United States Patent

[11] 3,601,720

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[33] **Japan**
[31] **42/52543**

[54] HELICAL WAVEGUIDE WITH VARIED WALL IMPEDANCE ZONES

9 Claims, 12 Drawing Figs.

[52] **U.S. Cl.** ..... **333/95,** 333/83 A, 333/98 M
[51] **Int. Cl.** **H01p 3/12,** H01p 1/16
[50] **Field of Search** ..... 333/95, 95 A, 95 S

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Primary Examiner—Herman Karl Saalbach
Assistant Examiner—Saxfield Chatmon, Jr.
Attorney—Carothers & Carothers

ABSTRACT: Manufacturing methods of the helical waveguide that the wall impedance of the wall structure of the waveguide is alternated discontinuously or continuously in the direction of the axis of the helix by means that jacket or tape of insulating or lossy material having diverse dielectric constants, or roving of lossy material is located on the helix of the waveguide to make the wall structure having the alternated wall impedance and their products.

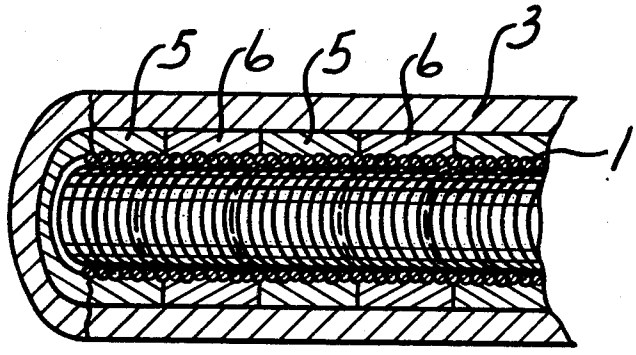


Fig. 1

PRIOR ART

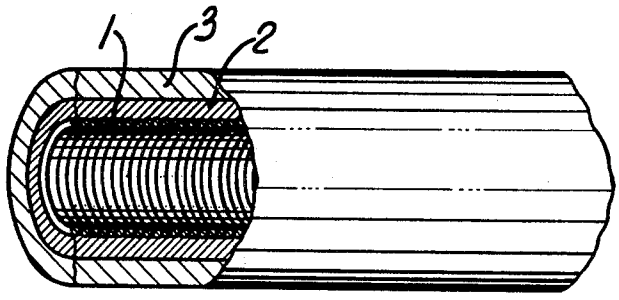
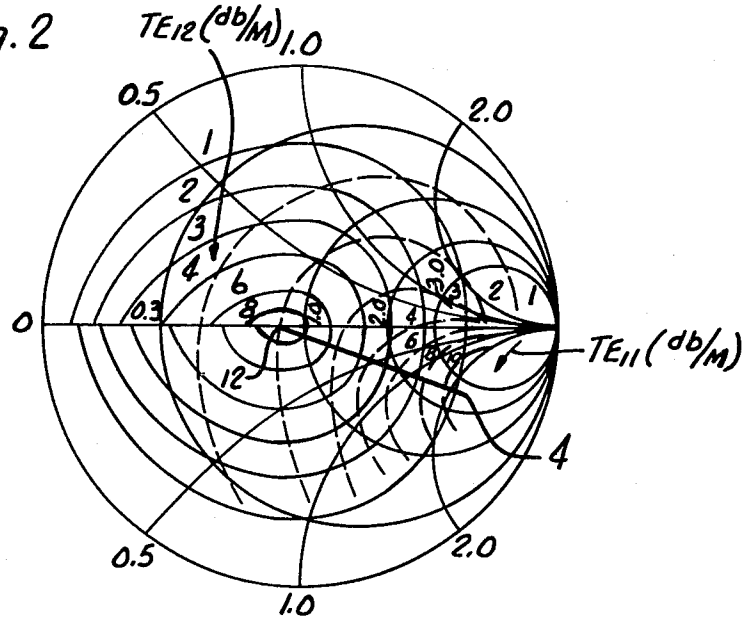


Fig. 2



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Fig. 3

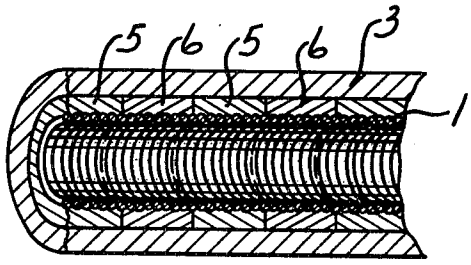


Fig. 4

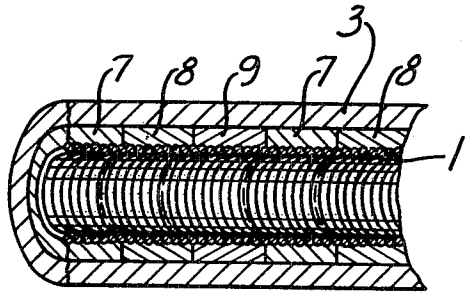
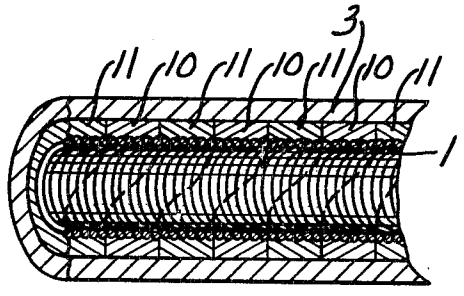


Fig. 5



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Fig. 6a

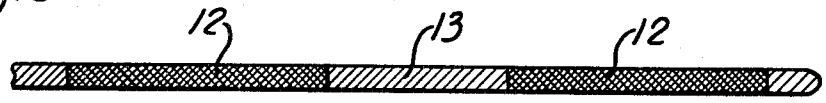


Fig. 6b

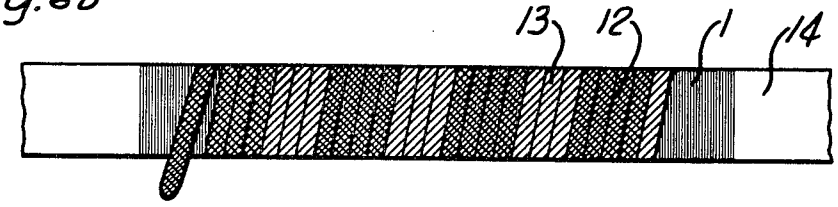


Fig. 7a

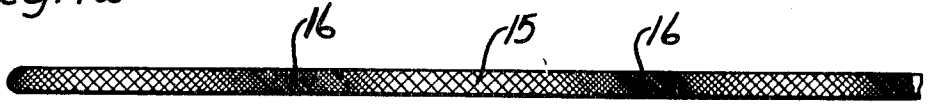
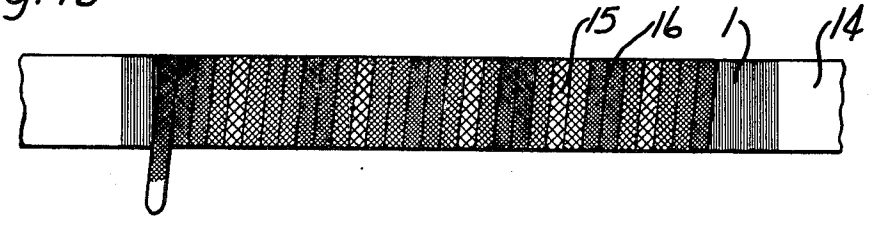


Fig. 7b



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Fig. 8

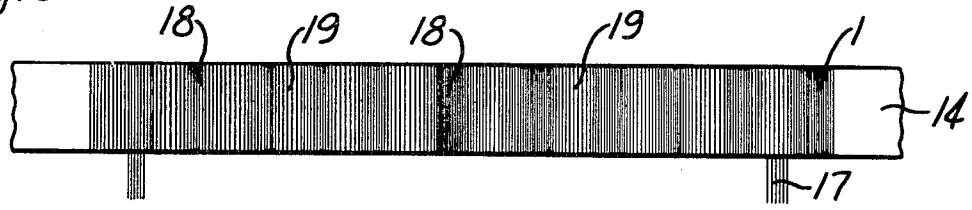


Fig. 9

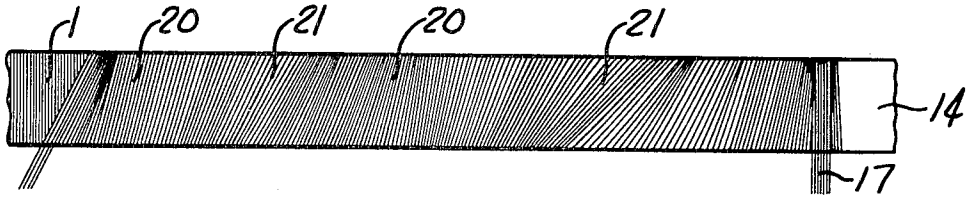
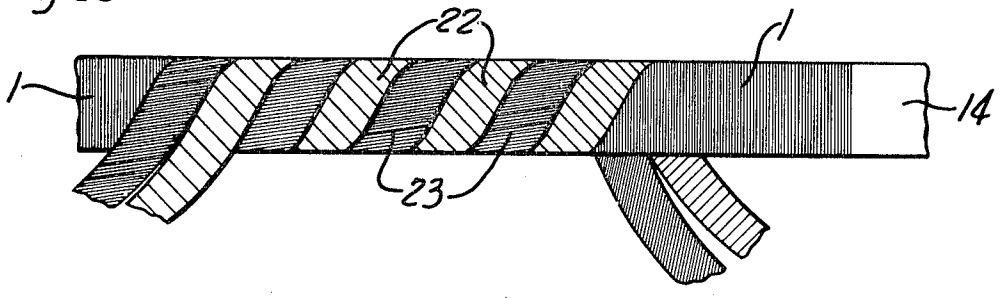


Fig. 10



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Fig. 11

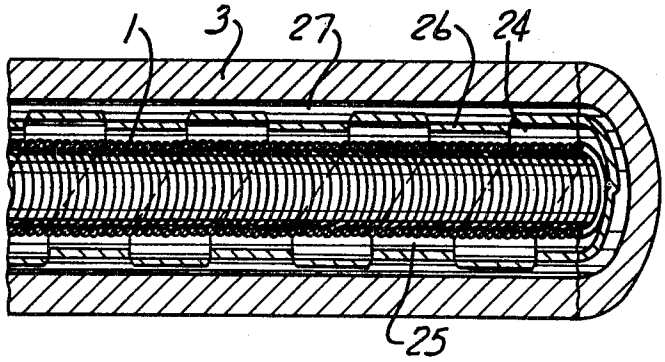
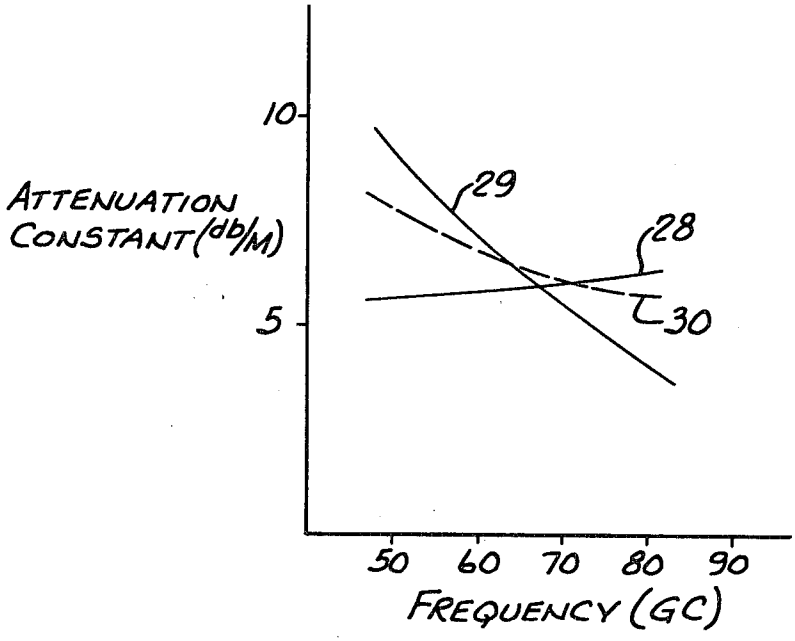


Fig. 12



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HELICAL WAVEGUIDE WITH VARIED WALL IMPEDANCE ZONES

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a device for the long-distance transmission of electromagnetic wave energy, particularly millimeter wave energy.

2. Description of the Prior Art

A helical waveguide is known as the best transmission line for the TE_{01} wave mode transmission of millimeter wave energy. A helical waveguide of the prior art is shown in FIG. 1, which has a construction wherein a thin insulated copper wire 1 is helically wound to make an inner surface of the waveguide, said helical wire being surrounded by a jacket 2 of a uniform thickness, usually comprising two layers, one of which is an impedance-transforming layer and the other a lossy layer placed thereon, said jacket 2 being further covered by a protective jacket 3 such as an iron pipe. In place of the helically wound wire, conductor rings sufficiently thin for the wavelength may be placed side-by-side to form the inner wall of the waveguide. The electric conductivity of the inner surface of such a helical waveguide is anisotropic. That is to say, the resistivity in the circumferential direction of the helix 1 is small, but the resistivity in the axial direction is infinitely large.

A helical waveguide has a property that a TE_{01} mode which has circular electric component, propagates almost without suffering any attenuation, while, on the contrary, the mode waves which have the electric current component in the axial direction are absorbed and greatly attenuated.

For instance, an attenuation of the TE_{01} mode is approximately 1.3–1.4 db./km. as proved by experiment, for a helical waveguide of 51-mm. inner diameter at 50 GC.

Generally speaking, if the inner surface of a helical waveguide is perfectly round and geometrically straight in the direction of the axis, spurious modes will not appear due to mode conversion and there takes place only the attenuation of an exponential function of axial distance due to the heat loss, when the TE_{01} mode is applied to said helical wire waveguide.

In the instance where the inside of the helical waveguide has some irregularity or deformation, however, the TE_{01} mode degenerates into other spurious modes and a mode conversion loss takes place. The modes degenerated from the TE_{01} mode are dependent on the irregularity or deformation.

TE*on* (here *n* is a positive integer) modes are caused by the variations in the inner diameter of waveguide, while TX*in* (here X is E or M, *n* is a positive integer) modes, such as TM_{11}, TM_{12} ..... TE_{11}, TE_{12} ..... are caused by the bending of the axis.

Among these spurious modes, the TE_{11} and TE_{12} modes deteriorate, particularly the transmission characteristics therein of the TE_{01} mode. The TE_{12} mode couples strongly with the TE_{01} mode and is extremely difficult to remove.

It is well known that the jacket 2 shown in FIG. 1 contributes effectively to the absorption of these unwanted modes as much as possible.

The Smith chart of wall admittance of the helical waveguide as shown in FIG. 1 is shown in FIG. 2.

The central point of this chart is normalized by the wall admittance viewed radially from the inside of waveguide, for example $4/\sqrt{3}Yo$ (Yo: free space admittance) where the jacket 2 on the helix 1 is made of insulating material having dielectric constant of 4 and the frequency of the transmission wave is 55.5 GC.

On this admittance chart, two groups of lines of equal transmission losses are drawn, one group of solid lines being for the TE_{12} mode and the other group of dotted lines for the TE_{11} mode. It is noted from this chart that any one point on this chart which represents a wall admittance of the helical waveguide corresponds to two transmission losses for the TE_{12} mode and the TE_{11} mode shown by two groups of lines.

When a wall admittance is determined to give a greater transmission loss for TE_{12}, the transmission loss for TE_{11} cannot be taken freely.

The thick line 4 in this chart denotes a trajectory of wall admittance which should be selected to take both transmission losses of the TE_{12} and TE_{11} modes greater values at the same time. It follows from this that the transmission loss of the TE_{11} mode is restricted by the transmission loss of the TE_{12} mode.

It is necessary to take both transmission losses of the TE_{12} and the TE_{11} as great as possible in order to suppress the signal distortion due to the spurious modes.

This is the essential shortcoming of the helical waveguide of the prior art as shown in FIG. 1.

BRIEF EXPLANATION OF DRAWINGS

FIG. 1 is a cross-sectional view of a helical waveguide of the prior art.

FIG. 2 is a Smith chart of the wall admittance of a helical waveguide showing two groups of lines of equal attenuation constants of the TE_{11} and TE_{12} modes.

FIGS. 3—5, and 11 are cross-sectional views in side elevation of the helical waveguides constructed in accordance with the present invention.

FIG. 6*b*, FIG. 7*b* FIG. 8, FIG. 9 and FIG. 10 are perceptional views to explain the manufacturing method of the embodiments of the present invention.

FIG. 12 is a graph of the frequency characteristic curves of the attenuation constant of the TE_{12} mode wave.

DESCRIPTION OF PREFERRED EMBODIMENTS

The present invention provides a new improved helical waveguide which is free from the shortcomings of prior art. The undesirable interrelationship between the attenuations of the TE_{12} and TE_{11} modes can be broken by the present invention. The present invention provides helical waveguides in which the wall impedance is alternated continuously or discontinuously in the direction of the axis of the helix, for example, by means such that jackets of insulating materials having diverse dielectric constants respectively are located alternately on the helix of the waveguide in the axial direction. Referring to FIG. 3, a cross-sectional view of a helical wave guide is shown as an illustrative embodiment of the present invention.

This waveguide comprises an insulated conductive wire 1 of a relatively fine diameter closely wound in a helix, with two kinds of jackets 5 and 6 of insulating materials having different dielectric constant from each other alternately surrounding the helix 1 and the outer protective jacket 3 further surrounding the jackets 5 and 6.

In the embodiment as shown in FIG. 3, it is made possible by the present invention to design the jackets 5 and 6 to have greater transmission losses for the TE_{12} and TE_{11} modes than those of a conventional helical waveguide having a uniform wall impedance. For example, when the wall admittance of the jacket 5 is selected to give 10 db./m. and 2 db./m. of the transmission losses for the TE_{12} and TE_{11} respectively, those of the jacket 6 are 0.5 db./m. and 20 db./m. for the TE_{12} and TE_{11} respectively, and the lengths in the axial direction of jacket 5 and 6 are taken as 5 cm. and 10 cm. with respect to each other, the transmission losses of this helical waveguide are approximately 7 db./m. for the TE_{12} mode and 8 db./m. for TE_{11} mode which is enhanced more than 5–6 db./m. as compared to the case where a loss of 2–3 db./m. of the TE_{11} could hardly be obtained by the undesirable interrelationship between the losses when the loss of the TE_{12} of a helical waveguide having a uniform wall impedance is selected as 7 db./m. or so.

A practical structure of this helical waveguide is as follows.

A copper 0.14 mm. diameter wire 1 coated with an enamel layer of 20μ thickness, is wound closely in a helix to form a circular inner surface of the waveguide of 5.1-cm. diameter. Jackets 5 and 6 are surrounded on this helix 1 repeatedly in an alternate sequence. Their lengths in the axial direction are 5 cm. and 10 cm. respectively. Jacket 5 is made of an insulating material layer of dielectric constant 4 and a thickness of 120μ, and the lossy layer has a specific resistance 2Ω-cm. of 0.4-mm. thickness placed over the insulating material layer.

This lossy layer is for example of a graphite fiber (acryl fiber carbonized at temperature near 800° C.).

The transmission losses at the jacket portion **5** are 10 db./m. for the TE_{12} and 2 db./m. for the TE_{11}.

Jacket **6** is made of a lossy layer of metallized fiber (cotton tape plated by copper) of 0.5-mm. thickness having the specific resistivity of 1.5Ω–cm.

The transmission losses at the jacket portion **6** are 0.5 db./m. for the TE_{12} mode and 20 db./m. for the TE_{11} mode.

The apparent transmission losses of the waveguide of such a structure become approximately 7 db./m. for the TE_{12} and 8 db./m. for the TE_{11}. This embodiment of the present invention has a wall structure making use of two kinds of jacket portions, but it is equally applicable to the embodiment of the present invention to make use of three or more kinds of jackets.

It is also applicable to the embodiment of the present invention to form the wall structure making use of tapes of two or more kinds of material having diverse dielectric constants wrapped in parallel over the helix.

It is further applicable to the embodiment of the present invention to form the wall structure making use of an electrically lossy roving wound closely and sparsely over the helix. An embodiment of the present invention which has the wall structure of three jackets is shown in FIG. **4**.

In FIG. **4**, **1** denotes a helical wire, **7**, **8** and **9** denote three jackets of insulating materials of different dielectric constants from each other having predetermined axial lengths respectively. **3** denotes an outer protective jacket.

Another embodiment of the present invention which has the wall structure of wrapped tapes is shown in FIG. **5**.

In FIG. **5**, **1** denotes a helical wire, **10** and **11** denote the two tapes of insulating materials of different dielectric constants from each other wound over the helix **1**, and **3** denotes an outer jacket.

A helical waveguide having the wall structure of jackets or tapes of different materials has an apparent transmission constant of an equivalent waveguide; for example, when two kinds of jackets or tapes are used, their wall impedances are *Za* and *Zb* respectively and their axial lengths are **1***a* and **1***b* longer than the wavelength of the transmission wave, the apparent transmission constant is approximately equal to the transmission constant of a waveguide which has a wall impedance represented by following formula:

$$Za1a+Zb1b/1a+1b$$

The design of a helical waveguide having a desirable transmission constant will be easily performed by means of selecting the insulating materials of the jackets to have the desirable wall impedances and the axial lengths of the jacket.

It is also possible to design a helical waveguide having a broad frequency band, for example, 30–100 GC, in such a manner that the wall structures are designed for several frequencies over a broad frequency band, for example 40, 60 and 80 GC, and these wall structures are located repeatedly and axially.

A brief explanation of a manufacturing method of the helical waveguides of the invention will be taken up in the following discussion. In FIG. **6***a*, a tape forming the wall structure of the helical waveguide is shown.

This tape has two different dielectric zones **12** and **13** alternately changed with a pitch distance longer than a number of circumferences or turns of the helix of the waveguide.

This tape is wrapped as shown in FIG. **6***b* over the helical wire **1** forming the inside wall of waveguide of an insulated enameled copper wire being wound closely on a smoothly polished mandrel **14** which will be subsequently removed.

The wrapped tape forms the wall structure having the two zones **12** and **13** of different wall impedance, which is made of several turns of tapes. After wrapping this tape, a glass fiber roving is wrapped spirally many times on the tape until the required thickness is built up.

Then this fabricated material is held in an iron pipe, the gases and moisture filled in the space between mandrel and iron pipe are evacuated, this space is filled by the thermosetting epoxide resin and the resin is set by heating.

Another embodiment of the present invention is shown in FIG. **7**. The tape shown in FIG. **7***a*, which has two different dielectric constant parts **15** and **16**, are varied continuously with a pitch distance sufficiently longer than a number of circumferences or turns of the helix of the waveguide and is wrapped helically and closely on the helix **1** formed upon the mandrel **14** to form a wall structure of the waveguide having varying wall admittance zones **15** and **16** as shown in FIG. **7***b*.

Still another embodiment of the present invention is shown in FIG. **8**.

In FIG. **8**, a lossy roving **17** is wound in turns closely and sparsely, alternately, around the helix **1** formed upon mandrel **14** to form the wall structure of the waveguide having varying wall admittance zones **18** and **19**.

Still another embodiment of the present invention is shown in FIG. **9**.

In FIG. **9**, lossy roving **17** is wound in a direction nearly vertical and in a direction slanting to the vertical direction, repeating these winding alternately over the helix **1** formed on the mandrel **14** to form the wall structure of the waveguide having varying wall admittance zones **20** and **21**.

Another embodiment of the present invention is shown in FIG. **10**. In FIG. **10**, two kinds of tapes **22** and **23** of insulating materials with different dielectric constants of sufficiently broader width than the wavelength of transmission wave, are wrapped in parallel with each other helically and closely over the helix **1** formed on the mandrel **14** to form the wall structure of the waveguide having different wall admittance zones **22** and **23**. The tapes used in the examples of FIG. **6** and **7** are prepared by making the tape of glass fiber conductive repeatedly in such a manner that it is immersed in an electroconductive material or by partially carbonizing a tape of acryl resin fiber. The roving used in the examples of FIG. **8** and **9** is prepared by making a roving of glass fiber conductive by coating it with graphite.

Another embodiment of the present invention is shown in FIG. **11**. In FIG. **11**, two kinds of tapes of insulating material of sufficiently broader width than the wavelength and of the different thickness, are wrapped helically in parallel and in close contact with each other on the helix **1** to form the wall structures having the different impedance-transforming layers **24** and **25**.

A lossy layer **26** is formed upon the layers **24** and **25**. Over the lossy layer **26**, a glass fiber roving is wrapped many times to get the required thickness of the glass fiber layer **27**. An armor **3**, for example an iron pipe surrounds the glass fiber layer **27**.

FIG. **12** shows the frequency characteristics of the attenuation constant of the TE_{12} mode wave of the helical waveguides as shown in FIG. **11**, and of the helical waveguide having a uniform transforming layer of the prior art.

In FIG. **12**, two solid lines **28** and **29** show the characteristic curves of a prior art helical waveguide and a dotted line **30** shows that of the helical waveguide as shown in FIG. **11** from the results of experiment.

One of the helical waveguide of the prior art used in this experiment showing the results of curve **28**, has an impedance-transforming layer of a uniform thickness of 50μ and consists of insulating material having a dielectric constant 4. Thereupon a lossy layer of 0.4-mm. thickness, made of the acryl resin fiber roving carbonized at the temperature near 800° C. and having a specific resistivity nearly 2 Ω-cm., was applied.

Attenuation constants of this helical waveguide are 5.5 db./m. for the TE_{12} mode and 3 db./m. for the TE_{11} mode at 50 GC and 6 db./m. for the TE_{12} mode and 1 db./m. for the TE_{11} mode at 80 GC.

Another waveguide of the prior art showing the curve **29** has an impedance-transforming layer of a uniform thickness of 150μ and consists of insulating material having a different dielectric constant, and thereupon the lossy layer of 0.4-mm. thickness made of the same material as in the former case was applied.

Attenuation constants of this latter helical waveguide are 9 db./m. for the TE_{12} mode and 1.5 db./m. for the TE_{11} at 50 GC and 4 db./m. for the TE_{12} and 1 db./m. for the TE_{11} at 80 GC.

The waveguide as shown in FIG. **11** showing the curve **30**, has two kinds of impedance-transforming layers of the different thicknesses 50μ and 150μ of same axial length 7 cm., located alternately, which is made of a same insulating material of the dielectric constant 4 and thereupon a lossy layer of the same material of the specific resistivity 2 Ω-cm.

It is noted from FIG. **12** that the attenuation characteristic curve of TE_{12} mode in accordance with the present invention lying between the curves **26** and **27** has good frequency characteristics.

It is possible to easily design helical waveguides having various attenuation characteristic curves lying between the curves **26** and **27**, according to the present invention.

We claim:

1. A helical waveguide comprising a conductive wire wound in a substantially helical form, a jacket over said helix which has a plurality of axially arranged zones, any two adjacent ones of which have different wall impedance values, said wall impedance values being substantially uniform over each of said zones, the axial length of each of said zones being large compared to the wavelength to be used.

2. A helical waveguide comprising a conductive wire wound in a substantially helical form, a jacket over said helix which has a plurality of axially arranged zones, any two adjacent ones of which have different wall impedance values, said jacket made of a plurality of tubes of insulating material, any two adjacent ones of which have different dielectric constants, the axial length of each of said tubes being sufficiently longer than the wavelength in use, and a lossy layer surrounding said tubes.

3. The helical waveguide of claim **1** wherein said helical conductor wire is insulated.

4. A helical waveguide comprising a conductive wire wound in a substantially helical form, a jacket over said helix which has a plurality of axially arranged zones, any two adjacent ones of which have different wall impedance values, the axial length of each of said zones being large compared to the wavelength to be used, said jacket consisting of a helical wound tape having different adjacent electrically dissipative zones therealong.

5. A helical waveguide comprising a conductive wire wound in a substantially helical form, a jacket over said helix which has a plurality of axially arranged zones, any two adjacent ones of which have different wall impedance values, the axial length of each of said zones being large compared to the wavelength to be used, said jacket consisting of a roving of electrically dissipative material helically and alternately wound densely and sparsely in adjacent longitudinal zones respectively on said helix to alternately provide said zones.

6. A helical waveguide comprising a conductive wire wound in a substantially helical form, a jacket over said helix which has a plurality of axially arranged zones, any two adjacent ones of which have different wall impedance values, the axial length of each of said zones being large compared to the wavelength to be used, said jacket consisting of an insulative tape helically wound on said helix and having a plurality of different zones therealong of different dielectric constants, each of said tape zones being sufficiently long to provide said axially arranged zones.

7. A helical waveguide as claimed in claim **6** wherein said tape zones graduate one into the other without abrupt change.

8. A helical waveguide comprising a conductive wire wound in a substantially helical form, a jacket over said helix which has a plurality of axially arranged zones, any two adjacent ones of which have different wall impedance values, said jacket consisting of a plurality of tapes wound helically in parallel over said conductive wire, each tape being made of insulating material having different dielectric constants than another, the width of each of said tapes being sufficiently longer than the wavelength in use, and a lossy jacket surrounding said insulating jacket.

9. A helical waveguide comprising a conductive wire wound in a substantially helical form, a jacket over said helix which is made of a plurality of tubes of insulating material, any two adjacent ones of which have substantially the same dielectric constant and different thicknesses, the axial length of each of said tubes being sufficiently longer than the wavelength in use, and a lossy layer surrounding said tubes.