Design of Compact Symmetric Four-Port Crossover Junction

Yi-Chyun Chiou, *Member, IEEE*, Jen-Tsai Kuo, *Senior Member, IEEE*, and Hsuan-Rong Lee

***Abstract*—Performance of a fully planar four-port crossover coupler is investigated. This bisymmetric circuit consists of a ring and two inner orthogonal sections connecting the diagonal ports. Based on the transmission line theory, analysis equations are formulated and design curves are presented. Two crossover junctions are fabricated and measured for validity confirmation. The measured data have good agreement with simulation.**

***Index Terms*—Crossover, directional coupler, four-port network, transmission line theory.**

I. INTRODUCTION

MICROSTRIP crossing is one of the fundamental discontinuities in microwave and millimeter-wave integrated circuits [1]–[3]. When two transmission lines cross over each other, an intuitive way to isolate the signals on them is to employ three-dimensional structures, e.g., bond wires or air bridges [2], [3]. These elements will definitely increase the fabrication cost. It is noted that a series of multiport coupler circuits in a fully planar configuration have been developed for the crossover applications [4]–[9]. An ideal four-port crossover provides 0 dB insertion loss to diagonal ports and perfect isolation to adjacent ports. In [4], microstrip and stripline crossovers are designed based on a cascade of two branch-line hybrids. In [5], octave-wide matched symmetrical and reciprocal four- and five-port networks are investigated. In [6], a circular disk is proposed for a symmetrical and reciprocal four-port crossover junction. In [7], a novel planar configuration of 0 dB directional coupler is presented as a single-layer crossover in microwave integrated circuits. The "window"-shape circuits in [8] are composed of several branch-line couplers connected in two dimensions. Such circuits may have an improved bandwidth if the characteristic impedances of the constitution branches can be properly designed. Recently, in [9], a double-ring structure is proposed for design of microstrip four-port crossover coupler. The eigenmode model is developed to investigate the circuit performance. The measured data show that the isolation and return losses of the prototype coupler exceed 20 dB over a bandwidth of 20%.

In this letter, the symmetric four-port crossover junction in [5] is analyzed and its performance is investigated. It deserves further investigation since only several discrete sets of solutions, but neither simulation nor measured results, are shown in [5] and its circuit structure, and hence its analysis, is much simpler than the double-ring configuration in [9]. Design graphs are generated based on formulation by the transmission line theory, and simulated circuit bandwidths of the solutions are discussed. Two circuits are fabricated and measured for confirmation.

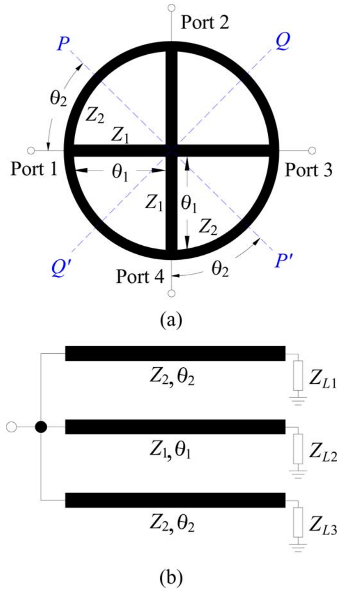

Fig. 1. Crossover coupler under analysis. (a) Circuit layout. (b) Reduced transmission line circuit in formulation.

II. ANALYSIS

Fig. 1(a) shows the layout of the crossover coupler under analysis, where *PP'* and *QQ'* are planes of symmetry. Let the characteristic impedance and the electric length of each section (from center to port) be Z_1 and θ_1, respectively, and the counterparts of the entire ring peripheral be Z_2 and 8 θ_2. Since the structure possesses bisymmetry, *PP'* and *QQ'* can be assigned as either electric or magnetic wall for ease of analysis. When this is done, the reduced network becomes a one-port network shown as in Fig. 1(b). The load impedances $Z_{Li} (i = 1, 2, 3)$ are either zero or infinite depending on electric or magnetic wall is applied. Four reflection coefficients can be derived and all S-parameters of the junction can be obtained [10]. When input is excited at port 1, for instance, $S_{11} = S_{21} = S_{41} = 0$ and $|S_{31}| = 1$ at the design frequency are required. It leads to $\Gamma_{mm} = \Gamma_{ee} = -\Gamma_{em} = -\Gamma_{me}$ and $|\Gamma_{mm}| = |\Gamma_{ee}| = |\Gamma_{em}| = |\Gamma_{me}| = 1$, where the subscripts e and m stand for that *PP'* and *QQ'* planes are placed with electric and magnetic

---

Manuscript received March 05, 2009; revised May 20, 2009. First published August 11, 2009; current version published September 02, 2009. This work was supported in part by the MoE ATU program and by the National Science Council, Taiwan, under Grants NSC 97-2221-E-009-039 and NSC 98-2218-E-009-011.

The authors are with the Department of Communication Engineering, National Chiao Tung University, Hsinchu 300, Taiwan. (e-mail: jtkuo@mail.nctu.edu.tw).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2009.2027054

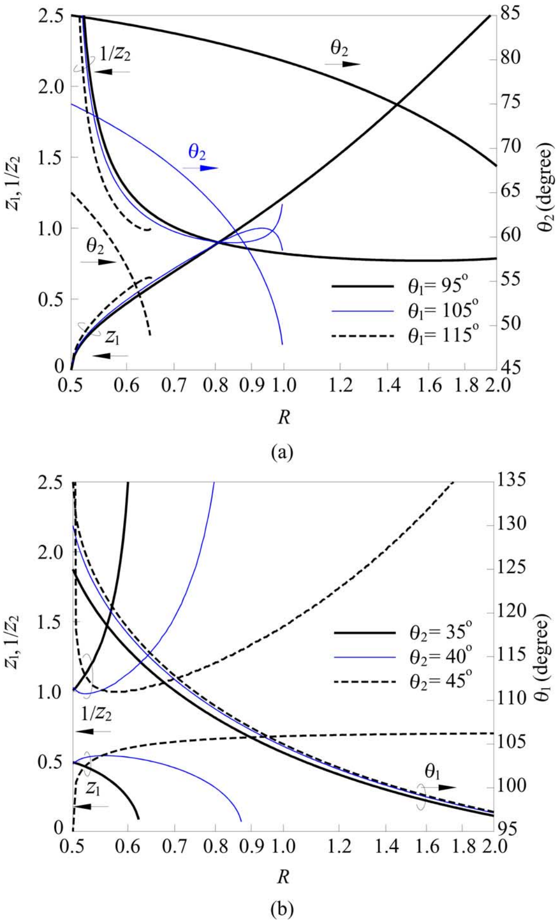

Fig. 2. $z_1, 1/z_2$ and θ_k as functions of R. (a) $k = 2$. (b) $k = 1$.

TABLE I

CIRCUIT BANDWIDTHS (%) OF SAMPLED SOLUTIONS IN FIG. 2(A)

R	θ_1	$\lvert S_{11}\rvert < -20$ dB	$\lvert S_{21}\rvert < -20$ dB	$\lvert S_{31}\rvert > -0.5$ dB
0.6	95°	0.45	0.40	0.10
	105°	0.48	0.57	1.09
	115°	1.95	2.92	5.35
0.8	95°	0.13	0.13	0.29
	105°	2.62	2.50	2.13
1.8	95°	0.47	0.47	0.97

TABLE II

CIRCUIT BANDWIDTHS (%) OF SAMPLED SOLUTIONS IN FIG. 2(B)

R	θ_2	$\lvert S_{11}\rvert < -20$ dB	$\lvert S_{21}\rvert < -20$ dB	$\lvert S_{31}\rvert > -0.5$ dB
0.6	35°	1.29	65.53	4.57
	40°	10.98	18.17	15.66
	45°	10.85	9.95	16.98
0.85	40°	0.84	77.38	2.97
	45°	9.08	9.88	12.86
1.8	45°	2.90	15.74	7.80

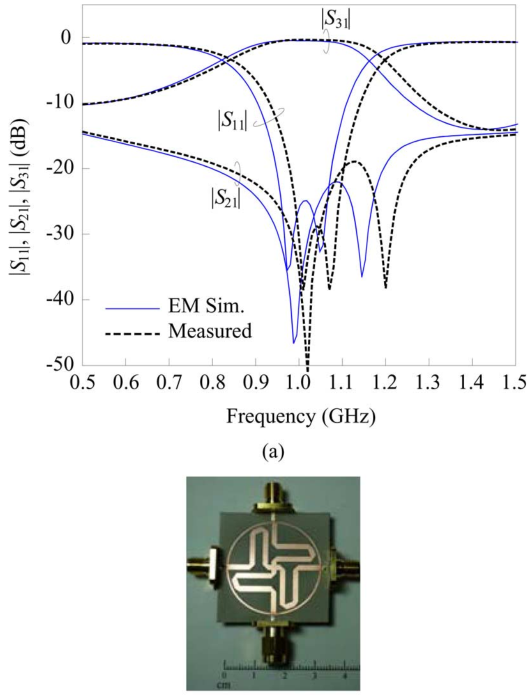

Fig. 3. (a) Magnitudes of the S-parameters. (b) Photograph of the measured crossover. $Z_1 = 26.23\ \Omega$, $Z_2 = 50.8\ \Omega (R = 0.52), \theta_1 = 125°, \theta_2 = 38°$.

walls, respectively. Consequently, the following two equations can be derived:

$$s_2 c_2 + 2R s_1 c_1 = 0 \tag{1}$$

$$c_2^2 \left[c_1^2 \left(3 - t_2^2\right) - c_2^2 \left(1 - t_2^2\right)\right] = 2c_1^2 \left(z_1^2 s_1^2 + c_1^2\right) \tag{2}$$

where $R = Z_1/Z_2, z_k = Z_k/Z_o$ ($k = 1$ and 2), Z_o is reference impedance, $t_k = \tan\theta_k, s_k = \sin\theta_k$, and $c_k = \cos\theta_k$. These two equations are used to solve the four circuit parameters z_1, z_2, θ_1 and θ_2. Here, θ_k denotes electric length of the corresponding section at the design frequency.

Fig. 2(a) plots $z_1, 1/z_2$ and θ_2 as functions of R (in log scale) given that $\theta_1 = 95°, 105°$ and $115°$. When $\theta_1 = 105°$ and $115°$, and when R is larger than 1 and 0.655, respectively, θ_2 has no real solutions. When $\theta_1 = 95°, z_1$ and $1/z_2$ solutions cover $0.5 \leq R \leq 2.0$. Fig. 2(b) plots z_1, z_2 and θ_1 as functions of R for $\theta_2 = 35°, 40°$ and $45°$.

III. SIMULATION AND MEASUREMENT

The solutions in Fig. 2 possess different circuit performances. Tables I and II compare the simulation bandwidths of some solutions sampled at $R = 0.6, 0.8(0.85)$ and 1.8 in Figs. 2(a) and (b), respectively. The bandwidths are measured using $|S_{11}| < -20$ dB, $|S_{21}| < -20$ dB, and $|S_{31}| > -0.5$ dB. It is found that many results in Table I have a bandwidth less than 1%. To have the three bandwidths of about 10% or more, Table II suggests θ_2 be close to $40° \sim 45°$ and R close to $0.5 \sim 0.6$. However, both z_1 and z_2 may be far beyond the fabrication limit of the standard PCB process when $R < 0.55$. Based on the simulation results (not shown), the maximum bandwidth of the proposed structure is approximately 20%. If wider bandwidths are required, optimization could be inevitable.

Two circuits designed at $f_o = 1$ GHz are fabricated and measured for demonstration. The circuit substrate has a relative dielectric constant $\varepsilon_r = 10.2$ and thickness = 0.635 mm. Fig. 3(a) plots the simulated and measured results of the first circuit. The circuit dimensions are listed in the caption. Note that

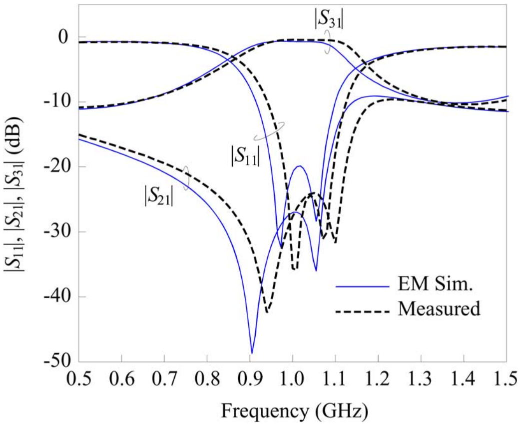

Fig. 4. Performance of the second coupler. $Z_1 = 25.06\ \Omega, Z_2 = 55.2\ \Omega (R = 0.45), \theta_1 = 132^\circ, \theta_2 = 32.5^\circ$.

θ_1 is larger than the radius of the ring, i.e., 8 $\theta_2/2\pi$, the inner sections then have to be folded to accommodate the area inside the ring. Circuit simulation is done by the software package IE3D [11]. At the design frequency, the measured data show that $|S_{11}|, |S_{21}| = |S_{41}|$ and $|S_{31}|$ are -31.6 dB, -50.5 dB and -0.385 dB, respectively, and that the total power loss $(P_L = 1 - |S_{11}|^2 - 2|S_{21}|^2 - |S_{31}|^2)$ is 8.48%. The 20 dB bandwidths of $|S_{11}|$ and $|S_{21}|$ are 12.3% and 25.6%, respectively, and the 0.5 dB bandwidth of $|S_{31}|$ is 13%. One can see that the measured results agree well with the simulation data. It is worth mentioning that this circuit occupies about 25% of the area of the double-ring structure in [9]. Fig. 3(b) shows the photograph of the measured coupler.

Fig. 4 plots the simulated and measured results of the second crossover junction. The measured return loss and isolation at f_o are 26.4 dB and 24.9 dB, respectively, and coupling between ports 1 and 3 is 0.455 dB. In comparison with the previous coupler, the 20 dB isolation bandwidth is larger, while the return loss and insertion loss are more or less the same. The circuit area is 73% of that of the previous one.

IV. CONCLUSION

Performance of a symmetric four-port crossover coupler is investigated. Compared to the circuit reported recently in [9], it has a much simpler configuration and analysis equations. The design graphs show that the designated crossover function can be achieved with versatile circuit dimensions and performances. Two circuits with different areas are fabricated and measured for verification. Both circuits show good insertion loss between diagonal ports and excellent isolation between adjacent ports.

REFERENCES

[1] S.-C. Wu, H.-Y. Yang, N. Alexopoulos, and I. Wolff, “A rigorous dispersive characterization and microstrip cross and T junctions,” *IEEE Trans. Microw. Theory Tech.*, vol. 38, no. 12, pp. 1837–1844, Dec. 1990.

[2] G. E. Ponchak and E. Tentzeris, “Development of finite ground coplanar (FGC) waveguide 90 degree crossover junctions with low coupling,” in *IEEE MTT-S Int. Dig.*, Jun. 2000, pp. 1891–1894.

[3] T.-S. Hong, “A rigorous study of microstrip crossovers and their possible improvements,” *IEEE Trans. Microw. Theory Tech.*, vol. 42, no. 9, pp. 1802–1806, Sep. 1994.

[4] J. S. Wight, W. J. Chudobiak, and V. Makios, “A microstrip and stripline crossover structure,” *IEEE Trans. Microw. Theory Tech.*, vol. MTT-24, no. 5, p. 270, May 1976.

[5] F. C. de Ronde, “Octave-wide matched symmetrical, reciprocal, 4- and 5 ports,” in *IEEE MTT-S Int. Dig.*, Jun. 1982, pp. 521–523.

[6] K. C. Gupta and M. D. Abouzahra, “Analysis and design of four-port and five-port microstrip disk circuits,” *IEEE Trans. Microw. Theory Tech.*, vol. MTT-33, no. 12, pp. 1422–1428, Dec. 1985.

[7] D. V. Kholodniok and I. Vendik, “A novel type of 0-dB directional coupler for microwave integrated circuits,” in *Proc. 29th Eur. Microw. Conf.*, Nov. 1999, pp. 341–344.

[8] D. V. Kholodniok, G. Kalinin, E. Vernoslova, and I. Vendik, “Wideband 0-dB branch-line directional couplers,” in *IEEE MTT-S Int. Dig.*, Jun. 2000, pp. 1307–1310.

[9] Y. Chen and S.-P. Yeo, “A symmetrical four-port microstrip coupler for crossover application,” *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 11, pp. 2434–2438, Nov. 2007.

[10] R. E. Collin, *Foundations for Microwave Engineering*, 2nd ed. Singapore: McGraw-Hill, 1992.

[11] *IE3D Simulator*. Fremont, CA: Zeland Software, Inc., Jan. 1997.