

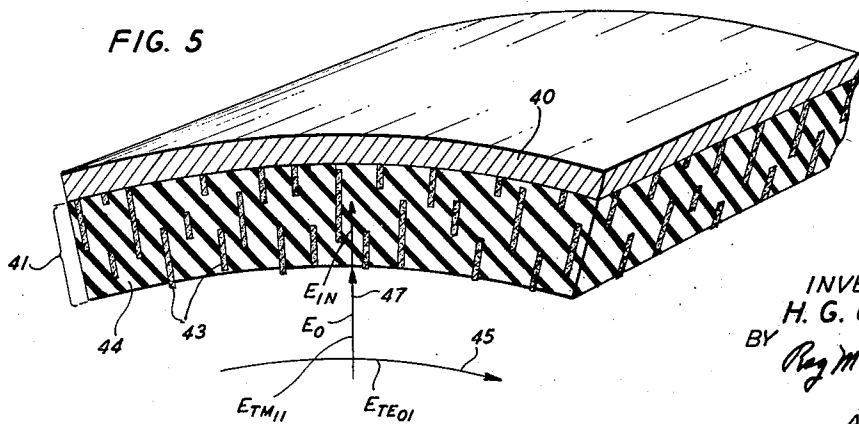
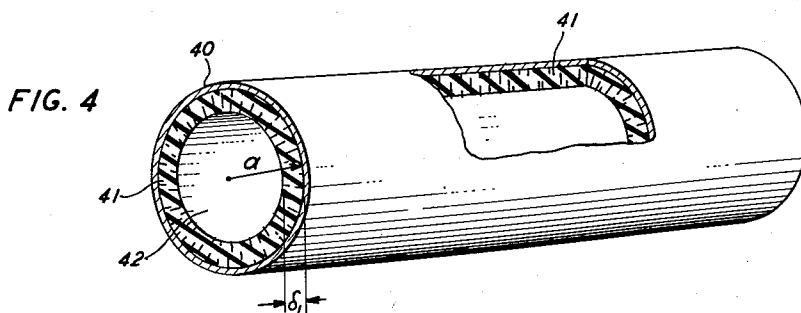
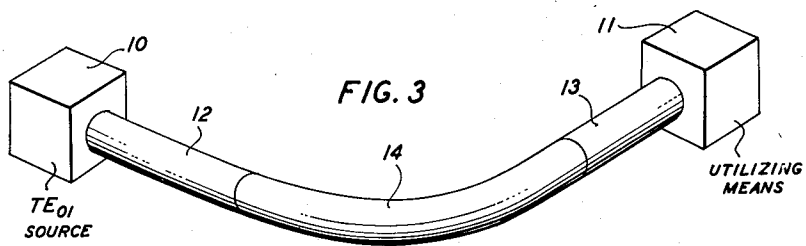
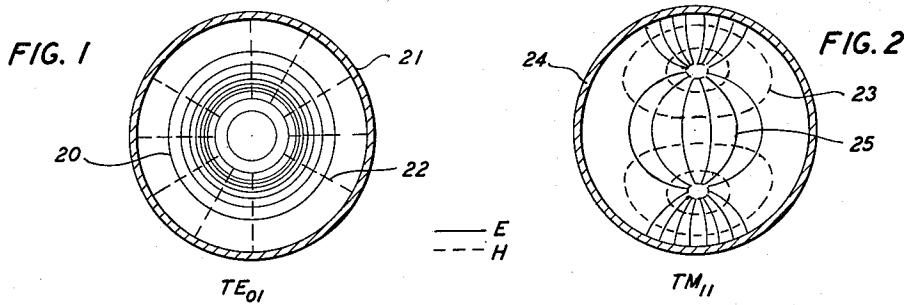
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SPURIOUS MODE SUPPRESSING WAVE GUIDE

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SPURIOUS MODE SUPPRESSING WAVE GUIDE

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This invention relates to electromagnetic wave transmission and, more particularly, to apparatus for propagation of the circular electric or TE_{01} wave mode through wave guiding structures of circular transverse cross section.

In the transmission of electromagnetic wave energy in a hollow pipe or other type wave guide, it is well known that the energy can be supported in a number of different transmission modes, or characteristic electric and magnetic field configurations, depending upon the cross sectional size and shape of the guide itself and upon the operating range of frequencies selected. It is also well known that the larger the cross section of the guide, or the higher the range of operating frequencies, the greater is the number of modes which may be supported at a given frequency or within a guide of a given cross section, respectively. Generally it is desirable to confine the energy propagation to one particular mode, chosen because its propagation characteristics are particularly suited to the specific application involved. However, other considerations may dictate the use of guide sizes which support not only the desired mode but also one or more modes which are unwanted or undesirable. This is particularly true of systems utilizing TE_{01} circular electric waves. Propagation of microwave energy in the TE_{01} mode is well known to be suited to long distance transmission of high frequency wide band signals since the attenuation characteristic of this mode, unlike that of other modes, decreases with increasing frequency. Furthermore, transmission losses associated with the TE_{01} mode are inversely proportional to the third power of the guide diameter. Thus, current practice whenever possible is to use uninterrupted runs of relatively large diameter pipe for long runs in all wave guide communication systems. However, the use of large diameter pipe causes the system to be susceptible to generation of unwanted, spurious modes which propagate concurrently with the desired mode.

In an ideal system utilizing guides which are perfectly straight, uniform, and conducting, propagation of TE_{01} waves therethrough would be undisturbed, and the fact that the guide is capable of supporting other modes, once excited therewithin, is not a problem. However, terminal operations and curvature of the longitudinal axis of the pipe within the system, as well as inherent imperfections in the guiding members themselves tend to disturb the TE_{01} mode and to cause conversion and reconversion of power between that mode and unwanted modes. One major conversion problem involves the TE_{01} and TM_{11} modes, while others involve the TE_{01} and TE_{12} modes as well as the TE_{01} and other higher order modes. These spurious modes are perfectly capable of being propagated in the system and therefore have a deleterious effect upon transmission of information through the system. Obviously every reasonable effort must be made to minimize the spurious mode conversion and reconversion process by appropriate methods and means.

It is therefore an object of the present invention to suppress the tendency of TE_{01} waves to convert to unwanted modes in circular electric wave mode systems. Another object is to absorb power in unwanted modes before reconversion to the TE_{01} mode.

The ease with which conversion between the TE_{01} and TM_{11} mode occurs is explained by an equality, in perfectly conducting uniform round wave guide, of the phase con-

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stants of these modes. The proposed methods of approach to this moding problem may be divided into two broad categories. The first category includes those disclosures in which the conductive structure of the guiding means is itself modified. Among these disclosures are guides having a corrugated wall, and guides comprising a helical winding or a series of spaced conductive rings. The second category on the other hand includes those disclosures in which the conductive structure of the guiding means itself comprises an unmodified pipe of circular transverse cross section, but into which some additional means is inserted to affect the transmission properties of wave energy. Included among such means are homogeneous lossless dielectric liners, homogeneous lossy liners, and composite liner structures of both lossless and lossy materials. The present invention falls into the second category above and represents an alternative structure which may be more particularly suited for a given application than some of the other known structures.

Accordingly, it is a further object of the present invention to suppress spurious mode generation and to absorb spurious mode power in TE_{01} wave mode systems through the introduction of improved means into an ordinary hollow pipe guide.

Generally, prior art structures falling within the second category above were characterized by liners having isotropic propagation characteristics. That is, propagation characteristics within the liner were identical regardless of the particular propagation direction. Restrictive limits are placed upon the radial thickness of such an isotropic liner since the TE_{01} mode, while having low field intensity adjacent the guide wall, as will become more apparent hereinafter, will be adversely affected if the lining means and its electrical effects are extended into regions of substantial TE_{01} field intensity. Oftentimes the maximum allowable prior art liner thickness from TE_{01} loss considerations is less than that desirable from considerations relating to the conversion to and attenuation of unwanted modes. It is in such situations that the present invention finds particular application.

It is therefore a further object of the present invention to increase the radial extent of a surface liner within a guide propagating TE_{01} waves without adversely affecting such mode while at the same time both substantially removing the degeneracy between the TE_{01} and TM_{11} modes, and introducing selective attenuation of spurious modes.

In accordance with the present invention, the inside surface of a round wave guide supportive of TE_{01} waves is overlaid with a liner exhibiting anisotropic electrical characteristics to propagating electromagnetic waves. More specifically, the liner is chosen to exhibit both conductivity and attenuation in a direction normal to the guide wall considerably greater than the same quantities in a direction parallel thereto. As will become more apparent in a later portion of this specification, such an anisotropic liner affects TM_{11} and other spurious modes to a significant degree while at the same time affecting the TE_{01} mode only slightly.

In a preferred embodiment of the invention, elongated fibers which are electrically conductive are disposed throughout a thin dielectric surface liner within a round wave guide, the fibers being oriented with their long dimension normal to the guide surface. Each fiber, in addition to its conductive character, is electrically slightly lossy and introduces substantial attenuation to mode currents induced therein by unwanted modes. Since the fibers are conductive, their physical orientation in a direction normal to the guide wall may be accomplished by immersing the guide assembly in a properly directed electrostatic field during fabrication of the liner.

A feature of the invention therefore resides in a method

of electrostatic fabrication of the anisotropically conductive liner.

The above and other objects and features, the nature of the present invention and its various advantages will appear more fully upon consideration of the drawing and the detailed description thereof which follows.

In the drawing:

FIGS. 1 and 2 show, for purposes of illustration, the electromagnetic field patterns of the TE_{01} and TM_{11} wave modes, respectively, in round wave guide;

FIG. 3 is a perspective view of a simplified wave guide installation;

FIG. 4 is a partially broken away perspective view of a section of round wave guide having a surface liner in accordance with the present invention; and

FIG. 5 is an enlarged perspective view of a portion of a transverse cross section of the guide shown in FIG. 4.

Referring more particularly to the drawing, FIGS. 1 and 2 illustrate the distribution of the electric and magnetic fields at a given instant in transverse cross sections of circular wave guides supporting the TE_{01} and TM_{11} transmission modes, respectively. The transverse electric TE_{01} wave illustrated in FIG. 1 is commonly designated the circular electric wave mode inasmuch as the electric field, shown by the solid lines, consists of circular lines 20 coaxial with the conductive guide 21 and lying transversely thereto with no longitudinal components. The magnetic field is described by the dashed radial lines 22. It may be seen from the figure that the electric field intensity diminishes as the conductive boundary is approached and that the electric field has a low intensity in the vicinity of the interior surface of the wave guide.

The transverse magnetic TM_{11} wave illustrated in FIG. 2 is described by a magnetic field, illustrated by dashed lines 23, lying entirely in planes transverse to the longitudinal axis of the guiding structure 24. The electric field pattern, indicated by the solid lines 25, has substantial radial components at the inner surface of the wave guide. Thus the TM_{11} mode, in contradistinction to the TE_{01} mode above described, has a substantial electric field intensity in the vicinity of the interior surface of the wave guide. The significance of this difference in field intensity at the wave guide surface will become apparent in a later portion of this specification.

FIG. 3 is a perspective view of a wave guide transmission system comprising microwave source 10 supplying energy in the form of TE_{01} waves through a continuous circular wave guiding passage comprising uniform straight sections 12, 13 and curved section 14 to a microwave utilizing means 11. Utilizing means 11 may be a microwave amplifier, a receiver, or an antenna, for example. Curved section 14, which joins sections 12 and 13, is a generalized representation of the wave guide curvature inherent in any long distance wave guide transmission system. This curvature may be intentional, for example, to follow rights of way, or it may occur unintentionally as manufacturing or laying imperfections or as a result of elastic deformation of the guide under its own weight.

In a microwave system for the transmission of TE_{01} waves, such as, for example, the system of FIG. 3, the inside radius a of the circular pipe guide selected for the propagation of these waves must be greater than the critical or cut-off radius a_c for the TE_{01} mode at the frequencies of interest. The cut-off radius a_c for TE_{01} mode is equal to $0.61\lambda_0$ where λ_0 is the wavelength in free space of the lowest frequency wave in the transmission band. In practice a is made greater than a_c and may vary in different systems from $1.5\lambda_0$ to $15\lambda_0$. For illustrative purposes, a suitable inner radius for the wave guide structures to be described herein may be $7.7a_c$ or $4.7\lambda_0$. Thus, if a hollow pipe guide two inches in diameter were chosen for transmission of TE_{01} waves, λ_0 in accordance with the above would be 0.213 inch or 5.4 millimeters.

The characteristic problem of conversion between

power in the TE_{01} mode and power in the TM_{11} mode arises because the phase constants, i.e., the phase velocities and wavelengths, of these two modes are substantially identical in hollow circular wave guides. Since the phase constants are nearly identical, these modes interact strongly in a manner analogous to coupled transmission lines as set out in an article by W. J. Albersheim entitled "Propagation of TE_{01} Waves in Curved Waveguides" appearing in the Bell System Technical Journal, vol. 28, No. 1, January 1949. In the specific embodiment of the invention which follows, the wave guide sections of the system of FIG. 3 are modified by the introduction of a liner which both changes the phase velocity of the TM_{11} mode relative to the TE_{01} mode and introduces attenuation to the TM_{11} and other unwanted modes. These modifications cause significant relative differences in the phase and attenuation constants between the TM_{11} and other modes on the one hand and the TE_{01} mode on the other hand. With the relative differences thus introduced, intermode coupling loss in wave guide sections in which TE_{01} waves are propagating is substantially reduced.

FIG. 4 is a perspective view of a partially broken away section of a hollow pipe wave guide 40 of circular transverse cross section containing a lossy liner 41 in accordance with the present invention. The liner comprises a dielectric layer having elongated lossy fibers, which are also slightly conductive, disposed therein. The fibers are physically oriented to lie on radii of the guide 40, and therefore the fibers extend in directions normal to the guide wall. Surface coatings including oriented fibers are generally designated "flock" coatings. In the application of flock coatings it is generally the practice to suspend the flock, here the conductive fibers, in a liquid dielectric adhesive before application to the desired member. The individual fibers are oriented after the liquid suspension has been painted or sprayed on. In embodiments of the present invention, the fibers, by virtue of their being conductive in some degree may be properly aligned by applying an electrostatic field of proper orientation to the interior of the guide to be flocked. In the presence of the electrostatic field, the conductive fibers will then orient themselves. Since the fibers are preferably aligned after application in a liquid suspension, it is essential that the material chosen for the dielectric layer be adaptable to liquefaction and subsequent setting. Stycast 35 resin would easily meet electrical as well as mechanical requirements.

Hollow conductive guide 40 is of inside radius a which is selected to be above cut-off at the operating frequencies as set out above. Liner 41, which extends concentrically within guide 40 and is disposed on its inside surface, comprises a cylinder of material having anisotropic electrical characteristics as set out above. Liner 41 has a radial thickness δ_1 which may be of the order of 5 mils, and is disposed within guide 40 such that the outer surface of the liner is contiguous with the inner surface of the guide. The remainder of the transverse cross section of guide 40, consisting of the cylinder shaped area 42, is filled with a homogeneous low loss material different from the material of liner 41. As illustrated in FIG. 4, area 42 comprises air, with a relative dielectric constant of unity.

The essential electrical and physical characteristics of liner 41 may be more readily appreciated by reference to FIG. 5, which is an enlarged perspective view of a portion of the guide shown in FIG. 4. In FIG. 5 liner 41 is seen to comprise fibers 43 embedded in an adhesive dielectric medium 44. The electrical function of liner 41 is two-fold. On the one hand, the liner introduces a phase constant differential between the TE_{01} and TM_{11} modes and on the other hand, it increases the attenuation constant of unwanted modes without similarly affecting the TE_{01} mode. For the purposes of the introduction of the phase constant differential, the electrical characteristics of adhesive medium 44 are of primary interest and liner 41 may

be considered to be a homogenous dielectric medium comprising the material of adhesive 44. As will be recalled from an earlier portion of this specification, the TE₀₁ mode is characterized by very low field intensity in the vicinity of the wall of guide 40 and therefore has very low intensity within liner 41. In FIG. 5 vector 45 represents the electric field of the TE₀₁ mode but since its intensity is very low, it undergoes no significant change as a result of the presence of liner 41. The TM₁₁ mode on the other hand is characterized by radial electric field components of substantial intensity in the region of liner 41 and is therefore significantly affected by its presence. These radial components are designated by vector 47 in FIG. 5 and are seen to be normal to the interface between the liner 41 and the remainder of the guide filling. Since the normal component of the displacement density E/ϵ is continuous through the interface, the ratio E_{ln}/E_0 is proportional to $1/\epsilon$ where ϵ is the relative dielectric constant of liner 41.

As will be seen hereinafter, it is necessary for attenuation purposes that a substantial portion of the transversely directed TM₁₁ component be present within liner 41. Accordingly, an upper limit is set on the allowable relative dielectric constant of the liner. In practice this dielectric constant should not exceed a value of the order of 3. Typical materials for medium 44, subject to the limitations relative to liquefaction set forth above, would be polystyrene with a relative dielectric constant of 2.5 or Stycast 35 casting resin with a relative dielectric constant of 3.

For the purpose of increasing the attenuation constant of unwanted modes, the electrical properties of fibers 43 are of primary interest. In general, the purpose of fibers 43 is significantly to increase the conductivity of liner 41 in a direction normal to the wall of guide 40 while at the same time affecting the conductivity in a direction parallel to the wall but slightly. The reason for this anisotropy will be immediately apparent from the discussion which follows.

For the TE₀₁ mode, the increase in the attenuation constant is proportional to the product of the dielectric constant of the liner and its loss tangent in a direction parallel to the guide wall. That is,

$$\Delta\alpha_{TE_{01}} \sim \epsilon \tan \delta_{//}$$

The loss tangent may be expressed as the conductivity in a direction parallel to the guide wall, $\sigma_{//}$, divided by the product of radian frequency ω and the dielectric constant $\epsilon\epsilon_0$. Substituting,

$$\Delta\alpha_{TE_{01}} \sim \frac{\sigma_{//}}{\omega\epsilon_0}$$

It is therefore clear that the attenuation constant of the desired TE₀₁ mode will not be increased significantly if the conductivity of liner 41 in a direction parallel to guide wall 40 is very low.

On the other hand, the increase in the attenuation constant of the TM₁₁ mode caused by liner 41 is proportional to its loss tangent in a direction normal to the guide wall divided by its dielectric constant. That is

$$\Delta\alpha_{TM_{11}} \sim \frac{\tan \delta_{\perp}}{\epsilon\epsilon_0}$$

Again substituting for $\tan \delta$ its equivalent in terms of conductivity.

$$\Delta\alpha_{TM_{11}} \sim \frac{\sigma_{\perp}}{\omega\epsilon^2\epsilon_0}$$

Since the dielectric constant of liner 41 is fixed from the phase splitting considerations set out above, the attenuation constant for the TM₁₁ and other unwanted modes may best be increased by providing substantial conductivity in a direction normal to the guide wall. Summarizing, liner 41 preferably has a relative dielectric constant of the order of 3, a low conductivity parallel to

the guide wall and a relatively high conductivity normal to the wall.

Such electrical characteristics are provided by orienting thin conducting fibers within a dielectric binder or adhesive such that the fibers are normal to the guide wall, in the form of a "flock" coating.

In FIG. 5, fibers 43 extend within dielectric medium 44 with their long dimension always normal to wall 40. Typical examples of materials suitable for use as fibers 43 are graphite, carbon coated glass, tin oxide coated glass, and carbon coated paper pulp. When these fibers are distributed throughout a dielectric binder or adhesive, the over-all medium exhibits anisotropic conductivity characteristics. The amount of fibers distributed per unit volume of the liner 41 is determined by the initial conductivity of the fibers themselves and the over-all desired bulk conductivity of the liner desired. The fibers themselves are electrically lossy with respect to currents generated therein. By electrically lossy, it is meant that the fibers are capable of converting into heat energy substantial amounts of the currents generated therein as the result of the incidence thereupon of electric field components associated with unwanted wave modes. It should be noted that each of the suggested materials for fibers 43 is capable of such dissipative conversion.

From a practical viewpoint, a loss tangent normal to guide 40 of the order of unity is a value reasonably to be expected for lossy liner 41. In an earlier portion of the specification a relative dielectric constant of 3 was suggested as reasonable. From these values, the bulk conductivity of liner 41 in a direction normal to the wall may be calculated. At a frequency of 55 kilomegacycles, this bulk conductivity is 0.1 ohm-centimeter. The bulk conductivity of graphite alone is of the order of 1000. By distributing the graphite fibers throughout dielectric medium 44 in proper amount, the desired bulk conductivity may be realized.

In the operation of a wave guide system in accordance with the present invention wave energy in the TE₀₁ mode is launched at the transmitting terminal. By virtue of junctions between guide sections, inherent imperfections in the guiding members, and both intentional and unintentional curvature of the guides, there is a tendency toward conversion of TE₀₁ wave power to TM₁₁ and other spurious modes. The effect of dielectric medium 44 and slightly conductive lossy fibers 43 is to reduce conversion and to attenuate unwanted wave mode power. The TE₀₁ wave mode is unaffected by the lossy conductive fibers due to (1) the extremely low field intensity in their vicinity and (2) the negligible extent of each fiber in the direction of the TE₀₁ electric field lines thereby presenting substantially no attenuating mechanism to the few field lines which do extend within the liner.

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 present 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 combination, a hollow pipe wave guide of circular transverse cross section containing inherent imperfections and curvature, means for applying electromagnetic wave energy in the circular electric TE₀₁ wave mode to said guide, first means disposed within said guide for increasing the phase constant associated with the TM₁₁ wave mode without significantly changing the phase constant of said circular electric mode, and second means disposed within said first means for causing said first means to exhibit anisotropic conductivity and for selectively attenuating the wave modes into which said circular electric mode converts as a result of said imperfections and curvature.

2. The combination according to claim 1 in which

said first means comprises a substantially lossless dielectric liner with a relative dielectric constant equal to or less than three.

3. The combination according to claim 1 in which said second means comprise elongated elements having conductive properties to induce electric currents therein and lossy properties to attenuate said currents.

4. A transmission path for electromagnetic wave energy in the circular electric wave mode comprising a section of hollow conductively bounded wave guide of circular transverse cross section, and means contiguous with the inner surface of said guide comprising a hollow cylindrical liner having anisotropic conductivity with maximum conductivity in a direction normal to said surface, the remainder of the cross section of said guide being filled with a homogeneous lossless material different from the material of said liner.

5. A transmission path for electromagnetic wave energy within a given range of operating frequencies comprising a hollow pipe wave guide of circular transverse cross section with an inside radius greater than five times the cut-off radius at the lowest operating frequency, and means having anisotropic conductivity lining the inner surface of said guide, the remainder of said guide being filled with a homogeneous isotropic lossless material.

6. The transmission path according to claim 5 in which said lining means comprises a flock coating of slightly conductive lossy fibers extending in a direction normal to the guide wall within a dielectric binder of moderate dielectric constant.

7. The transmission path according to claim 6 in which the bulk conductivity of said liner in said normal direction is 0.1/ohm-centimeter at a frequency of 55 kilomegacycles.

8. A transmission path for electromagnetic wave energy in the TE_{01} wave mode comprising a hollow pipe wave guide of circular transverse cross section, a dielectric liner of moderate dielectric constant overlaying the inner surface of said guide, and means disposed within said liner for imparting a conductivity thereto in a direction normal to said surface considerably greater than its conductivity in a direction parallel thereto.

9. The transmission path according to claim 8 in which said means comprises a flock of slightly conductive fibers of lossy material.

10. The transmission path according to claim 9 in which said fibers comprise graphite.

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