

Nov. 22, 1960

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2,961,619

MICROWAVE FILTER

Filed June 21, 1957

3 Sheets-Sheet 1

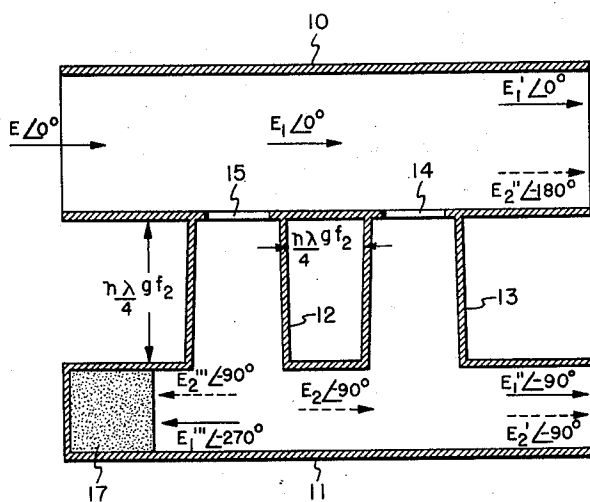
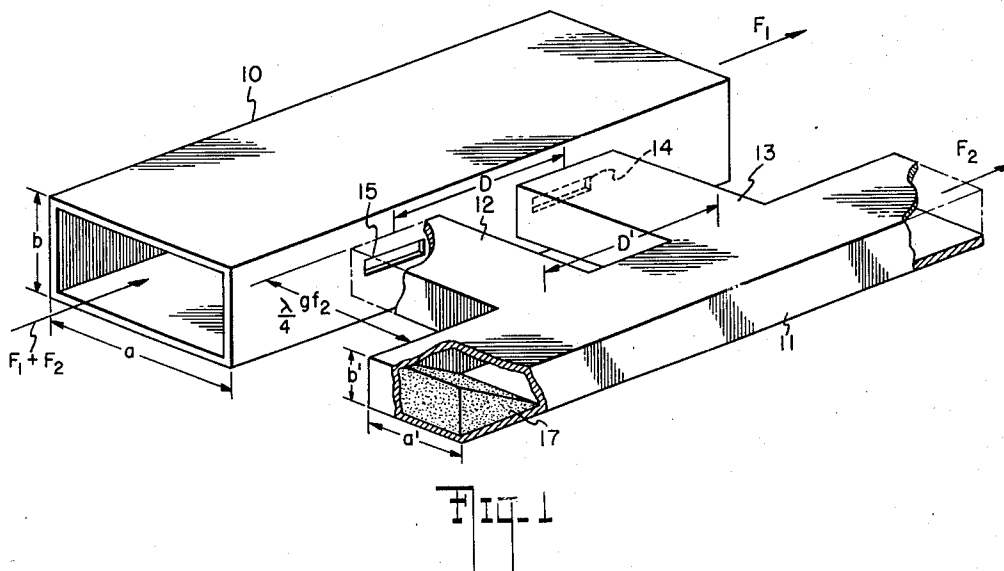


FIG. 2

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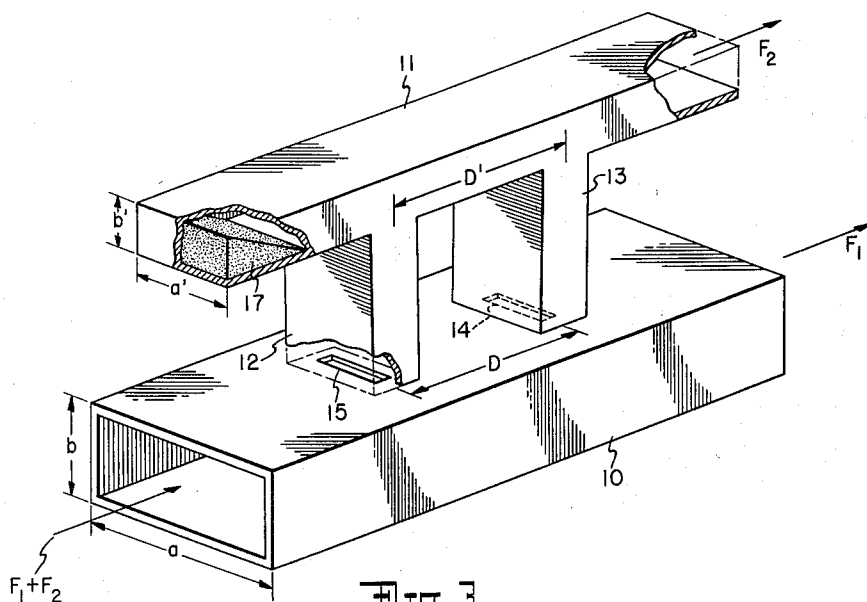


FIG. 3

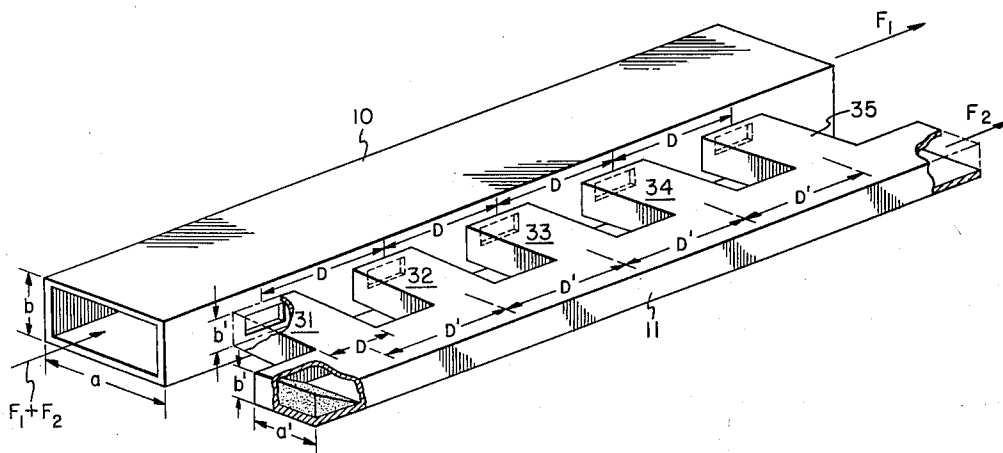


FIG. 4

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Filed June 21, 1957

3 Sheets-Sheet 3

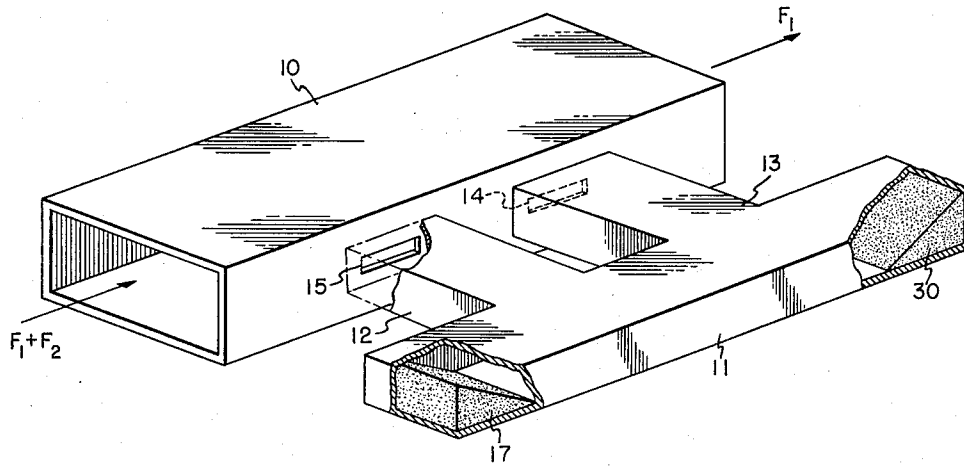


FIG. 5

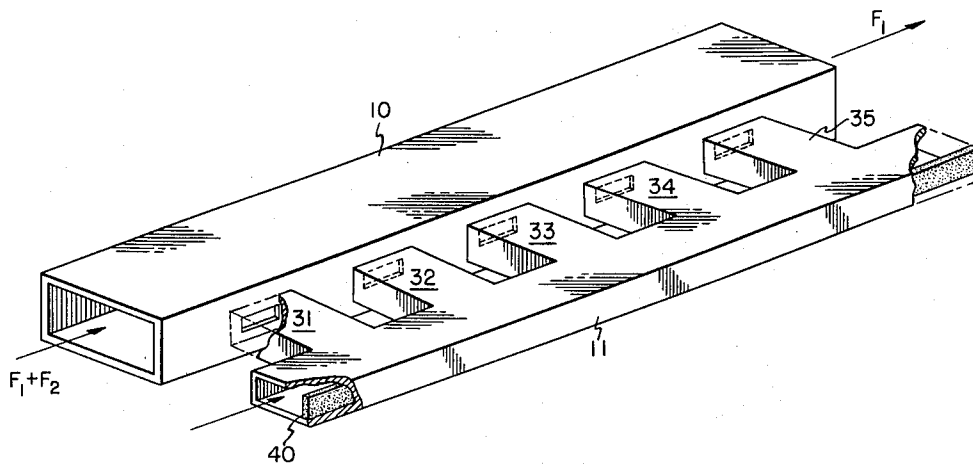


FIG. 6

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1

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Filed June 21, 1957, Ser. No. 667,085

6 Claims. (Cl. 333-10)

This invention relates to microwave apparatus and more particularly to a novel microwave energy filter.

In the past, microwave energy at different frequencies has been separated by a variety of methods such as by placing resonant structures in the main transmission line, or by shunting the main transmission line with shorted stubs or resonant cavities, or by employing coupling means so spaced on the transmission line as to select a particular frequency.

These filter means, as well as others not mentioned, are often undesirable for one or more of the following reasons: the filter means reflect the separated frequency back into the transmission line and create objectionable standing waves in the transmission line; the filtering means are not highly selective; and discontinuities and restrictions are placed in the transmission line, thus decreasing the power handling capabilities of the transmission line.

Therefore, it is an object of this invention to provide a microwave filter which introduces substantially no reflections of the separated energy back into the main transmission line.

A further object of this invention is to provide a microwave filter which is capable of operating at high power levels.

It is a further object of this invention to provide a means for eliminating objectionable harmonics from a microwave transmission line.

These and other objects which will become more apparent as the description proceeds are achieved by a microwave filter comprised of a first waveguide which propagates microwave energy of at least two different frequencies. Coupled to the first waveguide by resonant apertures are a plurality of branch waveguides which also couple to a second waveguide. The branch waveguides and the second waveguide have dimensions which will permit microwave energy at a second frequency to propagate therein, but are beyond cut-off to microwave energy at a first frequency. The apertures are resonant at the second frequency and are spaced a distance substantially equal to an odd multiple of a quarter waveguide wavelength of waves at the second frequency. The branch waveguides each have a length substantially equal to an odd multiple of a quarter waveguide wavelength of waves at the second frequency, and are directly coupled to the second waveguide at regions which are spaced by an odd multiple of a quarter waveguide wavelength of waves at the second frequency. Substantially all the energy at the second frequency is coupled into the second waveguide and propagates in one direction therein. Energy at the first frequency cannot couple into the second waveguide because of the resonant apertures and because of the waveguides beyond cut-off, and consequently propagates directly through the first waveguide virtually unaffected by the presence of the apertures.

For a better understanding of the present invention, reference is made to the drawings wherein:

Fig. 1 is a perspective view, partially cut-away, showing one embodiment of the present invention;

2

Fig. 2 is a drawing used to explain the operation of a device constructed in accordance with this invention;

Fig. 3 is a perspective view showing an alternative embodiment of the invention wherein the coupling apertures are located on the broad wall of the primary transmission line;

Fig. 4 illustrates another embodiment of the invention employing a plurality of branch waveguides coupling the primary and secondary waveguides;

Figs. 5 and 6 are illustrations of devices constructed in accordance with this invention adapted for use as harmonic suppressors.

For a more detailed description, reference is made to Fig. 1 wherein a first waveguide 10 has broad and narrow walls of dimensions a and b , respectively. A second waveguide 11 is disposed adjacent waveguide 10 and has broad and narrow walls of dimensions a' and b' , respectively, where a' is smaller than a , and b' is smaller than b . Waveguide 10 is coupled to a source of electromagnetic energy (not shown) which supplies microwave energy at two different frequencies to waveguide 10. The dimensions a' and b' of waveguide 11 are such that waveguide 11 is beyond cut-off to microwave energy at the first frequency.

The cut-off condition is reached when the wavelength of microwave energy is equal to twice the broad dimension of the waveguide, i.e., $\lambda C = 2a$. At frequencies lower than the so called cut-off frequency, no appreciable amount of energy at that frequency is propagated through the waveguide. Therefore, when the broad dimension of a waveguide is less than one-half the free space wavelength of a wave, the waveguide may be said to be beyond cut-off to that wave.

Branch waveguides 12 and 13 are coupled to the narrow walls of the first and second waveguides 10 and 11. Branch waveguides 12 and 13 have dimensions substantially equal to a' and b' and are beyond cut-off to waves of the first frequency.

Resonant apertures 14 and 15, in the form of rectangular irises, provide the coupling means between waveguide 10 and branch waveguides 12 and 13. It is desirable that the irises should be quite thin in order that the attenuation and reflection of the waves that are passed by the irises be kept at a minimum. If the irises are relatively thick, they tend to act as waveguides beyond cut-off to the waves at the resonant frequency and thus introduce attenuation and reflection of these waves. Additionally, the widths of the irises should be narrow in order to produce the least perturbation to the waves at the first frequency of propagating in waveguide 10, as will be discussed further hereinafter.

It is to be understood, however, that resonant irises having shapes other than rectangular shapes may be employed as well.

Branch waveguides 12 and 13 are directly coupled to waveguide 11 at spaced regions which are separated by a distance D' . The coupling at these regions may be accomplished by conventional waveguide junctions, and in the discussion to follow it is assumed that they are not resonant apertures.

Branch waveguides 12 and 13 have lengths substantially equal to an odd multiple of a quarter waveguide wavelength of a wave at the second frequency, this length usually being one-quarter waveguide wavelength. This length may be equal to any odd multiple of the waveguide wavelength so long as the two branch waveguides are the same length.

The spacing D of resonant apertures 14 and 15, and the spacing D' of the regions where branch waveguides 12 and 13 couple to waveguide 11 are substantially equal to an odd multiple of a quarter waveguide wavelength of a wave at the second frequency. These spacings should

be substantially equal to each other in electrical length.

It is to be noted that the waveguide wavelength of a wave at the second frequency will be different in waveguide 10 and in waveguide 11 since these waveguides are of different dimensions. The waveguide wavelength of waves at the second frequency will be longer in waveguide 11 than in waveguide 10. Therefore, in constructing a device in accordance with this invention, optimum results will be obtained if the dimension D' is made slightly larger than D , in accordance with the wavelength of waves at the second frequency in the respective waveguides.

Another fact to be considered in choosing the spacing D is the propagating mode of the energy at frequency f_2 in waveguide 10. It may happen that if the frequency f_2 is a long way from cut-off in waveguide 10, and if sufficient discontinuities are present in the transmission line, the energy at frequency f_2 may propagate in waveguide 10 in a higher order mode rather than in the dominant TE_{10} mode. The waveguide wavelength for the higher order modes is longer than the dominant mode waveguide wavelength, so if the energy at frequency f_2 is propagating in a higher order mode the spacing D should be accordingly larger.

It may be seen that the device of Fig. 1 takes the form of a branch waveguide directional coupler, and does in fact function as a directional coupler to microwave energy at the second frequency.

When apertures 14 and 15 are resonant at a particular frequency they will function individually as 3 db couplers to energy at that frequency and the structure of Fig. 1 will function as a zero db directional coupler to microwave energy at the frequency at which the apertures are resonant.

It is to be noted that branch waveguides 12 and 13 do not operate as resonant cavities, but operate as normal waveguide sections to waves at frequency f_2 . This results from the fact that branch waveguides 12 and 13 are directly coupled to the second waveguide 11.

In operation, microwave energy at two different frequencies f_1 and f_2 is coupled into the first waveguide 10 and will commence to propagate therein. Frequency f_1 is lower than frequency f_2 and it is assumed that energy at frequency f_2 is to be separated from the energy at frequency f_1 propagating in waveguide 10. Apertures 14 and 15 are resonant at frequency f_2 . The dimensions a' and b' of waveguide 11 are such that microwave energy at frequency f_2 will freely propagate therein, but waveguide 11 is beyond cut-off to microwave energy at frequency f_1 . Likewise, branch waveguides 12 and 13 are beyond cut-off to energy at frequency f_1 , but will freely propagate energy at frequency f_2 .

As the microwave energy propagates along the first waveguide 10 it will first encounter resonant aperture 15. This aperture, located in the narrow wall of waveguide 10 and being resonant at frequency f_2 , will provide a 3 db coupling aperture to energy at frequency f_2 , and substantially one-half of the energy at frequency f_2 will enter branch waveguide 12 and will couple into waveguide 11. Because of resonant aperture 15 and because branch waveguide 12 and waveguide 11 are beyond cut-off to energy at frequency f_1 , substantially no energy at frequency f_1 will couple into waveguide 11.

Similarly, coupling aperture 14 will couple energy at frequency f_2 into waveguide 13 and waveguide 11, but no energy at frequency f_1 will couple into waveguide 11.

Because of the spacings D and D' , the length of branch waveguides 12 and 13, and the two 3 db couplers provided by resonant apertures 14 and 15, the device of Fig. 1 will operate as a zero db directional coupler to microwave energy at frequency f_2 and substantially all the energy at f_2 will be coupled from waveguide 10 to waveguide 11 and will propagate to the right in waveguide 11.

The behavior of this device as a zero db directional coupler to microwave energy at frequency f_2 only, results

in a filter which has high selectivity since substantially all the energy at frequency f_2 will be eliminated from waveguide 10, and substantially no energy at frequency f_1 can be coupled into waveguide 11 because of the resonant apertures and because the branch waveguides 12 and 13 and secondary waveguide 11 are beyond cut-off at frequency f_1 .

The means by which the energy at frequency f_2 is eliminated from transmission line 10 is illustrated in connection with Fig. 2. Considering only the wave of energy at frequency f_2 in this discussion, this wave is represented as $E\angle 0^\circ$ entering primary waveguide 10. Because aperture 15 is resonant at frequency f_2 , it will provide a 3 db coupling aperture which has the effect of causing the wave $E\angle 0^\circ$ to divide into two substantially equal components. Component E_1 is the direct wave and continues to propagate to the right in waveguide 10. Component E_2 is the coupled component and couples into branch waveguide 12 and is coupled into secondary waveguide 11. Considering only the phase shifts of the two components relative to each other, the coupled component E_2 in waveguide 11 will have a phase shift of -90° relative to the direct component E_1 . When the direct component $E_1\angle 0^\circ$ encounters coupling aperture 14 it will divide into two equal components; $E_1'\angle 0^\circ$ the direct component, continuing to the right in waveguide 10, and E_1'' , the coupled component, entering branch waveguide 13 and coupling into waveguide 11. The coupled component E_1'' experiences a -90° phase shift with respect to E_1' in passing through the coupler.

The original coupled component $E_2\angle -90^\circ$ will propagate to the right in waveguide 11 and will encounter branch waveguide 13 and will be divided into two equal components; a direct component, $E_2'\angle -90^\circ$ continuing in waveguide 11, and the coupled component E_2'' coupling into branch waveguide 13 and entering waveguide 10. This coupled component experiences an additional 90° phase shift in passing through the coupler so that it now has a phase displacement of -180° . It may be seen that the two components in waveguide 10 are 180° out of phase with respect to each other, and since they are substantially equal in amplitude they will combine in destructive interference and cancel, the result being that substantially no energy at frequency f_2 propagates to the right in waveguide 10. The two components in waveguide 11, however, both have a phase displacement of -90° and will combine in phase and the resultant wave will propagate to the right in waveguide 11.

It may be seen that the energy coupled into waveguide 11 will propagate in only one direction by considering a component of E_2 which tends to propagate to the left in waveguide 11. This component E_2''' has a phase displacement of -90° , having passed through the coupler at branch arm 12. The component of E_1 which couples through branch waveguide 13 and propagates to the left will arrive at the left of waveguide 11 with a phase displacement of -270° since it has traveled between branch waveguides 12 and 13 twice, once in waveguide 10 and once in waveguide 11 ($90^\circ + 90^\circ$), and has passed through the coupler once (90°). Therefore, the two components are 180° out of phase with each other and will cancel.

It is thus seen that there are substantially no reflections of the separated frequency f_2 back into the main transmission line 10 and the possibility of appreciable standing waves being set up is greatly diminished.

A non-reflective termination 17 may be provided in waveguide 11 in order to absorb any energy which may tend to couple in the non-preferred direction in waveguide 11.

Energy at frequency f_1 propagating in waveguide 10 cannot couple into branch waveguides 12 and 13 because of the resonant apertures and because waveguides 12 and 13 are beyond cut-off, consequently, it will propagate directly through waveguide 10 substantially unattenuated.

By designing the resonant irises 14 and 15 so as to

5

have a narrow width, the irises will appear as small reactances to the wave at frequency f_1 and will have little effect on the wave traveling directly through waveguide 10. The reactive effects created by irises 14 and 15 may be further reduced by selecting the distance D to be in the vicinity of a quarter waveguide wavelength at frequency f_1 , thereby causing the reactances presented by the apertures 14 and 15 to partially cancel.

Because there are no discontinuities or obstructions across the primary waveguide 10, the device of this invention will operate at high power levels at frequency f_1 .

Waveguide filtering devices employing resonant structures in a transmission line, or shorted stubs, or resonant cavities on a waveguide wall to separate one frequency from another cannot achieve the results achieved by the device of this invention because such other devices will reflect energy at the separated frequency back into the transmission line thus setting up standing waves in the main transmission line.

In Fig. 3 is shown an alternative embodiment of the present invention wherein resonant apertures 14 and 15 are located on the broad walls of primary waveguide 10 and secondary waveguide 11. The distances D and D', and the length of branch waveguides 12 and 13 are the same as for the embodiment shown in Fig. 1. Again branch waveguides 12 and 13 and secondary waveguide 11 are beyond cut-off to energy at frequency f_1 , and resonant apertures 14 and 15 are resonant at the frequency to be separated.

The device shown in Fig. 3 operates in the same manner as the device of Fig. 1, so long as the energy at frequency f_2 is propagating in the TE₁₀ mode. If the energy at frequency f_2 is propagating in an even order mode, no coupling will be achieved with the apertures 14 and 15 centered on the broad wall of waveguide 10 since the electric field will be substantially zero at the center of the waveguide, and of opposite senses on each side of the center line.

The embodiment of this invention shown in Fig. 1 is preferable for use in high power systems because the resonant apertures 14 and 15 located on the narrow wall of waveguide 10 will withstand higher powers than will the apertures located on the broad wall of waveguide 10, as shown in Fig. 3. This is believed to be a result of the fact that the electric field at the narrow wall of the waveguide is very small and there will be a relatively small potential gradient across the apertures on the narrow wall, while the electric field in the center of the waveguide is strong and there will be a high potential gradient across the apertures on the broad wall, thus resulting in greater possibility of breakdown across the apertures located on the broad wall.

In the embodiment of this invention shown in Fig. 4, the separation of the energy at frequency f_2 from the energy at frequency f_1 propagating in waveguide 10 is achieved by means of a plurality of branch waveguides 31-35 between primary waveguide 10 and waveguide 11. The lengths of the branch waveguides 31-35 are substantially equal to an odd multiple of a quarter waveguide wavelength of waves at frequency f_2 , this length usually being one-quarter waveguide wavelength, and the branch waveguides are separated by distances substantially equal to an odd multiple of a quarter waveguide wavelength of waves at frequency f_2 . Again, as in the embodiment of Fig. 1, the distances D and D' take into account the difference in waveguide wavelength of waves at frequency f_2 in waveguides 10 and 11.

Branch waveguides 31-35 and waveguide 11 are beyond cut-off to energy at frequency f_1 , but will freely propagate energy at frequency f_2 .

In this embodiment, resonant apertures are not employed as in the other embodiment referred to above.

Because branch waveguides 31-35 and waveguide 11 are beyond cut-off at f_1 , only energy at frequency f_2 will

6

couple into waveguide 11. The spacings D and D', and the length of the branch waveguides are such that the device operates as a directional coupler to energy at frequency f_2 , and by employing a sufficient number of branch waveguides, substantially all of the energy at f_2 can be coupled from waveguide 10 to waveguide 11. Energy at frequency f_1 will propagate directly through waveguide 10 since it cannot couple into the branch waveguides and secondary waveguide which are beyond cut-off at this frequency.

Many high power microwave sources such as magnetrons and klystrons generate an appreciable amount of second harmonic energy. The presence of this harmonic energy in a transmission line is often objectionable because the transmission line is not matched to waves at the second harmonic and standing waves will be created in the transmission line. For this reason it is desirable that this higher harmonic be eliminated from the transmission line. A device for accomplishing this is illustrated in Fig. 5 in which the structure is similar to that illustrated in Fig. 1, with the addition of a non-reflecting termination 30 placed in the end of waveguide 11. In this embodiment a generating source would be coupled to waveguide 10, and waveguide 10 would be the main transmission line of the microwave system. This device will operate as previously described to separate substantially all the second harmonic energy f_2 from the main transmission line 10. Because of the directional characteristics of the device, the separated harmonic energy will propagate to the right in waveguide 11 and will be absorbed by termination 30. By absorbing the separated energy in termination 30, the harmonic energy cannot reflect back into the main transmission line 10.

Another embodiment of this invention employed as a harmonic suppressor is shown in Fig. 6 wherein a structure similar to that shown in Fig. 4 has a lossy material 40 disposed along one narrow wall of waveguide 11.

In the operation of this device the energy at frequency f_2 will be absorbed by lossy material 40 as the energy is coupled into waveguide 11 by the branch waveguides 31-35.

In this manner the higher harmonic energy is separated from the main transmission line 10 and is dissipated in waveguide 11 by the lossy material 40.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than of limitation and that changes within the purview of the appended claims may be made without departing from the true scope and spirit of the invention in its broader aspects.

What is claimed is:

1. A microwave filter comprising a first wave guide adapted to freely propagate microwaves of at least two different frequencies, a second waveguide having dimensions sufficient to freely propagate waves at a second of said frequencies but being beyond cut-off to waves at a first of said frequencies, a plurality of branch waveguides, each having a length substantially equal to an odd multiple of a quarter waveguide at said second frequency wavelength for transferring waves at said second frequency from the first waveguide to the second waveguide, said branch waveguides being non-resonant to waves at said second frequency and beyond cut-off to waves at said first frequency, resonant apertures coupling said branch waveguides to said first waveguide, said apertures being resonant at said second frequency, said apertures being separated by a distance substantially equal to an odd multiple of a quarter waveguide wavelength of waves at said second frequency in said first waveguide, said branch waveguides being directly coupled to said second waveguide at regions displaced from each other by an odd multiple of a quarter waveguide

wavelength of waves at said second frequency in said second waveguide.

2. A microwave filter comprising a branch waveguide directional coupler comprised of a primary waveguide, two branch waveguides, and a secondary waveguide, said primary waveguide having dimensions sufficient to propagate microwaves of at least two different frequencies, said branch waveguides and said secondary waveguide being beyond cut-off to waves at a first of said frequencies but having dimensions sufficient to freely propagate waves at a second of said frequencies, resonant apertures coupling said primary waveguide to said branch waveguides, said apertures being resonant at said second frequency, said resonant apertures being displaced from each other by a distance substantially equal to an odd multiple of a quarter waveguide wavelength of waves at said second frequency in said primary waveguide, said branch waveguides being non-resonant to waves at said second frequency and being directly coupled to said secondary waveguide at regions displaced from each other by an odd multiple of a quarter waveguide wavelength of waves at said second frequency in said secondary waveguide, whereby substantially all the waves at said second frequency couple into said secondary waveguide and propagate but one direction therein and substantially all the waves at said first frequency propagate directly through said primary waveguide.

3. The microwave filter of claim 2 including a non-reflecting termination located in said secondary waveguide for absorbing waves at said second frequency.

4. The microwave filter of claim 1 including a lossy material disposed in said second waveguide for absorbing waves at said second frequency.

5. A microwave filter comprising a first waveguide having dimensions sufficient to propagate waves of at least two different frequencies, a second waveguide disposed parallel to said first waveguide and having dimensions sufficient to freely propagate waves at a second of said frequencies but being beyond cut-off to waves at a first of said frequencies, two branch waveguides beyond cut-off to waves at said first frequency providing means for coupling said first waveguide to said second waveguide, two apertures resonant at said second frequency providing zero db coupling of waves at said second frequency from said first waveguide to said second waveguide, said resonant apertures being displaced

from each other on said first waveguide by a distance substantially equal to an odd multiple of a quarter waveguide wavelength of waves at said second frequency in said first waveguide, said branch waveguides being non-resonant to waves at said second frequency and being directly coupled to said second waveguide at regions displaced from each other by an odd multiple of a quarter waveguide wavelength of waves at said second frequency in said second waveguide, whereby substantially all of the waves at said second frequency are coupled into said second waveguide and propagate in but one direction therein and the waves at said first frequency propagate directly through said first waveguide.

6. A microwave filter comprising a source producing electromagnetic waves at first and second different frequencies, first and second parallel disposed waveguide sections, the first of said waveguide sections being coupled to said source and being adapted to propagate waves at said two frequencies, at least two branch waveguides coupled between said first and second waveguide sections, each of said branch waveguides having a length substantially equal to an odd multiple of a quarter waveguide wavelength at said second frequency, said branch waveguides being non-resonant to waves at said second frequency and being beyond cut-off only to waves at said first frequency, resonant apertures coupling said branch waveguides to said first waveguide, said apertures being resonant at said second frequency, said apertures being separated by a distance substantially equal to an odd multiple of a quarter waveguide wavelength of waves at said second frequency in said first waveguide, said branch waveguides being directly coupled to said second waveguide at regions displaced from each other by an odd multiple of a quarter waveguide wavelength of waves at said second frequency in said second waveguide.

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