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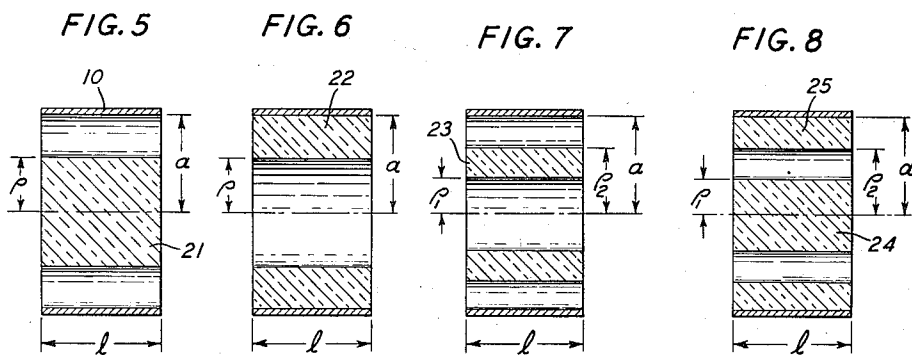
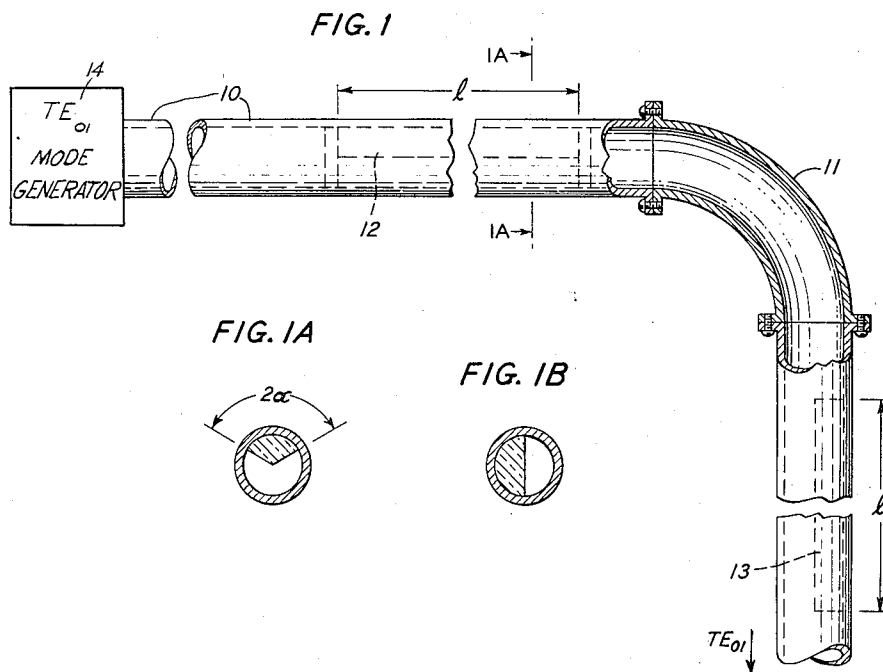
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2,762,981

MODE CONVERSION IN WAVE GUIDES

Filed Nov. 10, 1951

2 Sheets-Sheet 1



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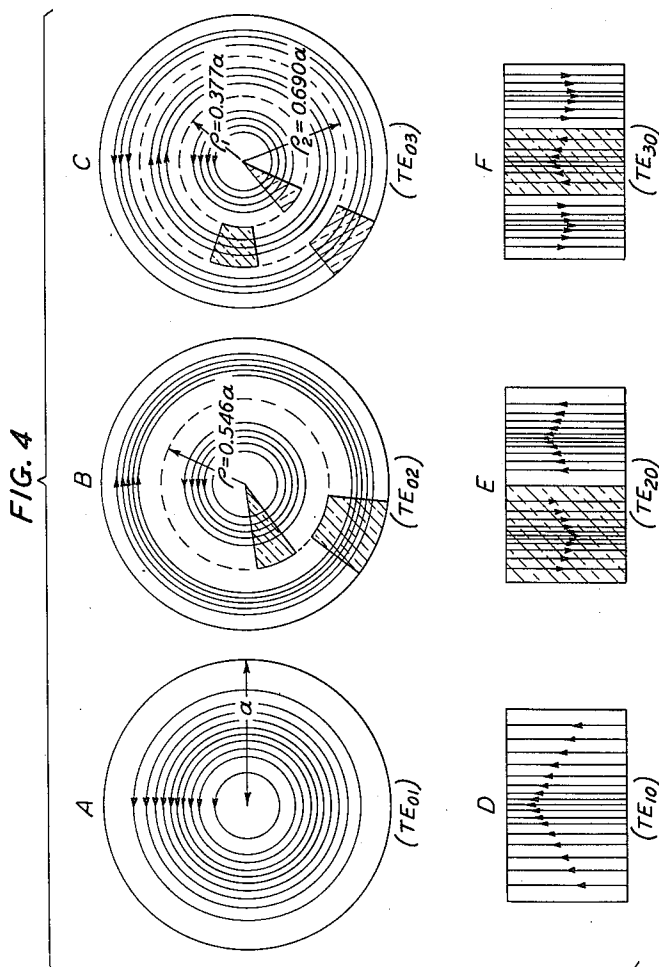
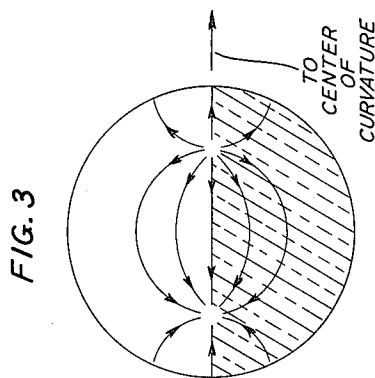
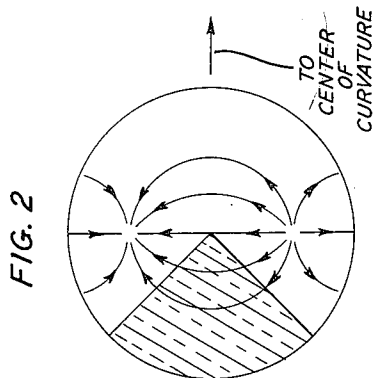
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MODE CONVERSION IN WAVE GUIDES

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2 Sheets-Sheet 2



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2,762,981

MODE CONVERSION IN WAVE GUIDES

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4 Claims. (Cl. 333—21)

This invention relates to the transmission of electromagnetic wave energy in the microwave frequency range through wave guides. It is concerned primarily with the spurious wave modes that may tend to appear in a wave guide in addition to the desired or operating wave mode, and with the transformation of guided waves from one mode to another.

In the transmission of electromagnetic energy through a hollow conductive pipe or other wave guide it is well-known that the energy can propagate in one or more transmission modes, or characteristic field configurations, depending on the cross-sectional size and shape of the particular guide and the operating frequency, and that the larger the cross-section of the guide is made the greater is the number of modes in which the energy can propagate at a given operating frequency. Very generally it is desired to confine propagation of the energy to one particular mode, chosen because its propagation characteristics are favorable for the particular application involved. If the desired mode happens to be the so-called dominant mode it is feasible to restrict the cross-sectional dimensions of the guide so that no modes other than the dominant mode can be sustained therein. This expedient is not available, however, if the desired mode is not the dominant mode or if a guide of large cross section is prescribed in order, for example, that advantage may be taken of its relatively low attenuation.

For practical example, it may be desired to transmit circular electric waves of lowest order viz., TE_{01} , through a long-distance wave guide of circular cross section having a diameter several times the operating wave length. Both the choice of mode and large diameter in this case tend to reduce the attenuation, or power loss, suffered by the waves as they propagate through the guide. In such case, however, the guide can sustain numerous other modes including the transverse magnetic mode TM_{11} and circular electric modes of higher order such as TE_{02} and TE_{03} , and to the extent that the wave power is actually transmitted in these other modes the power loss is substantially increased and other ill effects may occur.

Progressive changes in the size, shape or direction of a wave guide very generally result in the conversion of power from the principal, or operating mode into one or more subordinate, spurious modes. Bends, elbows and taper sections of guide, for example, tend accordingly to generate additional modes and these will be propagated, if the guide be large enough, and thereby introduce deleterious effects. This tendency is so pronounced that under appropriate conditions a single bend, even though of large radius, may convert all of the wave power supplied to it in one mode into a distinctly different and unwanted mode.

The present invention has as one of its general objectives the reduction or suppression of unwanted modes in a wave guide. More particular objectives are to effect such reduction or suppression with minimum loss of wave power, over relatively broad frequency bands,

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and/or without substantial reflection of wave power in the operating mode or other ill effect.

A further and more specific objective of the invention is to facilitate the transmission of wave power through curved sections of wave guide.

The present invention proceeds in part upon the observation that a curved section or other element of a wave-guide system that tends to convert wave power from the operating mode to some other mode, may itself have natural modes of wave propagation, that is, modes in which the element will transmit power without any tendency to mode conversion.

In accordance with the invention a mode transducer is incorporated within a wave guide adjacent a curved section or the like to convert wave power from the operating mode in the guide to a natural mode in the curved section or the like, or to convert from the natural mode to the operating mode in the opposite direction of transmission.

In embodiments of the invention to be described in detail hereinafter, a bend or other wave guide element that has a natural propagation mode other than the operating mode, is preceded by a first mode transducer such that the wave power passes through the element without further mode conversion, and a second mode transducer follows the element to restore the wave power to the operating mode. The conversion of wave power from the one mode to the other is effected by a dielectric transducer comprising dielectric material that is disposed within the guide in predetermined relation to the characteristic electric field patterns of the two modes, and that may extend a substantial distance longitudinally through the guide.

In accordance with a feature of the invention the transducers may be constructed of a material having a dielectric constant that is only slightly higher, for example less than ten per cent higher and preferably in some cases only of the order of two per cent higher, than the dielectric constant of the medium (air or other gas, e. g.) filling the rest of the guiding structure.

The nature of the present invention and its various objectives, features and advantages will appear more fully on consideration of the embodiments illustrated in the accompanying drawings and hereinafter described.

In the drawings:

Fig. 1 illustrates an embodiment of the invention involving a curved section of wave guide;

Figs. 1A and 1B are cross-sectional views of dielectric mode transducers that may be employed alternatively in the Fig. 1 embodiment;

Figs. 2 and 3 are explanatory diagrams pertaining to Figs. 1A and 1B, respectively; and

Figs. 4 to 8 are diagrams to illustrate an exposition of the principles of mode transducer design.

The present application is in part a continuation of my application Serial No. 226,869 filed May 17, 1951, the disclosure of which is to be deemed incorporated herein.

Referring now to Fig. 1, the specific embodiments of the invention chosen for presentation herein involve the transmission of wave power in the circular electric (TE_{01}) mode through a hollow-pipe guide 10 of uniform circular cross section that has an interposed curved section 11 of the same cross section. The TE_{01} mode is applied to the circular wave guide 10 by any suitable TE_{01} mode generator 14. A typical structure for generating the TE_{01} mode is shown in Fig. 9.6-4 on page 355 of a book entitled "Waveguide Transmission," by George C. Southworth, D. Van Nostrand Co., Inc., New York, 1950.

The theory of propagation of TE_{01} waves through an arcuately curved wave-guide bend has been extensively

treated in the literature (see for example, M. Jouget, *Cables et Transmission*, v. 1, No. 2, July 1947, pp. 133-153, and v. 2, No. 4, October 1948, pp. 257-284) and it is there shown that when such a bend is encountered the applied TE_{01} waves are progressively converted into the TM_{11} mode with a particular polarization. It is also known that the two modes have exactly the same phase velocity in a straight pipe, a circumstance which leads to close coupling between these two modes in a curved guide. In the bend the conversion into the TM_{11} mode may be partial or complete, depending on the dimensions, and in fact there may be several complete conversions from one mode to the other in alternation.

A curved wave guide has several natural modes, that is, modes which it will propagate without mode conversion. Certain of these modes are so-called "mixed" modes, i. e., combinations containing both transverse electric and transverse magnetic components. Two of these natural modes in a curved guide of circular cross section are known as the $TE_{01}+TM_{11}$ mode and the $TE_{01}-TM_{11}$ mode, each comprising a TE_{01} component and an equal TM_{11} component. Both of the TM_{11} components have a particular orientation relative to the plane of the bend, as illustrated in Fig. 2, and each has a particular phase relation with its associated TE_{01} component. Those phase relations are not the same as the phase relation between an applied TE_{01} wave and the TM_{11} mode produced in the bend by mode conversion.

A third natural mode of the bend 11 is the TM_{11} mode. It has only a TM_{11} component and it is oriented in the bend in the manner shown in Fig. 3. The polarization of this component, it will be observed, is displaced ninety degrees from that of the TM_{11} component of the $TE_{01}\pm TM_{11}$ modes.

Referring again to Fig. 1, the straight section of guide 10 between the source of TE_{01} waves and the bend 11 contains a mode transducer 12 that is adapted to convert the TE_{01} waves applied to it into one of the above-described natural modes of the bend. Similarly, in the straight section of guide 10 at the other end of the bend there is incorporated a mode transducer 13 that converts the waves issuing from the bend back into the TE_{01} operating mode. Both of the transducers are reciprocal in their operation and so may have the same construction.

With regard to the space, if any, between the transducers 12 and 13 and the bend 11, it is to be noted that the natural modes of the bend are also natural modes of the straight guide and that, accordingly, there is no mode distortion in these spaces. The transducers should be disposed adjacent the bend, however, for in a long section of straight guide the TM_{11} component would have a substantially higher attenuation than the TE_{01} mode. This arrangement also reduces or eliminates any shift in the polarization of mode components that might arise from imperfect circularity of the guide.

The transducers 12 and 13 in Fig. 1 are dielectric mode transducers of the general type treated in my co-pending application, supra. Suitable specific structures in accordance with the present invention will be set forth hereinafter. The underlying principles may be better understood, however, from a consideration of the following exposition of related structures disclosed and claimed in the aforesaid application.

Referring now to Fig. 4, there is represented diagrammatically at A the electric field configuration characteristic of the TE_{01} mode in a circular guide, while B and C are applicable similarly to the TE_{02} and TE_{03} modes, respectively. In each case the electric field is symmetrical about the axis and varies in intensity from center to periphery of the guide in known manner. In the TE_{01} mode the phase is the same from axis to periphery, as indicated by the arrows. In the TE_{02} mode the phase is the same from the axis out to a cylindrical node of radius ρ_1 equal to $0.546 a$ where a is the radius of the

guide, and the opposite relative phase prevails in the tubular zone extending from that node to the periphery. In the TE_{03} mode there are three such "cophasal" zones, viz., a central zone extending from the axis to a node of radius ρ_1 equal to $0.377 a$; an outer cophasal zone, of the same phase as the first, extending from a node of radius ρ_2 equal to $0.690 a$ to the periphery; and a third cophasal zone, opposite in phase relative to the other two and lying between them.

I have found that if in a wave guide carrying the TE_{01} mode, as in A, dielectric material be placed in one or the other of the two cophasal zones of B, some of the energy of the operating mode will be converted into the TE_{02} mode, and further that any tendency to generate non-circular modes can be reduced by disposing the dielectric material symmetrically about the axis of the guide, i. e., in the form of a (solid or hollow) cylinder coaxial with the guide. The maximum generation of the TE_{02} mode occurs if the dielectric just fills the inner cophasal zone, i. e., the space from the axis of the guide to the first node of the electric field, as illustrated in Fig. 5, or if it just fills the outer cophasal zone, i. e., the space between the first node and the metal shell 10 of the guide, as illustrated in Fig. 6. The two dielectric elements 21, 22, of Figs. 5 and 6, assuming them to be of the same length, are complementary in that the TE_{02} waves they generate are equal in amplitude and opposite in phase. This can be readily appreciated on observing that the two (generalized) cylinders together would form a solid dielectric plug filling the guide and that such a plug would generate no modes other than TE_{01} under the influence of a pure TE_{01} wave.

Similarly, the most efficient disposition of dielectric material for the generation of the TE_{03} mode is in the form of a hollow cylinder or tube 13 just filling the intermediate cophasal zone, as illustrated in Fig. 7, or in the form of a pair of cylinders 24, 25, one just filling the inner cophasal zone and the other a tube just filling the outer one, as illustrated in Fig. 8. The dielectric structures in Figs. 7 and 8, respectively, are complementary to each other with respect to the generation of the TE_{03} mode or any other mode.

The same principles are applicable to other guide shapes and modes generally, excepting only unusual cases where the electric field vector of the mode to be generated is perpendicular at every point to the electric field vector of the operating mode. The cophasal zones can be identified readily by superposing the electric field diagrams of the operating mode and the mode to be derived, and marking the boundaries between regions in which the electric vector of the operating mode (or, more generally, the projection thereof) coincides in direction and phase with the electric vector of the other mode, and similar regions in which the relative phases are reversed. Diagram D in Fig. 4, for example, illustrates the dominant mode TE_{10} in a guide of rectangular cross section, while at E are illustrated the TE_{20} mode in the same guide, the two equal cophasal zones that appear, and the disposition of dielectric material in one of the two cophasal zones for maximum conversion of wave power from the first of these modes to the second. For maximum generation of the TE_{30} mode the dielectric material may fill the central one of the three equal cophasal zones shown at F in Fig. 4 or it may fill both of the adjoining zones which constitute a cophasal region of the opposite relative phase.

The specific dimensions that have been assigned to the dielectric mode transducers of Figs. 5 to 8 are, as indicated, those that, with a given dielectric material, yield maximum generation of a prescribed secondary mode for a given over-all length of transducer, and it has been pointed out that complementary transducers are equally effective. In various practical applications of the invention, however, other factors than maximum generation are significant or even controlling and they may

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dictate the choice of one transducer over another or call for modification of the dimensions given. One such factor is ease of fabrication, or mechanical support for the dielectric members. The tubular dielectric member in Fig. 6, e. g., is self-supporting within the guide; the complementary dielectric member in Fig. 5 is not. The latter can be supported by a contiguous dielectric plug; or if the transducer is interposed in a wave guide that is filled with solid dielectric material it can be supported by a surrounding tube of that same material. In some cases another factor, the total volume of dielectric material required, may favor the choice of one design instead of another.

Another factor in the design of a dielectric mode transducer that may be significant in certain circumstances is the tendency of the transducer to generate modes other than the prescribed secondary mode or modes. The transducers of Figs. 5 and 6, for example, generate the TE_{03} mode in some slight degree, because the dielectric fills one of the like-phased cophasal zones of this mode (Fig. 4C), and thus tends to generate the TE_{03} mode but it does not extend quite the proper distance into the adjacent oppositely-phased zone to effect cancellation. A secondary mode so generated will be suppressed, however, if its cut-off frequency is greater than the operating frequency, i. e., if the guide be of sufficiently small size. If not so suppressed it may happen to be of such amplitude and phase as to oppose and reduce a wave component of the same mode originating elsewhere in the guide. The generation of any particular secondary mode can be obviated, in any event, by so disposing the dielectric material of the mode transducer that any dielectric material in one cophasal zone of that mode is balanced by dielectric material in a cophasal zone of the opposite phase. Applying this principle to the transducers of Figs. 5 and 6, for example, it will be found that if the indicated radius is changed from $0.546 a$ to $0.529 a$ none of the TE_{03} mode will be generated.

Still another factor is the relation between the dielectric constants of the several dielectric media, that is, the two dielectric media in the transducer section and the dielectric medium in the adjoining sections of guide. The more closely the average or effective dielectric constant in the transducer section approximates the dielectric constant in the adjoining sections, the more completely is the transducer reflectionless. The more nearly alike the dielectric constants of the media in the transducer section the lower are internal reflections and reflection losses in composite transducers. The greater, too, is the length of transducer required, and in some cases this in itself is advantageous. It will be understood, then, that as a special case the adjoining guide may contain a solid dielectric medium and the transducer may comprise a first dielectric of the same or lower dielectric constant and a second dielectric (a gas, for example) of still lower dielectric constant.

Consistently with the foregoing principles of mode transducer design, and as illustrated in Figs. 2 and 3, conversion between TE_{01} and TM_{11} modes in a round guide can be effected by a dielectric obstacle placed on one side or the other of the diametral plane of symmetry of the TM_{11} mode. The maximum rate of conversion is obtained if the obstacle is of semi-circular cross section, as in Fig. 3 where it completely fills one of the cophasal zones.

If in Fig. 1 the natural mode selected for propagation through the bend 11 is either the $TE_{01}+TM_{11}$ mode or the $TE_{01}-TM_{11}$ mode the transducer 12 is required to translate half of the TE_{01} wave power supplied to it into a TM_{11} component that is oriented with its diametral plane of symmetry perpendicular to the plane of the bend, as indicated in Fig. 2, and that has the proper phase relative to the TE_{01} component. For this purpose the transducer may take the specific form illustrated in Figs. 1A

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and 2 where the cross section of the dielectric member appears as sector of half-angle α disposed with the bisector in the plane of the bend and directed toward or away from the center of curvature depending on which of the two mentioned natural modes is chosen. If the $TE_{01}+TM_{11}$ mode be chosen, the dielectric is disposed toward the outside of the bend, that is, with the bisector directed away from the center of curvature of the bend. The length l and the half-angle α of the transducer affect both the amplitude and relative phase of the generated TM_{11} component, and they may be calculated as follows.

The half-angle α is a function only of the ratio $\nu=\lambda/\lambda_c$, where λ is the free wavelength corresponding to the operating frequency and $\lambda_c=2\pi a/3.8317$ is the cut-off wavelength for the TE_{01} and TM_{11} modes in a straight guide of the given radius a . α in radians satisfies the equation

$$\cos \alpha = \frac{\sqrt{1-\nu^2}}{0.1957+0.4641 \nu^2} \quad (1)$$

where $0 < \alpha < \pi$.

With α so determined, the required length l of the mode transducer is given by

$$l = \frac{\lambda}{0.6823(\epsilon_r - 1) \sin \alpha} \quad (2)$$

where ϵ_r is the relative dielectric constant of the transducer material, and it is assumed that ϵ_r does not differ much from unity.

The second mode transducer, 13, may be of exactly the same construction as transducer 12 and disposed in the same way relative to the bend.

A disadvantage of the embodiment last described is that Equation 1 yields a real value of α only for values of ν ranging from 0.85 to unity. That is, the operating frequency must be closer to the cut-off frequency than will be found desirable in many instances in practice.

The foregoing disadvantage is avoided and various advantages are secured in an alternative embodiment of the invention that makes use of another of the natural modes of wave propagation in the bend, viz., the TM_{11} mode. In this embodiment the dielectric obstacle comprising each transducer is semicircular in cross section and disposed with its diametral surface in the plane of the bend, as illustrated in Figs. 1B and 3. The length l of the obstacle is that required for the complete conversion of TE_{01} waves into TM_{11} waves, and this may be easily determined empirically or by calculation as follows:

$$l = \frac{2.073\lambda}{\epsilon_r - 1} \quad (3)$$

where λ is the free-space wavelength corresponding to the operating frequency.

In a specific illustrative example, λ is 1.25 centimeters, a is 2.54 centimeters, ν is calculated to be 0.300, ϵ_r is 1.0200, and l is 130 centimeters.

In the empirical determination of the length l one need only assemble semicircular plates of the dielectric material in the guide, one after another, until test shows no residue of power in the TE_{01} mode.

To hold the dielectric transducer members in place various expedients may be employed. For example, discs of the same dielectric material may be attached, integrally or otherwise, to the ends of the members, as shown in Fig. 1, and cement may be used to prevent longitudinal or rotational displacement. The transducers described do not tend to generate modes other than TM_{11} in any substantial degree since all modes other than TM_{11} differ in phase velocity from the TE_{01} mode. Hence over a distance of many wavelengths these other modes will phase in and out so often that the net power transfer will be small.

Numerous other embodiments within the spirit and

scope of the invention, in addition to those specifically described herein, will be obvious to those skilled in the art.

What is claimed is:

1. In combination, an elongated substantially circular wave guide having two straight sections and a curving bend section interconnecting said straight sections, means for generating electromagnetic waves of the TE_{01} mode coupled to one of said straight sections of wave guide, and means for interconverting electromagnetic wave energy between the TE_{01} mode in said straight sections and a natural mode of said curved section, said means including two elongated substantially sector-shaped dielectric obstacles each of which have a relative dielectric constant greater than 1.0 but less than 1.1 located respectively in said two straight sections of wave guide adjacent said curved section.

2. In combination, an elongated substantially circular wave guide having two straight sections and a curving bend section interconnecting said straight sections, means for generating electromagnetic waves of the TE_{01} mode coupled to one of said straight sections of wave guide, and means for interconverting electromagnetic wave energy between the TE_{01} mode in said straight sections and a natural mode of said curved section, said means including two elongated substantially sector-shaped dielectric obstacles each of which has a relative dielectric constant greater than 1.0 but less than 1.1 located respectively in said two straight sections of wave guide on one side of a diametral plane parallel to the plane of the curved section of wave guide.

3. In combination, an elongated substantially circular wave guide having two straight sections and a curving bend section interconnecting said straight sections, means for generating electromagnetic waves of the TE_{01} mode coupled to one of said straight sections of wave guide, and means for interconverting electromagnetic wave energy between the TE_{01} mode in said straight sections and a natural mode of said curved section, said means including two elongated substantially sector-shaped dielectric obstacles each of which has a relative dielectric constant greater than 1.0 but less than 1.1 located respectively in said two straight sections of wave guide adja-

cent said curved section, said dielectric obstacles being symmetrically oriented with respect to a diametral plane parallel to the plane of the curved section of wave guide and passing through the center thereof.

4. In combination, a microwave frequency wave guide transmission line of circular cross-section, said line comprising at least two straight portions interconnected by a curved portion, said line being adapted to transmit wave energy of the TE_{01} mode, means for eliminating the degeneration of the TE_{01} mode wave energy into unwanted modes of wave energy while traversing a curved portion of said wave guide transmission line, said means comprising a pair of mode converters, one of said converters being situated in said wave guide immediately adjacent each end of said curved portion, respectively, said mode converters each comprising elongated substantially sector-shaped dielectric obstacles, said mode converters converting TE_{01} mode wave energy into TM_{11} mode wave energy and TM_{11} mode wave energy into TE_{01} mode wave energy, respectively, whereby TE_{01} mode wave energy entering said curved portion of wave guide is converted into TM_{11} wave energy and TM_{11} wave energy emerging from said curved portion is converted into TE_{01} mode wave energy, and no degeneration of said TE_{01} mode wave energy into unwanted modes of wave energy occurs.

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