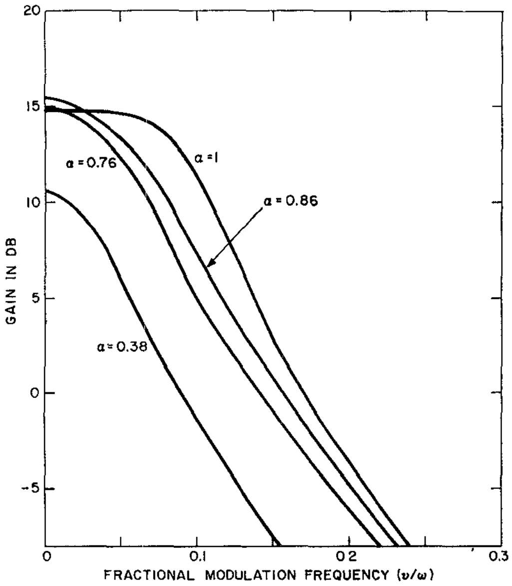

Fig. 12—Network response for several values of transmission factor and $r=1.333$, $\omega CoZo=6$.

first setting up the network problem for constant parameter elements, and then formally substituting the hypercomplex representation for the ordinary admittance functions. In this manner the solution of variable parameter circuits can take advantage of the existing methods of ordinary circuit analysis.

Appendix I

Notation

In general, the notation used throughout this paper is based on the conventional symbols of circuit theory and each term is defined as introduced. However, in our work, voltages and currents are represented by real vectors and by complex vectors, in addition to their usual forms. Impedances and admittances may also be real or complex matrices. To distinguish between the various mathematical forms for these quantities we introduce the following notation:

Vectors (*e.g.*, $\mathbf{V}$, $\mathbf{I}$): denoted by bold-face.

Matrices (*e.g.*, $\overline{Y}$): denoted by horizontal bar.

Unit matrices of the hypercomplex representation $(1, \hat{\jmath}, \hat{k}, \hat{l})$: denoted by circumflex (^). (Observe that this notation distinguishes between $j=\sqrt{-1}$ and the unit matrix

$$\hat{\jmath} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}.$$

Complex quantities (*e.g.*, $\overline{Y}^{\sim}$, $\mathbf{V}^{\sim}$): denoted by tilde (~) next to the symbol.

Acknowledgment

The authors wish to acknowledge many profitable discussions during the course of this work with K. E. Schreiner and M. G. Smith.

Broad-band Directional Couplers*

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Summary—**It is shown how to connect two identical hybrids to obtain a directional coupler of arbitrary power division that operates over a broader band than that of the components. The broadbanding technique is possible with a certain kind of hybrid that includes Riblet couplers, multihole hybrids, coaxial hybrids and semioptical hybrids, but excludes *T* hybrids and ring hybrids.**

Riblet couplers have a geometry particularly adaptable to the broad-banding technique. Where the balance of one of these couplers is better than 1 db, the balance of the broad-band hybrid can be made better than 0.16 db.

The broad-banding technique is particularly effective in the case of the 100 per cent transfer directional coupler type of circuit used for band separation filters and radar duplexers. In the semioptical waveguide band-splitting filters the bandwidth can be increased from about one to about four octaves (35–75 kMc to 35–580 kMc).

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Introduction

In a large variety of directional couplers such as the Riblet coupler,[1] the multihole directional coupler,[2] the coaxial directional coupler[3] and the semioptical directional coupler,[4] the power division varies with frequency. We show here that it is possible to connect two identical hybrids[5] in such a way that the

[1] H. J. Riblet, "The short-slot hybrid junction," Proc. IRE, vol. 40, pp. 180–184; February, 1952.
[2] S. E. Miller, "Coupled wave theory and waveguide applications," *Bell Sys. Tech. J.*, vol. 33, pp. 661–719; May, 1954.
[3] E. A. Marcatili, "A circular electric hybrid junction and some channel-dropping filters," *Bell Sys. Tech. J.*, vol. 40, pp. 185–196; January, 1961.
[4] E. A. Marcatili and D. L. Bisbee, "Band-splitting filter," *Bell Sys. Tech. J.*, vol. 40, pp. 197–212; January, 1961.
[5] As usual we understand the hybrid to be a directional coupler with 50–50 power division at least at one frequency of the band of operation.

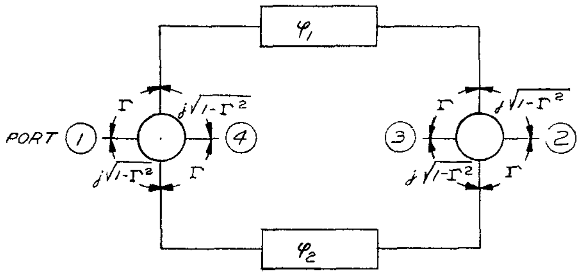

Fig. 1—Broad-banded directional coupler.

final device is a directional coupler with any desired power division and that this power division is far less frequency-sensitive than that of the components.

The broad-banding technique is possible only using matched hybrids whose scattering matrices are symmetrical with respect to both diagonals and are independent of the order in which the ports are selected. Hybrids of the types mentioned at the beginning satisfy this requirement but T hybrids and ring hybrids do not.

An outstanding result is achieved by using the broad-banding technique in the band-splitting filters proposed for the long-distance waveguide communication system.[6] Up to now the band of those filters was limited to approximately one octave, 35–75 kMc, but the broad-banding technique widens the spectrum to four octaves, 35–580 kMc.

Broad-Banding Technique

Consider a matched and lossless directional coupler with scattering matrix symmetric with respect to both diagonals irrespective of the order in which the ports are selected. Because of the symmetry demand and because of conservation of energy,[7] the scattering matrix is

$$e^{j\theta}\begin{vmatrix} 0 & \Gamma & \pm j\sqrt{1-\Gamma^2} & 0 \\ \Gamma & 0 & 0 & \pm j\sqrt{1-\Gamma^2} \\ \pm j\sqrt{1-\Gamma^2} & 0 & 0 & \Gamma \\ 0 & \pm j\sqrt{1-\Gamma^2} & \Gamma & 0 \end{vmatrix}$$

where Γ is a positive quantity smaller than one and θ is an angle that depends on the location of the planes of reference.

Power entering in one port divides in two outputs, Γ^2 and $1-\Gamma^2$. Their ratio measures the power balance of the directional coupler.

$$r = \frac{1}{\Gamma^2} - 1 \tag{1}$$

Now let us connect two of these directional couplers through the two paths of electrical lengths, ϕ_1 and ϕ_2, as in Fig. 1. This device is also a directional coupler which we shall call broad-banded. Power entering in port 1 splits in ports 2 and 3, and the ratio between these outputs measures the balance of the broad-banded directional coupler

$$R = \frac{P_3}{P_2} = \frac{(1+r)^2}{4r}\sec^2\frac{\phi}{2} - 1 \tag{2}$$

where[8]

$$\phi = \phi_1 - \phi_2. \tag{3}$$

Let us plot R and $1/R$ as a function of r using ϕ as a parameter, Figs. 2 and 3. Each curve passes through a minimum (Fig. 2) or a maximum (Fig. 3) for $r=1$. This means that the power division R or $1/R$ of the broad-banded coupler made of two hybrids is insensitive to the first-order variations of the power division r of these hybrids. As a limiting case, for $\phi=\pi$ (Fig. 3) $1/R=0$ independently of the value of r. This important fact will be used later on to broad-band a band-splitting filter.

In general, not only r but ϕ also is frequency dependent and, in principle, it is possible to design the paths connecting the hybrids in such a way that ϕ tracks r making R frequency-independent. This is not an easy task. What we can easily do is to build both paths out of waveguides of constant cross section but different lengths L_1 and L_2 and different guided wavelengths λ_{g1} and λ_{g2}. Thus

$$\phi = 2\pi\left(\frac{L_1}{\lambda_{g1}} - \frac{L_2}{\lambda_{g2}}\right). \tag{4}$$

It is possible to select L_1, L_2 and the cutoff wavelengths λ_{c1} and λ_{c2} to minimize the frequency sensitivity of the power division R of the broad-banded coupler.

We will consider two cases: 1) broad-banded coupler

[6] S. E. Miller, "Waveguide as a communication medium," *Bell Sys. Tech. J.*, vol. 33, pp. 1209–1265; November, 1954.

[7] N. Markuvitz, "Waveguide Handbook," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., 1st ed., vol. 10, p. 108; 1951.

[8] If the hybrids are not matched, lossless and identical, R is substantially more complicated. Nevertheless, for the two cases of interest discussed later ($r\simeq 1$ and $\phi=\pi/2$ or $\phi=\pi$), first-order effects on r become in general second-order effects on R and consequently we can assume the hybrids to be matched, lossless and identical without seriously impairing the validity of the results and without uselessly complicating the analysis.

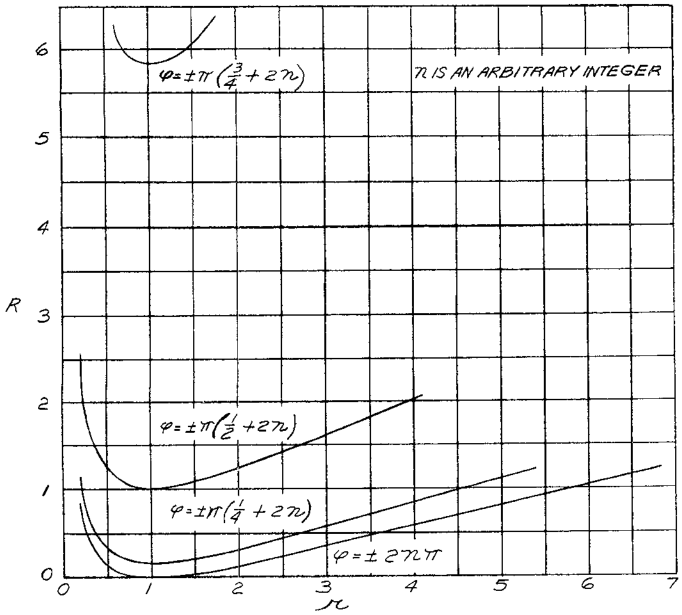

Fig. 2—Power division of a broad-banded coupler.

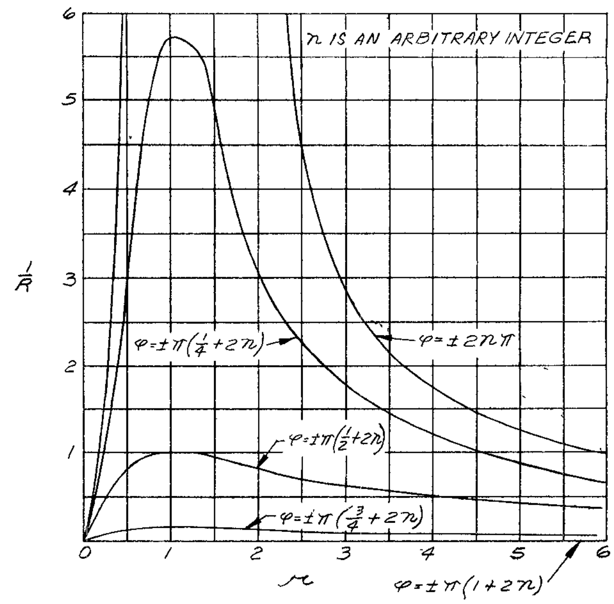

Fig. 3—Inverse of the power division of a broad-banded coupler.

in dominant mode waveguide, and 2) broad-banded coupler in multimode waveguide. The solutions of these cases differ only in the approximations involved.

Broad-Banded Coupler in Dominant Mode Waveguide

We want to minimize the wavelength sensitivity of the power division, (2), of a broad-banded coupler that operates in dominant mode waveguide.

The useful bandwidth covers only a few per cent around the center wavelength λ_0. Then let us expand r and ϕ in Taylor's series.

$$r = 1 + \delta r' + \frac{\delta^2}{2!} r'' + \cdots \tag{5}$$

$$\phi = \phi_0 + \delta\phi' + \frac{\delta^2}{2!}\phi'' + \cdots \tag{6}$$

where

$$\delta = \frac{\lambda - \lambda_0}{\lambda_0} \tag{7}$$

$$r^{(n)} = \lambda_0^n \frac{d^n r}{d\lambda^n} \tag{8}$$

$$\phi^{(n)} = \lambda_0^n \frac{d^n \phi}{d\lambda^n} \tag{9}$$

and the derivatives are taken at $\lambda = \lambda_0$.

If one selects

$$L_2 = \frac{\lambda_{g10}}{\lambda_{g20}} L_1 \tag{10}$$

where λ_{g10} and λ_{g20} are the guided wavelengths in the two paths at $\lambda = \lambda_0$, it follows from (4), (9) and (10) that

$$\phi_0 = \frac{2\pi L_1}{\lambda_{g10}}\left(1 - \frac{\lambda_{g10}^2}{\lambda_{g20}^2}\right) \tag{11}$$

$$\phi' = 0 \tag{12}$$

$$\phi'' = \phi_0\left(\frac{\lambda_{g10}\lambda_{g20}}{\lambda_0^2}\right)^2. \tag{13}$$

Substituting (5) and (6) in (2) and replacing the values of ϕ' and ϕ'' found in (12) and (13), one obtains an approximate expression for the power division

$$R = \tan^2\frac{\phi_0}{2} \cdot \left[1 + \left(\frac{\delta}{2}\right)^2 \frac{(r')^2 + \left(\dfrac{\lambda_{g10}\lambda_{g20}}{\lambda_0^2}\right)^2 2\phi_0 \tan\dfrac{\phi_0}{2}}{\sin^2\dfrac{\phi_0}{2}}\right]. \tag{14}$$

Terms with powers of δ bigger than two have been neglected and the result is not valid in the neighborhood of $\phi_0 = \pm\pi$ because the term in δ^2 diverges

The power division of the broad-banded coupler R is proportional to δ^2 and therefore is far less frequency-sensitive than the power division of each component (5), which is proportional to δ. Furthermore, R is independent of r''. This means that if $r' = 0$, as it may be with multihole directional couplers, then R varies only because of the frequency sensitivity of the connecting paths.

Assume for the time being that in (14)

$$(r')^2 + \left(\frac{\lambda_{g10}\lambda_{g20}}{\lambda_0^2}\right)^2 2\phi_0 \tan\frac{\phi_0}{2} > 0; \tag{15}$$

then, the power division of the broad-banded coupler is a parabola with a minimum

$$R_0 = \tan^2\frac{\phi_0}{2} \tag{16}$$

at $\delta=0$. At $\delta = \pm\delta_m$ the power division is

$$R_m = \tan^2\frac{\phi_0}{2} \cdot \left[1 + \left(\frac{\delta_m}{2}\right)^2 \frac{(r')^2 + \left(\frac{\lambda_{g10}\lambda_{g20}}{\lambda_0^2}\right)^2 2\phi_0 \tan\frac{\phi_0}{2}}{\sin^2\frac{\phi_0}{2}}\right]. \tag{17}$$

The wavelengths associated with $\pm\delta_m$ are deduced from (7)

$$\begin{cases}\lambda_a = \lambda_0(1-\delta_m)\\ \lambda_b = \lambda_0(1+\delta_m).\end{cases} \tag{18}$$

We define them to be the extreme wavelengths of the band of operation of the broad-banded coupler and therefore R_0 and R_m are the minimum and maximum power divisions of the coupler. We minimize the departure of R_0 and R_m from the ideal power division R_i by making

$$R_m - R_i = R_i - R_0. \tag{19}$$

Substituting the expressions given in (16) and (17) for R_0 and R_m in (19), one derives

$$\phi_0 = \pm 2\left\{\tan^{-1}[R_i(1-\Delta)]^{1/2} + n\pi\right\} \tag{20}$$

where

$$\Delta = \frac{1}{2}\left(\frac{\delta_m}{2}\right)^2\left(1+\frac{1}{R_i}\right) \cdot \left[(r')^2 + \left(\frac{2\lambda_{g10}\lambda_{g20}}{\lambda_0^2}\right)^2 \sqrt{R_i}(\tan^{-1}\sqrt{R_i} + n\pi)\right], \tag{21}$$

n is an integer, and the inverse trigonometric function is chosen in the first quadrant.

The explicit values of R_0 and R_m are derived from (16), (17) and (20).

$$R_0 = R_i(1-\Delta) \tag{22}$$

$$R_m = R_i(1+\Delta). \tag{23}$$

The reader can check that these results are also valid if

$$(r')^2 + \left(\frac{\lambda_{g10}\lambda_{g20}}{\lambda_0^2}\right)^2 2\phi \tan\frac{\phi_0}{2} < 0, \tag{24}$$

only that now R_m is the minimum power division achieved by the broad-banded coupler in the band of interest and R_0 is the maximum.

Let us elaborate a numerical example. We want a broad-banded hybrid that operates between

$$\lambda_a = 0.9\lambda_0 \tag{25}$$

$$\lambda_b = 1.1\lambda_0. \tag{26}$$

The power division of each component hybrid is

$$r = 1 + 2.6\delta \tag{27}$$

and consequently,

$$r' = 2.6. \tag{28}$$

Then the power division r at λ_a and λ_b is approximately ± 1 db. What are the maximum and the minimum power division of the broad-banded hybrid and what are the dimensions of the connecting paths?

The ideal power division of a hybrid is

$$R_i = 1 \tag{29}$$

and the extreme values of δ are deduced from (18), (25) and (26).

$$\delta_m = \pm 0.1. \tag{30}$$

The substitution of these numerical values in (11), (12), (20), (22) and (23) yields

$$R_0 = 1 - \Delta \tag{31}$$

$$R_m = 1 + \Delta \tag{32}$$

$$\Delta = 0.0025\left[2.6^2 + \left(\frac{\lambda_{g10}\lambda_{g20}}{\lambda_0^2}\right)^2 (4n+1)\pi\right] \tag{33}$$

$$L_1 = \pm\frac{\lambda_{g10}}{\pi\left(1 - \frac{\lambda_{g10}^2}{\lambda_{g20}^2}\right)}\left[\tan^{-1}(1-\Delta)^{1/2} + n\pi\right]. \tag{34}$$

Since we want to make Δ as small as possible we choose[9]

$$n = 0 \tag{35}$$

and we should select

$$\lambda_{g10} \cong \lambda_{g20} \cong \lambda_0, \tag{36}$$

but L_1 and L_2 given by (10) and (34) would be long. The choice of λ_{g10} and λ_{g20} must be made then as a compromise to the demands on Δ, L_1 and L_2.

Let us choose arbitrarily[10]

$$\frac{\lambda_{g20}}{\lambda_0} = 1.3 \tag{37}$$

and

$$\frac{\lambda_{g10}}{\lambda_0} = 1.25. \tag{38}$$

[9] The reader should notice that if r' in (21) were big enough, it would be possible to choose n negative and make $\Delta=0$. Then the power division R would be sensitive only to powers of δ bigger than two.

[10] For $\lambda_0 = 3$ cm, (10 kMc) and *RG* 52/*U* waveguide, $\lambda_{g20}/\lambda_0 = 1.3$.

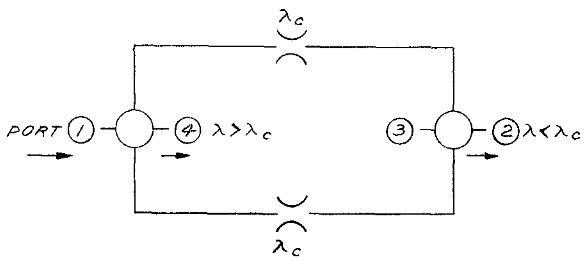

Fig. 4—Schematic of a band-splitting filter.

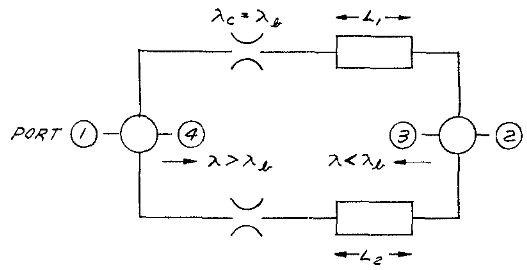

Fig. 5—Schematic of a broad-banded band-splitting filter.

Then substituting (35)–(37) in (31)–(34) and (10), one derives

$$10 \log_{10} R_0 = -0.16 \text{ db} \tag{39}$$

$$10 \log_{10} R_m = 0.16 \text{ db} \tag{40}$$

$$L_1 = 4.16\lambda_0 \tag{41}$$

$$L_2 = 4\lambda_0. \tag{42}$$

For $0.9\lambda_0 < \lambda < 1.1\lambda_0$ the power division of the component hybrids is better than ± 1 db, while that of the broad-banded hybrid is better than ± 0.16. The dimensions of the connecting paths are derived from (37), (38), (41) and (42).

Broad-banded Coupler in Multimode Waveguide

The band of operation of a band-splitting filter[4] can be made several times wider by using the broad-banding technique described in this memorandum.

A band-splitting filter is a device of paramount importance for the separation of channels in the proposed long-distance waveguide communication system.[6] It consists of two hybrids connected by two identical paths, as shown in Fig. 4. Each path has a high-pass filter that cuts off all wavelengths longer than λ_c. Power entering in port 1 divides equally between the two balanced arms and travels towards the second hybrid. Power at $\lambda < \lambda_c$ passes through the filters and is delivered to port 2. Power at $\lambda > \lambda_c$ is rejected by the filters and is delivered to port 4. It has been shown[4] that even when the power division of the hybrids is as poor as 3 db the power recovered in ports 2 or 4 has only 0.5-db insertion loss. The hybrids available have a better balance than 3 db from 35–75 kMc (8.57–4 mm). Beyond that range the band-splitting filter behaves poorly.

In order to handle a much wider band with the same hybrids we can follow two different methods. One of them consists in broad-banding each one of the hybrids as explained previously; but then, each band-splitting filter requires four hybrids and furthermore, the band of operation of the broad-banded filter is limited by the frequency sensitivity of the power division of each component hybrid as shown in Fig. 3, for $\phi = \pi/2$. A second method that bypasses these drawbacks consists in treating the hybrids of the band-splitting filter for $\lambda < \lambda_c$ as the components of a broad-banded directional coupler with ideal power division $1/R_i = 0$. As shown in Fig. 3, for $\phi = \pi$ the power division $1/R$ is independent of the power division r of the component hybrids.

Fig. 5 depicts the broad-banded band-splitting filter. For wavelengths $\lambda > \lambda_c$ the plain and the broad-banded filters, Figs. 4 and 5, are identical. We know that the shortest wavelength at which the available semioptical hybrids[4] used in the band-splitting filter provides tolerable insertion loss (0.5 db) is 4 mm; therefore we choose $\lambda_c = 4$ mm. This is also the longest wavelength that must be received by the second hybrid and consequently is the longest wavelength of operation of the broad-banded coupler. Then

$$\lambda_b = \lambda_c = 4 \text{ mm}. \tag{43}$$

What is the power division R of the broad-banded coupler? The approximate result (14) is not applicable because the band of operation covers several octaves and because we are now interested in the region $\phi \cong \pm\pi$ where (14) fails. So we start with the exact expression (2).

We want R to be as large as possible, and therefore we make a conservative approximation by replacing $(1+r)^2/4r$ by its minimum value of one. Then

$$R = \tan^2 \frac{\phi}{2} \cdot \tag{44}$$

In order to minimize the wavelength sensitivity we satisfy (10) and select the connecting paths L_1 and L_2 far from cutoff, as shown in Fig. 5. Consequently the cutoff wavelengths λ_{c1} and λ_{c2} obey the inequality

$$\lambda_{c1}, \lambda_{c2} \gg \lambda \tag{45}$$

and ϕ (4) can be expanded in powers of λ. Then (44) is reduced to

$$R \cong \tan^2 \left[\frac{\phi_0}{4} \left(\frac{\lambda_0}{\lambda} + \frac{\lambda}{\lambda_0} \right) \right] \tag{46}$$

where

$$\phi_0 = 2\pi L_1 \lambda_0 \left(\frac{1}{\lambda_{c2}^2} - \frac{1}{\lambda_{c1}^2} \right). \tag{47}$$

Again, the extreme departure of the power division R_0 and R_m must be equidistant from the ideal R_i. These extremes occur at $\lambda = \lambda_a$, $\lambda = \lambda_0$ and $\lambda = \lambda_b$.

$$R_0 = R_m = \tan^2 \frac{\phi_0}{2} = \tan^2 \left[\frac{\phi_0}{4} \left(\frac{\lambda_0}{\lambda_a} + \frac{\lambda_a}{\lambda_0} \right) \right]$$

$$= \tan^2 \left[\frac{\phi_0}{4} \left(\frac{\lambda_0}{\lambda_b} + \frac{\lambda_b}{\lambda_0} \right) \right]. \quad (48)$$

Since

$$R_0, \ R_m \gg 1 \quad (49)$$

the minimum value of $|\phi_0|$ derived from (48) is

$$|\phi_0| \cong \pi - \frac{2}{\sqrt{R_0}} \cdot \quad (50)$$

From (48) also follows

$$\lambda_a = \lambda_0 \frac{1 - \left(\dfrac{2}{\pi R_0^{1/2}} \right)^{1/2}}{1 + \left(\dfrac{2}{\pi R_0^{1/2}} \right)^{1/2}} \quad (51)$$

$$\lambda_b = \lambda_0 \frac{1 + \left(\dfrac{2}{\pi R_0^{1/2}} \right)^{1/2}}{1 - \left(\dfrac{2}{\pi R_0^{1/2}} \right)^{1/2}} \quad (52)$$

and from (10), (47) and (50)

$$L_1 = \frac{\lambda_{c1}^2}{2\lambda_0} \frac{1 - \dfrac{2}{\pi R_0^{1/2}}}{\dfrac{\lambda_{c1}^2}{\lambda_{c2}^2} - 1} \quad (53)$$

$$L_2 = L_1 - \frac{\lambda_0}{4} \left(1 - \frac{2}{\pi R_0^{1/2}} \right). \quad (54)$$

Now we complete the numerical calculations of the broad-banded band-splitting filter. Assuming that the tolerable insertion loss between ports 1 and 3 is 0.5 db (Fig. 5), one derives

$$10 \log \left(\frac{1}{R_0} + 1 \right) = 0.5 \text{ db}. \quad (55)$$

and consequently

$$R_0 = 8.2. \quad (56)$$

Since $\lambda_b = 4$ mm has been fixed previously (43), we deduce from (51), (52) and (56)

$$\lambda_0 = 1.44 \text{ mm} \quad (57)$$

$$\lambda_a = 0.517 \text{ mm}. \quad (58)$$

We saw before that the band between 35 and 75 kMc (8.58–4 mm) is received in port 4, Fig. 5, with insertion loss not greater than 0.5 db. We find now that the band between 75 and 580 kMc (4–0.517 mm) is received in port 3 also with insertion loss not greater than 0.5 db. Each of these sub-bands can in turn be divided by using other band-splitting filters.

The lengths L_1 and L_2 and the cut-off wavelengths λ_{c1} and λ_{c2} have not been determined yet. They can be calculated from (53) and (54). λ_{c1} and λ_{c2} can be selected arbitrarily, but since the hybrids are made with 2-in ID waveguides we choose the upper path of the same diameter. Then for TE_{01}^0 mode

$$\lambda_{c1} = \frac{2\pi}{3.832} = 1.64 \text{ in} = 41.6 \text{ mm}.$$

The choice of λ_{c2} controls the length of L_1 and L_2. As a matter of fact, for $\lambda_{c2} < \lambda_{c1}$, L_1 and L_2 decrease monotonically with decreasing λ_{c2}. We calculate several examples

$\lambda_{c2}/\lambda_{c1}$	L_1	$L_1 - L_2$
0.9	93 in	0.011 in
0.8	32.7 in	0.011 in
0.7	17.7 in	0.011 in.

The last line does not necessarily give the shortest over-all length of the filter because given the tolerable mode conversion, the tapered connecting sections are longer for smaller $\lambda_{c2}/\lambda_{c1}$.

The problems of minimization of over-all filter length and of the ways of providing the right cutoff wavelengths by changing the waveguide diameter or by partially filling the waveguide with dielectric are not treated here.

Other Applications

It has been shown that in general the response of circuits comprising two identical directional couplers depends on the relative phase length of the connecting lines. By suitable design of the connecting lines the phase can be controlled to compensate for known variations in the response of the component couplers. In general, for circuits like that of Fig. 1 with input in port 1, if the phase difference $\phi_1 - \phi_2 = 2n\pi$ all the power will be recovered at port 2 but if $\phi_1 - \pi_2 = \pi(1+2n)$ all the power will be recovered at port 3, the latter yielding a wider band for the same value of n. This property can be used to advantage in other applications besides the ones that have been discussed in detail.

One application of this principle that should be particularly valuable is the case of radar duplexer circuits. In these circuits high degree of balance over wide bands is desirable. Fig. 6 shows a commonly used radar duplexing circuit which normally results in a neat mechanical package using Riblet couplers and equal length lines. This yields $\phi = 0$ for the receiver-antenna path. This circuit can be improved with respect to

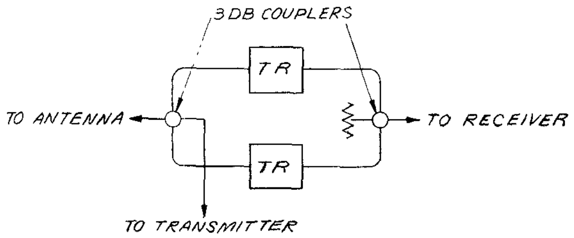

Fig. 6—A common radar duplex circuit.

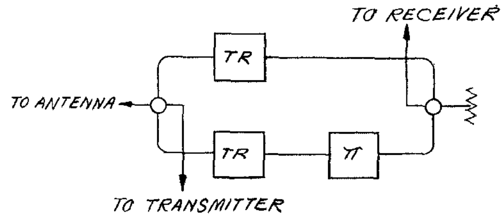

Fig. 7—Broad-banded radar duplex circuit.

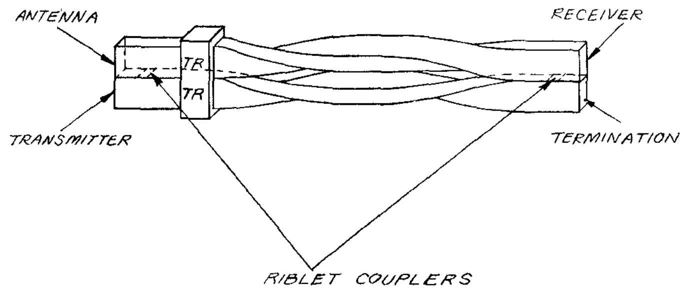

Fig. 8—Compact method of constructing broad-band duplex circuit with Riblet-type couplers.

coupler deficiencies by inserting a 180° phase shift in one of the connecting lines on the receiver side yielding the equivalent circuit shown in Fig. 7. If this is accomplished by adding an extra length of line, it then becomes a question of which produces the greater limitation—the variations in the couplers or the variation in phase due to the extra line. The extra line length also introduces an awkward mechanical problem. Both these difficulties can be overcome and an improved duplexer constructed by using the arrangement shown in Fig. 8. This shows one of the lines twisted 180° to produce the required π value of ϕ. The other connecting line is twisted 90° in one direction and then 90° back again, thus preserving the equal mechanical length. Electrically the lines will differ by exactly 180° at all frequencies in the single mode range of the waveguide.

Conclusions

It has been shown how to connect two identical hybrids and obtain a directional coupler of arbitrary power division that operates over a broader band than that of the components.

Riblet couplers have a geometry particularly adaptable to the broad-banding technique, and in the band where the balance is better than 1 db, the balance of the broad-banded hybrid can be made better than 0.16 db.

The broad-banding technique applied to semioptical hybrids extends the range of operation of band-splitting filters from one to four octaves (35–70 kMc to 35–580 kMc). It can be similarly applied to other band-splitting arrangements, and to the widely used balanced radar duplexing circuit.