A High-Directivity Microstrip Directional Coupler With Feedback Compensation

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Abstract **— A new directivity-enhancement method for a microstrip directional coupler is presented. The method utilizes feedback elements between the collinear ports of the parallel-line coupler to generate an isolation zero at the desired frequency. The closed-form equations for designing such compensating elements are developed. Experiments are conducted to verify the proposed method. More than 30 dB directivity improvement is achieved, compared to the conventional microstrip parallel coupler.**

I. Introduction

Microstrip directional couplers with parallel coupled lines are widely used in baluns, filters, and various microwave integrated circuits. However, the microstrip directional couplers suffer from poor directivity due to the inhomogeneous dielectric material, which results in different phase velocity of the even mode and the odd mode. Various compensation techniques have been developed for equalizing phase velocities. These include the modification of the structure such as using a different dielectric permittivity overlay on the top of the coupled lines [1]-[4] or wiggling coupled edges of the coupled lines [5]-[7]. The compensation can also be effectively obtained by adding single or multiple lumped elements at the ends or the center of the coupled lines [8]-[12].

In this paper, we introduce a new compensation method by connecting lumped or distributed elements between the collinear ports of coupled lines. The enhancement of the directivity is resulted from the generation of isolation zero due to the feedback element. The frequency of the isolation zero is determined by the reactance of the compensation element. The closed-form equations for the design are derived by the normal mode theory. The circuit and EM simulation is performed to show the effects of adding these feedback elements. Finally, a -10 dB parallel-line coupler is designed and measured to verify our proposed method.

II. Analysis of the Newly Proposed Directional Coupler

The proposed feedback directional coupler consists of a pair of parallel-coupled microstrips with an inductive element or a microstrip line connected between the collinear ports, respectively, as shown in Fig. 1. Since the structure is symmetric, the normal mode theory can be employed to analyze the performance. The original four-port problem can be reduced to a two-port problem by exciting the even mode and odd mode voltage to two collinear ports. The even-mode and odd-mode problem are shown schematically in Fig. 2, where the coupled region of coupled line is characterized by two transmission lines, respectively, with the characteristic impedances Z_{0e} and Z_{0o} and the effective relative dielectric constants ε_{effe} and ε_{effo}. Since the phase velocities of the even and odd mode are different such that their corresponding electrical lengths, θ_e and θ_o, are unequal and have the following relation

$$\theta_o = \theta_e \sqrt{\frac{\varepsilon_{effo}}{\varepsilon_{effe}}}.$$

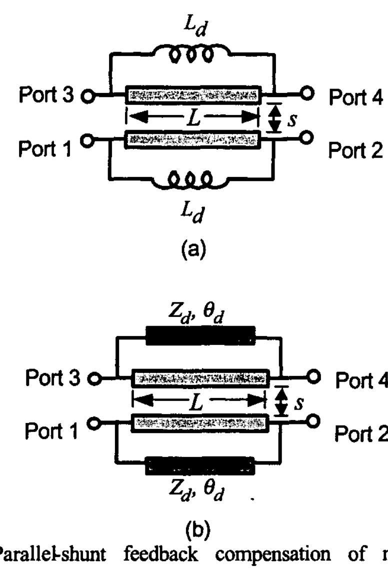

Fig. 1. Parallel-shunt feedback compensation of microstrip directional coupler by (a) inductor, (b) microstrip line.

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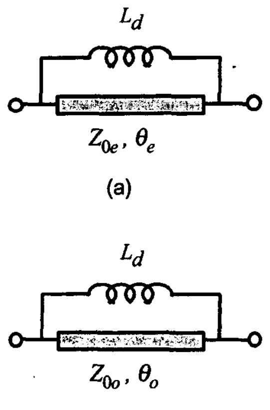


Fig. 2. Equivalent circuit of parallel-shunt inductor compensated directional coupler (a) even-mode, (b) odd-mode.

By adding the Y matrix of the inductor and the odd-mode line, the Y matrix of the compensated odd-mode circuit can be obtained as

$$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}_{odd} = \begin{bmatrix} \dfrac{\cos\theta_o}{jZ_{0o}\sin\theta_o} + \dfrac{1}{j\omega L_d} & \dfrac{-1}{jZ_{0o}\sin\theta_o} + \dfrac{-1}{j\omega L_d} \\ \dfrac{-1}{jZ_{0o}\sin\theta_o} + \dfrac{-1}{j\omega L_d} & \dfrac{\cos\theta_o}{jZ_{0o}\sin\theta_o} + \dfrac{1}{j\omega L_d} \end{bmatrix} \quad (1)$$

Similarly, the compensated even-mode circuit has the Y matrix as

$$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}_{even} = \begin{bmatrix} \dfrac{\cos\theta_e}{jZ_{0e}\sin\theta_e} + \dfrac{1}{j\omega L_d} & \dfrac{-1}{jZ_{0e}\sin\theta_e} + \dfrac{-1}{j\omega L_d} \\ \dfrac{-1}{jZ_{0e}\sin\theta_e} + \dfrac{-1}{j\omega L_d} & \dfrac{\cos\theta_e}{jZ_{0e}\sin\theta_e} + \dfrac{1}{j\omega L_d} \end{bmatrix} \quad (2)$$

Eq. (1) and (2) are converted into their corresponding odd-mode and even-mode S matrix with the following relationship

$$\begin{aligned} S_{11}^{e,o} &= \left.\frac{(Y_0 - Y_{11})(Y_0 + Y_{22}) + Y_{12}Y_{21}}{\Delta}\right|_{e,o} \\ S_{12}^{e,o} &= \left.\frac{-2Y_{12}Y_0}{\Delta}\right|_{e,o} \\ S_{21}^{e,o} &= \left.\frac{-2Y_{21}Y_0}{\Delta}\right|_{e,o} \\ S_{22}^{e,o} &= \left.\frac{(Y_0 + Y_{11})(Y_0 - Y_{22}) + Y_{12}Y_{21}}{\Delta}\right|_{e,o} \\ \Delta_{e,o} &= (Y_{11} + Y_0)(Y_{22} + Y_0) - Y_{12}Y_{21}\Big|_{e,o} \end{aligned} \quad (3)$$

Then the four-port S matrix of the compensated coupler is calculated with the following relationship

$$\begin{aligned} S_{11} &= \frac{1}{2}\left(S_{11}{}^{e} + S_{11}{}^{o}\right) \\ S_{21} &= \frac{1}{2}\left(S_{21}{}^{e} + S_{21}{}^{o}\right) \\ S_{31} &= \frac{1}{2}\left(S_{11}{}^{e} - S_{11}{}^{o}\right) \\ S_{41} &= \frac{1}{2}\left(S_{21}{}^{e} - S_{21}{}^{o}\right) \end{aligned} \quad (4)$$

The isolation S_{41} has a null value when the compensating inductance satisfies

$$L_d = \frac{Z_{0e}Z_{0o}\sin\theta_e\sin\theta_o}{\omega(\cos\theta_o - \cos\theta_e)}\left(\frac{1-\cos\theta_o}{Z_{0o}\sin\theta_o} - \frac{1-\cos\theta_e}{Z_{0e}\sin\theta_e}\right) \quad (5)$$

Eq. (5) offers a closed-form expression to design the compensating inductance for achieving high directivity at the desired frequency. Similarly, for the microstrip line feedback case, the isolation zero can be obtained if the length θ_d and the characteristic impedance Z_d of the feedback microstrip line satisfy the following equation

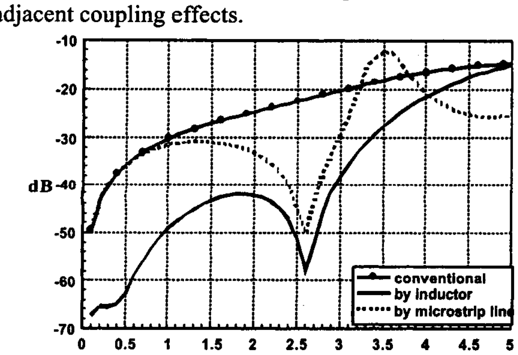
$$\frac{\cos\theta_e - \cos\theta_o}{Z_{0e}Z_{0o}\sin\theta_e\sin\theta_o} + \frac{\cos\theta_e - \cos\theta_d}{Z_{0e}Z_d\sin\theta_e\sin\theta_d} - \frac{\cos\theta_o - \cos\theta_d}{Z_{0o}Z_d\sin\theta_o\sin\theta_d} = 0 \quad (6)$$

Note that the directivity is defined as the ratio between coupling and isolation. The isolation zero implies a theoretically infinite directivity. By substituting the calculated element value from (5) or (6) into (4), the coupling is found slightly altered. Therefore, the line spacing must be adjusted to recover the original coupling value.

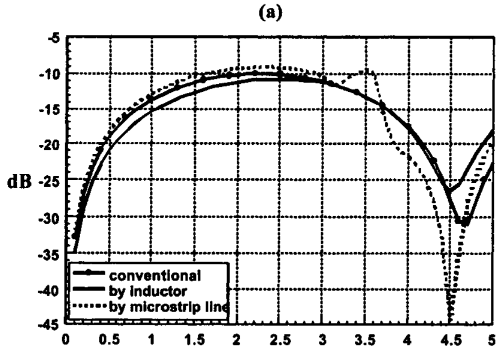
III. Simulated Frequency Characteristics

To demonstrate the properties of the conventional and proposed couplers, a -10 dB coupler at 2.6 GHz is designed. Fig. 3 shows simulation results by the circuit simulator. For the conventional case, the coupling length L = 18 *mm*, the line width W = 1.1 *mm* and the line spacing S = 0.16 *mm*. For the inductor feedback case, L = 18 *mm*, W = 0.66 *mm*, and S = 0.13 *mm*, and the inductance L_d = 16.5 *nH*. For the microstrip feedback case, L = 23.8 *mm*, W = 0.2 *mm*, S = 0.13 *mm*, and the feedback microstrip line size as L_f = 14.4 *mm* and W_f = 0.3 *mm*. Note that the line spacings of the feedback couplers are adjusted to meet the 10 dB coupling requirement. The isolation zero is clearly observed from Fig. 3(a), which agrees well with the theoretical prediction. The isolation of the conventional case deteriorates with the frequency, which is only -20 dB at 3 GHz. The inductor compensation case has at least -40 dB isolation upto 3 GHz, while the microstrip compensation case has -30 dB. The coupling is slightly affected, less than 1 dB variation, as indicated in Fig. 3(b). The input and output feeding points must be carefully chosen such that the parallel-shunt combination of the feedback element and original parallel-coupled line is well matched to the port impedance. Fig. 3(c) dictates at least 20 dB return loss up to 3 GHz. On the directivity, the improvement is at lease 25 dB from low frequency to 3 GHz for the inductor compensation case and 5-to-30 dB improvement for the microstrip compensation case.

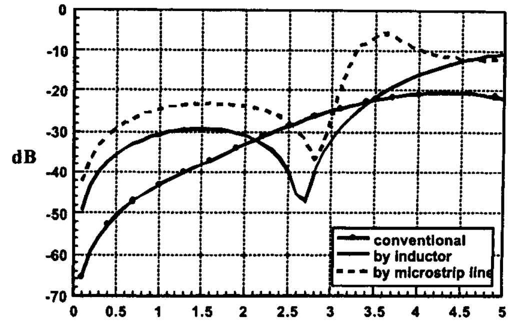
Although the inductor compensation shows a better improvement capability, it is difficult to implement such a lumped inductor with the microstrip parallel-line coupler. Thus, in the following section, we implement the parallel-line coupler with the microstrip compensation scheme for experiment, where the EM simulation will be employed to examine the microstrip discontinuities and adjacent coupling effects.



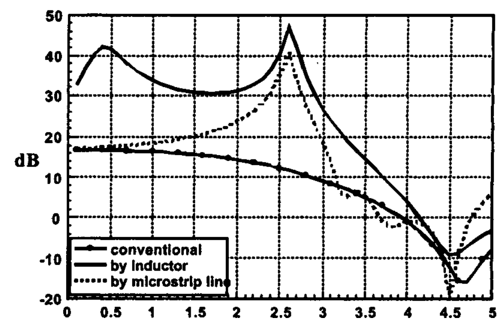
(a)



(b)



(c)



(d)

Fig. 3. Simulation characteristics of microstrip parallel-line coupler, (a) isolation, (b) coupling, (c) return loss, (d) directivity.

IV. Input/ Output Feeding Junction Effects and Experiment Results

The circuit layout and photograph are shown in Fig. 4, where $L = 23.8$ *mm*, $W = 0.2$ *mm*, $S = 0.13$ *mm*, $L_f = 14.4$ *mm*, $W_f = 0.3$ *mm*, and $S_f = 0.5$ *mm*. The circuit is fabricated on the FR4 substrate with a relative dielectric constant $\varepsilon_r = 4.52$ and a thickness $h = 0.735$ *mm*. Although the microstrip feedback case has four lines in the circuit but it occupies slightly larger size than the conventional parallel-coupled line.

To take into account the discontinuity effect of the input and output feeding junctions and the adjacent coupling of the four parallel microstrip lines, the EM simulator IE3D[13] is employed. Fig. 5 indicates that the isolation zero is quite sensitive to these discontinuities, which shift the isolation zero to a higher frequency at 2.7 GHz and reduce isolation to -30 dB level. The measured isolation-zero frequency is 3.25 GHz and the isolation level is 5 dB worse than the EM simulation. The reason is that the feedback microstrip, in conjunction with these discontinuities, must be accurately controlled on its phase response. The fabrication tolerance of the 0.1 *mm* spacing between 0.2 *mm*-width lines induces extra phase error. Except this discrepancy, the measured frequency response of the isolation and coupling agrees well with the EM simulation and circuit simulation.

V. CONCLUSION

A feedback compensation method is developed to enhance the directivity of a microstrip parallel-line coupler. The connection of an inductor or a microstrip line between the collinear ports introduces an isolation zero with little coupling variation. The general methodology of determining the isolation zero is provided, where the frequency location of the isolation zero can be determined from the reactance of the feedback inductor or the length and the characteristic impedance of the feedback microstrip line. The circuit simulation, EM simulation and the experiment all confirm the existence of the isolation zero. The improvement of the directivity is at least 30 dB.

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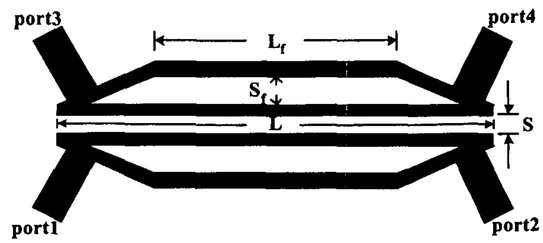
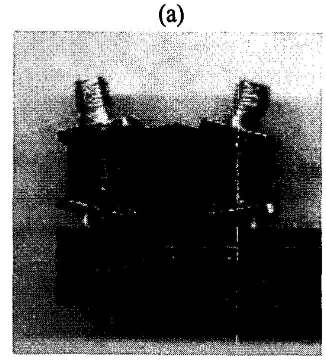


(a)



(b)

Fig. 4. Microstrip-feedback compensated parallel-line coupler, (a) layout, (b) photograph.

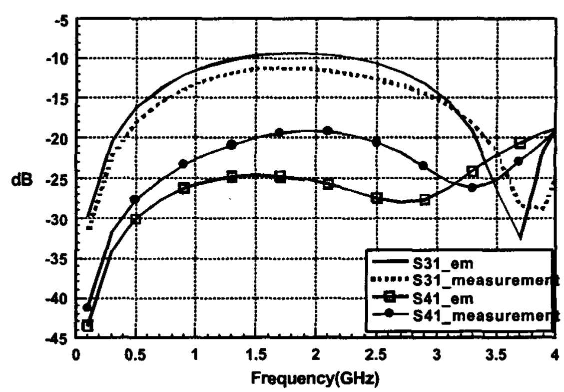


Fig. 5 EM simulation and measurement results of a microstrip-feedback parallel-line coupler