with the values of a and c as shown in Table I. The results for the three arm coupler agree with those already plotted.[3]

Fig. 7 shows the results calculated for branch guide hybrids which give even power split. In this graph the power out arms (2), (3), and (4), expressed in decibels below incident power, is plotted as a function of λ_{g0}/λ_g. The input VSWR to be expected looking into arm (1) is also plotted. These curves are for couplers of 4, 6, and 14 branches with the values of a and c given in Table I.

Fig. 8 shows the results calculated for the 8.5-db coupler discussed earlier as an example. Fig. 9 shows the results to be expected if the length of the branch guides is reduced to 0.22 λ_{g0} while the distance between them is maintained at 0.25 λ_{g0} and all factors remain the same as in Fig. 8. The curves, of course, will not be symmetrical about the $\lambda_{g0}/\lambda_g = 1$ value.

In the practical application of the above calculations it is seen that the longer the coupler is the broader the band that can result. As the sizes of the coupling slots decrease in size the discontinuity effects get less and less so that the performance approaches the theoretical value closer and closer. Thus the effect of more slots and longer length is doubly beneficial. The theoretical performance becomes better and the actual performance approaches the theoretical.

ACKNOWLEDGMENT

The author expresses his appreciation to Thomas A. Weil who programmed and ran the computer.

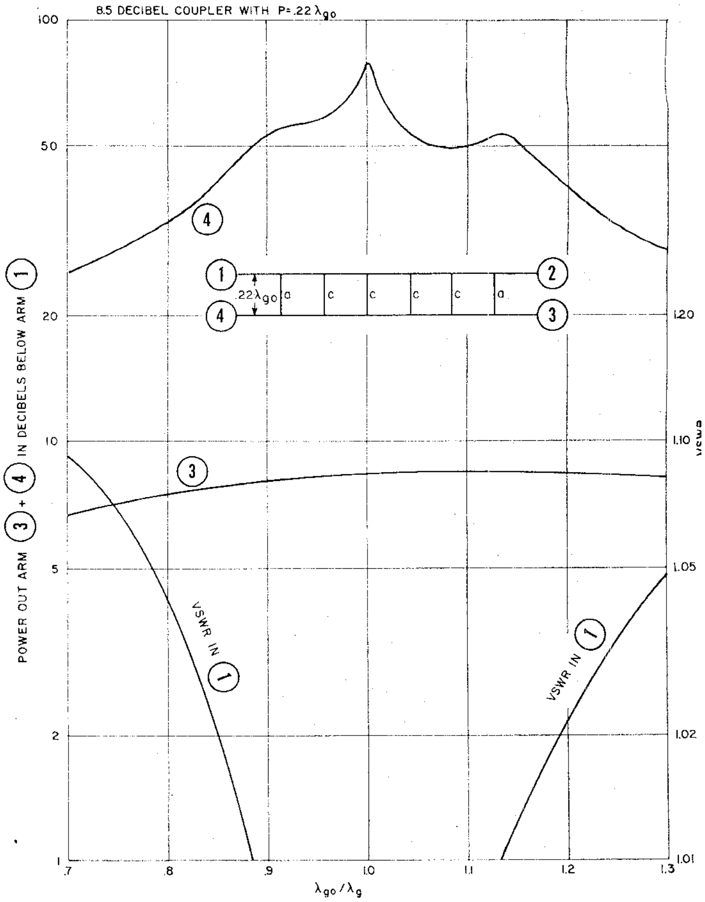

Fig. 9—8.5-db coupler with P reduced.

Coupled-Transmission-Line Directional Couplers*

J. K. SHIMIZU† AND E. M. T. JONES†

Summary—**Formulas are presented for the design of coupled-transmission-line directional couplers that are rigorous for any value of coupling. Two basic types are treated in detail; the simplest is one-quarter wavelength long at the center of its frequency band, while the other is three-quarter wavelength long. The quarter-wavelength type can be used over an octave of frequencies with approximately constant coupling, while the three-quarter-wavelength type can be used equally well over more than two octaves. For example, a −3-db coupler of the first type has a variation of ±0.3 db over a 2:1 band, while the second type has the same variation over a 4.5:1 band. Theoretically both types should have infinite directivity at all frequencies. The experimental results for models of these directional couplers have been found to conform very closely to the theoretical coupling functions, while the directivity, although usually good, is limited by discontinuity effects and constructional tolerances.**

INTRODUCTION

SEVERAL investigators have recently pointed out that coupled transmission lines can be made into directional couplers having excellent wide-band performance, with infinite directivity and constant input impedance theoretically available at all frequencies

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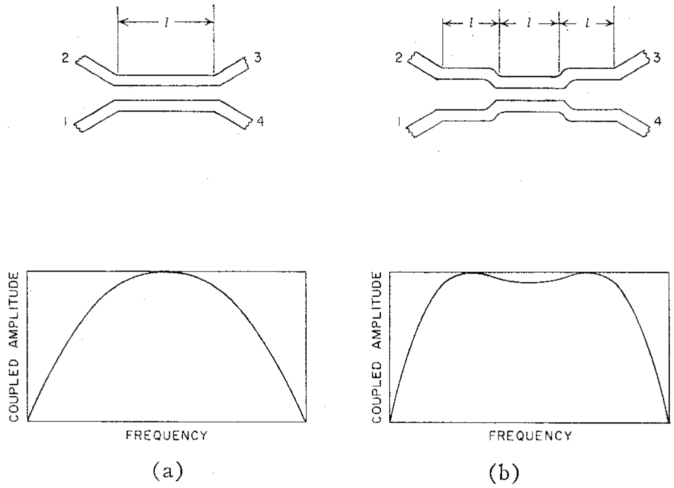
and for all degrees of coupling.[1-5] The basic directional coupler of this type is shown schematically in Fig. 1(a), and is seen to consist simply of a pair of coupled transmission lines. As shown, the amplitude of the coupled wave varies approximately sinusoidally with frequency, with maximum coupling occurring when the length of the coupling region is an odd multiple of a quarter wavelength. Usually, a coupler of this type is designed to be one-quarter wavelength at the center of its frequency band, and hence it will be referred to as the *quarter-wavelength* directional coupler. A wider bandwidth with more uniform coupling may be achieved when three basic couplers are connected in cascade as shown in Fig. 1(b) to form a *three-quarter-wavelength* directional coupler. With the center quarter-wavelength coupler more tightly coupled than the outer quarter-wavelength couplers, a maximally flat or equal-ripple coupling response may be obtained. The direction of coupling with coupled transmission lines is backward rather than forward. Thus, if a signal is fed into one port, the coupled signal emerges from the adjacent port, and the diagonally opposite port is isolated. For example, if Port 1 is energized, the coupled wave emerges from Port 2, and no signal is present at Port 3. The power emerging from Port 4 in the case of an ideal, lossless structure is simply the input power minus the coupled power.

Design formulas for the quarter-wavelength and three-quarter-wavelength directional couplers are given. Also, the measured performance of a number of couplers is presented showing close agreement with theory. The formulas given here apply to all types of TEM-mode transmission lines. However, the design information is particularized to the shielded-strip type of transmission line.

DESIGN FORMULAS FOR QUARTER-WAVELENGTH DIRECTIONAL COUPLERS

The principal results of the theoretical analysis of the coupled-transmission-line directional couplers presented by Jones and Bolljahn[6] are reproduced here for completeness.

They show that when all the ports of the directional coupler as shown in Fig. 1(a) are terminated in its characteristic impedance, Z_o, the coupled voltage, V_2, at Port 2 produced by the applied voltage, V_1, at Port 1 is equal to



(a) (b)

Fig. 1—(a) Quarter-wavelength and (b), three-quarter-wavelength coupled-transmission-line directional couplers.

$$\frac{V_2}{V_1} = \frac{jk \sin\theta}{\sqrt{1-k^2}\cos\theta + j\sin\theta} \tag{1}$$

while the voltage, V_4, at the end of the straight-through arm at Port 4 under these conditions is

$$\frac{V_4}{V_1} = \frac{\sqrt{1-k^2}}{\sqrt{1-k^2}\cos\theta + j\sin\theta}. \tag{2}$$

The voltage, V_3, at Port 3 is zero for all frequencies. Here θ is the electrical length of the coupled-line region.

The midband amplitude coupling factor, k, is given in terms of the even and odd characteristic impedances, Z_{oe} and Z_{oo}, as

$$k = \frac{Z_{oe} - Z_{oo}}{Z_{oe} + Z_{oo}}, \tag{3}$$

while the characteristic impedance Z_o is expressed in terms of the even and odd characteristic impedance as

$$Z_o = \sqrt{Z_{oe}Z_{oo}}. \tag{4}$$

Here Z_{oe} is the even or unbalanced impedance, which is equal to the characteristic impedance of one strip to ground when each strip is at the same potential. The impedance Z_{oo} is the odd or balanced impedance, which is equal to the characteristic impedance of one strip to ground when the strips are at equal but opposite potentials with respect to ground.

ANALYSIS OF THE SLOT-COUPLED STRIP-LINE DIRECTIONAL COUPLER

Fig. 2 shows a slot-coupled strip-line configuration that is particularly suited for weak-coupling applications. The degree of coupling is easily controlled from about −20 db to as low a value as may be desired through the choice of the slot width. For this cross section, the even and odd-mode characteristic imped-

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[1] W. L. Firestone, "Analysis of transmission line directional couplers," PROC. IRE, vol. 42, pp. 1529–1538; October, 1954.

[2] B. M. Oliver, "Directional electromagnetic couplers," PROC. IRE, vol. 42, pp. 1686–1692; November, 1954.

[3] R. C. Knechtli, "Further analysis of transmission-line directional couplers," PROC. IRE, vol. 43, pp. 867–869; July, 1955.

[4] E. F. Barnett, P. D. Lacy, and B. M. Oliver, "Principle of directional coupling in reciprocal systems," *Proc. Symp. Modern Advances in Microwave Techniques*, sponsored by Polytechnic Inst. of Brooklyn, Microwave Res. Inst., Brooklyn, N. Y., vol. 14, pp. 251–268; November, 1954.

[5] G. D. Monteath, "Coupled transmission lines as symmetrical directional couplers," *Proc. IEE, London*, pt. B, vol. 102, pp. 383–392; May, 1955.

[6] E. M. T. Jones and J. T. Bolljahn, "Coupled-strip-transmission-line filters and directional couplers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-4, pp. 75–81; April, 1956.

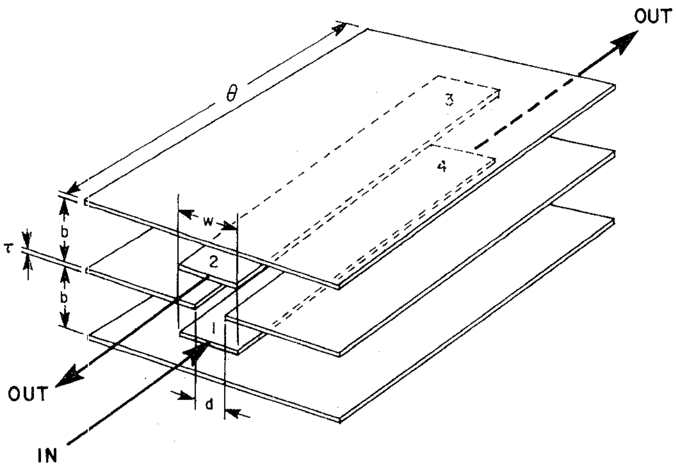

Fig. 2—Slot-coupled strip-line directional coupler.

ances would be difficult to compute rigorously, and therefore an approximate method valid for weak coupling has been used. This method, based on Bethe's[7] small-aperture theory, leads to the following formula for the voltage coupled to Port 2:

$$\frac{V_2}{V_1} = \left(\frac{d^2E_s^2Z_o\sqrt{\epsilon_r}}{1920V^2}\sin\frac{2\pi l}{\lambda}\right)\exp j\left(\frac{\pi}{2}-\frac{2\pi l}{\lambda}\right) \qquad (5)$$

where, in MKS units,

d = width of the coupling slit
λ = wavelength in the strip line
l = length of the coupling slit
E_s = electric field existing normal to the coupling slit in the absence of the slit
Z_o = characteristic impedance of the strip line
V_1 = voltage from one strip to ground
ϵ_r = relative dielectric constant of the medium filling the cross section of the strip line.

Examination of (5) shows that maximum signal is coupled to Port 2 when the slit is a quarter wavelength long. The exact expression for E_s is

$$E_s = \frac{\pi}{b}\,\frac{V_1}{K\left(\operatorname{sech}\frac{\pi}{2}\frac{w}{b}\right)} \qquad (6)$$

where K is a complete elliptic integral of the first kind. When the width of the strips w is much greater than the separation b of the ground planes

$$E_s \approx \frac{2V_1}{b}. \qquad (7)$$

When the coupling aperture has a finite thickness τ, it acts as a waveguide below cutoff having an attenuation α of approximately

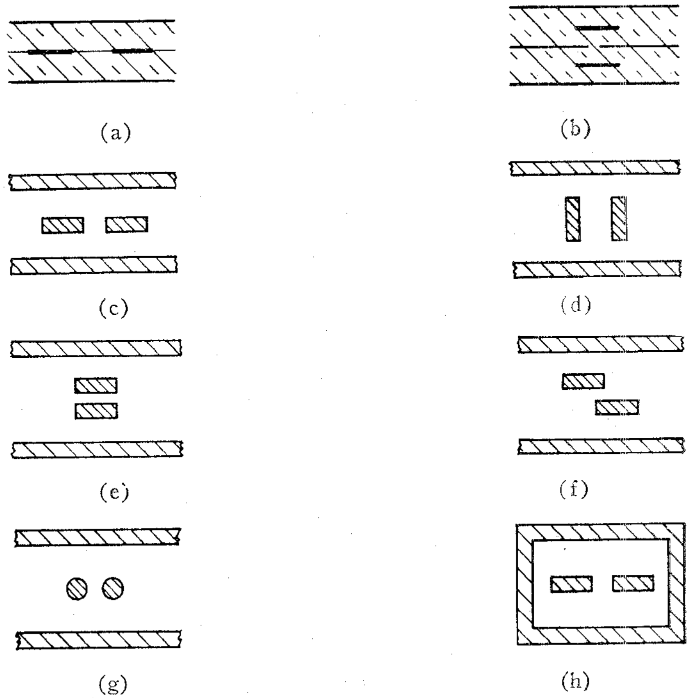
(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 3—(a)–(b) Loosely coupled types of directional-coupler cross sections. (c)–(h) Tightly coupled types of directional-coupler cross sections.

$$\alpha = \frac{27.3\tau}{d}\ \text{(decibels)}. \qquad (8)$$

For the usual values of τ and d encountered in practice the attenuation through the aperture is not negligible, and it is well to apply (8) as a correction to (5). For loose coupling the characteristic impedance of this strip-line coupler will be practically the same as that of a single strip line of the same dimensions.

EXPERIMENTAL QUARTER-WAVELENGTH DIRECTIONAL COUPLERS

Experimental data on a number of quarter-wavelength coupled-strip-line directional couplers are presented. Some of these models utilize the photo-etched cross sections of Fig. 3(a) and 3(b), which are particularly useful for loose coupling (*i.e.*, less than about −8 db) but which, for tighter coupling, require impractically small spacings between the coupled strips. Six other cross sections that are practical for tighter coupling are shown in Fig. 3(c)–(h). Cross sections (c), (d), and (e) have been used successfully in 3-db directional couplers. The cross section (h) was used in a three-quarter-wavelength directional coupler to be described in the next section.

Loosely Coupled Models

Two experimental directional couplers having the cross section of Fig. 3(a) were constructed of copper-clad Teflon-impregnated Fiberglas cloth (GB-116-T) manufactured by Continental Diamond Fiber Company. This material has a nominal relative dielectric constant of 2.8 and a loss tangent of 0.003 at 1000 mc.

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[7] H. A. Bethe, "Lumped Constants for Small Irises," Radiation Lab., Mass. Inst. Tech., Cambridge, Mass., Rep. 43-22; March, 1943.

The strip pattern was cut with a sharp knife on one surface of one sheet, and the unwanted foil was stripped off. The copper foil on the mating surface was removed completely, but on the outer surfaces of the sandwich the foil was left intact to serve as the ground planes. In production, of course, the photo-etching technique would generally be preferred. The design formulas, which apply to all degrees of coupling, are (3) and (4). These relate the coupling factor k and the characteristic impedance Z_o of the connecting lines to the even and odd-mode characteristic impedances Z_{oe} and Z_{oo}. The strip widths and spacings of the two models were computed under the assumption of zero strip thickness, so that Cohn's nomograms[8] could be used. If the thickness had been taken into account, slightly different results might be expected. The actual dimensions of the finished models were measured accurately, and are given in Table I. From these dimensions, the theoretical center frequency, midband coupling, and characteristic impedance of the couplers were computed and are included in the Table. In this calculation, the relative dielectric constant was assumed to be 2.80, and the strip thickness was assumed to be zero.

TABLE I
DIRECTIONAL COUPLER CHARACTERISTICS

Plate Spacing b (inch)	Strip Width w (inch)	Strip Spacing s (inch)	Length of Coupling Region L (inch)	Center Frequency (kmc)	Theoretical Midband Coupling (db)
0.123	0.0498	0.0081	0.56	2.84	− 8.9
0.123	0.0597	0.028	0.57	2.9	−15

Fig. 4(a) and 4(b) shows a comparison between the theoretical and experimental values of coupling of these models as a function of frequency.[9] It is seen that the coupling at midband is almost exactly that predicted by theory, while the deviations at other frequencies are undoubtedly due to constructional irregularities and mismatch effects.

An experimental model of the slot-coupled directional coupler of Fig. 3(b) was designed by means of (5). Four layers of Teflon-impregnated glass cloth were used, with the attached copper foil cut and stripped away as necessary to form the two strips, the three ground planes and the coupling slot. The actual measured plate spacing was 0.122 inch, the strip width 0.220 inch, the slit width 0.0713 inch, and the length of the coupling region 0.57 inch. From these dimensions, the theoretical center frequency was computed to be 2.9 kmc, the midband coupling −31.2 db, and the characteristic impedance of the terminating lines 25.0 ohms. The theoretical and experimental coupling curves plotted in Fig. 4(c) show a discrepancy of only about 0.6 db.[9]

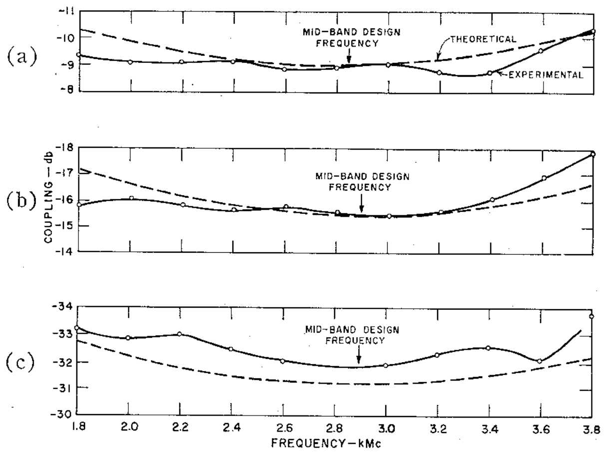

Fig. 4—Measured performance of coupled-strip-line quarter-wavelength directional couplers.

The measured directivities of the three directional couplers averaged about 20 db. Fixed terminations having VSWR's of about 1.1 were used, and therefore better matched terminations (or the use of sliding terminations) would most likely lead to the measurement of higher directivity.

Models Having 3-db Couplings

Three types of 3-db strip-line directional couplers have been constructed and tested and their performance described.[10] A summary of the performance of one of these couplers is presented here.

Fig. 5 shows a photograph of the interior of this coupler, and its pertinent dimensions are summarized in Table II. The 50-ohm strip transmission lines are joined to the coupled strips by smooth transitions. Residual reflections are canceled by means of the conducting cylindrical posts placed at the ends of the coupling region. The dimensions of the tapered transition between the 50-ohm strip lines and the Type-N connectors were determined experimentally with the aid of the strip-line standing-wave meter which was constructed at Stanford Research Institute, Menlo Park, Calif. The measured VSWR of the transition in series with a matched pair of Type-N connectors varied from 1.03 to 1.07 over the frequency range 800–1600 mc.

All metal parts of the directional coupler were machined from brass stock. The center conductors were supported at their ends by the Type-N connectors, and small polyfoam supports above and below the coupled lines held them centered between the ground planes. Also, two small polystyrene spacers were placed between the coupled strips to maintain an accurate gap

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[8] S. B. Cohn, "Shielded coupled-strip transmission line," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-3, pp. 32–33; October, 1955.

[9] The actual measured coupling included about 0.5 db of dissipation loss in the connecting strip lines. Therefore, all values of measured coupling were increased by 0.5 db to obtain the coupling that would be measured if the strip lines were lossless. It is the corrected values of coupling that are plotted in Fig. 4.

[10] J. K. Shimizu, "Strip-line 3-db directional couplers," 1957 IRE WESCON CONVENTION RECORD, pt. 1, pp. 4–15.

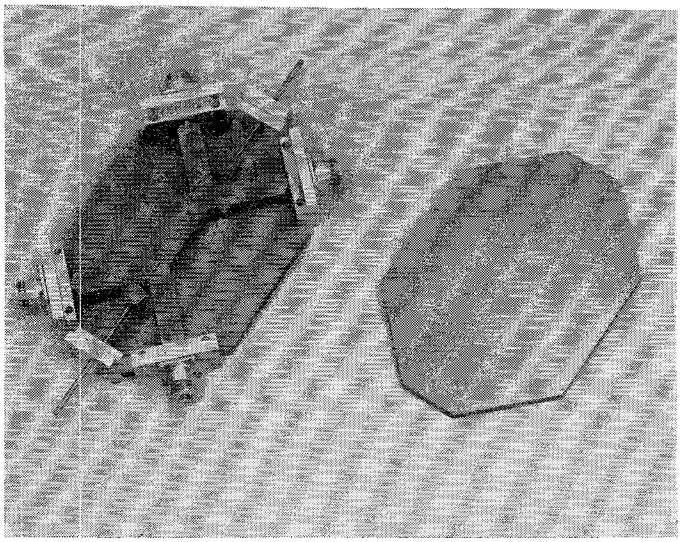

Fig. 5—800–1600 mc 3-db strip-line directional coupler.

TABLE II

Dimensions of 3-db Directional Coupler

Dimension	Frequency Range (mc)
	800–1600
Center frequency (mc)	1200
Input impedance-Z_o (ohms)	50
Theoretical midband coupling (db)	-2.7
Midband coupling factor k	0.734
Z_{oe} (ohms)	127.8
Z_{oo} (ohms)	19.6
Plate spacing b (inch)	0.500
Strip thickness t (inch)	0.063
Strip width w (inch)	0.185
Strip spacing s (inch)	0.0084
Length of coupling region l (inch)	2.460
Terminating lines (inch)	$w=0.550$, $t=0.063$

spacing. These spacers had no appreciable effect on the electrical performance of the coupler.

The experimental data for this coupler is plotted in Fig. 6. In order to achieve this performance the positions of the matching posts were adjusted for minimum VSWR and maximum directivity at the center frequency of 1200 mc. The coupling response of the coupler shown in Fig. 6 is $-(3\pm0.3)$ db over its 2:1 frequency band. The VSWR of the coupler is less than 1.2 over the band. The VSWR and directivity measurements of the coupler were made with the aid of sliding loads placed on Ports 2 and 4. Hence, these measurements include the mismatch of the coaxial transitions as well as the mismatch of the couplers.

Theory of the Three-Quarter-Wavelength Directional Coupler

Recently Barnett, Lacy, and Oliver[4] have shown that improved bandwidth can be obtained compared to that of the quarter-wavelength directional coupler by connecting three coupled pairs of lines in cascade in the manner shown in Fig. 1(b). Theoretically, this composite *three-quarter-wavelength* coupler can be made to have infinite directivity and constant input impedance at all frequencies, and for all values of coupling, if each of the cascaded couplers has the same characteristic impedance. The formula given by Barnett, Lacy, and Oliver[4] for the coupling of this directional coupler applies only for weak coupling because of the simplifying assumptions made at the beginning of their analysis. In this section, formulas are given for the three-quarter-wavelength directional coupler that are valid for all degrees of coupling. Also, design information and experimental results are presented for 3-db couplers of this type.

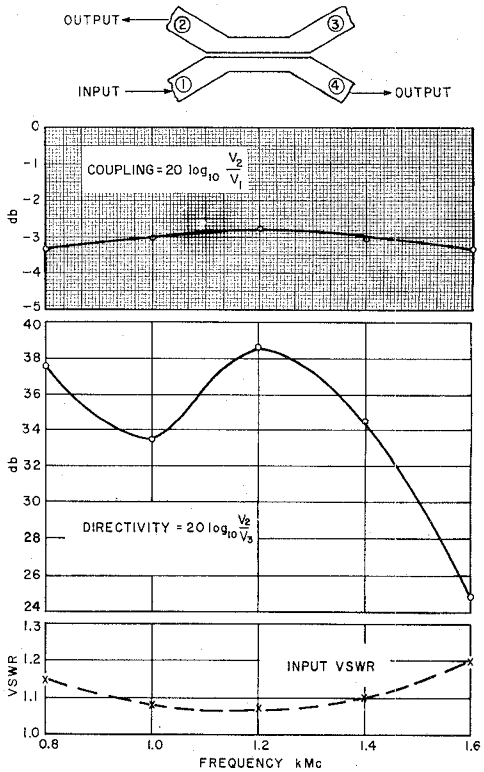

Fig. 6—Experimental performance of the 800–1600-mc 3-db strip-line directional couplers.

A theoretical analysis of strong coupling is presented by Cohn, Sherk, Shimizu, and Jones.[11] They show that in order for the composite directional coupler to have a perfect match at all frequencies, it is necessary that each individual coupler have the characteristic impedance, Z_o, of the transmission lines connected to the coupler. Thus

$$\sqrt{Z_{oo}Z_{oe}} = \sqrt{Z_{oo}'Z_{oe}'} = Z_o. \tag{9}$$

Here, Z_{oe} and Z_{oo} are the even and odd characteristic impedances, with the unprimed and primed values denoting the characteristic impedance of the center and end couplers, respectively, as shown in Fig. 7. Eq. (9) also ensures that the composite directional coupler will have infinite directivity, since each individual coupler

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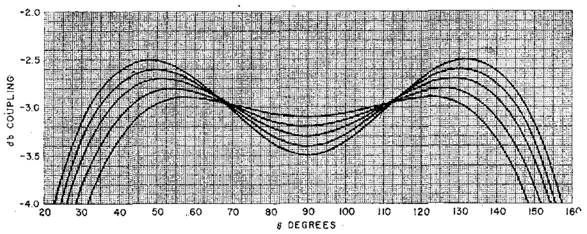
[11] S. B. Cohn, P. M. Sherk, J. K. Shimizu, and E. M. T. Jones, "Strip Transmission Lines and Components," Stanford Res. Inst., Menlo Park, Calif. Final Rep. on SRI Proj. 1114, Contract DA 36-039 SC-63232, DA Proj. 3-26-00-600, SC Proj. 2006A; March, 1957.



Coupling Deviation db	k	k′	k_o	$\frac{k'}{k}$
±0.1	0.8273	0.15505	0.6998	0.18741
±0.2	0.8405	0.18367	0.6918	0.21852
±0.3	0.85241	0.21104	0.6839	0.24758
±0.4	0.86119	0.23371	0.6760	0.27138
±0.5	0.86838	0.25373	0.6683	0.29218

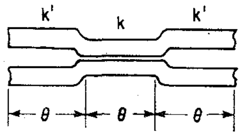


Fig. 7—Equal-ripple response of three-quarter-wavelength directional couplers.

has infinite directivity when it is matched to the connecting transmission lines of characteristic impedance Z_o.

Subject to the condition given in (9) and with all the ports of the directional coupler as shown in Fig. 1(b) terminated by Z_o, the coupled voltage, V_2, at Port 2 produced by the applied voltage, V_1, at Port 1 is equal to

$$\frac{V_2}{V_1} = \frac{j\left[\left(\frac{3k_0}{\sqrt{1-k_0^2}}+\frac{2k'}{\sqrt{1-k'^2}}+\frac{k}{\sqrt{1-k^2}}\right)\sin\theta - \left(\frac{k_0}{\sqrt{1-k_0^2}}-\frac{2k'}{\sqrt{1-k'^2}}-\frac{k}{\sqrt{1-k^2}}\right)\sin 3\theta\right]}{\left\{\left[2-\sqrt{\frac{(1+k)(1-k')}{(1-k)(1+k')}}-\sqrt{\frac{(1-k)(1+k')}{(1+k)(1-k')}}\right]\cos\theta + \left[2+\sqrt{\frac{(1+k)(1-k')}{(1-k)(1+k')}}+\sqrt{\frac{(1-k)(1+k')}{(1+k)(1-k')}}\right]\cos 3\theta + j\left[\left(\frac{1}{\sqrt{1-k^2}}+\frac{2}{\sqrt{1-k'^2}}-\frac{3}{\sqrt{1-k_0^2}}\right)\sin\theta + \left(\frac{1}{\sqrt{1-k^2}}+\frac{2}{\sqrt{1-k'^2}}+\frac{1}{\sqrt{1-k_0^2}}\right)\sin 3\theta\right]\right\}}. \tag{10}$$

The voltage at Port 3 is zero because each of the individual directional couplers has infinite directivity and the same characteristic impedance Z_o as the terminating lines. By conservation of energy the voltage at Port 4 is

$$\left|\frac{V_4}{V_1}\right| = \left[1-\left(\frac{V_2}{V_1}\right)^2\right]^{1/2}. \tag{11}$$

Here θ is the electrical length of the coupled line of each section and k_0, k, and k' are respectively the midband coupling factor of the three-quarter-wavelength composite directional coupler, the center coupler, and the end coupler.

The midband coupling factor k_0 of the three-quarter-wavelength composite directional coupler is given by

$$k_0 = \frac{\frac{Z_{oe}}{Z_{oo}}\left(\frac{Z_{oo}'}{Z_{oe}'}\right)^2 - 1}{\frac{Z_{oe}}{Z_{oo}}\left(\frac{Z_{oo}'}{Z_{oe}'}\right)^2 + 1} \tag{12}$$

while the midband coupling factor of the center coupler is

$$k = \frac{\frac{Z_{oe}}{Z_{oo}} - 1}{\frac{Z_{oe}}{Z_{oo}} + 1} \tag{13}$$

and that of the end couplers is

$$k' = \frac{\frac{Z_{oe}'}{Z_{oo}'} - 1}{\frac{Z_{oe}'}{Z_{oo}'} + 1}\cdot \tag{14}$$

For very weak coupling (10) reduces to

$$V_2 = jV_1(k_1 \sin\theta + k_3 \sin 3\theta)e^{-j3\theta} \tag{15}$$

where k_1+k_3 and k_3 are the midband voltage coupling factors of the center and end sections, respectively.

One of the most useful forms of the three-quarter-wavelength directional coupler is one that has an equal-ripple frequency variation of coupling. Design information for such couplers is obtained by numerical substitution in (10) and (15).

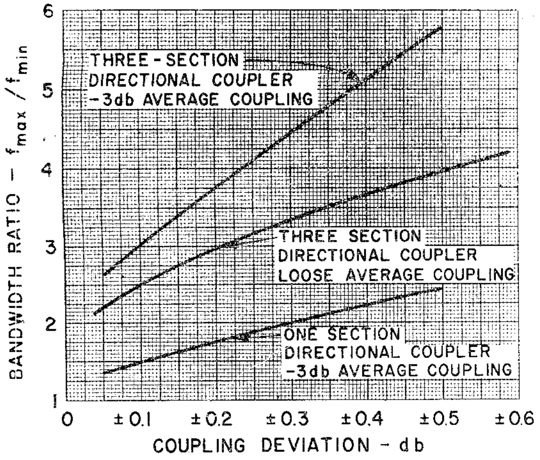


Fig. 8—Bandwidth of various directional couplers.

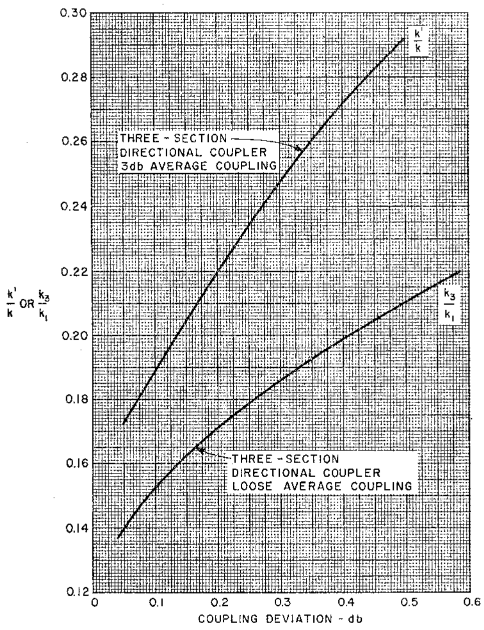


Fig. 9—Design data for three-quarter-wavelength directional couplers.

Fig. 7 shows the variation of coupling with frequency of directional couplers having equal-ripple variations of ±0.1, ±0.2, ±0.3, ±0.4, and ±0.5 db. Fig. 8 shows the bandwidth of operation vs coupling deviation for three-quarter-wavelength and quarter-wavelength directional couplers having an average coupling of −3 db, and for a three-quarter-wavelength coupler having very loose coupling. The ratio of k'/k and k_3/k_1 necessary to achieve this performance with a three-quarter-wavelength coupler is shown in Fig. 9.

It is seen that the −3-db three-quarter-wavelength coupler has an extremely wide bandwidth of operation. For example, a bandwidth of 5.8:1 can be obtained for a maximum coupling deviation of ±0.5 db. Since such a bandwidth is almost unparalleled in microwave components at the present time, it is anticipated that these couplers will find wide application.

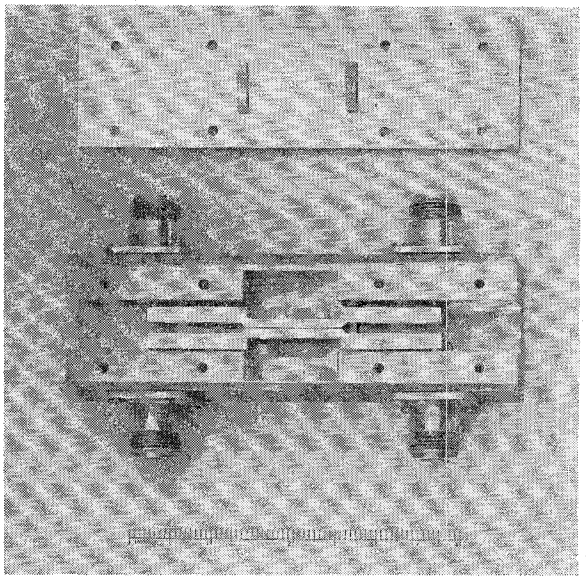


Fig. 10—1.1–3.6-kmc 3-db strip-line directional coupler.

EXPERIMENTAL THREE-QUARTER-WAVELENGTH DIRECTIONAL COUPLER

A photograph of an experimental 3-db strip-line three-quarter-wavelength directional coupler is shown in Fig. 10. This directional coupler was designed to operate over a 3:1 frequency band centered at 2400 mc with a ±0.1-db coupling deviation around −3 db. Necessary coupling factors, k, k', and k_0, for the design of this coupler are tabulated in Fig. 7. Examination of the coupling factors $k=0.8273$ and $k'=0.15505$ shows that at midband the coupling of the center coupler is −1.75 db and that of the end couplers is −16.2 db. The input impedance of this coupler was chosen to be $Z_o=50$ ohms, and the even and odd characteristic impedances of the center and end couplers were computed from (9), (13), and (14) to be $Z_{oe}=162.6$ ohms, $Z_{oo}=15.4$ ohms, $Z_{oe}'=58.5$ ohms and $Z_{oo}'=42.8$ ohms. To achieve reasonable separation between the conductors, the coupling cross section given in Fig. 3(c) was used for the center coupler. However, for the two end couplers, a calculation of the strip dimensions of the cross section given in Fig. 3(c) indicated that the strip widths of the end couplers would have to be approximately five times wider than the center coupler strip widths. In order to reduce this large discontinuity, the cross section of Fig. 3(h) was used for the end couplers. Inspection of the strip cross sections of Fig. 3(c) shows that when conducting side walls are introduced, the dimensions of the coupling slot between the coupled strips need not be altered, but the strip widths must be reduced to maintain the same capacitances to ground. That is, it is only necessary to equate the capacitances of the two cross sections of Fig. 3(c) and 3(h) to each other in order to maintain the same characteristic impedances. Calculations showed that the strip width is reduced to 0.176 inch from 0.488 inch by using the cross section of Fig.

3(h) rather than the one shown in Fig. 3(c), when the side walls are located 0.050 inch away from the strip.

The principal dimensions of the experimental three-quarter-wavelength directional coupler are included in Table III. As may be seen in Fig. 10, each end coupler strip was joined to its terminal by the round center conductor emerging from the coaxial line. The design of this junction was determined experimentally with the aid of the strip-line standing-wave meter. The measured VSWR of the transition in series with a pair of male and female Type-N connectors varied from 1.01 to 1.09 over the frequency range of 1.3 to 4 kmc. To match the junction over this frequency range, it was necessary to extend the strips slightly beyond the junction as shown in Fig. 10. Residual reflections resulting from the steps between the center coupler and end coupler strips were partially canceled by adding a 45-degree transition at each step, and by placing ridges on the ground planes near these points. These matching structures are visible in Fig. 10.

TABLE III

Dimensions of Three-Quarter-Wavelength Directional Coupler

Plate spacing, b	0.500 inch
Strip thickness, t	0.125
Mid-section strip width, w	0.107
Mid-section strip spacing, s	0.0096
End-section strip width, w'	0.176
End-section strip spacing, s'	0.135
Spacing between capacitive wall and edge of strip, s'	0.053
Length of each coupling region, L	1.110

The center conductors and ground planes of this directional coupler were machined from brass stock. The center conductors were supported at their ends by the Type-N connectors. Small polyfoam supports placed above and below the coupled lines held them centered between the ground planes. The gap between the center coupler coupled strips was maintained accurately by means of two small polystyrene spacers.

The experimental data for this directional coupler are plotted in Fig. 11. The coupling response averages -3 db with ± 0.1-db variation from 1.1 to 3.6 kmc. The VSWR over this frequency range is under 1.31. The VSWR was measured with the aid of sliding loads placed on Ports 2 and 4, and hence includes the mismatch of the strip-to-coax transition and connector pair between the strip line and the 50-ohm coaxial load, as well as the mismatch of the coupler. Within the coupler, the mismatch due to the steps between the center coupler and end coupler strips is believed to be particularly important.

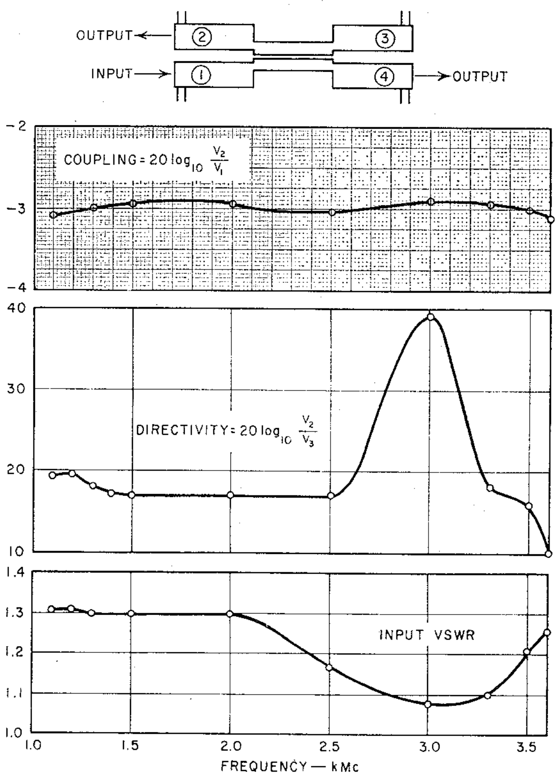


Fig. 11—Experimental performance of 1.1–3.6–kmc 3-db strip-line directional coupler.

The directivity response of this directional coupler, measured with the aid of sliding loads on Ports 2 and 3, varies from 17 to 39 db over the 3:1 band from 1.1 to 3.3 kmc. However, at 3.6 kmc the minimum directivity drops to 10 db. A higher directivity response could certainly be obtained by further work on the various discontinuities.

Conclusion

For all the strip-line directional couplers presented here, very close agreement has been obtained between experiment and theory. The 3-db quarter-wavelength directional coupler has almost constant coupling over a two-to-one frequency band, while the three-quarter-wavelength coupler has almost constant coupling over bandwidths up to 5:1. The various quarter-wavelength directional couplers discussed in this paper have sufficiently good performance to warrant immediate application, while with additional development to improve its directivity, the three-quarter-wavelength model should prove highly useful.

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