A Diplexer Using Hybrid Junctions

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Abstract—A diplexer is a filter which connects a transmitter and a receiver to a common antenna so that both the transmitter and the receiver may be operated simultaneously when their frequencies are not identical. The diplexer described in this report uses hybrid junctions, is easily tuned, and can be designed in a simple, straightforward manner. Its maximum power-handling capacity is the same as that of the connecting transmission line, and its insertion loss is unusually low. An analysis of this filter and a long-stub filter is presented, in addition to the design procedure for, and the experimental results obtained with, a specific model.

A DIPLEXER connects a transmitter and a receiver to a common antenna terminal so that both the transmitter and receiver may be operated simultaneously when their frequencies are not identical. Although the design described here is not unique, it is not commonly used because other devices[1] which perform the same function have been employed in the past in order to meet a given end, rather than to provide a greater flexibility of diplexer design. For example, many of the systems using long short-circuited, or open-circuited, transmission-line stubs shunted across the line, or cavity filters or elements similar to them, usually result in a device which, though straightforward in design, is difficult to tune. In contrast, a diplexer using hybrid junctions is inherently matched and has an inherent isolation between the transmitter and receiver; consequently, optimum performance is realized without fine adjustment of any parameter. The only tuning necessary is that required to maintain a low insertion loss between the transmitter, receiver, and antenna terminals, and this is a relatively coarse adjustment.

The diplexer consists of two hybrid junctions whose side arms are connected by transmission lines of different length. The difference in length is adjusted so that input signals at the transmitter frequency arrive at the output hybrid junction in-phase, whereas signals at the receiver frequency arrive 180° out-of-phase. Therefore, if the receiver is connected to the difference arm of a hybrid junction and the transmitter is connected to its sum arm, the signals will proceed from the antenna to their respective terminals with minimum insertion loss. The transmitter and the receiver are isolated at all frequencies because of an inherent property of the hybrid junction. Additional filtering can be accomplished by using auxiliary long stubs, cavities, or similar devices which employ hybrid junctions.

In the following discussion, the theory of operation, the general design procedures, and some experimental results are presented; because of its similar properties, the long-stub filter is also discussed. Design curves (see Section VI) for use with any transmission line can be constructed permitting the rapid design of a hybrid diplexer that will operate at any frequency in the range 0.7 through 41 kMc/s.

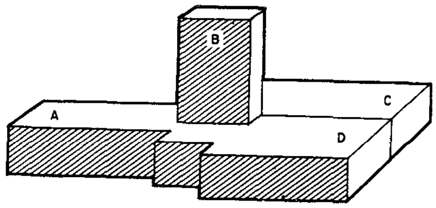

Fig. 1. Folded-tee hybrid junction.

I. The Hybrid Junction

Before the diplexer is discussed in detail, it is important to point out the fundamental properties of a hybrid waveguide junction[2,3] such as a folded, or magic, tee (see Fig. 1). The sum arm is labeled A, the difference arm B, and the side arms C and D. This type of junction has three fundamental properties: 1) signals incident upon terminal A are divided equally between terminals C and D and arrive at these terminals in-phase; 2) signals incident upon terminal B are also divided equally between terminals C and D, but arrive there 180° out-of-phase; and 3) the isolation between terminals A and B is usually about 40 to 50 dB. The inherent isolation between terminals A and B is due to the geometry of the structure and is essentially independent of frequency. Hence, it becomes apparent that when the receiver is connected to terminal B and the transmitter is connected to terminal A, the inherent isolation between them will be equivalent, or approximately equal, to the isolation afforded by the hybrid tee. This characteristic is different from that existing in a system which requires that the rejection, or isolation, be achieved by tuning the device at a certain frequency, as would be true in the case of a cavity, or long-stub, filter. Other hybrid junctions could be employed in the diplexer described here; however, the waveguide folded-tee hybrid will be the junction considered throughout the following discussion.

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[2] P. A. Loth, "Recent advances in waveguide hybrid junctions," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-4, pp. 268–271, October 1956.

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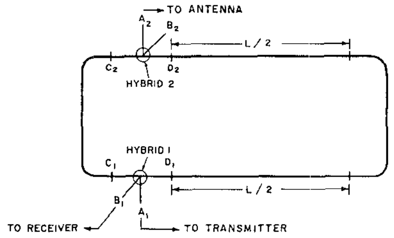


Fig. 2. Schematic of West Ford diplexer.

II. Theory of Operation

A schematic drawing of the basic diplexer circuit is shown in Fig. 2, where the hybrid junctions are referred to as 1 and 2. The side arms, or the C and D terminals, are connected by waveguides whose lengths differ by the amount L, or by two lengths equal to $L/2$, as is shown in the schematic. Assume that the antenna is connected to terminal A_2, the transmitter is connected to A_1, and the receiver is connected to B_1, with B_2 terminating in a matched load. A signal incident upon A_1 will be transmitted to A_2 if L is equal to an even number of half-wavelengths. Further, a signal incident on B_1 will be transmitted to A_2 if L is equal to an odd number of half-wavelengths.

The degree to which these conditions are not fulfilled determines the amount of power that will be delivered to B_2, and thus the increase of insertion loss. Since it is usually desirable that the insertion loss at the transmitter frequency be extremely low compared with that at the receiver frequency (primarily because of the power levels involved), the path-length difference L is given by the following set of simultaneous equations:

$$L = n\lambda_{gt} \tag{1}$$

and

$$L = \frac{2n-1}{2}\lambda_{gr}, \tag{2}$$

where λ_{gt} equals the waveguide wavelength at the transmitter frequency, λ_{gr} equals the waveguide wavelength at the receiver frequency, and n is an integer. In some cases, it is not necessary that n be the same integer for both (1) and (2); however it will be shown later that the most practical solution to the problem is obtained when n is the same integer, as implied in the simultaneous equations above. In (1) and (2), n is given by

$$n = \frac{1}{2}\left|\frac{\lambda_{gr}}{\lambda_{gt}-\lambda_{gr}}\right|. \tag{3}$$

It is apparent that n will be an integer only if the associated waveguide wavelengths have specific values and that, in general, (3) will not give an integer value of n. Thus, a disadvantage of using this diplexing device is that the path-length difference must be chosen so as to obtain a one-half waveguide wavelength difference in length for signals at the transmitter and receiver frequencies and, at the same time, the path-length difference must be an integer number of wavelengths at the transmitter frequency—a situation which is, in general, impossible to realize. In practice, one merely selects the integer value closest to that calculated by means of (3) and sets the length L equal to $n\lambda_{gt}$, as given by (1). The result is an increase in the insertion loss that occurs between A_2 and B_1 at the receiver frequency. It is desirable to determine the amount of insertion loss due to this effect; toward this end, the following discussion is presented.

Consider two signals of equal magnitude incident upon terminals C_2 and D_2, and assume that the junction is matched so that energy travels in only one direction toward the junction and then to either terminal A_2 or B_2. The power delivered to the junction is given by

$$P_{\text{in}} = \frac{4E_1^2}{Z_0}. \tag{4}$$

The power delivered to the sum channel, or terminal A_2, is given by

$$P_{A_2} = \frac{2E_1^2}{Z_0}, \tag{5}$$

and the power delivered to the difference channel, or terminal B_2, is given by

$$P_{B_2} = \frac{2E_1^2}{Z_0}(1-\cos\theta), \tag{6}$$

where θ is the phase angle between the signals arriving at terminals C and D, and Z_0 is the characteristic impedance of the waveguide. Since it is desirable to deliver all the power to terminal A_2, the insertion loss is given by

$$\text{Insertion Loss} = IL = 10\log\frac{P_{\text{in}}}{P_{\text{out}}} = 10\log\frac{P_{\text{in}}}{P_{\text{in}}-P_{B_2}}. \tag{7}$$

Substituting from (4) and (6), we have

$$IL = 10\log\left[\frac{2}{1+\cos\theta}\right], \tag{8}$$

which, for small values of θ, can be approximated by

$$IL \approx 10\log\left[\frac{1}{1-\left(\frac{\theta}{2}\right)^2}\right]. \tag{9}$$

When the expression

$$\tau = \frac{\Delta L}{\lambda_g} \tag{10}$$

is introduced, the following relationship between insertion loss and path-length error ΔL is produced if n [as given by (3)] is not an integer:

$$IL = 10\log\frac{1}{1-(3.14\tau)^2}. \tag{11}$$

Equation (11) is plotted in Fig. 3.

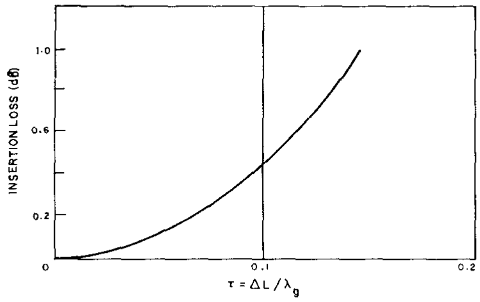


Fig. 3. Insertion loss vs. path-length error of diplexer.

The results of (11) make it possible to determine the operating bandwidth compatible with a given maximum permissible insertion loss. It is then possible to specify the maximum insertion loss necessary in order to realize random choice of the receiver frequency once the transmitter frequency is specified. For optimum operation at either frequency, the path-length difference L_0 is given by $N\lambda_g/2$ (λ_g = waveguide wave length), where N must be even if λ_{gt} is used and odd if λ_{gr} is used.[4] The maximum and minimum values of the path-length difference are

$$L_{\max} = L_0 + \lambda_g \tau \tag{12}$$

and

$$L_{\min} = L_0 - L_g \tau. \tag{13}$$

Substituting $N\lambda_g/2$ for L_0 in (12) and (13) and solving for λ_g will produce the general relationships between waveguide wavelengths, the number of half-wavelengths of path-length difference desired, and the maximum and minimum path length possible for a given insertion loss:

$$\lambda_g = \frac{2L_{\max}}{N + 2\tau}, \tag{14}$$

$$\lambda_g = \frac{2L_{\min}}{N - 2\tau}. \tag{15}$$

(If N is even, $\lambda_g = \lambda_{gt}\theta$ if N is odd, $\lambda_g = \lambda_{gr}$.) These equations are plotted in Fig. 4 for values of N from 1 to 6. The solid line indicates $\tau = 0$; the boundaries, at the edge of the shaded area represent a specific value of τ. At a given transmitter frequency and for a given value of N (for example, $N = 2$), the desired path length L_0 for optimum operation at the transmitter frequency is given by the appropriate curve in Fig. 4. The intersection of L_0 and the boundaries associated with the one-half wavelength path-length difference line (i.e., $N = 1$) and its permissible tolerance (the shaded area to the left and to the right) indicate that any receiver frequency having a wavelength shorter than λ_2 and longer than λ_l will be accommodated satisfactorily by the diplexer. Since the path-length difference L_0 can vary by $\pm\tau\lambda_{gt}$

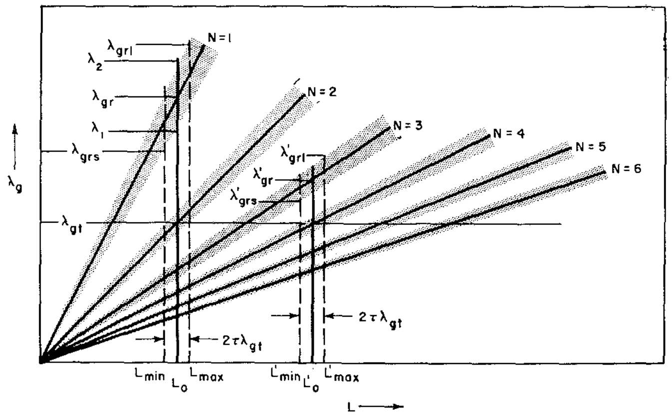


Fig. 4. Hybrid diplexer characteristics.

and still result in satisfactory operation at the transmitter frequency, the receiver can operate between a maximum wavelength of λ_{grl} and a minimum wavelength of λ_{grs} (see Fig. 4). Similarly, when $N = 4$, a second range of receiver signal wavelengths, λ'_{grl} and λ'_{grs}, can be obtained. Then, if the value of τ which makes λ_{grs} equal to λ'_{grl} is determined, the insertion loss that will permit random choice of the transmitter, and receiver frequencies can be calculated from (11).

In general, the equation for the line defining the minimum path-length difference for satisfactory operation at a given receiver waveguide wavelength can be expressed as follows:

$$\lambda_{gr} = AL = A\lambda_{gr}\left(\frac{N}{2} - \tau\right), \tag{16}$$

where

$$A = \frac{2}{N - 2\tau}. \tag{17}$$

When (17) is substituted into (16), we obtain the general relationship between λ_{gr} and the path-length difference which will produce the maximum tolerable insertion loss; that is,

$$\lambda_{gr} = \frac{2}{N - 2\tau} L. \tag{18}$$

In a similar fashion, it can be shown that the maximum path-length difference for satisfactory operation is related to the wavelength as follows:

$$\lambda_{gr} = \frac{2}{N + 2\tau} L. \tag{19}$$

In practice, the actual path-length difference can assume any value between those two specified by the following equations:

$$L_{\max} = \lambda_{gt}(N_0 + \tau), \tag{20}$$

$$L_{\min} = \lambda_{gt}(N_0 - \tau). \tag{21}$$

In the present discussion, N_0 must be even because the

[4] If the transmitter and receiver connections (see Fig. 2) are interchanged, N must be odd if λ_{gt} is used and even if λ_{gr} is used. $N = 2n$, but for purposes of generalization in the following sections, N is introduced.

transmitter and the antenna are connected to the sum arm of their respective hybrid folded tees. The values of L_{max} and L_{min} are shown in Fig. 4 for $N_0=2$. Satisfactory operation at the receiver frequency requires that $N=N_0\pm 1$. In the case where N_0 is decreased, (19) becomes

$$\lambda_{grs} = \frac{2}{(N_0 - 1) + 2\tau} L_{min}. \tag{22}$$

If $N=N_0+1$, (18) will yield the following relationship between λ'_{grl} and L'_{max}:

$$\lambda'_{grl} = \frac{2}{(N_0 + 1) - 2\tau} L'_{max}. \tag{23}$$

When we substitute (20) and (21) into (23) and (22), respectively,

$$\tau = \frac{1}{3N_0 + 2} . \tag{24}$$

The nearest even integer value of $|\lambda_{gr}/(\lambda_{gt}-\lambda_{gr})|$ is N_0 [see (3)]. The maximum insertion loss necessary for random choice of λ_{gr} for a given λ_{gt}, as determined by (24), can be found by referring to Fig. 3. This does not mean that the insertion loss between the antenna terminal and the receiver, or transmitter, terminal will equal this value, but that it *could* equal it. Since the minimum value of N_0 is 2, the maximum expected insertion loss for any diplexer design of this type is 0.71 dB. This value does not take into account the insertion loss intrinsic to the components and the attenuation in the waveguide. The values of τ and the corresponding insertion loss are tabulated below for values of N_0 between 2 and 10.

N_0	τ	Insertion Loss (dB)
2	0.120	0.710
4	0.071	0.220
6	0.050	0.100
8	0.038	0.042
10	0.031	0.020

If the antenna is connected to the sum terminal and the transmitter can be connected to either the sum or the difference arm, N_0 can also equal an odd integer. In most instances, when the values of insertion loss are actually those listed above, they can be reduced somewhat by setting N_0 equal to an odd integer. For example, if $N_0=2$, the insertion loss may be as high as 0.71 dB; it could be reduced to less than 0.35 dB by setting $N_0=3$ and interchanging the transmitter and receiver terminals.

III. The Long-Stub Filter

In many practical applications of the hybrid tee diplexer, the isolation between transmitter and receiver is usually not sufficient, and some additional means of isolation must be provided to make the system usable. That is, the normal isolation between the sum and difference arms of a folded tee is approximately 40 to 50 dB; many systems require an isolation between transmitter and receiver in excess of 70 or 80 dB. If a circuit similar to that shown in Fig. 2 is inserted between the transmitter and the diplexer, the isolation between the transmitter and the receiver, at the receiver frequency, will be increased more than 50 dB. A similar device in the receiver arm would increase the isolation between transmitter and receiver at the transmitter frequency by an equivalent amount. However, at some frequencies the size of the components may render this particular solution economically unsound and may also result in more than the required isolation; in such a case, the use of a long-stub filter may prove to be the best solution. The long-stub filter consists of a section of short-circuited waveguide attached to either the E-plane or the H-plane of the main waveguide line in the form of a tee. Adjusting the length of the short-circuited section of waveguide can bring about a high mismatch in the main waveguide at the reject frequency, and a reasonably good match at the pass frequency. In particular, when the length is chosen such that

$$L_s = (2M - 1) \frac{\lambda_{gs}}{4} \tag{25}$$

(where L_s is the length of the stub, M is an integer, and λ_{gs} is the waveguide wavelength at the intended stop frequency), the input impedance of the stub will be high and the insertion loss in the main waveguide will increase to approximately 30 dB. In order to obtain the minumum amount of insertion loss at the pass frequency, the length L_s should be

$$L_s = 2M \frac{\lambda_{gp}}{4}, \tag{26}$$

where λ_{gp} is the waveguide wavelength at the pass frequency. Since it is possible to have only one length of stub, M can be evaluated as follows:

$$(2M - 1) \frac{\lambda_{gs}}{4} = 2M \frac{\lambda_{gp}}{4}, \tag{27}$$

$$M = \frac{1}{2} \left| \frac{\lambda_{gs}}{\lambda_{gp} - \lambda_{gs}} \right|. \tag{28}$$

As in the previous section, M will not, in general, be an integer, and it is not possible to satisfy the requirements of (25) and (26) simultaneously for all values of λ_{gs} and λ_{gp}. In the analysis in the preceding section, the inability to satisfy this requirement resulted in an increased insertion loss of the diplexing filter. In the case of the long-filter stub, there is an increase in the VSWR that is measured at the input to the filter in the pass band. The following analysis relates the bandwidths involved and the VSWR expected, much as the insertion loss and the bandwidth were related in the previous analysis. In the case of the long-stub filter, the problem is simplified, since the stop band wavelength and the length of line must be related as indicated by (25) in order to satisfy the rejection requirements. It will be shown that the maximum and minimum wavelengths of the acceptable pass band will be determined for a given length which satisfies the requirements of (25) and which results in a tolerable VSWR in the pass band.

The relationship between λ_g and L_s for optimum pass or rejection is given by

$$\lambda_g = \frac{4L_s}{M}, \tag{29}$$

where M is an odd number for stop band operation, an even number for pass band operation, and equal to the number of quarter-wavelengths. The length L_{s0} of the stub is determined by setting M equal to an odd integer M_0 and choosing the waveguide wavelength equal to that at the stop frequency. The maximum and minimum waveguide wavelengths in the pass band can be expressed as

$$\lambda_{gp_{\max}} = \frac{L_{s0}}{\dfrac{L_{s0}}{\lambda_{gp}} - \dfrac{\Delta}{2\pi}} \tag{30}$$

and

$$\lambda_{gp_{\min}} = \frac{L_{s0}}{\dfrac{L_{s0}}{\lambda_{gp}} + \dfrac{\Delta}{2\pi}}, \tag{31}$$

where Δ is the deviation in the length of the long-stub filter from an even number of quarter-wavelengths at the pass frequency. Equations (29), (30), and (31) are plotted in Fig. 5, for various values of M, with Δ equal to 0 and Δ_1. Also shown in Fig. 5 are specific stub lengths L_{s0} and L_{s1}. The intersections of L_{s0} with the lines represented by (29), (30), and (31) are indicated by $\lambda_{gp_{\max}}$, λ_{gp}, $\lambda_{gp_{\min}}$, and λ_{gs}. The corresponding prime values indicate similar intersections as determined by L_{s1}. It is intended to determine Δ_1 in such a way that the range of wavelengths over which satisfactory operation can be achieved with a stub length of L_{s0} is continuous with the expected range of L_{s1}. Toward this end, $\lambda_{gp_{\min}}$ is set equal to $\lambda'_{gp_{\max}}$.

In terms of (29), L_{s0} is given by

$$L_{s0} = M_0 \frac{\lambda_{gs}}{4}, \tag{32}$$

and it follows that

$$\lambda_{gp} = 4 \frac{L_{s0}}{M_0 \pm 1}, \tag{33}$$

where the plus sign signifies that the stop frequency is less than the pass frequency, and the minus sign signifies that the pass frequency is less than the stop frequency.

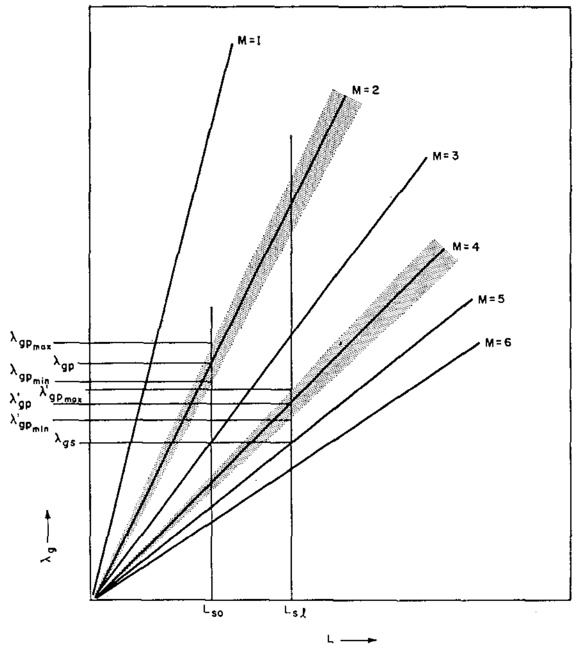


Fig. 5. Long-stub filter characteristics.

When only the latter case is considered, and (33) is substituted into (30) and (31),

$$\lambda_{gp_{\max}} = \frac{L_{s0}}{\dfrac{M_0 - 1}{4} - \dfrac{\Delta_1}{2\pi}} \tag{34}$$

and

$$\lambda_{gp_{\min}} = \frac{L_{s0}}{\dfrac{M_0 - 1}{4} + \dfrac{\Delta_1}{2\pi}}. \tag{35}$$

In a similar fashion, we obtain

$$\lambda'_{gp_{\max}} = \frac{L_{s1}}{\dfrac{M_0 + 1}{4} - \dfrac{\Delta_1}{2\pi}} \tag{36}$$

and

$$\lambda'_{gp_{\min}} = \frac{L_{s1}}{\dfrac{M_0 + 1}{4} + \dfrac{\Delta_1}{2\pi}}. \tag{37}$$

when (35) is equated with (36)

$$\Delta_1 = \frac{\pi}{2(1 + M_0)}. \tag{38}$$

Next, is is necessary to determine the relationship between Δ_1 and the input VSWR in the pass band. Figure 6 shows the general configuration of a long-stub filter and its approximate equivalent circuit. The input impedance Z_s of the filter is given by

$$Z_s = jZ_0 \tan\left[(M_0 - 1)\frac{\pi}{2} \pm \Delta\right] \tag{39}$$

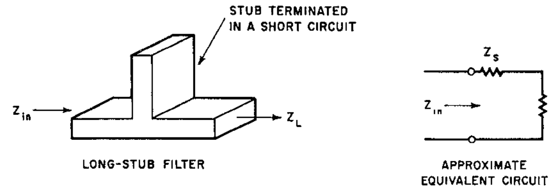


Fig. 6. Approximate equivalent circuit of long-stub filter.

and

$$Z_s = \pm jZ_0 \tan \Delta. \tag{40}$$

The input impedance Z_{in} to the filter is given by

$$Z_{\text{in}} = Z_s + Z_L. \tag{41}$$

If the load is matched (i.e., $Z_L = Z_0$), the input VSWR is given by

$$\text{VSWR} = \frac{\sqrt{\dfrac{4}{\tan^2 \Delta} + 1} + 1}{\sqrt{\dfrac{4}{\tan^2 \Delta} + 1} - 1}. \tag{42}$$

When we set $\Delta = \Delta_1$ and substitute (38) into (42), the following relationship between the input standing wave ratio and M_0 results:

$$\text{VSWR} = \frac{\sqrt{\dfrac{4}{\tan^2\left[\dfrac{\pi}{2(1+M_0)}\right]} + 1} + 1}{\sqrt{\dfrac{4}{\tan^2\left[\dfrac{\pi}{2(1+M_0)}\right]} + 1} - 1}, \tag{43}$$

which, for $M_0 > 4$, can be approximated by

$$\text{VSWR} = \frac{4M_0 + 7}{4M_0 + 1}. \tag{44}$$

The dispersive characteristics of a waveguide transmission line make a comparison of M_0 and the separation between transmitter and receiver frequencies difficult. Nevertheless, it is possible to list some representative values of expected input VSWR as a function of M_0 and a typical separation between the transmitter and receiver frequencies.

M_0	ρ	Typical Frequency Separation (percent)
2	11.5:1	—
3	1.8:1	20
4	1.38:1	16
5	1.28:1	13
6	1.24:1	11
7	1.21:1	9
8	1.18:1	7
9	1.16:1	6
10	1.14:1	5.5

IV. Detail Design

The previous sections have described the theory of operation of this diplexer in some detail. With this background, it is now possible to present a very simple method of adjusting the path-length difference of both the hybrid diplexer and the long-stub filter such that satisfactory operation can be achieved. The curves presented in Figs. 4 and 5 are intentionally general so as not to confuse the derivations presented with some particular application.

The application of this theory can best be explained by describing the method of selecting the length of the long-stub filter and the path-length difference that will result in a particular diplexer design. The diplexer assembly (Fig. 7) will be discussed from the standpoint of detailed design and choice of the critical lengths; in addition, a method of adjusting for optimum performance will be described. Let us assume that the antenna and the transmitter are connected to the sum arm of their respective hybrids, that the transmitter frequency is 8.35 kMc/s, and that the receiver frequency is 7.75 kMc/s. A long-stub filter is included in both the receiver and the transmitter arms in order to increase the isolation between the transmitter and the receiver. A slid-screw tuner is included between the transmitter and the long-stub filter in order to reduce the expected, or probable, VSWR resulting from the use of the long-stub filter. The same arrangement applies in the case of the receiver channel.

Figure 8 is essentially the same as the plot shown in Fig. 4, except that the curve relating frequency to waveguide wavelength has been added, and the path-length difference is given in inches rather than in waveguide wavelengths. The crosshatched areas represent satisfactory operating path-length differences (for the associated wavelengths) that will result in a 1/10-dB insertion loss, or less, for an odd multiple of half-wavelengths of path-length difference. The operating bands that are not crosshatched represent similar satisfactory operating ranges when the path-length difference is an even number of half-wavelengths; the numbers appearing in each band represent the number of half-wavelengths of path-length difference. The waveguide wavelength obtained by projecting from the frequency axis at 8.35 kMc/s is equal to 1.82 inches. Similarly, the waveguide wavelength at the receiver frequency is 2.07 inches. The intersection of the waveguide wavelength at the transmitter frequency with the edges of the bands which are not crosshatched represents a satisfactory operating path-length difference based upon the criterion that a maximum insertion loss of 0.1 dB is permissible. The minimum and the maximum path-length differences determined in this manner are labeled L_1 and L_2. It can be seen in Fig. 8 that the minimum and maximum waveguide wavelengths required for a satisfactory operation at the receiver frequency are determined by the intersection of L_1 and L_2 with the band numbered one less

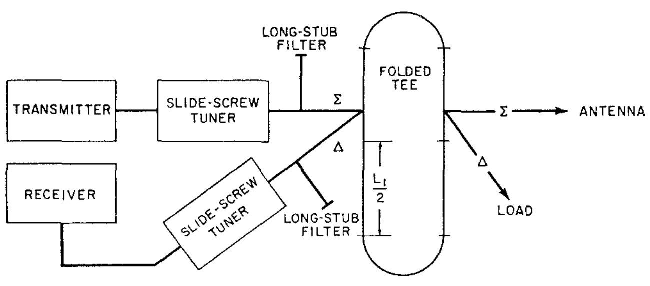


Fig. 7. Schematic of typical diplexer circuit.

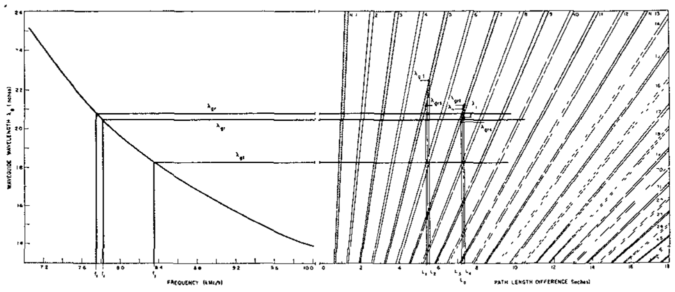


Fig. 8. Hybrid diplexer characteristics.

than the band which determines L_1 and L_2. It will be noticed immediately that the resulting receiver band does not include the waveguide wavelength desired. Hence, it is necessary to determine another path-length difference, such as L_3 or L_4, which will be satisfactory for operation at the transmitter frequency. Any path-length difference between L_3 and L_4 will result in satisfactory operation at the intended receiver frequency. It is advisable to choose a length between L_3 and L_4 which minimizes the insertion loss at both frequencies. If the receiver frequency were 7.81 Mc/s (λ''_{gr} in Fig. 8), then it would be advisable to operate at a path-length difference equal to L_3, which is approximately 7.2 inches; in the actual case, the optimum path-length difference is 7.28 inches. Moreover, Fig. 8 shows the tolerance in path-length difference required to meet the desired performance. If the transmitter were connected to the difference arm of the associated hybrid and the antenna were connected to the sum arm of its hybrid, then a similar construction would be carried out, except that the odd-numbered areas would become those associated with the transmitter-frequency band, and the even-numbered areas would be associated with the receiver-frequency band.

In summary, the following step-by-step procedure is presented so that the desired path-length difference L_1 (see Fig. 7) may be determined.

Step 1: Determine the λ_{gt} and λ_{gr} by using the curve at the left of Fig. 8.

Step 2: If the transmitter and the antenna are connected to the sum arms of their respective folded tees, then determine the intersection of the limits of the even-numbered operating bands and λ_{gt}. (If the transmitter is connected to the difference arm of its hybrid, and the antenna is connected to the sum arm of its hybrid, or vice versa, then determine the intersection of λ_{gt} and the odd-numbered operating bands.)

Step 3: The path-length difference determined by the intersection of the λ_{gt} and the appropriate operating band is then projected upward or downward (depending upon whether λ_{gr} is greater or less than λ_{gt}), to determine the operating band associated with the receiver frequency. If the intersection of the path-length differences determined in this fashion and the edges of the operating band include λ_{gr}, then the path-length difference has been determined. If λ_{gr} is greater than λ_{gt} and the operating band determined in this manner includes wavelengths longer than λ_{gr}, then it will be necessary to increase the path-length difference to the next operating band at λ_{gt} and repeat the previous steps. On the other hand, if λ_{gr} is shorter than the operating band determined in this manner, then it is necessary to decrease the path-length difference and repeat the previous steps. If λ_{gr} is shorter than λ_{gt}, use the same procedure and interchange the words "increase" and "decrease" in the two previous sentences.

In general the long-stub filter would be so designed that its length could be varied continuously for a distance of approximately one-quarter wavelength, or more. Coarse adjustment may be needed to place the desired fine adjustment in the proper range. The fine adjustment of the long-stub filter is necessary in order to achieve maximum rejection at the stop band. The center of the range of fine adjustment or, in other words, the nominal length of the long-stub filter, can be determined as follows.

1) If the long-stub filter is intended to reject the transmitter frequency, then the nominal length is equal to half the path-length difference determined from Fig. 8 and reduced by $\lambda_{gt}/4$.[5]

2) If the long-stub filter is to reject the receiver frequency, then the nominal length of the stub should be equal to half the path-length difference as determined from Fig. 8. (The stub length should be increased by $\lambda_g/4$ if the transmitter is connected to the sum arm and the antenna is connected to the difference arm, or vice versa.)

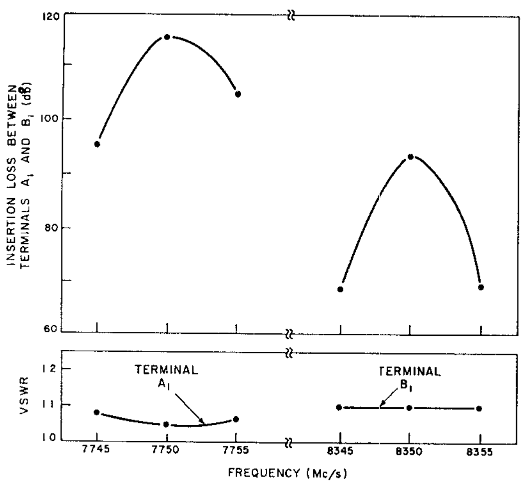
In this way, the path lengths necessary to produce satisfactory diplexer operation for a given application can be determined in a direct manner. When a particular design has been selected, it may prove helpful to reproduce curves similar to those shown in Figs. 5 and 8, so that the necessary path-length differences and long-stub filter lengths can be determined with a higher degree of accuracy. The slide-screw tuners are provided as a means of reducing the VSWR contributed by the long-stub filter in the pass band; however, if the frequency

[5] The transmitter and antenna are connected to the sum arms or to the difference arms. If the transmitter is connected to the sum arm and the antenna is connected to the difference arm, or vice versa, then the nominal length is equal to one-half the path-length difference, determined from Fig. 8.

separation is less than five percent, the tuners may not be necessary. It is also true that if two long-stub filters are used in each arm, their separation is usually approximately $\lambda_g/4$; hence, their mutual interaction would tend to cancel any mismatch produced in the pass band because the stubs would introduce identical reflections at points separated by approximately 90° along the transmission line.

V. Experimental Data

A diplexer based on the design just described and using an oxygen-free copper waveguide having the same dimensions as RG-51/U was constructed. The circuit configuration is shown in Fig. 7 without the slide-screw tuners, which were not necessary since the separation between transmitter and receiver frequencies was small enough to prevent excessive pass band mismatch contributed by the long-stub filters. The measured insertion loss, isolation, and VSWR are shown in Fig. 9. It should be noted that these data were obtained without any tuning procedure, except in the case of the long-stub filter. The entire diplexer was constructed in accordance with the design dimensions and performed as indicated.



FREQUENCY	INSERTION LOSS BETWEEN A_1 AND A_2	B_1 AND A_2
8350		0.1 dB
7750	0.1 dB	

Fig. 9. Measured characteristics of diplexer using hybrid junction.

VI. Design Curves

The design curves presented in Fig. 8 can be produced in a rather simple and straightforward manner to accommodate any particular frequency band and transmission line. The plot of λ_g vs. f is not necessary if the values of λ_{gr} and λ_{gt} can be obtained by some other method. The remaining part of the graph can be constructed in the following manner.

1) Determine τ from (11) or Fig. 3.
2) Plot the straight lines

$$\lambda_g = \frac{2L}{N \pm 2\tau},$$

where $N = N_0 \pm 1$ and $N_0 \pm 2$, and N_0 is calculated using (3). In general, the scale should be chosen such that the design bandwidth ($\Delta\lambda_{gr}$ and $\Delta\lambda_{gt}$) is on the order of the smallest increment of the scale.

VII. Comparison with Other Diplexers

A more conventional and perhaps more frequently used diplexer consists of cavity filters located in the arms of a three-port "Tee" junction. Since bandwidth and insertion loss are the essential performance defining parameters for this device and the hybrid junction filter, it would be interesting to use them as a basis for comparison. However, the character of these parameters is not the same for both devices. For example, the hybrid junction diplexer has, in general, a much larger "pass" bandwidth, but the maximum isolation (insertion loss between transmitter and receiver) is determined by the directivity of the hybrid junction. It follows that additional cavity, or long-stub, filters would be required in order to increase the isolation; this tends to reduce the bandwidth perhaps to the point where it is not very different from that obtained with the cavity filters and a "Tee" junction. Therefore, the major advantage of the hybrid junction diplexer is then reduced to the facility with which one can match the three-port junction of the diplexer and the inherent "across the band" isolation provided by the hybrid junction.

VIII. Conclusions

A theoretical analysis of a diplexer employing hybrid junctions and long-stub filters has been presented. Considering a pair of signals with an arbitrary frequency difference, the maximum possible insertion loss of the diplexer is calculated. It is, in general, less than 0.1 dB; the isolation between the transmitter and the reciever is approximately equal to the directivity of the hybrid junction. The design of a device which uses both hybrid junctions and long-stub filters, and has an insertion loss less than 0.1 dB, a VSWR less than 1.1, and isolation between transmitter and receiver greater than 90 dB, was carried out and experimentally verified.