June 7, 1960 S. E. MILLER 2,940,057

SELECTIVE MODE FILTERS

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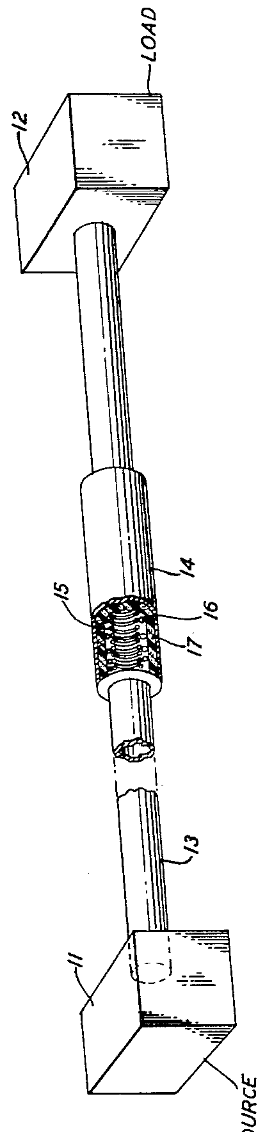

FIG. 1

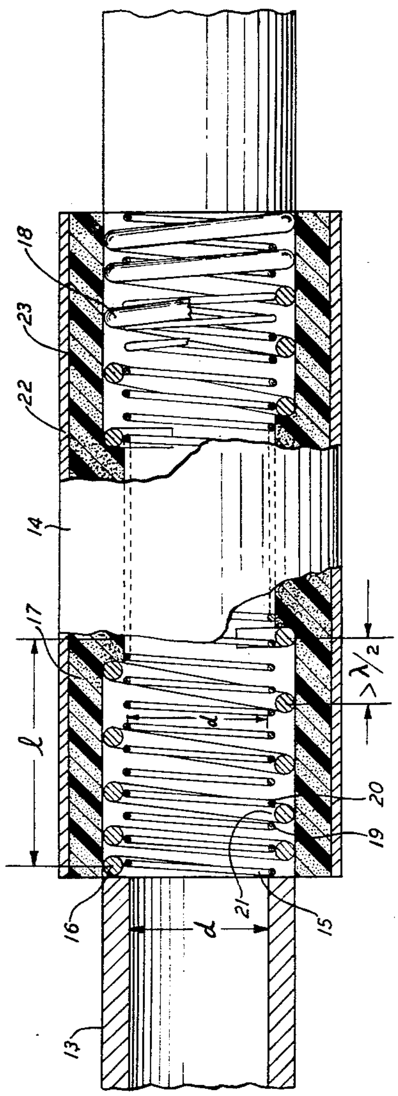

FIG. 2

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SELECTIVE MODE FILTERS

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This invention relates 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, mainly the TM_{11} 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 J. R. Pierce, Serial No. 416,315, filed Mar. 15, 1954, now U.S. Patent 2,848,695, issued Aug. 19, 1958, it is disclosed that a helical conductor of diameter greater than 1.2 free space wavelengths will propagate a properly excited circular electric TE_{01} mode with a different phase constant than the TM_{11} mode. This provides a substantial decoupling between

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these modes. In my copending application, Serial No. 416,316, filed Mar. 15, 1954, now U.S. Patent 2,848,696, issued Aug. 19, 1958, it was shown that if the respective TE_{01} and TM_{11} modes propagated along the resulting helical transmission path are exposed in a special way to electrically dissipative or lossy material so that they have substantially different attenuation constants, the coupling between the two modes may be made arbitrarily small. The attenuation constant of the TM_{11} mode may be substantially increased, for example, without increasing that of the TE_{01} mode by surrounding the helical guide with a cylinder-like casing of dissipative material having an inside surface contiguous with the outermost part of the helical conductor. Thus, the longitudinal currents of the TM_{11} mode must pass through the lossy material, giving to that wave a large attenuation constant while the component of the circumferential currents of the TE_{01} mode which follows the helix conductor is unaffected.

Where the transmission path is constructed substantially as outlined above, the conversion of TE_{01} wave energy to other spurious modes may be made negligibly small. However, it is often not feasible to provide helical waveguiding means for the circular electric mode. It may, instead, be necessary or desirable to use solid cylindrical pipe as the transmission medium. Where this is so, it will be essential to interpose at regular intervals, mode filtering means for the purpose of removing those spurious modes that will be inevitably generated in any practical system thus minimizing the likelihood of conversion-reconversion distortion effects. It would appear reasonable to construct such a mode filter in the form of a segment of helical waveguide as described above to eliminate any spurious non-circular modes. However, it has been found that merely to insert segments of helical waveguide between portions of solid wall guide had the effect of generating additional spurious modes by virtue of the conversion of the TM_{11} mode to TM_{12}, TE_{11} and TE_{12} modes. This conversion takes place at the junction of the solid and the helical waveguide and is a result of the change in transmission characteristics experienced by the TM_{11} mode at this point. While the additional modes thus generated will also be dissipated in the mode filter as well as the TM_{11} mode, it has been found that to achieve the desired spurious mode level at the output of the filter, a filter of longer length is needed than would be needed if the TM_{11} mode was the only spurious mode present.

It is, therefore, an object of this invention to couple, with minimum mode conversion, non-circular electric mode wave energy in a multimode system from one transmission medium to another having different transmission constants.

It is an additional object of this invention to produce such coupling over a broad frequency band.

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 a specific embodiment of the selective mode filter of the present invention, to be described in greater detail hereinafter, a composite helical structure is provided. The filter includes a first helical member constituting a smooth transmission medium for the desired circular mode. The second helix, which surrounds the first helix over a region, is a tapered member which is tight wound at one end, but in which the pitch gradually increases until the spacing between turns is approximately one-half wavelength of the lowest frequency to be transmitted. At this point the second helix is discontinued. The dissipative jacket comprises a cylinder-like casing having an inside surface contiguous with the outermost part of the helical conductors. Thus, the longitudinal currents of the TM_{11} mode, which must pass through the lossy material, are gradually exposed to the lossy material, thereby causing this wave to experience a smoothly increasing attenuation constant, while the component of the circumferential currents of the TE_{01} mode which follows the innermost helix conductor are unaffected. By gradually introducing the non-circular modes to the lossy jacket, the tendency for further mode conversion is minimized. The filter length is calculated to reduce the spurious mode level in the system to a specified level and is then discontinued, returning to the solid wall guide. Since the transmission characteristics of both the filter and the solid wall guide are the same for the circular electric modes, there is no need for any matching means at either end of the filter for these modes. If the system is limited to transmissions in only one direction, it is sufficient to have only one tapered helical member at the input end of the filter. If however, wave energy is to be transmitted in both directions, similar tapered helical members must be provided at both ends of the filter.

These and other objects, the nature of the present invention, and its various features and advantages, will appear more fully upon more detailed consideration of the specific illustrative embodiment shown in the accompanying drawings and analyzed in the following detailed description of these drawings.

In the drawings:

Fig. 1 is a perspective view of a wave transmission system employing a helical filter in accordance with the principles of the invention; and

Fig. 2 is a partially cut away view of the helical filter shown in Fig. 1.

Referring more particularly to Fig. 1, there is shown an electromagnetic wave transmission system comprising a source **11** of TE_{01} circular electric microwave energy connected to load **12** by means of solid wall waveguide transmission path **13** of substantially circular cross-section. Load **12** is adapted to utilize TE_{01} circular electric mode wave energy, while transmission path **13** represents the type of transmission line having bends, joints, slight physical imperfections, and deliberately inserted components, any of which tend to introduce mode conversion effects therealong. As is well known, these effects convert portions of the TE_{01} wave into non-circular spurious waves, particularly the TM_{11} mode. To prevent undue reflections and other deleterious effects, these spurious modes must be eliminated in some manner prior to entering load **12**.

In accordance with the present invention, the spurious modes introduced by path **13** are eliminated from the output thereof by a filter **14** comprising the helically wound conductors **15** and **16** surrounded and supported by a lossy jacket **17**. If the distance between source **11** and load **12** is great, more than one filter is used. In practice a filter is placed at regular intervals of from 50 to 100 feet. For the purposes of illustration only one filter is shown between the source and load.

Fig. 2 shows in detail the construction of the filter embodying the principles of the invention. The inner member **15** comprises a conductor wound as a helix having a uniform pitch and an internal diameter *d* equal to the inside diameter of cylindrical guide **13**. Conductor **15** may be solid or stranded and may comprise a base metal such as iron or steel plated by a highly conductive material such as copper or silver. Adjacent turns **19** and **20** of the helix are electrically insulated from each other by either leaving a small air gap **21** between adjacent turns when bare wire is used, or by using enameled or plastic insulated wire. Conductor **15** may, for example, be a number 37 size, enameled or plastic insulated solid copper wire (0.005 inch overall diameter). By close winding the helix, a uniform and appropriate spacing between successive turns is provided by the insulation. The pitch angle of the helix, should be as small as possible consistent with the above-mentioned insulating requirement. This distance in any event must be less than one-quarter wavelength and is preferably such that the gap **21** between adjacent turns is less than the diameter of conductor **15**.

The outer member **16** comprises a second conductor wound in a substantially helical form of varying pitch. Helix **16** is wound directly over, but insulated from, the inner helix **15**, starting at one end as a close wound helix and extending towards the other end of the filter, the space between successive turns increasing with each successive turn until the space therebetween is greater than one-half wavelength of the lowest frequency to be transmitted. The longitudinal extent of helix **16** is represented in Fig. 2 as *e*, and is between one-half to one beat wavelength, a beat wavelength being defined as

$$\gamma_b = \frac{\lambda_2 \lambda_1}{\lambda_2 - \lambda_1}$$

where λ_1 is the wavelength of the exciting mode and λ_2 is the wavelength of an induced spurious mode. For example, λ_1 could be the wavelength in the filter of the TM_{11} mode and λ_2 could be the wavelength in the filter of the TE_{12} mode. Calculations must be made of all possible combinations of exciting and induced modes to assure that the proper helix length is obtained. However, experience will generally indicate to one skilled in the art which of the spurious modes are of importance and which are not, thus the number of calculations are generally very small. In a typical 2-inch diameter transmission system, the length of helix **16** will be about one foot.

Conductor **16** may be in all physical respects similar to conductor **15** except that it has a larger diameter. A typical wire diameter for **16** would be approximately four times the diameter of **15**.

If the system is limited to transmissions in only one direction, it is only necessary to have a tapered helical member at the input end of the filter. If, however, wave energy is to be transmitted in both directions, a second tapered helix **18** is placed on the other end of the filter. Unless considerations dictate otherwise, helix **18** will be identical to helix **16**.

The space between adjacent turns of helix **15**, **16** and **18**, are exposed to electrically dissipative or lossy material. This may be done by enclosing the helices in a cylinder-like casing **17** of material having a high electrical loss. Casing **17** may be made of any suitable plastic or dielectric material, such as polyethylene, in which small particles **23** of resistive material, such as iron dust or carbon black, are suspended. It is not desirable that the material of casing **17** extend into the space between adjacent helix turns and therefore casing **17** preferably has a smooth internal surface of diameter substantially equal to the outside diameter of helices **16** and **18** where they extend over helix **15** and the outside diameter of helix **15** over the region between **16** and **18**. Casing **17** also serves as a protective and supporting structure for the filter and may therefore be either semi-rigid, forming a more or less permanent structure, or pliable, forming a flexible one.

Casing **17** may then be covered with a non-corrosive conductive shield **22** which serves to protect the line from outside mechanical influences such as weather, moisture and insects and from electrical influences such as stray radiation from adjacent transmission lines. It is desirable that the cross-section of helix **15** be maintained as nearly circular as possible. This condition may be maintained by the resilience of casings **17** and **22**. It may, however, be maintained by employing for the conductor of helix **15** a spiral of spring steel plated by a highly conductive material. Thus, the effect of the spring itself will maintain the desired circularity and shield **22** may then be wound of overlapping, thin strips or may be made of a woven braid. Other means of constructing the helical filter are disclosed in a copending application by Kohman et al., Serial No. 679,835, filed August 23, 1957.

The inside diameter d of helix **15** is equal to the diameter of the solid wall circular guide **13** transmitting waves of the same frequency. This diameter d must be greater than the critical or cut-off diameter for the TE_{01} mode in the circular guide. This cut-off diameter is equal to $1.22\lambda_0$, where λ_0 is the wavelength in free space of the longest wave in the transmission band. In practice, d might be in the range 1.25 to 10 times the cut-off diameter, depending on the transmission loss desired.

In operation, the circular electric TE_{01} wave being transmitted along guide **13** will be excited within helix **15** as it enters the filter section. A major component of the circular current associated with this mode is conducted along the helical path by each turn. Since the pitch of the helix is small, this component constitutes substantially the entire current of the wave. A very small component of the wave is presented with a small reactance caused by the discontinuity between adjacent turns. This reactance will have the effect of changing the phase velocity of the total wave very slightly. Very little of the total TE_{01} current will pass through the resistive material of casing **17** and therefore the attenuation constant of the TE_{01} mode is changed very little and the filter will not affect the latter to any substantial degree.

With respect to the TM_{11} mode however, the picture is quite different. The TM_{11} mode has a predominantly longitudinal current flow along the walls of the wave-guiding path and will, as a consequence, be seriously affected by any discontinuities between adjacent turns of helix **15**. By forcing the longitudinally flowing currents to pass through the dissipative material of casing **17** exposed between successive turns of the helices, the effective attenuation constant of the wave-guiding path to the TM_{11} mode energy will be greatly increased. While this is the purpose of the filter section, unless this increase is brought about gradually, the TM_{11} mode will degenerate into other spurious modes having smaller longitudinal current components. Since the attenuation per unit length is directly related to the strength of the longitudinal component of current, these spurious modes would not be as effectively attenuated in a helical filter and consequently a longer filter section would be required.

The extent of exposure of the longitudinal currents to the dissipative material, and hence the attenuation, is a function of the ratio of the spacing between turns to the diameter of the wire, and for a fixed spacing such ratio is inversely related to the wire diameter. Larger wires present greater turn-to-turn capacitance and effectively shield the inner region from the outer region. It is for this reason that helix **16**, used to couple the non-circular modes to the mode filter is made of larger size wire. By close winding the larger diameter wire over the end of the filter, the exposure of the casing **17** to the longitudinal currents is initially very small. As the pitch of helix **16** opens up, more and more of the lossy jacket is exposed until the second helix is discontinued, at which time, the dissipative effect of the lossy jacket is a maximum. The effect of helix **16** might be likened to an aperture which is slowly opened, allowing more and more of the dissipating effect of the resistive casing to become effective. By extending the aperture opening over a length equal to from one-half to one beat wavelength, moding is reduced to a tolerable level within a reasonably short distance.

An alternative embodiment of the present invention uses a resistance film in between the lossy jacket and the helical waveguide instead of a tapered helix. The resistance film acts as a shunt impedance to the surface impedance of the lossy jacket. By varying the resistivity of the film, any prescribed distribution of surface resistance may be realized. Thus, the transition from the high isotropic conductivity of the copper wall to the low and anisotropic conductivity of the helix and lossy jacket structure may be made either gradually or in steps to reduce spurious mode conversion in the filter.

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. A selective mode filter for the preferential transmission of circular electric wave energy comprising a first means for propagating circular electric and non-circular electric modes of wave energy, said first means having a first and a second attenuation constant for said modes respectively, second means coupled to said first means for propagating said circular electric and said non-circular electric mode wave energy, said second means having a third and a fourth attenuation constant for said modes respectively, and third means coupled to said first and said second means to vary gradually the attenuation constant for said non-circular electric mode wave energy between said second and said fourth attenuation constants, said first and said third attenuation constants being substantially equal.

2. Means for selectively attenuating high frequency non-circular electric mode wave energy comprising a first elongated member of conducting material wound in a substantially helical form having equally spaced turns, a second member of conducting material wound over a longitudinal region of said first member in a substantially helical form having progressively increasing spaces between successive turns, and a casing of dissipative material surrounding said helices.

3. The combination according to claim 2 wherein the diameter of said second conducting material is approximately four times the diameter of said first conducting material.

4. The combination according to claim 2 wherein said second helix extends longitudinally along said first helix from between one-half to one beat wavelength where a beat wavelength λ_b is defined as

$$\gamma_b = \frac{\lambda_2 \lambda_1}{\lambda_2 - \lambda_1}$$

λ_1 being the wavelength in the attenuator of an incident non-circular electric mode and λ_2 being the wavelength in the attenuator of a spuriously generated mode.

5. The combination according to claim 2 wherein the maximum distance between successive turns of said second helix is approximately one-half wavelength of the lowest non-circular mode to be applied to said attenuator.

6. A high frequency electromagnetic wave mode filter comprising a first helix of insulated closely spaced turns for the propagation therethrough of circular electric wave energy, second and third helical members conductively insulated from each other and from said first helix having non-uniform spacing between turns thereof wound directly over said first helix each of said members extending longitudinally from an end to a region towards the center of said first helix being close wound at said ends and having a progressively increasing pitch, said members terminating when the space between successive turns has increased to approximately one-half wavelength of the lowest frequency non-circular electric mode to be filtered therein, and a high loss outer jacket surrounding said helices.

7. The combination according to claim 1 wherein said third means comprises an elongated member of conducting material wound over a longitudinal region of said second propagating means in a substantially helical form having progressively increasing spaces between successive turns, and a casing of dissipative material surrounding said helix.

8. In an electromagnetic wave transmission system propagating circular electric and non-circular electric

mode wave energy, a selective mode filter for the preferential transmission of said circular electric wave energy comprising an elongated member of conducting material wound in a substantially helical form having equally spaced turns, said helix having a first and a second attenuation constant for said circular and said non-circular electric mode wave energy, respectively, a second transmission path having third and fourth attenuation constants, respectively, for said circular and said non-circular electric mode wave energy comprising a conductively bounded circular cylindrical pipe, and means coupled to said helix and to said pipe to vary gradually the attenuation constant for said non-circular electric mode wave energy between said second and said fourth attenuation constants, said first and said third attenuation constants being substantially equal.

9. An electromagnetic wave transmission system adapted for propagating circular electric and non-circular electric mode wave energy comprising a section of solid conductive pipe connected at one point to a transmission medium comprising an elongated member of conducting material wound in the form of a helix, said pipe and said helix having low attenuation constants for both of said modes, means for introducing a region of high attenuation constant to said non-circular mode energy comprising a jacket of electrically dissipative material surrounding said helix, and transforming means in a region surrounding said helix adjacent said one point for gradually exposing said non-circular mode to said dissipative material thereby gradually increasing the attenuation constant presented to said non-circular modes from said low attenuation constant to said high attenuation constant.

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