A Study of Meandered Microstrip Coupler with High Directivity

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Abstract **— A novel design technique to improve the directivity of a microstrip direction coupler by a meandered structure is proposed in this paper. Increasing of even-mode phase velocity by the proposed meandering method is reported for the first time. An analytical method to obtain closed-form equations of even-mode phase velocity is developed. The proposed structure is verified by experiments. More than 40 dB measured directivity improvement comparing to conventional microstrip coupler is achieved.**

I. Introduction

Directional couplers consisting of parallel-coupled microstrip transmission lines are frequently used in balun, filter and various microwave circuits because they are easily to implement in microwave and millimeter wave hybrid or monolithic integrated circuits. Unfortunately, the microstrip direction couplers suffer from poor directivity especially when the coupling is decreased or the substrate dielectric permittivity is increased [1]. Due to the inhomogeneous dielectric material that results the odd-mode phase velocity commonly faster than the even mode. Several techniques have been reported to equalize or compensate the unequal modal velocities of the coupled microstrip section. These methods modify the coupled-line structure such as overlaying a substrate with different dielectric permittivity on top of the coupled lines [2-4]; or wiggling coupled edges of coupled lines [5-6], or compensation by adding single or multiple lumped elements at the ends or the center of the coupled lines [7-9]. All of the techniques given above are focused on reduction of the effective odd-mode phase velocity.

In this paper, we introduce a novel structure that can increase the even-mode phase velocity effectively by meandering the parallel microstrip coupled lines as shown in Fig 1. By analyzing the even-mode phase velocity of the structure versus the meandering distance D in Fig. 1. The closed-form equations for estimating the even-mode phase velocity can be obtained by multiport network connection method [10]. The EM simulations and experiments are performed to show the validity of proposed novel structure. A 10 dB meandered microstrip direction coupler with ε_r =10.2 high permittivity substrate is designed and measured to verify the theory.

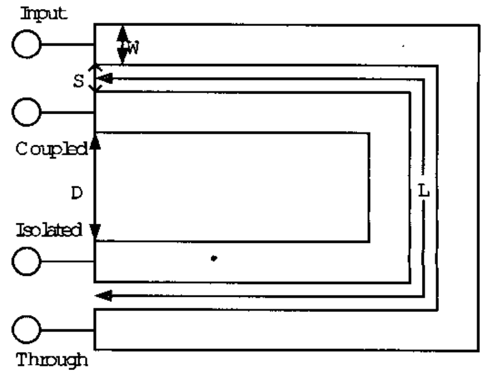

Fig. 1. The meandered parallel coupler structure

II. Principle And Circuit Analysis

Consider a meandered coupled lines as shown in Fig. 1. It can be simplified as a meandered single line when it is operated in even mode as shown in Fig. 2(a). The meandered single line shows dispersive phase responses that first observed by Schiffman [11]. The relation between transmission phase ϕ and coupled electrical length θ of the two-port network is determined by

$$\cos\phi = \frac{(Z_{0e}/Z_{0o}) - \tan^2\theta}{(Z_{0e}/Z_{0o}) + \tan^2\theta} \tag{1}$$

where Z_{0e} and Z_{0o} are the even- and odd-mode impedances, respectively. The equation (1) neglects the length of interconnecting line. From (1) the dispersive phase responses can be shown in Fig. 2(b). Figure 2(b) indicates clearly that as two lines close to each other, the transmission phase ϕ for θ<90° is reduced and equivalently the phase velocity is increased. According to the field distribution, as a parallel-coupled lines operates in the even mode, the electrical behavior can be approximated to a single microstrip line with line width equals to two coupled-line line widths plus the gap spacing (2W+S). Similarly, the even-mode phase velocity increasing effect occurs after meandering the parallel-coupled lines.

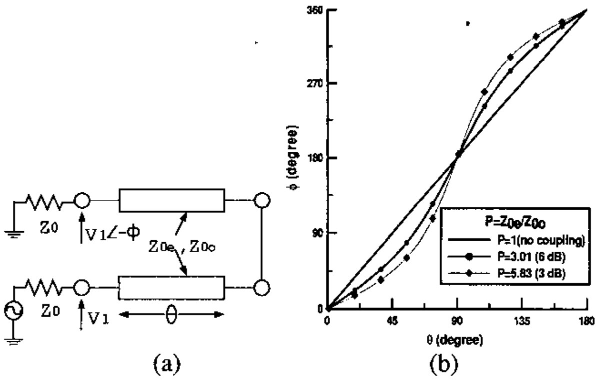

Fig. 2. (a) The Schiffman section and (b) dispersive phase responses

In the original Schiffman's work the length of interconnecting line is neglected. The omission of this interconnecting line has little influence on phase shifter performance. Here, however, the omission of this interconnecting line is very sensitive to the location of isolation dip. Therefore we must analysis the structure including the interconnecting line. In order to analytically estimate the even-mode phase velocity of meandered parallel coupler, the meandered parallel coupler is equivalent to a meandered single microstrip line as shown in Fig. 3(a). Then separates the circuit into a parallel-coupled lines and an interconnecting microstrip line as shown in Fig. 3(b), where θ_A and Z_{0e_eff} and Z_{0o_eff} are the coupled electrical length and the effective even- and odd-mode impedances of the parallel-coupled lines, respectively, and θ_B is the electrical length of the interconnecting microstrip line. The closed-form equations of total transmission phase θ_e can be obtained by connecting the individual S matrix of two circuits by multiport network connection method [10]. Then the even- mode phase velocity can be obtained as

$$V_p^e = \frac{\omega}{\theta_e} L \tag{2}$$

where L is the total coupling length. Figure 4 indicates that the even-mode phase velocity rises as the meandering distance D reduced, and the analytical values closed to the results of the EM simulation. Consequently, we can quickly evaluate the even-mode phase velocity without EM simulation with acceptable accuracy. According to EM simulation, the odd-mode effective dielectric constant $\varepsilon^o{}_{reff}$ is also raised slightly. The reason is similar to even-mode case due to variation of field distributions. EM simulation can estimate the odd-mode phase velocity V_p^o. Finally, we can find the optimum distance that makes equal V_p^e and V_p^o.

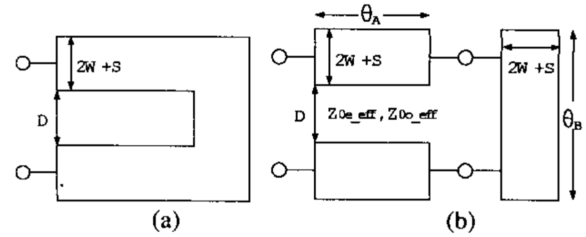

Fig. 3. (a) The meandered microstrip line and (b) the equivalent circuit

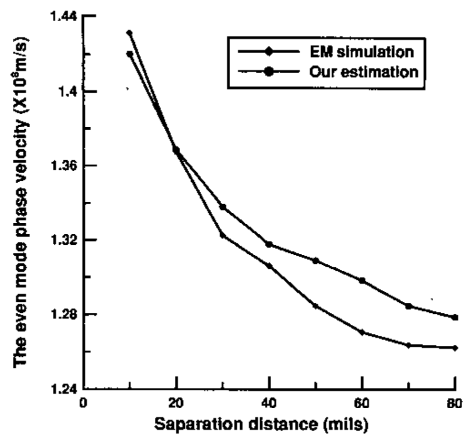

Fig. 4. The even mode phase velocity comparison between EM simulation and our estimation

III. Simulations And Measurements

To demonstrate the validity of the proposed method, a 10 dB coupler at 2.4 GHz is designed by the previous analysis. In the beginning, the coupling length L=540 mil, the line width W=38 mil, the line spacing S=16 mil, and the distance D=30 mil are obtained simply by considering the balance of modal phase velocity only. Unfortunately, as the meandering distance reduced, Z_{0e} and Z_{0o} also decrease greatly and slightly, respectively. This phenomenon causes the reduction of the system impedance which equals to square root of Z_{0e} and Z_{0o}. The Z_{0e} and Z_{0o} are given by

$$Z_{0_e} = \frac{1}{cC_{0_e}\sqrt{\varepsilon^e{}_{reff}}} \tag{3}$$

$$Z_{0_o} = \frac{1}{cC_{0_o}\sqrt{\varepsilon^o{}_{reff}}} \tag{4}$$

where c, C_{0_e} and C_{0_o} denote, respectively, the velocity of light in free space, the even and odd mode capacitance of either line obtained by replacing the relative permittivity of the surrounding dielectric material by unity. Although both ε^{e}_{reff} and ε^{o}_{reff} are reduced in the proposed structure, C_{0_e} and C_{0_o} are raised a lot. Therefore, Z_{0e} and Z_{0o} are reduced. The problems can be solved by reducing the line width and the line spacing, and which influences the modal phase velocity slightly.

Here, we use an EM simulator Sonnet [12] to do the fine tuning to get the final meandering distance D, line width W, line spacing S, and total line length L. The optimum values of L=540mil, W=27 mil, S=12 mil, D=30mil is obtained. Figure 5 shows the simulated isolation of conventional and proposed coupler. An excellent improvement can be observed. The coupling is slightly affected, less than 1 dB variation, as shows in Fig.6. Figure 7 indicates that the return loss is better than 20 dB up to 3.3 GHz.

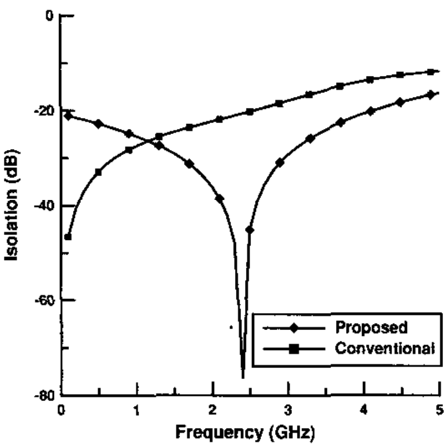

Fig. 5. The simulated isolation of conventional and proposed coupler

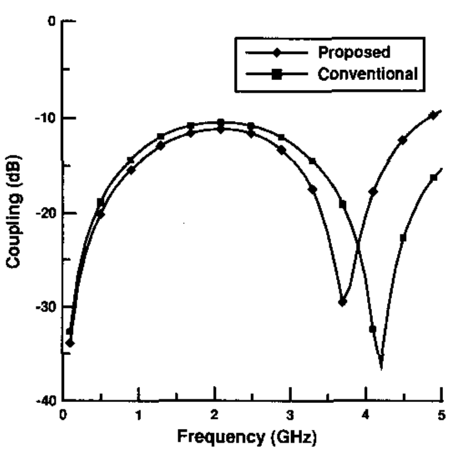

Fig. 6. The simulated coupling response of conventional and propose

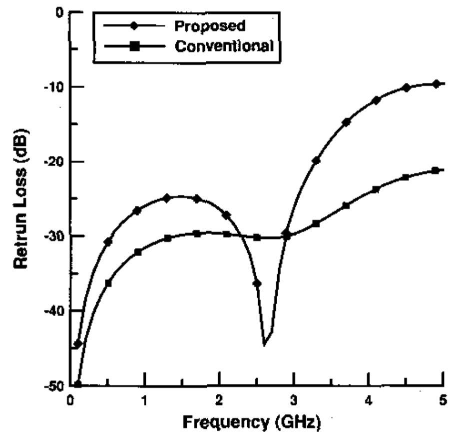

Fig. 7. The simulated return loss of conventional and proposed coupler

The circuit layout and photograph are shown in Fig. 8 and Fig. 9, respectively. The circuit is fabricated on a Rogers RT/6010 substrate. The substrate has a relative dielectric constant of 10.2, a thickness of 50 mils, and a copper cladding of half an ounce. The measured responses of return loss are better than 20 dB which match well with the simulation as shown in Fig. 10. The coupling is 12.3 dB which has less than 2 dB variation as shown in Fig. 11. The measured isolation and directivity are also shown in Fig. 11. The isolation can achieve 67 dB at center frequency, and the directivity has a more than 40 dB improvement to compare with the conventional coupler. This directivity improvement is significant and matches excellently with the simulation.

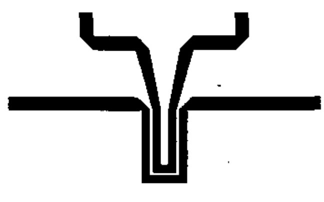

Fig. 8. The layout of proposed coupler

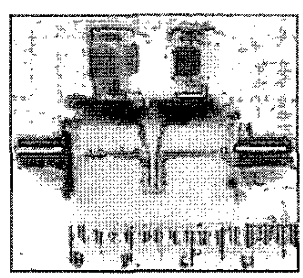

Fig. 9. The photograph of proposed coupler

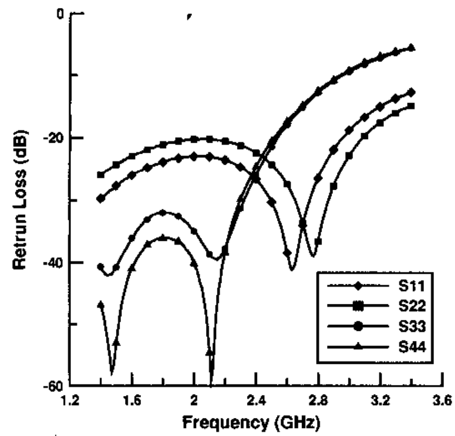

Fig. 10. The measured results of return loss

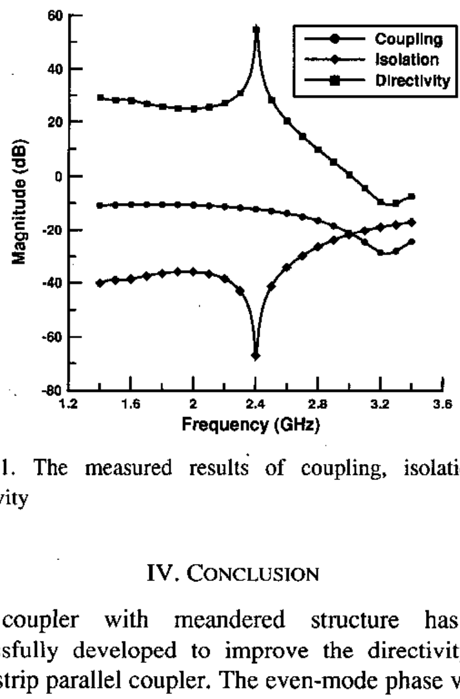

Fig. 11. The measured results of coupling, isolation and directivity

IV. Conclusion

A coupler with meandered structure has been successfully developed to improve the directivity of a microstrip parallel coupler. The even-mode phase velocity is speeded up and matches to the odd-mode phase velocity by the proposed meandering structure. Equal modal phase velocities have generated an isolation zero. An analytical method has been developed to obtain even-mode phase velocity by closed-form equations with good accuracy. The design procedures are based on the closed-from equations for obtaining the even-mode phase velocity. Then, an EM simulator is used for getting the odd-mode phase velocity. The design procedures are simple. The overall coupler size is reduced due to meandering. An excellent improvement of directivity is observed in EM simulation, and at least 40 dB directivity improvement is obtained in experiments. The experimental results verify the validity of the proposed structure.

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