

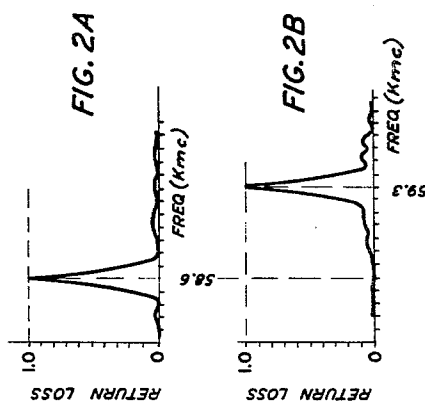
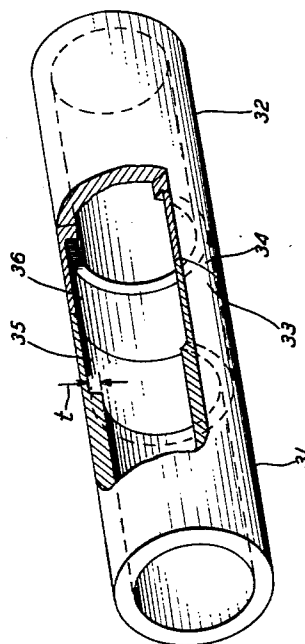
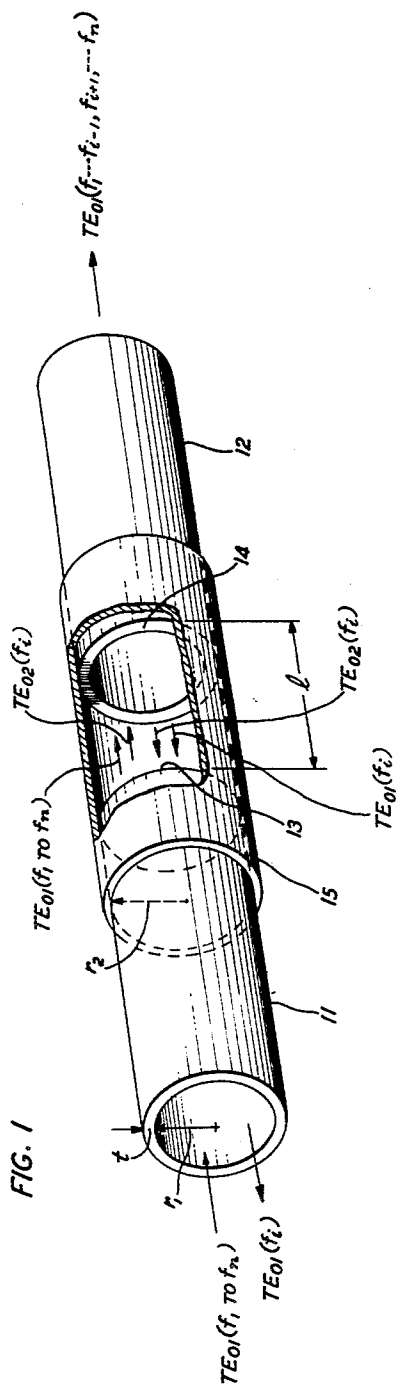
Aug. 23, 1960

E. A. J. MARCATILI
MICROWAVE DEVICES

2,950,452

Filed April 29, 1958

4 Sheets-Sheet 1



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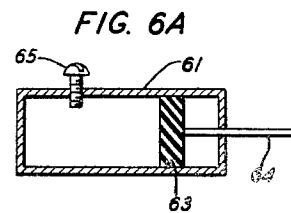
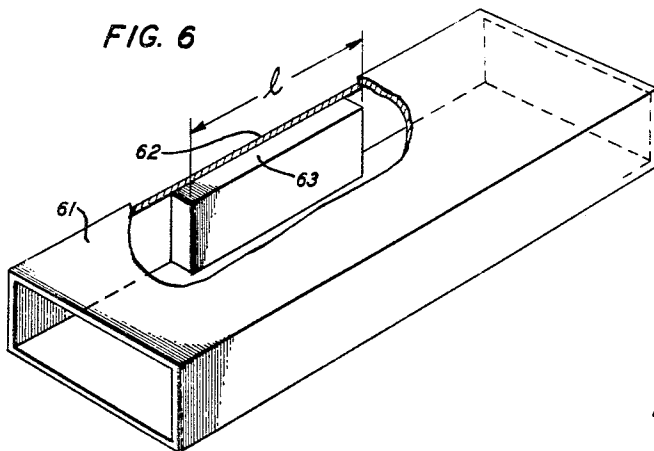
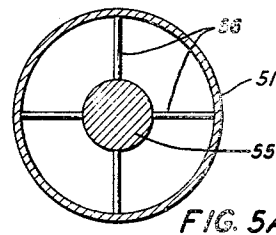
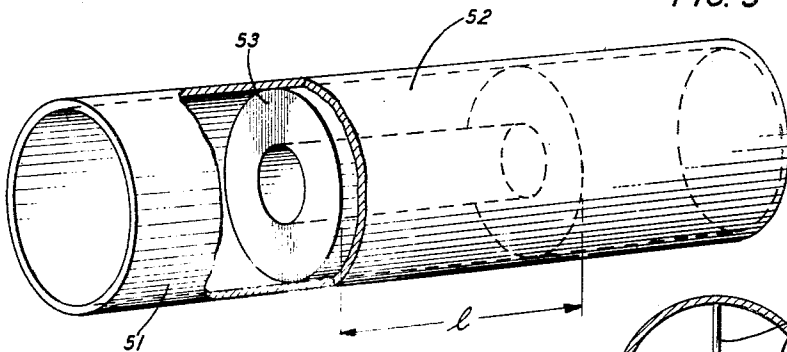
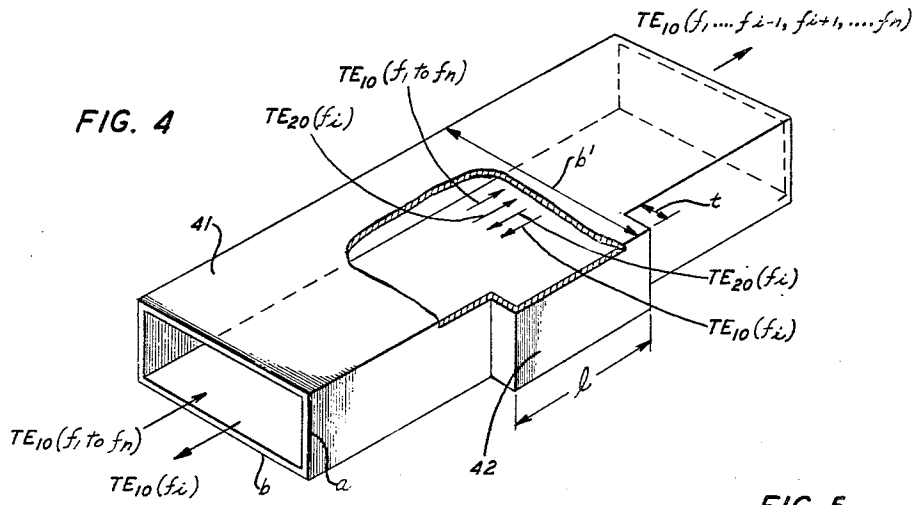
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4 Sheets-Sheet 2



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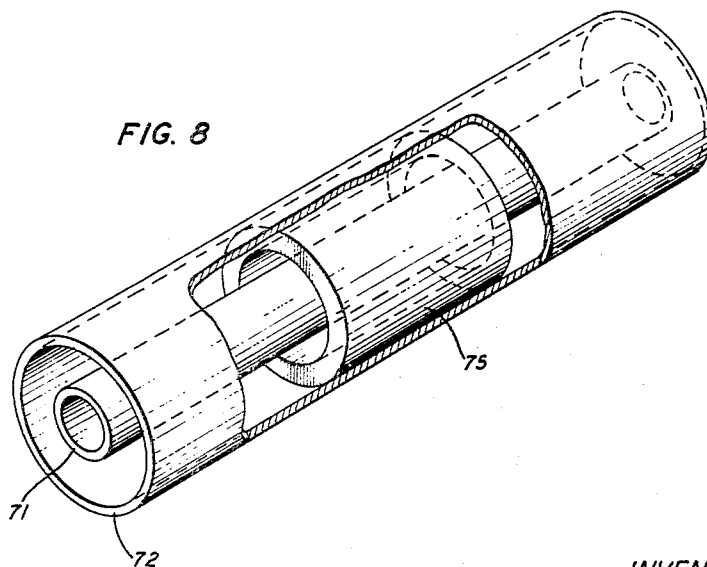
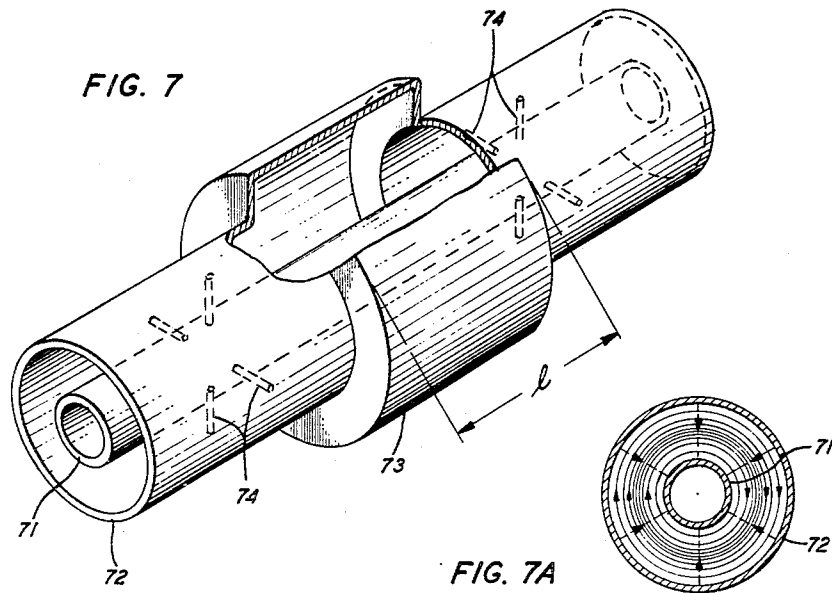
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4 Sheets-Sheet 3



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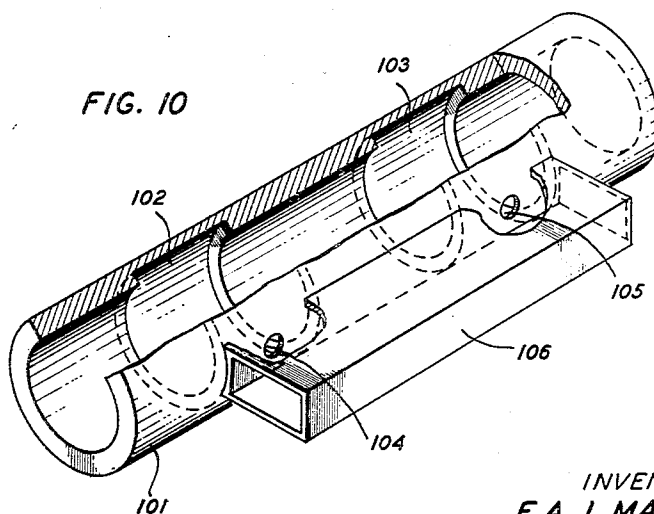
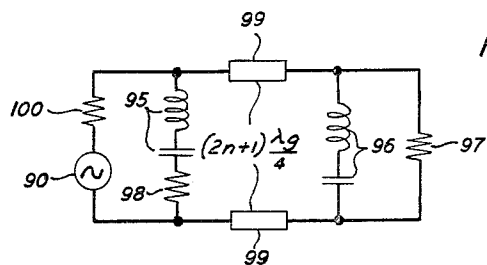
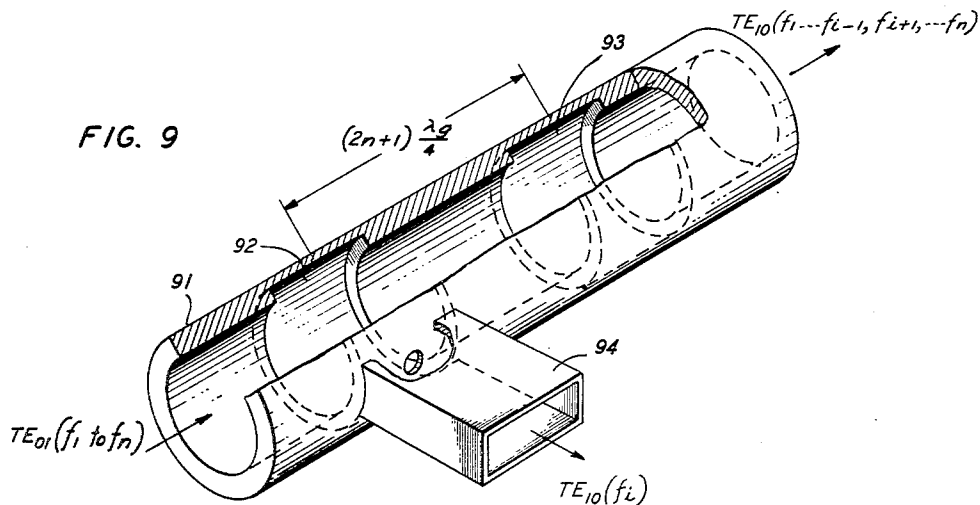
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MICROWAVE DEVICES

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4 Claims. (Cl. 333-73)

This invention relates to electromagnetic wave transmission systems and more particularly to wave guide band reflection filters for use in such systems.

One of the important microwave components in frequency division multiplex transmission systems is the band reflection filter in the form of a hollow pipe wave guide component which reflects a given frequency band for the purpose of separating it from the rest of the operating frequency range so that the passed and reflected bands may be separately utilized. Wave guide band reflection filters are well known in the art and take many and varied structural forms. Because of the important role that band reflection filters play in wave guide transmission systems, there is always a need for structurally simplified and improved devices.

Simplification and improvement 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, a dual mode wave guide, adapted to support first and second distinct electromagnetic modes of propagation, at a mid-band frequency f_1 , having different phase constants β_1 and β_2 , respectively, interconnects two wave guides each of which is supportive solely of the first of those two modes at f_1 . A small portion of the wave energy in the form of the first mode from one of the single mode guides will, upon entering the dual mode section, be converted into wave energy propagating in the second mode. Upon reaching the other end of the dual mode section and the beginning of the second single mode guide, most of the energy in the second mode (which mode cannot be supported by the succeeding single mode guide), will be reflected back through the dual mode section, while a small portion will be reconverted into the field pattern of the first mode. By adjusting the parameters of the dual mode section, it may be made resonant at f_1 in the second mode. As a consequence of this resonance in the second mode, that portion of the second mode at f_1 which is reconverted into the first mode will be precisely equal in amplitude and oppositely phased to that portion of the wave energy at f_1 which had remained in the form of the first mode throughout the entire process. Thus transmission at f_1 in the first mode is nullified, i.e., f_1 in the form of the first mode is completely reflected back through the dual mode guide and into the first single mode guide from whence it came.

The dual mode guide is made resonant at f_1 in the second mode, in a manner in accordance with the principles of the invention now to be described. At the beginning and end of the dual mode section, it was noted, mode conversion and reconversion occur, respectively. In this process a phase difference is generated between the two modes at each end of the dual mode section. Thus, that portion of the wave energy converted into the second mode, at the beginning of the dual mode section, will differ in phase at that point from that portion of wave energy in the first mode, by an amount, ϕ . On

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reconversion to the first mode at the end of the dual mode section, a like phase shift occurs such that the reconverted energy experiences another phase shift ϕ relative to that portion of the wave energy which had propagated the length of the dual mode section undisturbed in the form of the first mode. The total phase difference between the two portions of wave energy at the end of the dual mode section due exclusively to the mode conversion and reconversion of one of the portions is equal, therefore to 2ϕ . The first and second modes supported by the dual mode section having different phase constants, β_1 and β_2 , propagate therealong with different phase velocities. Accordingly, the energy at f_1 in the form of the second mode experiences a phase shift $l\beta_2$, where l is the physical length of the dual mode guide, due to its propagation along the length of the dual mode section. The total electrical length of the dual mode section is, therefore, $2\phi + l\beta_2$, for the second mode. By making this length $n\pi$, i.e. an integral number of half wavelengths at f_1 , the dual mode section is resonant at f_1 in the second mode. In accordance with the invention, the filter is arranged such that the physical length, l , results in a dual mode guide having an electrical length equal to $n\pi$ at f_1 . With such an arrangement, wave energy in the frequency band whose mid-band frequency is f_1 , will be completely reflected in the form of the first mode from the end of the dual mode section, while all energy outside this band will continue propagating into the single mode guide beyond the dual mode section.

While the mid-band frequency of the band to be rejected by the filter is determined primarily by the electrical length of the dual mode section, the width of the band that the filter rejects is determined primarily by the electrical width of the dual mode section. This section is capable of supporting its second mode by virtue of having a greater electrical width than the single mode sections, i.e., the single mode sections have transverse dimensions small enough to render them non-supportive of the second mode at f_1 , which is a mode of higher order than the first mode, while the dual mode section is wide enough to support the second mode at f_1 . Thus, the single mode sections have a cut-off frequency greater than f_1 for the second mode, while the dual mode section has a cut-off frequency less than f_1 for the second mode. The greater, and more abrupt, the differences between the electrical widths of the single and dual mode sections, the greater the amount of energy that will be coupled from the first mode to the second mode on reaching the impedance discontinuity (the increased electrical width) at the beginning of the dual mode section. This is analogous to increasing the size of the coupling hole between wave guides to increase the amount of energy transfer. Analysis demonstrates that the greater the coupling to the second mode, the larger the loaded Q of the filter, and thus the larger the band width of the rejected band. It may be seen, therefore, that the band width of the band rejection filter is determined primarily by the electrical width of the dual mode section relative to that of the single mode section.

In accordance with certain embodiments of this invention, later to be described in greater detail, the dual mode section is adapted to support a higher order mode by virtue of its having a wider physical width than that of the single mode sections. In these embodiments the physical length of the wider width section effectively determines the mid-band frequency of the filter. This physical length, and accordingly the mid-band frequency to be rejected, may be rendered variable as disclosed in one embodiment of the invention. In this embodiment the two single mode sections consist of two similar hollow cylindrical conductive pipes of given wall thickness which

are slidably inserted into a hollow cylindrical conductive pipe of larger diameter which constitutes a dual mode section. The external surfaces of the single mode pipes are contiguous to the inside surface of the dual mode pipe and may be positioned longitudinally with respect to each other by sliding one or both of them in a longitudinal sense within the dual mode pipe. In this way the electrical length of the dual mode pipe as a wave guiding section is fixed by the distance between adjacent ends of the single mode pipes. Furthermore, the thickness of the single mode pipe walls is an index of the band width of the filter since this is the amount by which the dual mode pipe has a greater radius than the single mode pipe.

In certain other embodiments in accordance with the invention the difference in transverse dimensions between the dual mode section and the single mode pipe is provided by dielectric loading of the dual mode section so that its electrical width is increased even though its physical width may be the same as that of the single mode pipe. In these embodiments the electrical length, and therefore the mid-band frequency of the filter, is determined by the physical length of the dielectric element and by its effective dielectric constant.

The extreme simplicity in the geometries of the filters in accordance with the invention results in low heat losses, and consequently high intrinsic Q , because of the absence of the high density currents.

Important microwave applications are disclosed wherein the band reflection filters in accordance with the invention are utilized to provide constant resistance channel dropping filters for frequency division multiplex systems. The channel dropping filters perform the function of removing the rejected band from the main transmission path to be appropriately separately utilized. The advantages of the band rejection filters, e.g. structural simplicity and low loss, are maintained in the channel dropping filters.

Other objects and certain features and advantages of the invention will become apparent during the course of the following detailed description of the specific illustrative embodiments of the invention shown in the accompanying drawings.

In the drawings:

Fig. 1 is a perspective view of a band rejection filter in accordance with the principles of the invention, given by way of example, for purposes of illustration, utilizing guides of circular transverse cross section and operative in the circular electric modes, whose frequency characteristic is variable by mechanical adjustment;

Figs. 2a and 2b are curves used to illustrate the return loss versus frequency characteristic of the embodiment of Fig. 1;

Fig. 3 is a perspective view, having a cut-away section, of a modification of the embodiment of the invention of Fig. 1, wherein the frequency characteristic is fixed;

Fig. 4 is a perspective view of a band rejection filter, in accordance with the invention, utilizing rectangular cross sectioned wave guide and supportive of the dominant mode in such a guide;

Figs. 5 and 5a are perspective and transverse cross sectional views, respectively, of band rejection filters given by way of example, wherein wave guides of circular transverse cross section supporting circular electric modes are loaded with dielectric elements;

Figs. 6 and 6a are perspective and transverse cross sectional views, respectively, of rectangular cross sectioned wave guide filters, in accordance with the invention, loaded with dielectric elements;

Fig. 7 is a perspective view of the filter, in accordance with the principles of the invention, adapted to the circular electric mode in coaxially related hollow wave guides;

Fig. 7a is an electromagnetic field diagram representing the TE_{01} mode in an outer coaxial guide, and is presented for purposes of illustration;

Fig. 8 is a transverse cross sectional view of a modification of the filter of Fig. 9 utilizing a dielectric element;

Fig. 9 is a perspective view of a constant resistance channel dropping filter utilizing two of the filters of Fig. 3;

Fig. 9a is a schematic diagram of a lumped parameter circuit useful in explaining the operation of the embodiment of Fig. 9, by analogy; and

Fig. 10 is a perspective view of another type of channel dropping filter of the directional coupler type.

More particularly, Fig. 1 discloses a band rejection filter, in accordance with the invention, which is presented by way of example for purposes of illustration, operative upon the circular electric modes of wave energy propagation supported by wave guides of circular transverse cross section. Two circular wave guides 11 and 12 are disposed in longitudinal succession along a common axis, with adjacent ends 13 and 14 of guides 11 and 12 spaced from each other by a distance l . The relationship between l and other parameters of the filter will be hereinafter discussed in greater detail. Guides 11 and 12 have equal diameters 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, at frequency f_1 within the operating frequency range, f_1 to f_n . Surrounding the adjacent ends 13 and 14 of guides 11 and 12, respectively, and extending from end 13 to end 14 is a circular wave guide 15 in coaxial relation with guides 11 and 12. The outside surfaces of guides 11 and 12 in the regions of ends 13 and 14 are contiguous to the inside surface of guide 15. In addition, guides 11 and 12 are slidably disposed longitudinally relative to each other within guide 15. It may be seen that the radius r_2 of guide 15 is greater than the radii r_1 of guides 11 and 12 solely by an amount equal to the wall thickness, t , of guides 11 and 12.

Guides 11 and 12 in addition to being proportioned to support the TE_{01} mode at frequency f_1 , are dimensioned so as to be non-supportive of any higher order circular electric mode at this frequency. 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 at f_1 . However, guide 15 supports these two modes to the exclusion of any circular electric mode of higher order than the TE_{02} mode at this frequency.

With these conditions determined, the dimensions of guides 11, 12 and 15 required to satisfy them may be readily set. As is well known in the art, every electromagnetic mode, at a given frequency, requires a wave guide of a certain minimum transverse dimension in order for it to be propagated. Conversely, a round wave guide of a given radius will support only those frequencies, in the particular mode of interest, which are above a certain minimum frequency, whose wavelength is known as the cut-off wavelength. Lower frequencies, having larger wavelengths, will not be supported by the wave guide. Parametric expressions relating the cut-off wavelength, the radius of the circular wave guide, and a function of the electromagnetic mode, are well known in the art. Thus, it is known that the cut-off wavelength for the TE_{01} mode is

$$\lambda_c = \frac{2\pi r}{3.83}$$

for the

$$TE_{02} \text{ mode } \lambda_c = \frac{2\pi r}{7.02}$$

for the

$$TE_{03} \text{ mode } \lambda_c = \frac{2\pi r}{10.17}$$

λ_c is the cut-off wavelength, r is the radius of the wave guide, and the denominator in each instance is the ap-

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appropriate Bessel function root for the particular transverse electric mode involved. It follows, therefore, that the radii r_1 of guides 11 and 12 must fall within the range

$$\frac{3.83\lambda_1}{2\pi} < r_1 < \frac{7.02\lambda_1}{2\pi} \quad (1)$$

where λ_1 is the guide wavelength for frequency f_1 . Wave guide 15, which must support f_1 in the TE_{02} mode, but not in the TE_{03} mode, accordingly has a radius r_2 which falls within the range:

$$\frac{7.02\lambda_1}{2\pi} < r_2 = (r_1 + t) < \frac{10.17\lambda_1}{2\pi} \quad (2)$$

In the operation of the device of Fig. 1, let us consider a frequency band with mid-band frequency f_1 , to be the band to be rejected by the filter. Wave energy is excited at the left-hand end of guide 11 by a source (not shown) in the form of TE_{01} wave energy over the entire frequency range, f_1 to f_n . Wave energy propagating to the right will encounter the impedance discontinuity formed by end 13 of guide 11, and guide 15. The wave will continue propagating to the right in the TE_{01} form, except for a small reflection, and some conversion or coupling to the TE_{02} mode, which guide 15 is capable of supporting. Effectively then, the wave energy continuing to the right, is divided into two portions defined by the TE_{01} and TE_{02} modes, with the major portion remaining in the lower order mode. In the process of dividing between the two modes, the portion which is converted to the higher order mode will be shifted in phase at the left-hand end of guide 15 by an amount φ relative to the portion remaining in the form of TE_{01} mode energy. As is well known in the art, the TE_{01} and TE_{02} modes have different phase constants β_1 and β_2 and will accordingly propagate along wave guide 15 with different phase velocities. On reaching the right-hand end of guide 15 and end 14 of guide 12, the TE_{02} mode energy has traveled a distance l and thus experienced a shift in phase equal to φ plus the $l\beta_2$. At this point the major portion of the TE_{02} mode energy, of necessity, is reflected back into guide 15, while a small portion is reconverted into TE_{01} mode energy, since guide 12 cannot accept TE_{02} mode energy. In this process of reconversion that portion of the energy which is reconverted, once again undergoes a phase shift equal to an amount φ . Accordingly, that portion of the wave energy which had propagated in the form of the TE_{02} mode has, upon reconversion, experienced a total phase shift between ends 13 and 14 of guides 11 and 12 equal to $2\varphi + l\beta_2$. The dual mode guide is proportioned such that it is resonant for the TE_{02} mode at f_1 , i.e. is proportioned to satisfy the following equation:

$$2\varphi + l\beta_2 = n\pi \quad (3)$$

At resonance, the intensity of the TE_{02} mode reconverted into the TE_{01} mode at the impedance discontinuity formed by end 14 and guide 15, is very large even though it is a small portion of the total magnitude of the field at that point in the TE_{02} form. Thus with Equation 3 satisfied, frequency f_1 energy at end 14 which is reconverted into the TE_{01} mode is equal in amplitude but oppositely phased to the TE_{01} mode energy at f_1 which propagated in that form undisturbed throughout the entire dual mode guide 15. Accordingly, a frequency band centered about f_1 is reflected to the left in the form of TE_{01} mode energy and continues to the left into guide 11. All other frequencies continue propagating to the right into guide 12 to be utilized as desired.

It can be demonstrated that the loaded Q of the dual mode guide 15 is

$$Q_L = \frac{l\beta_2}{2|\Gamma|^2(1 - \cos \delta)} \quad (4)$$

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where $|\Gamma|$ is the amplitude of the coupling coefficient at one of the impedance discontinuities between the two modes and δ is the phase difference between two portions of energy at end 14 which had propagated through the dual mode guide in the form of the two different modes, respectively, i.e. $\delta = 2\varphi + l(\beta_2 - \beta_1)$. Since $|\Gamma|$ is proportional to the wall thickness t of guides 11 and 12, it is clear that the greater the impedance discontinuity the smaller the loaded Q and thus the broader the frequency band, centered about f_1 , that will be rejected.

By rewriting Equation 3 in the following form

$$l = \frac{n\pi - 2\varphi}{\beta_2} \quad (5)$$

it can be seen that by changing l the mid-band frequency of the rejected band must of necessity change since the dual mode section will be resonant in the higher order mode at a different frequency. It may be seen, therefore, that by sliding guides 11 and 12 closer together or further apart within guide 15, the length l between ends 13 and 14 is changed and as a consequence the mid-band frequency of the band rejected by the filter is changed accordingly. In practice, therefore, it is possible to design a filter to reject a particular frequency band by designing it in accordance with the above described theory. Alternatively a filter, mechanically variable as in Fig. 1, may be empirically adjusted to reject the frequency band desired, i.e. guides 11 and 12 may be moved relative to each other to vary length l until the mid-band frequency that is rejected is that frequency which is desired. Thus, for example, the curves of Figs. 2a and 2b demonstrate the results of such an adjustment in one of the several successful reductions to practice of the invention. A filter in all ways similar to the embodiment of Fig. 1, was developed wherein guides 11 and 12 have internal diameters of 0.437 inch and guide 15 has an internal diameter of 0.500 inch. Fig. 2a shows the rejected band with the length l between guides fixed at 0.335 inch; Fig. 2b shows precisely the same arrangement with the guides 11 and 12 moved relative to each other so that the distance l therebetween is 0.308 inch. It may be seen that this change in l resulted in a shift in the mid-band frequency of the rejected band by 700 megacycles, i.e. from 58.6 kmc. to 59.3 kmc. Furthermore, in each case, this filter has a loaded Q of 550 and a very high intrinsic Q of 10,090. The ordinate of Figs. 2a and 2b is the return loss, a numeric ratio defined as power reflected from the filter divided by power into the filter while the abscissa is frequency in kilomegacycles per second.

Although the embodiment of Fig. 1 is shown as comprising hollow conductive wave guides whose walls are of solid conductive material, the helical wave guides known in the art for supporting the circular electric modes may also be utilized. The filter, in every other respect, however, should be precisely the same as the embodiment disclosed in Fig. 1. For a detailed discussion of the theory and structure of helical wave guides, reference may be had to United States Patent 2,848,695, issued to J. R. Pierce on August 19, 1958, and United States Patent 2,848,696, issued to S. E. Miller on August 19, 1958.

Fig. 3 discloses a modification of the filter arrangement of Fig. 1 in that a structure is shown having a dual mode section of fixed length, l . In this arrangement two hollow conductive metallic wave guides 31 and 32 of circular transverse cross section having the same radii and wall thicknesses are serially disposed in longitudinal succession with adjacent ends 33 and 34 of guides 31 and 32 in contiguous relation with each other. At each end 33 and 34, the inside wall of guides 31 and 32 is partially removed to form annular recesses 35 and 36 within guides 31 and 32, respec-

tively. By virtue of the serial and contiguous relationship of the two guides, annular recesses 35 and 36 form a single annular recess, in the overall wave guide 31-32, which has a longitudinal extent, l . The depth of the recess is designated t . Radii r_1 of guides 31 and 32 in their single mode portions are otherwise fixed by the same conditions discussed above with respect to Fig. 1, as is the radius r_2 of the dual mode supportive recessed annular region which corresponds to the radius of dual mode section 15 of Fig. 1. It may be noted that in both Figs. 1 and 3, $r_2 = r_1 + t$; but in Fig. 3 t physically corresponds to the depth of the raised annular region while in Fig. 1 it corresponds to the thickness of the wall of the single mode guides 11 and 12 within dual mode guide 15. Guides 31 and 32 may be held in contiguous relation at ends 33 and 34 by a sleeve (not shown) or alternatively may be soldered together. The filter of Fig. 3 is in all respects electrically similar to the filter of Fig. 1 except that it is not variable; the operation is otherwise precisely the same as described above.

The embodiments in accordance with the invention thus far described are appropriate for filtering operations upon the circular electric modes of wave energy propagation. Fig. 4 discloses a filter wherein electromagnetic wave energy in rectangular wave guides is filtered in accordance with the principles of the invention. In Fig. 4 there is represented a hollow conductive wave guide 41 having a rectangular transverse cross section whose wide horizontal transverse dimension is designated b and whose narrow vertical transverse dimension is designated a . Guide 41 is proportioned to support the dominant mode TE_{10} mode energy to the exclusion of all higher order modes in rectangular guides at frequency f_1 . Along a length l defining a section 42 of guide 41, the wide transverse dimension b of the guide is increased to b' while its narrow transverse dimension remains constant. Thus guide 41 has a stepped out section 42 wherein the width of the guide therealong is equal to b' which is greater than b by an amount t (alternatively, with wave guide walls of considerable thickness, stepped out section 42 may be formed by removing a solid right parallelepiped from one of the narrow inside walls of guide 41). Section 42, by virtue of width b' , is proportioned to support the propagation of the TE_{20} rectangular guide mode but not the propagation of the TE_{30} mode wave energy at frequency f_1 . Thus the relationship of higher and lower order mode supported by the single and dual mode guides is completely analogous to the arrangement of the circular electric wave guides of Figs. 1 and 3. The specific dimensions b and b' of the rectangular guide, however, may not be determined from Equations 1 and 2 which were appropriate for circular guides. The cut-off wavelength λ_c for any TE_{mn} mode in a rectangular wave guide is $\lambda_c = 2ab(m^2b^2 + n^2a^2)^{-1/2}$. Since, for all the modes of interest supported by wave guide 41, $n=0$, it follows that the cut-off wavelength is determined by the expression,

$$\lambda_c = \frac{2b}{m}$$

To meet the required mode cut-off conditions, then, the following relationships must hold:

$$\frac{\lambda_1}{2} < b < \lambda_1 \quad (6)$$

$$\lambda_1 < b' = b + t < \frac{3\lambda_1}{2} \quad (7)$$

The operation of the embodiment of Fig. 4 follows a close parallel to the embodiments heretofore described. Wave energy in the form of the dominant TE_{10} mode, over frequency range f_1 through f_n , is excited in the

left-hand end, single mode portion, of guide 41 and propagates to the right until dual mode section 42 is reached. At this point, wave energy at frequency f_1 which may be supported in both the TE_{10} and TE_{20} modes within dual mode section 42 is resolved into two components each of which consists of one of those modes, with a resulting phase shift ϕ between the two component modes. As is well known in the art, the TE_{10} and TE_{20} modes have different phase constants and accordingly propagate along the length l of dual mode section 42 with unequal phase velocities. Length l is defined by Equation 5 and accordingly the dual mode section 42 is resonant in the TE_{20} mode at f_1 . Accordingly, a frequency band centered about f_1 is reflected back to the left in the form of the dominant f_1 is reflected wave energy, while the rest of the operating frequency range continues propagating to the right in guide 41, away from section 42, in the form of dominant mode wave energy, to be utilized as desired.

In the embodiments of the invention thus far described the effective length and width of the dual mode section were determined exclusively by the physical geometry of the structures. In the embodiments of the invention to follow, these dimensions are electrically determined as well.

In Fig. 5 there is disclosed a filter operating upon circular electric modes, comprising a wave guide 51 in all respects similar to guides 11 and 12 of Fig. 1 to perform the function of a single mode guide. A dual mode section 52 of length l is defined by a hollow cylindrical dielectric cylinder 53 disposed within wave guide 51. Cylinder 53 has blunt ends as indicated and a relative dielectric constant ϵ_r . As is well known in the art, the cut-off wavelength of any wave guide is a function of the dielectric constant of the medium within the wave guide. In particular, the equations presented above with respect to Fig. 1, giving the cut-off wavelength for the circular electric modes in wave guides must be multiplied by the factor $(\mu_r \epsilon_r)^{-1/2}$, (where μ_r is relative permeability), when the medium within the guide is other than air. It follows, therefore, that the greater the dielectric constant (or permeability) of the medium within the wave guide, the greater the cut-off wavelength for the guide. Consequently, loading the wave guide with dielectric material is effectively the same as increasing the transverse dimension of the wave guide with respect to cut-off wavelength considerations. It may be seen, therefore, that the dielectric constant of the material of cylinder 53, and its transverse dimension will effect the cut-off wavelength of guide 51 along section 52. The greater the value of ϵ_r , and the thicker the wall of dielectric cylinder 53, the greater the effective electrical width of guide 51 along section 52, and the greater the cut-off wavelength. Accordingly, ϵ_r and the thickness of cylinder 53 may be selected so that the cut-off condition discussed above for the dual section, as described by Equation 2, will be satisfied.

It is also the case that the phase constants of the TE_{01} and TE_{02} modes will be changed by the dielectric loading of guide 51, since β is a function of $(\mu_r \epsilon_r)^{1/2}$. Accordingly the value β_2 in the product $l\beta_2$ is affected by the dielectric loading. This factor must be kept in mind, therefore, when selecting the physical length, l , of dielectric cylinder 53, i.e., Equation 5 must still hold in the embodiment of Fig. 5.

Fig. 5a is a transverse cross section of waveguide 51 demonstrating a modified type of dielectric loading wherein a dielectric rod 55, replacing cylinder 53 of Fig. 5 is supported along the center line of guide 51 by radially extending thin metallic rods 56 which are everywhere perpendicular to the circular electric lines of force of the circular electric modes. The geometry of the support rods 56 leaves these modes undisturbed.

The theory of operation of the embodiments of Figs.

5 and 5a is in all respects similar to that of the filter of Fig. 1.

The dielectric loading features of the filter of Fig. 5 may be incorporated in band rejection filters operative in other modes. For example, the embodiment of Fig. 6 discloses such an arrangement in a rectangular wave guide system wherein a single mode guide 61 is proportioned to support the dominant TE_{10} mode as does guide 41 in Fig. 4. A dielectric slab 63 of length l defines a dual mode section 62 along guide 61. It may be noted that in this arrangement the dielectric slab 63 is against one of the narrow wave guide walls. For the same reasons as discussed with respect to the filter of Fig. 5, the dielectric slab 63 renders sections 62 a dual mode section supportive of both the TE_{10} mode and the TE_{20} mode at frequency f_1 , while being non-supportive of the TE_{30} mode. The filter of Fig. 6 is, therefore, electrically similar to the filter of Fig. 4.

Fig. 6a is a transverse cross section of a modified form of the filter of Fig. 6, arranged to render the band width of the rejected band variable. The structures are similar except that in Fig. 6a the dielectric slab 63 may be moved across the wide dimension of guide 61 by means of a dielectric push rod 64, which may be of polystyrene. One end of rod 64 is connected to a wide face of slab 63 and the other end extends out of guide 61 through a small hole in one of the narrow walls thereof. A change in the transverse location of slab 63 results in a change in the magnitude of coupling between the TE_{10} and TE_{20} modes. In particular, the location of slab 63 away from the narrow wall of guide 61 as indicated provides greater coupling between the two modes than in Fig. 6 wherein slab 63 is against the narrow wall of the guide. In general, a transverse location of the slab away from the narrow walls, other than in the vicinity of the center line will provide the increased coupling. In particular, maximum coupling is obtained from slab location one-quarter the wide dimension of the guide from either of the narrow walls. As a consequence, the value of $|r|$ in Equation 4 is greater for Fig. 6a than Fig. 6, and accordingly the band width is increased. A dielectric tuning screw 65 penetrates into guide 61 through a wide wall thereof to be used to adjust the electric length of the resonant cavity, and thus the mid-band frequency f_1 of the rejected band. In this way the mid-band frequency f_1 may be kept fixed even though a change in band width is introduced through a change in the transverse location of slab 63. One or more of tuning screws 65 may be also used in the embodiments of Figs. 4 and 6, for example, for fine tuning of the resonant frequency of the dual mode sections.

In my copending application, Serial No. 724,724, filed March 28, 1958, there is disclosed a directional coupler particularly adapted for operation in the circular electric modes. One of the ports of this circular electric wave guide is formed between two coaxially arranged wave guides of circular transverse cross section. A coaxial structure of that type is here represented in Fig. 7. Wave energy propagating between internal guide 71 and external guide 72 is in the form of a circular electric mode but in coaxial pipe as shown in Fig. 7a and may be called the TE_{01} mode in coaxial guide (the solid concentric circle represents the electric lines of force). In accordance with the principles of the invention, the wave path formed between guides 71 and 72 may be proportioned as a single mode guide for the TO_{01} coaxial mode at f_1 while section 73 having length l may be viewed as the dual mode section for coaxial guide which would be supportive of the TE_{02} but not the TE_{03} mode in coaxial guide at f_1 . In this way, the structure will serve as a band rejection filter for the TE_{01} coaxial mode having the characteristics defined by Equations 3 and 4. While section 73 is shown as having a diameter greater than that of wave guide 72, it may, in accordance with the principles of the invention, be of the same physical dimensions as guide 72 with a

cylindrical dielectric insert 75 as indicated in Fig. 8. In both Figs. 7 and 8, guide 71 may be supported coaxially within guide 72 by radially extending thin metallic rods 74 which are everywhere perpendicular to the circular electric lines of force of the circular electric modes. This geometry leaves these modes undisturbed.

The embodiments of the invention described have been operative in certain important electromagnetic modes of propagation, for example, the circular electric mode in circular and coaxial guides and the dominant mode in rectangular wave guide. However, these principles are equally applicable to any electromagnetic mode known to the microwave art. Thus, the single mode wave guide discussed above may be single mode for any mode of interest while the dual mode section may be arranged to support that mode and any other mode to which that mode will couple at an impedance discontinuity. The universality of the applications of the principles in accordance with the invention is therefore apparent.

Figs. 9 and 10, now to be considered are examples of particularly useful applications of the band rejection filters in accordance with invention heretofore illustrated. In particular they are constant resistance channel dropping filters for use in frequency division multiplex systems for isolating a frequency band of interest to be separately utilized at a point in the system.

Fig. 9 represents a channel dropping filter in accordance with the principles of the invention, operating to exclusively transfer a frequency band having a mid-band frequency f_1 from a circular wave guide supporting the circular electric mode into a rectangular wave guide supporting the TE_{10} mode. A hollow conductive wave guide 91 of circular transverse cross section has disposed therein, in tandem relation, two dual mode wave guide sections 92 and 93 whose mid-points are separated by a distance equal to an odd integral number of quarter wavelengths at f_1 for the TE_{01} mode. Each of sections 92 and 93 may be, for example, of the type represented by the embodiment of Fig. 3. A rectangular wave guide 94, whose axis is perpendicular to that of guide 91, is coupled at one end to guide 91 at resonant section 92 through a coupling aperture 95. In the operation of the channel dropping filter of Fig. 9 wave energy over a frequency range f_1 to f_2 , including f_1 , is excited at the left in guide 91 in the form of the TE_{01} circular electric mode. All this energy, with the exception of a band centered about f_1 , will pass through resonant sections 92 and 93 and continue to the right in guide 91 since sections 92 and 93 are only resonant in the TE_{02} mode at f_1 . However, the band centered at f_1 will be coupled to rectangular guide 94 through aperture 95 in the form of TE_{10} mode energy. This type of coupling in the wave guide circuit of Fig. 9 may be understood by considering its lumped-parameter circuit analog in Fig. 9a. First and second resonant circuits 95 and 96 are disposed in two separate parallel branches, respectively, across a wire pair, with a resistor 97 in a third branch in parallel with the first and second branches; a resistor 98 is in series with resonant circuit 95 in the first branch. The first and second branches are separated by quarter wave delay lines 99 in the wire pair. The network is excited by oscillator 90 through resistor 100. Resonant circuits 95 and 96 correspond to dual mode resonant sections 92 and 93 of Fig. 9; resistor 98 corresponds to rectangular guide 94; resistor 97 corresponds to guide 91 to the right of section 93; resistor 100 corresponds to guide 91 to the left of section 92; and delay lines 99 correspond to the length of guide between sections 92 and 93. From Fig. 9a it may be seen that at resonance the first and second branches containing elements 95 and 96 are short circuited, but because of delay lines 99 that part of the network to the right of the first branch appears as an open circuit and all power passes through resistor 98 in the first branch.

The principles of the embodiment of Fig. 9 may readily be applied to an all rectangular wave guide system by

substituting a rectangular guide for circular guide 91, and using the resonant sections shown for example in Fig. 4 in lieu of sections 92 and 93.

Another type of constant resistance channel dropping filter, operative to exclusively transfer a frequency band from a circular guide supporting the circular electric mode to a rectangular guide supporting the dominant TE₁₀, is shown in Fig. 10. Circular guide 101 has two dual mode sections 101 and 103, of the type described in Fig. 3, disposed therein in tandem in manner similar to that of Fig. 9. However, each of sections 102 and 103 has a coupling aperture 104 and 105 disposed therein for coupling to rectangular guide 106. The longitudinal axis of guide 106 is parallel to that of guide 101, and the coupling apertures 104 and 105 in resonant sections 102 and 103, simultaneously penetrate a narrow dimensioned wall of rectangular guide 106. This two-point coupling provides a directional coupler type of operation in this channel dropping filter. The coupling apertures are spaced apart a distance sufficient to provide a phase shift θ_1 , for the TE₁₀ mode in rectangular guide 106 and θ_2 for the TE₀₁ mode in circular guide 101; the dimensions of guides 101 and 106 are proportioned to provide phase constants for these modes at frequency f_1 which will provide electrical lengths θ_1 and θ_2 satisfying the condition

$$\theta_1 - \theta_2 = \pm (2n + 1) \frac{\pi}{2}$$

Wave energy is excited at the left in guide 101 in the TE₀₁ mode over frequency range f_1 to f_n . A band centered about f_1 (for which sections 102 and 103 are resonant in the TE₀₂ mode) is coupled to guide 106 in the dominant TE₁₀ mode and propagates therein to the left, while the rest of the wave energy continues propagating to the right in guide 101 in the TE₀₁ mode.

In all cases, it is to be understood that the above described arrangements are simply illustrative of a small number of the many possible specific embodiments which 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. In an electromagnetic wave transmission system operative over a broad frequency range f_1 through f_n , means for energizing said system over said frequency range in a first mode of electromagnetic wave propagation, a channel dropping filter for separating a specified frequency band

from the remaining frequency components having a mid-band frequency f_1 within said range comprising first, second and third sections of electromagnetic wave transmission line supportive of said frequency range f_1 through f_n in said first mode of electromagnetic wave propagation, a fourth section of transmission line interconnecting said first and second sections being adapted to support a frequency f_1 in said range of frequencies f_1 through f_n in said first mode and in a second mode of wave propagation, a fifth section of transmission line interconnecting said second and third sections being adapted to support said frequency f_1 in said first mode and in said second mode of wave propagation, said fourth and said fifth sections each having a physical length l proportioned to render said sections resonant at said frequency f_1 in said second mode, a sixth section of transmission line coupled to said fourth section, and means for utilizing said specified frequency band to the exclusion of said remaining frequency components connected to said sixth section of transmission line.

2. A combination as recited in claim 1 wherein said first through fifth sections are in the form of hollow conductive cylindrical wave guides in tandem relation and said sixth wave transmission line is a hollow conductive wave guide of rectangular transverse cross section whose longitudinal axis is perpendicular to that of said fourth section.

3. A combination as recited in claim 1 wherein said sixth wave transmission line is also coupled to said fifth section.

4. A combination as recited in claim 3 wherein said first through fifth sections are in the form of hollow conductive cylindrical wave guides in tandem relation and said sixth wave transmission line is a hollow conductive wave guide of rectangular transverse cross section whose longitudinal axis is parallel to that of said fourth and fifth sections.

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