United States Patent

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[72] Inventors **Lewis A. Bondon**
90 Yantacaw Brook Road, Upper Montclair, N.J. 07043;
David L. Bondon, Northgate Apts. #107K, One Mile Road, Cranbury, N.J. 08512

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[54] **SEMI-RIGID ELLIPTICAL WAVEGUIDE**
6 Claims, 9 Drawing Figs.

[52] **U.S. Cl.** **333/95,** 138/177, 138/118
[51] **Int. Cl.** **H01p 3/14**
[50] **Field of Search** ..... 333/95 (A), 95

[56] **References Cited**

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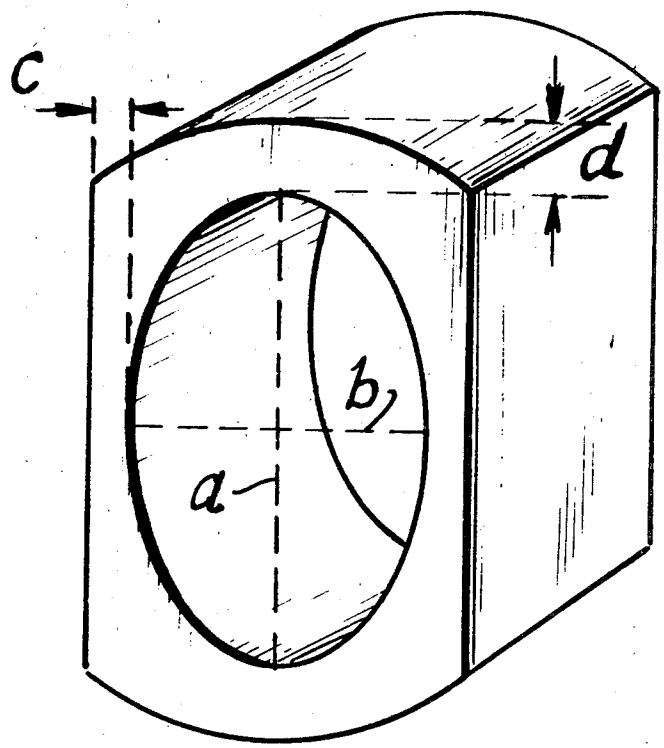
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Primary Examiner—Herman Karl Saalbach
Assistant Examiner—Saxfield Chatmon, Jr.
Attorney—Hopgood and Calimafde

ABSTRACT: A flexible radio frequency transmission line of the waveguide-type consisting of a waveguide structure of semirigid conductive material having a uniform longitudinal profile whose interior cross section is defined by an ellipse and whose exterior cross section is defined by the intersection of a circle and rectangle, the rectangular sides being parallel to the major diameter of the ellipse and transitioning at both ends into sectors of the circle.



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2 Sheets-Sheet 1

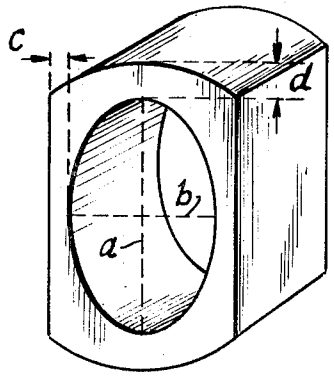


FIG. 1

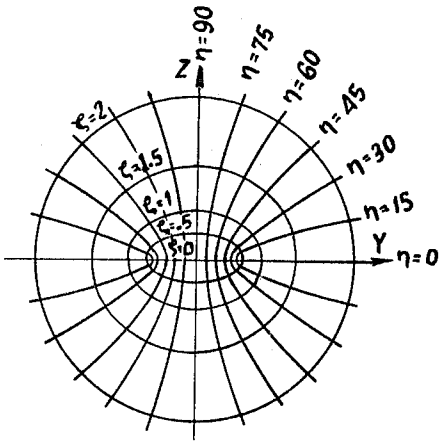


FIG. 2

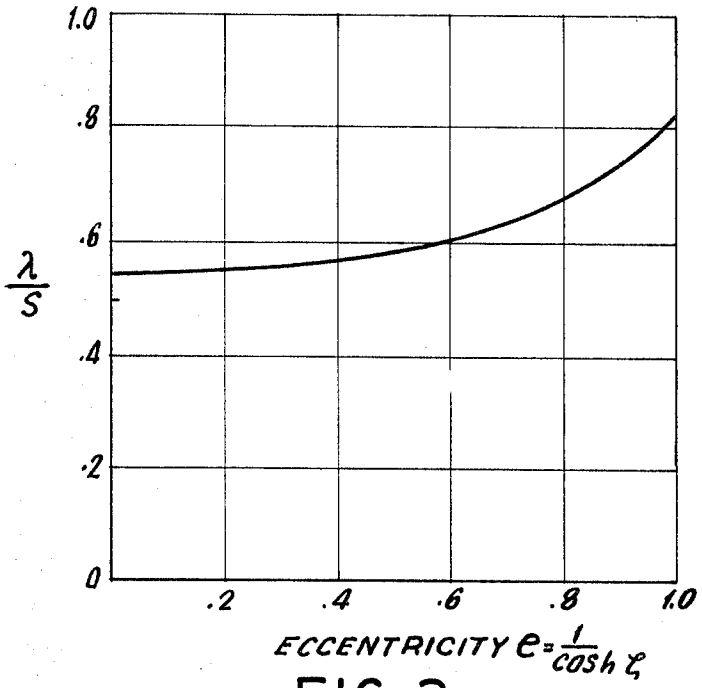


FIG. 3

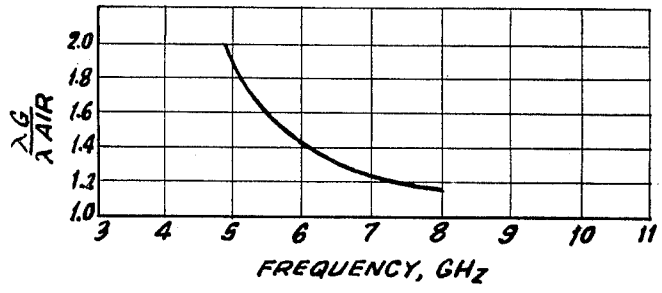


FIG. 4

INVENTORS
LEWIS A. BONDON
DAVID L. BONDON
BY
Hopgood & Calimafde
ATTORNEYS

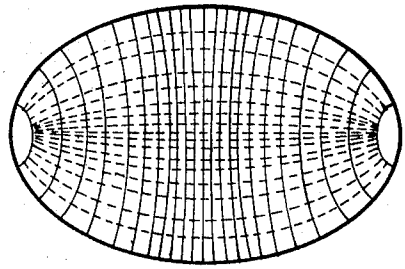


FIG. 5

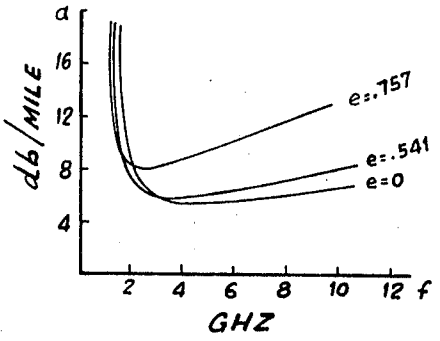


FIG. 6

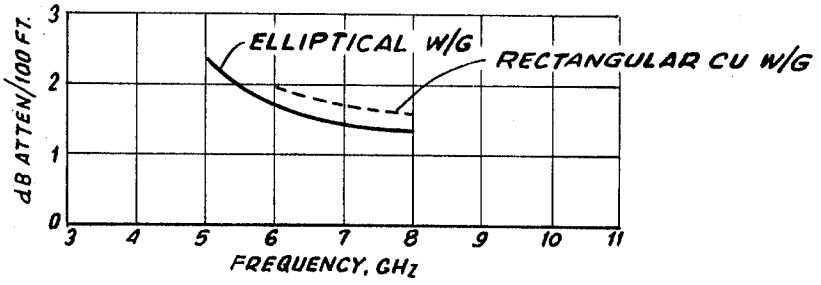


FIG. 7

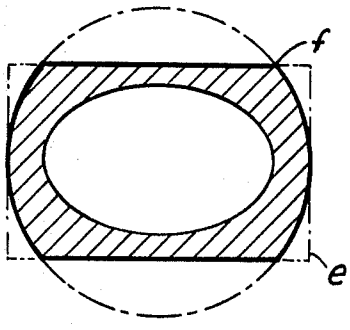


FIG. 8

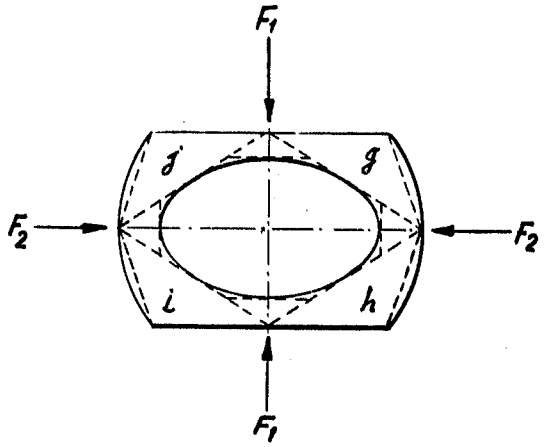


FIG. 9

INVENTORS
LEWIS A. BONDON
DAVID L. BONDON
BY
Hopgood & Calimafde
ATTORNEYS

SEMI-RIGID ELLIPTICAL WAVEGUIDE

BACKGROUND OF THE INVENTION

Waveguides may be either open or closed structures. In the former, the field in the cross-sectional plane of the guide extends to infinity. In the latter, the field will be confined to a defined region. Parallel wire transmission line represents an open waveguide, and coaxial and hollow metal pipe are examples of closed waveguides. This application is concerned with waveguides of the hollow, metal pipe-type, and the term "waveguide" (or "guide") when used herein may be deemed to be so restricted.

To date, the most efficient form of microwave transmission media is waveguide, and in particular, circular waveguide. When properly designed, the performance characteristics of this type of transmission line are practically unmatched. In most cases, however, optimum performance criteria is costly and this is particularly true of circular waveguide.

For propagation of energy at microwave frequencies through hollow metal tubes, a number of different waves are available known as TE and TM waves. A TE wave is a transverse electric wave, sometimes called an H wave, characterized by the fact that the electric vector (the E vector) is always perpendicular to the direction of propagation. That is, there is no electric vector longitudinally in the pipe. TM, or transverse magnetic, waves, also called E waves, are characterized by the fact that the magnetic vector (H vector) is always perpendicular to the direction of propagation and there is no magnetic component longitudinally in the pipe.

The solution for the field configuration in waveguides is characterized by the presence (after the designation TE or TM) or integers *m* and *n* which take on separate values from 0 or 1 to infinity. Only a limited number of these different *m*, *n* modes can be propagated depending upon the dimensions of the guide and the frequency of the excitation.

In circular waveguide, to provide the lowest attenuation, the TE_{01} mode must be launched and maintained throughout the system. Any dimensional discontinuities in the circular waveguide will generate higher order modes which significantly degrade the performance of the waveguide. Accordingly, in order to insure purity, circular guide and its associated components must be constructed with extreme accuracy. Where bends are required, they are difficult and costly to obtain and filters are generally inserted in the system to control unwanted modes.

In recent years, the considerations of attenuation vis-a-vis cost have generally dictated the use of rigid rectangular waveguide. Rectangular waveguide installations, like circular waveguides, however, must meet design criteria which almost always require the insertion of bends or twists in the guide to adopt the physical positioning of the system itself. In order to insure that such bends and twists do not introduce discontinuities which would create modes adversely affecting the system, the bends are separately constructed with great precision and with every effort being expended to maintain the interior dimensional integrity of the bent section. Moreover, depending upon the plane in which the bend is taking place, separate types of bends are required to accommodate E and H plane directional changes.

Separate bent waveguide sections are hardly a completely satisfactory answer since their use allows practically no adjustment in the configuration of the final assembly, nor does it permit simple field modification of element positions.

Thus, there has sprung into being a family of flexible waveguides whose physical characteristics vary widely. One conventional type of flexible waveguide is constructed of a continuous spiral of interlocking strips externally covered with rubber. Another conventional-type flexible guide includes a continuous metal corrugated to permit flexing; recently, elliptical corrugated guide has been introduced. Corrugated guide offers the advantage of no leakage where the guide is to be pressurized. Still another type has a spiralled periphery, which, once the final configuration has been achieved, is soldered, brazed or welded.

The foregoing flexible guide structures, however, present several disadvantages. Primarily, the attenuation tends to be extremely high as opposed to, for example, rectangular sections into which they terminate, and is therefore prohibitive for long runs. The brazing, welding or soldering operations are in themselves extremely inconvenient, and the resultant structure will not withstand torsional stresses which will part the seams. Corrugated waveguide has a high fatigue factor and the chances of crystallization are relatively high; the system tending to be de-ruggedized by this weak link.

Moreover, each junction point where a flexible waveguide element meets a rigid element invariably, unless very closely toleranced, produces a discontinuity giving rise to the injection of higher order modes which disadvantageously affect the output.

OBJECTS OF THE INVENTION

It is the object of this invention to provide a radio frequency transmission media of the waveguide-type which may be twisted and formed with comparative ease (semirigid) into any installation configuration, and which is sufficiently low in attenuation so that it may replace not only flexible waveguide but also the rigid guide, thereby reducing the number of discontinuities caused by junctions.

It is a further object of this invention to provide a structure of the foregoing type which may be supplied in continuous reeled lengths for rapid field assembly.

It is a further object of this invention to provide a waveguide structure which has greater width and requires a minimum number of sizes to cover frequency ranges in which other types of waveguide are currently being employed.

It is a further object of this invention to provide a waveguide structure which is integral longitudinally and has no welded seams to fail and cause pressurization leaks.

It is a further object of this invention to provide a flexible or semirigid guide with a low fatigue factor which minimizes its chance of crystallization and which will take substantial twist moments without failure.

It is a further object of this invention to provide a flexible waveguide with electrical characteristics at least equivalent to those now found in rigid rectangular waveguide.

It is a still further object of this invention to provide a flexible waveguide which may be economically manufactured by accepted fabrication techniques and which is capable of being simply and expeditiously terminated into rectangular and/or circular waveguide sections.

A BRIEF SUMMARY OF THE INVENTION

Briefly, the invention is predicated upon the concept of providing a waveguiding structure of semirigid material with a longitudinally uniform profile defined on the interior cross section by an ellipse and in thickness by a virtual truss configuration which maintains the inside elliptical integrity when the waveguide is either bent or twisted by allowing the metal to yield without interior distortion of the ellipse.

The above mentioned and other features and objects of this invention and the manner of attaining them will become more apparent and the invention itself will best be understood by reference to the following description of an embodiment of the invention taken in conjunction with the accompanying drawings, the description of which follows.

DESCRIPTION OF VIEWS OF THE DRAWINGS

FIG. 1 is a perspective illustration of one embodiment of waveguide according to the invention.

FIG. 2 shows the elliptical coordinate system.

FIG. 3 is a graph of the cutoff wavelength as a function of the eccentricity of the eH_1 mode.

FIG. 4 is a graph of wavelength, in elliptical guide, versus frequency.

FIG. 5 shows the field configuration of the eH_1 wave in elliptical pipe having an eccentricity of 0.75.

FIG. 6 is a graph of the attenuation in an air-filled copper pipe.

FIG. 7 illustrates the comparative attenuation data for rectangular waveguide as opposed to the waveguide according to the invention.

FIG. 8 schematically shows how the exterior configuration of the waveguide may be defined by geometric figures; and

FIG. 9 shall be used to illustrate the theoretical force lines encountered in bending.

DETAILED DESCRIPTION OF THE INVENTION

In order to more fully appreciate the invention and its employment in the radio frequency field, a brief examination of the field configurations in hollow conducting pipes of elliptical cross section is desirable.

The coordinate system for an ellipse such as is under consideration is given in FIG. 2. The elliptic coordinate system may be defined in terms of a right-hand Cartesian system by the equations

$$x=x;\ y=q\cosh\zeta\cos n;\ z=q\sinh\zeta\sin n.$$

The contour surfaces of constant ζ are confocal elliptic cylinders, and those of constant n are confocal hyperbolic cylinders. The constant q represents half the distance between the foci. One of the confocal elliptic cylinders with $\zeta=\zeta_o$ is assumed to coincide with the inner boundary of the elliptic pipe, and the x axis coincides with its longitudinal axis. The major and minor axes of the boundary ellipse are $q\cosh\zeta_o$ and $q\sinh\zeta_o$, respectively, ad its eccentricity, e,95 given by $1/\cosh\zeta_o$.

The Maxwell equations for a wave in an elliptical pipe can be employed in the usual manner to derive the wave equations for E_x and H_x. After separating the variables ζ and n, the equations are known as the Mathieu equations, and their solutions as the Mathieu functions. A more detailed examination of the mathematics involved may be had be resort to "Electromagnetic Waves in Elliptic Hollow Pipes of Metal," Lan Jen Chu, Journal of Applied Physics, Vol. 9, pp. 583—591, Sept. 1938. As enunciated by Mr. Chu, an H or E wave in an elliptic pipe may be designated by the prescript e or o indicating that the wave is described by either the even or the odd Mathieu functions. A double subscript nm is also employed in the usual manner where n denotes the order of the Mathieu function and m denotes the particular route. For present purposes, it is necessary only to investigate the six lowest order waves. Since this is the first route, the distinguishing characteristic $m=1$ will be omitted and the six lowest order waves may be designated eH_0, eH_1, oH_1, eE_0, eE_1, and oE_1.

From extensive analysis of various elliptical configurations and transitions from rectangular and circular guide, it appears that the dominant mode transmitted in elliptical waveguide is the eH_1 mode. Accordingly, references hereinafter shall be made almost exclusively to this mode. Should such assumption prove to be incorrect, the general concepts and formulae derived are nevertheless value and may be resorted to in considerations of the newly assumed dominant mode.

Applying the general consideration that when the phase constant is 0, waves cannot travel through the pipe; the value of the wavelength for which the phase constant is 0, commonly called the critical or cutoff wavelength, λ_c, may be determined from a Bessel-Fourier series expansion for the Mathieu functions.

In FIG. 3, the ratio of $\lambda_{c/s}$ is plotted for the eH_1 mode for various degrees of eccentricity; S is the peripheral length of the guide.

From knowledge of the cutoff wavelength, the guide wavelength may be obtained using standard procedure. A graphic illustration of the wavelength in elliptical guide may be seen by reference to FIG. 4 which shall be referred to again hereafter.

The field configuration of the eH_1 wave may be seen in FIG. 5 where the solid lines represent the electric field and the dashed lines the magnetic field. Where the conductivity of the metal pipe is assumed to be finite, the field inside the pipe obviously distorts from the shape shown, since the finiteness of the conductivity requires different boundary considerations. However, if the conductivity is assumed to be very large, the wave may be assumed to take the form shown with very little deviation.

The calculation of the attenuation constants may be made upon the basis of the usual boundary considerations for metals of high conductivity, the solution of the longitudinal fields, the integration of the Poynting vector to determine the power loss into the metal, and a determination of the total power transmitted through the pipe; the latter by using field expressions of a perfectly conducting pipe.

FIG. 6 illustrates the attenuation of the waves for the eH_1 mode as a function of GHz. with varying degrees of eccentricity. FIG. 7 will be referred to hereinafter, and illustrates comparative attenuation data for a rectangular waveguide and the waveguide according to the invention.

Having briefly outlined the electrical considerations and characteristics of elliptical waveguide, an analysis shall now be made of the physical embodiment of the invention which gives rise to an elliptical waveguide capable of permitting bends and twists without distortion.

FIG. 1 illustrates one embodiment of the waveguide according to the invention. As may be seen, the interior of the guide is elliptical in cross section having a major diameter a and a minor diameter b. The guide exterior may be visualized as shown in FIG. 8 as a combination of a rectangle e and circle f. The width of the rectangle is greater than the minor ellipse diameter b by an amount $2c$, and the circle diameter is greater than the major ellipse diameter a by amount $2d$.

The exterior guide shape shown simultaneously resolves several considerations. First, the flat sides which are parallel to the major ellipse diameter allow the guide to be precisely indexed where it is to be transitioned into rectangular waveguide. The circular ends, on the other hand, permit the use of a proven connector gripping technique now used to terminate many other types of rf transmission lines without brazing or welding as described in U.S. Pat. No. 3,010,747. Seals may be added to the described connector to insure pressurized junctions.

The guide shown in FIG. 1 may be seen to be longitudinally uniform. That is, as one travels down the guide, the profile remains constant vis-a-vis corrugated or seam convoluted flexible waveguide.

The waveguide material is a highly conductive metal which has the further attribute of being semirigid. By semirigid is meant a material which can be twisted and bent with comparative ease and has physical characteristics roughly equivalent to that of pure copper or aluminum alloy 10–60 or 10–90; retaining imparted deformations without crystallizing, cracking or otherwise impairing its characteristics.

10–60 aluminum has been found to be an excellent material for the described use as it may be extruded with an extremely smooth inner surface, as a continuous seamless tube in lengths up to 300 feet or more; the inner surface may be held at close tolerances; and the finished waveguide may be easily cut with a hacksaw and filed to a smooth surface to be inserted into its terminating connector.

A waveguide made of -60 aluminum may also be bent (generally twisted as well) with bare hands in the field without difficulty, and any degree of twist up to 90° can be made during installation with simple tools. It will withstand relatively rough field treatment vis-a-vis existing waveguide. The exterior surface may be covered, for example, with an epoxy finish to protect it from pitting and corrosion, if required. For shipping purposes, the guide may be wound on a drum.

FIG. 9 illustrates how the waveguide according to the invention internally distributes bending forces. H and E plane bends, applied to the waveguide, will result in net effective forces F_1 or F_2. Regardless of the direction of the applied force, it will be supported by an archlike structure which resolves the vertical or horizontal pressure, into diagonal thrusts. Stated differently, regardless of the direction of the application of the force, it is met by an assemblage of triangular trusses so combined as to form a rigid framework which

cannot be deformed by the application of an exterior force without deformation of one or more of the sides of the particular triangle. As a consequence, the force is so distributed as to maintain the integrity of the internal configuration of the ellipse. Twist moments are similarly resolved by the truss configuration to maintain the ellipse.

From the foregoing explanation, it may be seen that it is not requisite for the exterior shape to be precisely that shown in FIG. 1. However, the flat sides do uniquely resolve indexing problems and the circular ends resolve termination considerations. With the latter considerations aside and with different means for joining sections, the external shape may vary widely so long as the resultant arch contains a virtual truss configuration such as shown in FIG. 9 to support the internal elliptical integrity. As may be seen from FIG. 9, the selected exterior profile closely approximates a triangle in each of quadrants *g*, *h*, *i* and *j* and thus has very little excess material.

The specific preferred profile dimensions for a given frequency and application involve considerations of mode stability, attenuation, formability, etc. An exemplary profile which meets the flexibility requirements desired and has excellent electrical characteristics in the range 5.0—8.0 GHz. has the following dimensions.

Major ellipse diameter *a* 1.660 inches
Minor ellipse diameter *b* 1.055 inches
Thickness *c* 0.125 inches
Thickness *d* 0.220 inches

The waveguide weighs 1 lb. 2 oz. per foot and may be bent by hand in the E plane to a 24-inch radius, and in the H plane to a 36-inch radius. Using known manufacturing techniques, more careful bends may be made at the factory in the E plane to a 6-inch radius, and in the H plane to a 12-inch radius.

The wavelength and attenuation characteristics of such a guide may be seen by reference to FIGS. 4 and 7, respectively. For purposes of comparison, FIG. 7 also includes the attenuation versus frequency response of conventional WR–137 rectangular copper waveguide. An examination of the graph will reveal that the inventive waveguide even when formed out of 10–60 aluminum is superior to rectangular waveguide made of copper.

Similar results were obtained vis-a-vis rectangular waveguide with inventive guide having a bandwidth of from 3.7 to 6 GHz. (major diameter 2.48 inches, minor diameter 1.56 inches) and also elliptical waveguide having a bandwidth from 7.0 to 11.0 GHz. (major diameter 1.830 inches and minor diameter 1.354 inches).

From the viewpoint of mechanical stability, it has been empirically found preferable to relate the thicknesses *d* and *c* roughly by a ratio of 2. This ratio, it is theorized, allows greater deformation, within the plastic limits, of the material at the ends of the major diameter where greater compression and expansion will take place when bent in the plane of the minor axis.

While bending may result in some distortion of the internal ellipse, this occurs at a point where the elliptical modes have already been launched, and is of minor effect since the gradual alteration of the ellipse diameters merely moves the consideration of that mode to a slightly different eccentricity. From FIG. 6, it may be seen that wide variations in eccentricity are possible without destroying or significantly affecting the mode. While FIG. 6 shows in particular the eH_1 wave, the same holds true for a majority of the modes.

The elliptical waveguide according to the invention satisfies all the objects delineated above and provides a broad bandwidth waveguide of excellent attenuation characteristics which can be manufactured, packaged and assembled with relative ease. No prefabricated bends or twists are necessary, and the multiple coupling flanges normally required with rectangular guide to join several sections are eliminated. The walls of the guide are sufficiently thick so that it cannot be easily dented and it will withstand relatively rough handling and permit rapid and economical means for attachment to its supporting structure. The cost of the inventive waveguide is competitive with rectangular waveguide, yet its bandwidth is greater and its attenuation lower. While a flexible guide, the waveguide of the invention is uniquely suitable to high gas pressurization which is often a necessary operational requirement where high power is to be handled.

The dominant mode in the elliptical guide is, as mentioned, thought to be the eH_1 mode which is similar to the TEO_1 mode in rectangular waveguide or the TE_{11} mode in circular waveguide. The power handling capability of the elliptical waveguide is somewhat in excess of rectangular waveguide but is less than TEO_1 circular waveguide; however, it requires no mode filtering as does circular waveguide.

One hundred feet of the inventive waveguide for the bandwidth for 5 to 8 GHz and including two transitions to rectangular waveguide exhibit a maximum VSWR of 1.06 with bends of 90° in the E plane of only 18 inches in radius only negligibly affect the VSWR of the line. An E plane bend with a 6-inch radius adds less than a 1.03 VSWR contribution.

While the principles of the invention have been described in connection with specific apparatus, it is to be clearly understood that this description is made only by way of example and not as a limitation to the scope of the invention as set forth in the objects thereof and in the accompanying claims. For example, while the specific embodiment described has an eccentricity of approximately 0.77, it has been found that any eccentricity below 0.8 (that is, 0.8 to 0) exhibits almost all of the characteristics described, and that above 0.8 the desired attributes rapidly deteriorate.

We claim:

1. A flexible radio frequency transmission media comprising a waveguiding structure of semirigid material having a longitudinally linear profile when said structure is rectilinear in attitude and defined on the interior cross section by an ellipse and in thickness by a virtual truss configuration maintaining the inside elliptical integrity when the waveguide is either bent or twisted.

2. The transmission media claimed in claim 1 wherein the eccentricity of the ellipse is 0.8 or less.

3. The transmission media claimed in claim 1 where the truss configuration defines substantially triangular sections in quadrants described by the elliptical axes.

4. The transmission media claimed in claim 3 where the exterior profile is rectilinear in cross section for a predetermined length parallel to, and on both sides of, the major elliptical axis.

5. The transmission media claimed in claim 4 wherein the exterior profile of the waveguide adjacent the end to the major diameter of the ellipse is circular and meets the said rectilinear portion.

6. The transmission media claimed in claim 3 wherein the thickness of the waveguide along the major diameter is greater than that along the minor diameter and wherein the ratio is approximately 2 to 1.