

July 4, 1961

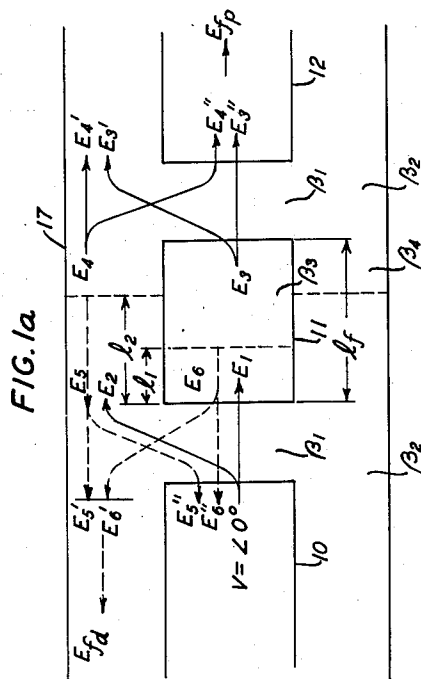
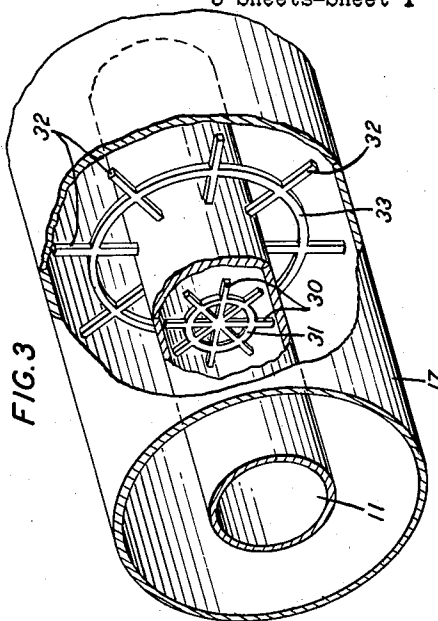
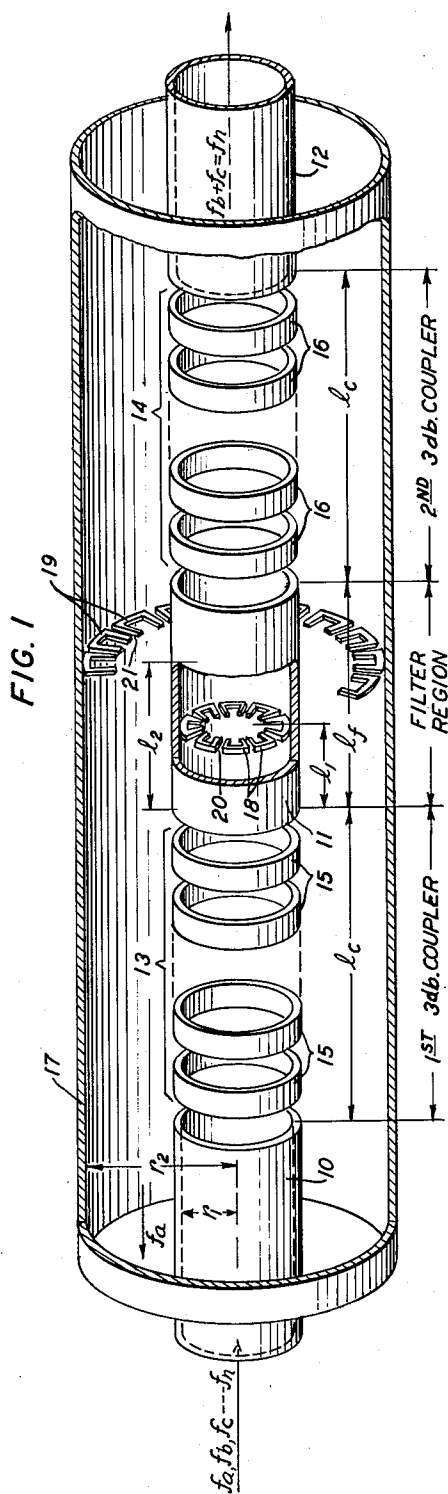
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2,991,431

ELECTROMAGNETIC WAVE FILTER

Filed May 27, 1959

3 Sheets-Sheet 1



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FIG. 4

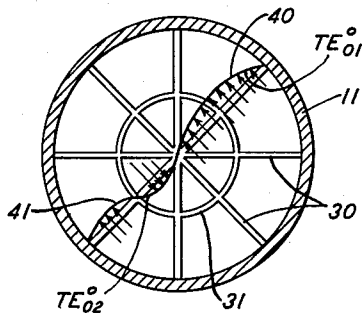


FIG. 5

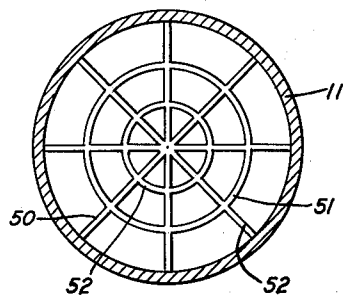


FIG. 2

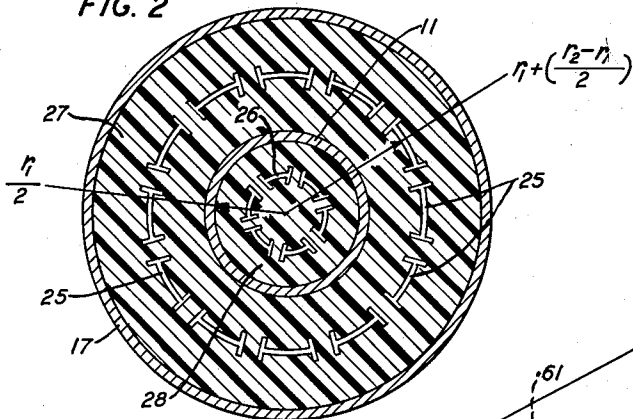
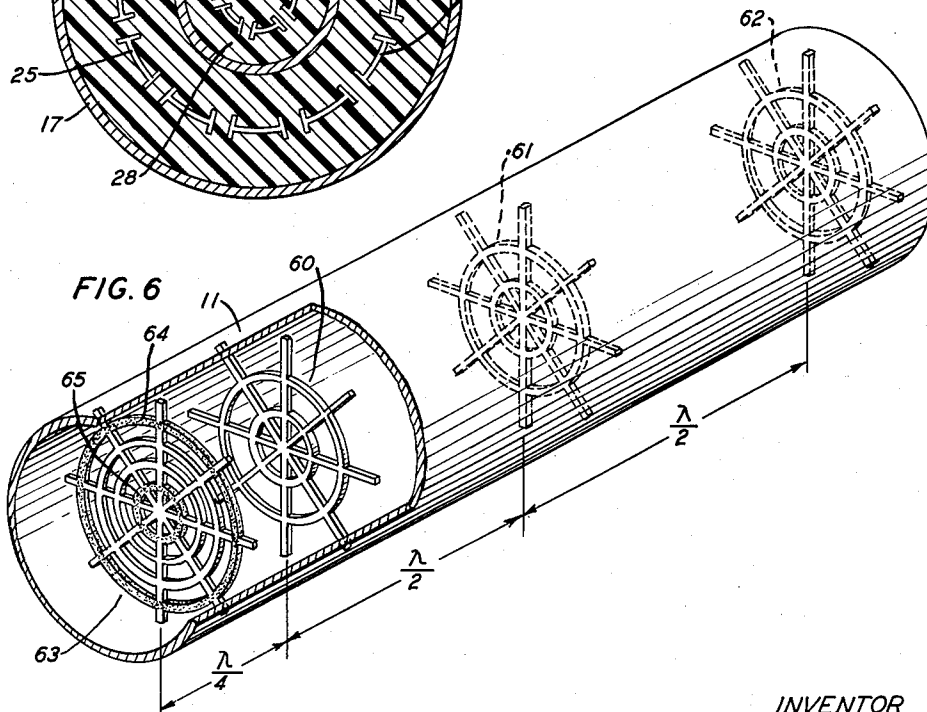


FIG. 6



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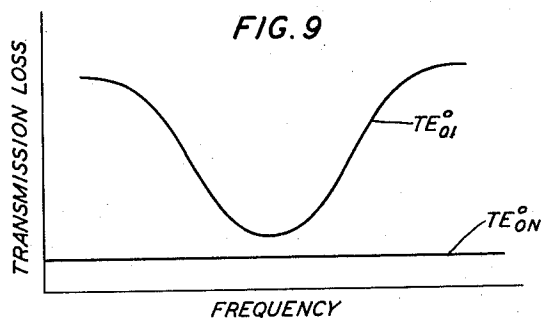
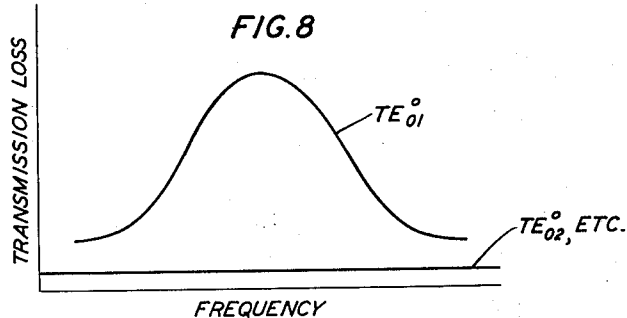
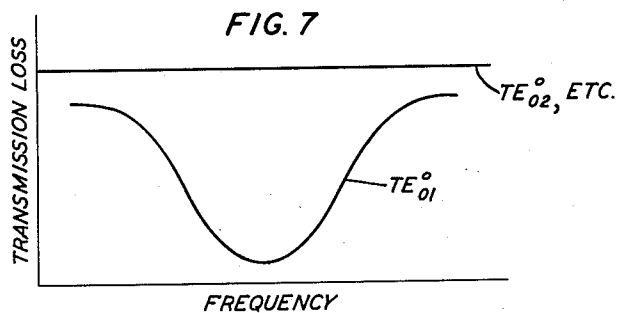
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ELECTROMAGNETIC WAVE FILTER

Filed May 27, 1959

3 Sheets-Sheet 3



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ELECTROMAGNETIC WAVE FILTER

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Filed May 27, 1959, Ser. No. 816,147

10 Claims. (Cl. 333-9)

This invention relates to electromagnetic wave transmission systems and more particularly to microwave filtering arrangements for use with cylindrical waveguiding paths transmitting wave energy in the circular electric mode.

As is well known, the propagation of microwave energy in the form of the circular electric TE_{01} mode in circular waveguides is ideally suited to the long distance transmission of high-frequency, wide band signals since the attenuation characteristic of this transmission mode, unlike that of other modes, decreases with increasing frequency. However, since the transmission means most often used in the propagation of energy through waveguides has been the rectangular waveguide supporting the dominant TE_{10} mode, and the circular waveguide supporting the TE_{11} mode, most of the component devices required in these transmission systems are adapted to these types of mode. The microwave art is replete with directional couplers, hybrids, circulators, isolators, frequency filters and the like, whose structural geometrics are peculiarly compatible with the electromagnetic field configurations of these noncircular modes of propagation.

This is not the case, however, with the circular electric mode. Very few components have been developed which are intrinsically suited to the circular electric mode. As a consequence, in order to perform the various operations upon the circular electric mode required in a transmission system, it has been necessary to convert to the TE_{10} mode in rectangular pipe, or the TE_{11} mode in circular pipe. Microwave components have been developed to do this. It seems clear, however, that there is a need for developing microwave components intrinsically suited to the circular electric mode.

It is, therefore, a broad object of this invention to provide microwave components adapted to operate directly upon transmission systems which support energy solely in a circular electric mode.

One very important operation in any broad-band multi-channel transmission system is that of separating the several channels at a repeater station or receiver.

It is, therefore, a more specific object of this invention to separate a plurality of broad-band frequency channels from a single transmission path in a system which supports energy solely in a circular electric mode.

In accordance with the invention, these objects are accomplished by means of a pair of directional couplers whose geometry is uniquely related to the geometry of the circular electric mode field pattern, and which are appropriately spaced and separated by particular wave filtering means. In particular, a band separation filter constructed in accordance with the invention comprises a pair of coaxially disposed circular cylindrical waveguides of different radii. The inner cylinder consists, in part, of two groups of several annular segments each longitudinally displaced from each other to form two broad-band power dividers for coupling one-half of the energy in a TE_{01} field from the inner guide into a TE_{01} coaxial field for propagation in the outer wave path between the two guides. The outer cylindrical waveguide is disposed external to and coextensive with at least a portion of each of the inner segments to provide a conductive boundary around each of the couplers. The relative transmission constants of the two wave-paths

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over the coupling intervals are adjusted by proportioning their radii, or by loading one or both of the wave paths with dielectric or magnetic material. Depending upon the type of band separation desired, appropriate filtering means are located between the couplers in both wave paths.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a first illustrative embodiment of the invention utilizing band rejection filtering means;

FIG. 1a shows, by way of illustration, the operation of the channel-dropping filter of FIG. 1;

FIG. 2 shows a second type of band rejection filtering means;

FIG. 3 is a second embodiment of the invention utilizing band-pass filtering means;

FIG. 4, given for the purposes of explanation, shows the electric field distribution for the TE_{01} and the TE_{02} modes with respect to the filter structure of FIG. 3;

FIG. 5 is a modification of the band-pass filter of FIG. 3 having TE_{03} mode rejection properties;

FIG. 6 is a perspective view of a filter using a plurality of filter structures of the type shown in FIG. 5, one of which has lossy rings, and

FIGS. 7 through 9 are transmission characteristics illustrative of the type of filter responses which may be obtained in accordance with the teachings of this invention.

Referring more specifically to FIG. 1, there is shown an illustrative embodiment of a band-separation filter in accordance with the principles of the invention. The filter, in general, comprises an inner and an outer wave path, a first 3 decibel directional coupler to electromagnetically couple the two paths, a filter region and a second 3 decibel directional coupler.

The inner wave path consists in part of the three segments 10, 11, and 12 of hollow conductive waveguide each having a circular transverse cross section that is proportioned to support the circular electric TE_{01} mode over the entire operating frequency range of interest. Guides 10, 11 and 12 are of the same radius r_1 , and are colinearly disposed in longitudinal succession with adjacent ends spaced from each other by a given distance l_c . The two intervals 13 and 14, thus formed, have distributed therein a plurality of smaller circular cylindrical sections or rings 15 and 16, respectively. The series of rings 15 and 16 are of the same radius r_1 and are colinearly disposed in longitudinal succession with adjacent ends spaced from each other and from sections 10, 11 and 12 by a given distance, which distance depends upon the nature of the coupling desired between the inner and outer wave paths.

In the embodiment of FIG. 1, each of the rings has the same longitudinal dimension and is uniformly spaced from the next adjacent cylindrical section. In particular, the ring size and spacing is adjusted to couple half the wave energy propagating in either the inner or outer guide to the other of said guides, with the transferred energy continuing to propagate in the same direction as the original wave energy.

Separating the two coupling intervals 13 and 14 is the section of waveguide 11, comprising the filter region of length l_f . The specific nature of the filter and the determination of the length of section 11 will be considered in greater detail hereinafter.

Surrounding guides 10, 11, and 12 and the annular sections 15 and 16, and coaxially disposed with respect to each of them, is a hollow conductive waveguide 17 of circular cross section providing a continuous conduc-

tive boundary thereabout. Guide 17 in the region of the coupling intervals 13 and 14 has a radius indicated as r_2 . The radii r_1 and r_2 bear a special relationship to each other, which relationship will be discussed in greater detail below.

The guides 10, 11, and 12 and the annular sections 15 and 16, may be supported within guide 17 in any of several methods well known in the art. For example, hollow dielectric cylinders or washers may be used as coaxial spacers; alternately thin metallic or dielectric rods may extend radially from the external surface of the inner guides to the internal surface of guide 17 to support the internal guide in coaxial relationship to the external guide. In this latter arrangement all of the TE_{0N} modes remain undisturbed by the supporting thin metallic rods since these circular electric modes have electric lines of force in the form of concentric circles which would everywhere be perpendicular to the metallic rods. Thus, the rods present no substantial impedance discontinuity to any of the TE_{0N} modes. To avoid unduly cluttering up the various figures, however, none of the above specified support techniques have been shown.

For ease of reference, the terms coaxial guides 10-17, 13-17, etc., will be used to designate the wave guiding path comprising the annular region between the outer guide 17 and the appropriate segment of the inner guide. The wave energy propagating in the coaxial region where necessary will be indicated by means of the superscript $\circ$, i.e., TE_{0N}° .

It is the general function of the channel-dropping filter of FIG. 1 to accept a plurality of input signals, each centered about a different frequency, and to segregate one of these bands while transmitting substantially unattenuated the remaining signals.

In the operation of the channel-dropping filter of FIG. 1, a plurality of input signals having center frequencies $f_a, f_b, f_c, \dots, f_n$ propagating in the TE_{01} mode are applied to guide 10, it being the function of the filter to separate one of the channels, such as, for example, the band centered about f_a . The energy propagates undisturbed until reaching the first coupling interval 13 whereupon some of the energy is coupled from the inner path to the outer path at each successive interval until upon reaching section 11, half the energy has been coupled over to the coaxial path, 17-11. The coupled portion of the wave energy in the region between the inner and the outer conductive boundaries continues to propagate in the circular electric mode configuration, more specifically in the coaxial circular electric mode TE_{01}° .

The radii r_1 and r_2 of the annular sections 15, and guide 17, respectively, are selected with respect to the coupling factor c and the coupling interval l_c , along which it is maintained, according to the principles developed and defined in detail in my prior Patent 2,820,202, granted January 14, 1958, in order to produce a broad-band transfer of one-half of the incident wave power from guide 10 into guide 15-17. In particular, the radius r_1 is proportioned to produce a phase velocity constant over the coupling region 13 of β_1 radians per unit length, and the radius r_2 is proportioned to produce a phase velocity constant for the coaxial guide 15-17 of β_2 , such that for a distributed coupling per unit length c along the interval l_c .

$$\left| \frac{\beta_1 - \beta_2}{2c} \right|^2 = 1 \quad (1)$$

and

$$cl_c = \frac{\pi}{2} \frac{1}{\sqrt{2}} \quad (2)$$

The derivation of these relationships and the broad-band

power transfer that results are fully set forth in the above-mentioned patent. For further information, reference may also be had to my article, "Coupled Wave Theory and Wave Guide Applications," Bell System Technical Journal, May 1954, pages 661 through 719.

Considering the channels to be passed, $f_b, f_c, \dots, f_n$, the length l_t of the filter section is adjusted so that the phase shift for the energy propagating through the inner guide is the same as the phase shift for the energy propagating through the outer coaxial guide. This requires that

$$\beta_3 l_t = \beta_4 l_t \pm 2n\pi \quad (3)$$

where n is an integer, and β_3 and β_4 are the phase constants in guides 11 and 11-17, respectively. Obviously, if $\beta_3 = \beta_4$, this is true for any length l_t . With these phase conditions satisfied, substantially all the energy in the channels to be passed will recombine in channel 12.

However, the channel to be dropped, f_a , does not propagate through the filter section but is instead reflected by appropriate band rejection means located in guides 11 and 11-17.

As is well known, there are various configurations of conductive discontinuities which, when placed inside a waveguide will fairly well approximate an inductance or a capacitance. By proportioning the conductors so that at some prescribed frequency the magnitude of their respective components of inductive and capacitive susceptance are equal, the discontinuity exhibits the properties of resonance. Depending upon the size and shape of the discontinuity, the resonance thus produced may be either of the parallel type, offering a high impedance across the guide to wave energy at the resonant frequency, or of the series type, offering a low impedance across the waveguide at the resonant frequency. If so proportioned to produce series resonance, the discontinuity appears as a short-circuit to wave energy at the resonant frequency and such energy is reflected. In FIG. 1, the rejection of band f_a is obtained by using a series-resonant type discontinuity or iris comprising a plurality of C-shaped elements 18, 19 distributed about the inner periphery of guides 11 and 17, respectively. The elements are conductively connected to the inner surface of the respective waveguides but circumferentially spaced from each other by the small distances 20 and 21. The two sets of elements 18 and 19 are longitudinally displaced from each other by a distance such that the energy reflected from each of the filters 18 and 19 reappears at the coupling interval 13 in phase. In particular, if l_1 is the longitudinal displacement of the resonant elements 18 in guide 11 from the coupling region 13 and l_2 the longitudinal displacement of the resonant elements 19 in guide 17 from the coupling region 13, the required phase shift is produced by adjusting the distance l_1 and l_2 such that

$$\beta_4 l_2 = \beta_3 l_1 + \frac{\pi}{2} (2n - 1) \quad (4)$$

where n is an integer greater than zero. Under these conditions substantially all of the energy associated with channel f_a recombines at the coupling interval 13 and emerges in guide 10-17.

The operation of the branching filter may be shown in greater detail by considering FIG. 1a. Assuming that the phase constants of the inner and outer paths are unequal, but that the attenuation constants are the same, the power division at either of the couplers is given by Equations 29 and 31 in my paper "Coupled Wave Theory and Waveguide Applications" cited above. If the driving source in guide 10 is equal to $E = 1 \angle 0^\circ$, then the

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through voltage E_T and the coupled voltage E_C are given as:

$$E_T = K \cos \left[\sqrt{\frac{(\beta_T - \beta_C)^2}{4c^2} + 1} x \right] - \frac{i(\beta_T - \beta_C)}{2c} \frac{1}{\sqrt{\frac{(\beta_T - \beta_C)^2}{4c^2} + 1}} \sin \left[\sqrt{\frac{(\beta_T - \beta_C)^2}{4c^2} + 1} x \right] \quad (5)$$

$$E_C = \frac{i}{\sqrt{\frac{(\beta_T - \beta_C)^2}{4c^2} + 1}} \sin \left[\sqrt{\frac{(\beta_T - \beta_C)^2}{4c^2} + 1} x \right] \quad (6)$$

where β_T is the phase constant of the wave path containing the driving source, and β_C is the phase constant of the coupled path. Substituting from Equations 1 and 2 and assuming that

$$\beta_T = \beta_1 > \beta_C = \beta_2$$

$$E_T = E_1 = .707 \angle -90^\circ$$

and

$$E_C = E_2 = .707 \angle 90^\circ$$

With the length l_1 adjusted in accordance with Equation 3, there is no additional relative phase shift induced between E_1 and E_2 as the energy in each of the respective wave paths 11 and 11-17 propagates to the second coupling interval. Thus,

$$E_3 = .707 \angle -90^\circ$$

$$E_4 = .707 \angle +90^\circ$$

At the second coupling interval, the energy again divides. Considering E_3 first,

$$E_3' = .5 \angle 0^\circ$$

$$E_3'' = .5 \angle -180^\circ$$

With respect to E_4 , it should be noted that the driving source is now in the guide with the smaller phase constant. Thus,

$$\beta_T = \beta_2 < \beta_C = \beta_1$$

and

$$E_4' = .5 \angle 180^\circ$$

$$E_4'' = .5 \angle 180^\circ$$

Adding components in each wave path gives

$$E_3' + E_4' = 0$$

and

$$E_3'' + E_4'' = 1 \angle +180^\circ = E_{T_0}$$

Thus, all the passed power, E_{T_0} , leaves by way of guide 12.

Consider now the reflected power E_6 in guide 11, and the reflected power E_5 in guide 11-17. Because of the relative displacement of the two filters, there is, in accordance with Equation 4, an additional 180 degree relative phase shift introduced in E_2 with respect to E_1 so that the reflected voltages E_5 and E_6 are

$$E_5 = .707 \angle -90^\circ$$

and

$$E_6 = .707 \angle -90^\circ$$

The reflected voltages, as stated above, reappear at the first coupler in phase.

The coupled and through components of E_5 and E_6 are computed from Equations 5 and 6 as

$$E_5' = .5 \angle 0^\circ$$

$$E_5'' = .5 \angle 0^\circ$$

$$E_6' = .5 \angle 0^\circ$$

$$E_6'' = .5 \angle -180^\circ$$

Combining components in the respective guides,

$$E_5' + E_6' = 1 \angle 0^\circ = E_{T_0}$$

$$E_5'' + E_6'' = 0$$

Thus, all the energy in the dropped channel, E_{T_0} , leaves by way of guide 10-17.

In the embodiment shown in FIG. 1, the differences

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between the phase constants β_1 and β_2 , and between β_3 and β_4 were established by adjusting the ratio of the radii r_1 and r_2 . However, where the relative radii are fixed by other considerations, the desired phase constants may be obtained by the addition of dielectric material of appropriate dielectric constant in either the coupling regions or in the filter region or both. The dielectric material may be simultaneously used to support the inner guide as well as to provide the necessary dielectric loading.

In FIG. 1, the resonant irises comprising the band rejection filters consisted of a series of C structures distributed about the periphery of the inner and outer guides. Enough of them are used to minimize mode conversion from the preferred circular mode to other spurious modes. Specifically, if the guide is capable of supporting a total of n modes there should be at least $(n+1)$ C structures used. More, however, are preferred. In FIG. 2 alternate series resonant band rejection filtering means are shown, consisting of a series of I structures distributed along the center of the two wave paths. Specifically, FIG. 2 shows a transverse cross section of guides 17 and 11 with the I sections 25 and 26 coaxially distributed about the guide axis parallel to the electric vectors associated with the TE_{01} mode.

In the inner guide 11, the resonant elements 26 are located at a distance midway between the guide axis and the inner surface of guide 11, or at a radius $r_1/2$. In the annular outer path, the resonant elements 25 are located midway between the outer surface of the inner guide and the inner surface of the outer guide, or at a distance from the axis of approximately

$$\left[r_1 + \frac{r_2 - r_1}{2} \right]$$

The elements 25 and 26 are imbedded in a suitable dielectric material 27 and 28, respectively, which material may simultaneously be used to support the inner guide 11 and provide the appropriate dielectric loading to satisfy Equations 1 through 4.

In a channel-dropping filter using series resonant discontinuities in the filter region, the dropped channel, f_a , leaves the channel-dropping filter in the outer guide, while the remaining channels, $f_b, f_c, \dots, f_n$, continue to propagate along the inner guide. For those applications in which the reverse is desired, that is, the dropped channel is to continue along the inner guide and the remaining channels are to leave by way of the outer guide, the series resonant elements in the filter region are replaced with parallel resonant elements.

In FIG. 3 there is shown a parallel resonant filter which, in addition to providing the requisite frequency selectivity, has mode suppression properties which are extremely useful in broad-band systems wherein higher order modes can exist. In guide 11 the filter comprises a series of radial conductive arms 30 which extend from the region of the guide axis to the inner surface of guide 11, which arms introduce a capacitive reactance in the circuit. The several arms are conductively connected to each other at the guide center and likewise are conductively connected to the guide at the other end. Midway between the guide axes and the inner surface of the guide is a conductive ring 31, concentrically located with respect to the guide, which conductively connects to each of the radial arms 30 and introduces an inductive reactance to the circuit. The radial and circumferential dimensions of the ring and arms are chosen to have equal reactive impedances as to resonate at the primary mode at the frequency of the channel to be dropped.

A similar arrangement of arms and ring is located in the coaxial guide 11-17. The coaxial filter likewise comprises a series of uniformly spaced conductive radial arms 32 which extend from the outer surface of guide 11

to the inner surface of guide 17. The arms are conductively connected to the two waveguides at their corresponding ends. Midway between the guides 11 and 17 is a concentrically located conductive ring 33 which conductively connects to each of the arms 32. The two filters are longitudinally displaced with respect to each other as before to satisfy the phase relationship set forth in Equation 4.

In addition to being frequency selective, the symmetry of the filter tends to suppress any tendency for the TE_{02}^o mode to be generated. Or, if present, the filter tends to reflect the TE_{02}^o mode at the resonant frequency while passing the TE_{01}^o mode. If FIG. 4 is considered, the reason for the mode selective properties of the band-pass filter become apparent. In FIG. 4, curve 40 shows the electric field distribution for the TE_{01}^o mode in guide 11. The field intensity is a minimum along the guide axis and at the guide wall, whereas it reaches a maximum at the center of the guide. For the TE_{02}^o mode, the field distribution has a minimum at the guide axis and at the guide wall, as shown by curve 41, but there is an additional minimum at the guide center, the field reversing its direction on either side of the guide center. Thus, ring 31, located in the region of the center null for the TE_{02}^o mode, is completely ineffective as far as the second order mode is concerned. The higher order mode sees only the untuned capacitance introduced by the radial arms 30 and is consequently reflected by the discontinuity. The TE_{01}^o mode, on the other hand, sees both the radial arms 30 and the ring 31, and the discontinuity appears as a high shunt impedance to the primary mode.

Where there exists the possibility of third order modes being generated, the band-pass filter shown in FIGS. 3 and 4 may be modified as shown in FIG. 5. In this latter embodiment of the filter, there are the radial arms 50 as before, but two inductive rings 51 and 52 are used instead of the single ring as shown in FIGS. 3 and 4. The rings are placed about one-third and two-thirds of the distance between the guide axis and the guide wall, or approximately in the region of the guide wherein the TE_{03}^o mode has its field nulls. The effect is to detune the filter for the TE_{03}^o mode.

To enhance the reflective properties of the filter, where there exists an appreciable amount of higher order mode energy, a series of such filters may be used in tandem, spaced a half wavelength apart for the particular higher order mode of interest. Where the presence of the reflected higher order mode is also a problem, resistive elements may be added as shown in FIG. 6 to attenuate the reflected spurious modes. FIG. 6 shows, by way of illustration, guide 11 with a plurality of parallel resonant irises 60, 61 and 62 of the type discussed above, spaced half a wavelength from each other. A quarter wavelength on the other side of iris 60 is the resonant iris 63, upon which is mounted the two resistive rings 64 and 65.

Assuming that the capacitive susceptance introduced by the radial arms of filter 60, normalized with respect to the characteristic admittance of the line, is $Y_c = 2j$ where the characteristic admittance for the TE_{03}^o mode is unity, the admittance at iris 60 is $1 + 2j$. At iris 63, located a quarter wavelength away, the admittance looking toward iris 60 is $Y = 0.2 - 0.4j$. By making the iris 63 have an admittance $Y = .8 + 0.4j$, the line is matched for the TE_{03}^o mode and approximately eighty percent of the TE_{03}^o power is absorbed in the resistive filaments 64 and 65. Since the resistive filaments are placed at the TE_{03}^o maxima, the effect of the added conductance on the TE_{01}^o mode is relatively small.

With respect to the TE_{01}^o mode, the loss in power for the particular values chosen is about 1.6 decibels as compared to a power reduction of 7 decibels for the TE_{03}^o mode. Better discrimination between the two modes may be obtained by making the capacitive susceptance larger

and suitably adjusting iris 63 and the resistive filaments for matched conditions at iris 63.

The same approach can be used with respect to the TE_{02}^o mode by placing the conductive ring as shown in FIG. 4 and adding resistive filaments on either side of ring 31.

In all of the above arrangements, there is an optimum position at which to put the resistive filament. Specifically, the filaments are placed in that region of the guide to which the ratio of electric field for the TE_{01}^o mode to the electric field for the undesired TE_{0N}^o mode is a minimum (for equal power in each mode). These optima do not depend upon frequency.

In the arrangements of FIGS. 5 and 6, the filters reflect the undesired waves (frequency selective) and undesired modes (mode selective) but pass the desired frequency and desired mode. This type of response is shown graphically in FIG. 7. It is also possible, however, to apply the same reasoning to the series resonant filter of FIG. 2 and obtain a filter that selectively rejects the TE_{01}^o mode at the resonant frequency of the filter and passes all other modes and other frequencies to give the type of response shown in FIG. 8. In the simplest arrangement only one ring of I elements would be used, but a tandem arrangement of rings, spaced half a wavelength for the mode that is to be rejected, enhances the effect.

Finally, assuming it is desired to selectively pass the TE_{01}^o mode and pass, rather than reject, a higher order mode at all frequencies, a series of TE_{01}^o band-pass filters of the type shown in FIGS. 3 and 4 are used but spaced a quarter wavelength for the undesired TE_{0N}^o mode. By spacing the filters a quarter wavelength apart, reflections from the successive irises cancel, giving the response as shown in Fig. 9.

In all cases it is understood that the above described arrangements are illustrative of a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A band separation filter for wave energy propagating in the circular electric mode comprising a pair of coaxially disposed circular waveguides of radii r_1 and r_2 wherein r_1 is smaller than r_2 , the smaller of said pair of radius r_1 comprising a first and second plurality of sections extending colinearly in longitudinal succession with adjacent ends of said sections spaced apart to form gaps in the boundary formed by said sections, said first and said second plurality of sections being separated by a common section of predetermined length to form two power dividing networks, the larger of said pair of waveguides of radius r_2 longitudinally disposed coextensive with at least a portion of each of said smaller sections to provide a boundary surrounding said gaps, and wave filtering means disposed between said power dividing networks in said inner and said outer circular waveguides.

2. A channel dropping filter for wave energy propagating exclusively in the circular electric mode comprising an inner and an outer wave path, said inner path comprising a first, a second and a third section of cylindrical hollow conductive waveguide, and sections extending colinearly in longitudinal succession with adjacent ends of said successive sections spaced apart a given distance to form a pair of gaps in the conductive boundary along said inner path, a plurality of cylindrical rings distributed in each of said gaps, said rings being colinearly disposed in longitudinal succession with adjacent ends thereof spaced from each other and from said sections a given distance to form a pair of coupling intervals, a fourth hollow conductive cylindrical guide disposed external to and coaxial with at least a portion of said first and said third

guides to provide a conductive boundary surrounding said second guide and said coupling intervals, the region between said outer guide and said inner guides comprising said outer wave path, and filtering means disposed between said coupling intervals in each of said inner and said outer paths.

3. The combination according to claim 2 wherein said inner path has a propagation constant β_1 along said coupling intervals and said outer path has a propagation constant β_2 along said coupling intervals, said propagation constants being related to c , the coupling per unit length along each of said intervals, by the relation

$$\frac{(\beta_1 - \beta_2)^2}{2c} = 1$$

and wherein c is related to the length of said coupling intervals l_c by the relationship

$$cl_c = \frac{\pi}{2\sqrt{2}}$$

4. The combination according to claim 2 wherein said filtering means comprises a plurality of C-shaped resonant irises distributed in a ring arrangement about the inner periphery of said second and said fourth sections of waveguide between said coupling intervals, said irises being conductively connected to said respective waveguides and circumferentially spaced from each other.

5. The combination according to claim 2 wherein said inner path has a propagation constant β_3 in the region between said coupling intervals, said outer path has a propagation constant β_4 in the region between said coupling intervals and the length of said region l_t is given by the relationship $\beta_3 l_t = \beta_4 l_t \pm 2\pi n$, where n is an integer.

6. The combination according to claim 5 wherein the filtering means in said inner path is located a distance l_1 from one of said coupling intervals and wherein the filtering means in said outer path is located a distance l_2 from said one coupling interval, l_1 and l_2 being related by the equation

$$\beta_3 l_2 = \beta_4 l_1 + \frac{\pi}{2}(2n-1)$$

where n is an integer greater than zero.

7. The combination according to claim 2 wherein said filtering means comprises a plurality of radial conductive members and at least one conductive ring contacting each of said members.

8. The combination according to claim 2 wherein said filtering means comprises a circle of I-shaped conductive elements circumferentially spaced from each other.

9. A frequency-selective mode filter comprising a plurality of tuned irises adjusted to be resonant at a given frequency in the TE_{01}^o circular electric mode, said irises being spaced a half wavelength apart for a given higher order mode at said resonant frequency, said irises comprising a plurality of radial conductive members and at least one conductive ring contacting each of said members, said ring being located at a null point in the electric field pattern for said higher order mode.

10. A frequency selective mode filter for electromagnetic wave energy comprising a plurality of tuned irises longitudinally distributed along a wave path adjusted to be resonant at a preselected frequency for the TE_{01}^o circular electric mode, said irises being spaced a half wavelength from each other for a given higher order mode at said resonant frequency, each of said irises comprising capacitive and inductive discontinuities for said wave energy, at least one of said inductive discontinuities being located at a null point in the electric field pattern for said higher order mode, an additional resonant iris located a quarter wavelength from the first of said plurality of irises having resistive filaments for selectively dissipating said given higher order mode, said filaments being located in said wave path wherein the ratio of electric field for the TE_{01}^o mode to the electric field for said given higher order mode is a minimum for equal power in each mode.

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