

April 23, 1963

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3,087,130

WAVEGUIDE ELBOW

Filed March 8, 1962

3 Sheets-Sheet 1

FIG. 1

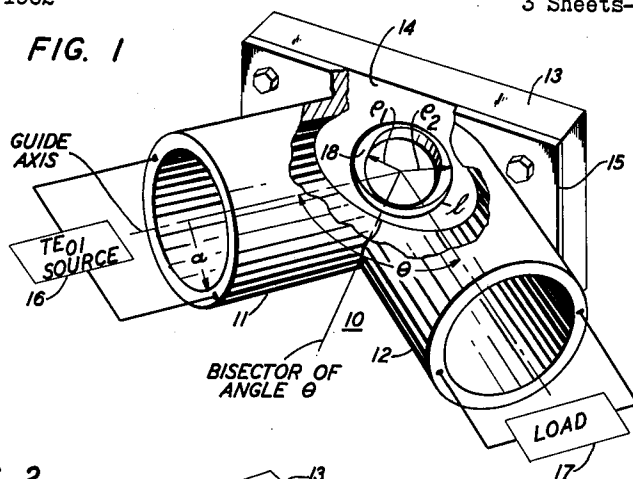


FIG. 2

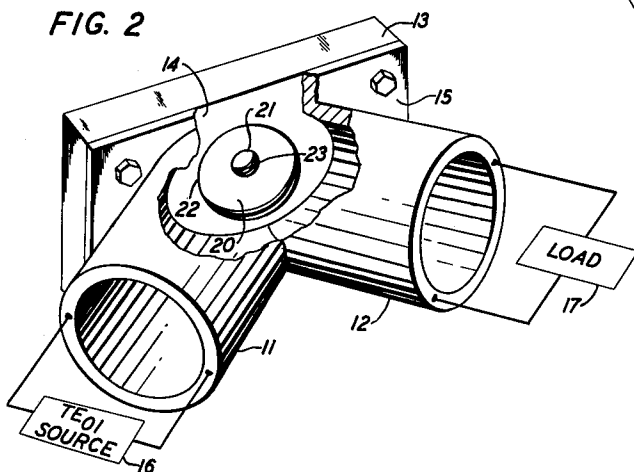
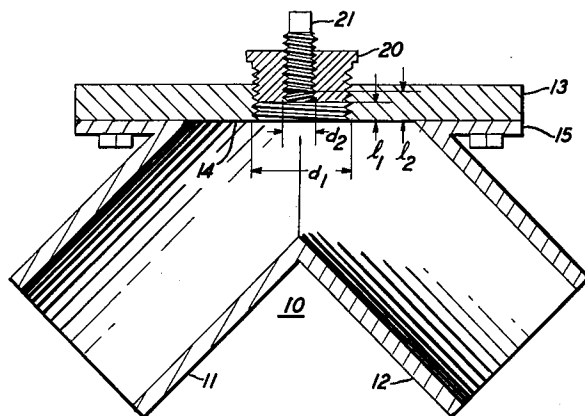


FIG. 3



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FIG. 4

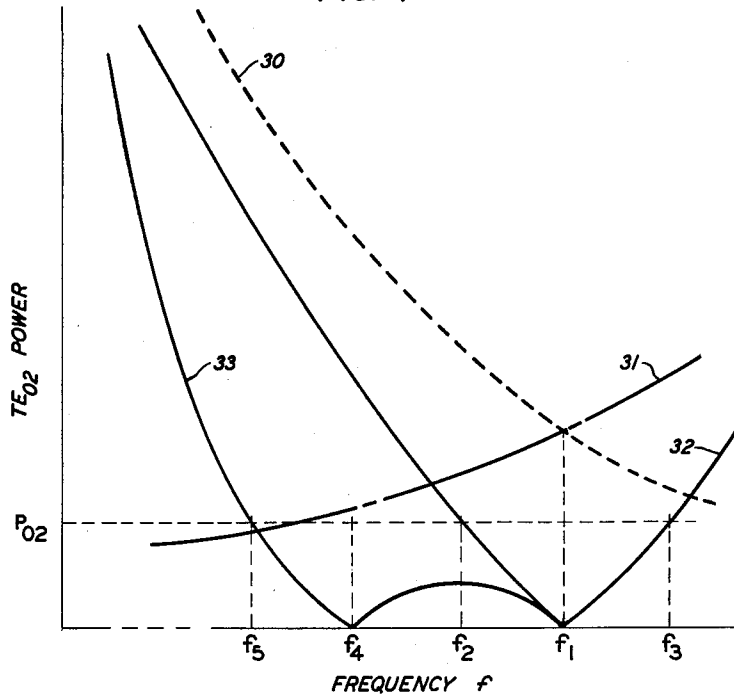


FIG. 5

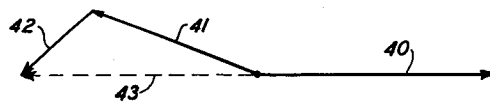
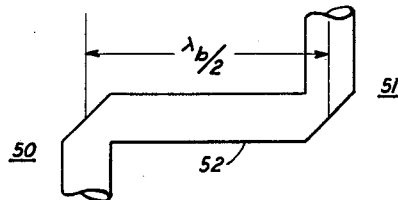


FIG. 6



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FIG. 7

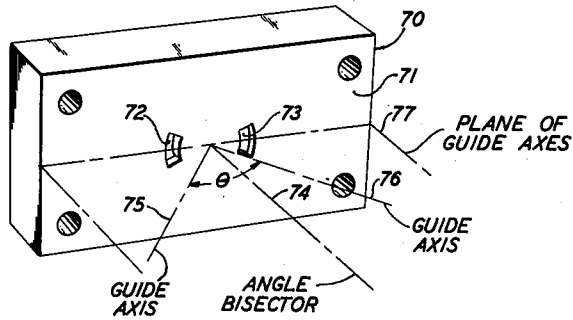


FIG. 8

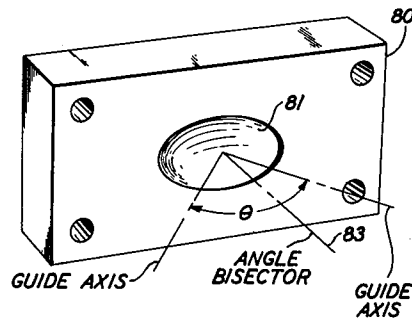


FIG. 9

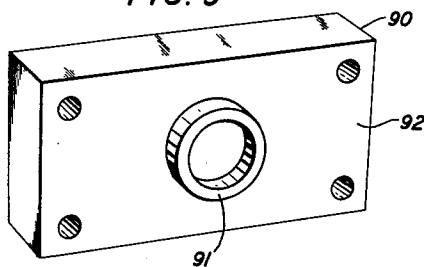
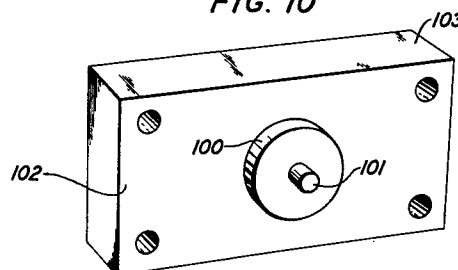


FIG. 10



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WAVEGUIDE ELBOW

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14 Claims. (Cl. 333-98)

This invention relates to electromagnetic wave transmission systems and, more particularly, to miter elbows for use in such systems. The invention has particular application to systems in which the wave energy propagates in the circular electric mode.

As is well known, the propagation of electromagnetic wave energy in the form of the circular electric TE_{01}° mode in circular waveguides is ideally suited to the long distance transmission of high frequency, wide band signals since the attenuation characteristic of this transmission mode, unlike that of other modes, decreases with increasing frequency. However, since the TE_{01}° mode is not the dominant mode supported in a circular waveguide, energy may be lost to lower order modes capable of transmission therein. Furthermore, it is desirable from loss considerations to propagate the TE_{01}° mode wave in waveguides whose physical dimensions are substantially larger than those dictated by cut-off considerations. Thus, the transmission medium used to guide TE_{01}° mode wave energy is inherently multimode with respect to modes of higher order than the preferred mode as well as with respect to modes of lower order.

In the January 1961 issue of The Bell System Technical Journal, volume 40, No. 1, there are numerous articles describing various circuit components intended for use in transmission systems propagating wave energy in the circular electric mode. In particular, the article by E. A. J. Marcatili and D. L. Bisbee, entitled "Band-Splitting Filter," pages 197 to 212, describes a miter elbow to change the direction of wave propagation in a transmission system operating in the TE_{01}° mode.

Typically, a miter elbow comprises a pair of intersecting waveguides arranged so that their axes intersect at some given angle. A reflecting, planar surface for changing the direction of propagation through said angle is placed so as to pass through the point of intersection of the guide axes and is oriented with its reflecting surface perpendicular to the bisection of the angle between the guide axes. Bends at any desired angle can thus be made.

It has been found, however, that a miter elbow of the type described in the aforementioned article, causes mode conversion from the preferred TE_{01}° mode to other spurious modes.

It is, accordingly, an object of the invention to minimize the amount of wave energy coupled to a particular spurious mode in a miter elbow propagating wave energy in the TE_{01}° circular electric mode.

It is a more specific object of the invention to induce out-of-phase components of the spurious mode wave which tend to cancel at the output of the elbow.

In accordance with the principles of the invention out-of-phase components which tend to cancel at the output of the elbow are induced by distorting the wavefront of the incident wave. In particular, the wavefront is distorted by delaying a portion of the incident wave. By adjusting the size and shape of the delay means, the net power loss due to conversion to a particular spurious mode, such as for example, the TE_{02}° mode, is substantially eliminated. In an elbow designed to propagate circular electric mode wave energy, the delay means are symmetrically located about the bisector of the angle between the intersecting guide axes.

While the principles of the invention can be used to

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cancel other spurious modes, the higher order circular electric modes and, in particular, the TE_{02}° circular electric mode, are the most troublesome since they cannot be eliminated with simple helical mode filters. Accordingly, in the various illustrative embodiments to be described hereinafter reference is particularly made to the TE_{02}° mode. This, however, is not intended to limit the scope of the invention to this particular mode. Thus, it is to be understood that the structures disclosed can readily be adapted to eliminate other spurious modes. In addition, the principles of the invention are equally applicable to multimode waveguides of other geometries propagating wave energy in modes other than the circular electric mode.

In a first specific embodiment of the invention for use in circular electric mode systems, the delay means employed comprise an annular depression in the planar reflecting surface of the elbow. In a second embodiment, a pair of concentric depressions are used whose size and shape are adjustable by means of a pair of concentric screws. Alternatively, the entire reflecting surface can be curved or compensating discontinuities can be placed essentially in the region of the reflecting surface which intersects the plane defined by the axes of the two waveguides.

Various other embodiments are disclosed in which delay is produced by means of one or more dielectric members of suitable size and shape.

Because a compensated elbow of the type described is relatively narrow band, a pair of elbows, suitably separated, are advantageously used. With the mode conversion for each elbow minimized at a first frequency by spacing the elbows at a distance equal to half the TE_{01}° - TE_{mn} beat wavelength at a second frequency, the conversion to TE_{mn} mode wave energy can be reduced over a greater band of frequencies. Besides broadbanding the range of frequencies for which the TE_{mn} conversion is reduced, the use of two elbows permits having any angle between the input and output waveguides.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 shows a first embodiment of a compensated miter elbow in accordance with the invention having an annular depression in the reflecting surface;

FIG. 2 is a second embodiment of the invention having a pair of coaxial depressions in the reflecting surface;

FIG. 3 is a cross-sectional view of the embodiment of FIG. 2;

FIG. 4, given by way of illustration, shows the level of TE_{02}° mode wave energy produced at a miter elbow for various conditions of operation;

FIG. 5 is a vector diagram showing the various components of TE_{02}° mode wave energy induced in the elbow at the frequency for which TE_{02}° mode wave energy is a minimum;

FIG. 6 shows a pair of miter elbows separated at half the beat frequency to increase the bandwidth over which TE_{02}° mode energy is below a given maximum level;

FIGS. 7 and 8 show two alternate embodiments of the invention; and

FIGS. 9 and 10 show two additional embodiments of the invention using dielectric delay means.

Referring to FIG. 1, there is shown a miter elbow 10 in accordance with the invention. Elbow 10 comprises a pair of substantially similar circular waveguides 11 and 12 of radius a whose respective axes intersect at an angle θ . Guides 11 and 12 are proportioned to support the TE_{01}° circular electric mode at an operating frequency

f_1 and at least the next higher order (TE_{02}°) circular electric mode. In practice, the diameters of guides 11 and 12 are sufficiently large so that wave energy at the operating frequency is far above cut-off. In embodiments of the invention built and tested, an inside guide diameter of two inches was utilized successfully at operating frequencies of from 35 to 80 kilomegacycles. Since a two inch guide diameter corresponds to a TE_{01}° mode cut-off frequency of 7.7 kilomegacycles, the above operating range represents frequencies at least five times the cut-off frequency. So proportioned, the propagating wave energy exhibits significant optical propagating properties. The significance of this is explained in some detail in the copending application of E. A. J. Marcantili and D. H. Ring, Serial No. 77,928, filed December 23, 1960.

Metallic member 13, having a reflecting surface 14 which passes through the point of intersection of the guide axes, is oriented with its face perpendicular to the bisector of angle θ . The reflecting surface 14 is common to both waveguides and extends completely across the full cross-sectional area of both guides.

Guides 11 and 12 are shown mounted on a flange 15 and member 13 is illustrated as bolted to the flange 15. However, any other suitable means for mounting the intersecting guides and reflecting member can be employed.

A source of TE_{01}° circular electric mode wave energy 16 is connected to guide 11 and a load 17, adapted to utilize wave energy in the TE_{01}° mode, is connected to guide 12.

In accordance with the teachings of the invention, the conversion of TE_{01}° mode wave energy to TE_{02}° mode wave energy is minimized by delaying a portion of the incident TE_{01}° mode wave at the reflecting surface 14. In the embodiment of FIG. 1, delay is obtained by means of an annular depression 18 in member 13, whose center lies along the bisector of angle θ .

For the particular case where θ equals ninety degrees, the conversion of TE_{01}° mode wave energy to TE_{02}° mode wave energy is approximately proportional to

$$S_{02} = \frac{2 \left(e^{-i \left(\frac{2\pi}{\lambda} \right) 2.83l} - 1 \right)}{J_0(r_1) J_0(r_2)} e^{-i(\Gamma_{02} - \Gamma_{01})a} \int_{\bar{\rho}_1}^{\bar{\rho}_2} J_1(r_1 \rho) J_1(r_2 \rho) \rho d\rho$$

where

S_{02} is the TE_{02}° scattering coefficient due to the annular depression 18 (in amplitude and phase),

$$\Gamma_{0n} = \frac{2\pi}{\lambda} \sqrt{1 - \left(\frac{r_n \lambda}{2\pi a} \right)^2} \quad (\text{in which } n=1, 2)$$

J_0 is the Bessel function of the first kind and zero order,

$i = \sqrt{-1}$,

a is the guide radius,

$r_1 = 3.832$,

$r_2 = 7.016$,

γ = free space wavelength at the operating frequency, and

$$\bar{\rho}_n = \frac{1 + \frac{1}{\sqrt{2}}}{2} \rho_n \quad (\text{in which } n=1, 2)$$

The TE_{02}° scattering coefficient of an uncompensated elbow is given by

$$\bar{S}_{02} = 0.019 \left(\frac{\lambda}{a} \right)^{3/2} r_1 r_2 \left[\frac{1 - \left(\frac{r_2 \lambda}{2\pi a} \right)^2}{1 - \left(\frac{r_1 \lambda}{2\pi a} \right)^2} \right]$$

The dimensions of the annular recess for minimum TE_{02}° mode conversion are determined by setting

$$S_{02} + \bar{S}_{02} = 0$$

For the special case where $\rho_1 = 0$, the annular depression 18 degenerates into a simple circular cylindrical re-

cess whose axis lies along the bisector of angle between the guides. A practical embodiment of this special case, shown in FIG. 2, comprises a pair of coaxial metallic screws 20 and 21 mounted in member 13. The axes of the screws are colinearly aligned with the bisector of angle θ .

Screw 20 is threaded into an aperture 22 in member 13 and screw 21 is, in turn, threaded into an aperture 23 in screw 20. Each of these screws is independently adjustable with respect to member 13 and with respect to each other. Preferably, the inner faces of the screws are smooth, planar surfaces, extending in a direction parallel to surface 14 such that a smooth, continuously reflective surface is obtained when the screws are positioned with their inner faces flush with the reflective surface 14.

A cross-sectional view of the miter elbow of FIG. 2 is shown in FIG. 3. Corresponding identification numerals are used in FIGS. 1, 2 and 3 to facilitate identifying the various common components of the elbows.

The operation of the compensated miter elbow of FIG. 2 can best be explained with reference to FIGS. 4 and 5. FIG. 4 shows the level of TE_{02}° mode wave energy produced in the elbow for various conditions of operation. With both screws 20 and 21 positioned with their inner faces flush with the reflective surface 14, the conversion of wave energy to the TE_{02}° mode decreases with increasing frequency as depicted by curve 30 in FIG. 4. If now the screws are displaced so as to produce a depression in the surface of reflector 14, a discontinuity in the wave path is produced. In the region of the discontinuity, the wave path is lengthened and the TE_{02}° mode wave produced is delayed in phase with respect to the rest of the TE_{02}° mode wave induced in the elbow. The amplitude of the TE_{02}° mode wave induced at the discontinuity is primarily a function of the diameters d_1 and d_2 of apertures 22 and 23. The relative phase of the TE_{02}° mode waves induced is primarily a function of the depths l_1 and l_2 of apertures 22 and 23. Because the apertures 22 and 23 seem bigger to wave energy at higher frequencies, the net result is to induce a second component of TE_{02}° mode wave energy which increases in amplitude as a function of frequency. This is illustrated by curve 31 in FIG. 4.

The net conversion to TE_{02}° mode wave energy for the corrected elbow, given by curve 32, is the difference between curve 30 and 31. As can be seen, curve 32 has a null point at frequency f_1 .

The situation at frequency f_1 is illustrated by the vector diagram of FIG. 5 in which vector 40 represents the amplitude and phase of the TE_{02}° mode wave generated in the uncompensated elbow and vectors 41 and 42 represent the phase and amplitude, respectively, of the TE_{02}° mode wave induced by the discontinuity introduced by screws 20 and 21. At frequency f_1 , the sum of the three vectors is zero and no net TE_{02}° mode wave energy propagates away from the elbow. It will be noted that if only a single screw (i.e., 20) is used, it is possible to align vector 41 so as to be equal in amplitude and opposite in phase to vector 40 thereby making the cancellation with but a single discontinuity. As a practical matter, however, this would be an extremely critical adjustment. Accordingly, two or more discontinuities are to be preferred.

In FIGS. 2 and 3, l_2 is shown larger than l_1 . This, however, is not necessarily the situation in all cases. The position of screw 21 relative to screw 20 depends upon the amplitude and phase of the component of TE_{02}° wave energy produced primarily by screw 20. Referring to the vector diagram of FIG. 5, it can be seen that depending upon the phase of vector 41, the delay induced by screw 21 (the phase of vector 42) may be greater than ($l_2 > l_1$) or less than ($l_2 < l_1$) that produced by screws 20.

Referring again to FIG. 4, it is seen that the net TE_{02}°

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mode wave energy generated in the corrected elbow is a minimum at frequency f_1 but increases at frequencies above and below f_1 . If P_{02} is the maximum permissible TE_{02}° power at any frequency which can be tolerated in the system, it is seen that the usable bandwidth of the corrected elbow extends from frequency f_2 to frequency f_3 .

In FIG. 6, there is shown schematically a method for increasing the usable bandwidth from frequency f_2 to some lower frequency by the addition of a second elbow 51 spaced a distance

$$\frac{\lambda_b}{2}$$

from a first elbow 50, where λ_b is the TE_{01}° - TE_{02}° beating wavelength at some arbitrarily selected frequency f_4 lower than f_2 . If λ_{01} and λ_{02} are the guided wavelengths of the TE_{01}° and the TE_{02}° modes at frequency f_4 , then the beat wavelength is given by

$$\lambda_b = \frac{\lambda_{01}\lambda_{02}}{\lambda_{02} - \lambda_{01}}$$

The over-all TE_{02}° conversion for the two elbows is given by curve 33 in FIG. 4. It will be noted that due to the particular spacing of the elbows a second null is introduced at frequency f_4 , thus reducing the level of the TE_{02}° mode conversion below the selected maximum level P_{02} between frequency f_3 and frequency f_5 .

In the illustration the mode conversion curve remains below P_{02} at all points between frequencies f_1 and f_4 . In practice, however, if the frequency difference ($f_4 - f_1$) selected is too great, the mode conversion may exceed the permissible level at some point between f_1 and f_4 . This places an upper limit on the amount of broadbanding that is possible using a second elbow, in the manner described.

It is apparent that if a frequency f_4 greater than f_3 is selected, the same technique can be used to extend the usable bandwidth upward.

While reference was made to the TE_{02}° mode in connection with the discussion of FIG. 6, the use of two compensated elbows to broaden the range of frequencies over which the spurious mode level is minimized can be applied to other spurious modes. Thus, designating the particular mode to be minimized more generally as the TE_{mn} mode, the elbows would be separated a distance given by

$$\frac{\lambda_b}{2} = \frac{\lambda_{01}\lambda_{mn}}{\lambda_{mn} - \lambda_{01}}$$

where λ_{mn} is the guide wavelength of the TE_{mn} mode.

In FIG. 7 there is illustrated an alternate arrangement for minimizing the spurious mode level in a miter elbow. Shown is the metallic member 70 having a planar reflecting surface 71 in which there are a pair of depressions 72 and 73. The depressions are symmetrically disposed about both the bisector 74 of the angle between the intersecting guide axes 75 and 76 and the plane 77 defined by said axes.

While all of the embodiments illustrated heretofore have utilized planar reflecting surfaces having lumped or discrete compensating arrangements, other arrangements can be used. Thus, for example, the entire reflecting surface can be made uniformly concave thereby producing a distributed compensating reflector. This is illustrated in FIG. 8 in which the entire reflecting surface 81 of member 80 common to the intersecting guides (not shown) is in the form of a concave surface that is symmetric about the bisector 83 of the angle formed by the two axes of the waveguides. The optimum curvature of surface 81, however, varies as a function of the ratio of the frequency to the guide diameter and as a function of the spurious mode that is to be suppressed.

In the embodiments of the invention described hereinabove, the requisite delay was produced by physically

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lengthening a portion of the wave path. However, the wave path can be electrically lengthened by placing a dielectric member in the wave path adjacent to the reflecting surface 14 whose dielectric constant is greater than that of the dielectric material filling guides 11 and 12. Two embodiments of the invention using dielectric delay means are illustrated in FIGS. 9 and 10.

FIG. 9 shows the metallic member 90 with an annular ring 91 of low loss, dielectric material mounted upon the reflecting surface 92 and centered about the bisector of the angle defined by the guide axes. The ring 91 is the electrical equivalent of the annular recess 18 of FIG. 1. The height of ring 91 from surface 92 and the width of the ring are a function of the dielectric constant of the dielectric material. The higher the dielectric constant, the smaller are its physical dimensions.

In the embodiment of FIG. 10 two concentric circular cylinders 100 and 101 are mounted on the reflecting surface 102 of member 103 and centered about the bisector of the angle defined by the guide axes. The composite dielectric structure is the electrical equivalent of the delay means illustrated in FIGS. 2 and 3. The relative heights of cylinders 100 and 101 are arrived at in the manner described above in connection with FIGS. 4 and 5.

While the various illustrative embodiments specifically described hereinabove have related to circular waveguide systems propagating wave energy in the circular electric mode, it is to be understood that the principles of the invention are equally applicable to other waveguide structures. For example, the same techniques can be employed in a multimode rectangular waveguide propagating waves in the TE_{10} mode. In such a system the particular discontinuities comprising the delay means would differ from those disclosed in that they would conform to the geometry of the TE_{10} mode. Thus, it is understood that the above-described arrangements are illustrative of only a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a guided wave transmission system supportive of wave energy in a first preferred mode of wave propagation and in at least a second, higher order mode of wave propagation;

means for changing the direction of propagation of said wave energy from a first direction of propagation to a second direction of propagation comprising a reflective surface oriented with said surface perpendicular to the bisector of the angle between said directions of propagation;

and means located along said reflective surface for delaying a portion of the wave incident upon said reflective surface with respect to other portions of such wave.

2. In a guided wave transmission system supportive of wave energy in a first preferred mode of wave propagation and in at least a second, higher order mode of wave propagation;

a first waveguide propagating wave energy in a first direction;

a second waveguide propagating wave energy in a second direction intersecting said first waveguide;

means for changing the direction of propagation of said wave energy from said first direction of propagation to said second direction of propagation comprising:

a metallic member having a planar, reflective surface oriented with the plane of said surface perpendicular to the bisector of the angle between said directions of propagation and passing through the point of intersection of said waveguide axes;

and means for delaying of a portion of the wave en-

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ergy incident upon said surface comprising a depression in said metallic member.

3. The combination according to claim 2 wherein said delay means comprises an annular depression whose center is located along the bisector of the angle between said directions of propagation.

4. The combination according to claim 2 wherein said delay means comprises a circular cylindrical depression whose axis lies along the bisector of the angle between said directions of propagation.

5. The combination according to claim 2 wherein said delay means comprises a pair of depressions symmetrically situated with respect to both said angle bisector and to the plane defined by the guide axes.

6. In a guided wave transmission system supportive of wave energy in a first preferred mode of wave propagation and in at least a second, higher mode of wave propagation;

a first waveguide propagating wave energy in a first direction;

a second waveguide propagating wave energy in a second direction intersecting said first waveguide;

means for changing the direction of propagation of said wave energy from a first direction of propagation to a second direction of propagation comprising a metallic member having a planar, reflective surface oriented with said surface perpendicular to the bisector of the angle between said directions of propagation and passing through the point of intersection of said waveguide axes;

and means for delaying a portion of the wave energy incident upon said surface comprising at least one dielectric member located adjacent thereto.

7. The combination according to claim 6 wherein said dielectric member is in the form of an annular ring whose axis lies along the bisector of the angle between said directions of propagation.

8. The combination according to claim 6 wherein said dielectric member is in the form of a circular cylinder whose axis lies along the bisector of the angle between said directions of propagation.

9. In combination, first and second sections of circular waveguide supportive of wave energy at a given frequency in the circular electric TE_{01}° mode of wave propagation and in higher order circular electric modes including at least the TE_{02}° mode;

said guides intersecting at an angle θ ;

a metallic member having a planar, reflective surface extending across said guides;

said surface oriented at an angle $(90-\theta/2)$ with respect to the longitudinal axes of said guides and passing through their point of intersection;

said member having at least one circular cylindrical depression of adjustable dimension at its center.

10. A miter elbow for changing the direction of propagation of circular electric mode wave energy comprising:

first and second sections of circular waveguide supportive of wave energy at a frequency f_1 in the TE_{01}° circular electric mode and in higher order circular electric modes including at least the TE_{02}° mode;

said guides positioned with their longitudinal axes intersecting at an angle θ ;

means for changing the direction of wave propagation from said first guide to said second guide comprising

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a metallic member having a planar, reflective surface extending across said guides;

said member being oriented with its surface perpendicular to the bisector of angle θ ;

a pair of coaxial cylindrical metallic elements mounted in said member with the axes of said elements collinearly aligned with the bisector of angle θ ;

and means for independently varying the position of each of said elements with respect to said surface.

11. In a guided transmission system supportive of wave energy at a frequency f_1 in the TE_{01}° circular electric mode and in at least a second, spurious TE_{mn}° mode;

a pair of miter elbows each compensated to minimize the conversion of said TE_{01}° mode wave to said spurious mode wave at said frequency f_1 ;

said elbows separated by a distance equal to half a beat wavelength λ_b at a second frequency f_2 where

$$\lambda_b = \frac{\lambda_{01}\lambda_{mn}}{\lambda_{mn} - \lambda_{01}}$$

in which λ_{01} and λ_{mn} are the guided wavelengths, respectively, of the TE_{01}° and TE_{mn}° mode wave at frequency f_2 .

12. The combination according to claim 11 where said spurious mode is the TE_{02}° circular electric mode and where

$$\lambda_b = \frac{\lambda_{01}\lambda_{02}}{\lambda_{02} - \lambda_{01}}$$

where λ_{02} is the guided wavelength of the TE_{02}° mode wave.

13. In a guided wave transmission system supportive of wave energy in a first preferred mode of wave propagation and in at least a second, spurious mode of wave propagation;

a first waveguide propagating wave energy in a first direction;

a second waveguide propagating wave energy in a second direction intersecting said first waveguide;

and means for changing the direction of propagation of said wave energy from said first direction to said second direction of propagation comprising:

a metallic member having a planar surface oriented with the plane of said surface perpendicular to the bisector of the angle between said direction of propagation and passing through the point of intersection of the axes of said waveguides;

said member having a concave reflecting surface extending over the total area of said member common to both of said waveguides.

14. A miter elbow comprising a pair of intersecting waveguides;

a metallic member extending across said waveguides in a direction perpendicular to the bisector of the angle between said waveguides and passing through the point of intersection of the axes of said waveguides; and at least one depression in the surface of said member common to both of said waveguides.

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