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ELECTROMAGNETIC WAVE TRANSMISSION

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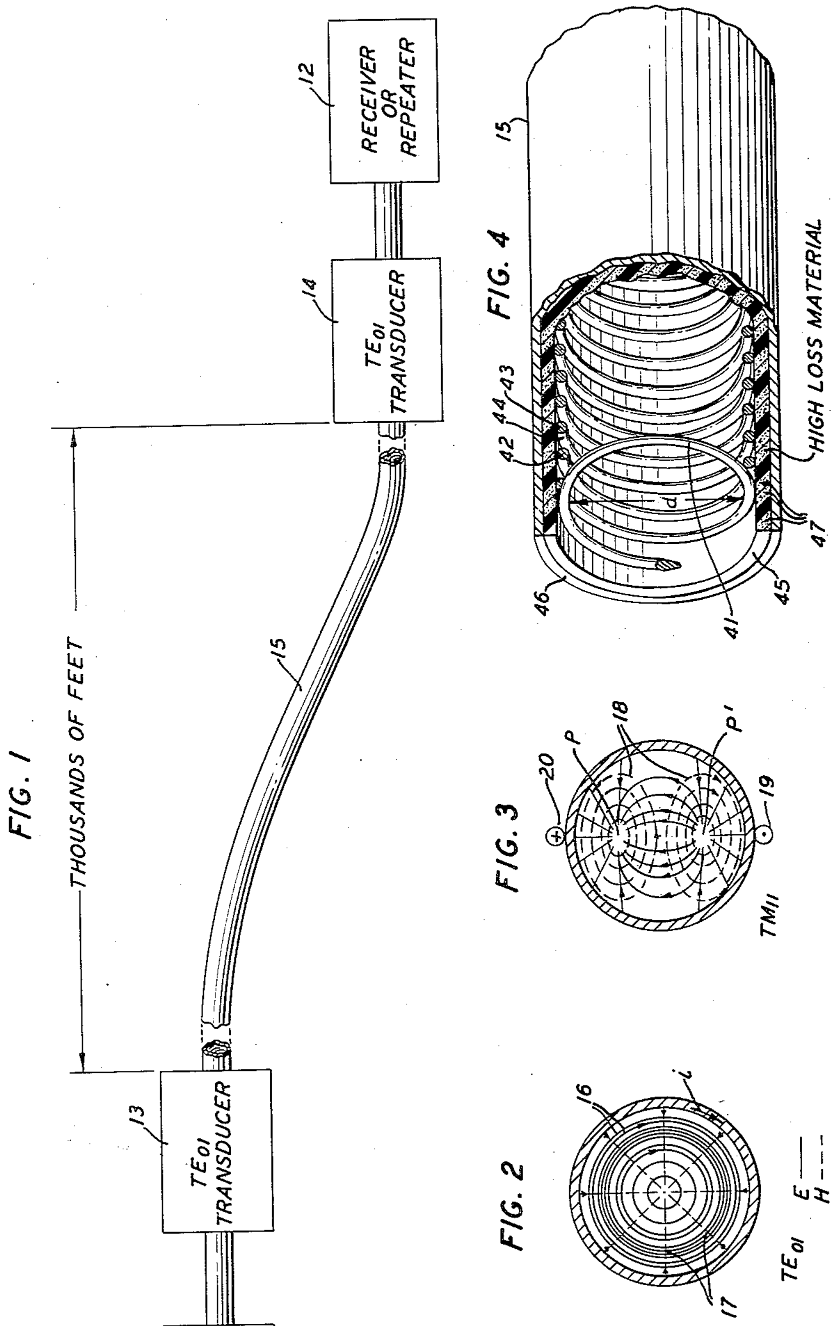

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FIG. 5

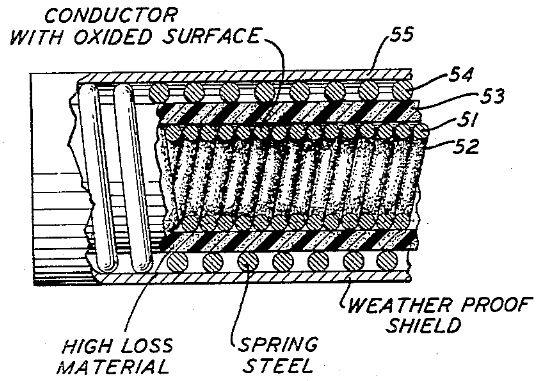


FIG. 6

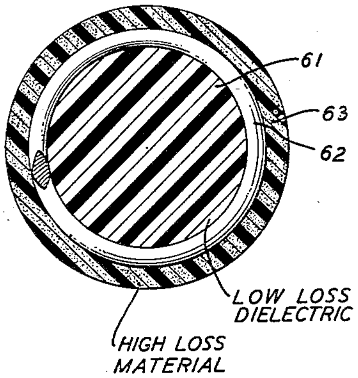
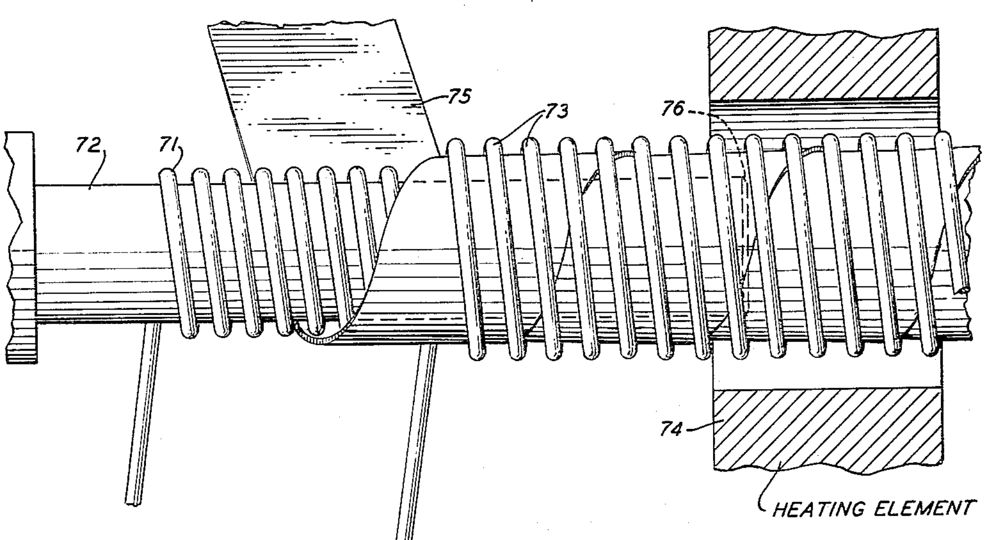


FIG. 7



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ELECTROMAGNETIC WAVE TRANSMISSION

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Application March 15, 1954, Serial No. 416,316

1 Claim. (Cl. 333—95)

This invention relates to electromagnetic wave transmission systems, and more particularly, to the transmission of the circular electric or TE_{01} mode of wave propagation over long distances in a guided wave transmission system which either through choice or inherency does not follow a perfectly straight path.

The propagation of microwave energy in the form of TE_{01} waves in circular wave guides is ideally suited for the long distance transmission of wide band signals since the attenuation characteristic of this transmission mode, unlike that of all other modes, decreases with increasing frequency. However, one difficulty with this method of transmission is that the TE_{01} mode is not the dominant mode supported in a circular wave guide, and consequently energy may be lost to other modes also capable of transmission therein. In an ideal wave guide 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 wave-guide 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} and other transmission 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 at the same phase velocity of propagation, the prior art has provided a large number of devices for negotiating bends or turns in the guides. Thus, the phase velocity of the TM_{11} mode (which is normally equal to that of the TE_{01} mode) is changed relative to that of the TE_{01} mode, to increase the relative differences in their propagation constants and to reduce the effective coupling therebetween.

Of the several prior art devices operating according to this principle, one of the most satisfactory is described as a spaced ring line. It comprises a plurality of conductive ring-shaped sections, coaxially arranged, and successively spaced from each other at a uniform distance by insulating material. As will be considered in more detail hereinafter, the desired circular electric TE_{01} mode produces circumferential currents which are not appreciably interfered with by the ring structure. The undesired modes produce predominantly longitudinal currents which are seriously affected by the division of the guide into the short cylindrical sections and therefore these modes are given velocities of propagation different from the TE_{01} mode. While this structure is very satisfactory for a short section of line and may be used at a specifically contemplated bend, it is too expensive and too difficult to fabricate as a long section to be used as the transmission line itself and thus to include within its length all bends that cannot be anticipated.

It is therefore an object of the present invention to

transmit circular electric mode wave energy over long distances without its degenerating into other modes.

It is a further object of the invention to provide a circular electric wave mode transmission medium which may be economically fabricated in long lengths.

In the copending application of J. R. Pierce, Serial No. 416,315, filed March 15, 1954, 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 these modes, and is in addition, a structure that is easily and economically wound in sections of arbitrarily long lengths. In accordance with the present invention, 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. It will be shown that if the difference between the attenuation constants is large, the coupling between the TE_{01} and TM_{11} modes may be made arbitrarily small, resulting in a minimum of degeneration of the TE_{01} mode, without however, any substantial amount of energy being actually lost in the dissipative material.

In the specific illustrative embodiments of the invention to be described in detail hereinafter the dissipative material comprises a cylinder-like casing 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 material, giving to the wave a large attenuation constant while the component of the circumferential currents of the TE_{01} mode which follows the helix conductor is unaffected.

Features of the invention reside in the particular physical arrangements of these components and in the manner of assembly thereof.

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

In the drawings:

Fig. 1 diagrammatically illustrates a guided microwave communication system employing the circular electric wave and having a long distance transmission line of the type provided by the present invention;

Figs. 2 and 3 illustrate the transverse electric and magnetic field patterns of the TE_{01} and TM_{11} waves, respectively;

Fig. 4, partially in cross section, illustrates the construction of a small section of transmission line in accordance with the present invention;

Figs. 5 and 6 are cross-sectional views showing first and second alternative constructions of sections of transmission line in accordance with the invention; and

Fig. 7 shows the structure and also one method of assembling the structure of another alternative embodiment of the invention.

Referring more specifically to Fig. 1, a long distance guided microwave communication system is schematically shown. The system is characterized as long to distinguish it from the short distances found in terminal equipment and to define a system in which the factor of transmission attenuation becomes relatively important. The length of such a system would be measured in terms of thousands of feet and perhaps miles as opposed to several inches or a few feet in the terminal equipment. This system comprises a terminal station **11** which may be a transmitter, or if this is an intermediate station, a repeater **11** which is to be connected to a receiver or subsequent repeater comprising station **12**. The circular electric TE_{01} mode is the mode in which energy is transmitted between stations and since this mode is not usually produced or utilized directly in the components of a station, transducers **13** and **14** are interposed between stations **11** and **12** and the long distance transmission line **15**. Transducers **13** and **14** may be of any suitable well known types for converting TE_{01} wave energy to and from a dominant wave mode configuration. For example, they may be structures of the types disclosed in United States Patent 2,656,513 granted to A. P. King, October 20, 1953, or of the copending applications of S. E. Miller, Serial No. 245,210, filed September 5, 1951, which on May 29, 1956, issued as United States Patent 2,748,350, and S. E. Miller, Serial No. 357,665, filed May 27, 1953.

Line **15** is not completely straight along its entire length since in practical installation it is substantially impossible to maintain the line along a precisely straight path over a long distance. Intentional bends may also be included in order that the line may follow right of ways or turn corners. It is these bends that produce the characteristic moding or degeneration of the TE_{01} into TM_{11} wave power. As noted above, this moding is ascribed to the fact that these waves have substantially the same phase constants, i. e., phase velocity and wavelength and, therefore, interact strongly in a manner analogous to coupled transmission lines.

Fig. 2 illustrates the distribution of the electric and magnetic fields in a transverse section of a circular conductive wave guide supporting the TE_{01} transmission mode. This wave is designated the circular electric type inasmuch as the electric field, shown by the solid lines **16**, consists of circular lines coaxial with the guide and lying transversely thereto without any longitudinal components. The transverse component of the magnetic field, indicated by the dotted lines **17**, forms at various points along the guide in a radial pattern. The electric field intensity attains a maximum approximately half way between the axis and surface of the guide and drops to zero at the surface. The current flow associated with the TE_{01} wave is predominantly circular around the periphery of the guide as illustrated in Fig. 2.

The configuration of the transverse TM_{11} mode is shown in Fig. 3 and is similar to that of a shielded conductor pair. The magnetic field pattern is entirely transverse without any longitudinal components and is indicated by the dotted lines **18** encircling the respective poles P and P'. Since the magnetic lines must form closed paths, they tend to spread out near the center of the guide and to crown close together at the inner surface mostly near the axis passing through poles P and P', thus inducing a considerable longitudinal conduction of current in the wall of the guide. The direction of this current flow is shown conventionally by the symbols **19** and **20** on Fig. 3.

Fig. 4 shows in detail a short section of the transmission line **15** of Fig. 1. Thus line **15** comprises a conductor **41** wound in a helix having an internal diameter *d*. Conductor **41** 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 such as **42** or **43** of the helix are electrically insulated from each other, and this may be provided by a small air gap such as **44**. The pitch distance of the helix, i. e., the distance between the center of turns **42** and **43**, 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 **44** between adjacent turns is less than the diameter of conductor **41**.

The space between adjacent turns of helix **41**, i. e., gap **44**, is exposed to electrically dissipative or lossy material. This may be done by enclosing helix **41** in a cylinder-like casing **45** of material having a high electrical loss. Casing **45** may be made of any suitable plastic or dielectric material, such as polyethylene, in which small particles **47** of resistive material, such as iron dust or carbon black, are suspended. It is not desirable that the material of casing **45** extend into the space between adjacent helix turns and therefore casing **45** preferably has a smooth internal surface of diameter substantially equal to the outside diameter of helix **41**. Casing **45** also serves as a protective and supporting structure for helix **41** and may therefore be either semi-rigid, forming a more or less permanent structure, or pliable, forming a flexible one.

Casing **45** may then be covered with a non-corrosive conductive shield **46** 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 **41** be maintained as nearly circular as possible. This condition may be maintained by the resilience of casings **45** and **46**. It may, however, be maintained by employing for the conductor of helix **41** 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 **46** may be wound of overlapping, thin strips or may be made of a woven braid.

The inside diameter *d* of helix **41** is related to the diameter of the circular pipe guide which would transmit waves of the same frequency. Thus the diameter *d* must be greater than the critical or cut-off diameter for the TE_{01} mode in a 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 having the field pattern of Fig. 2 is excited within helix **41**. A major component of the circular current *i* of the wave 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 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 **45** and therefore the attenuation constant of the TE_{01} wave is changed very little.

The TM_{11} mode, however, has a predominantly longitudinal current flow along the wave-guiding path and will be seriously affected by the discontinuity between adjacent turns of helix **41**. Not only is the phase constant of this mode increased by the reactance of each discontinuity, but the longitudinal currents are forced to flow through the dissipative material of casing **45**. It may be shown that the amount of degeneration of the TE_{01} mode into the TM_{11} mode along a bent section of waveguide is proportional to the coefficient of coupling between these two modes along such bend and may be expressed as

$$C=\frac{1.16r}{R\lambda_0}$$

in which *r* is the radius of the circular wave-guiding path, λ_0 is the free space wavelength of the wave energy, and R is the radius of the bend. While this expression is derived with the assumption that the pitch angle of the helix is zero, experimental data indicates that the behavior of an actual helix of the type described does not depart substantially from results predicted by this expression.

The loss to the TE_{01} wave in a bend is governed by the ratio

$$\frac{a_{01}-a_{11}}{C}$$

in which a_{01} and a_{11} are the attenuation constants for the TE_{01} and TM_{11} modes, respectively. More specifically, it may be shown by starting with the expression derived as Equation 22 in applicant's paper "Notes on methods of transmitting the circular electric wave around bends" in the Proceedings of the I. R. E., volume 40, September 1952, pages 1104 through 1113 and making the assumption that

$$\frac{a_{11}-a_{01}}{2C}$$

is much greater than unity, that the attenuation coefficient for the TE_{01} wave in a bend is equal to

$$a_{01}+\frac{C^2}{a_{11}-a_{01}}$$

Thus it is seen that the quantity $a_{11}-a_{01}$ is made large by increasing the factor a_{11} much more than the factor a_{01}, the amount of degeneration and loss for TE_{01} may be made arbitrarily small. Therefore the loss of casing **45** should be intentionally made as large as possible.

As indicated hereinbefore it is desirable that adjacent turns of the helix be as close together as consistent with the requirement that they be insulated from each other. A novel embodiment of the invention is shown in Fig. 5 by which both of these requirements are met. Thus in Fig. 5 helix **51** is illustrated as being wound of a conducting material of the type that forms a high resistance oxide coating upon the surfaces thereof exposed to air, such as aluminum. Thus an oxide coating **52** forms upon helix **51** which provides a uniform insulating separation between adjacent turns. A principal advantage of this structure is that if the transmission line is damaged in any way, i. e., by too sharp a bend or by prolonged friction between the helix turns, the oxide insulating layer will be self healing. Furthermore, the necessary spacing between turns may be made very small. Lossy casing **53** of the type already described is laid over helix **51**. Since materials such as aluminum have little resilience, a helix **54** of spring steel may be wound over casing **53** to maintain the circularity of helix **51**. An outer weather proof casing **55** may then form the outside shield.

In Fig. 6 another embodiment of the invention is shown that is suitable for application where unusual mechanical strength is required of the transmission line, such as in an underground or underwater application. Thus the line comprises a solid core **61** of low loss dielectric material. Core **61** may be extruded from a semi-flexible material such as polyethylene. Helix **62** is wound directly upon core **61**. A high loss casing **63**, in accordance with the invention is applied over helix **62**.

In Fig. 7 a novel method and apparatus for assembling a transmission line is shown in diagrammatic form. Thus the conductive helix **71** is wound upon a suitably held mandrel **72** of diameter equal to the required internal diameter of the helix. Over this is spirally wound a

tape or ribbon **75** of the lossy, resistive material suspended in a binder of thermal setting plastic such as Minnesota Mining and Manufacturing Company type EC–880. Over this is wound the supporting spring **73** or protective casing or both as a particular application may require. As this assembled combination is slipped or drawn from the free end **76** of mandrel **72**, it is passed through an oven or near a heating element **74**, which causes successive turns of ribbon **75** to melt, fuse or blend together to form a substantially unitary cylindrical casing. Alternatively, a ribbon of lossy, resistive material may be coated on one or both sides by a thermal bonding adhesive before it is wound. Upon heating, the adhesive binds all of the assembled components together.

It should be noted that while the conductive and supporting helical members in the above described embodiments have been illustrated as having substantially circular cross-sections certain advantages have been found to making these members of elongated materials of rectangular cross section. In particular the helix should be wound with the wide dimension of the rectangular cross section extending parallel to the axis of the helix. This provides a maximum of longitudinal coverage along the helix with a minimum of the material being used.

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:

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, transmission means connecting said utilizing means to said producing means comprising an elongated member of conductive material wound in a substantially helical form and a jacket of electrically dissipative material surrounding said conductive material, said helix having a diameter greater than one wavelength of said wave energy, said helix having adjacent turns thereof electrically insulated from each other to expose all longitudinal current components to said electrically dissipative material at least once every quarter wavelength of high frequency wave energy propagated along said transmission means and spaced substantially less than one quarter wavelength to expose circumferential current components of said circular electric mode to said dissipative material to a substantially smaller degree than the exposure of said longitudinal current components.

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