Multiconductor Couplers

YUSUKE TAJIMA AND SUSUMU KAMIHASHI

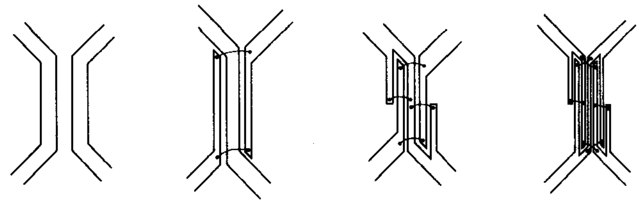
Abstract—Analysis of electromagnetic fields of interdigitated couplers and derivation of propagation parameters such as the line impedances and wavelengths for even and odd modes resulted in designs of couplers with an arbitrary number of strips. Calculations were carried out on two-, three-, four-, and six-strip couplers and showed that results for two- and four-strip couplers were consistent with available published data. The three-strip coupler, which was designed and fabricated, achieved 3-dB coupling with a simpler configuration than Lange's interdigitated coupler and with characteristics consistent with calculated data. Coupling as tight as 1.5 dB was achieved by a six-strip coupler which was designed with a part of the ground plane of the microstrip substrate removed. This coupler can be used as the middle part of a three-section coupler for which test data shows a wide range of balanced coupling, from 2.5 to 12 GHz, with a coupling unbalance of less than ±0.6 dB. It was concluded from the calculation that couplers with more than six strips would not be very practical.

I. Introduction

As MICROSTRIP circuit technology advances, more broad-band quadrature hybrids are being used, especially in balanced mixers, balanced amplifiers, and phase shifters. Since introduced by Lange [1], interdigitated couplers composed of four coupling strips tied together in pairs are commonly used to meet this requirement. Some attempt [2] has been made to derive "equivalent" even and odd modes for an interdigitated coupler in order to apply the conventional two-strip coupled-line method by Bryant and Weiss [3], assuming equal-mode velocities. However, these velocities are unequal, and the charge distribution for the four-strip coupler is completely different from that of two-strip coupled lines.

The first complete analysis of a four-strip coupler was given by Paolino [4], who regarded it as a section of multiconductor transmission lines [5]. However, Paolino restricted himself to the case of even-numbered coupling strips for analysis and gave only the results of four-strip couplers. Also, the couplers in his paper were limited to those with a microstrip structure.

This paper extends the concept of interdigitated couplers to include multistrip couplers of N elements, where N can be any number greater than 2. Illustrated in Fig. 1 are a two-strip directional coupler and a four-strip Lange's coupler, as well as a three- and a six-strip coupler, where strips are connected alternately. Quadrature couplers with arbitrary numbers of strips are thus constructed. The configuration under analysis is generalized by placing it in three layers of dielectric materials; thus both microstrip and suspended structure are treated.



(a) (b) (c) (d)

Fig. 1. Variation of multistrip couplers with (a) two, (b) three, (c) four, and (d) six strips.

Calculated data for two- and four-strip couplers were rigorously checked against reported results. Experiments were performed on three- and six-strip couplers, showing good agreement with the expected coupling of 3 dB and 1.5 dB, respectively.

A Lange's coupler can achieve coupling as tight as 3 dB for nearly an octave band, but it is not tight enough to construct multisection couplers which can achieve 3-dB coupling over a multioctave band. For example, a three-section coupler with 3-dB coupling requires a 1.5-dB quadrature coupler for the middle section [7]. Using a six-strip coupler as the middle section, a three-section coupler was fabricated, showing balanced coupling over a bandwidth of 2.5 to 12 GHz.

Properties of multiconductor couplers are discussed as well as the practical limits on the number of strips interdigitated. A design chart of multiconductor couplers is given for the convenience of coupler designers.

II. Basic Equations

Yamashita and Atsuki [6], [8] calculated characteristics of coupled striplines in a rectangular outer conductor by deriving the Green's function and using the point matching method. We extend their work to apply to multiconductor couplers with an arbitrary number of strips. Also, calculation time is reduced by restricting the structure to be symmetric.

The coupling section under analysis is placed in three layers of dielectric sheets shielded by a rectangular outer conductor, as shown in Fig. 2. We restrict the structure to be symmetric at $x=0$ so that strip widths and spacings are

$$W_1=W_1' \quad W_2=W_2', \cdots, W_n=W_n' \quad \text{and}$$
$$S_1=S_1' \quad S_2=S_2', \cdots, S_n=S_n'. \tag{1}$$

Spacings S_1 and S_1' should be reduced to zero when an odd-number strip coupler is considered. The thickness of

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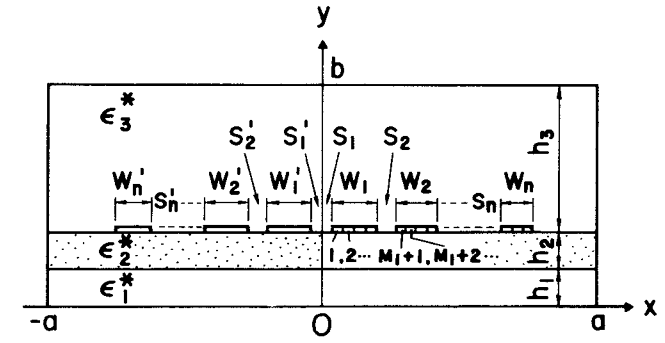
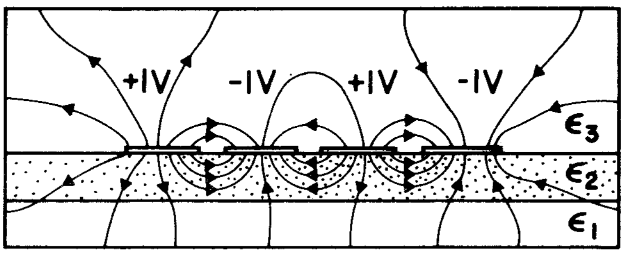
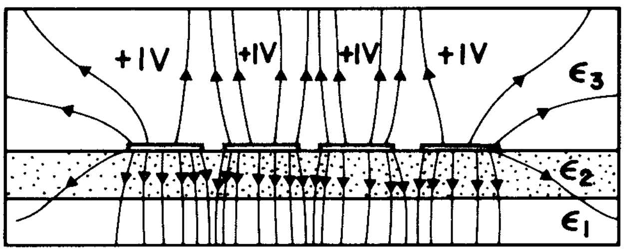


Fig. 2. Configuration of multistrip coupler under analysis. The symmetric plane at $x=0$ is considered as an electric or magnetic wall according to the conditions.



(a)



(b)

Fig. 3. Two independent modes excited on a four-strip coupler when strips are connected alternately by wire bounds: (a) Odd mode. (b) Even mode.

strips is assumed to be infinitely small. In the following analysis the number of strips is taken to be three or more. In the case of a two-strip coupler only one conductor has to be considered because of the symmetric structure, and its calculation can be done straightforwardly.

We assume the TEM mode for wave propagation even when a nonuniform medium is used. This approximation has been used and proven reliable below X band where, in most cases, the cross-sectional dimension of the outer conductor is much smaller than the wavelength, and the propagation is only slightly dispersive.

The strips are connected alternately by thin wires, as shown in Fig. 1, such that the strips are separated into two groups. Within each group, the voltage and direction of current are set equal on all the lines. Between the groups, the voltage and current are independent and can be described in terms of two orthogonal modes, namely the even and odd modes. Fig. 3 is a sketch of the electric field lines for both modes in a cross section of a multiconductor coupler. Even-mode excitation occurs when all conductors are at the same potential; the odd-mode excitation occurs when succeeding adjacent conductors are held at opposite polarity potentials of equal magnitude. With couplers of an even number of strips, the plane of symmetry at $x=0$ is an electric wall for the odd mode and a magnetic wall for the even mode. With an odd number of strips, it is a magnetic wall for both modes. Thus the problem of solving the fields of Fig. 3 is reduced to solving the half-section ($0 \leqslant x \leqslant a$ in Fig. 2) with a magnetic or electric wall at $x=0$.

The Green's function, $G(x,y|x_0,y_0)$, is the potential at (x,y) due to a unit line charge at (x_0,y_0), and is the solution of

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)G(x,y|x_0,y_0)=-\frac{1}{\epsilon}\delta(x-x_0)\delta(y-y_0) \quad (2)$$

where $\delta(x-x_0)$ is Dirac's delta function representing the unit-line charge. Associated with this differential equation are boundary conditions similar to those given by (2) in [6], except that we are only concerned with a half-section with the following additional conditions at the plane of symmetry ($x=0$ in Fig. 2). They are

$$\phi(0,y)=0 \quad (3)$$

for an electric wall and

$$\frac{\partial}{\partial x}\phi(0,y)=0 \quad (4)$$

for a magnetic wall.

To satisfy the boundary conditions, the Green's function is expanded in a sinusoidal series of exclusively even or odd terms in the x coordinate, according to the boundary condition at $x=0$. The delta function is also expressed by even or odd terms only, such that by choosing the appropriate form, the partial differential equation (2) is reduced to a set of ordinary differential equations of variable y. When the boundary conditions are applied, the amplitude constants of the sinusoidal terms of the Green's expanded function are determined. Thus the Green's function is derived in two forms according to the boundary condition at $x=0$:

$$G(x,y|x_0,h_1+h_2)$$
$$=\sum_{n=1,3}^{\infty}\frac{1}{n}A_n\sinh\left\{\frac{n\pi}{a}(b-y)\right\}\cos\left(\frac{n\pi x}{2a}\right)\cos\left(\frac{n\pi x_0}{2a}\right) \quad (5a)$$

or

$$=\sum_{n=2,4}^{\infty}\frac{1}{n}A_n\sinh\left\{\frac{n\pi}{a}(b-y)\right\}\sin\left(\frac{n\pi x}{2a}\right)\sin\left(\frac{n\pi x_0}{2a}\right) \quad (5b)$$

where

$$A_n = \frac{1}{\pi\epsilon_0}\left\{\epsilon_2^*\epsilon_3^* \tanh\left(\frac{n\pi h_1}{2a}\right)+\epsilon_1^*\epsilon_3^* \tanh\left(\frac{n\pi h_2}{2a}\right)\right\}$$

$$/\left[\left\{\epsilon_1^*\epsilon_3^* \tanh\left(\frac{n\pi h_2}{2a}\right)+\epsilon_2^*\epsilon_3^* \tanh\left(\frac{n\pi h_1}{2a}\right)\right\}\right.$$

$$\cdot\cosh\left(\frac{n\pi h_3}{2a}\right)$$

$$+\left\{\epsilon_2^*\epsilon_1^*+\epsilon_2^* \tanh\left(\frac{n\pi h_1}{2a}\right)\tanh\left(\frac{n\pi h_2}{2a}\right)\right\}$$

$$\left.\cdot\sinh\left(\frac{n\pi h_3}{2a}\right)\right]$$

and ϵ_1^*, ϵ_2^*, and ϵ_3^* are the relative dielectric constants of the layers. Equation (5a) shows the Green's function when the boundary at $x=0$ is a magnetic wall, and (5b), when the boundary at $x=0$ is an electric wall.

Once the Green's function is obtained, the potential due to an arbitrary charge distribution is given by the superposition principle:

$$\phi(x,y)=\int_l G(x,y|x_0,h_1+h_2)\cdot\rho(x_0,h_1+h_2)\,dx_0 \tag{6}$$

where the integral is defined over the conductor surface. Here $\rho(x_0,h_1+h_2)$ is the charge density, and the charge is assumed to be distributed on infinitely thin conductors at $y=h_1+h_2$.

In order to express (6) in a difference form, we divide the first and second groups of conductors into M_1 and M_2 substrips, respectively, and label those from the first group $1,2,\cdots,M_1$ and those from second group $M_1+1,M_1+2,\cdots,M$, where $M=M_1+M_2$, as shown in Fig. 2. Then we can use the same equation derived by Yamashita and Atsuki as a difference form of (6) by assuming uniform distribution of charge on each substrip and taking the average potential in the region of the substrip as its potential:

$$\phi_i=\sum_{j=1}^{M}\left\{\frac{1}{w_iw_j}\int_{w_i}\int_{w_j} G(x|x_0)\,dx_0\,dx\right\}q_j,\qquad i=1,2,\cdots,M. \tag{7}$$

Here, w_j and q_j are the width and amount of charge on the jth substrip. $G(x|x_0)$ is the Green's function given by (5) with y set at h_1+h_2, and should be properly chosen according to the mode and the boundary condition at $x=0$.

Equation (7) is a set of linear simultaneous equations in terms of q_j $(j=1,2,\cdots,M)$ and can be solved numerically once ϕ_i is given. Because only two orthogonal modes can be excited between the two groups of conductors, there are two independent potentials V_1 and V_2 for substrips $i=1,2,\cdots,M_1$, and substrips $i=M_1+1,M_1+2,\cdots,M$, respectively,

$$\phi_i=V_1,\qquad i=1,2,\cdots,M_1$$
$$\phi_i=V_2,\qquad i=M_1+1,M_1+2,\cdots,M.$$

In our calculations, (V_1,V_2) are a set equal to $(1,-1)$ for the odd mode and $(1,1)$ for the even mode. The line capacitances C'_{11} and C'_{22} of strip groups I and II, respectively, of the half-section $(0\leqslant x\leqslant a)$ and the coupling capacitance C'_{12} between the groups are obtained from charge distribution q_j derived from (7). The capacitances for the full-section $(-a\leqslant x\leqslant a)$ are simply obtained as follows:

$$C_{11}=C_{22}=C'_{11}+C'_{22}$$
$$C_{12}=2C'_{12} \tag{8}$$

for the even-number coupler, and

$$C_{11}=2C'_{11}\quad C_{22}=2C'_{22}$$
$$C_{12}=2C'_{12} \tag{9}$$

for the odd-number coupler. Here C_{11} and C_{22} are the full-section line capacitances of the strip groups I and II, respectively, and C_{12} is the coupling capacitance between the groups. Thus the coupler design parameters such as line impedances Z_{0o}, Z_{0e} and wavelengths λ_{go}, λ_{ge} of the odd and even modes, respectively, are calculated from the capacitances C_{11}, C_{22}, and C_{12}, and the values of these capacitances when $\epsilon_1^*=\epsilon_2^*=\epsilon_3^*=1$. Design charts for multistrip couplers are given in Fig. 9 and will be discussed in Section IV.

For a coupler with two strips, only one conductor needs to be considered. The charge distribution of the conductor for the odd and even modes can be obtained by using the Green's function, (5a) or (5b), according to the mode. Line capacitances $C_{11}(=C_{22})$, C_{12} are calculated straightforwardly.

Special care must be taken to calculate an odd-number strip coupler because it is an asymmetric coupler. Characteristic impedances of odd and even modes are defined separately for each group of strips as Z_{0o1} and Z_{0e1} for the first group of strips and Z_{0o2} and Z_{0e2} for the second group of strips. However, when the configuration of the coupler is chosen so that the odd- and even-mode impedances of the first group of strips are equal to those of the second group, i.e., $Z_{0o1}=Z_{0o2}$, $Z_{0e1}=Z_{0e2}$, the coupler becomes electrically symmetric, which is most useful for practical applications. In the remainder of this paper, the odd-number strip couplers are calculated to have a configuration which satisfies the condition of electrical symmetry.

III. Calculation and Performance of Multiconductor Couplers

Calculations were carried out on two-, three-, four-, and six-strip couplers. Calculation time was reduced by combining partial and infinite summations as is shown in the Appendix.

TABLE I
COMPARISON OF OUR CALCULATION FOR FOUR-STRIP COUPLERS WITH LANGE'S EXPERIMENTAL AND PAOLINO'S CALCULATED DATA

Ref.	Dimensions (mm)	Coupling	Calculation (this paper)
Lange[1]	h_1 = 0, h_2 = 1.016 s = .0762, W = .1143	(experiments) 3 dB	3.049 dB
Paolino[4]	h_1 = 0, h_2 = .635 s = .0508, W = .0711	(calculation) 3.058 dB	3.121 dB

Results on two- and four-strip couplers were consistent with available published data. Table I shows a comparison of our results for four-strip couplers with those of Lange [1] and Paolino [4].

Three-strip couplers have a coupling tightness which is between that of two- and four-strip couplers. Compared to four-strip couplers, the configuration is simpler, and less wire bonding is required between strips. Thus parasitic discontinuity reactances at the ports are reduced.

A 3-dB coupler was fabricated on an alumina substrate with the following dimensions (mm):

$$S_1 = S_1' = 0 \quad S_2 = S_2' = 0.023 \quad W_1 + W_1' = 0.247$$
$$W_2 = W_2' = 0.049 \quad h_1 = 0 \quad h_2 = 0.635 \quad h_3 = 100.$$

Thickness of the metal conductor was only 0.004 mm which we regarded as negligible compared to other dimensions. Fig. 4 compares the calculated response, represented by solid lines, with our experimental data, represented by dots. Microstripline and connector losses, ranging from 0.3 to 0.6 dB in the frequency band, are extracted from the experimental data so that the comparison is clear. Midband coupling of 3 dB was consistent with the calculated coupling of 2.94 dB.

A six-strip coupler was designed for 1.5 dB of coupling. In order to achieve such tight coupling within practical etching limits, a suspended stripline structure was used. The ground plane of the microstrip substrate beneath the coupling section was removed by etching and a 0.2-mm deep recess was made in the carrier plate coinciding with the etched area of the ground plane, leaving an air gap between the substrate and carrier plate, Fig. 5.

To avoid the difficulty of connecting the interdigitated strips alternately by AU wire, which becomes especially hard when the stripwidth and the gap between the strips are narrow, an alternate method of constructing the coupling section was devised. Alternate strips are joined by a connecting stripline and AU wires are used to rejoin the strips which are broken by the new connecting stripline.

Dimensions were calculated for a 1.5 dB coupler to be

$$h_1 = 0.2 \quad h_2 = 0.635 \quad h_3 = 100$$
$$W_1 = W_2 = W_3 = W_1' = W_2' = W_3' = 0.033$$
$$S_1 + S_1' = S_2 = S_2' = S_3 = S_3' = 0.032 \quad \text{(mm)}.$$

The measured coupling at midband was 1.5 dB and the frequency response corresponds closely to the calculated response, Fig. 6. Again, stripline and connector losses are extracted.

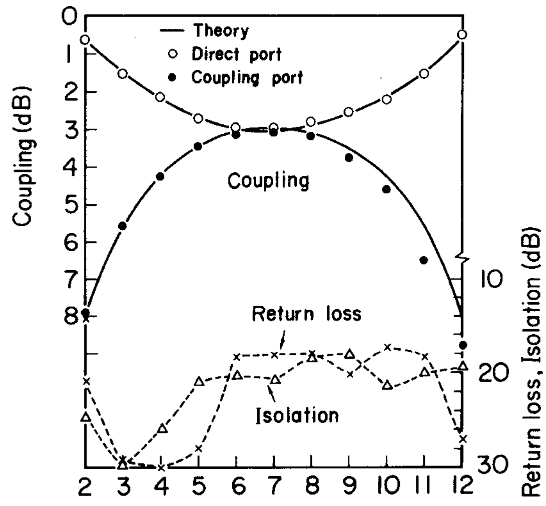


Fig. 4. Test data (dots) of a three-strip 3-dB coupler. Correspondence to calculated coupling coefficients which are represented by solid lines.

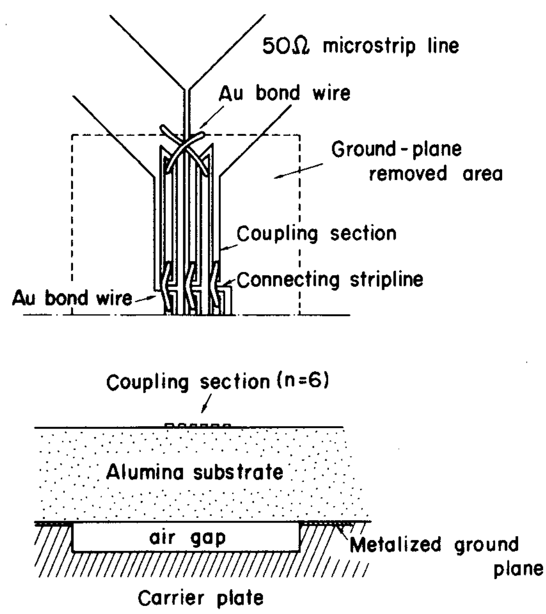


Fig. 5. Configuration of a six-strip coupler. Top view of a half-section (above) and cross section (below).

Using this coupler as a middle section with a 14-dB microstrip coupler at each end, Fig. 7, a three-section coupler was fabricated with 3-dB coupling, according to the design procedure given in [7]. The design parameters are shown in Table II. Note that λ_{ge} is larger than λ_{go} for the middle section because of the air gap under the substrate. The test data on this coupler as shown in Fig. 8 shows a coupling unbalance of less than ±0.6 dB from 2.5 to 12 GHz. Although agreement of test data with calculations is considerable, test data do show greater unbalance and transmission loss especially at high frequency range. Unexpected characteristics can be attributed to wire bond effects, discontinuity parasitics at the junctions of cou-

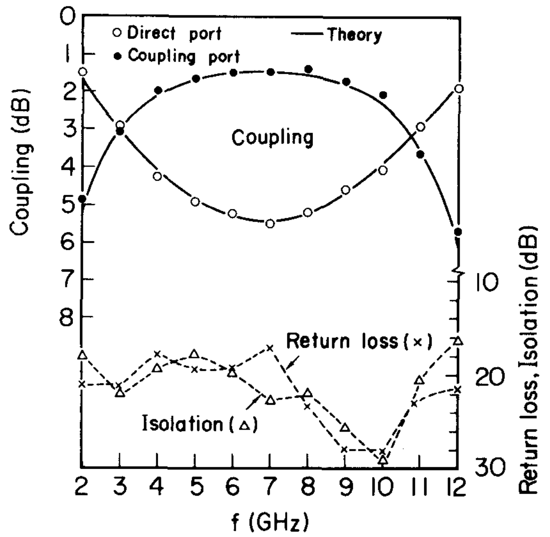


Fig. 6. Test data (dots) of a six-strip 1.5-dB coupler. Calculated coupling coefficients (solid lines).

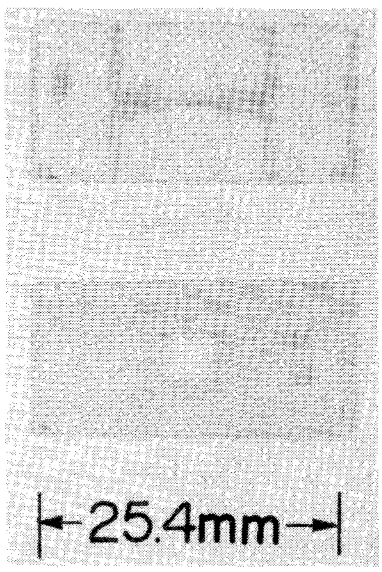


Fig. 7. Photograph of multioctave band coupler with 3-dB coupling, showing coupling circuit pattern (above) and ground plane with section removed (below).

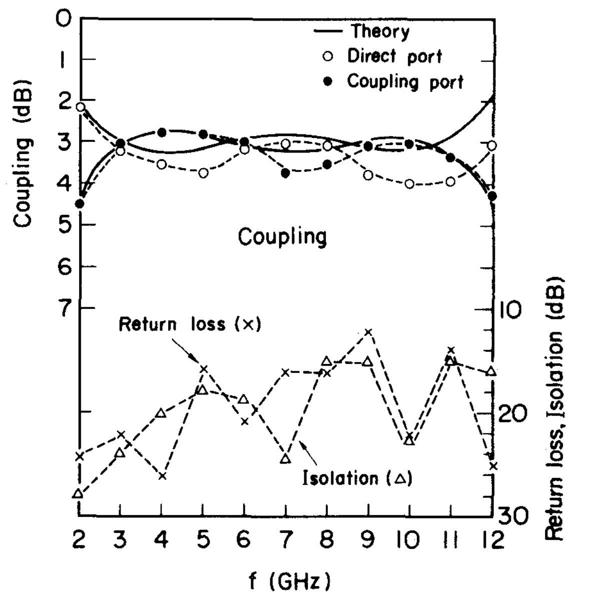


Fig. 8. Test data (dots) of a three-section coupler. Calculated data (solid lines).

TABLE II
DESIGN PARAMETERS OF A THREE-SECTION HYBRID COUPLER, SHOWN IN FIG. 7

Section	No. of strips	Spacing (mm)	Line width (mm)	Coupling (dB)	λ_{go}/λ_o	λ_{ge}/λ_o
End	2	0.420	0.60	14.5	0.413	0.374
Middle	6	0.032	0.033	1.5	0.427	0.497

*λ_0 = free space wavelength.

plers, transition from TEM to dispersive mode at the suspended structure section, and connector and line losses, none of which were computer programmed.

IV. Discussion

Fig. 9 shows design charts for multiconductor couplers in which matching impedance $Z_m = \sqrt{Z_{0o} \cdot Z_{0e}}$ was maintained at 50 Ω. It gives the midband coupling coefficient as well as the wavelength and stripwidth as the spacing s changes.

With a given spacing, the coupling tightens as the number of strips increases. At the same time, the stripwidth has to be reduced to keep Z_m at 50 Ω. Because of the fringing capacitance of strips, stripwidth must be reduced much faster than the rate at which the number of strips increases. Given the practical limits of spacing and linewidth, it would be difficult to achieve six-strip couplers with microstrip structures on alumina substrates ($\epsilon_r = 10$) of less than 1 mm thickness, Fig. 9(a). However, introducing a gap underneath the substrate and making it a suspended structure, enables tighter coupling with wider stripwidths (dotted lines in Fig. 9(a)).

With a quartz substrate, Fig. 9(b), because of a smaller dielectric constant ($\epsilon_r = 3.8$), wider strips are required. Thus six-strip couplers can achieve a coupling as tight as 1.5 dB within a practical dimensional limit. However, it would be difficult to avoid discontinuity parasitics at the ports when 50-Ω lines are to be connected, because the coupling section would be less than 1/3 of the linewidth of a 50-Ω line.

To overcome this discontinuity problem which is caused by the dimensional reduction when the number of strips increases, it would be effective to decrease the dielectric constant of the substrate only underneath the coupling section. In our experiment, the effective dielectric constant was reduced by making a gap under the alumina substrate. This technique would also be effective for quartz substrates to some degree.

Considering the above discussion, we can conclude that multiconductor couplers with more than six strips would

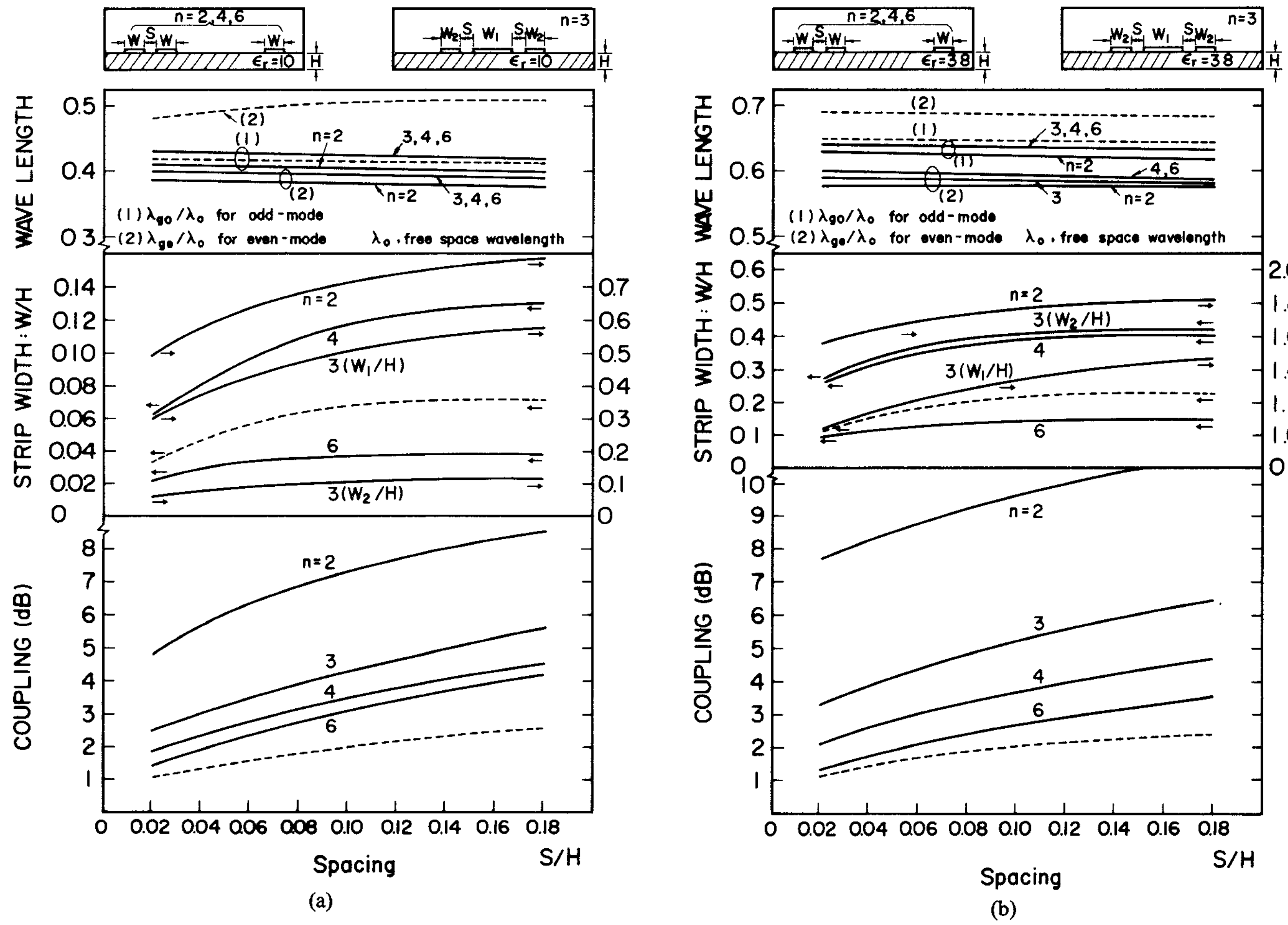


Fig. 9. Design charts of multiconductor couplers with two, three, four, and six strips. Matching impedance $Z_m = \sqrt{Z_{0o} \cdot Z_{0e}}$ is 50 Ω. Dotted lines represent the structure shown in Fig. 5. (a) Alumina substrate ($\epsilon_r = 10$). (b) Quartz substrate ($\epsilon_r = 3.8$).

not be very practical and the strongest coupling that the couplers could achieve would be about 1.5 dB.

V. Conclusion

Interdigitated couplers usually refer only to four-strip couplers but have been generalized here to mean multi-strip-coupling sections of N elements, where N can be any number greater than 2. By conceiving of an arbitrary number of coupling strips, new possibilities of circuit design exist.

Three-strip couplers are found practical in obtaining a coupling tightness of that between conventional two-strip couplers and four-strip Lange's couplers. Compared to four-strip couplers, the configuration is simpler and less wire bonding is required between strips.

Six-strip couplers can be designed to obtain coupling as strong as 1.5 dB when part of the ground plane of the microstrip substrate is removed. Use of this tight coupler as a middle section, in combination with a 14-dB two-strip coupler at each end, made it possible to fabricate three-section couplers with balanced coupling within a ±0.6-dB variation over a frequency range of 2.5 to 12 GHz.

Practical limits to the number of coupling strips are discussed. In order to keep the matching impedance at some value, the stripwidth has to be reduced much faster than the rate at which the number of strips increases. Because of this rapid reduction in size there are two kinds of difficulties that limit the number: 1) realization of the coupling pattern and 2) discontinuity with the outer circuit. We concluded that couplers with more than six strips would not be very practical and the strongest coupling that the couplers could achieve would be about 1.5 dB.

VI. Appendix

In order to calculate (7) with high precision in a short time, the following procedure was utilized. The coefficients in (7) will be expressed as

$$P_{ij} = \frac{1}{w_i w_j} \left(\frac{2a}{\pi} \right)^2 \sum_{\substack{n=1,3 \\ \text{or} \\ n=2,4}}^{\infty} \frac{1}{n^3} g_n F_n \qquad \text{(A-1)}$$

where

$$g_n = A_n \sinh\left(\frac{n\pi}{2a} h_3\right)$$

and

$$F_n = 4 \sin\left(\frac{n\pi}{2a}\frac{w_i}{2}\right) \sin\left(\frac{n\pi}{2a}\frac{w_j}{2}\right) \begin{matrix}\cos\\ \sin\end{matrix}\left(\frac{n\pi}{2a} x_i\right) \begin{matrix}\cos\\ \sin\end{matrix}\left(\frac{n\pi}{2a} x_j\right)$$

where x_i is the x coordinate of the ith substrip.

In the above equations, the upper notation applies to a magnetic wall boundary condition at $x=0$; the lower notation applies to an electric wall. As g_n converges fairly rapidly on g_∞, (A-1) can be rewritten as

$$P_{ij} = \frac{1}{w_i w_j}\left(\frac{2a}{\pi}\right)^2 \left\{ \sum_{\substack{n=1,3\\ \text{or}\\ n=2,4}}^{N} \frac{(g_n - g_\infty)}{n^3} F_n + g_\infty \sum_{\substack{n=1,3\\ \text{or}\\ n=2,4}}^{\infty} \frac{F_n}{n^3} \right\} \tag{A-2}$$

where N is taken to be large enough for g_n to be regarded as g_∞. Since the second term in (A-2) can be analytically obtained and $(g_n - g_\infty)$ reduces to zero rapidly as n increases, (A-2) shows much faster convergence than (A-1).

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Interdigitated Microstrip Coupler Design

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Abstract—**A design procedure for four-line interdigitated couplers is presented which provides excellent agreement between performance and actual coupler dimensions. The inclusion of a correction term for the finite metal thickness of the microstriplines is significant. Using existing odd-and-even mode impedance data of only two coupled lines in the array actual coupling coefficients in the 2.5–6.5-dB range are predictable to within ±0.05 dB. Graphs are shown which relate fabrication tolerances of dielectric constant and physical line dimensions to deviations in coupling and characteristic coupler impedance. The design was verified on 3-, 5-, and 6-dB couplers in the 1–5-GHz frequency range.**

I. Introduction

THE INTERDIGITATED 3-dB coupler as described by Lange [1] is a quadrature coupler and is well-suited for realization in microstrip form. The main advantages are its small size and the relatively large line separation when compared with the gaps of a conventional two-coupled line device and its relatively large bandwidth when compared with branch-line couplers. In the 3-dB form, it is an ideal component for balanced MIC amplifiers and mixers, and for binary power divider trees.

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Interdigitated couplers can be fabricated with coupling coefficients other than 3 dB and, therefore, can be used as components for serial type dividers with power divisions other than binary. There is a need for reliable design procedures that lead to producible couplers and predictable performance.

The original description of the interdigitated coupler [1] did not provide any design information in terms of the known coupled line parameters of a line pair or the parameters derived from a rigorous charge distribution of the four-line set. A more recent publication [2] presents design equations for such couplers with an arbitrary even number of coupled lines. The equations are written in terms of even- and odd-mode impedances of only two adjacent coupled lines in the array which are identical to any other pair in the structure. These equations together with published [3] microstrip data were used in a coupler design. The basic design assumes zero conductor thickness. The physical dimensions as determined by the basic design resulted, however, in overcoupled responses of fabricated couplers in the 3- to 6-dB range on two types of substrates, namely, alumina and BeO. A metallization thickness correction applied to the line and gap dimensions, similar to those described in [4], gave better results.

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