacitance and inductance per unit length are added to the equivalent circuit models for the even and odd modes, respectively, which are given based on the transmission line theory as [1]:

$$\begin{aligned} L_a&=\frac{1}{d_s}(\frac{Z_s}{\omega}\tan\beta_s(\frac{l_s+s}{2}))\approx\frac{Z_s\,\beta_s(l_s+s)}{2\,\omega\,d_s}, \\ C_a&=\frac{1}{d_s}(\frac{1}{\omega Z_s}\tan\beta_s(\frac{l_s+s}{2}))\approx\frac{\beta_s(l_s+s)}{2\,\omega Z_s\,d_s} \end{aligned} \tag{6}$$

where Z_s and β_s represent characteristic impedance and phase constant of the shunt stubs, respectively.

Series impedance and shunt admittance of these equivalent circuit models in even and odd modes are given by:

$$Z_e = j\omega L, \quad Y_e = j\omega(C_e + C_a), \\ Z_o = j\omega L, \quad Y_o = j\omega C_o + 1/j\omega L_a. \tag{7}$$

According to the transmission line theory, the propagation constants and the characteristic impedances of the transmission coupled-lines in even and odd modes are:

$$\gamma_e = \sqrt{Z_e Y_e} = j\omega\sqrt{L(C_e + C_a)} = j\beta_e, \\ \gamma_o = \sqrt{Z_o Y_o} = j\omega\sqrt{L(C_o - 1/\omega^2 L_a)} = j\beta_o \tag{8}$$

and

$$Z_{ce} = \sqrt{\frac{Z_e}{Y_e}} = \sqrt{\frac{j\omega L}{j\omega(C_e + C_a)}} = \sqrt{\frac{L}{(C_e + C_a)}}, \\ Z_{co} = \sqrt{\frac{Z_o}{Y_o}} = \sqrt{\frac{j\omega L}{j\omega(C_o - 1/\omega^2 L_a)}} = \sqrt{\frac{L}{(C_o - 1/\omega^2 L_a)}}. \tag{9}$$

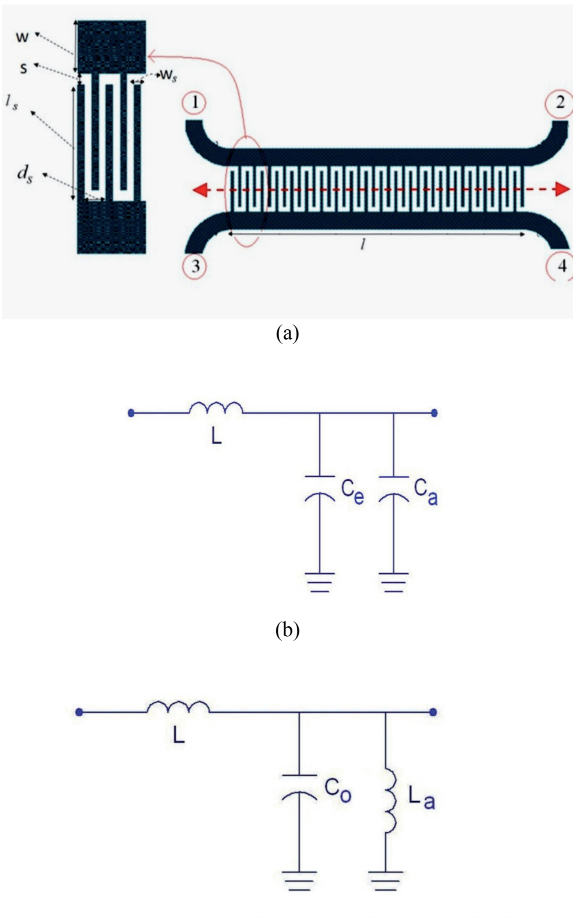


Fig. 2. a) Proposed forward-wave coupled-line coupler with periodic stubs. b) Even mode, and c) Odd mode, equivalent circuit models of each coupled line for one period.

Since, the length of the stubs is relatively large, the value of C_{12} would be very smaller than C_{11} and C_{int}. So, (3) can be approximated as:

$$C_o \cong C_{11} + 2C_{\text{int}}. \tag{10}$$

As it is seen in (8), the difference between β_e and β_o in the proposed structure becomes larger than conventional structures without stubs in coupled-line couplers. Moreover, this difference can be controlled by the stub length, so that for a fixed coupling-level, the increasing length of stubs l_s results in reduction of structure length (Fig. 3).

In the coupled-line couplers, input matching condition for termination of impedance Z_c ($Z_{in} = Z_c$) is achieved under condition which is given by [1]:

$$Z_c = \sqrt{Z_{ce} Z_{co}}. \tag{11}$$

Fig. 4 presents some curves for selecting dimension of the proposed coupler for three coupling levels (0 dB, 3 dB and 6 dB) with $W_s = 0.2$ mm, $d_s = 0.6$ mm and $S = 0.2$ mm on FR-4 substrate ($\varepsilon_r = 4.8$, $h = 1.6$ mm).

These curves illustrate that with increasing the coupling level, dimension of the coupler increase. But, it is interesting to note that for a fixed coupling level, the area of the coupler (product of the stub length by the structure length) will remain constant, approximately.

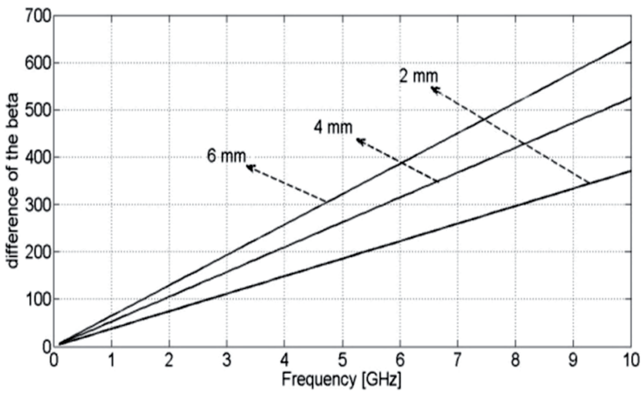


Fig. 3. $|\beta_e - \beta_o|$ for three lengths of the stubs ($l_s = 2$, 4 and 6 mm).

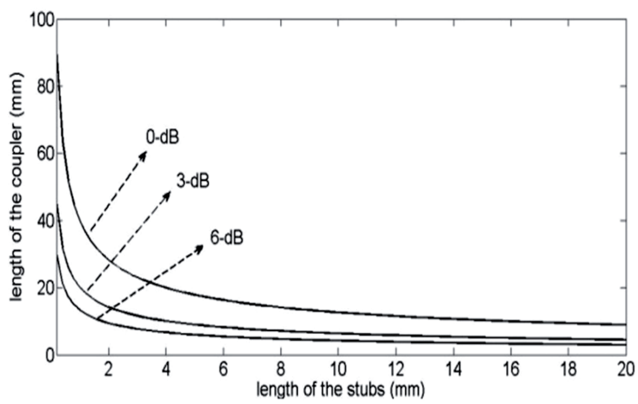


Fig. 4. Data for designing dimension of the proposed coupler on FR-4 substrate ($\varepsilon_r = 4.6$, $h = 1.6$ mm).

3. Simulation and Experimental Results

The proposed structure of the forward-wave CLC in this paper is fabricated on the FR4 substrate with 1.6 mm thickness and dielectric constant of 4.6, as shown in Fig. 5. The full-wave simulator Agilent Technologies Advanced Design System (ADS) is used to examine the structure. For good matching, the width of the microstrip transmission lines for 50Ω port impedances is selected equal to 1 mm (i.e. $W = 1$ mm). To have a coupling level of 0 dB, according to the derived relations and Fig. 4, the length l and width $l_s + 2W$ of the structure in Fig. 2 have been chosen equal to 26 mm and 4 mm, which are approximately $\lambda_g/2$ and $\lambda_g/13$ at center frequency of 3 GHz, respectively. Therefore, the proposed CLC is more compact than the microstrip coupler with the coupled-line length around 0.75 λ_g presented in [3]. Also, the width W_s and period distance d_s of the stubs are considered as: $W_s = 0.2$ mm, $d_s = 0.6$ mm and the space between the stubs and transmission lines is 0.2 mm (i.e. $S = 0.2$ mm).

The measured and simulated S-parameters of the proposed coupler are shown in Fig. 6. This figure shows the measured amplitude balance of ±2 dB over a bandwidth of 66% (2-4 GHz). In this figure, full-wave simulation and equivalent circuit model results have also been presented for verification. A good agreement between measurement, full-wave simulation and equivalent circuit model results is obtained and thus the usefulness of the presented equivalent circuit model is validated. The element values of the equivalent circuit model (Fig. 2) for the layout are: $L = 1.8$ nH, $L_a = 3.2$ nH, $C_a = 0.1$ pF, $C_e = 0.2$ pF and $C_o = 1.8$ pF.

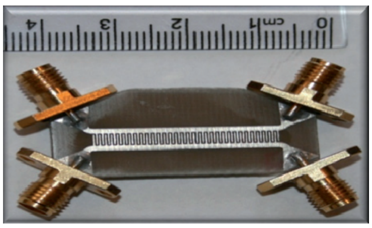
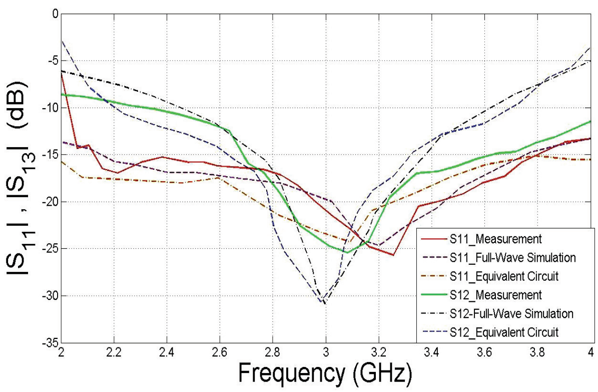
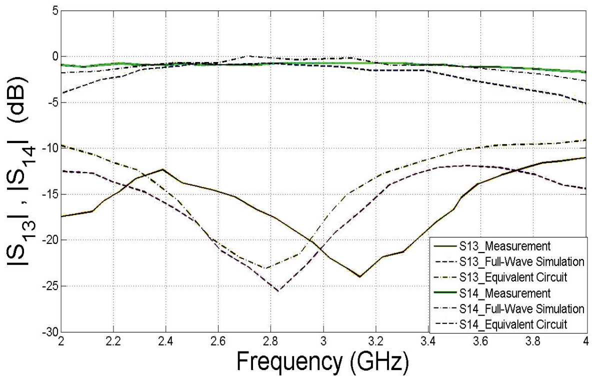


Fig. 5. The proposed coupler realized on FR-4 substrate ($\varepsilon_r = 4.6$, $h = 1.6$ mm).



(a)



(b)

Fig. 6. Magnitude of the S-parameters, a) S_{11}, S_{12}, b) S_{13}, S_{14} for the proposed coupler obtained by full-wave simulation, equivalent circuit model and measurement results.

In comparison with the conventional forward CLCs, the electrical length of the proposed CLC is more compact than CLCs presented in [8-10]. For instance, the coupled-line electrical length of the coupler is shortened to 50% of the conventional CLC electrical length reported in [8]. Moreover, the bandwidth of the proposed CLC is wider than forward CLCs presented in [4], [5], [8] and [10]. For example, compared with the forward couplers reported in [8], the proposed structure is capable of producing 65% bandwidth enhancement for the amplitude and a 0-dB coupling level with a smaller coupled-line length. Also, the coupled-line couplers which presented in [12] and [4] exhibit 19% and 43% fractional bandwidth, respectively. But, the first one requires long length of the coupled line, i.e., 1.28 λ_g, and the other one shows low coupling level, i.e., about 10 dB. So, all the couplers reported in [4], [5], [8], [9], [10] and [12], have at least a bad result in bandwidth, size or coupling level, whereas, our CLC exhibits good behavior in coupling level, bandwidth and size.

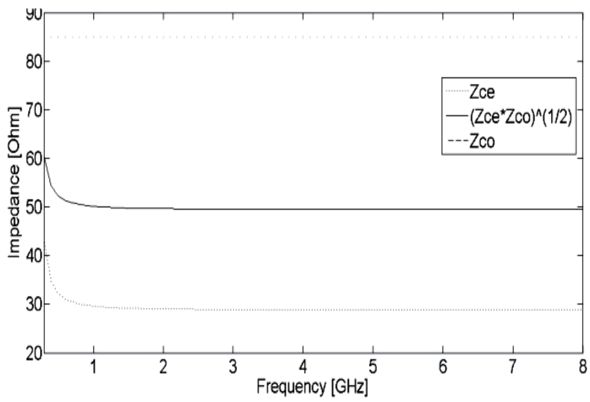


Fig. 7. Characteristic impedances of the even and odd modes.

Fig. 7 shows the even- and odd-mode characteristic impedances computed using full-wave simulation. This result indicates that the proposed structure is matched to 50 Ω port impedance over the operating bandwidth, such that the additional tapered structure at each port for impedance matching can be eliminated. Hence, the proposed forward coupler would be more compact in size. As it was mentioned, for the proposed forward CLC, the coupler area is approximately constant. It means that reduction of the structure length results width increasing, proportionally (Fig. 4).

4. Conclusion

A new type of forward coupled-line coupler composed of two identical microstrip transmission lines and periodic shunt stubs between them has been proposed and investigated experimentally and theoretically. Using loaded stubs between two microstrip coupled-lines forms the proposed 0-dB forward CLC which exhibits the amplitude balance of ±2 dB around center frequency of 3 GHz from 2 GHz to 4 GHz (66% bandwidth). A matching ($|S_{11}|$ < 15 dB) bandwidth of over 4 GHz (1-5 GHz) bandwidth and at least 15dB isolation between adjacent ports have been seen in measurement results. The corresponding equivalent circuits are presented and validated by measurement and full-wave simulation results. In this forward-wave CLC, by increasing the length of the stubs, the coupler length decreases, proportionally. Also, some curves for designing dimension of the coupler for indicated values of impedance port and coupling level on FR4 substrate have been presented. Moreover, it is seen from the presented curves that the structure size of the proposed CLC reduces and bandwidth enhances by decreasing the coupling-level.

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