United States Patent

Craven et al.

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[54] **WAVEGUIDE FILTER UTILIZING EVANESCENT WAVEGUIDE, WITH TUNABLE FERRITE LOADING**

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[21] Appl. No.: **681,637**

[30] **Foreign Application Priority Data**

Nov. 30, 1966 Great Britain 53,635/66

[52] **U.S. Cl.** ....**333/73 W**, 333/24.1, 333/81

[51] **Int. Cl.** **H03h 7/00**, H03h 7/10

[58] **Field of Search** ....333/73, 73 C, 73 W, 95, 97, 333/81, 24.1, 24.2

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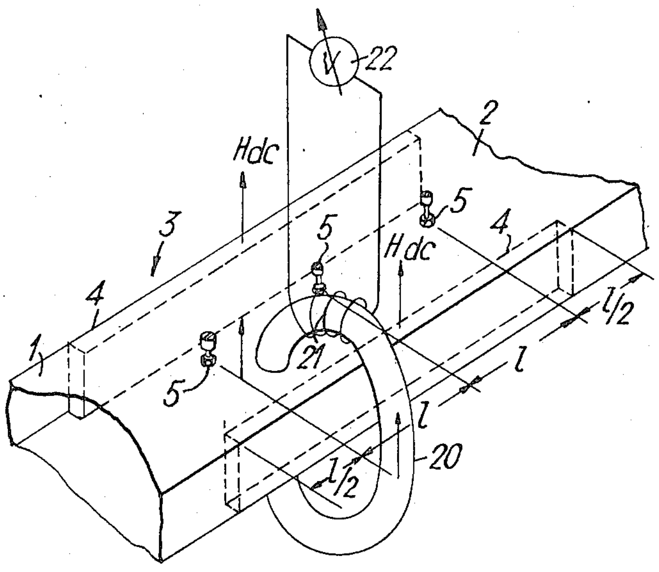
[57] **ABSTRACT**

A waveguide filter wherein transversely magnetized ferrite-loading strips are mounted within a waveguide section to produce cutoff at a higher frequency than in an empty waveguide, thereby providing evanescent-mode operation at the operating frequencies. The waveguide section is then terminated in a capacitive reactance which at the center frequency of the desired passband is the conjugate of the positive imaginary characteristic impedance of the length of evanescent waveguide. Means for varying the magnetic field applied to the ferrite-loading strips is provided for tuning the filter over a predetermined range of passband frequencies.

9 Claims, 14 Drawing Figures



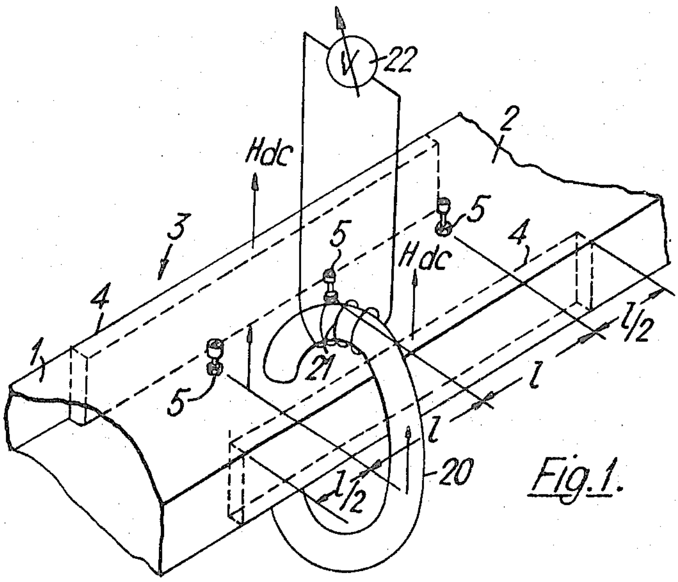


Fig.1.

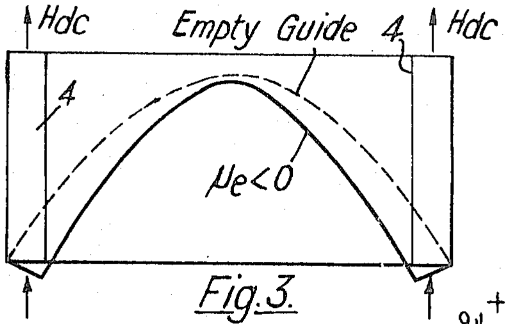


Fig.3.

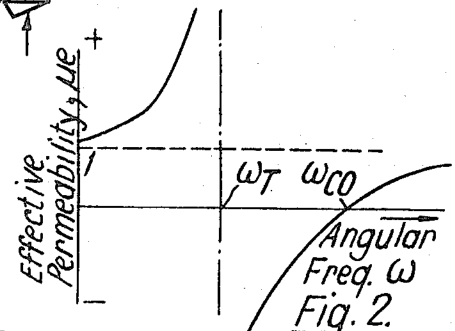


Fig. 2.

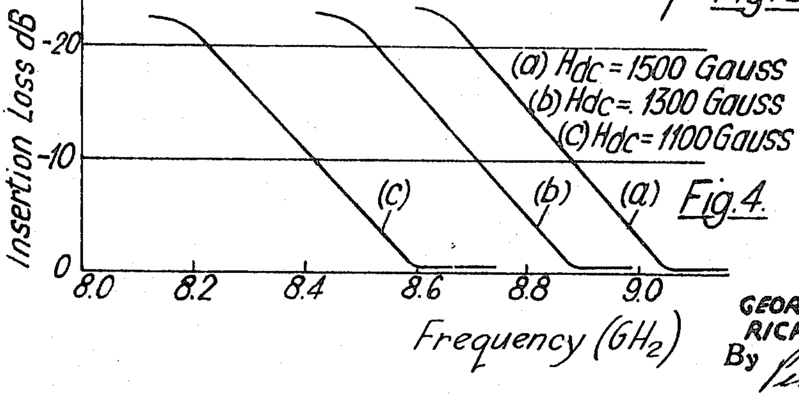


Fig.4.

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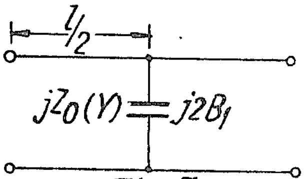
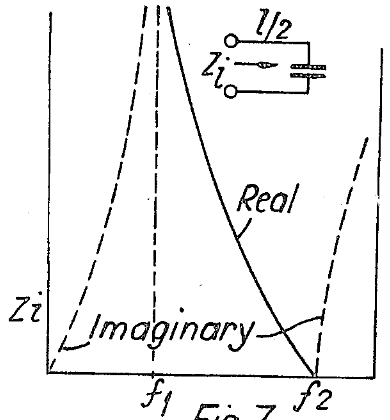


Fig. 5.



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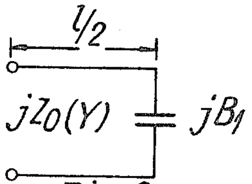

Fig. 6.

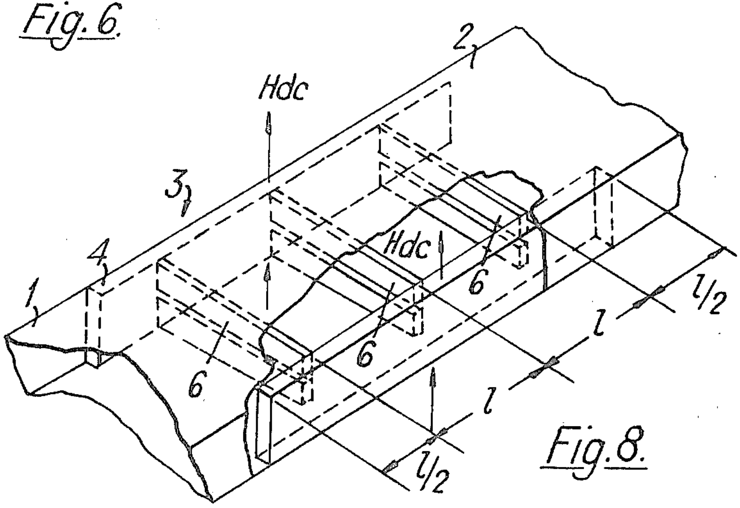

Fig. 8.

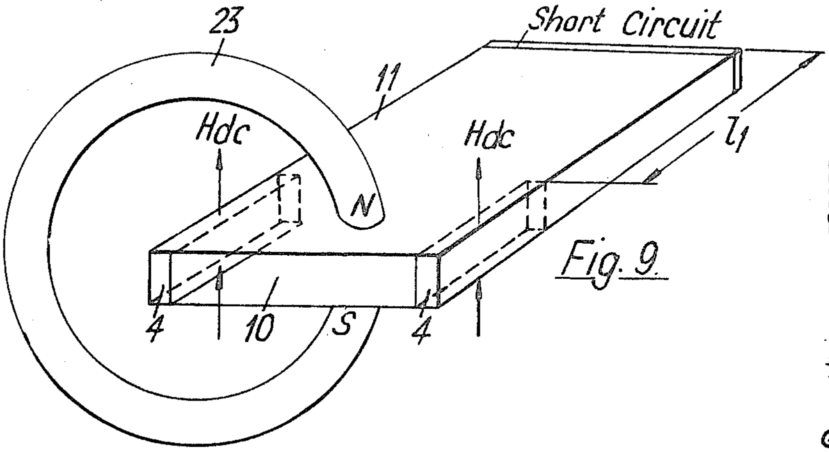

Fig. 9.

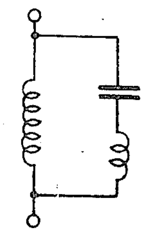

Fig. 10.

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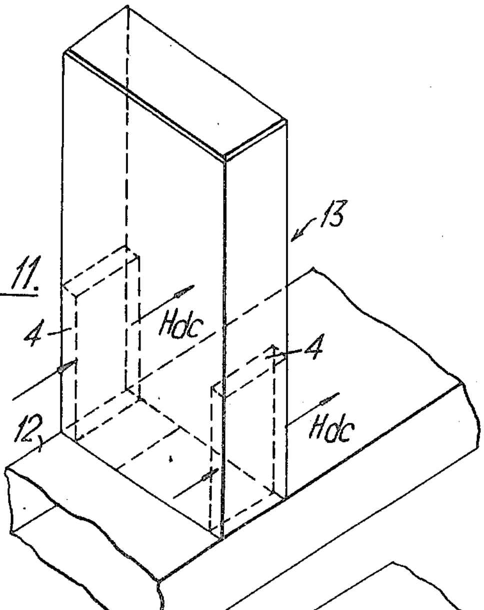
Fig. 11.



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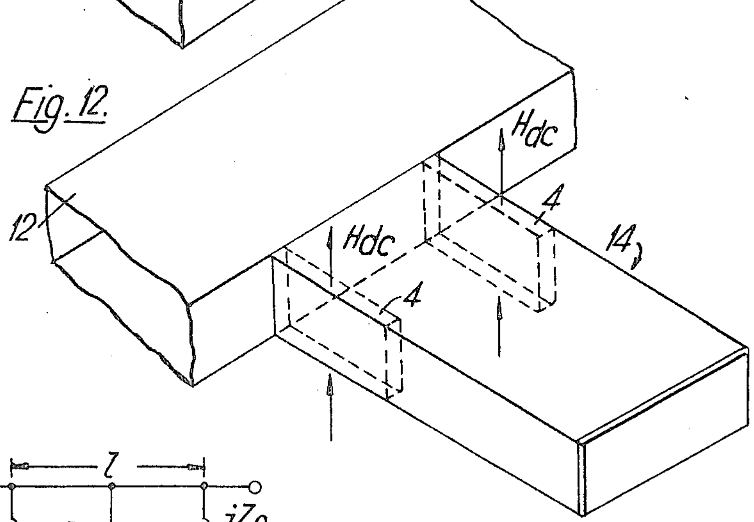

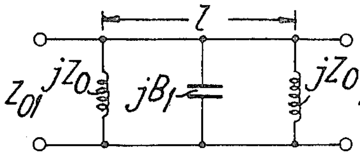

Fig. 14.

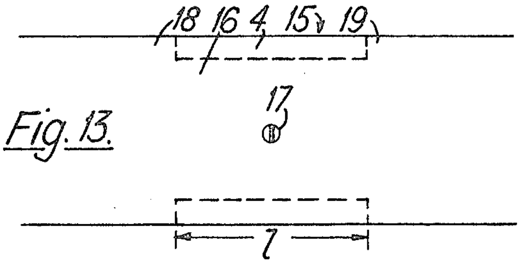

Fig. 13.

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WAVEGUIDE FILTER UTILIZING EVANESCENT WAVEGUIDE, WITH TUNABLE FERRITE LOADING

BACKGROUND OF THE INVENTION

The invention relates to waveguide filters.

Waveguide band-pass filters have heretofore been constructed in waveguide in which a propagating mode–usually the dominant–exists.

SUMMARY OF THE INVENTION

According to the invention there is provided an H-wave band-pass filter or filter section comprising a length of waveguide loaded with ferrite material such that when subjected to a transverse unidirectional magnetic field the effective dimensions of the length of waveguide are such that only evanescent H-waves can exist therein at the operating frequency. Further provided is means for terminating the said length of waveguide in a capacitive reactance which at the center frequency of the desired passband is the conjugate of the positive imaginary characteristic impedance of the said length of waveguide.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows two lengths of propagating waveguide interconnected by a three-section band-pass filter embodying the invention,

FIG. 2 shows effective permeability vs. angular frequency for transversely magnetized ferrite,

FIG. 3 shows a section of waveguide loaded with ferrite sidewall strips,

FIG. 4 shows insertion loss vs. frequency for a ferrite-loaded section of waveguide in cutoff condition with DC magnetic field as a parameter,

FIG. 5 is the equivalent circuit of one section of the band-pass filter of FIG. 1,

FIG. 6 is the circuit of FIG. 5 bisected,

FIG. 7 is the image impedance characteristic of the band-pass filter of the present invention,

FIG. 8 shows an alternative form of the band-pass filter of FIG. 1,

FIG. 9 shows another form of band-pass filter embodying the invention,

FIG. 10 is the approximate equivalent circuit of the band-pass filter of FIG. 9,

FIG. 11 shows the filter section of FIG. 9 coupled as a series stub to dominant-mode waveguide,

FIG. 12 shows the filter section of FIG. 9 coupled as a shunt stub to a dominant-mode waveguide,

FIG. 13 shows a single-section band-pass filter coupled between dominant-mode waveguides; and

FIG. 14 is the equivalent circuit of the single-section band-pass filter of FIG. 13.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, dominant-mode H-waves are propagated in a length 1 of propagating waveguide from any suitable microwave source (not shown), such as a generator or a receiving aerial. A length 2 of propagating waveguide is interconnected with the length 1 by a three section band-pass filter 3 constructed in the same waveguide as the lengths 1 and 2, but containing loading strips 4 of ferrite material symmetrically arranged one at each sidewall of the waveguide. There are three capacitive screws 5, and the ferrite material strips 4 are subjected to a DC magnetic field H_{DC} transverse to the direction of propagation by suitably positioned permanent or electromagnetic pole pieces.

In FIG. 1 there is shown an electromagnetic apparatus for producing the DC magnetic field which includes a core 20 having a winding 21 wound thereon. Coupled to winding 21 is a source of energy 22, the output of which is variable. This enable the magnitude of the magnetic field H_{DC} to be varied. The production of the DC magnetic field by means of a permanent magnet 23 is shown in FIG. 9.

It has been established that for a transversely magnetized ferrite in rectangular waveguide ($H_{01\ mode}$) the cutoff frequency may be controlled by the DC magnetic field. The cutoff frequency can be made higher or lower than the empty waveguide value. This is a consequence of the fact that the effective permeability μ_e of the ferrite can be varied from positive to negative values by the DC magnetic field as shown in FIG. 2, in which ω_{co} is the cutoff frequency and ω_r gyromagnetic resonance for the infinite ferrite medium. Thus for $\mu_e>0$ the RF field is concentrated in the ferrite and the effective width of the waveguide is increased, whereas for $\mu_e<0$ the RF energy is excluded from the ferrite and the effective width is reduced. It is this latter effect which is used in the present invention, and is illustrated in FIG. 3.

In a rectangular waveguide loaded with ferrite magnetized transverse to the direction of propagation as shown in FIG. 2, the transcendental equation involving the required propagation constant β, by solving the boundary value problem for such a structure, is

$$\tan k_a\,(L-2\delta)=\frac{2\dfrac{K_m\mu_o}{\mu_e K_a}\sin K_m\delta\cos K_m\delta}{\left\{1-\left(\dfrac{\beta\mu_o}{\mu_e \bigcirc K_a}\right)^2\right\}\sin^2 K_m\delta-\left(\dfrac{K_m\mu_o}{\mu_e K_a}\right)\cos^2 K_m\delta}$$

$$\overline{\overline{\mu}}=\begin{pmatrix}\mu & -jk & 0\\ jk & \mu & 0\\ 0 & 0 & 1\end{pmatrix}=\text{tensor permeability of the ferrite}$$

$$p=\frac{\mu\mu_o}{(\mu^2-k^2)}=\frac{\mu_o}{\mu_e}=\frac{1+X_{xx}}{(1+X_{xx})^2+X_{xy}{}^2}\qquad(2)$$

$$\theta=\frac{\mu}{-jk}=\frac{1+X_{xx}}{X_{xy}}\qquad(3)$$

$$k_m^2=\frac{\omega^2\epsilon\mu_o}{p}-\beta^2\qquad(4)$$

$$k_a^2=\omega^2\epsilon_c\mu_o-\beta^2\qquad(5)$$

$$X_{xx}=\frac{\Upsilon 4\pi M_s\Upsilon H_i}{[(\Upsilon H_i)^2-\omega^2]}=\mu-1$$

$$X_{xy}=\frac{-j\omega\Upsilon 4\pi M_s}{[(\Upsilon H_i)^2-\omega^2]}=-jk$$

$4\pi M_s$ = saturation magnetization of the ferrite
Y = gyromagnetic ratio
H_i = internal DC magnetic field in ferrite
k_m = propagation constant in the ferrite in x direction
k_a = propagation constant in air in x direction
ϵ = permittivity of the ferrite
L = width of rectangular waveguide
δ = thickness of ferrite material

Within the ferrite the RF fields vary as $_ej(k_mx-\beta y)$ and in the air part as $_ej(k_ax-\beta y)$

From equation 1 the condition for cutoff, $\beta=0$ yields the expression

$$\frac{\mu_e\epsilon_o}{\mu_o\epsilon}\tan h^2\{\omega_c(\mu_e\epsilon)^{1/2}\delta\}=\frac{1+\cos\{\omega_c(\mu_o\epsilon_o)^{1/2}(L-2\delta)\}}{1-\cos\{\omega_e(\mu_o\epsilon_o)^{1/2}(L-2\delta)\}}$$

where ω_c = cutoff angular frequency.

If by some appropriate means it can be arranged that $k_m=j|k_m|$ i.e. the propagation constant in the x direction in the ferrite is real (corresponding to an exponential behavior with distance x) then equation 4 may be written

$$\beta^2 = \frac{\omega^2 \mu_o \epsilon}{p} + |k_m|^2 \tag{7}$$

and it follows that by having $\frac{\omega^2 \mu_o \epsilon}{p}$ negative and greater than $|k_m|^2$

then β^2 is made negative i.e., evanescent condition. This is brought about by adjustment of the DC magnetic field on the ferrite (by varying the output of source **22** of FIG. **1**, for example) so that for the frequency of operation p is made sufficiently negative (see FIG. **2**).

The net effect is as if the width 'L' of the waveguide has been reduced.

The width 'L' of the waveguide in FIG. **1** is in the evanescent condition brought about as explained above by the DC magnetic field H_{DC}. This condition is illustrated in FIG. **4** and FIG. **4** also shows how the cutoff frequency of the section is dependent on the value of DC magnetic field. The field, and how the insertion loss increases at a specific frequency for increases in the strength of the DC magnetic field may be made variable in value when applied as shown in FIG **1** by varying the output of the energy source **22**. When permanent magnet means is used to provide the electromagnetic field H_{DC}, the field may be varied by changing the position of the magnetic poles with respect to the waveguide structure.

The filter is tunable in frequency by variation in the value of the DC magnetic field. An increase in field raises the frequency, and a reduction in field lowers the frequency.

Waveguide which is evanescent has a positive imaginary characteristic impedance i.e., at its input terminals (if infinitely long) it will appear as a pure inductance. Consider now a section of the filter of FIG. **1** of finite length l terminated in a capacitance C_1, and a propagation constant γ. Such a section is shown in the familiar T-section form in FIG. **5**. Because the network is symmetrical it can be bisected (FIG. **6**) and its properties determined in terms of its open-circuit and short circuit parameters. The A matrices for such a network are;

$$\begin{vmatrix} E_1 \\ I_1 \end{vmatrix} = \begin{vmatrix} \cos h \frac{\gamma l}{2} & jZ_o \sin h \frac{\gamma l}{2} \\ \frac{1}{jZ_o} \sin h \frac{\gamma l}{2} & \cos h \frac{\gamma l}{2} \end{vmatrix} \begin{vmatrix} 1 & 0 \\ jB_1 & 1 \end{vmatrix} \begin{vmatrix} E_2 \\ I_2 \end{vmatrix} \tag{8}$$

The combined matrix is then

$$\begin{vmatrix} E_1 \\ I_1 \end{vmatrix} = \begin{vmatrix} \cos h \frac{\gamma l}{2} - Z_oB_1 \sin h \frac{\gamma l}{2} & jZ_o \sin h \frac{\gamma l}{2} \\ \frac{1}{jZ_o} \sin h \frac{\gamma l}{2} + jB_1 \cos h \frac{\gamma l}{2} & \cos h \frac{\gamma l}{2} \end{vmatrix} \begin{vmatrix} E_2 \\ I_2 \end{vmatrix} \tag{9}$$

The image impedance is then given by

$$Z_i = \sqrt{Z_{oc} Z_{sc}} \tag{10}$$

$$\text{where } Z_{oc} = \frac{\cos h \frac{\gamma l}{2} = Z_oB_1 \sin h \frac{\gamma l}{2}}{\frac{1}{jZ_o} \sin h \frac{\gamma l}{2} + jB_1 \cos h \frac{\gamma l}{2}}$$

$$Z_{sc} = jZ_o \tan h \frac{\gamma l}{2}$$

The image transfer constant $\cos h \frac{\phi}{2}$ is given by

$$\cos h^2 \frac{\phi}{2} = \cos h \frac{\gamma l}{2} \left(\cos h \frac{\gamma l}{2} - Z_oB_1 \sin h \frac{\gamma l}{2} \right) \tag{11}$$

or

$$\cos h\, \phi = 2 \left(\cos h^2 \frac{\gamma l}{2} - Z_oB_1 \sin h \frac{\gamma l}{2} \cos h \frac{\gamma l}{2} \right) - 1 \tag{11a}$$

Standard texts on image parameter filter theory state that the band limits occur when

$$\cos h\, \phi = \pm 1 \tag{12}$$

This is so in (11a) if either

$$\cos h^2 \frac{\gamma l}{2} - Z_oB_1 \sin h \frac{\gamma l}{2} \cos h \frac{\gamma l}{2} = 0 \text{ or } 1 \tag{13}$$

If

$$\cos h^2 \frac{\gamma l}{2} - Z_oB_1 \sin h \frac{\gamma l}{2} \cos h \frac{\gamma l}{2} = 0$$

Then

$$Z_oB_1 = \cot h \frac{\gamma l}{2} \tag{14}$$

Alternatively, if

$$\cos h^2 \frac{\gamma l}{2} - Z_oB_1 \sin h \frac{\gamma l}{2} \cos h \frac{\gamma l}{2} = 1$$

$$Z_oB_1 = \tan h \frac{\gamma l}{2} \tag{15}$$

In equations (14) and (15) the susceptance is given by the usual expression

$$B_1 = 2\pi f C_1$$

and, therefore, these equations give the pass band frequency limits in terms of the transmission line parameters (γl) and the terminating capacitance (C_1). If the two pass band frequencies at which (14) and (15) are satisfied are f_1 and f_2, respectively.

$$f_1 = \frac{\tan h \frac{\gamma l}{2}}{Z_{o1} 2\pi C_1}$$

$$f_2 = \frac{\cot h \frac{\gamma l}{2}}{Z_{o2} 2\pi C_1}$$

The center frequency, f_o, occurs at the geometric mean,

$$f_o = \sqrt{f_1 f_2}$$

Therefore,

$$f_o = \frac{1}{2\pi Z_o C_1} \tag{16}$$

Further,

$$Q = \frac{f_0}{f_{2-f_1}} \approx \frac{1}{\coth \frac{\alpha l}{2} \tanh \frac{\alpha l}{2}}$$

wherein Z_0, Z_{01} and Z_{02} are the impedance at respective frequencies f_0, f_1, and f_2. Clearly, the network of Fig. 5 is a band-pass filter, the image impedance of which is given by (10). In general, it will be desirable to match the filter at its center frequency, f_0. Substituting the value of B at the center frequency $\left(2\pi f_0 C_1 = \frac{1}{Z}\right)$ in (10), the image impedance, Z_{i0}, at f_0 is given by

$$Z_{i0} = Z_0 \quad \tanh\frac{\alpha l}{2} \qquad (17)$$

An obvious characteristic of the filter is that its bandwidth is a function of γ and (in the ideal lossless case) as $\gamma l \to \infty$ then $\tanh \gamma l \to \coth \gamma l$ and the bandwidth $(f_1 - f_2)$ reduces towards zero. The behavior of the image impedance as a function of frequency is interesting. At very low frequencies γl is extremely large and B_1 tends to zero. Thus Z_i is given by $Z_i \approx jZ_0$. At the lower frequency band limit, f_1, the denominator in (10) becomes zero so that Z_i becomes infinite. At the upper frequency limit, f_2, the numerator becomes zero and, therefore, Z_i is also zero. The behavior is illustrated in FIG. 7.

Returning to FIG. 1, the rejection below resonance is intrinsically higher than other filters (because γ increases with wavelength) and the loss per sections is not excessive. As in all microwave filters unwanted passbands can occur but the usual dominant-mode multipleicavity resonance effect is obviously absent. In the simplest case when identical guide is used throughout free transmission must be expected above the cutoff frequency for that particular guide. In order to control this effect the construction of FIG. **8** is used where the capacitive screws are replaced by capacitive ridges **6**. This style of construction is, of course, identical to that of the familiar corrugated low-pass filter. It is then possible to completely suppress this passband, or alternatively, employ it as a second controllable passband in systems requiring this feature. The magnetic field H_{DC} may be applied as shown in FIGS. **1** or **9**.

Networks of the type described above have useful properties as reactance networks when considered as purely single-port devices. This is illustrated by the network of FIG. **6** with its output terminals open circuited. The input impedance is then given by (10*a*) which slightly rearranged is

$$\text{rearranged is } Z = -jZ_0 \frac{\left(\cosh\frac{\alpha l}{2} - Z_0 B_1 \sinh\frac{\alpha l}{2}\right)}{\left(Z_0 B_1 \cosh\frac{\alpha l}{2} - \sinh\frac{\alpha l}{2}\right)};$$

This network has the zero and infinity values of Z_i as described above and is roughly the equivalent of the m-derived section shown in FIG. **9**. The approximate equivalent circuit is given in FIG. **10**.

In this form of filter, the length of evanescent waveguide **10** may be terminated by a short-circuited section of propagating waveguide **11** having a length l such that tan $(2\pi l/\lambda g)$ is negative, and thus forms the required terminating capacitive reactance for the length of evanescent waveguide. This form of terminating prevents energy being lost at the termination if this form of construction is used for example as a stub. A permanent magnet **23** supplies the magnetic field H_{DC}. It is pointed out that magnets having other shapes and movable poles may be used.

Several applications for the reactance section of FIG. **9** are now given. When coupled to conventional dominant-mode guide **12** it can be used as a shunt or series stub in the usual way (**13** or **14** in FIGS. **11** and **12** respectively). By using it as a shunt stub the passband appears at a lower frequency than the rejection band; as a series stub the positions of the two bands are reversed. It can, for instance, be used as the series element in a terminating m-derived section for the evanescent waveguide filter. Alternatively, in this type of filter it can be used as part of an internal section giving high rejection at a specified frequency.

A more accurate version of the equivalent circuit of a single-section filter similar to that of FIG. **1** is shown in FIG. **14**, the filter **15** being shown schematically in FIG. **13** as a length of evanescent waveguide **16** with a central capacitive screw **17**, between dominant-mode guides **18** and **19**.

The inclusion of the inductance shunt susceptances, represented by the junction with dominant-mode guide, has the effect of bringing the two resonances much closer together than predicted by (**10***a*). The junction susceptances, if sufficiently large can completely eliminate the resonances. Experiments with X-band guide at 4,000 mc./sec. (junction between 2×2/3-in. and 0.9×0.4-in. guides) failed to demonstrate this effect until the junction susceptances were tuned out with capacitive screws in shunt.

By constructing the filter to have capacitive screws at each end of the evanescent waveguide section to have the form of a π section, the capacitive screws then serve both to tune out the junction susceptances and as the terminating capacitive reactance of the filter section.

The evanescent waveguide section or sections may be constructed in waveguide of different dimensions from that of the propagating waveguide. If the waveguide dimensions are larger than that required for the cutoff condition at the operating frequency, the ferrite material loading strips have applied thereto a transverse DC magnetic field such that the effective permeability of the material is made sufficiently negative to bring the section to the evanescent condition.

Conversely, the waveguide dimensions may be smaller than required for the operating frequency, and the ferrite material loading strips have applied thereto a transverse DC magnetic field such that the effective permeability of the material is made sufficiently positive to bring the effective dimensions of the section to the evanescent condition at the desired frequency.

It is pointed out that the magnetic field H_{DC} for the filters of FIGS. **8**, **11**, **12** and **14** are applied in the same manner as for the filter of FIGS. **1** and **9**. That is, by an electromagnet such as shown in FIG. **1** or by a permanent magnet **23** such as shown in FIG. **9**.

While we have described above the principles of our invention in connection with specific apparatus, it is to be clearly understood that this description is made only by way of example and not as a limitation to the scope of our invention as set forth in the objects thereof and in the accompanying claims.

We claim:

1 An H-band-pass filter or filter section comprising:

a first section of waveguide;

ferrite-loading means mounted within said first section waveguide;

means for applying a transverse unidirectional magnetic field to said ferrite-loading means for changing the effective dimensions of said section of waveguide with respect to the propagating wave so as to vary the cutoff frequency above the operating passband frequencies; and

means for terminating said section of waveguide including a capacitive screw having a capacitive reactance which at the center frequency of the desired passband is the conjugate of the positive imaginary characteristic reactance of said first section of waveguide.

2. A band-pass filter or filter section as claimed in claim **1** wherein said ferrite-loading means is symmetrically disposed on each sidewall of said first waveguide section.

3. A band-pass filter or filter section as claimed in claim **1** wherein said applying means includes a permanent magnet.

4. A band-pass filter or filter section as claimed in claim **1** wherein said applying means includes an electromagnet.

5. A band-pass filter or filter section as claimed in claim **1** wherein said first section of ferrite-loaded waveguide has dimensions such that the cutoff frequency is below the operating frequencies of said first section, said applied magnetic field causing the effective dimensions of the first waveguide section to be reduced to a value such that the cutoff frequency is above the operating frequencies of said first section.

6. A band-pass filter or filter section as claimed in claim **1** wherein said capacitive reactance means is located at the middle of the said section of waveguide.

7. A band-pass filter or filter section as claimed in claim **1** including a capacitive reactance terminating means disposed at each end of the said section of waveguide.

8. A band-pass filter or filter section as claimed in claim 1 further comprising:

first and second and third sections of waveguide in which a propagated mode can exist at the operating frequency of the system; and

means coupling said first section of waveguide between said second and third lengths of waveguide.

9 An H-band-pass filter or filter section comprising:

a first section of waveguide;

ferrite-loading means mounted within said first section waveguide;

means for applying a transverse unidirectional magnetic field to said ferrite-loading means for changing the effective dimensions of said section of waveguide with respect to the propagating wave so as to vary the cutoff frequency above the operating passband frequencies; and

means for terminating said section of waveguide including capacitive ridge disposed in said first section of waveguide having a capacitive reactance which at the center frequency of the desired passband is the conjugate of the positive imaginary characteristic reactance of said first section of waveguide.

* * * * *