A Novel Structure of Tightly Coupled Lines for MMIC/MHMIC Couplers and Phase Shifters

Yansheng Xu and Renato G. Bosisio, *Fellow, IEEE*

***Abstract*— In this paper, a new structure of tightly coupled lines compatible with monolithic-microwave integrated-circuit/minature hybrid-microwave integrated-circuit (MMIC/ MHMIC) technology is introduced. Different from previous designs, short subsections of two or more different coupled lines are alternatively connected together to achieve the needed performance of a single-section coupler or phase shifter. Theoretical calculations are given and some typical design data are provided. A design example of a wide-band coplanar-waveguide (CPW) quadrature coupler using standard MMIC foundry technology is provided. Only metal–insulator–metal (MIM) capacitors and air-bridges are used to achieve tight coupling—no via holes are necessary. Experimental results are in good agreement with simulations. The proposed structure of coupled lines is very flexible and easily achieves very tight coupling factors.**

***Index Terms*— Coplanar waveguides, coupled transmission lines, couplers, microwave integrated circuits, MMIC's.**

I. Introduction

The design of microwave quadrature couplers and phase shifters is well-documented in the literature. Tightly coupled structures required in the design of broad-band quadrature couplers and Schiffman phase shifters are generally realized using interdigitated multiconductor lines [1]–[3] or broadside-coupled structures [4]–[6] including quasi-broadside coupled lines [7] and semireenterant sections [8]. Lange couplers are ordinarily constructed using microstrip lines and broadside-coupled lines are compatible only with multilayer monolithic-microwave integrated-circuit (MMIC) technology, which is not always readily accessible. Recently, a MMIC-compatible tightly coupled line structure using an embedded microstrip was introduced [9]. However, the analysis of such structures is not easy and the design is necessarily based on an empirical approach. In this paper, we study designs of structures where the coupled section is composed of numerous alternatively connected short subsections having two or more different types of coupled lines, as shown in Fig. 1. This arrangement makes the design more flexible, since design parameters are more than doubled and it can be easily realized using both microstrip lines or coplanar waveguides (CPW's). The total length of the coupled section remains near to a quarter-wavelength long for design of single-section quadrature couplers. The total coupling of the composed line is the average of the two types of coupled lines, but the directivity of the coupler is improved by a proper adjustment of the phase velocity of the coupled modes. By using this new structure of coupled lines, it is easy to design wide-band quadrature couplers using only metal–insulator–metal (MIM) capacitors and air-bridges which are available in every MMIC or miniature hybrid-microwave integrated-circuit (MHMIC) foundry. It should be noted that the more readily available MHMIC technology can be used with air bridges at high frequencies ($\geq$ 20 GHz), and bond wires used at lower frequencies ($\leq$ 20 GHz).

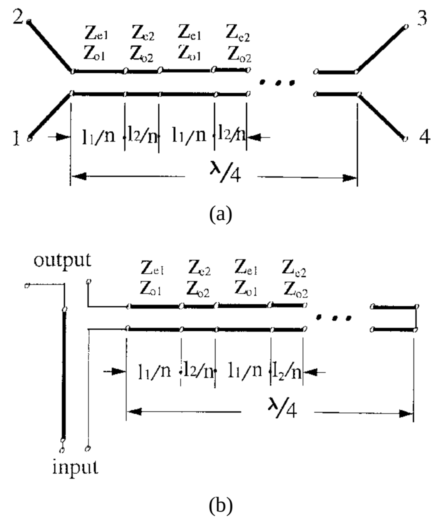

Fig. 1. Illustration of (a) one-section coupler and (b) phase shifter using the proposed multisection coupled line where Z_{o1} and Z_{o2} are the odd impedances, and Z_{e1} and Z_{e2} are the even impedances of lines having lengths l_1/n and l_2/n.

II. Theoretical Analysis of Multisection Tightly Coupled Lines

The model of calculation for the coupler case is shown in Fig. 1. The impedances, phase velocities, and electrical length of the two types of coupled lines are different and equal to Z_{e1}, Z_{e2}, Z_{o1}, Z_{o2}, V_{e1}, V_{e2}, V_{o1}, V_{o2}, θ_{e1}, θ_{e2}, θ_{o1}, and θ_{o2}, respectively, where index $e1$ refers to the even mode of the first type of coupled line and index $o1$ refers to the odd mode of the first type of coupled line and so forth. The number of subsections of each structure of coupled lines is equal to n and the total number of the subsections is $2n$ or $2n+1$. In our simulation, at first the quasi-TEM analysis of the cascaded

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The authors are with the Groupe de Recherches Avancées en Microondes et en Electronique Spatiale, (Poly-Grames), Département de Génie Electrique et de Génie Informatique, Ecole Polytechnique de Montréal, Montréal, P.Q., Canada H3C 3A7.

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TABLE I
VALUES OF l_1, l_2 AND IMPEDANCES OF COUPLED LINES FOR A 3-dB COUPLER

$Z_{e1}(\Omega)$	$Z_{o1}(\Omega)$	$Z_{e2}(\Omega)$	$Z_{o2}(\Omega)$	l_1	l_2
83.3	30	200	12.5	0.52	0.48
		500	5	0.81	0.19
71.43	35	200	12.5	0.45	0.55
		500	5	0.76	0.24
62.5	40	200	12.5	0.37	0.63
		500	5	0.7	0.3

multisection line is performed [10]. The transfer matrices of the even and odd modes take the following form:

$$\overline{\overline{A}}_{e,o} = \overline{\overline{A}}_{e1,o1} \cdot \overline{\overline{A}}_{e2,o2} \cdot \overline{\overline{A}}_{e1,o1} \cdot \overline{\overline{A}}_{e2,o2}, \cdots, \overline{\overline{A}}_{e1,o1} \qquad (1)$$

with

$$\overline{\overline{A}}_{e1,o1} = \begin{pmatrix} \cos\,\theta_{e1,o1} & jZ_{e1,o1}\,\sin\,\theta_{e1,o1} \\ (j/Z_{e1,o1}\,\sin\,\theta_{e1,o1}) & \cos\,\theta_{e1,o1} \end{pmatrix} \quad (2)$$

and

$$\overline{\overline{A}}_{e2,o2} = \begin{pmatrix} \cos\,\theta_{e2,o2} & jZ_{e2,o2}\,\sin\,\theta_{e2,o2} \\ (j/Z_{e2,o2}\,\sin\,\theta_{e2,o2}) & \cos\,\theta_{e2,o2} \end{pmatrix}. \quad (3)$$

The reflection and transmission coefficients for the even and odd modes are

$$\Gamma_{e,o} = \left(\frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D}\right)_{e,o} \qquad (4)$$

and

$$T_{e,o} = \frac{2}{(A + B/Z_0 + CZ_0 + D)_{e,o}} \qquad (5)$$

where A, B, C, D are the elements of the transfer matrices of even and odd modes and Z_0 is the characteristic impedance of the input and output ports. The S-parameters of the coupler are readily obtained from the combination of the reflection and transmission coefficients of the even and odd modes Γ_e, Γ_o and T_e, T_o [10].

III. NUMERICAL RESULTS AND DESIGN RULES

In principle, the number n may be arbitrary. However, in practice we make n much larger than unity to improve the performances of the coupler. Moreover, in the case when air-bridges are used to realize tight coupling, the length of each subsection is quite short, and hence, n should be made large. From our calculation, the performances of the coupler is almost independent on the value of n for $n \geq 10$ when the total length of the section and the portions of the two different subsections are kept constant. Therefore, in the following calculations we put $n = 10$. The proposed coupled lines are mostly used in the design of tightly coupled lines to provide the needed coupling and to compensate the discrepancy of the line impedance from matching conditions. To give an idea how the combination of tight and weak coupling subsections can achieve a 3-dB

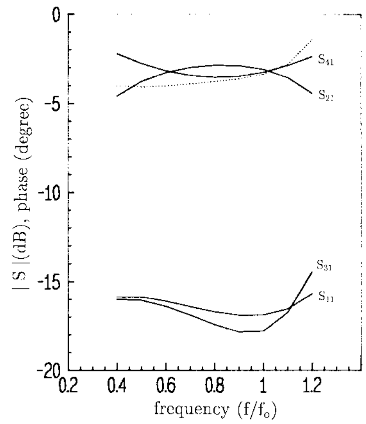

Fig. 2. Dependence of the performance of the coupler on the normalized frequency value with $Z_{e1} = 94\,\Omega$, $Z_{e2} = 133\,\Omega$, $Z_{o1} = 37\,\Omega$, $Z_{o2} = 7\,\Omega$, $V_{e1} = V_{e2} = V_{o1} = V_{o2}$, and $l_1 = l_2$. Dotted curve shows phase deviation from 90°.

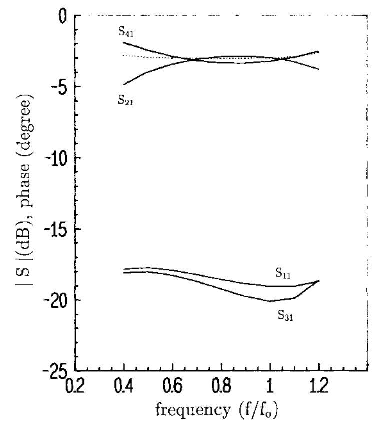

Fig. 3. Dependence of the performance of the coupler on the normalized frequency value with $Z_{e1} = 94\,\Omega$, $Z_{e2} = 133\,\Omega$, $Z_{o1} = 37\,\Omega$, $Z_{o2} = 7\,\Omega$, $V_{e1} = V_{e2} = V_{o1} = (1/0.85)V_{o2}$, and $l_1 = l_2$. Dotted curve shows phase deviation from 90°.

coupler, some calculated data are presented in Table I with 0.5-dB difference of output power in the two coupled ports at center frequency. The ordinary design data for this case are $Z_e = 125\ \Omega$ and $Z_o = 20\ \Omega$. In Table I, l_1 and l_2 denote the total lengths of the two types of coupled lines in fraction of a quarter guide wavelength. In these cases, the matching condition is satisfied and the directivity of the coupler approaches infinity.

The feasibility of the proposed design is demonstrated by typical curves presented in Figs. 2–6. Fig. 2 shows the case when $Z_{e1} = 94\ \Omega$, $Z_{e2} = 133\ \Omega$, $Z_{o1} = 37\ \Omega$, $Z_{o2} = 7\ \Omega$, $l_1 = l_2$, and $V_{e1} = V_{e2} = V_{o1} = V_{o2}$ where V_e and V_o are the phase velocities of even and odd modes, respectively. In this case, the matching condition is not satisfied. It is clear from Fig. 2 that the coupling of the two different lines is averaged, producing a 3-dB coupler with octave bandwidth with relatively poor directivity. The parameters of curves in Fig. 3 are the same as in Fig. 2, the only difference is that $V_{o2} = 0.85V_{o1}$. It is clear that the directivity of the new design is improved. Fig. 4 demonstrates that for $Z_{e1} = 83.3\,\Omega$, $Z_{e2} = 400\ \Omega$, $Z_{o1} = 30\ \Omega$, $Z_{o2} = 6.25\ \Omega$, $V_{e1} =$

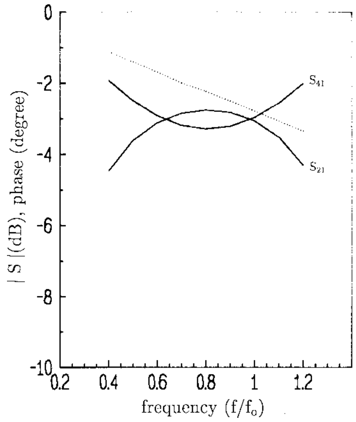

Fig. 4. Dependence of the performance of the coupler on the normalized frequency value with $Z_{e1} = 83.3\,\Omega$, $Z_{e2} = 400\,\Omega$, $Z_{o1} = 30\,\Omega$, $Z_{o2} = 6.25\,\Omega$, $V_{e1} = V_{e2} = V_{o1} = (1/0.85)V_{o2}$, and $l_1 = (77/23)l_2$. Dotted curve shows phase deviation from 90°. Directivity is basically infinite.

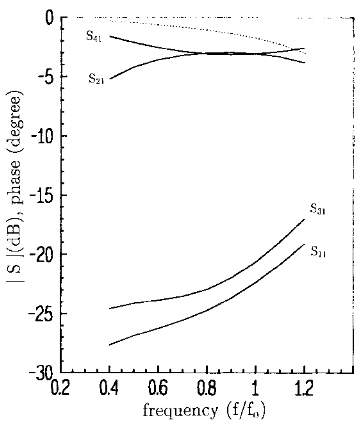

Fig. 5. Dependence of the performance of the coupler on the normalized frequency value with $Z_{e1} = Z_{e2} = 125\,\Omega$, $Z_{o1} = 30\,\Omega$, $Z_{o2} = 6\,\Omega$, $V_{e1} = V_{e2} = V_{o1} = V_{o2}$, and $l_1 = (8/2)l_2$. Dotted curve shows phase deviation from 90°.

$V_{e2} = V_{o1} = V_{o2}$, and $l_1 = (77/23)l_2$, produces a coupler with almost the same performance as the above two figures with the directivity approaching infinity as expected, since the matching condition is satisfied in this case. Fig. 5 shows the case with $Z_{e1} = Z_{e2} = 125\ \Omega$, $Z_{o1} = 30\ \Omega$, $Z_{o2} = 6\ \Omega$, $V_{e1} = V_{e2} = V_{o1} = V_{o2}$, and $l_1 = (8/2)l_2$, in this case we have a coupler with a similar performance as in Figs. 2 and 3. It should be pointed that the matching condition is not satisfied in this case as well. The directivity in Fig. 6 is improved over Fig. 5 by keeping the parameters in Fig. 5 unchanged and by reducing the phase velocity V_{o1} to 80% of its previous value. From the above calculated curves we may draw the following design rules for the proposed type of coupler.

1) In order to obtain good performance of the coupler, the number of subsections should be no less than ten.
2) The parameters of the two different coupled lines should be near the parameters of the ideal case. If Z_{e1} is larger than Z_e, then Z_{e2} should be less than Z_e, and the same applies for the odd mode, i.e., the value of $\sqrt{Z_{e1}Z_{o1}Z_{e2}Z_{o2}}$ is made as near to Z_{in} as possible.

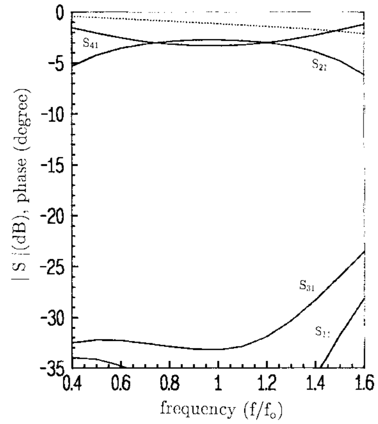

Fig. 6. Dependence of the performance of the coupler on the normalized frequency value with $Z_{e1} = Z_{e2} = 125\,\Omega$, $Z_{o1} = 30\,\Omega$, $Z_{o2} = 6\,\Omega$, $V_{e1} = V_{e2} = (1/0.8)V_{o1} = V_{o2}$, and $l_1 = (8/2)l_2$. Dotted curve shows phase deviation from 90°.

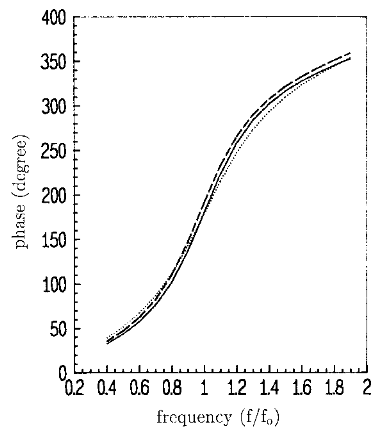

Fig. 7. Dependence of the phase characteristics of the short-circuited coupled line used in Schiffman phase shifter on the normalized frequency value with $Z_{e1} = 93\,\Omega$, $Z_{e2} = 133\,\Omega$, $Z_{o1} = 37\,\Omega$, $Z_{o2} = 7\,\Omega$, $V_{e1} = V_{e2} = V_{o1} = (1/0.6)V_{o2}$, and $l_1 = l_2$ (dashed line), and $Z_{e1} = 93\,\Omega$, $Z_{e2} = 133\,\Omega$, $Z_{o1} = 37\,\Omega$, $Z_{o2} = 7\,\Omega$, $V_{e1} = V_{e2} = (1/0.8)V_{o1} = (1/0.8)V_{o2}$ and $l_1 = (77/23)l_2$ (dotted line). Solid line shows the homogeneous coupled line case with $Z_{e1} = Z_{e2} = 125\,\Omega$, $Z_{o1} = Z_{o2} = 20\,\Omega$, and $V_{e1} = V_{e2} = V_{o1} = V_{o2}$.

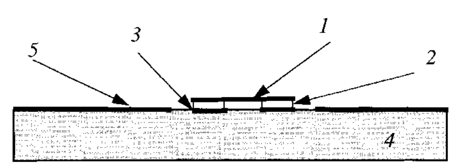

Fig. 8. The proposed tightly coupled subsection of a MMIC coupler. 1: air bridge, 2: dielectric film, 3: coupled CPW line, 4: substrate, 5: ground plane.

3) The directivity of the coupler may be improved by a proper adjustment of the phase velocity of the different modes of the coupled lines when the matching condition is not satisfied.

The same calculation applies for a section of shorted coupled line used in a Schiffman phase shifter. The results in Fig. 7 show that by a proper choice of parameters the proposed coupled lines possess approximately the same phase behavior as the homogeneous coupled line. For CPW lines, the phase velocities of even and odd modes are often near to each other,

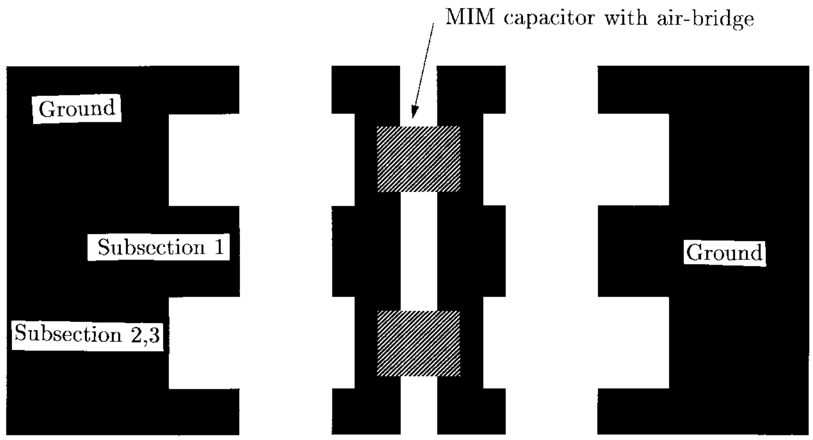

Fig. 9. The loosely coupled subsection (subsection 1), tightly coupled subsections (subsection 2 with capacitor and subsection 3 without capacitor) and air-bridges, capacitors of the fabricated quadrature coupler.

and hence, in the above figures we put the same value to most of them. However, the difference in phase velocity can easily be encountered in the simulation whenever necessary and this difference will ordinarily deteriorate the directivity of the designed coupler.

IV. MMIC CPW Wide-Band Quadrature Coupler Using the Proposed Tightly Coupled Line Design

The proposed structure of tightly coupled lines is very general, it may be realized by using different transmission lines normally encountered in microwave technology, such as a microstrip line, coplanar waveguide (CPW), slot line, and so forth. However, for a MMIC quadrature coupler, the best choice is CPW, since it is more flexible in dimension selection and needs no expensive via-holes.

An actual example of the proposed coupled-lines' structure is shown in Figs. 8 and 9, respectively, and the layout of the coupler for test is shown in Fig. 10, where loosely coupled subsections are made from ordinary coupled CPW's; MIM capacitors and air-bridges are added to achieve the strong coupling for the tightly coupled subsections. This design is very simple and easy to fabricate in either MMIC or MHMIC technology. In Fig. 10, the transmission and coupling ports of the coupler are terminated by 50-Ω loads for testing the isolation of the coupler. The total area of the layout of the designed coupler in Fig. 10 is 0.45 $\times$ 1.9 mm^2. The design of the loosely coupled CPW lines can be easily performed by using well-known numerical methods such as the spectral-domain method, method of lines, method of moments, finite-element method, or commercial software such as Momentum or High-Frequency Simulation Software (HFSS).[1] The additional MIM capacitor will have no effect on the even-mode impedance, and the change of the odd-mode impedance of the tightly coupled subsection due to the MIM capacitor may be calculated as follows,

The capacitance of a parallel-plate capacitor is given by the well-known formula

$$C = 8.86\epsilon_r F/S \tag{6}$$

[1]Trade names of Hewlett-Packard.

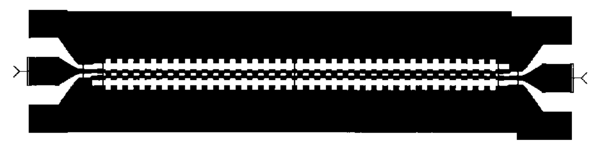

Fig. 10. The layout of the designed quadrature coupler ready for testing.

where C is the capacitance calculated (in pF), F stands for the area of the capacitor (in square meters), ϵ_r is the relative dielectric constant of the dielectric medium filling the capacitor, and S stands for the distance between the two plates of the capacitor (in meters). The impedance of a transmission line is expressed as

$$Z_L = 10000\sqrt{\epsilon_r}/3C_L \tag{7}$$

where Z_L is the impedance of the line in ohms and C_L stands for the capacitance of the line per unit length (picrofarads per meter). The resultant impedance of the tightly coupled subsection may be calculated from the parallel capacitance of the coupled CPW line and the MIM capacitor. The above simplified calculation is valid for MMIC versions where the dimensions of the coupler are much smaller than the wavelength at the microwave frequency. On the other hand, the resultant odd-mode impedance of the tightly coupled subsection may be also obtained from the simulation results of HFSS and the results of the above two methods appear near to each other for the MMIC fabrication.

The design dimensions of the MMIC CPW quadrature coupler are (see Fig. 9): the loosely coupled subsection (subsection 1): the width of the center strips are 15 μm, the distance between these two center strips is 8 μm, the two slots between the center strips and the ground are equal to 20 μm and the tightly coupled subsection (subsection 2): the width of the center strips are 10 μm, the distance between these two center strips is 8 μm, the two slots between the center strips and the ground are equal to 40.5 μm, the area of the MIM capacitor is 4 μm by 14 μm.

Altogether 36 loosely coupled subsections and 35 tightly coupled subsections are used, the length of each subsections is equal to 20 μm. Due to fact that the length of the MIM

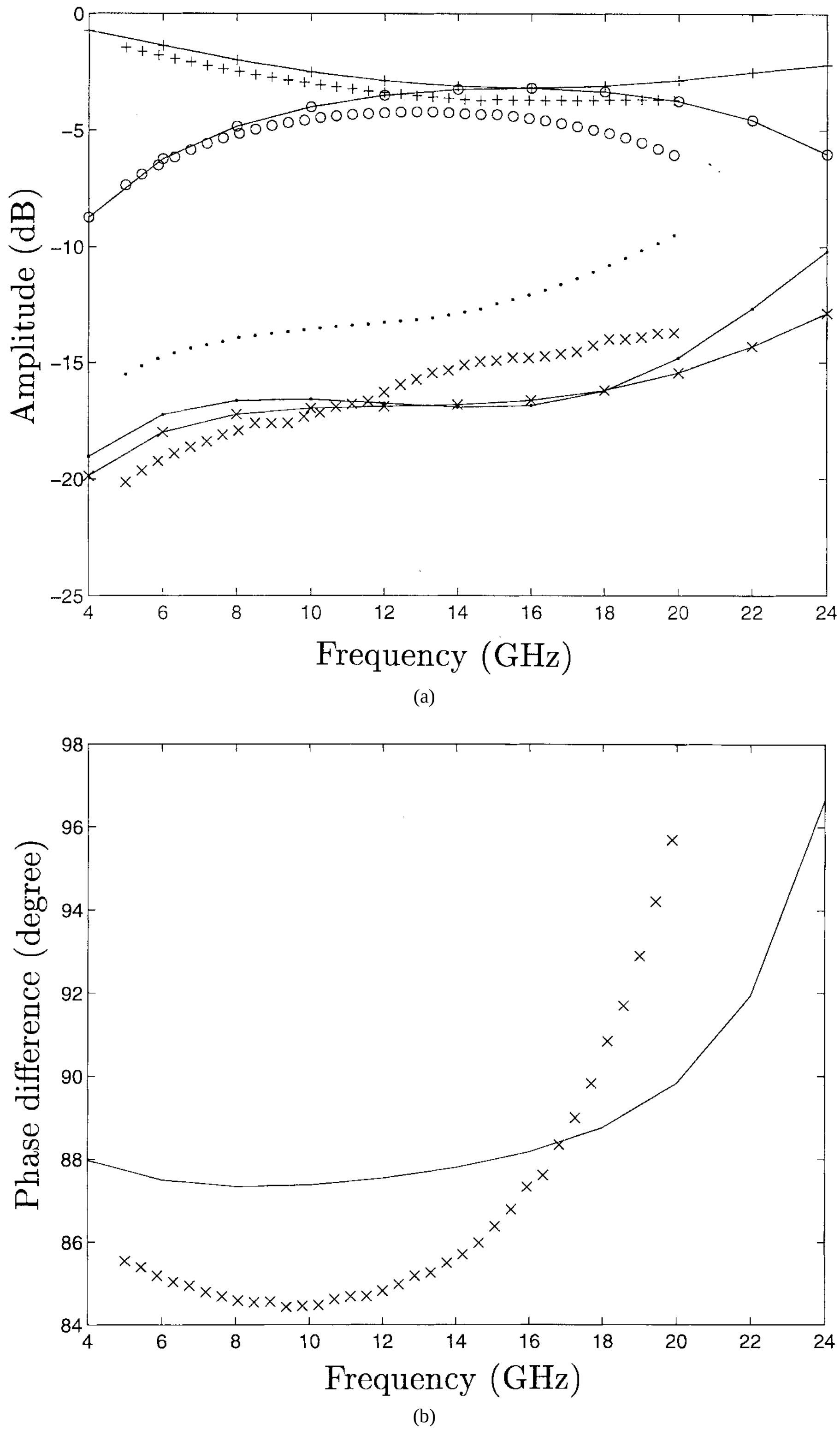

Fig. 11. Calculated and experimental results of the performance of the designed quadrature coupler. (a) Results of coupling, reflection, and isolation. Simulated data: (—), measured data: (+ + +) transmission, oooo coupling, (· · ·) reflection, (xxxx) isolation, and (b) phase difference between the coupling and transmission ports: simulated (—), measured (xxxx).

capacitor is only 14 μm, which is less than the length of subsection 2 (20 μm), we have three different subsections, namely: 1) the loosely coupled subsection; 2) the tightly coupled subsection with a MIM capacitor; and 3) one short tightly coupled subsection without a MIM capacitor. It is noted that subsection 2 is connected to subsection 1 through subsection 3, as required by the design rules of the foundry. The width of the MIM capacitor (4 μm) is also limited by the same design rules.

The coupler is fabricated on 625-μm GaAs substrate. The simulated even- and odd-mode impedances of the three subsections are $Z_{e1} = 96.2\ \Omega$, $Z_{e2} = Z_{e3} = 135.4\ \Omega$, $Z_{o1} = 37.8\ \Omega$,

$Z_{o2} = 5.2\ \Omega$, and $Z_{o3} = 47.6\ \Omega$, respectively. All three subsections are accounted for in the simulation. The phase velocity of all modes of different CPW subsections are very near to each other, except that the phase velocity of the odd mode of subsection 2 is around 90% of other modes, and this point is helpful to improve the isolation of the coupler as indicated above. The size effects of the discontinuities due to the connections of different subsections are unimportant, as shown by the results of the simulation, since the dimensions of the discontinuities are much smaller than the microwave wavelength. However, their effects can also be included into the simulation if necessary.

The simulated and experimental results are shown in Fig. 11. A wide-bandwidth quadrature coupler with good performances is achieved. In spite of the large number of air-bridges and capacitors used in the design, the agreement between the theoretical and experimental data appears quite good. The shift of the center frequency to the lower end and the drop of the output of the coupling and transmission ports at the high-frequency end is explained by the excessive losses of the fabrication when the operating frequency is high.

It is to be noted that the recently proposed MMIC braided-microstrip quadrature coupler [11] is in appearance very complicated. From the above analysis, it can be treated as a special case of the proposed coupler. The tightly coupled subsections are actually coincident portions of the air-bridges and the lower level metal, and the loosely coupled subsections represent the remaining portion in [11, Fig. 1].

V. Conclusion

A novel structure of tightly coupled lines is proposed for the design of MMIC quadrature couplers and Schiffman phase shifters. Simulation results show that the nonuniform lines can provide similar performances as ordinary homogeneous coupled lines, with the added advantages of providing design flexibility, as shown by the design of a MMIC CPW wide-band quadrature coupler. Experimental results are in good agreement with theoretical values. An additional advantage of this structure of tightly coupled lines lies in that its simulation and design is quite simple and no special design programs or softwares are necessary. In this design, only standard MIM capacitors and air-bridges are used. Such circuit technology is quite mature and it is available in every MMIC/MHMIC foundry. Although only single quarter-wave section couplers and phase shifters are studied in this paper, the proposed method may be readily extended to the multiple-section version where extremely tightly coupled lines are required [12].

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Yansheng Xu graduated from Tsing Hua University, Beijing, China, in 1952, and received the Candidate of Technical Science degree from the Institute of Radio Physics and Electronics, Academy of Science, Moscow, Russia, in 1961.

He joined the Beijing Institute of Radio Measurements, working in radio communications and radar techniques. He is currently with the Groupe de Recherches Avancées en Microondes et en Electronique Spatiale, (Poly-Grames), Département de Génie Electrique et de Génie Informatique, Ecole Polytechnique de Montréal, Montréal, P.Q., Canada. He has authored or co-authored over 80 technical papers. His main research interests include MMIC's, MHMMIC's, microwave communications, microwave measurements, microwave ferrite devices, and electromagnetic waves in bi-anisotropic media.

Mr. Xu is a fellow of the Chinese Institute of Electronics (CIE).

Renato G. Bosisio (M'79–SM'89–F'95) was born in Monza, Italy. He received the B.Sc. degree from McGill University, Montreal, P.Q., Canada, in 1951, and the M.S.E.E. degree from the University of Florida at Gainesville, in 1963.

He is an Emeritus Professor at Ecole Polytechnique de Montreal, Montreal, P.Q., Canada, and is currently engaged in designing new six-port-based receivers, MMIC's, and computer-aided testing. He has been engaged in microwave research and development work with Marconi and Varian (Canada), Sperry (U.S.A.), and English Electric (U.K.).