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Development of Forward-wave Directional Couplers Loaded by Periodic Shunt Shorted Stubs

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ABSTRACT

In this paper a new procedure for designing forward-wave directional couplers using periodic shunt short circuited stubs is proposed. A new type of cell using these stubs, which enlarge the phase difference between even- and odd modes of a uniform microstrip coupled line is introduced. Using the equivalent circuit model for even- and odd-modes of the proposed cell, the elements of the *ABCD* transmission matrix of the cell are derived. The design procedure of the forward-wave directional couplers (FWDC) is disccused using the equivalent circuit model. To verify the accuracy of the proposed method, three FWDCs with different levels of coupling are designed and studied at the central frequency of 1.5 GHz. The couplers are numerically simulated using high frequency structure simulator (HFSS) and the results including *S*-paramerters, coupling level and the overall bandwidth are compared with those obtained by equivalent circuit model. Moreover, a prototype of the proposed 0 dB coupler is made using a single layer of substrate and it is succesfully tested. Measured results show that 0.62 dB level of coupling is obatined with 1 dB flatness from 1.45 GHz to 1.63 GHz, which corresponds to 11.7% fractional bandwidth and the length of the fabricated coupler is $0.26\lambda_g$.

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1. INTRODUCTION

A coupled-line coupler is a four-port network constituted of combination of two unshielded transmission lines in close proximity. Due to this proximity, the electromagnetic fields of each line interacts with the other one, which results in power exchange between the lines [1].

Microstrip coupled-line directional couplers are widely used in microwave and millimeter wave circuits due to their attractive performances. They have been used for discriminators, feed networks in antenna arrays, phase shifters and antenna beam forming networks [2]. Essentially, two different coupling mechanisms are possible, depending on the nature of the transmission lines constituting the coupled-line structure and the distance between these lines [3].

In the first mechanism backward coupling is obtained by equal phase velocities and different characteristic impedances of even- and odd-modes. Based on equal phase velocities, the coupling strength is based on the difference between even and odd mode characteristic impedances, whereas, the length of the coupler is a quarter-wave length long [4,5], the highest coupling level is obtained. By reducing interspacing between lines, the difference between characteristic impedances is increased. However, due to fabrication constraints, the minimum value of the line distance is limited in practice and so, only low values of the coupling level are attained [2].

In the second coupling mechanism, forward coupling is obtained using equal even- and odd-mode characteristic impedances and unequal phase shifts between these two modes. The coupling strength of the forward coupler is dependent on difference in phase between the even and odd modes [2]. The coupling strength can be as high as 0 dB in these types of couplers. However, implementing these components by microstrip coupled lines is not an easy task, due to the small difference between even- and odd-mode propagation constants, which requires a very long coupling length of the coupled lines and non-identical

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characteristic impedances of even and odd modes, which degrades the coupling level and reduces directivity performance of the coupler.

In order to obtain large values of phase difference between even- and odd-modes, a few techniques have been suggested in literature. A size-reduced 3 dB forward coupler loaded with periodic shunt capacitive stubs has been reported in literature [6]. Also, improving forward coupling using a periodically patterned ground plane is reported in reference [7]. Moreover, using a non-uniform transmission line, the phase difference between the even- and odd-modes is increased. This method is used as the wiggly or serpentine configurations [8-10], the microstrip coupled line with photonic-bandgap (PBG) structures on the ground plane [10] and the composite right/left-handed (CRLH) transmission lines [11-16].

In this paper forward-wave directional couplers using a new type of unit cell loaded with periodic shunt shorted stubs are proposed. The stubs help to enlarge the phase difference between even- and odd-modes of the structure and therefore, large value of coupling strength is obtained using a small length of coupled lines. The equivalent circuit model for the cell is reported and the results are compared with those obtained by numerical investigation using high frequency structure simulator (HFSS). Three couplers with different coupling levels are designed based on the proposed cell. One of the proposed couplers with 0 dB coupling level is implemented using a single layer of substrate and the measured results are compared with those obtained by the equivalent circuit model and numerical investigation.

2. COUPLER DESCRIPTION

Figure 1 shows the unit-cell of the proposed coupler. It consists of a pair of microstrip coupled lines, which are loaded by shunt short circuited stubs. The widths of both lines are the same and is designated by *W*. Also, *d* represents the period of the unit cell and *h* is the thickness of the substrate. These lines are separated from each other by the distance *s*. Using metal vias having diameter of *r*, the stubs are connected to the ground. Stubs have the width of *a* and the length of *l*.

To analyze the coupler as a symmetrical structure even and odd mode analysis can be utilized. Figures 2(a) and (b) show the even and odd mode equivalent circuit models of the unit cell respectively. They also correspond to the structure with perfect magnetic wall and perfect electric wall at the center of the coupler, respectively.

3. THEORETICAL MODELING

Figures 2(a) and (b) depict the even and odd mode equivalent models of the unit cell respectively. In this model, $\theta_{m,e}$ stands for the phase delay along a half unit cell and $Z_{m,e}$ is the characteristic impedance of the coupled microstrip lines under the even-mode excitation. *Y* is the equivalent admittance of the short circuited stub and if characteristic admittance and electrical length of the stubs are designated by Y_h and θ_h, *Y* can be obtained from Equation (1).

$$Y = -jY_h \cot\theta_h \tag{1}$$

In case of odd mode equivalent model, $\theta_{m,o}$ and $Z_{m,o}$ represent phase delay along the half unit cell and characteristic impedance of the coupled lines respectively. The *ABCD* matrix of the unit cell is given by Equation (2).

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\theta_m & jZ_m \sin\theta_m \\ \frac{j\sin\theta_m}{Z_m} & \cos\theta_m \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_m & jZ_m \sin\theta_m \\ \frac{j\sin\theta_m}{Z_m} & \cos\theta_m \end{bmatrix} \tag{2}$$

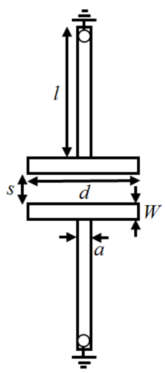

Figure 1. The unit-cell of the proposed coupler

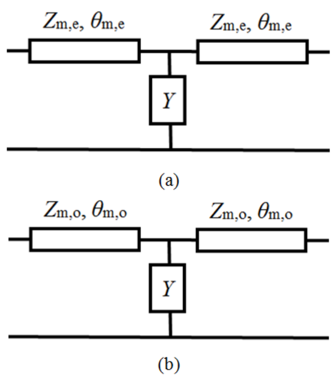

Figure 2. The equivalent-circuit models of the forward-wave coupler, a) even mode, b) odd mode

The elements of the *ABCD* matrix are obtained using the folowing equations.

$$A = \cos^2\theta_m - \sin^2\theta_m + \frac{Z_m}{2Z_h}\cot\theta_h \sin 2\theta_m \tag{3}$$

$$B = jZ_m \sin 2\theta_m + j\frac{Z_m^2}{Z_h}\sin^2\theta_m \cot\theta_h \tag{4}$$

Using the above equations, Bloch impedances and electrical lengths of the two modes are derived based on the equivalent models [17].

$$Z_B = \frac{B}{j\sqrt{1-A^2}} \tag{5}$$

$$\theta = \cos^{-1} A \tag{6}$$

Then, the characteristic impedances and electrical lengths of the whole structure are obtained from Equations (7a) to (7d).

$$Z_{t,e} = Z_{B,e} \tag{7a}$$

$$Z_{t,o} = Z_{B,o} \tag{7b}$$

$$\theta_{t,e} = N\theta_e \tag{7c}$$

$$\theta_{t,o} = N\theta_o \tag{7d}$$

in which N is the number of the unit cells. In order to design the forward-wave coupler with a high value of directivity and also to achive impedance matching at different ports, Equation (8) should be satisfied [1].

$$Z_o = Z_e = 50\ \Omega \tag{8}$$

The coupling level for the forward-wave coupler is given by Equation (9) [1].

$$C_\varphi = -je^{-j\frac{\theta_e+\theta_o}{2}}\sin\left(\frac{\theta_e-\theta_o}{2}\right) \tag{9}$$

4. SIMULATION RESULTS

Using equations of the previous section and also the presneted equations in reference [18] for obtaining characteristic impedance and effective permittivity of the microstrip coupled lines, one can design a directional coupler with an arbitrary coupling level. For this purpose, dimensions of the coupler is changed, until Equations (8) and (9) are satisfied. TLY031 substrate with electrical characteristics of $\varepsilon_r = 2.2$, $h = 0.7874$ mm and tangent loss of 0.001 is used for couplers implementations. The structure of different couplers propsed in this paper is shown in Figure 3.

4. 1. 0 dB coupler A 0 dB coupler with four numbers of the proposed cell is designed. The dimensions of the designed coupler are shown in Table 1. The simulated S-parameters which are obtaind using HFSS software including those obtained using the equiavalet circuit model are plotted in Figures 4(a) and 4(b).

It can be seen that the proposed coupler provides 0.12 dB coupling level with 1 dB flatness over the frequency range of 1.5 GHz upto 1.62 GHz, which corresponds to 7.7% fractional bandwidth. The coupler length is 0.26λg which is smaller than the size of a conventional forward wave coupler.

Figure 5 illustrates the even- and odd-mode Bloch impedances and the electrical lengths of the 0 dB coupler in pass band, which are calculated from Equations (5) and (6). As shown in Figure 5, these impedances are real and nearly 50 Ω in pass band and so, a good impedance matching is acheievd. Moreover, Figure 5 shows 3.54 rad phase difference between even and odd modes, which corresponds to 0.17 dB level of coupling.

4. 2. 3 dB Coupler A 3 dB coupler is also designed using four proposed cells. The dimensions of the designed couplers are summerized in Table 1.

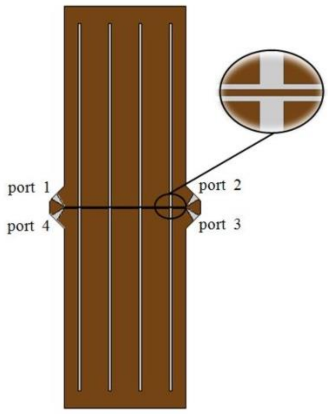

Figure 3. General structure of the proposed FWDC couplers

TABLE 1. The geometrical parameters of the proposed couplers, (units in: mm)

Parameters	0 dB Coupler	3 dB Coupler	10 dB Coupler
W	0.2	0.2	0.2
s	0.24	0.55	1.1
d	10.0	8.2	8.4
l	59.94	59.59	59.59
a	0.87	1.1	1.1
r	0.4	0.6	0.6

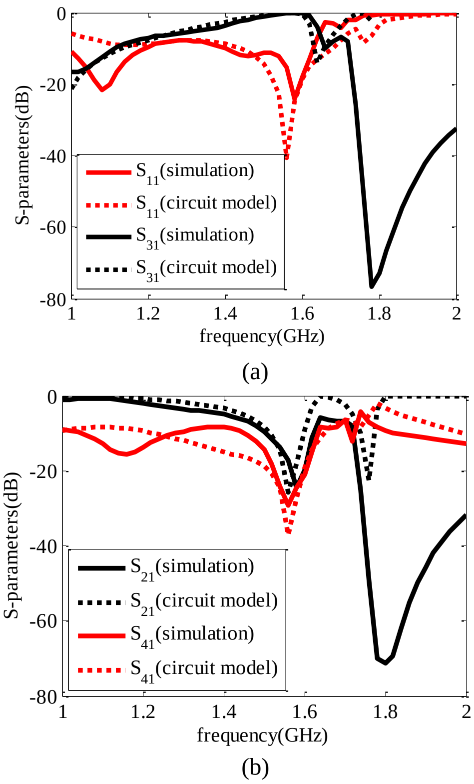

Figure 4. The simulated and equivalent circuit model *S*-parameters of the proposed 0 dB coupler

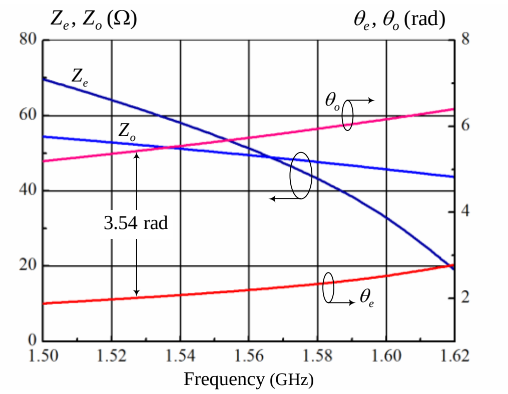

Figure 5. Bloch impedances Z_e, Z_o and the electrical lengths of the proposed 0 dB coupler in pass band

The simulation results for different paprameters including the obtained results by the equivalent circuit model are illustrated in Figures 6(a) and 6(b) versus frequency. It can be seen that the proposed coupler provides 3 dB coupling level with 1 dB flatness from 1.56 GHz to 1.63 GHz, which corresponds to 4.4% fractional bandwidth. There is a discrepancy at 1.8 GHz between the equivalent circuit model and simulation results of the coupler. Apart from that this frequency is out of the inetrested band, it is belevided that this is due to limited accuracy of the eqivlanet circuit model across the bandwidth of interest.

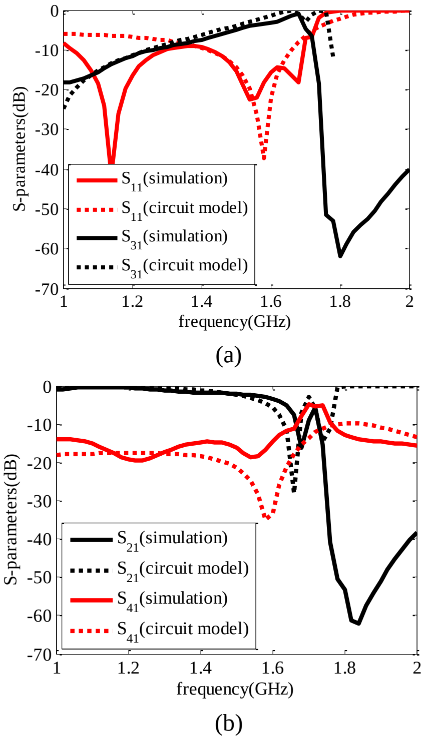

Figure 6. The simulated and equivalent circuit model *S*-parameters of the proposed 3 dB coupler

4. 3. 10 dB Coupler

A 10 dB coupler is also designed using four cells with the geomerical parametres listed in Table 1. The simulated results of *S*-parameters of this coupler including those obtained by the equivalent circuit model of the cells are provided in Figures 7(a) and 7(b) for comparison.

These Figures confirm that the proposed coupler provides 9 dB level of coupling with 1 dB flatness over the frequency range of 1.5 GHz up to 1.66 GHz, which corresponds to 10.1% fractional bandwidth. Also, a good agreement is obtained by simulation and the equivalent circuit model. It is notable that the discrepancy at 1.8 GHz is repeated in Figure 7.

5. MEASUREMENT RESULTS

To evaluate the accuracy of the propsed procedure in designing directional couplers, a prototype of a directional coupler with 0 dB level of coupling is implemented using single layer of TLY031 substrate. Photo of the fabricated coupler under test is shown in Figure 8.

The measured results of the *S*-parameters are shown in Figure 9 including the simulation ones for comparison. It can be seen that the measured level of coupling is 0.62 dB with 1 dB flatness from 1.45 GHz to 1.63 GHz, which corresponds to the 11.7% fractional bandwidth. The detailed performnces of the designed 0 dB proposed coupler are summerized in Table 2.

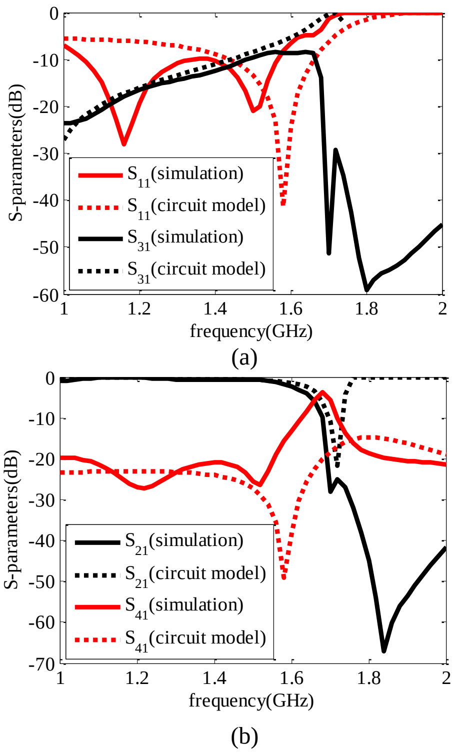

Figure 7. Simulated and equivalent circuit model *S*-parameters of the 10 dB proposed coupler

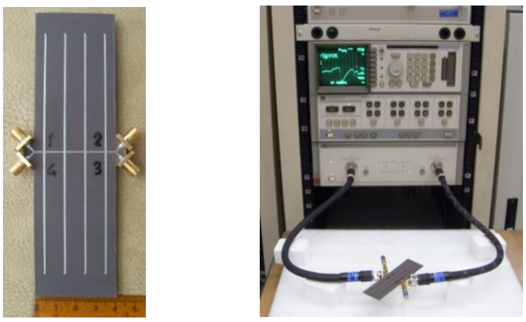

Figure 8. Photograph of the fabricated 3 dB proposed coupler and the measurement set up

TABLE 2. Detailed simulation and measured results of the proposed 0 dB FWDC.

Parameters	Simulationn (HFSS)	Equivalent Cicuit model	Measurement
FBW	7.7%	7.7%	11.7%
Coupling level	0.12 dB	0.06 dB	0.62 dB

6. COMPARISON WITH RECENTLY PUBLISHD COUPLERS

The performances of our proposed 0 dB coupler are compared with those of recently published researches in Table 3.

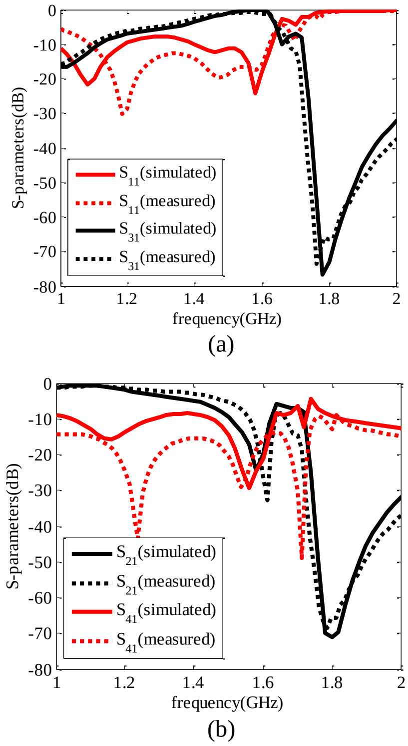

Figure 9. Measured results of the S-parameters

TABLE 3. Comparison of the measured performance of the proposed FWDC coupler with those of recently published ones

Coupler	FBW (%)		Coupling Level (dB)		Length (mm)
	Simul.	Measu.	Target	Measu.	
[19]	14	12	0	0.5	$0.55\lambda_g$
[20]	21.4	19	0	1.1	$1.28\lambda_g$
[8]	-	38	0	1.4	$2.47\lambda_g$
[7]	16	19	0	1.5	$2.23\lambda_g$
[11]	18	6	0	4.5	$1.57\lambda_g$
[21]	38.2	38.5	3	3.3	$1.01\lambda_g$
[22]	48.7	49.5	3	3.8	$0.9\lambda_g$
This paper	7.7	11.7	0	0.62	$0.26\lambda_g$

The target and meaured values of the level of coupling are provided in this table. It can be seen that the proposed coupler provides the smallest length among different couplers, but it suffers from low coupling bandwidth.

7. CONCLUSION

A compact forward-wave directional coupler (FWDC) is presented in this paper using a new type of cell. The proposed cell is loaded by periodic shunt short circuited stubs structure to enlarge the phase difference between even- and odd modes of the coupled lines. Based on the equivalent circuit model of even- and odd-mode analysis, the elements of *ABCD* transmission matrix of the cell are derived. Then, the crresponding Bloch impedances and the electrical lengths of the two modes are calculated. Using the derived equations, three FWDCs are designed by four numbers of the proposed cell including 0 dB, 3 dB and 10 dB level of coupling. The designed couplers are numerically investigated by HFSS software and the equivalent circuit model. The simulation results agree well with those obtained by the equivalent circuit model. To verify the acuuracy of the design method, a prototype of the 0 dB forward wave coupler is made using a single layer of Printed Circuit Board (PCB) procces. The fabricated coupler is successfully tested and its *S*-parameters are measured. It is shown that measured results agree well with those obtained by simulation. For the implemented coupler with 0 dB coupling level, the measured results for the level of coupling is 0.62 dB with 1 dB flatness over frequency range of 1.45 GHz up to 1.63 GHz corresponding to 11.7% fractional bandwidth. The total fractional length of the coupler is only $0.26\lambda_g$ providing a compact size coupler, which can be used in microwave circuits.

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چکیده

در این مقاله، با استفاده از شاخه های متناوب اتصال کوتاه شده، روشی جدید برای طراحی تزویج کننده جهتی رو به جلو پیشنهاد شده است. یک سلول جدید متشکل از شاخه های متناوب برای افزایش اختلاف فاز بین مُدهای زوج و فرد خط ریز نواری معرفی و بررسی شده است. با استفاده از بررسی مُدهای زوج و فرد، مدار معادل سلول برای این مُدها معرفی و عناصر ماتریس انتقال آن استخراج شده است. هم‌چنین روند طراحی تزویج کننده‌ها با استفاده از سلول پیشنهادی و با کمک مدار معادل معرفی شده است. با توجه به افزایش اختلاف فاز بین مُدهای زوج و فرد، می توان تزویج کننده های رو به جلو با طول کم طراحی کرد. برای بررسی دقت روند پیشنهادی، سه کوپلر رو به جلو به‌ترتیب با سطح تزویج‌های ۰، ۳ و ۱۰ dB با فرکانس مرکزی حوالی ۱/۵ GHz طراحی شده‌اند. نتایج به‌دست آمده شامل سطح تزویج، امپدانس ورودی و پهنای باند به روش مدار معادل با نتایج شبیه سازی حاصل از نرم افزار HFSS مقایسه شده است. یک نمونه آزمایشگاهی از تزویج کننده ۰ dB با استفاده از یک زیر لایه ساخته شده و با موفقیت آزمایش شده است. نتایج ساخت نشان می دهد که ضریب تزویج ۰/۶۲ dB در محدوده فرکانسی ۱/۴۵ تا ۱/۶۳ GHz به دست آمده و طول نسبی تزوج کننده ۰/۲۶ λ_g است.

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