Int. J. Electron. Commun. (AEÜ) 66 (2012) 569–574

Contents lists available at SciVerse ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.de/aeue

A broadband and compact asymmetrical backward coupled-line coupler with high coupling level

Rasool Keshavarz[a], Masoud Movahhedi[a,*], Abdolali Abdipour[b]

[a] Electrical Engineering Department, Shahid Bahonar University of Kerman, Kerman, Iran
[b] Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 7 April 2011
Accepted 20 November 2011

Keywords:
Microstrip coupled-line coupler
Asymmetrical coupler
Backward broadband coupler
Interdigital capacitor

ABSTRACT

A new wideband asymmetric microstrip coupled-line coupler with 3 dB coupling value and quadrature phase difference is presented. Compared with the conventional edge-coupled couplers, this structure, consisting of two different transmission lines (interdigital and conventional microstrip transmission lines) as coupled lines, achieves wider operating bandwidth and larger coupling level. The coupled-line length of the proposed structure is approximately $\lambda_g/4$. To characterize the structure, an equivalent circuit model has been established. A 3 dB designed and fabricated coupler with 0.2 mm spacing between coupled lines exhibits an amplitude balance of 2 dB from 2.2 GHz to 4.2 GHz. Good agreements between the full-wave simulation and equivalent circuit model results has been achieved and verified the effectiveness of the proposed circuit model. Also, measurement results have been presented.

1. Introduction

Coupled-line couplers (CLCs) are one of the most commonly used building blocks in microwave and RF systems. In these structures two unshielded transmission lines are close together and power can be coupled between the lines. Such lines are referred to as coupled transmission lines [1]. Couplers are widely employed in microwave and millimeter wave applications as key elements in balanced amplifiers, balanced mixers, (de)modulators, frequency discriminators, and circularly polarized antennas [1]. However, conventional coupled-line couplers based on the planar transmission lines exhibit loose coupling levels (typically <10 dB). Usually in these structures, in order to get the tight coupling-level, the space between two coupled-lines in the structure must be very small and it would be difficult to obtain due to the fabrication constrains.

In general, two types of coupled-line couplers have been proposed; backward and forward coupled-line couplers. When the coupled port is located on the same side of the structure as the input port and power is subsequently coupled backward to the direction of the source, this coupler is conventionally called a backward coupler and otherwise the coupled-line coupler is called forward coupled-line coupler [1]. Also, two types of edge-coupled backward coupled-line couplers are presented. The first is a symmetrical coupler. When the two lines constituting a coupled-line coupler are the same, the structure is called symmetric. In the symmetric structures, coupling mechanism is based on the difference between the characteristic impedances of the even and odd modes [1]. The second one is an asymmetrical coupler. This coupler is asymmetrical as it is constituted of two different transmission lines. In this case, decomposition in even and odd modes is not possible anymore. The analysis becomes more difficult and the even/odd modes have to be replaced by the more general c and π modes, which are two fundamental independent modes, as described in [1].

Symmetrical coupled lines represent a very useful but restricted class of couplers. In many practical cases, it might be more useful or even necessary to design components using asymmetrical coupled lines. For example, in some situations, the terminal impedance of one of the coupled lines may be different from those of the other. It may then be more useful to choose two coupled lines with different characteristic impedances. Also, an asymmetrical coupled-line coupler has usually broader bandwidth than symmetrical one [1].

In the past few years, the great interest in the field of metamaterials has been attracted and the composite right/left handed (CRLH) structures, as metamaterial transmission lines, have been used in active and passive microwave circuits design, particularly. Equivalent circuit model of each cell of a CRLH transmission line consists of series capacitor and series inductor along with shunt capacitor and shunt inductor [2]. Several methods for realizing CRLH transmission lines have been proposed. One of these methods in microstrip structures is the use of interdigital/stub configuration. In this method, the elements of the equivalent circuit model of CRLH are realized by interdigital capacitor as series capacitor and shorted stub as shunt inductor. Parasitic elements of interdigital capacitor and shorted stub play the role of series inductor and shunt

* Corresponding author.
E-mail address: Movahhedi@ieee.org (M. Movahhedi).

1434-8411/$ – see front matter © 2011 Elsevier GmbH. All rights reserved.
doi:10.1016/j.aeue.2011.11.009

capacitor in equivalent circuit model [2]. It is interesting to note that the proposed interdigital transmission line in this paper is similar to a CRLH transmission line with infinite shunt inductances.

In this paper, a novel compact 3 dB microstrip backward (directional) coupled-line coupler with wide bandwidth is presented. This coupler consists of an interdigital capacitor and a conventional microstrip transmission line as coupled lines in an asymmetric configuration. Compared with the other backward coupled-line couplers presented in [3–8], the proposed structure has more achievable dimension, wider bandwidth and higher coupling-level.

In the following, theoretical description and principle of the proposed microstrip asymmetrical backward coupled-line coupler is presented. Then a design example of a 3 dB coupler with flat coupling is shown. The proposed coupler is modeled by an equivalent circuit model and also full-wave simulation results of the proposed coupler are demonstrated by using an electromagnetic simulator (Agilent ADS). Finally, experimental verification is presented and conclusions are drawn.

2. Interdigital transmission line

An interdigital capacitor is a multifinger periodic structure which can be used as a series capacitor in microstrip transmission lines technology. This capacitor uses the capacitance that occurs across a narrow gap between thin-film conductors [8]. Fig. 1(a) shows an interdigital capacitor and its equivalent circuit model. As seen in this figure, an interdigital capacitor is made of some gaps. In this structure, the series capacitor can be increased by increasing the number of fingers, or by using a thin layer of high dielectric constant material such as a ferroelectric between the conductors and the substrate [9].

Series capacitance of an interdigital capacitor, i.e., C_{int}, with structure parameters which have been presented in Fig. 1(a) is equal to [9]:

$$C_{\text{int}} = \frac{\varepsilon_r + 1}{W'}\ell_{\text{int}}\left[(N-3)A_1 + A_2\right] \tag{1}$$

where ε_r is relative permittivity of the microstrip substrate and N is the number of structure fingers. Approximate expressions for A_1 and A_2 are obtained by curve fitting the data given in [9]. These expressions are as:

$$\begin{aligned} A_1 &= 4.409 \tanh\left[0.55\left(\frac{h}{W}\right)^{0.45}\right] \times 10^{-6} (\text{pF}/\mu\text{m}) \\ A_2 &= 9.92 \tanh\left[0.52\left(\frac{h}{W}\right)^{0.5}\right] \times 10^{-6} (\text{pF}/\mu\text{m}) \end{aligned} \tag{2}$$

where h is the thickness of the substrate. In Fig. 1(a), L and C in the equivalent circuit model represent conventional series inductance and shunt capacitance in microstrip transmission line and are considered as parasitic elements in interdigital structure. Values of these elements can be obtained from transmission line theory from the length of the structure, i.e., l_{int}, as [10]:

$$\begin{aligned} L &= \frac{\sqrt{\varepsilon_{\text{re}}}Z_0}{c}\ell_{\text{int}} \\ C &= \frac{\sqrt{\varepsilon_{\text{re}}}}{Z_0 c}\ell_{\text{int}} \end{aligned} \tag{3}$$

where ε_{re} is effective relative permittivity of the microstrip transmission line whose strip width is W, Z_0 is characteristic impedance of a microstrip transmission line with strip width of $W' (= (2N-1)S + 2NW)$ and c is the velocity of light in free space.

As it is seen in Fig. 1(b), an interdigital transmission line is constructed by cascading some interdigital capacitors. In this new planar transmission line, each interdigital capacitor can be considered as unit cell of the transmission line structure. Now, for this new transmission line, the parameters can be derived as the following. If we define per-unit-length impedance (Z') and admittance (Y') as:

$$\begin{aligned} Z' &= j\left(\omega L' - \frac{1}{\omega C'_{\text{int}}}\right) \\ Y' &= j\omega C' \end{aligned} \tag{4}$$

where

$$L = L'\ell_{\text{int}},\ C = C'\ell_{\text{int}},\ C_{\text{int}} = \frac{C'_{\text{int}}}{\ell_{\text{int}}} \tag{5}$$

It is well known from transmission line theory that propagation constant γ and characteristic impedance Z_c of a transmission line with series impedance Z' and shunt admittance Y', is obtained from following equations [10]:

$$\gamma = \sqrt{Z'Y'} \tag{6}$$

$$Z_c = \sqrt{\frac{Z'}{Y'}} \tag{7}$$

So, for an interdigital transmission line, the complex propagation constant and characteristic impedance are:

$$\gamma_{\text{int}} = j\sqrt{\left(\omega L' - \frac{1}{\omega C'_{\text{int}}}\right)(\omega C')} = j\sqrt{\omega^2 L'C' - \frac{C'}{C'_{\text{int}}}} = j\beta_{\text{int}} \tag{8}$$

$$Z_{c,\text{int}} = \sqrt{\frac{j\left(\omega L' - (1/\omega C'_{\text{int}})\right)}{j(\omega C')}} = \sqrt{\frac{L'}{C'} - \frac{1}{\omega^2 C' C'_{\text{int}}}} \tag{9}$$

It is clear from above equations that γ_{int} and $Z_{c,\text{int}}$ have real values for $\omega > \omega_{\text{se}} = \frac{1}{\sqrt{LC_{\text{int}}}}$.

3. Proposed asymmetrical coupled-line coupler

Recently, a symmetrical coupled-line coupler based on the coupled interdigital transmission lines has been proposed and its specifications along with advantages have been reported in [11]. The structure consists of two interdigital capacitors with one finger as coupled lines. In this paper, an asymmetrical coupled-line coupler based on the interdigital transmission line is presented. Fig. 2 shows the layout and circuit model of the interdigital and conventional microstrip transmission lines which are adjacent to each other as proposed asymmetrical backward coupled-line coupler. As depicted in Fig. 2(b), C_m represents the mutual capacitance between interdigital and strip of the microstrip conductors in the absence of the structure ground conductor while C_1 and C_2 represent the capacitance between interdigital or microstrip strip conductors and ground, respectively. Moreover, the circuit model includes mutual inductance (L_m) and self-inductances of interdigital (line 1) and conventional microstrip (line 2) conductors, i.e., L_1 and L_2, respectively. C_{int} is series interdigital capacitor of line 1. It should be stated that all of parameters in the circuit model are per unit length quantities. Also, Fig. 3 shows the capacitance representation for quasi-TEM mode of cross section of the proposed asymmetrical coupler. For structure analysis, it is assumed that lines 1 and 2 are terminated to impedances Z_a and Z_b, respectively.

Characteristics of the proposed coupled transmission line can be described by a superposition of characteristics of c and π modes. As it was mentioned, in the coupled-line couplers when two coupled-lines are similar to each other, the coupler is symmetrical and otherwise the structure is asymmetrical. A set of two coupled lines can support two fundamental independent modes of propagation (called normal modes). For asymmetrical coupled lines, the two normal modes of propagation are known as c and π modes [1]. Both c and π modes are composed of two traveling waves in the backward and forward directions. The c mode is characterized by four

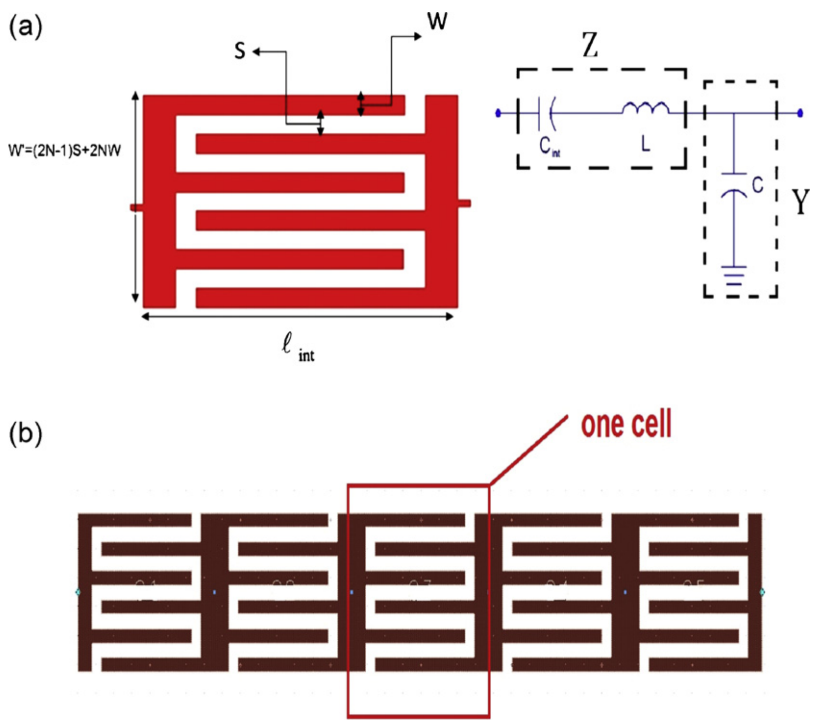

Fig. 1. (a) Interdigital capacitor and its equivalent circuit model. (b) Interdigital transmission line.

parameters: γ_c, Z_{c1}, Z_{c2} and R_c which are the propagation constant of the mode, the characteristic impedances of lines 1 and 2 and the ratio of the voltages on the two lines of the c mode, respectively. Similarly, the π mode is also characterized by four parameters: γ_π, $Z_{\pi1}$, $Z_{\pi2}$ and R_π which are propagation constant of the mode, characteristic impedances of lines 1 and 2 and the ratio of the voltages on the two lines of the π mode, respectively [1].

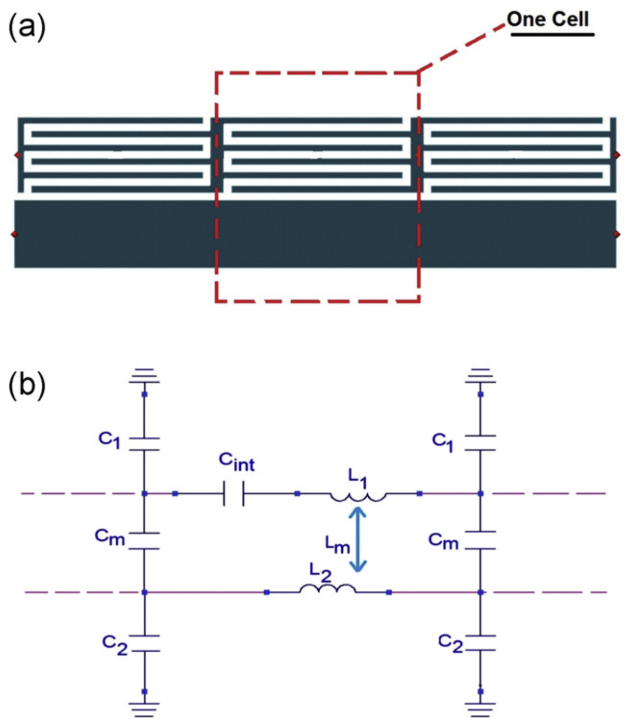

Fig. 2. Proposed asymmetrical coupled-line coupler consisted of interdigital transmission line and microstrip conventional transmission line. (a) Its layout and (b) lumped equivalent circuit model.

As it has been shown in [1], the relation between the characteristic impedances, i.e., Z_{c1}, Z_{c2}, $Z_{\pi1}$ and $Z_{\pi2}$, and also the ratio parameters, i.e., R_c and R_π, are as:

$$\frac{Z_{c2}}{Z_{c1}} = \frac{Z_{\pi2}}{Z_{\pi1}} = -R_c R_\pi \tag{10}$$

So, a total number of only six quantities, i.e., $\gamma_c, \gamma_\pi, Z_{c1}$ or $Z_{c2}, Z_{\pi1}$ or $Z_{\pi2}, R_c$ and R_π, are required to characterize asymmetrical coupled lines. For a lossless TEM-mode coupled-line, the propagation constants of both c and π modes are the same, and are given by [12]:

$$\gamma_c = \gamma_\pi = j\beta \tag{11}$$

By assuming the quasi-TEM mode for proposed structure and according to Eqs. (9) and (10) and [12] for above asymmetrical coupler (Fig. 2), it is obtained that:

$$R_c = -R_\pi = \sqrt{\frac{Z_2}{Z_1}} \tag{12}$$

where

$$Z_1 = \sqrt{\frac{L_1}{C_1} - \frac{1}{\omega^2 C_{\text{int}} C_1}}, \qquad Z_2 = \sqrt{\frac{L_2}{C_2}} \tag{13}$$

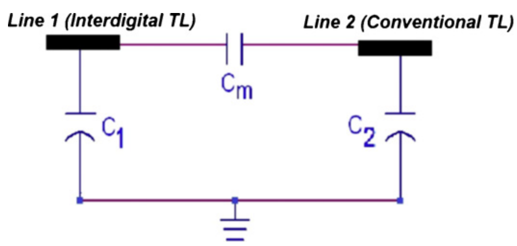

Fig. 3. Equivalent capacitance representation for cross section of the asymmetrical coupler presented in Fig. 2.

where Z_1 and Z_2 are characteristic impedances of uncoupled lines 1 (interdigital transmission line) and 2 (conventional microstrip transmission line), respectively.

Moreover, the capacitance matrix of the coupled lines (Fig. 2) can be expressed as [12]:

$$[C] = \begin{bmatrix} C_1 & C_{12} \\ C_{21} & C_2 \end{bmatrix} = \begin{bmatrix} C_1 + C_m & -C_m \\ -C_m & C_2 + C_m \end{bmatrix} \tag{14}$$

According to Eqs. (12) and (13), c and π mode characteristic impedances of interdigital transmission line ($Z^a_{0c}, Z^a_{0\pi}$) and the conventional microstrip transmission line ($Z^b_{0c}, Z^b_{0\pi}$) are obtained as [12]:

$$\begin{cases} Z^a_{0c} = \sqrt{\dfrac{L_1}{C_1} - \dfrac{1}{\omega^2 C_{int} C_1}} \\ Z^a_{0\pi} = \sqrt{\dfrac{L_1}{(C_1 + 2C_m)} - \dfrac{1}{\omega^2 C_{int}(C_1 + 2C_m)}} \\ Z^b_{0c} = \sqrt{\dfrac{L_2}{C_2}} \\ Z^b_{0\pi} = \sqrt{\dfrac{L_2}{C_2 + 2C_m}} \end{cases} \tag{15}$$

and

$$Z'^a_{0c} = \sqrt{\frac{L_1}{C_1}}, \qquad Z'^a_{0c} = \sqrt{\frac{L_1}{(C_1 + 2C_m)}}, \tag{16}$$

Z'^a_{0c} and $Z'^a_{0\pi}$ are c and π mode characteristic impedances of a conventional microstrip transmission line with a strip of width W', where $W'(= (2N-1)S' + 2NW)$ is the total width of the interdigital capacitor.

In coupler design procedure, for an indicated coupling-level (k) and impedance ports Z_a and Z_b of lines 1 and 2, respectively, Z^a_{0c}, $Z^a_{0\pi}$, Z^b_{0c} and $Z^b_{0\pi}$ can be calculated from following equations [12]:

$$\begin{cases} Z^a_{0c} = \dfrac{Z_a Z_b \sqrt{1-k^2}}{Z_b - k\sqrt{Z_a Z_b}} \\ Z^a_{0\pi} = \dfrac{Z_a Z_b \sqrt{1-k^2}}{Z_b + k\sqrt{Z_a Z_b}} \\ Z^b_{0c} = \dfrac{Z_a Z_b \sqrt{1-k^2}}{Z_a - k\sqrt{Z_a Z_b}} \\ Z^b_{0\pi} = \dfrac{Z_a Z_b \sqrt{1-k^2}}{Z_a + k\sqrt{Z_a Z_b}} \end{cases} \tag{17}$$

In order the values of Z^a_{0c} and Z^b_{0c} to be positive, it is necessary that:

$$\frac{1}{k^2} \geq \frac{Z_a}{Z_b} \quad \text{and} \quad \frac{1}{k^2} \geq \frac{Z_b}{Z_a} \tag{18}$$

where k^2 denotes the power coupling coefficient between two coupled lines.

4. Simulated results and discussions

As it was mentioned, for indicated coupling level (k) and ports impedance (Z_a, Z_b) in the proposed coupler, the c and π characteristic impedances, i.e., $Z^a_{0c}, Z^a_{0\pi}, Z^b_{0c}$, and $Z^b_{0\pi}$, can be determined using (17). It is clear from (15) that selecting a small C_{int} in the introduced coupler, increases values of Z'^a_{0c} and $Z'^a_{0\pi}$ which can lead to smaller value for C_m. It means that in this situation, the required spacing between two coupled-lines can be increased in comparison with the conventional microstrip coupled-lines. It is due to the inverse relationship between mutual capacitance value and spacing between coupled lines. Therefore, it is suitable for realizing high coupling-level coupled-line couplers with relatively larger spacing between two lines than conventional coupled-line couplers.

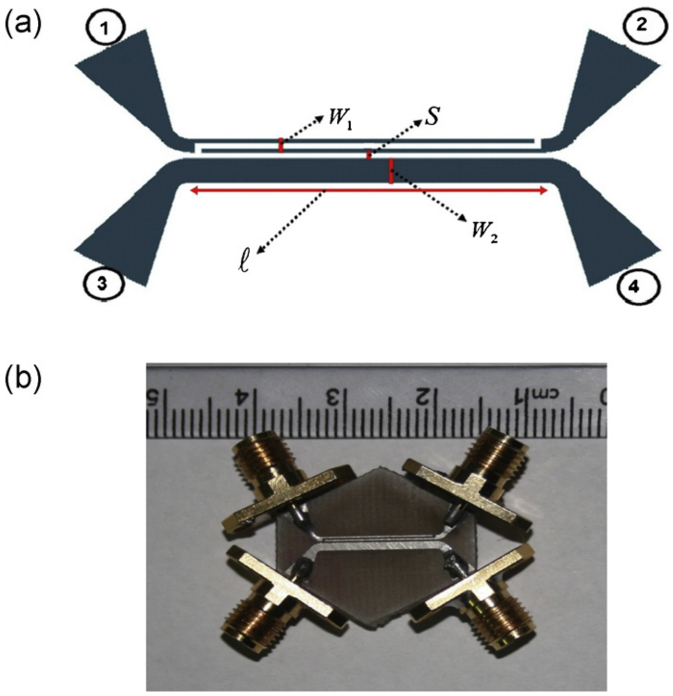

Fig. 4. Proposed asymmetrical backward coupler based on the interdigital and conventional microstrip coupled transmission lines. (a) Structure layout. (b) Fabricated coupler.

According to (1), selecting one finger, i.e., $N = 1$, for the interdigital capacitor, leads to a small C_{int} which is convenient for increasing coupling-level with relatively large spacing between two lines. Moreover, for getting better isolation and impedance matching in the coupler ports, we use only one interdigital capacitor to realize interdigital transmission line as one of the coupled-lines. Fig. 4 illustrates the layout and fabrication of the proposed asymmetrical coupler that above considerations have been considered in its design.

For an asymmetric coupled microstrip lines of the type shown in Fig. 4, the design graphs presented in Figs. 5–7 can be used to determine the necessary interdigital and microstrip strip widths and spacing for a given set of characteristic impedances,

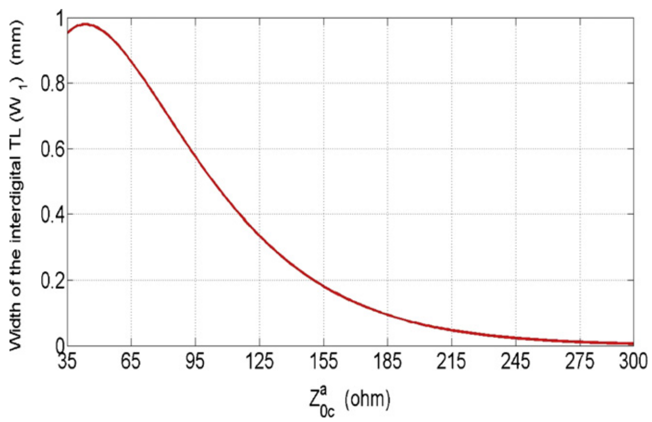

Fig. 5. Design graph for width of the interdigital transmission line (W_1) on FR-4 substrate versus c mode characteristic impedance.

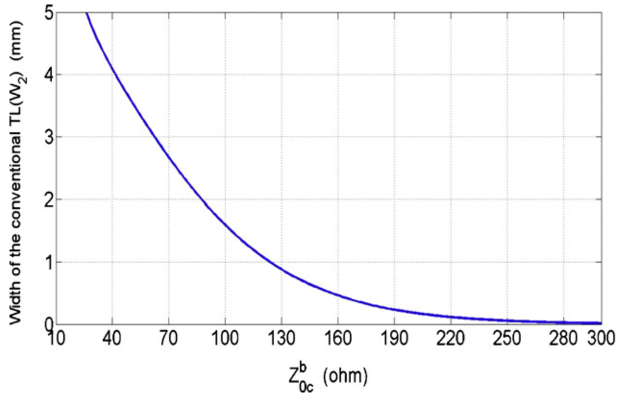

Fig. 6. Design graph for width of the conventional microstrip transmission line (W_2) on FR-4 substrate versus c mode characteristic impedance.

Z^a_{oc}, Z^b_{0c} and Z_m, on FR-4 substrate with $\varepsilon_r = 4.6$ and thickness of 1.6 mm. In Fig. 7, Z_m is defined as:

$$Z_m = \frac{2Z^b_{0c}Z^b_{0\pi}}{Z^b_{0c} - Z^b_{0\pi}} \tag{19}$$

By using theses figures, the physical dimension of the introduced coupler, i.e., W_1, W_2 and S, can be determined using given values of Z^a_{oc}, Z^b_{0c} and Z_m, where W_1 and W_2 are widths of the interdigital and microstrip lines, respectively, and S is spacing between two lines. It is clear that for implementation of the coupler on the other substrates, similar graphs can be developed and used in design procedure.

The asymmetrical coupled line coupler presented in this study is a 3 dB coupler at center frequency of 3 GHz which is simulated on FR-4 substrate with 1.6 mm substrate thickness and a dielectric constant of 4.6. Impedances of all four ports have been considered equal to 50Ω $\left(Z_a = Z_b = 50\Omega\right)$. The final structure of designed coupler has been presented in Fig. 4(b) with W_1 = 0.6 mm, W_2 = 1 mm and the spacing between two coupled lines (S) is 0.2 mm. The structure coupled-line length (l) is equal to 12 mm, which is approximately $\lambda_g/4$ at center frequency of 3 GHz.

In addition to the equivalent circuit model which is used to simulate the designed coupler, a full-wave electromagnetic simulator (ADS) is also used to examine the structure. Fig. 8 illustrates the full-wave and equivalent circuit model analysis results of the proposed asymmetric backward coupler along with its measured S-parameters. Excellent agreement can be observed between full-wave simulated and experimental results.

From this figure it is concluded that the equivalent circuit model is an initial approximation for designed structure and it is not very accurate at all frequencies. The equivalent circuit model is

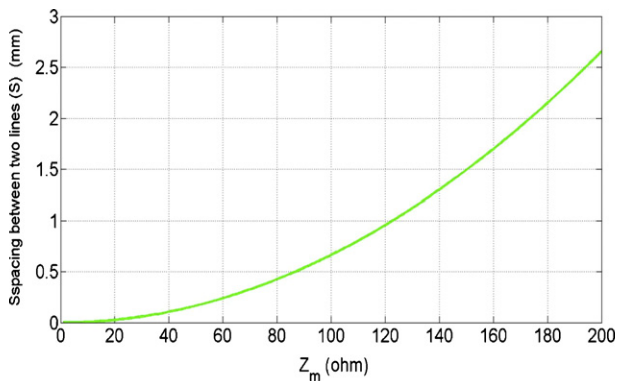

Fig. 7. Design graph for two lines separation (S) on FR-4 substrate versus Z_m.

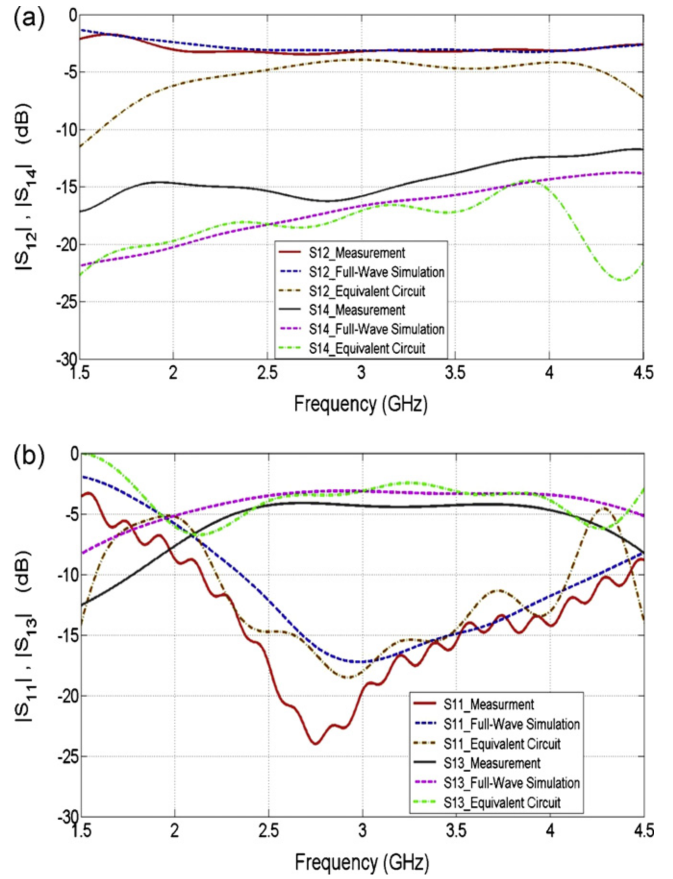

Fig. 8. Magnitude of the S-parameters for the proposed coupler obtained by full-wave simulation, equivalent circuit model and measurement results. (a) $|S_{12}|$,$|S_{14}|$, (b) $|S_{11}|$,$|S_{12}|$.

more accurate at frequencies near 3 GHz which is the design center frequency. So, in Fig. 8(b), the equivalent circuit model result is different from the full-wave and measurement results and this difference is more at frequencies far from the design frequency (3 GHz).

The elements of the equivalent circuit model (Fig. 4) are obtained using Eqs. (15) and (17) and for this example are equal to L_1 = 7.33 nH, C_1 = 0.7 pF, C_{int} = 1.82 pF, L_2 = 6.18 nH, C_2 = 0.86 pF. As it was mentioned, a good agreement among full-wave simulation and equivalent circuit model results is obtained and thus the usefulness of the presented equivalent circuit model is validated.

Using this figure, performance of the introduced 3 dB edge-coupled coupled-line coupler can be stated as the following: the power which is coupled to port 3 is approximately −3 dB; or in the other word, the insertion loss from port 1 to port 2 is 3 dB, the return loss is less than −14 dB and the isolation is better than −13 dB over the bandwidth of 66% from 2.2 GHz to 4.2 GHz. Moreover, Fig. 9 shows the phase difference between the ports 2 and 3 of the coupler. As it is seen, this difference is equal to $90 \pm 10^{\circ}$ for a frequency range from 2.2 GHz to 3.5 GHz.

Recently, coupled-line couplers using CRLH transmission lines with broad bandwidth and arbitrary coupling-levels (until 0 dB) have been developed [2,5–8,13]. In CRLH backward couplers, the coupling-level depends on the difference between the even and odd modes characteristic impedances and the length of the coupled lines [2]. The proposed coupler in this paper, besides having advantages compared to the conventional microstrip backward coupled-line couplers, it has also some advantages in comparison with CRLH backward couplers. In the conventional microstrip coupled-line couplers, the coupling-level is typically lower than

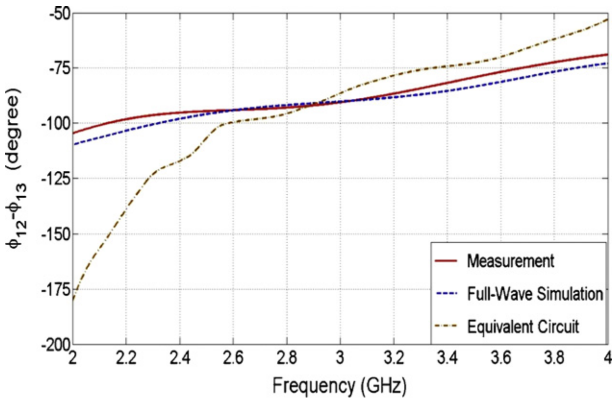

Fig. 9. Phase difference between the through and the coupled ports for the proposed coupler of Fig. 4.

10 dB and for higher coupling values, spacing between the two coupled lines must be very small and it is not usually possible, practically [1]. So for this reason recently, CRLH transmission lines are extremely used to realize the coupled-line couplers with high coupling levels. But in the most cases, to obtain a high coupling-level in a CRLH coupled-line coupler, a large length of the coupled-line is required. Also, because of using shorted stubs in these structures, the width of this type of couplers is large. For instance, lengths of CRLH couplers which have been presented in [5–7] are $0.45\lambda_g$, $0.5\lambda_g$ and λ_g, respectively. Whereas, the length of the proposed coupler in this paper is $0.25\lambda_g$ that is more compact than them. Moreover, the widths of the CRLH couplers proposed in [5,7] are $0.4\lambda_g$ and $0.2\lambda_g$, respectively. However, width of the proposed structure is $0.04\lambda_g$.

In addition to size improvement in the proposed asymmetrical coupler, its bandwidth is also enhanced. Bandwidths of the couplers presented in [6,7] are nearly 30% around the center frequency of 3 GHz. According to obtained results which have been illustrated in Fig. 8, proposed coupler shows broader bandwidth. Moreover, the introduced coupler in this paper in comparison with the previously proposed symmetrical coupler [11], which has been realized based on the interdigital transmission line, exhibits bandwidth enhancement over 10%. Also, because of using the conventional microstrip line as one of the coupled lines in this structure, its return loss and isolation are better.

5. Conclusion

A new type of backward coupled-line coupler composed of two different coupled lines, i.e., interdigital and conventional microstrip transmission lines, has been proposed, fabricated, and investigated theoretically and experimentally. In this structure, an interdigital capacitor with only one finger is used as interdigital transmission line. This interdigital transmission line is coupled with a conventional microstrip transmission line and achieves an asymmetrical backward coupled-line coupler. The proposed backward-wave coupler with 0.2 mm spacing between two coupled lines exhibits the amplitude balance of ± 2 dB from 2.2 to 4.2 GHz and the phase balance of $90^\circ \pm 10^\circ$ from 2.2 to 3.5 GHz. In order to analyze the introduced coupler simply, an equivalent circuit model has been presented and validated by full-wave simulation and measured results. The proposed asymmetrical backward coupler exhibits obtainable dimension, broader bandwidth and more compact size in comparison with the conventional and CRLH coupled-line backward couplers.

Acknowledgment

This work was supported in part by the Education and Research Institute for ICT of Iran (ERICT).

References

[1] Mongia R, Bahl I, Bhartia P. RF and Microwave Coupled-Line Circuits. Norwood, MA: Artech House; 1999.
[2] Caloz C, Itoh T. Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications. Hoboken, NJ: John Wiley; 2006.
[3] Kil J-B, Kim C-S, Choi KS, Park J-S, Ahn D. A design mapping formula of asymmetrical multi-element coupled line directional couplers. Int Microw Symp 2001;2:1293–6.
[4] Deng JDS, Hsiao F-k, Kuo JI, Horng KY, Lee C-Y, Wu C-S. Tightly coupling LTCC microwave coupled lines: analysis, modeling and realization. Int Symp Electron Mater Packaging 2002:391–6.
[5] Mao SG, Wu MS. A novel 3 dB directional coupler with broad bandwidth and compact size using composite right/left handed coplanar waveguides. IEEE Microw Wireless Compon Lett 2007;17(May):331–3.
[6] Islam R, Elek F, Eleftheriades GV. Coupled-line metamaterial coupler having co-directional phase but contra-directional power flow. Electron Lett 2004;40(March (5)):315–7.
[7] Caloz C, Itoh T. A novel mixed conventional microstrip and composite right/left handed backward-wave directional coupler with broadband and tight coupling characteristics. IEEE Microw Wireless Compon Lett 2004;14(January (1)):31–3.
[8] Simion S, Sajin G, Marcelli R, Bartolucci G, Craciunoiu F. Design and fabrication of MMIC coupled lines coupler consisting of composite right/left-handed transmission lines. In: International Conference on Computer as a Tool (EUROCON), September. 2007. p. 2037–77.
[9] Bahl I. Lumped Elements for RF and Microwave Circuits. Boston: Artech House; 2003.
[10] Pozar DM. Microwave Engineering. 3rd ed. John Wiley; 2003.
[11] Keshavarz R, Movahhedi M, Hakimi A, Abdipour A. A novel broad bandwidth and compact backward coupler with high coupling-level. J Electromag Wave Appl (JEMWA) 2011;25(2–3):283–93.
[12] Cristal EG. Coupled-transmission-line directional couplers with coupled lines of unequal characteristic impedances. IEEE Trans Microwave Theory Technol 1966;14(July):337–46.
[13] Caloz C, Sanada A, Itoh T. A novel composite right/left-handed coupled-line directional coupler with arbitrary coupling level and broad bandwidth. IEEE Trans Microwave Theory Technol 2004;52(March):980–92.