June 19, 1956 A. P. KING 2,751,561

WAVE-GUIDE MODE DISCRIMINATORS

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FIG. 1

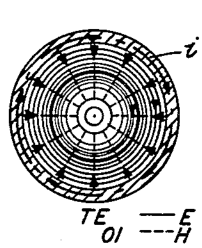

FIG. 2

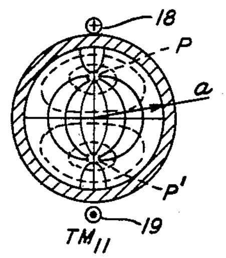

FIG. 3

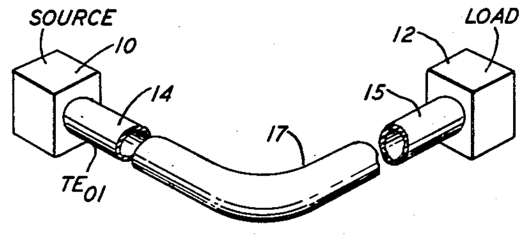

FIG. 4A

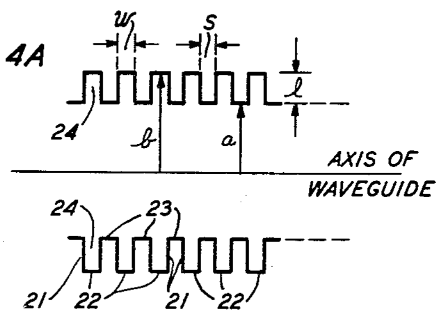

FIG. 4B

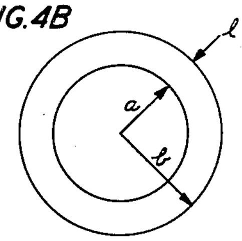

FIG. 4C

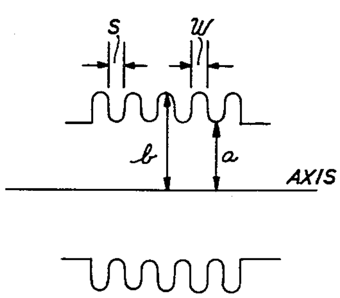

FIG. 4D

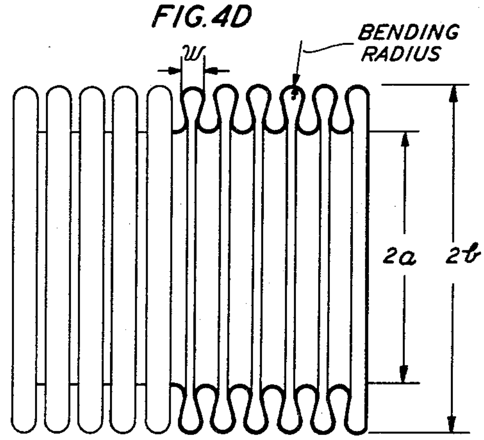

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FIG. 5A

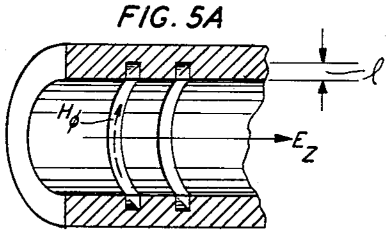


FIG. 5B

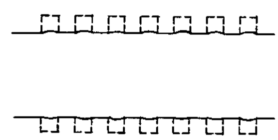


FIG. 6

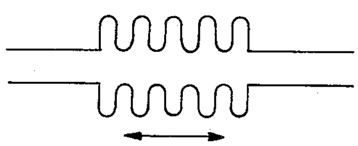
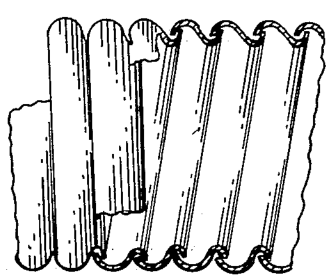


FIG. 7



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WAVE-GUIDE MODE DISCRIMINATORS

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Application December 20, 1950, Serial No. 201,792

3 Claims. (Cl. 333—98)

This invention relates to electromagnetic transmission lines and, more particularly, to mode discriminators for hollow pipe wave guides.

In accordance with the invention, corrugated or grooved walled tubing is employed for transmitting waves of the circular electric type in the TE_{01} transmission mode, for example, with a minimum of incidental generation or transmission of undesired modes such as the TM_{11} transmission mode.

One form in which the invention is employed is as either a straight or curved length of wave guide serving as an expansion section to allow for thermal changes in the dimension of the wave guide line. In another form, either a fixed or flexible elbow or bend is employed to change the direction of transmission of one mode such as TE_{01} waves with a minimum of conversion of the energy of these waves into an undesired mode such as the TM_{11} transmission mode. Either form or other suitable variation may be used in conjunction with smooth-walled cylindrical wave guides, the uncorrugated sections being appropriate for straight runs, while the corrugated or grooved sections may be confined to curves or to expansion sections, or the invention may be used in any application where a flexible or bent length of line is desired.

In the accompanying figures:

Figs. 1 and 2 represent field patterns of TE_{01} and TM_{11} waves, respectively, in a circular pipe;

Fig. 3 is a schematic representation of a hollow pipe transmission line having straight sections, broken to represent extension to any desired length, and a curved section, the line being shown connecting a conventional source with a conventional load;

Figs. 4A, 4B, 4C, and 4D are sectional views of various forms of corrugated wave guide useful in practicing the invention;

Figs. 5A and 5B are diagrams useful in explaining the operation of the invention;

Fig. 6 is a schematic representation of a corrugated expansion section in a straight transmission line; and

Fig. 7 is a cross-sectional view of an alternative structure having a single helical groove.

Referring to the figures, Figs. 1 and 2 illustrate the distribution of the electric and magnetic fields in transverse sections of a pair of circular wave guides supporting the TE_{01} and TM_{11} transmission modes, respectively. The transverse electric TE_{01} wave illustrated in Fig. 1 is designated as the circular electric type inasmuch as the electric field, shown by the solid lines, 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, forms at various points along the guide a radial pattern. The electric field intensity attains a maximum approximately half way between the axis and the 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. 1.

The configuration of the transverse magnetic TM_{11}

2

mode shown in Fig. 2 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 encircling the respective poles, P, P′ which, in the case of a plane bend, exhibit an orientation in a plane normal to the plane of the bend. Since the magnetic lines must form closed paths, they tend to spread out near the center of the guide and to crowd close together at the inner surface mostly near the vertical axis of the guide thus inducing a considerable longitudinal conduction current flow in the wall of the guide, the direction of which flow is shown conventionally by symbols 18 and 19 in Fig. 2.

In a microwave system for the transmission of TE_{01} waves the inside radius a of the circular pipe guide selected for the propagation of these waves must be greater than the critical or cut-off radius a_c for the TE_{01} mode. The cut-off radius a_c for the TE_{01} mode is equal to $0.61\lambda_0$, where λ_0 is the wavelength in free space of the longest wave in the transmission band. In practice a is made greater than a_c and may vary in different systems, from about $.75\lambda_0$ to $15\lambda_0$, for example. For long distance transmission the larger wave-guide sizes are to be preferred because the attenuation is less; for short distances and in terminal equipment where the attenuation is relatively unimportant the use of smaller wave guides may be advantageous. As an illustrative example of long distance TE_{01} wave transmission a wave guide 5 inches in diameter for wavelengths in the vicinity of 1 to 2 inches may be employed and for the short distance case the wave guide may be 2 inches in diameter, the wavelength 1¼ inches.

In Fig. 3, there is shown a simple wave-guide installation wherein a variable frequency source 10 of any suitable well-known type supplies microwave energy in the form of TE_{01} waves to a load 12, such as, for example, a microwave repeater or antenna, through a circular wave-guiding passage having a hollow interior. Throughout the greater part of its length, the passage comprises a pair of angularly disposed straight uniform sections of wave guide 14, 15, which are joined by a relatively short curved bend 17, the design of which may assume any of the forms described hereinafter.

It is recognized in the theory of traveling-wave devices such as magnetrons and traveling-wave amplifiers that where two waves travel along together in the same direction and at substantially the same phase velocity an exchange of energy may take place between the waves, one gaining energy at the expense of the other.

The characteristics moding or degeneration of TE_{01} into TM_{11} wave power 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 the following embodiments of the invention, the bends or flexible lengths are so modified as to change the phase velocity of the TM_{11} wave relative to the TE_{01} wave to increase the relative difference in propagation constants. This reduces the effective coupling between these two waves and avoids or reduces conversion of TE_{01} into TM_{11} wave power.

The general structure of a corrugated tubing for the bend 17 for use in a TE_{01} wave transmission system in accordance with the invention is illustrated in Figs. 4A and 4B which show longitudinal and cross-section views, respectively, of a corrugated circular wave guide in which the corrugations are rectangular in cross-sectional shape. Figs. 4C and 4D indicate some alternative cross-sectional shapes of the corrugations by way of rounding the corners of the folds to make such tubing more amenable to manufacture.

Figs. 5A and 5B are sketches designed to facilitate explanation of the operation of corrugated tubing and to illustrate grooves cut into a relatively thick wall as a structure alternative to corrugated tubing.

Let us consider in greater detail a corrugated tube in which the corrugations are rectangular in shape and which is illustrated in Figs. 4A and 4B. Here the wave guide of nominal radius a is connected serially with short lengths of circular wave guide of length w. Thus a series of rings, **22** and **23**, alternating in radius b and a respectively, are connected together in a seamless fashion by the annular rings **21**. The circular grooves **24** formed in this manner may be considered as disc or radial transmission lines, whose length $l=b-a$, open at wall or radius a and short circuited by a ring **22** at radius b. As indicated in Fig. 4A, these lines are spaced S distance apart and act as series reactive loading elements for line of radius a. For the conditions preferably prevailing in this application, where

$$w<\frac{\lambda}{2}$$

the series impedance presented by the radial transmission line is a function of length $l(l=b-a)$. As with other lines, the reactance is positive or inductive for

$$\frac{\lambda}{4}>l>0$$

and negative or capacitive when

$$\frac{\lambda}{2}>l>\frac{\lambda}{4}$$

The impedance of the line will now be considered in more detail.

The width of the radial line w may equal S, but in general these may be different. As with other lines, the smoothness of loading or the avoidance of lumpiness of the loading is a function of the number n of these radial lines per wavelength (λ_g) of the line radius a. Experiment has shown that

$$n=6 \text{ approx.}=\frac{\lambda_g}{w+S}$$

is sufficient and that a value $n=3$ approx. is too few. Thus it will be apparent that when $n=6$ and when $w=S$, then

$$w=\frac{\lambda_g}{12} \text{ approx.}$$

The corrugated wave guides of Figs. 4C and 4D show modifications of the form shown in Fig. 4A which facilitate the manufacture of the tubing. In commercial manufacture which commonly uses hydraulic pressure methods it is not feasible to produce the sharp corners of Fig. 4A. In the analysis it is assumed however that the dimensions in Figs. 4C and 4D are modified from those in Figs. 4A and 4B only slightly by the rounding of the corners.

Two illustrative applications of corrugated wave guide in a TE_{01} transmission system will be considered, the first of which is the use of such tubing as an expansion section in a straight wave-guide line to allow for thermal expansion or contraction of the wave-guide line, as in Fig. 6.

In a straight section of line no degenerate modes will be generated by the corrugated section, provided

$$w<\frac{\lambda}{2}$$

preferably less than

$$\frac{\lambda}{4}$$

for under these conditions the configuration of the TE_{01} wave is such that it does not tend to excite the radial line elements. Under these circumstances the length l of the radial line is non-critical. The number of corrugations employed depends upon the amount of expansion to be allowed for.

In the second example corrugated tubing may be used as either a fixed or flexible bend to avoid degenerative modes (TM_{11}) which occur in a plain bend. Structure is the same as Fig. 4 except that it is bent or curved.

It has been found by experiment that bending the tubing to a radius of 10 to 12 inches does not appreciably affect the transmission nor introduce appreciable amounts of the degenerate TM_{11} mode.

The function of the corrugations is to produce a large reactive loading factor for the TM_{11} wave component which tends to be produced in a plain bend, and thus to change its phase velocity relative to the TE_{01} wave component and thus reduce the coupling between the TE_{01} and TM_{11} waves.

The effect of the radial line upon the transmission of modes is dependent upon the field configuration of the mode and the dimensions of the groove or disc transmission line. In order to excite the line it is required that the magnetic field be parallel to the slot (tangential H in circular guide or H_φ) and that the electric field E be transverse to the slot (longitudinal E or Ez) as shown in Fig. 5A.

For a TE_{01} wave in a circular wave guide the electric field at the wall is tangential (E_φ) and the magnetic field longitudinal (Hz). Thus the TE_{01} wave has no field components to excite the radial lines, and only a minute penetration of the groove will occur. The presence of the grooves will make the wave guide appear to the TE_{01} wave as shown in Fig. 5B by the solid line. Since the TE_{01} wave does not penetrate appreciably in the groove the length l is unimportant, and it does not matter whether the end at the ring **22** (Fig. 4A) is shorted or not. As a result the effect of the grooves upon the TE_{01} wave is practically the same as a straight pipe without corrugations.

For the TM_{11} wave however the field at the wall possesses both longitudinal electric field Ez and tangential components of magnetic field H_φ and therefore can propagate a wave radially along the disc transmission line. For this wave these grooves act as reactive elements in series with the line, change the LC ratio of the line and hence the phase velocity of the TM_{11} wave. In a plain wave-guide bend the degenerate TM_{11} mode has the same velocity, but in a corrugated bend the reactive loading effect is to change this velocity and thus decouple the wave sufficiently so that there is no TM_{11} wave degeneracy in the bend.

Dimensions and tolerances which have been found to work well in the three-centimeter wavelength range in the structure of Fig. 4D are 2.000±0.010 inches for $2a$, 2.705±0.010 inches for $2b$, five convolutions per linear inch of wave guide, and bending radius of 0.020 inch. In this example,

$$\frac{a}{\lambda}\geq 2$$

which is in the present range of interest for long distance TE_{01} transmission. In relatively large wave guides where a larger part of the wave is in displacement current and a relatively smaller part in wall currents, the loading produced by corrugations may be expected to be less effective in changing the phase velocity of the TM_{11} wave.

The impedance of the radial line at the wall radius a of the wave guide is a function of its length $l(l=b-a)$. In general the greatest effect is obtained when the length $l=b-a$ is in the vicinity of $\frac{1}{4}\lambda_r$ or an odd multiple thereof, where λ_r is the wavelength in the radial line. For a plurality of radial lines in adjacent portions of the main line there may be a proximity effect which will cause the greatest effect to be obtained at a slightly different value of l. The length l which develops the maximum reactive impedance is close to the value $\frac{1}{4}\lambda_r$, and for a radial line wherein

$$w\leq\frac{\lambda}{10}$$

the length l may be calculated from the Bessel functions as follows, using the relationship given by S. A. Schelkunoff in "Electromagnetic Waves," page 269:

$$\frac{J_1(\beta a)}{N_1(\beta a)}=\frac{J_0(\beta b)}{N_0(\beta b)}$$

where β is the phase shift in radians per centimeter along the radius.

Thus for the case of $a=1$ inch=2.54 centimeters, and free space wavelength $\lambda=3.33$ centimeters.

$$\beta=\frac{2\Pi}{3.33}=1.89 \text{ radians per centimeter}$$

from which

$$\beta a=1.89\times 2.54=4.79 \text{ radians}$$

The values of $J_1(4.79)$ and $N_1(4.79)$ may be read off from "Tables of Functions," by E. Jahnke and F. Emde, Dover Publications, New York city, 1943, pages 157 and 191, respectively, as

$$J_1(4.79)=-0.2967$$

and

$$N_1(4.79)=+0.2167$$

from which is obtained the value

$$\frac{J_1(4.79)}{N_1(4.79)}=-1.37=\frac{J_0(\beta b)}{N_0(\beta b)}$$

Entering the chart of N_0/J_0 on page 201 of the same book, with the reciprocal of -1.37, the value of βb which satisfies this ratio is found to be

$$\beta b=6.46 \text{ radians}$$

from which and the value of βa,

$$l=b-a=0.91 \text{ centimeter}=0.358 \text{ inch}$$

Thus this calculated value of l is fairly close to the specified depth of the annular groove of the illustrative example of wave guide in Fig. 4D, which is 0.332 ± 0.010 inch.

Fig. 7 shows an alternative structure which has advantages in the way of ease of manufacture. A single helical fold or groove is used instead of a plurality of parallel circular ones. While the helical form may have a slight tendency to tilt the wave front of the circular electric wave, this effect is not objectionable in practice if the pitch of the helix is slight or moderate. This form of wave guide lends itself to good flexibility and may be manufactured in the manner of the sheathing commonly used in BX cable from a band or ribbon of metal wound helically with an interlocking joint between adjoining edges. This form of construction is also similar to that found in flexible speaking tubes as in dictating machines. The diameter of the tube is, of course, to be determined by the wavelength of the electric wave which it is desired to transmit.

The embodiments of the invention that are described herein are to be regarded as illustrative only and not as limiting the invention, which latter is applicable to many other materials, physical forms and uses within the scope of the appended claims.

What is claimed is:

1. In a fully confined wave guide system for circular electric waves characterized by circular field lines coaxial with the guide, a source of said circular electric waves, a first substantially straight length of fully enclosed hollow conductive wave guide of circular cross section connected to said source, a second substantially straight length of fully enclosed hollow conductive wave guide of circular cross section, said first and second straight lengths of wave guide having smooth, substantially cylindrical inner wall surfaces and having their respective longitudinal axes displaced so as to be out of alignment with each other, and a curved length of hollow conductive wave guide of circular cross section joining said straight lengths to form a fully enclosed hollow conductive wave guide system therewith, said curved length of wave guide having circumferential grooves in its inner wall surface, the depth of said grooves being such that and the spacing of said grooves along the length of said curve being small enough that the propagational velocity of a degenerate transverse magnetic wave mode within the curved length of wave guide is rendered materially different from the propagational velocity of the circular electric wave mode within the said curved length, thereby minimizing wave energy transfer from the circular electric mode to the degenerate transverse magnetic mode.

2. A high frequency electromagnetic wave transmission system comprising a source of wave energy in the circular electric mode, means for utilizing said circular electric mode energy, and a fully enclosed conductively bounded wave guide transmission line of substantially circular cross section connecting said source to said utilizing means, at least one portion of said line being a curved section of wave guide having a plurality of transverse annular grooves in its inner wall surface, said grooves having a radial depth differing from an odd multiple of quarter wavelengths of said wave energy by less than one-eighth wavelength, said grooves presenting substantial impedance to wave energy in the transverse magnetic mode normal to said curved section and substantially no impedance to said circular electric mode wave energy.

3. A high frequency electromagnetic wave transmission system comprising a source of wave energy in the circular electric mode, means for utilizing said circular electric mode energy, and a fully enclosed conductively bounded wave guide transmission line of substantially circular cross section connecting said source to said utilizing means, at least one portion of said line being a curved section of wave guide having a plurality of transverse annular grooves in its inner wall surface exceeding in number two per wavelength of said wave energy, said grooves presenting substantial impedance to wave energy in the transverse magnetic mode normal to said curved section and substantially no impedance to said circular electric mode wave energy.

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