

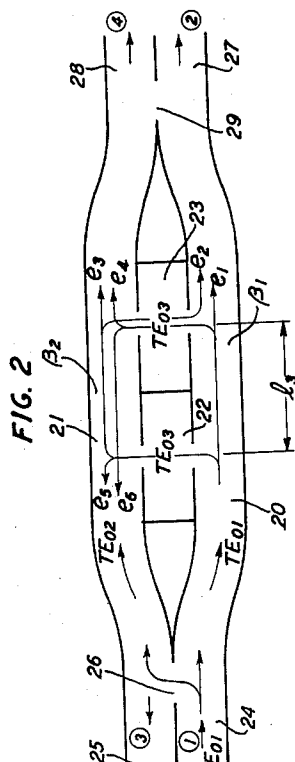
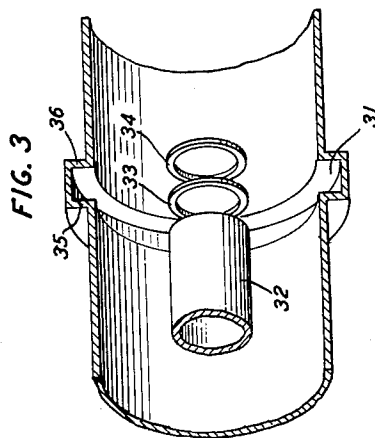
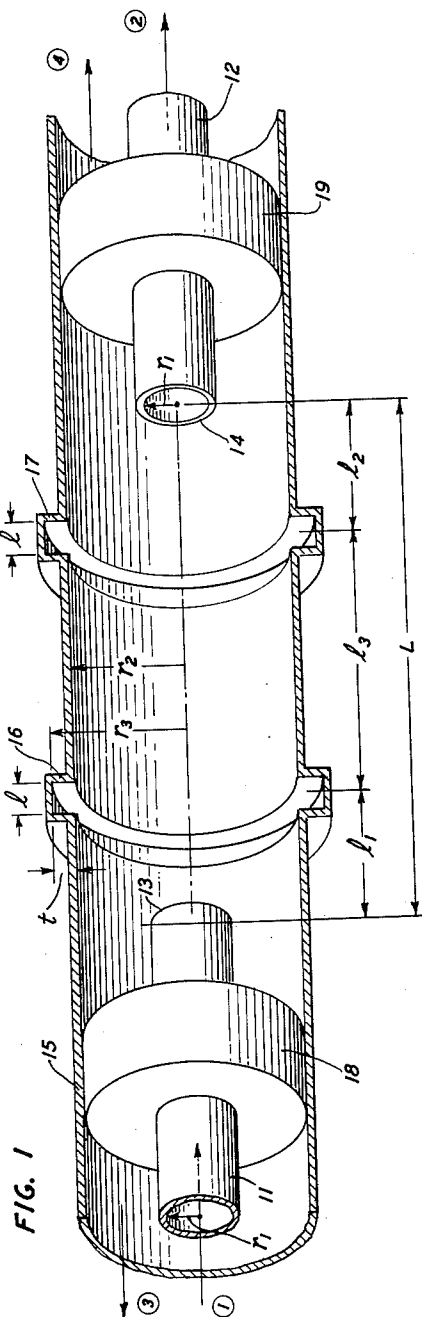
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MICROWAVE DEVICES FOR WAVEGUIDES OF CIRCULAR CROSS SECTION

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MICROWAVE DEVICES FOR WAVEGUIDES OF
CIRCULAR CROSS SECTION

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This invention relates to electromagnetic wave transmission systems whose primary mode of propagation is the circular electric mode, and more particularly to channel-dropping filters for use in such systems whose geometries are intrinsically compatible with the circular electric mode.

One of the more important microwave components used in frequency division multiplex transmission systems is the channel-dropping filter for separating the individual signal channels for either regeneration, such as at repeater stations, or for utilization at the receiver. Channel-dropping filters are well known in the art and take many and varied structural forms. However, with the increasing importance of the circular electric TE_{01} mode for broad-band, long-distance transmission, there is an obvious need for improved microwave components that are both intrinsically suited to the circular electric mode, and structurally simplified.

It is therefore the broad object of this invention to separate a plurality of signal channels propagating in the circular electric mode from a single transmission path.

Simplification and improvement in channel-dropping filters has been accomplished in accordance with the invention by utilizing an electromagnetic mechanism heretofore unappreciated in the microwave filter art. In its broad general outline, mode conversion effects are utilized to separate the signal frequency that is to be dropped and to direct the flow of the through channels to the appropriate branch of the filter network.

It is therefore a further object of this invention to effect channel separation by selectively inducing higher order circular electric modes in a broad-band transmission system.

In accordance with the invention, a dual mode waveguide, adapted to support first and second distinct electromagnetic modes of wave propagation interconnects the several branches of a power-dividing network, each branch of which is supportive solely of the first of these two modes. Coupling between the two modes is provided within the multimode section by means of resonant cavities proportioned to resonate at a third distinct mode of propagation at the frequency to be dropped. By appropriately proportioning the multimode sections of the filter, the dropped channel and the remaining channels may be caused to leave the filter through separate branches of the power-dividing network.

In an illustrative embodiment of the invention, the filter comprises a pair of coaxially disposed cylindrical waveguides of different radii each supportive of a single mode of wave propagation. The inner cylinder has a gap interrupting its longitudinally extending conductive boundary. Over a region coextensive with the gap interval, the outer guide is supportive of the first and second electromagnetic modes of wave propagation. Within this region, the outer cylinder undergoes a series of abrupt increases and decreases in diameter to form a pair of annular recesses, resonant at a third mode of propagation at the frequency of the channel to be dropped. By appropriately proportioning the relative diameters of the two cylinders and the size and spacing of the recesses, any preselected band may be separated from a plurality of frequency bands being transmitted there-through.

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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 perspective view of the channel-separating filter in accordance with the principles of the invention, showing the resonant annular recesses and their relative spacing;

FIG. 2, by way of illustration, is an equivalent circuit diagram of the filter shown in FIG. 1; and

FIG. 3 shows, by way of illustration, a portion of the filter of FIG. 1 including a pair of equalizing rings.

More particularly, FIG. 1 discloses a channel-dropping filter, in accordance with the invention, operative upon the circular electric modes of wave energy propagation supported by waveguides of circular transverse cross section. Two circular waveguides 11 and 12 of radius r_1 are disposed in longitudinal succession along a common axis, with adjacent ends 13 and 14 of guides 11 and 12 respectively spaced from each other by a distance L . The relationship between L and other parameters of the filter will be discussed hereinafter in greater detail. Guides 11 and 12 have equal radii and are also similar in all other respects. Each of guides 11 and 12 is proportioned to support the lowest order circular electric mode, i.e., the TE_{01} mode, over a specified range of frequencies f_1 to f_n .

Surrounding the adjacent ends 13 and 14 of guides 11 and 12, respectively, and extending at least from end 13 to end 14 is a hollow conductive circular waveguide 15 of radius r_2 in coaxial relationship with guides 11 and 12. Guide 15 provides a conductive boundary around both guides 11 and 12 and around the interval L therebetween. More specifically, guide 15 consists of a conductive cylinder of radius r_2 having two annular recesses 16 and 17 each of length l and of radius r_3 larger than r_2 .

Guides 11 and 12, in addition to being proportioned to support the TE_{01} mode over the frequency range f_1 to f_n , are dimensioned so as to be non-supportive of any higher order circular electric modes over this frequency range. Guide 15, on the other hand, is proportioned to support both the TE_{01} mode and, by virtue of its increased radius, the TE_{02} mode over the intervals wherein the radius is r_2 , and the TE_{01} , TE_{02} and TE_{03} modes over the intervals l coextensive with the annular recesses 16 and 17 wherein the radius is r_3 . However, guide 15 supports these order modes over the appropriate intervals to the exclusion of any circular electric mode of higher order than those specified above.

Supporting each of guides 11 and 12 in their coaxial positions within guide 15 are hollow dielectric cylinders or washers 18 and 19, circumscribing guides 11 and 12 and otherwise completely filling the region between said guides and guide 15, in a manner well known in the coaxial conductor art. Washers 18 and 19 are preferably made of low-loss dielectric material having a very low dielectric constant, such as polyfoam, so as to minimize the possibility of spurious reflections of wave energy incident thereon.

The operation of the channel-dropping filter shown in FIG. 1 may best be analyzed by first considering the component parts making up the filter and examining their individual operation, and then examining their operation in relationship to the rest of the filter device.

Specifically, the filter comprises a first 3 decibel directional coupler or hybrid made up of the inner guide 11 and outer guide 15; a mode conversion band rejection filter consisting of the interval of waveguide 15 between guides 11 and 12 and the annular recesses 16 and 17; and the second 3 decibel directional coupler made up of guides 12 and 15.

The directional couplers are substantially the same as those described in my copending application Serial No. 724,724, filed March 28, 1958. As described therein, wave energy propagating through guide 11 in the TE₀₁ mode, upon reaching end 13, will excite in the outer coaxial guide 15 the TE₀₁ and TE₀₂ modes, both of which guide 15 is proportioned to support. In particular, if the radii r_2 and r_1 of guides 15 and 11, respectively, are in the ratio of 7.016 to 3.832, the second and first roots of the Bessel function of the first kind and order, respectively, the incident energy will divide equally between the TE₀₁ and TE₀₂ modes. Since these two modes propagate with different phase velocities, the phase relationship between the two modes will vary with distance. This results in a power division between the internal guide 12 and the external guide 15 at the end of the interval L, the ratio of which is dependent of L. Thus, in the absence of recesses 16 and 17, if L is equal to an odd number of one-quarter beat wavelengths there will be an equal division of power between the guides 12 and 15; if L is one-half a beat wavelength, there will be a complete transfer of power from the internal guide 11, to the external guide 15; while if L is a whole beat wavelength, the energy will all recombine in guide 12 and continue to propagate within the internal guide on the other side of the interval L. The so-called "beat wavelength" herein referred to is defined as:

$$\lambda_b = \frac{1}{\frac{1}{\lambda_1} - \frac{1}{\lambda_2}}$$

where λ_1 and λ_2 are the guided wavelengths of the TE₀₁ and TE₀₂, respectively.

It is clear, therefore, from the above description, that any desired division of power may be obtained by the appropriate choice of the length L relative to the difference between the phase velocities of the two modes. In the channel-dropping filter of FIG. 1, since it is desired that all the bands to be passed continue to propagate in the inner guide, L is made to be one beat wavelength long, or multiples thereof.

In accordance with the present invention, channel separation is obtained by means of the two annular recesses 16 and 17 interposed between the two hybrids defined by guides 11 and 15, and 12 and 15. Specifically, the recesses are proportioned to be resonant at the TE₀₃ mode for the channel to be dropped. The effect upon the transmission of wave energy at the resonant frequency may best be shown by considering FIG. 2.

FIG. 2 is an equivalent circuit diagram of the channel-branching filter shown in FIG. 1. The first hybrid, comprising guides 11 and 15, is represented by the wave paths 24 and 25 coupled over the interval 26. The second hybrid, comprising guides 12 and 15, is represented by the wave paths 27 and 28 and the coupling interval 29. The network between the two hybrids, corresponds to the filter region comprising guide 15, the recesses 16 and 17, and the interval therebetween.

The inner wave path, bounded by guide 11 and labeled (1) in FIG. 1, is correspondingly indicated by the numeral (1) in FIG. 2. The coaxial path bounded by guides 11 and 15 and labeled (3) in FIG. 1, is correspondingly labeled (3) in FIG. 2. As indicated above, of the energy entering port (1) in the TE₀₁ mode, half is converted to the TE₀₂ mode upon reaching end 13. Correspondingly, in FIG. 2, half of the energy entering from port (1) in the TE₀₁ mode is converted to the TE₀₂ mode upon reaching the coupling aperture 26. Since, as is well known, the theory of coupled transmission lines may be used to determine many properties of a multimode transmission system, the individual modes of propagation can be considered as separate transmission lines which, in a perfect waveguide, are completely independent. However, geometric imperfections in the waveguide (such as the annular portions 16 and 17) cause a transfer of

power between modes which, in general, may be analyzed by utilizing coupled transmission line theory. Accordingly, the filter region between the two 3 decibel couplers of FIG. 1 may be represented by the equivalent circuit of FIG. 2, wherein the wave energy in the TE₀₁ and TE₀₂ modes in guide 15 is represented as propagating in separate paths 20 and 21, with phase velocities β_1 and β_2 , respectively. As explained above, the power in each of the modes is equal. In the absence of the recesses 16 and 17, the energy in the two modes would continue to propagate independently of each other. However, due to the geometric discontinuities introduced at the recesses, a portion of the energy in each of the modes is converted to the TE₀₃ mode. Since the TE₀₃ mode cannot propagate in guide 15, the converted energy is reconverted to the lower order modes. The effect of this conversion-reconversion is to introduce coupling between the two modes. This coupling is represented by the resonant cavities 22 and 23 between the two paths 20 and 21. Because recesses 16 and 17 are proportioned to resonate at the TE₀₃ mode, the cavities 22 and 23 are also to be considered as resonant for the TE₀₃ mode in this analysis.

Referring again to FIG. 2, of the energy entering path 20 in the TE₀₁ mode, a portion will be coupled through cavity 22 to guide 21 and be reradiated as TE₀₂ energy. Of the remaining TE₀₁ energy, a portion will couple to guide 21 through cavity 23, and the residue will continue along guide 20.

If the energy leaving path 20 is considered, it is seen that it consists of that portion of the incident energy that has come directly through guide 20, labeled e_1 , and a second portion, e_2 , which has undergone a process of conversion and reconversion. In traveling through guide 20, the signal e_1 has undergone a total phase shift

$$\varphi_{e1} = \frac{2\pi l_3}{\lambda_1}$$

where l_3 is the distance between cavities 22 and 23 and is equivalent to the distance between the centers of recesses 16 and 17 of FIG. 1, and

λ_1 is the wavelength of the TE₀₁ mode energy.

e_2 , on the other hand, has undergone a total phase shift

$$\varphi_{e1} = \varphi_{12} + \frac{2\pi l_3}{\lambda_2} + \varphi_2$$

where φ_1 and φ_2 represent the phase shift in passing through cavities 22 and 23, respectively, and can be shown to be equal to 180° , and λ_2 is the wavelength of the TE₀₂ mode energy.

The relative phase difference between e_1 and e_2 [neglecting the 360° introduced by $(\varphi_1 + \varphi_2)$] is then

$$\varphi_{e1} - \varphi_{e2} = \frac{2\pi l_3}{\lambda_1} - \frac{2\pi l_3}{\lambda_2}$$

$$\varphi_{e1} - \varphi_{e2} = 2\pi l_3 \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

Since all the energy in the channel to be dropped is to be reflected, $(\varphi_{e1} - \varphi_{e2})$ is made equal to $(2n-1)\pi$ where n is an integer. Thus

$$2\pi l_3 \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) = (2n-1)\pi$$

and

$$l_3 = \frac{(2n-1)}{2} \left[\frac{1}{\frac{1}{\lambda_1} - \frac{1}{\lambda_2}} \right]$$

or l_3 is an odd multiple of half a beat wavelength. By a similar analysis, it may be shown that with l_3 equal to half a beat wavelength or odd multiples thereof, e_3 and e_4 at the right-hand side of path 21 are likewise out of phase and cancel, whereas the energy in e_5 and e_6 are in phase, and consequently all the incident power in the TE₀₁ wave travels to the left in path 21. Similarly, all the in-

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cident energy in the TE_{02} mode may be shown to leave by way of the left-hand side of path 20.

The effect, therefore, of the presence of the resonant recesses 16 and 17 is to reflect all the energy at the resonant frequency whether in the TE_{01} or TE_{02} mode. In particular, the energy appears to be reflected from a shorting plane located in the center of recess 16 at a distance l_1 from end 13 of guide 11. However, because the propagation constants of the TE_{01} and TE_{02} modes differ, the energy in the two modes, upon reaching guide 11, will have undergone some relative phase shift in traversing the distance l_1 twice. As explained above, if the total distance traveled by the two modes is equal to half a beat wavelength, then all the energy will be transferred to guide 15. Since such a transfer will segregate the desired channel from the incident energy in guide 11, l_1 is adjusted to be a quarter of a beat wavelength.

In view of the above discussion, the over-all operation of a channel-dropping filter in accordance with the invention may be summarized briefly as follows:

Referring to FIG. 1, energy in the TE_{01} mode comprising a plurality of signal channels enters through port (1) in guide 11. Upon reaching end 13, half of the total energy is converted to the TE_{02} mode. The two modes then propagate along guide 15 until they reach the first recess 16 at which point a portion of the energy in each of the modes is converted to the TE_{03} mode. Since the TE_{03} mode cannot propagate in guide 15, there is a re-conversion back from the TE_{03} to the TE_{01} and TE_{02} modes. Reconverted energy propagates in both directions along guide 15. The energy then progresses along to the second recess where a similar conversion and re-conversion occurs. Because of the particular spacing and size of the resonant recesses which favor a particular frequency corresponding to the frequency of the channel to be dropped, the energy reradiated back towards guide 11 tends to reinforce and, in the manner described with reference to FIG. 2, recombines and leaves by way of port (3) in guide 15. All of the remaining energy to be passed, comprising those channels other than the channel to be dropped, continues to propagate towards the right, and because L is equal to a whole beat wavelength, recombines and leaves by way of port (2) in guide 12. By cascading a number of similar filters, each tuned to a different frequency, all of the channels comprising the total signal may be dropped in sequence.

It will be noted that the operation of the filter requires that equal amounts of TE_{01} and TE_{02} energy be converted to the TE_{03} mode at each recess. To insure that this occurs, it may be necessary to provide adjustments at the several discontinuities which define the recesses. In FIG. 3 there is shown a recess 31 adjacent to an inner guide 32. At the discontinuities 35 and 36, which define the annular recess 31, and coaxial with guide 32, are two conductive equalizing rings 33 and 34. These may be supported by means of a low-loss, low dielectric cylinder (not shown) in a manner well known in the art. By proportioning the dimensions of rings 33 and 34, the energy converted to the TE_{03} may be varied. A similar set of rings may also be located, if required, at the second annular recess, and similarly adjusted to produce the desired amount of conversion and re-conversion.

The recesses are adjusted to the desired frequency and bandwidth by controlling their longitudinal and transverse dimensions. For example, in FIG. 1 the resonant frequency of recesses 16 and 17 is determined by adjusting their length l . The bandwidth of the filter, on the other hand, is a function of the depth of the recess t . The deeper the recess, or the larger t , the greater the conversion to TE_{03} mode and the broader the bandwidth.

While the embodiments of the invention herein described in detail have utilized circular electric mode wave energy propagating in circular cylindrical waveguides, the invention may be practiced equally as well in a system utilizing the TE_{10} mode propagating in rectangular wave-

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guides. Thus, in all cases it is understood that the above-described arrangements are illustrative of only 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 channel-dropping filter comprising first and second hollow, cylindrical conductively bounded waveguides extending colinearly in longitudinal succession with adjacent ends of said first and second guides spaced apart a given distance to form a gap in the conductive boundary of said first and second guides, a third hollow conductively bounded waveguide disposed external to and coaxial with at least a portion of each of said first and second guides to provide a conductive boundary surrounding said gap, said third guide having a pair of annular recesses along its inside surface between said first and second guides in the region of said gap, said first and second guides being proportioned to support the first circular electric mode of electromagnetic wave energy within the operating range of said filter, said third guide being proportioned to support the first and second modes of said energy in the region of said gap, and said recesses being proportioned to support the first, second and third modes of said energy, said recesses also being resonant for said third mode.

2. The combination according to claim 1 wherein the radii of said third guide and said first guide, and said third guide and said second guide are in the ratio of 7.016 to 3.832.

3. A transmission system supportive of electromagnetic wave energy over a predetermined range of operating frequencies, said wave energy as supported having transversely extending field components identified by a pair of periodicity parameters descriptive of the cyclical variation in field intensity of said components in any given plane transverse to the direction of wave propagation, means for separating a specified band of frequencies from the remaining frequency components within said range of frequencies coupled to said system having sections proportioned to support first, second and third distinct modes of wave propagation within said band characterized in that one of the periodicity parameters of each mode is equal to the corresponding periodicity parameter of each of the other two modes and in that the other of said parameters of each mode is different from the remaining parameter of each of said other modes, said separating means comprising a pair of hybrid junctions each having two physically separate branches proportioned to support said first mode of wave propagation to the exclusion of said second and third modes, and a multimode branch proportioned to support said first and second modes to the exclusion of said third mode, means connecting the multimode branch of one of said hybrids to the multimode branch of the other of said hybrids, said connecting means proportioned to support said first and second modes to the exclusion of said third mode, and a pair of tuned cavities proportioned to resonate at a given frequency within said band in said third mode of said three modes longitudinally disposed between said hybrids and coupled to said connecting means.

4. The combination according to claim 3 wherein said connecting means has a length equal to $n\lambda_b$, and said cavities have a longitudinal separation between corresponding transverse regions within said cavities of

$$\left(\frac{2n-1}{2}\right)\lambda_b$$

where

$$\lambda_b = \frac{1}{\frac{1}{\lambda_1} - \frac{1}{\lambda_2}}$$

in which λ_1 is the wavelength of said given frequency in

said first mode, λ_2 is the wavelength of said given frequency in said second mode, and n is an integer.

5. For use in an electromagnetic wave transmission system adapted to support circular electric modes of wave propagation, apparatus comprising a first hollow conductively bounded waveguide of circular cross section proportioned to support the first and the second of said modes over a given range of operating frequencies, said second mode having an electric field null at a radius r from the center of said first guide, second and third hollow conductively bounded waveguides of radius r disposed in longitudinal succession within, and coaxial to, said first waveguide over an interval coextensive therewith, adjacent ends of said second and third waveguides being spaced apart a given distance to form a gap in the conductive boundary of said second and third guides, annular recesses located along the inside surface of said first guide between said second and third guides in the region of said gap, said recesses proportioned to support the first, second and third circular electric modes of wave propagation, said recesses also being resonant for said third mode at a given frequency within said range, and a plurality of conductive rings longitudinally disposed along said gap in the region of said recesses.

6. Apparatus according to claim 5 wherein each of said rings is coaxial with said first guide and disposed in a plane normal to the axis of said guide.

7. Apparatus according to claim 5 wherein each of said recesses comprises a pair of discontinuities in the conductive boundary of said first guide and wherein each of said conductive rings is coaxially disposed in said first

guide in a transverse plane including one of said discontinuities.

8. In combination, first and second power dividing transmission networks supportive of the circular electric mode of wave propagation within a given band of operating frequencies, each of said networks having a multimode branch proportioned to support a first and a second circular electric mode of wave propagation and at least one other branch proportioned to support the first of said modes to the exclusion of the second of said modes, means for connecting the multimode branch of said first network to the multimode branch of said second network, said connecting means being proportioned to support said first and second circular electric modes over said band of operating frequencies to the exclusion of a third circular electric mode of wave propagation, and means for inducing along said connecting means said third circular electric mode, said inducing means being resonant for said third mode at a given frequency within said band.

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