April 24, 1962 E. A. J. MARCATILI 3,031,630

FREQUENCY SEPARATOR

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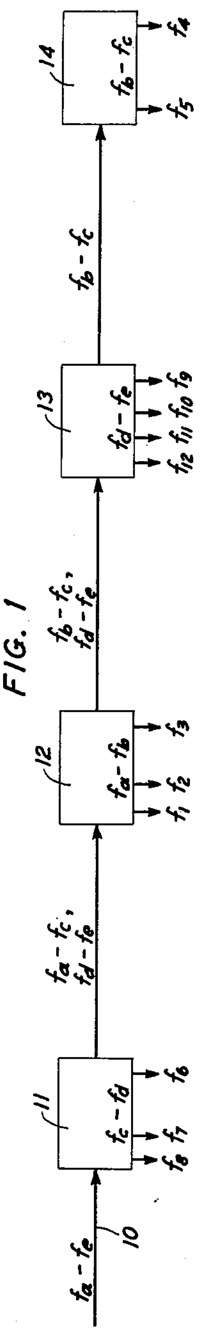

FIG. 1

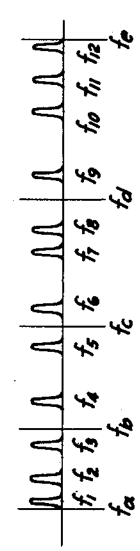

FIG. 2

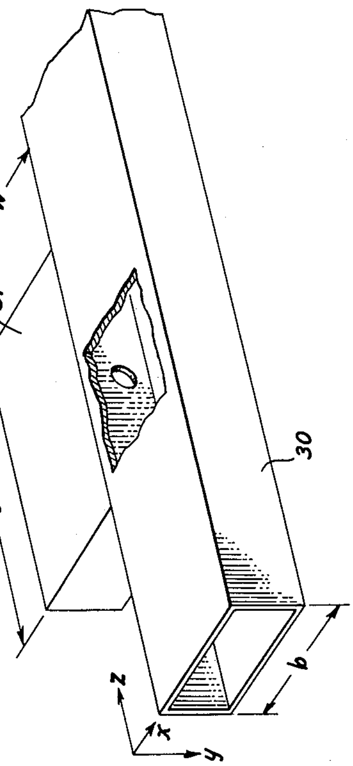

FIG. 3

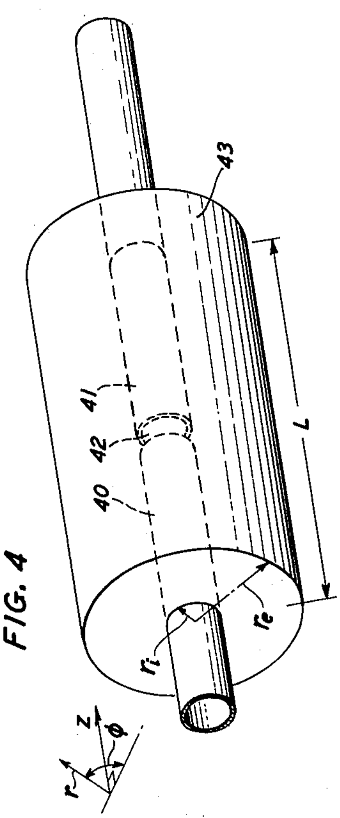

FIG. 4

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This invention relates to electromagnetic wave transmission systems, and in particular to arrangements for separating a plurality of discrete channels or bands of frequencies propagating in a common transmission line.

It is frequently necessary, in high frequency multichannel transmission systems, to segregate the individual channels propagating within a common transmission path in order to amplify the wave energy or ultimately to use it. Because of this recurring necessity, it is desirable that the branching networks be capable of handling as broad a frequency range as possible, yet still be simple and efficient in their operation. However, there are numerous practical considerations which limit the width of the spectrum that can be efficiently handled.

It is the broad object of this invention to extend the bandwidth over which efficient channel separation may be performed.

Consider a waveguide carrying a very broad spectrum of wave energy. The most obvious way to separate the bands within the spectrum is by simply cascading a series of channel-dropping filters. These filters generally consist of a through path and associated resonant elements tuned to the frequency to be dropped. In the conventional way, the channels are separated in order, either by starting from the high end of the spectrum or from the low end. However, if the lower channels are dropped first, in a system using tuned cavities, for example, the ratio of the resonance frequencies of the first and second cavity modes will limit the frequency spectrum since the large cavities needed to resonate at the lower frequencies will also be capable of resonating at some higher frequencies defined by this ratio. This will either cause the higher frequencies to be rejected or, at the very least, will cause the generation of spurious modes and increase the losses in the system. If, on the other hand, it is attempted to drop the higher frequencies first, the cross section of the through guide, being a single mode guide, will be cut off for the lower part of the spectrum.

An alternate arrangement consists in splitting the spectrum into two or more smaller bands which are physically separated, and then dropping the channels in each subband in accordance with either of the conventional arrangements described above. However, this alternate arrangement requires a number of bandpass filters capable of splitting the broad spectrum into two or more parts and is not, therefore, as attractive a method as the simple series arrangement described above.

It is, therefore, the specific object of this invention to separate, by means of a simple series arrangement of filters, the individual channels from within a broadband multichannel transmission path where the channels extend over a frequency range greater than an octave.

In accordance with the invention, a frequency spectrum extending over a range of frequencies f_a to f_e is divided into four subbands such that the end frequencies f_a and f_e and the intermediate frequencies f_b, f_c and f_d, defining the subbands, are related as follows:

$$f_d/f_a=f_e/f_b=n$$

and

$$f_c/f_a=f_d/f_b=f_e/f_c$$

where n is a characteristic of the wave path and is the ratio of the second mode cut-off frequency to the first mode cut-off frequency. For rectangular waveguide n is approximately equal to 2. In a cylindrical waveguide, propagating the circular electric mode, n is approximately equal to 1.83.

It should be noted, however, that the division contemplated here is not a physical division as suggested in the alternate arrangement discussed above. Rather, it is merely an assigning of reference frequencies for determining the bandwidth and the order in which the various channels are separated from the common wave path.

The resonant cavities associated with the channel-dropping filters are proportioned so that the ratio between the resonant frequencies of the second and first cavity modes is $n^{2/3}$. The order of dropping the subbands is then f_c to f_d, from f_a to f_b, from f_d to f_e and f_b to f_c.

By dividing the spectrum and dropping the subbands in accordance with the above plan, the maximum ratio of frequencies that can be separated by a simple series arrangement of channel-dropping filters is raised from n to $n^{4/3}$. The technique described may be applied to any type of single mode waveguide system.

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 shows, in block diagram, the arrangement of the channel-dropping filters in accordance with the invention and the order of dropping the several subbands;

FIG. 2 shows, by way of illustration, a typical distribution of channels within the several subbands;

FIG. 3 shows, by way of illustration, a portion of a channel-dropping filter using rectangular waveguides and comprises a through guide and a resonant cavity; and

FIG. 4 shows, by way of illustration, a portion of a channel-dropping filter using cylindrical waveguides comprising the through guide and a resonant cavity.

Referring to FIG. 1, there is shown in block diagram form the channel separating arrangement in accordance with the invention. In this figure there is represented a wave path 10 carrying a plurality of information-bearing channels distributed over a very broad frequency spectrum. In particular, the channels are shown as extending from a frequency f_a to a frequency f_e. In accordance with the invention, the spectrum f_a to f_e is divided into four subbands, f_a to f_b, f_b to f_c, f_c to f_d and f_d to f_e. This division is made in accordance with requirements which will be explained in greater detail hereinafter. It should be noted that the particular frequencies f_a, f_b, f_c, f_d and f_e do not necessarily designate channel frequencies. Thus, for example, there is shown in FIG. 2, by way of illustration, a portion of the frequency spectrum containing twelve channels $f_1, f_2 \ldots f_{12}$ propagating along a common transmission path and which are to be separated therefrom. In a system designated in accordance with the invention, the lowest frequency of channel f_1, i.e., f_a, and the highest frequency of channel 12, i.e., f_e, would be related by

$$f_e=n_{4/3}f_a \tag{1}$$

if the spectrum is to be utilized to the maximum extent possible. The subband limits f_b, f_c and f_d, are then related to f_a as follows:

$$f_b=n_{1/3}f_a \tag{2}$$

$$f_c=n_{2/3}f_a \tag{3}$$

$$f_d=nf_a \tag{4}$$

These relationships are derived from the following requirements, namely that:

$$f_d/f_a=f_e/f_b=n \tag{5}$$

and

$$f_c/f_a=f_d/f_b=f_e/f_c \tag{6}$$

where n is a characteristic of the wave path and is the ratio of the second mode cut-off frequency to the first mode cut-off frequency. For rectangular waveguide n is approximately equal to 2. In a cylindrical waveguide propagating the circular electric mode n is approximately equal to 1.83.

The intermediate frequencies f_b, f_c and f_d are also shown in FIG. 2. It will be noted that these may, but need not, correspond to any of the channels $f_1 \ldots f_{12}$. They merely provide the groupings which allow for an orderly sequence for separating purposes.

Referring again to FIG. 1, wave energy in path 10 is applied to a first set of channel-separating filters 11, wherein the channels included within the subband between f_c and f_d are dropped. The filters indicated by block 11 comprise a sufficient number of cascaded filters of suitable design to separate those channels within the range f_c to f_d. From FIG. 2, it is noted that there are three channels, f_6, f_7 and f_8, within the designated range. These are dropped in any convenient order. As shown in FIG. 1, they are separated in descending order, i.e., the highest frequency channel, f_8, is dropped first; channel f_7 next and channel f_6 last.

The channels in the remaining portions of the spectrum from f_a to f_c and from f_d to f_e are propagated through filter 11 and are applied to a second group of filters 12. The latter, as before, comprises a series of individual filters tuned to separate those channels within the designated subband extending from f_b to f_a. This, from FIG. 2, is seen to include channels f_1, f_2 and f_3 which are shown as being dropped in ascending order, i.e., the lowest frequency first. As indicated above, the order of separation within any specific subband is a matter of convenience.

The remaining subbands, f_b to f_c and f_d to f_e are applied to the third group of filters 13 where channels f_{12}, f_{11}, f_{10} and f_9 are separated. This is followed by the separation of the channels f_5 and f_4 in subband f_b to f_c in the last group of filters 14.

While the filters are shown as collected in four separate groups 11, 12, 13, 14, this is done only for the purposes of emphasis in the explanation of the operation of the invention. In practice, the individual filters are arranged in series, each tuned to a preassigned channel, but in the sequential order indicated above.

The particular channel-separating filter used will vary with the mode in which the energy is being propagated. For example, in systems propagating the circular electric mode of wave energy, the filter may be of the type disclosed in my copending application Serial No. 816,257, filed May 27, 1959, which utilizes mode conversion techniques to achieve channel separation. Other types may be used, however, without in any way detracting from the effectiveness of the arrangement.

To understand the reasons for the particular dropping sequence used and the relationships among the frequencies f_a to f_e, it is necessary to understand specifically what deleterious conditions are sought to be avoided by the invention. This may best be understood by considering, for a moment, the transmission conditions in an actual network. For example, a dropping filter generally comprises a through guide and a number of coupled resonant cavities associated therewith which are tuned to the frequency of the channel to be dropped. To avoid moding, the through guide is generally proportioned to support only the first order mode of the channel to be dropped. However, since it is necessary that the guide be made as large as possible, the guide is proportioned to be just below cut-off for the second order mode at this frequency. If, for example, we consider the rectangular waveguide shown in FIG. 3 this means that the width, b, of the through guide 30 is equal to one wavelength of the frequency of the channel to be dropped. If the channels are dropped in descending order, the guide will be cut off for all frequencies below one-half this frequency (the guide will be less than half a wavelength wide). Consequently, the maximum spectrum that can be multiplexed in a system in which the channels are separated in simple descending order, will have a bandwidth ratio of two to one.

If, on the other hand, the channels are sought to be dropped in ascending order, cut-off is not a problem since by making the guide wide enough for the lowest frequency it will, of necessity, be capable of passing the higher frequencies. However, here the problem is one of multiple resonances in the filter cavities which may prematurely drop or reject one of the higher frequencies or, at the very least, cause losses in the system due to spurious moding or undesirable resonances. This situation arises as a consequence of the fact that a cavity may resonate in many modes depending upon the exciting frequency. Thus, a cavity proportioned to resonate at the lowest frequency in the spectrum will also be capable of resonating at one of the higher frequencies. In fact, the next resonant mode for the rectangular cavity 31, of the type shown in FIG. 3, will be no greater than about 1.78 times the dominant cavity mode frequency. Thus, to attempt to drop the lowest frequency channel first would put a limit on the spectrum that could be handled which is 1.78 times its lowest frequency. In accordance with the invention, both of the above-described limitations are considered and the channels dropped accordingly.

Taking into account both of the above discussed factors, it becomes clear that the system mut be arranged so that the first channel to be dropped has a frequency which will not allow spurious modes to be generated at the higher frequencies and for which the through guide will not be below cut-off at the lower frequencies. Rewriting Equations 1 through 4 with the value 2 substituted for n gives:

$$f_b=1.26f_a \tag{7}$$
$$f_c=1.59f_a \tag{8}$$
$$f_d=2.0f_a \tag{9}$$
$$f_e=2.52f_a \tag{10}$$

from which it is seen that the frequencies between f_d and f_c satisfy the requisite conditions. Consider, for example, the highest frequency, f_d. The through guide at the f_d filter is a single mode waveguide proportioned to be just below cut-off for the second order transmission mode at frequency f_d. In a rectangular wave path transmitting the TE_{10} mode, the guide is made approximately one wavelength wide. From Equation 9 it is seen that for the lowest frequency f_a, which is half f_d, the waveguide is half a wavelength wide or just wide enough to support propagation at frequency f_a. Consequently, none of the intermediate channels between f_a and f_d are cut off. From Equations 9 and 10 it is likewise seen that the highest frequency f_e is only 1.26 times f_d. Since this ratio is substantially less than the maximum cavity mode ratio for rectangular cavities, which is 1.78, the resonant cavities of the f_d filter can readily be designed to prevent any of the higher frequencies between f_d and f_e from exciting the cavities and thereby producing spurious resonances.

For frequency f_c, the lowest frequency in this subband, a similar situation exists. From Equation 8 it is evident that the through guide is not cut off for any of the lower frequencies between f_a and f_c. It is also evident from Equations 8 and 10 that all of the higher frequencies between f_d and f_e are between 1.26 and 1.59 times f_c. Since this is less than 1.78 f_c, the resonant cavities in the f_c filter can likewise be designed not to respond to frequencies in the f_d to f_e range. Hence, there will be no spurious resonances produced in the f_c filter cavities.

It should be noted here that the maximum bandwidth that can be utilized in accordance with the invention is a function of the ratio n, which is a characteristic of the wave transmission path. The greater the ratio, the greater will be the useful spectrum. As was indicated above, the maximum ratio obtainable in a rectangular waveguide system is 2.

While the ratio n is a characteristic of the transmission path, the ratio between the resonant frequencies of the second and first cavity modes is a function of the cavity geometry and consequently may be designed to have any particular value up to and including the maximum theoretical value of 1.78. From the preceding discussion relating to the frequencies in the subband f_d to f_c, it was seen that this ratio should not be less than 1.59. However, if the second group of channels to be dropped (those lying between f_a and f_b) is considered, it is seen that the cavity mode ratio over a large portion of this subband should not be greater than 1.59. If it is, frequencies between f_d and f_e will be capable of resonating with some of the lower frequency cavities in the range between f_a and f_b. As a practical matter, a safe procedure is to design all the cavities to have a cavity mode ratio equal to 1.59. In particular, a ratio of 1.59 is obtainable in a rectangular cavity when the cavity has a length l equal to $\sqrt{2}\lambda$ and a width w equal to $1.06\sqrt{2}\lambda$, where λ is the free space wavelength of the frequency to be dropped. In general, however, the cavity should be designed so that the cavity mode ratio is equal to $n^{2/3}$.

Designating the general cavity mode as TE_{xzy} where x, y and z refer to the number of half-cycle variations in the electrical field intensity in the respective directions indicated by the reference axes shown in FIG. 3, the first cavity mode is designated TE_{101} and the second cavity mode TE_{201}. With the cavity dimensions proportioned as indicated above, frequency f_e would just be capable of exciting a cavity tuned to frequency f_c. In general, however, f_e, defining the upper limit of the frequency spectrum under consideration, will not contain an appreciable amount of energy, and consequently is not a problem.

The second group of channels to be dropped are those between f_a and f_b. By fixing the cavity mode ratio at 1.59 (or $n^{2/3}$, in general), the higher frequency channels capable of producing spurious resonances are limited to those frequencies between f_c and f_d. However, since the channels between f_c and f_d have already been removed, this possibility does not create any problem and the channels between f_a and f_b can be safely dropped.

Next in order are the channels between f_e and f_d. The through waveguides being just at cut-off for the second order modes between f_e and f_d are cut off for frequencies smaller than f_b. However, since the frequencies between f_a and f_b have previously been removed, frequencies below f_b need no longer be considered. Finally, the subband f_c to f_b can be dropped because those higher frequencies which would also excite the resonant cavities tuned to this range lie between f_e and f_d are no longer present.

It should be noted that if the dropping sequence shown here is not used, the maximum ratio of frequencies that a simple series arrangement of rectangular filters could multiplex is 2:1. However, in accordance with the invention this ratio is increased to over 2.52:1.

In a system utilizing the circular electric TE_{01} mode of wave propagation the same principles apply. However, the frequency ratios vary slightly. In FIG. 4 there is shown two cylindrical waveguides **40** and **41** of radius r_i supportive of the TE_{01} circular electric mode, separated by a coupling gap **42**. Surrounding the gap is the coaxial cavity **43** of radius r_e and length L, tuned to the frequency of the channel to be dropped. In such a system, n is approximately equal to 1.83. Substituting this value of n in Equations 1 through 4 the following is obtained:

$$f_b \cong 1.22 f_a \quad (11)$$

$$f_c \cong 1.5 f_a \quad (12)$$

$$f_d \cong 1.83 f_a \quad (13)$$

$$f_e \cong 2.24 f_a \quad (14)$$

The general cavity mode that can be supported in the coaxial cavity is designated $TE_{\phi rz}$ in accordance with the indicated ϕrz polar coordinate reference system. The ratio, $n^{2/3}$, between the resonant frequencies of the sec-

ond cavity mode, designated TE_{021}, and the first cavity mode, designated TE_{011}, is 1.5 and is obtained when the cavity is proportioned so that

$$r_i = 1.12\lambda \quad (15)$$

$$\frac{J_1\left(\sqrt{k^2-\frac{\pi^2}{L^2}}r_e\right)}{Y_1\left(\sqrt{k^2-\frac{\pi^2}{L^2}}r_e\right)} = \frac{J_1\left(\sqrt{k^2-\frac{\pi^2}{L^2}}r_i\right)}{Y_1\left(\sqrt{k^2-\frac{\pi^2}{L^2}}r_i\right)} \quad (16)$$

and

$$\frac{J_1\left(\sqrt{(1.5)^2k^2-\frac{\pi^2}{L^2}}r_e\right)}{Y_1\left(\sqrt{(1.5)^2k^2-\frac{\pi^2}{L^2}}r_e\right)} = \frac{J_1\left(\sqrt{(1.5)^2k^2-\frac{\pi^2}{L^2}}r_i\right)}{Y_1\left(\sqrt{(1.5)^2k^2-\frac{\pi^2}{L^2}}r_i\right)}, \quad (17)$$

where J_1 and Y_1 are the Bessel functions of the first and second kind, respectively, and

$$k = \frac{2\pi}{\lambda}$$

where λ is the free space wavelength of the frequency to be dropped.

A circular electric multiplexing system operated in accordance with the invention will have an effective bandwidth factor of 2.24 as compared with 1.83 for a simple series channel-separating scheme.

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 of 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, means for separating a plurality of channels in a frequency spectrum extending from a first frequency f_a to a last frequency f_e comprising a plurality of channel-dropping filters sequentially arranged to separate the channels in the bands from f_d to f_c, from f_b to f_a, from f_e to f_d and from f_c to f_b in the indicated order, where $f_b = n^{1/3} f_a$, $f_c = n^{2/3} f_a$, $f_d = n f_a$, and $f_e = n^{4/3} f_a$, and where n is a characteristic of the wave path and is the ratio of the second mode cut-off frequency to the first mode cut-off frequency.

2. The combination according to claim 1 wherein n is approximately equal to 2.

3. The combination according to claim 1 wherein n is approximately equal to 1.83.

4. In a broadband rectangular waveguide transmission system supportive of a plurality of spaced frequency bands of interest propagating in the TE_{10} mode of wave propagation extending from a first frequency f_a to a second higher frequency f_e, a plurality of filtering means each resonantly tuned to a given frequency of interest between said first and second frequencies and sequentially arranged to separate the bands in the frequency ranges from f_c to f_d, from f_a to f_b, from f_d to f_e and from f_b to f_c in the indicated order where

$$\frac{f_d}{f_a} = \frac{f_e}{f_b} = 2$$

and where

$$\frac{f_c}{f_a} = \frac{f_d}{f_b} = \frac{f_e}{f_c}$$

5. The combination according to claim 4 wherein each of said filtering means comprises a right-angle parallelepiped cavity in whcih the length of said cavity is equal to $\sqrt{2}\lambda$ and the width w is equal to $1.06\sqrt{2}\lambda$, where λ is the free space wavelength of the frequency of interest.

6. In a broadband cylindrical waveguide electromagnetic wave transmission system supportive of a plurality

of spaced frequency bands of interest propagating in the circular electric mode of wave propagation extending from a first frequency f_a to a second higher frequency f_e, a plurality of filtering means each resonantly tuned to a given frequency of interest between said first and said second frequency sequentially arranged to separate said bands in the frequency ranges from f_c to f_d, from f_a to f_b, from f_d to f_e and from f_b to f_c in the indicated order where

$$f_b \cong 1.22 f_a$$
$$f_c \cong 1.50 f_a$$
$$f_d \cong 1.83 f_a$$
$$f_e \cong 2.24 f_a$$

7. The method of separating a broad band of wave energy having frequencies extending from f_a to a higher frequency f_e into a plurality of channels each of smaller bandwidth than said band, comprising the steps of designating intermediate frequencies f_b, f_c and f_d within said band for which f_d/f_a and f_e/f_b are both equal to the ratio

of the cut-off frequency of the second order mode of propagation of the wave path supporting said energy to the cut-off frequency of the first order mode therein and for which $f_c/f_a = f_d/f_b = f_e/f_c$, separating these channels occurring between the intermediate frequencies f_d and f_c, subsequently separating those channels occurring between the frequencies f_b and f_a and then those occurring between f_e and f_d and finally those occurring between f_c and f_b.

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