Design of a Wide-Band Lumped-Element 3-dB Quadrature Coupler

Yi-Chyun Chiang, *Member, IEEE,* and Chong-Yi Chen

***Abstract*—Analysis and design techniques for designing a lumped-element 3-dB quadrature coupler with wide-band flat coupling are proposed for microwave integrated-circuit/monolithic-microwave integrated-circuit applications. The proposed design technique can produce a coupler with flat coupling over 50% fractional bandwidth, which is wider than the conventional lumped-element design methods. A prototype consisting of a capacitive coupled high-pass network is designed and fabricated to verify the design concept. Measurement and simulation results closely correspond to each other.**

***Index Terms*—Directional coupler, lumped-element circuit.**

I. Introduction

IN THE various microwave circuits, such as balanced amplifiers, image-rejection mixers, and phase shifters, quadrature couplers are used to achieve the desired circuit performance. At frequencies below 10 GHz, the conventional distributed couplers such as branch line or Lange coupler consume too much valuable microwave integrated circuit (MIC) or monolithic microwave integrated circuit (MMIC) area [1], [2]. Therefore, lumped-element design methods are used to realize the coupler circuit within a reasonable chip area in various MIC or MMIC applications [3]–[5]. In the conventional quadrature design methods, the capacitor connected one-section high-pass networks based on the branch-line design technique was proposed by Gupta and Getsinger [6]. The dual form of a two-section quadrature coupler constructed by low-pass networks was designed and analyzed by Vogel [7]. Although the lumped-element quadrature couplers designed by the previous methods achieve a good isolation and voltage standing-wave ratio (VSWR), the amplitude balance between output ports can be maintained only within a narrow fractional bandwidth. To achieve a flat coupling over a wider bandwidth, a hybrid of the lumped- and distributed-element method and a broad-band matching design technique is proposed by Vogel and Ohta, respectively [7], [8]. This paper will propose a design method that achieves a wide-band flat coupling by using pure lumped elements. The proposed design method directly analyses the three-branch lumped-element quadrature coupler and then generates the design equations to achieve a wider band characteristic. The commercial microwave-circuit simulator is used to analyze the frequency properties of the designed couplers. The simulation results show one of the designed couplers can achieve a flat coupling of 50% of the fractional bandwidth. To verify the design concept, a 2.4-GHz prototype circuit fabricated on FR4 printed circuit board (PCB) is designed and fabricated. The simulation result shows the operation bandwidth of the prototype is reduced to only 30%, when the parasitic effects in the lumped elements are taken into consideration, which matches the measurement result well.

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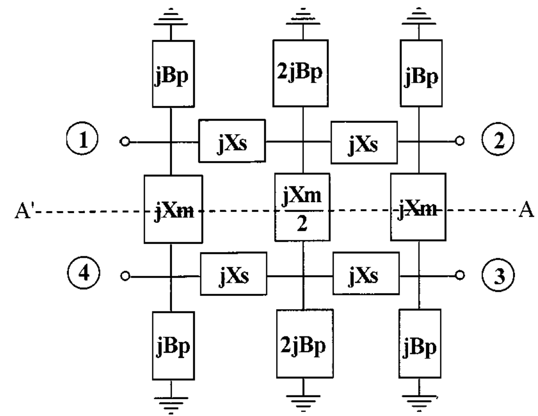


Fig. 1. Circuit presentation of a lumped quadrature coupler.

II. Analysis

Fig. 1 illustrates the circuit presentation of a quadrature coupler constructed by two pure lumped-element network sections. The circuit is symmetrical with regard to the AA'-plane and can be analyzed by the conventional even- and odd-mode method [1]. Following Vogel's analysis method [7], the transmission-wave matrix of the even- and odd-mode half-circuits are first derived and given by

$$[T_{e,o}] = \begin{bmatrix} T11_{e,o} & T12_{e,o} \\ T21_{e,o} & T22_{e,o} \end{bmatrix}$$

where the elements of the transmission matrix are given by

$$T_{11e,o} = 1 - 2X_sB_{e,o}(2 - X_sB_{e,o}) + j(1 - X_sB_{e,o}) \cdot \left[X_sY_0 + B_{e,o}Z_0(2 - X_sB_{e,o})\right] \quad (1a)$$

$$T_{12e,o} = -j(1 - X_sB_{e,o})\left[X_sY_0 - B_{e,o}Z_0(2 - X_sB_{e,o})\right] \quad (1b)$$

$$T_{21e,o} = -T_{12e,o} \quad (1c)$$

$$T_{22e,o} = 1 - 2X_sB_{e,o}(2 - X_sB_{e,o}) - j(1 - X_sB_{e,o}) \cdot \left[X_sY_0 + B_{e,o}Z_0(2 - X_sB_{e,o})\right] \quad (1d)$$

where $B_{e,o}$ represent the admittance introduced by parallel coupling elements excited by the even ("e") and odd ("o") modes, and B_e is equivalent to B_p and B_o is equivalent to $(B_p - 2/X_m)$, respectively. To construct a co-directional ($S_{41} = 0$) quadrature coupler, the following conditions must be satisfied:

$$T_{12e} = T_{12o} = 0 \tag{2}$$
$$|T_{11e}|^2 = |T_{11o}|^2 = 1. \tag{3}$$

Considering the phase relation of T_{11e} and T_{11o}, (3) can be rewritten as the following equations for even and odd mode T_{11}, respectively:

$$T_{11e} = \cos\theta + j\sin\theta \tag{4}$$
$$T_{11o} = \cos(\theta \pm \pi/2) + j\sin(\theta \pm \pi/2). \tag{5}$$

Substituting (2) into (1b) yields the following two conditions to let (1b) satisfy (2):

$$X_s Y_0 = B_{e,o} Z_0 (2 - X_s B_{e,o}) \tag{6}$$
$$X_s B_{e,o} = 1. \tag{7}$$

Bringing (4) and (5) into (1a), respectively, the corresponding $T_{11e,o}$ are simplified to

$$T_{11e,o} = 1 - 2(X_s Y_0)^2 + j2X_s Y_0 (1 - X_s B_{e,o}) \tag{8}$$
$$T_{11e,o} = -1. \tag{9}$$

Obviously (7) satisfies condition (3), however, one can easily prove (6) also satisfies (3) if condition (6) holds. Equating (4) and (8) reveals that only $\theta = \pm\pi/4$ can be used to obtain the desired solutions, and T_{11o} is the complex conjugate of T_{11e}. Following the previous design method, one can design the quadrature couplers the same as that proposed in [7]. Here, we will propose another design approaches. The proposed designed technique is first to use (9) to realize T_{11e} and, thus, we have $\theta = \pi$ and $B_e = 1/X_s$ from (4) and (7). Next, the previous condition $\theta = \pi$ is brought into (5) to yield $T_{11o} = \pm j$, which has to be realized by using (8). Since B_e must be greater than B_o, a reasonable solution can only come from $T_{11o} = +j$. Substituting $T_{11o} = +j$ into (8), produces $2(X_s Y_0)^2 = 1$ and $2X_s Y_0\ (1 - X_s B_o) = 1$. Finally, the values of the lumped elements are determined by $X_s = Z_0/\sqrt{2}$, $B_e = 1/X_s$, and $B_o = (1 - 1/\sqrt{2})/X_s$.

Interchanging the values of T_{11e} and T_{11o} and following the similar design procedure produces another set of equations for determining lumped-element values, which are $X_s = Z_0/\sqrt{2}$, $B_e = (1 + 1/\sqrt{2})/X_s$, and $B_o = 1/X_s$, respectively. The proposed design technique is applied to realize a quadrature coupler constructed by capacitive coupled three-branch high-pass networks, as shown in Fig. 2. According to the proposed design equations, two sets of element values corresponding to Fig. 2 are obtained by $C_s = \sqrt{2}Y_0/\omega_c$, $L_p = Z_0/\sqrt{2}\,\omega_c$, and $C_m = Y_0/2\omega_c$, and $C_s = \sqrt{2}\,Y_0/\omega_c$, $L_p = Z_0/(\sqrt{2}+1)\omega_c$, and $C_m = Y_0/2\omega_c$, respectively. A conventional microwave circuit simulator (e.g., SuperCompact) was used to evaluate the frequency characteristics of the designed couplers. Fig. 3(a) and (b) shows the frequency properties of couplers constructed by the proposed approaches. They reveal that both designs display wide-band flat coupling characteristics. In particular, the circuit of Fig. 3(b) has a very flat coupling over about a 50% fractional bandwidth, which is wider than that of the circuit of Fig. 3(a)

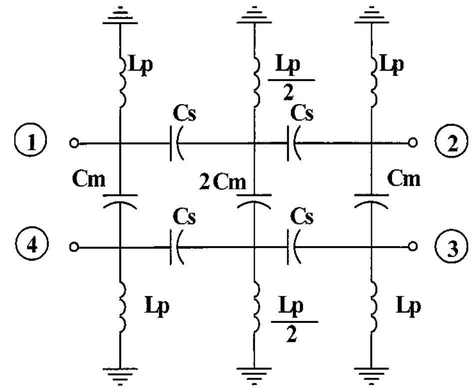
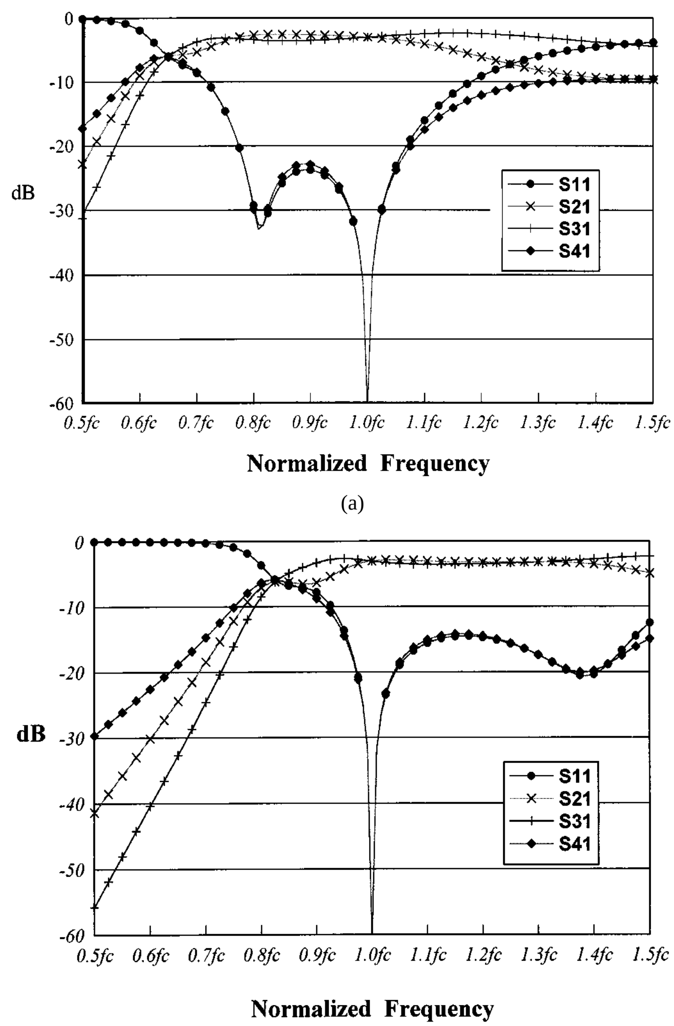


Fig. 2. 3-dB quadrature coupler consisting of capacitive coupled three-branch high-pass networks.



(b)

Fig. 3. (a) Frequency properties of a lumped quadrature coupler consisting of $C_s = \sqrt{2}Y_0/\omega_c$, $L_p = Z_0/\sqrt{2}\omega_c$, and $C_m = Y_0/2\omega_c$. (b) Frequency properties of a lumped quadrature coupler consisting of $C_s = \sqrt{2}Y_0/\omega_c$, $L_p = Z_0/(\sqrt{2}+1)\omega_c$, and $C_m = Y_0/2\omega_c$.

and more suitable for wide-band applications. The proposed design method is also applicable to realize the low-pass dual form of Fig. 2. The low-pass type coupler is constructed by replacing C_s, L_p, $L_p/2$, C_m, and $2C_m$ of Fig. 2 with L_s, C_p, $2C_p$, L_m, and $L_m/2$, respectively. The values of L_s, C_p, and L_m are given by ω_c^2/C_s, ω_c^2/L_p, and ω_c^2/C_m, respectively. The circuit simulator also evaluates the quadrature coupler realized by low-pass configurations. The simulation results show that the characteristics of low-pass-type couplers are the same as those for the high-pass-type coupler shown in Fig. 3.

III. Design and Measurement

A quadrature coupler prototype operated at 2.4 GHz is designed and fabricated to verify the design concept. According to Fig. 3(b), the optimum operation band of the coupler is between $0.95\omega_c$ and $1.45\omega_c$. To achieve the widest bandwidth at the operation frequency ($\omega_0 = 2.4$ GHz), a lower frequency located at $0.9\omega_0$ (2.16 GHz) is chosen as the frequency to calculate the value of practical elements. The practical element values of the quadrature coupler then work out to be $C_s = 2.08$ pF, $L_p = 1.52$ nH, and $C_m = 0.72$ pF, respectively. The prototype circuit was made of surface-mounted capacitors and the short lengths of 100-Ω microstrip lines short circuited at their ends. To realize the desired inductors, this study utilized a commercial electromagnetic (EM) simulator to analyze various lengths of the short-circuited 100-Ω microstrip line to obtain the precise inductances and to minimize parasitic elements. Based on the model extraction function provided by the EM simulator, we obtain the parasitic shunt capacitors associated with those short-circuited microstrip lines for realizing desired inductances are about 0.4 and 0.2 pF, respectively. To evaluate the characteristics of the prototype circuit, an equivalent circuit of a surface-mounted capacitor consisting of a capacitor in series with a small inductor, which is about 0.8nH calculated from the self-resonant frequency in the manufacture's data sheet, and the S-parameters of short-circuited microstrip lines generated from the EM simulator were inputted to the circuit simulator. The performance of the prototype coupler was simulated and it shows the degradation of amplitude balance of ports 3 and 4 due to the addition of the lumped-elements' parasitic effect. The lumped elements were then slightly adjusted to improve circuit performance through the commercial microwave circuit simulator's optimization function. Fig. 4 shows the final simulated characteristics of the coupler constructed by practical SMD capacitors and semi-lumped inductors. As shown, the operation band is about 1.9–2.5 GHz, which corresponds to $1.0f_0$ to $1.31f_0$, and the operation bandwidth is reduced to approximately 30%. It indicates that the narrowing of the designed bandwidth is mainly due to the parasitic effects, which lowers the high end of operation band, while the amplitude of S_{21} and S_{31} are almost equivalent and are less than 4 dB, and the return loss and isolation remain greater than 18 dB. Fig. 5 shows the photograph of the prototype circuit, which has an overall circuit size of about 10 mm $\times$ 10 mm. The measured results of the prototype of the quadrature coupler are obtained by mounting the coupler into the Arnitsu/Wiltron 3680 MIC test fixture and terminating two of four output ports with the 50-Ω terminator. The measured results are superimposed in Fig. 6. The S_{21} shown in Fig. 6 represent the insertion loss of the S-parameter measurement terminating at ports 3 and 4 of the coupler. S_{31} and S_{41} of Fig. 6 are obtained by using a measurement method similar to that used

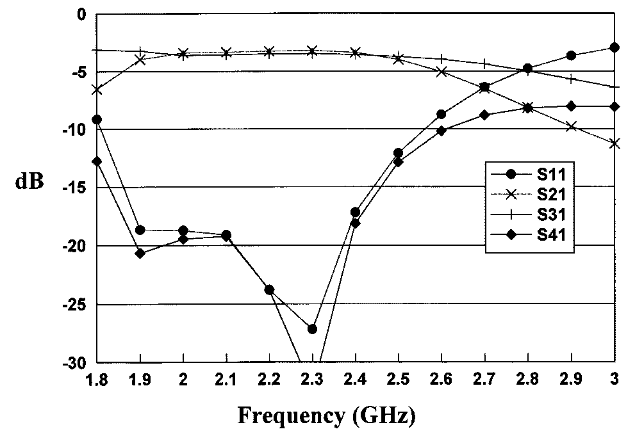


Fig. 4. Simulated frequency characteristics of a 2.4-GHz lumped quadrature coupler fabricated by SMD capacitors and a shorted-circuit 100-Ω microstrip line.

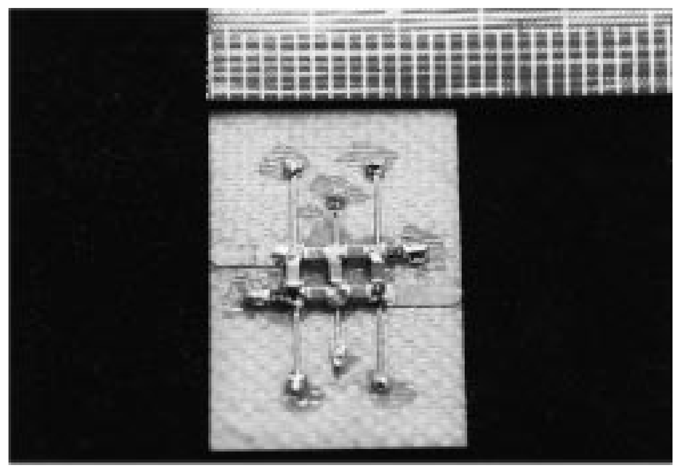


Fig. 5. Photograph of a 2.4-GHz quadrature coupler prototype circuit fabricated on an FR4 PCB.

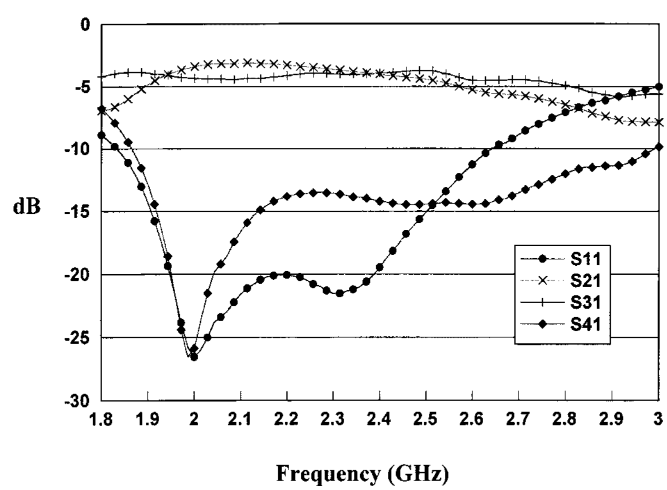


Fig. 6. Measured S–parameters of the lumped coupler prototype circuit shown in Fig. 5.

for measuring S_{21}. The S_{11} of Fig. 6 is the average of S_{11} obtained from three measurement results. Comparing Figs. 4 and 6 reveals a very good agreement between the measurements and the predictions made by the microwave circuit simulators. The little discrepancy between modeled and measured results is because the practical capacitances of the surface mount capacitors have certain variation from the listed values shown in the data sheet.

IV. CONCLUSION

This paper has proposed a new design technique for synthesizing a quadrature lumped-element coupler suitable for wide-band application. The measurement of an experimental prototype shows the proposed quadrature hybrid does have a wider fractional bandwidth than the conventional design technique. In producing a 2.4-GHz prototype, the maximum inductor and capacitor values are all less than 3 nH and 2 pF. These inductors and capacitors are easily constructed by applying conventional MMIC techniques. The proposed quadrature hybrid should be able to find applications in future MMICs.

REFERENCES

[1] D. M. Pozar, *Microwave Engineering*: Wiley, 1998, ch. 8, pp. 379–383.

[2] J. Lange, "Interdigitated stripline quadrature coupler," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 1150–1151, Dec. 1969.

[3] S. J. Parisi, "180° lumped element hybrid," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1989, pp. 407–410.

[4] H.-K. Chiou, H.-H. Lin, and C.-Y. Chang, "Lumped-element compensated high/low-pass balun design for MMIC double-balanced mixer," *IEEE Microwave Guided Wave Lett.*, vol. 7, pp. 248–250, Aug. 1997.

[5] Y.-C. Chiang and C. Y. Chen, "Design of lumped element quadrature hybrid," *Electron. Lett.*, vol. 34, pp. 465–466, Mar. 1998.

[6] R. K. Gupta and W. J. Getsinger, "Quasilumped element 3- and 4-port networks for MIC and MMIC applications," in *IEEE MTT-S Int. Microwave Symp. Dig.*, CA, 1984, pp. 409–411.

[7] R. W. Vogel, "Analysis and design of lumped- and lumped-distributed-element directional couplers for MIC and MMIC applications," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 253–262, Feb. 1992.

[8] I. Ohta, X.-P. Li, T. Kawai, and Y. Kokubo, "A design of lumped-element 3 dB quadrature hybrids," in *Proc. Asia–Pacific Microwave Conf.*, 1997, pp. 1141–1144.

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