A Compact 0-dB Coupled-Line Forward Coupler by Loading with Shunt Periodic Stubs

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***Abstract* — A wideband coupled-line forward (co-directional) coupler with tight coupling-level is presented. In this coupler we loaded two coupled microstrip lines with periodic shunt stubs that show capacitive and inductive nature in the even and odd modes, respectively. These periodic stubs, lead to increase the difference between the even and odd mode propagation constants of the coupled-line coupler, and also to decrease the structure length. Compared with the conventional forward coupler, this symmetrical structure, achieves wider operation bandwidth and smaller size with larger coupling level. The designed prototype is a 0-dB microstrip coupler over a wide bandwidth of 66% from 2GHz to 4GHz centered at 3GHz. The length of the coupled line is nearly $\lambda_g/2$ and length of the stubs is 2 mm, which make it more compact than other forward couplers have been proposed. To characterize this structure, the equivalent circuit model is established and verified by simulation. Moreover, we present some curves for selecting dimension of the proposed coupler for indicated coupling-level on FR-4 substrate.**

Index Terms* — *Coupled-line couplers, periodic structures, forward couplers, shunt stubs.

I. 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 result in power exchange between the two lines, or coupling [1].

Two types of edge-coupled coupled-line couplers are presented. The first one is a backward coupler. In this coupler, coupling mechanism is based on the difference between the characteristic impedances of the even and odd modes. In order to get a tight coupling-level in a backward couplers, the space between the two lines must be very small and it is very difficult to obtain due to the fabrication constrains [1].

The second one is a forward coupler. In this type of couplers, the coupling mechanism is based on the difference between the phase velocities of the c and π modes. The physical structures of these couplers are usually asymmetric, as it is constituted of two different TLs providing arbitrarily high coupling level (up to almost 0-dB), in addition to the broad-bandwidth characteristic of typically backward CLCs [2].

Forward-wave coupling appears between uniform symmetrical coupled lines if the even and odd modes phase velocities of the coupled lines are unequal and the backward-wave coupling between these lines can be reduced to a very small value by keeping a relatively large separation between the lines (such that the even and odd mode characteristic impedances of the coupled lines are nearly equal). These types of couplers can be realized by using non-TEM mode transmission lines such as metallic waveguide, microstrip lines and so on. However, since the difference of the velocities is not so large, the length of the coupled-line section becomes very long for a tight coupling, particularly looks impractical at low microwave frequencies. For this reason, the conventional forward couplers are often used in optics [1, 2].

Various methods for increasing the forward coupling-level and decreasing the size in the coupled lines have been proposed. A size-reduced 3-dB forward coupler loaded with periodic shunt capacitive stubs has been reported in [3]. Enhancing the forward coupling with a periodically patterned ground plane has been also reported in [4]. But, it seems that the coupler size is still large and it can be reduced using more suitable structures for forward couplers.

In this paper, a novel compact tight-coupling (0-dB) microstrip forward (co-directional) coupled-line coupler with wide bandwidth is presented. The proposed operating and design principle are based on increasing the difference between the phase velocities of the even and odd modes. For this purpose, we use periodic shunt stubs between the two coupled-lines. These stubs exhibit capacitive and inductive nature in the even and odd modes, respectively. Compared with the other forward coupled-line couplers presented in [2]-[7], the proposed structure has more attainable compact size and wider bandwidth.

The organization of the paper is as the following. At first, theoretical description and principle of the proposed microstrip forward coupled-line coupler is presented. Then, the effect of some structure physical parameters on the coupler specifications using equivalent circuit model is presented. Also, a design example of a 0-dB coupler with flat coupling based on the proposed approach is shown. Finally, simulation results of the proposed coupler are demonstrated by using an electromagnetic simulator (Agilent ADS).

II. Coupler Description and Principle

As is well-known, the forward coupling coefficient of a conventional symmetrical coupler is given as [1]:

$$|S_{41}| = \left|\sin\left[\frac{(\beta_e - \beta_o)\ell}{2}\right]\right| \tag{1}$$

where even and odd mode propagation constants, *i.e.* β_e and β_o, are equal to:

$$\beta_e = \omega\sqrt{LC_e}\,, \quad \beta_o = \omega\sqrt{LC_o} \tag{2}$$

and

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

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. For planar structures, C_{11} and C_{22} represent the capacitance between one strip conductor and ground in absence of the other strip conductor. So, if 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 $C_{11} = C_{22}$. Also, C_{12} represents the capacitance between the two strip conductors in the absence of the ground conductor [1]. Considering above relations, following inequalities hold:

$$C_e < C_o\,, \quad \beta_e < \beta_o \tag{4}$$

The complete power transfer from the input to the coupled port can be achieved if the length of the coupler is chosen as [1] (shortest length which is referred to as the coherence length):

$$l = \frac{\pi}{|\beta_e - \beta_o|} = \frac{\lambda_0}{2\left|\sqrt{\varepsilon_{eff_e}} - \sqrt{\varepsilon_{eff_o}}\right|} \tag{5}$$

In conventional microwave coupled line structures, the difference between the even and odd mode propagation constants is relatively small, which would require prohibitively long structures of several tens of wavelengths.

Now, consider a periodic structure shown in Fig. 1, where the coupled-lines have the same width of W and periodically stubs have been loaded between these coupled lines. In this figure, ℓ_s and W_s are the length and width of the stubs, respectively, and d_s is a period of the stubs. In this structure, the mid plane (red line) between the coupled-lines remains two different equivalent circuits for the even and odd modes, because the even and odd modes are associated with a magnetic wall (open-circuit) and with an electric wall (short circuit), respectively. These two equivalent circuits have been presented in Fig. 2 for one period.

In this figure, L is the inductance per unit length for a strip with width of W and C_e, C_o are the distributed capacitances for the even and odd modes, respectively. For the proposed structure, the even and odd modes capacitances are given by:

$$C_e = C_{11}, \quad C_o = C_{11} + 2C_{12} + 2C_{\text{int}} \tag{6}$$

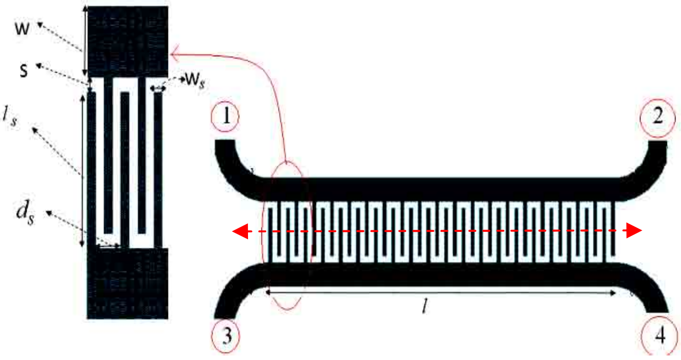

Fig. 1. Proposed forward coupled-line coupler structure with periodic stubs.

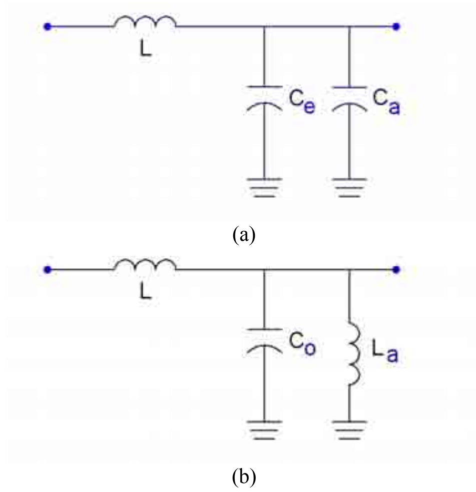

Fig. 2. (a) Even mode equivalent circuit of each coupled-line for one period, (b) Odd mode equivalent circuit of each coupled-line for one period.

where C_{11} represents the capacitance per unit length between the half section of the circuit conductor, without loaded stubs, and ground. From TL theory we know that its value is:

$$C_{11} = \frac{\sqrt{\varepsilon_{re}}\, Z}{c} \tag{7}$$

which ε_{re} is effective permittivity of a microstrip TL with a strip with W width, Z is characteristic impedance of this TL and c is the speed of light. C_{12} is capacitance per unit length between the two lines without stubs and C_{int} is capacitance per unit length of the interdigital capacitor formed between the two coupled-lines. Interdigital capacitor is a multifinger periodic structure which can be used as a series lumped capacitor in high frequencies and its series capacitance per unit length is equal to [8]:

$$C_{\text{int}} = \frac{\varepsilon'_{re}}{18\pi}\,(N-1)\,\frac{K(\kappa)}{K'(\kappa)}\,\frac{l_s}{l} \qquad \left(\frac{pF}{m}\right) \tag{8}$$

which ε'_{re} is effective permittivity of a microstrip TL with a strip with W_s width, N is the number of fingers and $\frac{K(\kappa)}{K'(\kappa)}$ is a constant that its value has been presented in [8].

Also, extra distributed shunt capacitance and inductance per unit length are added to the equivalent circuits for the even and odd modes, respectively, which are given as:

$$C_a = \frac{1}{d_s}\left(\frac{1}{\omega Z_s}\tan\beta_s\left(\frac{l_s + s}{2}\right)\right) \approx \frac{\beta_s(l_s + s)}{2\omega Z_s d_s} \quad (9)$$

$$L_a = \frac{1}{d_s}\left(\frac{Z_s}{\omega}\tan\beta_s\left(\frac{l_s + s}{2}\right)\right) \approx \frac{Z_s \beta_s(l_s + s)}{2\omega d_s} \quad (10)$$

where Z_s and β_s represent characteristic impedance and phase constant of the shunt stubs, respectively. Because length of the stubs is relatively large, the value of C_{12} would be very smaller than C_{11} and C_{int}. So, (6) can be approximated as:

$$C_o \cong C_{11} + 2C_{\text{int}} \quad (11)$$

So, the even and odd mode propagation constants of proposed structure ($\beta_e{}^p, \beta_o{}^p$) are equal to:

$$\beta_e{}^p = \omega\sqrt{L(C_e + C_a)} \ , \ \beta_o{}^p = \sqrt{LC_o\omega^2 - \frac{L}{L_a}} \quad (12)$$

As seen in above equations, the difference between $\beta_e{}^p$ and $\beta_o{}^p$ in proposed structure becomes larger than β_e and β_o in conventional structure without stubs. Moreover, this difference can be controlled by stub length, so that for a fixed coupling-level increasing length of stubs (ℓ_s) results reduction of structure length.

Fig. 3 presents some curves for selecting dimension of the coupler for three coupling-level (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 increases. But the interesting point is that for a fixed coupling-level, the area of the coupler (product of the stub length by structure length) will remain constant, approximately.

Based on the equivalent circuit model for the proposed structure as Fig. 2, the even mode characteristic impedance of the coupler (Z_{ce}) is similar to a conventional TL as:

$$Z_{ce} = \sqrt{\frac{L}{(C_e + C_a)}} \quad (13)$$

But, the odd mode equivalent circuit for the proposed structure is similar to the equivalent circuit of a composed right/left handed (CRLH) structure when C_L (series capacitance) is infinite ($C_L \to \infty$) [9]. According to the derived equations for CRLH TL [9], the odd mode characteristic impedance of the proposed structure is as:

$$Z_{co} = \sqrt{\frac{L\omega^2 L_a}{\omega^2 L_a C_o - 1}} \quad (14)$$

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

$$Z_c = \sqrt{Z_{ce} Z_{co}} \quad (15)$$

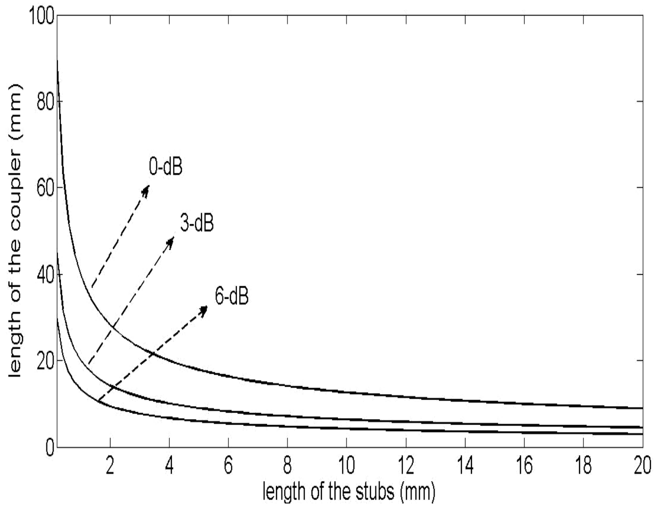

Fig. 3. Data for designing dimension of the proposed coupler on FR-4 substrate ($\varepsilon_r = 4.8$, $h = 1.6\,mm$).

III. Simulation Results

Prototype of the forward coupler, designed by the approach presented in this paper, is realized on the FR-4 substrate with *1.6 mm* thickness and dielectric constant of 4.8. In designed structure, the width (W_s) and period (d_s) of the stubs are considered as: $W_s = 0.2\,mm$, $d_s = 0.6\,mm$ and space between the stubs and TLs is *0.2 mm* (*i.e.* $S = 0.2\,mm$). Also for good matching, the width of the microstrip TLs 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. 3, the coupled-line (l) and stub (l_s) lengths are selected equal to *26 mm* and *2 mm*, respectively. Whereas the structure length is approximately $\lambda_g / 2$ at center frequency of f = 3 GHz which is smaller than the forward couplers presented in [4]-[7]. As it was mentioned, for the proposed structure, the coupler area is approximately constant. It means that reduce the structure length results width increasing, proportionally.

Fig. 4 shows the difference between the even and odd mode propagation constants versus the frequency for designed coupler. As seen in this figure, by decreasing the stub length, the frequency dependence of $\left|\beta_o{}^p - \beta_e{}^p\right|$ decreases and therefore bandwidth of the S-parameters is enhanced.

Fig. 5 illustrates the even and odd modes characteristic impedances of this structure. This figure shows that the coupler has good matching for port impedance $50\,\Omega$, in wide frequency interval (1-10 GHz).

The full-wave simulator Agilent ADS is used to examine the structure performance. The simulated S-parameters of the proposed coupler are shown in Fig. 6. A 0-dB forward coupled-line coupler over a bandwidth of 66% (from 2 GHz to 4 GHz) around the design frequency f = 3 GHz is achieved in the simulated prototype. These full-wave analysis results show that the equivalent circuits are exact and the usefulness of the presented relations for elements is validated. A matching (15dB bandwidth) bandwidth of over 4 GHz and an

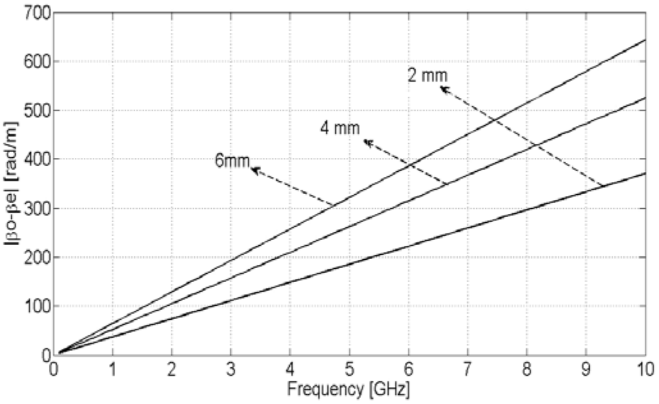

Fig. 4. $|\beta_e - \beta_o|$ for three lengths of the stubs ($l_s = 2, 4$ and $6\ mm$).

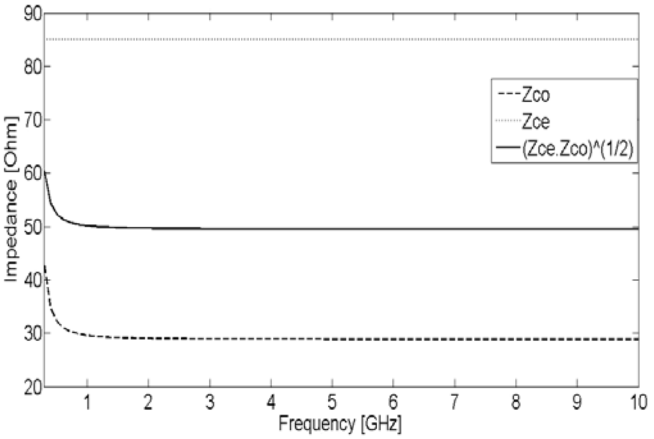

Fig. 5. Characteristic impedances of the even and odd modes.

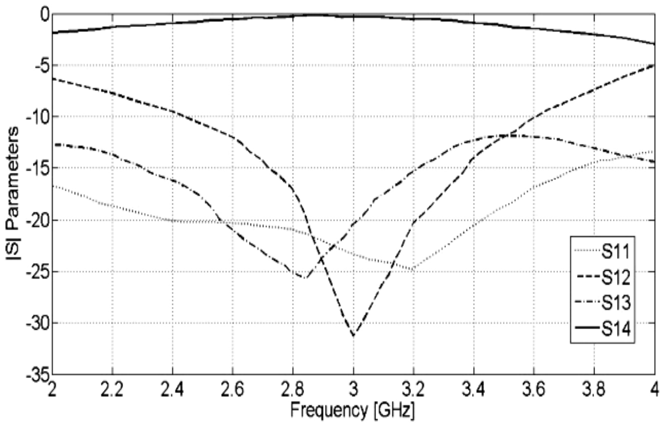

Fig. 6. Simulation results (|S|-Parameters) of the proposed coupler on FR-4 substrate ($\varepsilon_r = 4.8$, $h = 1.6\ mm$)

isolation at least 15dB over the bandwidth of 66% from 2 GHz to 4 GHz observe in this figure.

Compared with the 3-dB forward coupler proposed in [3], the coupled line length of the proposed coupler is shortened to 60%, whereas the length of this coupler [3] is 18% of a conventional unloaded coupled-line coupler. Moreover, proposed coupler exhibits 30% bandwidth enhancement compared to the forward coupler presented in [3].

IV. Conclusion

In this paper, we present a new structure for realizing a compact and tight-coupling (0-dB) microstrip coupled-line forward coupler. In this structure, we use periodic shunt stubs between two conventional coupled-lines. The corresponding equivalent circuits for even and odd modes are presented and values of the circuit elements and coupler parameters are derived and validated by full-wave simulation.

An interesting point in this coupler is that, to reach a fixed coupling level coupler, by increasing the length of the stubs, the coupler length decreases, proportionally. The proposed coupler has broad bandwidth (nearly 66%) and smaller size than the conventional forward couplers. Also, proposed coupler exhibits a matching (15 dB) bandwidth of over 4 GHz (1-5 GHz) and at least 15dB isolation between adjacent ports. Moreover, it is seen that in proposed coupler by decreasing the coupling-level, the structure size reduces and bandwidth is enhanced.

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