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MICROWAVE MODE FILTER

2,978,657

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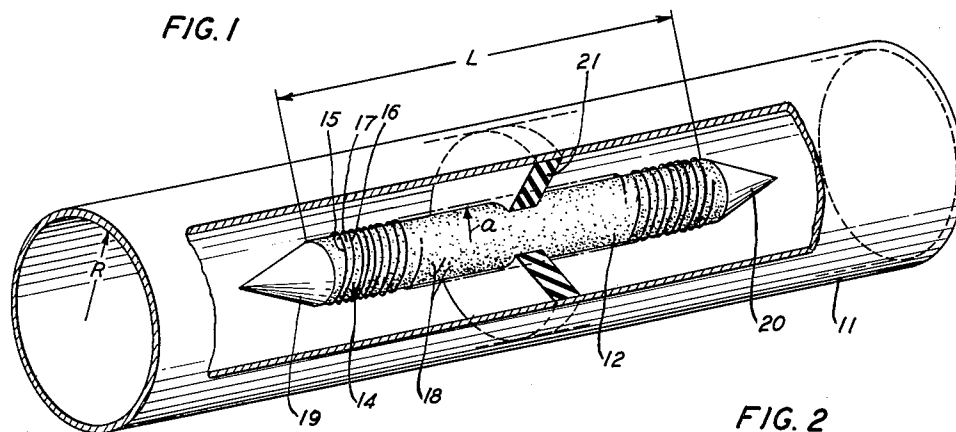


FIG. 2

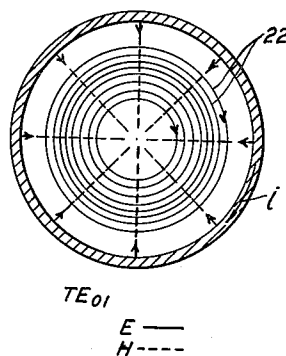


FIG. 3

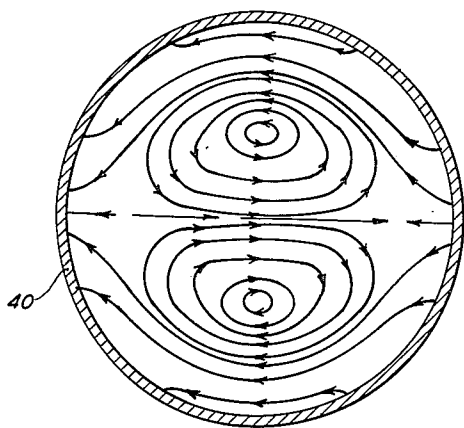
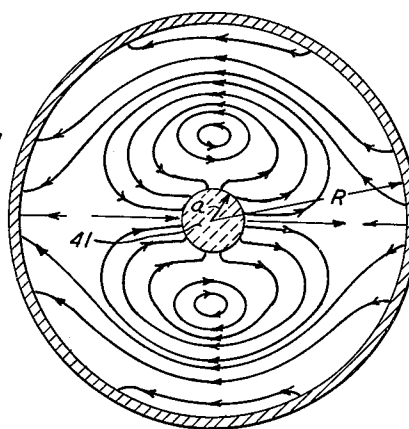


FIG. 4



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MICROWAVE MODE FILTER

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3 Claims. (Cl. 333-98)

This system relates to electromagnetic wave transmission systems, and in particular to selective mode filters for use with cylindrical waveguides transmitting circular electric wave energy.

In the transmission of electromagnetic wave energy through a hollow conductive pipe or other waveguide, it is well known that the energy can propagate in one or more transmission modes, or characteristic field configurations, depending upon the cross-sectional size and shape of the particular guide and the operating frequency, and that the larger the cross-section of the guide is made the greater is the number of modes in which the energy can propagate at a given operating frequency. Very generally, it is desired to confine propagation of the energy to one particular mode, chosen because its propagation characteristics are favorable for the particular application involved. If the desired mode happens to be the so-called dominant mode, it is feasible to restrict the cross-sectional dimensions of the guide so that no modes other than the dominant mode can be sustained therein. This expedient is not available, however, if the desired mode is not the dominant mode or if a guide of large cross-section is prescribed in order, for example, that advantage may be taken of its relatively low attenuation. This is particularly true of systems employing the TE_{01} circular electric mode. As is well known, the propagation of microwave energy in the form of the TE_{01} mode in circular waveguides is ideally suited for the long distance transmission of high-frequency wide-band signals since the attenuation characteristic of this transmission mode, unlike that of other modes, decreases with increasing frequency. However, since the TE_{01} mode is not the dominant mode supported in a circular waveguide, energy may be lost to other modes that are also capable of transmission therein.

In an ideal waveguide which is perfectly straight, uniform and conducting, the propagation of TE_{01} waves therethrough is undisturbed, but slight imperfections in the guide and especially curvature of the waveguide axis may excite waves of other modes and produce serious losses. These losses are attributed mainly to the fact that the bending of the guide produces a coupling between the desired TE_{01} mode and other undesired modes, such as the TM_{11} mode and the TE_{12} mode.

Recognizing that the coupling between these modes may be likened to the coupling between traveling waves on coupled transmission lines in that an exchange of energy will take place between the waves when they travel together in media in which they have the same propagation constants, the prior art has provided a large number of devices for modifying the propagation constants of the transmission path with respect to one of the modes.

In the copending application of S. E. Miller, Serial No. 693,973, filed November 1, 1957, now United States Patent 2,940,057, issued June 7, 1960, there is disclosed a mode filter comprising a section of helical waveguide surrounded by a dissipative jacket and coupling means for coupling in and out of the filter. While this type of filter

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is effective for attenuating those modes having strong longitudinal fields at the waveguide wall, such as the TM_{11} mode, it is not effective against those modes such as the TE_{12} , which have weak longitudinal field components at the guide wall.

It is, therefore, an object of this invention to attenuate noncircular electric mode wave energy having weak longitudinal field components at the guide wall.

It is a further object of this invention to produce such coupling without interfering with the desired TE_{01} circular electric mode.

In accordance with the invention the transmission constant of the wave path for the mode to be suppressed is selectively changed over an interval. In particular, a lossy material is introduced in a region of the path wherein optimum coupling between the material and the noncircular mode wave energy can be affected. In a specific embodiment of the selective mode filter of the present invention, the principle of the helical waveguide is utilized. However, the helical structure is placed at a region of the wave path where the field of the unsymmetrical mode to be attenuated is strong. The helix is wound on a thin rod of lossy dielectric material coaxially disposed within the wave path. The ends of the lossy rod are provided with metallic cones which are gradually tapered to zero diameter for matching purposes. Since the helical configuration is compatible with the circular modes, circular wave energy is propagated past the filter region substantially unaffected in the form of a coaxial mode, whereas the noncircular mode wave energy is selectively attenuated. Since the filter does not utilize tuned elements, it is broad-band in its operation, simple to construct and highly efficient in its operation.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

Fig. 1 is a perspective view of an embodiment of the invention showing the coaxial helical member and dissipative rod;

Fig. 2 shows, by way of illustration, the electric field pattern of the TE_{01} mode;

Fig. 3 shows, by way of illustration, the electrical field pattern of the TE_{12} mode;

Fig. 4 shows, by way of illustration, the electric field pattern of the TE_{12} mode as modified by a coaxial inner conductive member.

Referring to Fig. 1, there is shown a section 11 of hollow conductive waveguide having a circular transverse cross section of radius R , sufficiently large to support the TE_{01} circular electric mode, and, in general, numerous higher order circular electric modes. Coaxially disposed within guide 11 is a rod of lossy dielectric material 12, of radius a , and length L . Surrounding rod 12 is the conductor 14 wound in a helix having an internal radius a substantially the same as the radius of the rod. Adjacent turns such as 15 and 16 of the helix are electrically insulated from each other, and this may be accomplished by means of a small air gap such as 17. The pitch distance of the helix, i.e., the distance between the centers of turns 15 and 16, and therefore the pitch angle of the helix, should be as small as consistent with the above-mentioned insulating requirement. This distance in all events must be less than one-quarter wavelength and is preferably such that the gap 17 between adjacent turns is less than the diameter of conductor 14.

The space between adjacent turns of helix 14 is exposed to the electrically dissipative material comprising rod 12. The latter may be made of any suitable plastic or dielectric material, such as polyethylene, in which small particles 18 of resistive material, such as iron dust or

carbon black, are suspended. Since it is not desirable that the material of rod 12 extend into the space between adjacent helix turns, the rod 12 preferably has a smooth external surface of diameter substantially equal to the inside diameter of the helix.

Located at each end of rod 12 are the metallic cones 19 and 20, which gradually taper to zero diameter to minimize the possibility of spurious mode conversion as the wave propagates past the filter.

Supporting rod 12 in its coaxial position within guide 11 is the dielectric cylinder 21, circumscribing rod 12 and otherwise completely filling the region between the rod and the guide in a manner well known in the art. Cylinder 21 is preferably made of low-loss dielectric material having a dielectric constant to match that of its surroundings, so as to minimize the possibility of spurious reflections of wave energy incident thereon. Alternately, rod 12 may be supported by any other method well known in the coaxial art.

Fig. 2 illustrates the distribution of the electric and magnetic fields in a transverse section of a circular conductive waveguide supporting the TE₀₁ transmission mode. This wave is designated the circular electric type inasmuch as the electric field pattern, shown by the solid lines 22, consists of circular lines coaxial with the guide and lying transversely thereto, without any longitudinal components. The current flow associated with the TE₀₁ wave is predominantly circular around the periphery of the guide as indicated in Fig. 2. Similarly, the current flow in the presence of a conductive body placed elsewhere within the guide would likewise be predominantly circular. Thus, in operation, the circular electric TE₀₁ wave excites in the helix 14 of Fig. 1, a major component of current *i*, which is conducted along the helical path by each turn. If the pitch of the helix is small, this component constitutes substantially the entire current of the wave. A very small longitudinal component of the wave is presented with a small resistance caused by the rod 12 and the discontinuity between adjacent turns. Because very little of the total TE₀₁ current passes through the resistive material of rod 12, the attenuation of the TE₀₁ mode is correspondingly slight.

For the TE₁₂ mode, however, the direction of current flow is different. Fig. 3 shows the electric field configuration of the TE₁₂ wave. While the electric field pattern is entirely transverse without any longitudinal components, the currents that flow along the guide wall are predominantly longitudinal. However, it will be noted that the electric field intensity at the guide wall is relatively small compared to the field intensity within the guide. Consequently, the longitudinal currents that flow in the presence of a conductive member, such as the guide wall, is relatively weak, compared to the longitudinal currents that would flow in the presence of a conductive member placed within the guide. As will be shown, the current that the TE₁₂ mode induces on a center conductor made of solid metal, dissipates more power than the longitudinal current induced on the guide wall. (The case of a solid conductor is considered below rather than the helix merely for simplicity, since the mathematical analysis for the helical case is considerably more complicated.)

If a relatively small conductive element is coaxially disposed within the guide, it does not distort the field configuration of the TE₁₂ mode substantially, but it does cause longitudinal currents to flow. If, in particular, these currents are to be suppressed by using a helical structure with a lossy dielectric core as shown in Fig. 1, the mode will be distorted some but the relatively strong field in the region of the lossy dielectric which is generated by the strong longitudinal currents gives rise to a high attenuation.

In Fig. 4, there is shown the TE₁₂ mode electric field pattern as distorted by the solid conductive coaxial member 41. The field of the TE₁₂ mode in the coaxial struc-

ture, expressed in polar coordinates, is described by the following equations:

$$H_z = AV_1(kr) \sin \alpha \quad (1)$$

$$H_r = jA \frac{h}{k} V_1'(kr) \sin \alpha \quad (2)$$

$$H_\alpha = jA \frac{h}{k^2} \frac{1}{r} V_1(kr) \cos \alpha \quad (3)$$

$$E_r = jA \frac{\omega \mu_0}{k^2} \frac{1}{r} V_1(kr) \cos \alpha \quad (4)$$

$$E_\alpha = -jA \frac{\omega \mu_0}{k} V_1'(kr) \sin \alpha \quad (5)$$

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

$$k^2 = (\omega^2 \epsilon_0 \mu_0 - h^2)$$

$$V_1(kr) = J_1(kr) - \frac{J_1'(kr)}{N_1'(kr)} N_1(kr) \quad (6)$$

*J*₁(*kr*) being the Bessel function of the first order and *N*₁(*kr*) being the Neumann function of the first order.

Designating the inner conductor radius *a*, and the guide radius *R*, the boundary conditions require that *E*_α=0, at *r*=*a*, and at *r*=*R*.

Therefore, from Equation 4

$$V_1'(ka) = 0 \quad (7)$$

and

$$V_1'(kR) = 0 \quad (8)$$

Differentiating Equation 6 gives with *r*=*a*

$$V_1'(ka) = J_1'(ka) - \frac{J_1'(kR)}{N_1'(kR)} N_1'(ka) \quad (9)$$

which, from Equation 8, equals zero. To compute the relative power loss at the guide wall and the inner conductor, Equation 9 is solved for *k*.

Since the coaxial member is considered to be relatively small, for the purposes of analysis, the coaxial mode is almost equal to the undistorted TE₁₂ mode. For the TE₁₂ mode *J*₁'(*kR*) would be zero. However, for the coaxial TE₁₂ mode, the value of *J*₁'(*kR*) is small, but finite.

If it is assumed that

$$k = k_{12} + \sigma$$

where *σ* is a small value resulting from the disturbance caused by the inner conductor, and *k*₁₂ is the Bessel constant for the TE₁₂ mode, such that

$$k_{12}R = 5.33 \text{ and } J_1'(k_{12}R) = 0$$

then by the Taylor expansion,

$$J_1'(kR) = J_1'(k_{12}R) + J_1''(k_{12}R)\sigma R$$

and

$$J_1'(kR) = J_1''(k_{12}R)\sigma R$$

From the differential formula for the Bessel function, using approximations for a small argument,

$$J_1'(ka) = J_0(ka) - \frac{1}{ka} J_1(ka) = 1 - \frac{1}{2} = \frac{1}{2}$$

and

$$N_1'(ka) = N_0(ka) - \frac{1}{ka} N_1(ka)$$

$$= \frac{2}{\pi} \ln \frac{2}{ka} + \frac{2}{\pi} \frac{1}{(ka)^2}$$

$$\cong \frac{2}{\pi} \frac{1}{(ka)^2}$$

for *θ*=1.78.

Solving for σ gives

$$\sigma = \frac{\pi N_1'(5.33)}{4 J_1''(5.33)} \frac{(k_{12}a)^2}{R} = ca^2$$

where c is a constant.

The power per unit length dissipated by the longitudinal currents is proportional to H_a from Equation 3, or

$$P_R \approx \frac{1}{R} [V_1(kR)]^2$$

due to wall current at $r=R$, and

$$P_a \approx \frac{1}{a} [V_1(ka)]^2$$

due to current in the inner conductor $r=a$. Dividing gives

$$\frac{P_a}{P_R} = \frac{R [V_1(ka)]^2}{a [V_1(kR)]^2} = \frac{R}{a} \frac{(ka)^2}{J_1^2(5.33)} = \frac{k^2 R a}{J_1^2(5.33)} = \frac{(5.33)^2}{J_1^2(5.33)} \frac{a}{R}$$

and

$$\frac{P_a}{P_R} = \frac{a}{R} \times 237 \quad (10)$$

From Equation 10 it is seen that if

$$\frac{R}{a} = 237$$

the power dissipated in the guide wall is equal to the power dissipated in the inner conductor. However, as a increases, or for values of the ratio

$$\frac{R}{a}$$

less than 237, the power dissipated in the inner conductor is substantially larger than the power dissipated in the guide wall.

Based upon the assumption that the TE_{12} mode was relatively little disturbed by the presence of the coaxial member, the Equation 10 is only accurate for ratios of

$$\frac{R}{a}$$

of about 100 or greater. However, in practice a ratio of about 10 would be used, and the coaxial conductor would be the helical member shown in Fig. 1. Measurements made on a filter of this kind showed that the attenuation of the TE_{12} mode caused by a rod of 0.2 inch diameter in a 2 inch solid copper pipe was 0.65 decibel per inch. The attenuation of the TE_{01} mode in the presence of the filter structure was as little as 5×10^{-4} decibels per inch.

Whereas the coaxial helical filter structure was shown

utilized in a solid copper pipe, it could be used advantageously in a helical waveguide as well, or in conjunction with the filter structure described in the copending application of S. E. Miller cited above.

- 5 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 by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a multimode electromagnetic wave transmission system, means for producing the circular electric mode of said wave energy, means for utilizing said circular electric wave energy, mode selective means for connecting said utilizing means to said producing means for the preferential transmission of the circular electric mode, said connecting means comprising a circular cylindrical section of waveguide proportioned to support the TE_{01} circular electric mode and other higher order modes including at least the TE_{12} mode, an elongated member of conductive material wound over a rod of lossy material in a substantially helical form, said helix having a diameter less than one-half the diameter of said guide, and means for coaxially supporting said helix in said guide.
2. In an electromagnetic wave transmission system, means for producing the circular electric mode of said wave energy, means for utilizing said circular electric wave energy, means for connecting said utilizing means to said producing means comprising a conductively bounded hollow cylindrical section of waveguide, said section being conductively continuous for all circumferential and for all longitudinal current components of high frequency wave energy conducted along said section, said waveguide proportioned to support the TE_{01} circular electric mode and other higher order modes including at least the TE_{12} mode, and a helix of electrically conductive material having adjacent turns insulated from each other coaxially supported on a circular cylindrical rod of lossy dielectric material within said section.
3. The combination according to claim 2 wherein the ratio of the diameter of said guide to the diameter of said helix is approximately ten to one.

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