Aug. 11, 1959 D. A. LANCIANI 2,899,651

WAVEGUIDE BEND

Filed Jan. 3, 1955 2 Sheets-Sheet 1

Fig. 1

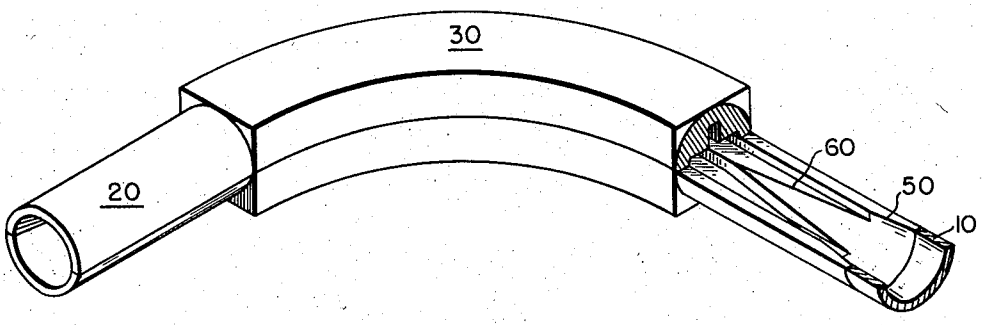


Fig. 3

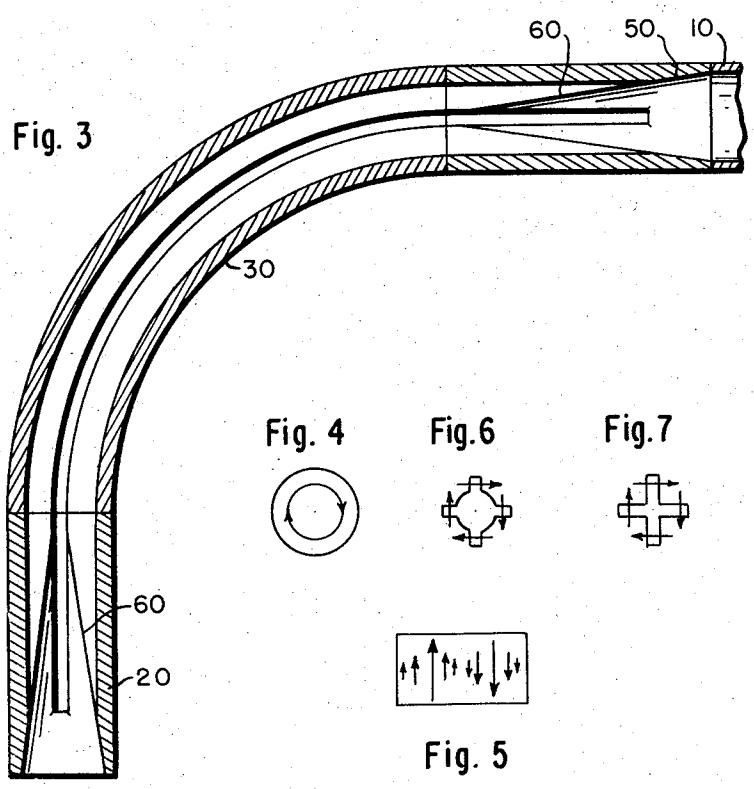


Fig. 2

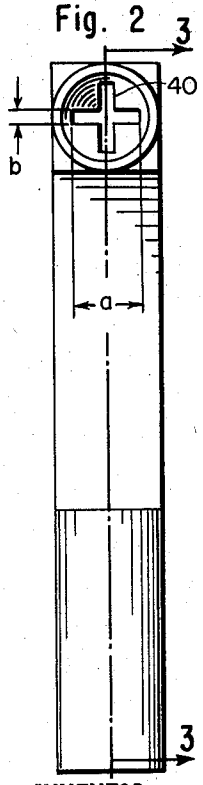


Fig. 4

Fig. 6

Fig. 7

Fig. 5

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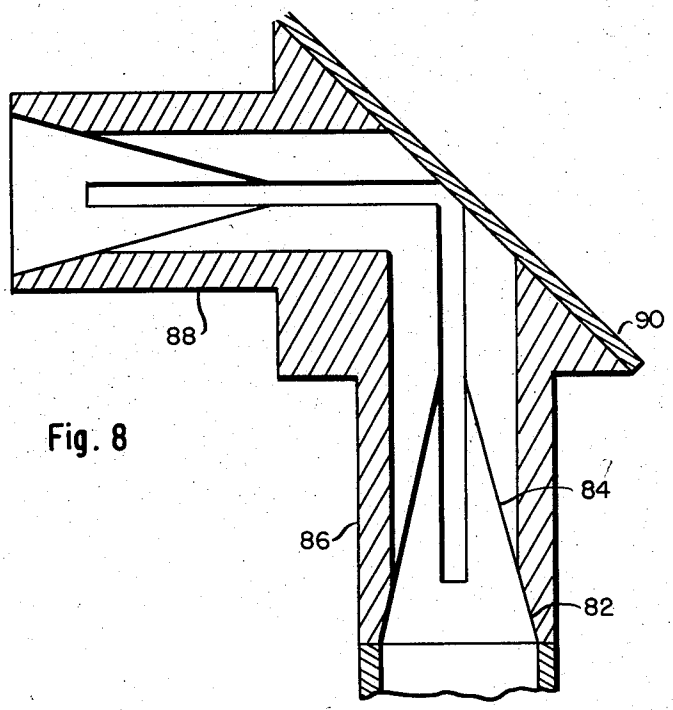


Fig. 8

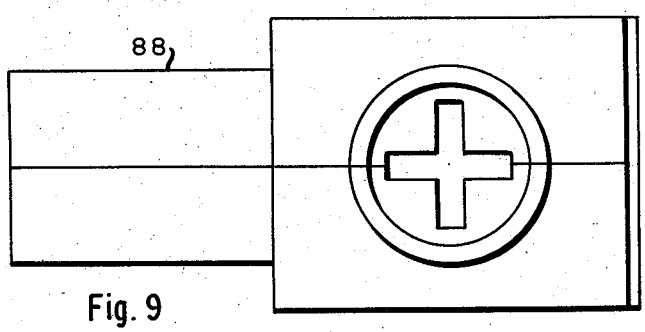


Fig. 9

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WAVEGUIDE BEND

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Application January 3, 1955, Serial No. 479,286

8 Claims. (Cl. 333—21)

This invention relates to waveguide bends and in particular to apparatus for propagating the TE_{01} mode of circular waveguide around bends or elbows without substantial loss of energy to spurious modes.

The TE_{01} mode of microwave energy which can be propagated in circular waveguides is well adapted to use in long distance microwave transmission since the attenuation of this mode decreases with increasing frequency, while the energy loss in other modes is increased as the frequency increases. However, this mode is not the dominant mode in a circular waveguide and, in fact, any disturbance as the TE_{01} mode is being propagated along a circular waveguide tends to excite other modes and produce serious attenuation.

A particularly severe problem arises from the fact that an attempt to bend a circular waveguide in which the TE_{01} mode is being propagated will result in serious losses of this nature, particularly due to the production of the TM_{11} mode which absorbs energy from the TE_{01} mode. It has, in the past, been necessary to form a bulky transition section from circular to rectangular waveguide, make the sharp bend or corner in the rectangular waveguide, and then have a second transition back to circular waveguide in order to propagate this mode around a corner. Transitions of this sort have been cumbersome and themselves associated with considerable attenuation. In addition, transitions interpose band width problems which have not been readily soluble.

Alternative constructions have utilized slotted bent sections in order to absorb the unwanted TM_{11} mode and have otherwise been designed to interfere with the formation of the TM_{11} mode and other spurious modes. A further awkward alternative has been the use of carefully designed double bends.

It is an object of this invention to provide a relatively simple and straight forward structure which will permit the propagation of the TE_{01} mode around curved bends or relatively sharp elbows with a high degree of mode purity and little attenuation. It is another object of this device to permit a relatively short bending radius and yet requires no bulky transition structures. It is a further object of this invention to eliminate the necessity for awkward double bends or for the precise orientation of structures inside of the waveguide to prevent the excitation of unwanted modes. As a result, the invention makes it possible to obtain bends having a radius of a foot or less for wavelengths of the order of 3 cm. and proportionately smaller radii at shorter wavelengths.

An understanding of the apparatus by which these results are achieved will be facilitated by the reference to the drawings, in which

Fig. 1 is a cut-away isometric view of the entire bend;

Fig. 2 is an end view looking into the bend;

Fig. 3 is a plan view taken on the section 3—3 in Fig. 2;

Fig. 4 is a vectoral illustration of the electric field distribution in a circular waveguide propagating the TE_{01} mode;

Fig. 5 is a vectoral illustration of the electric field across a rectangular guide propagating the TE_{20} mode;

Fig. 6 is a cross-section showing the mode coupling between the circular and cruciform waveguide cross-sections midway through the taper transitions;

Fig. 7 illustrates the electrical field distribution in the cruciform cross-section propagating the TE_{20} mode;

Fig. 8 is a sectional plan view of mitred cruciform right angle bend according to another embodiment of the invention; and

Fig. 9 is a side elevation of a mitred cruciform right angle bend according to Fig. 8.

The invention achieves the above-mentioned objectives by means of a pair of rectangular waveguides forming a cruciform cross-section in which there are generated two separate TE_{20} modes in crossed relationship. The generation of this mode in a cruciform cross-section is preferably achieved by means of a direct coaxial transition from the circular waveguide in which the TE_{01} mode is being propagated. This construction is shown in perspective in Fig. 1 and in sectional views in Figs. 2 and 3.

As illustrated in these views, the circular waveguides **10** and **20** are in axial registration with a section of rectangular waveguide **30** containing a cruciform cross-section **40**. The transition between the two types of sections preferably employs on each side a short tapered section **50** from the circumference of the circular guide to the outer edge of the cruciform followed by a conical cutaway section **60** in which the transition from TE_{01} to TE_{20} and back again is made gradually in a structure compatible with both modes. A principal advantage of this apparatus is the facility with which this transition can be made from one mode to the other employing if desired the conical or pyramidal transition having no abrupt discontinuities to foster unwanted modes. The transition may, of course, be stepped in accordance with conventional design procedures.

An understanding of this apparatus depends upon an understanding of the modes being propagated in its various sections. The TE_{01} mode is characterized by a circular electric field around the axis of the circular waveguide as shown in Fig. 4. This configuration is one in which none of the electric field lines terminate at the walls of the guide and the magnetic field at the wall surface is entirely longitudinal. As a result only transverse currents flow in the guide walls and the amount of attenuation caused by imperfectly conducting walls is markedly reduced. Unfortunately the TE_{01} wave has a relatively short cut-off length equal to approximately .82 times the guide diameter and there are four waves of equal or greater cut-off wavelength which may be propagated simultaneously unless the design is carefully controlled. Not only do imperfections and curves in the circular waveguide tend to produce unwanted modes, but tapers in the circular guide, particularly at higher frequences have been very difficult to operate successfully because of the tendency toward the production of higher order TE_{01} modes, where the latter are possible propagating modes.

The TE_{20} mode in a rectangular waveguide is illustrated in Fig. 5 and on superficial inspection would not appear to be in any way related to the TE_{01} mode in a circular guide either in appearance or in the shape of the structure in which it will propagate. However, it will be apparent from a more detailed consideration of the circular waveguide in Fig. 4 and the rectangular waveguide of Fig. 5 that if the electrical field vectors are properly superimposed the two modes can be made to have a useful relationship.

The invention creates such a relationship by the use of not one but two rectangular waveguides propagating what is substantially the TE_{20} mode, these two wave-

guides being formed to create a single cruciform opening. Such a cross-section is illustrated in Fig. 7. Propagation in such a cruciform takes place substantially independently in the two waveguides formed by the two opposed pairs of arms in the cruciform and each propagates a mode very similar to the pure TE_{20} mode in ordinary rectangular guides. To achieve the transition from the circular to the cruciform cross-section and back again it is preferable to use the shallow taper and transformer section referred to above. A direct transition might be possible but the formation of unwanted modes by a direct discontinuity makes an abrupt change in cross-section undesirable. To avoid this difficulty the transition **60** is employed which is formed by cutting away the solid material forming the arms of the cruciform to create a hollow conical cavity. For convenience the slope of the cone may be a continuation of the slope of the short taper section. The arms of the cruciform extend from the surface of the cone parallel to the axis of the cone and as the cone decreases in diameter a greater proportion of the microwave energy is propagated in the cruciform arms. Fig. 6 illustrates the simultaneous propagation in the circular and cruciform waveguides midway along the transition. Although the transition is illustrated in the form of a smoothly tapered cone it would be of course equivalent to use a stepped conical or pyramidal cavity designed for the specific wavelength in accordance with conventional practice in stepped transformers.

While a transition section is used in the preferred embodiment of this device, one of the features of this invention is the fact that the cruciform and the circular waveguide differ very little in maximum dimension and the one can be fed directly into the other. The discontinuities in the taper and the transition structure are minimized in this device and therefore the formation of spurious modes is avoided.

It is possible in the cruciform cross-section to use a mitered corner and re-taper back to the circular cross-section as illustrated by Figs. 8 and 9. However, this abrupt discontinuity tends to produce an excessive amount of mode impurity. Instead the preferred embodiment of the invention uses a curve in the cruciform cross-section, said curve having a radius large enough to minimize the differential phase shift between the E plane and the H plane portions of the bend. It can be shown that where there are E plane and H plane bends in rectangular waveguides of identical radius, the H plane bend will produce a greater phase shift from the equivalent E plane bend. In practice it can be shown that the guide wavelength of the H plane bend decreases with decreasing radius whereas the E plane bend wavelength is relatively unaffected. However, a shift in the H plane is not substantial until the radius becomes quite small. In fact, for X band standard waveguides it can be shown that the phase shift does not begin to rise substantially until the radius of the bend becomes less than one foot.

The difference in phase shift between an E plane and an H plane rectangular waveguide bend of identical radii can be derived from the formula

$$\theta=\frac{\pi^2 r}{\lambda g}$$

and is equal to

$$\pi^2 r\left(\frac{1}{\lambda gH}-\frac{1}{\lambda gE}\right)$$

The relative shift is thus a function of path length radius and guide wavelength. Assuming identical radii for the path length center lines in the cruciform section, it is apparent that bending radii on the order of one foot or less are possible for frequencies higher than 8 kilomegacycles, based on an acceptable level of mode impurities arising from unequal electrical path lengths. The predominant circular waveguide mode impurity arising from the unequal path lengths would be the TE_{21} mode.

Since the cruciform should have a cut-off wavelength approximately the same as that of the main circular waveguide, it is a relatively straightforward matter to calculate the dimensions of the cruciform once the dimensions of the circular waveguide have been determined. A circular waveguide propagating the TE_{01} mode has a cut-off wavelength equal to .82D where D is the waveguide diameter. The cut-off wavelength for the cruciform will be very close to that of the TE_{20} mode in a single rectangular waveguide which is equal to the wide dimension of such a waveguide. However it has been found that the cutoff wavelength in the cruciform is on the order of .9 in the wide dimension. It will be seen that with identical dimensions these two cross-sections would be very closely matched and would not need any taper, although the conical transition would still be desirable.

In the taper and transition sections from circular to cruciform cross-section a taper and transition of at least four times the wavelength being propagated was found to be desirable in order to minimize unwanted reflections. The overall insertion loss in this bend is approximately ¼ db over a greater than 6% band width and the loss for a bend in the 9.375 kmc. band is less than ⅛ db over the same percentage band width. In addition the use of these bends results in a mode purity of approximately 20 db.

An alternative construction for a bend of maximum compactness is illustrated in Figs. 8 and 9. In this construction the tapered section **82** and the transition section composed of the cruciform superimposed on a conical cavity **89** are the same as those shown for the gradual bends. However the cruciform is constructed in two straight sections **86** and **88** intersecting at right angles. The corner is mitred at 45° to the axis of each of the two intersecting cruciform sections and a conducting plate **90** is placed in the plane of the mitre cut. While the operation of this form of the invention is essentially the same as the gradual bend, there is a greater phase shift between the reflected waves between the E and H planes and somewhat greater tendency to produce spurious modes.

While this invention has been described in respect to two specific embodiments it will be understood that the invention is not restricted to these embodiments but rather to the principles disclosed herein as defined by the following claims.

I claim:

1. Apparatus for changing the direction of the TE_{01} mode in a circular waveguide which comprises a transition structure from circular waveguide to a waveguide having a cruciform cross-section in the shape of two intersecting rectangles of essentially constant width, a bent section of cruciform rectangular waveguide having the said cross-section, and a transition section transforming back from such cruciform to circular cross-section.

2. Apparatus for changing the direction of microwave energy propagating in the TE_{01} mode which comprises two circular waveguides capable of propagating the TE_{01} mode, two transition structures from circular waveguide to cruciform waveguide, joined by a curved cruciform waveguide whose cross-section has the shape of two intersecting rectangles of essentially constant width with the length of each arm of the cruciform waveguide of the same order of magnitude as the radius of the circular waveguide and having the axis of the cruciform waveguide in registration with the axes of the circular waveguides at either end.

3. Waveguide apparatus for propagating the TE_{01} mode around a bend which comprises two circular waveguides, a curved section of waveguide having a cruciform cavity in cross section in which two crossed modes resembling the TE_{20} mode of rectangular waveguide are propagated and a pair of axially symmetric transition sections at either end of said bend in axial alignment with the cruci-

form cross-section and with the circular waveguides whereby the TE_{01} mode transfers energy to the TE_{20} mode on entering the cruciform bend and transfers energy back to the TE_{01} mode on leaving the cruciform.

4. Waveguide apparatus for changing the direction of TE_{01} mode microwave energy propagating in circular waveguides with minimized attenuation which comprises two circular waveguides for propagating the TE_{01} mode, a bent cruciform waveguide whose cross-section has the shape of two rectangularly intersecting rectangles of essentially constant width, and two transformer sections between the circular and cruciform waveguides, said transformers being symmetrical in four quadrants about the axis of the circular waveguide and transferring energy from the TE_{01} mode in the circular waveguide to the TE_{20} mode in the cruciform cross-section.

5. Waveguide apparatus comprising a circular waveguide, a cruciform waveguide whose cross-section has the shape of two rectangularly intersecting rectangles of essentially constant width in axial alignment with the circular waveguide, and a transition structure separating the two waveguides and having a pyramidal cavity tapering between parallel walls from the center of the cruciform waveguide to the outer surface of the circular waveguide said cavity having slots along its surface which are in axial registration with the arms of the cruciform waveguide.

6. Waveguide apparatus for propagating the TE_{01} mode around a bend which comprises a circular waveguide, a tapering transition section having a length equal to at least three times the propagated wavelength, a pair of superimposed rectangular waveguides forming a cruciform having its axis in registration with the axis of the circular waveguide and having its widest dimension substantially equal to the widest dimension of the circular waveguide in order to propagate the TE_{20} mode, a bend in the cruciform cross-section having a radius substantially larger than four times the propagated wavelength and a second identical tapered transition from the cruciform to circular cross-section whereby the TE_{01} mode is reestablished in the circular waveguide.

7. Apparatus for changing the direction of energy propagating in the TE_{01} mode which comprises two circular waveguides, two transition structures from circular waveguide to cruciform waveguide, two cruciform waveguides whose cross-sections have the shape of two intersecting rectangles of essentially constant width in axial alignment with the circular waveguides and intersecting at right angles, and a conductive end plate at 45° to both axes through their point of intersection in a plane at right angles to the plane formed by the two axes.

8. Waveguide apparatus for propagating the TE_{01} mode around a bend which comprises: a circular waveguide; a first radially tapering transition section having substantially parallel longitudinal walls and having a length equal to at least three times the propagated wavelength; a pair of superimposed rectangular waveguides forming a cruciform having its axis in registration with the axis of the circular waveguide and having its widest dimension substantially equal to the widest dimension of the circular waveguide in order to propagate the TE_{20} mode, a circular bend in the cruciform cross section having a radius substantially larger than four times the propagated wavelength; and a second transition section, substantially identical to said first transition section, from the cruciform to circular cross section; whereby the TE_{01} mode is reestablished in the circular waveguide, the transition sections including axially tapering conical wall sections extending between the respective circular waveguides and the respective sides of the cruciform.

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