

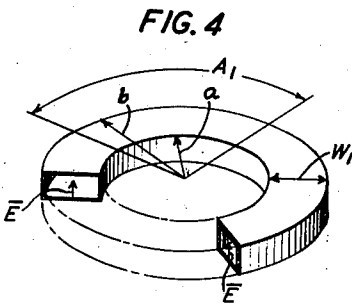
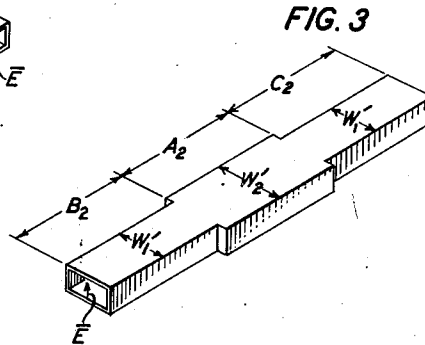
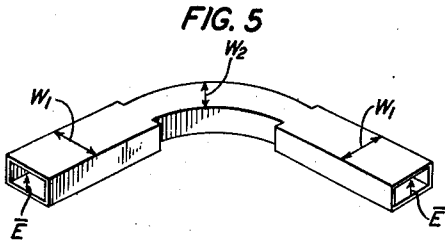
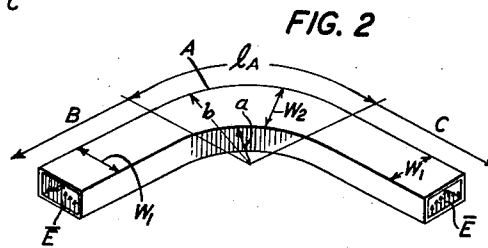
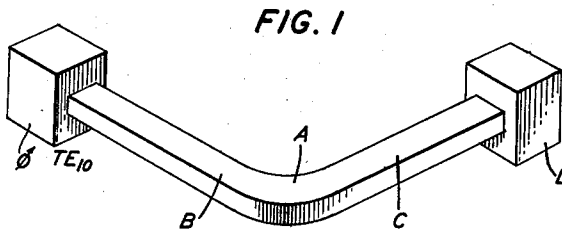
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MODE SUPPRESSION IN CURVED WAVE-GUIDE BENDS

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MODE SUPPRESSION IN CURVED WAVE-
GUIDE BENDS

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This invention relates to the guided transmission of ultra-high frequency electromagnetic waves, and more particularly to the suppression of undesirable wave reflection effects that are incident to changes in the direction of waveguide structures.

Practical wave-guide installations often require the use of considerable lengths of wave guide, and it is seldom that a guide can be installed directly between two distant points without undergoing changes in direction. Where it becomes necessary to introduce bends between sections of wave guide, great care is exercised in the design and construction of the bend in order to prevent wave reflections which are known to occur therein. It has been found, however, that even with bends designed in accordance with best known methods, sharp reflection and severe absorption effects occur over narrow frequency intervals of the operating frequency range in the vicinity of the cut-off frequency of the second order or TE_{20} transmission mode. It has been concluded by the present applicant that these effects are due in part, at least, to the fact that bending the guide increases the critical or cut-off wavelengths in the bend and to a resonance condition involving higher order modes generated in the bend.

Accordingly, it is an object of this invention to suppress reflections due to undesired transmission modes generated in curved wave-guide structures.

Another object of the invention is to provide an improved wave-guiding elbow for the transmission of ultra-high frequency waves around curved bends.

A further object is to provide a curved wave-guiding elbow operative over a wide frequency range.

In accordance with the invention the foregoing undesirable effects may be mitigated or eliminated by correlating the length of the bend and the operating signal frequencies or, more specifically, by correlating the frequency interval between the cut-off frequency of the straight wave-guide sections and the (lower) cut-off frequency of the curved guide with the length of the bend measured in terms of the wavelength of the higher order transmission mode.

In accordance with the invention, further, these effects are substantially eliminated by the use of a wave-guide elbow having a cut-off frequency for higher order transmission modes which is at least as high as the cut-off frequency

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of the main section of guide in which the elbow is to be used.

The nature of the present invention and other objects, features and advantages thereof will be apparent from a consideration of the following detailed description and explanatory drawings illustrating the invention and from the appended claims.

Fig. 1 diagrammatically illustrates a microwave oscillator supplying energy to a load through a rectangular wave-guiding structure including a curved bend;

Figs. 2, 3 and 4 are explanatory of the principles underlying the invention; and

Fig. 5 illustrates a form of the invention embodied in the guide of Fig. 1.

Referring then to the figures, in Fig. 1 there is shown a simple wave-guide installation in which a microwave oscillator O supplies energy in the dominant or TE_{10} mode to a load L through a hollow rectangular wave guide containing an arcuate magnetic or H-plane bend. The bend is so called because the magnetic vector is rotated in its traverse of the bend. The guide is illustrated in somewhat greater detail at Fig. 2 with the curved bend A inserted between a pair of angularly disposed straight sections B and C, the width W_1 of the straight sections being the same as the width W_2 of the curved section of the guide. Recommended practice would prescribe the bend of Fig. 2 to have a length l_A measured in terms of the dominant mode waves equal to an integral multiple of half wavelengths and a curvature a in the order of ten wavelengths.

In the disclosure that follows it may be assumed that the wave guide illustrated in Fig. 2 is an oversized air-filled structure with copper-conducting walls having a uniform rectangular cross-section and that it is operated over a wide frequency range which extends from a lower frequency up to and beyond the second order cut-off frequency of the bend and may extend substantially beyond the second order cut-off frequency of the main guide. The cut-off frequency of a uniform rectangular wave guide is related to the width of the guide. Thus, a structure possessing a cross-section $1\frac{1}{2}$ inches high by 3 inches wide, for example, would have a cut-off frequency for the second order or TE_{20} transmission mode in the order of 3,937 megacycles.

I have perceived that the observed anomalous irregularity in the transmission characteristics in the vicinity of the second order cut-off frequency are attributable to the bend, and more

particularly to the following peculiar combination of circumstances. First, the bend tends to generate higher order modes, that is, it tends to convert some of the wave power supplied to it in the dominant mode into the TE₂₀ mode (and other higher-order modes). Second, the cut-off frequency of the bend for this second-order mode is somewhat lower than that of the contiguous straight sections of guide. Third, the frequency band occupied by the transmitted waves extends into the frequency interval between the two second-order cut-off frequencies. In these circumstances the waves of second-order mode that the bend transforms from the dominant mode pass readily from the bend, excepting for those second-order waves whose frequency falls between the two cut-off frequencies. Those excepted waves, being above the relevant cut-off frequency of the bend, can propagate within the bend, but being below the relevant cut-off frequency of the connected guide sections they cannot propagate into the latter but are trapped within the bend and there dissipated. In the further circumstance that the length of the bend is an integral number of half-wavelengths for the trapped second-order waves, the bend behaves like a "ringing cavity" and thereby accentuates the absorption of wave power.

To understand the above action more fully attention will be focussed on the straight rectangular guide of Fig. 3 in which a similar situation occurs. In Fig. 3 there is shown a straight section of guide B₂ of width W₁' followed by a straight section of guide A₂ of width W₂', which is followed in turn by a straight section of guide C₂ also of width W₁'. The width W₂' is greater than the width W₁' so that in the section A₂ a second order mode can exist at wavelengths for which it is impossible for such a mode to exist in either section B₂ or C₂. The sections B₂ and C₂ then, over a narrow range of wavelengths, effectively act as pistons at either end of the section A₂ so that if this higher mode is generated in A₂ a ringing cavity will be produced. High currents will flow in the walls of this section of guide and energy will be dissipated. By constricting the width W₂' so that it is equal to the width W₁', the section A₂, B₂ and C₂ will all behave similarly, and there will be no range of wavelengths where modes can exist in one section and not in the others.

It is proposed in accordance with the present invention that the width W₂ of the curved bend of Fig. 2 be reduced an amount with respect to the width W₁ of the main sections of the guide so that the curved section A would have cut-off properties identical with the straight guide sections B and C. Since modes can then be propagated in section A only when they are also capable of being propagated in sections B and C, no ringing effect can arise and no reflections will occur.

The amount by which the width W₂ should be reduced compared to W₁ so that cut-off frequencies in A will be the same as those in B and C can be determined from an analysis of the cut-off frequencies in section A. Fig. 4 shows a toroidal section of wave guide in which the portion A₁ is made identical to the portion A of the curved guide of Fig. 2. The inner radius *a* and the outer radius *b* are the same as in Fig. 2. This circular section of guide is equivalent to a cylindrical cavity having a cylindrical center post and has been analyzed for example, at page 269 of S. A. Schelkunoff's text entitled "Electromagnetic

Waves" published in 1943 by D. Van Nostrand Company, New York. As indicated in this reference, the cut-off wavelength in such a cavity is given by Equation 1:

$$\frac{J_0(\beta a)}{N_0(\beta a)} = \frac{J_0(\beta b)}{N_0(\beta b)} \quad (1)$$

where *a* and *b* are the two radii involved, β is $2\pi/\lambda$, and $J_0(x)$ and $N_0(x)$ are the zero order Bessel and Neumann functions respectively.

From this equation it can be ascertained that the cut-off wavelength of the various modes in the toroidal cavity or in the curved section A of the rectangular guide of Fig. 2 is increased over that in the straight sections B and C. In particular, the generally objectionable mode, namely the TE₂₀ mode, has its cut-off wavelength increased by an amount which would be sufficient, in fairly sharp bends, to produce the undesired reflections mentioned earlier.

To verify that the cut-off wavelength is increased by the bend it is only necessary to show that the minimum difference *b* - *a* as given by (1) is less than λ , the cut-off wavelength of the TE₂₀ mode in the straight section of a rectangular wave guide. For example, when the small radius *a* is so chosen that

$$2\pi \frac{a}{\lambda} \text{ is } 2.405$$

the outer diameter *b* from Equation 1, for cut-off of the TE₂₀ mode, is given by

$$2\pi \frac{b}{\lambda} = 8.654$$

The width dimension W₂ of the curved section A of the guide in Fig. 2, i. e., *b* - *a*, for TE₂₀ cut-off is therefore

$$b - a = (8.654 - 2.405)/\beta = (6.249/2\pi)\lambda$$

which is seen to be less than λ , whereas in the sections B and C the width for cut-off of the second order mode is exactly equal to λ . Thus if W₂ in Fig. 2 equals W₁, the cut-off wavelength for the second order mode will be different in section A from that in sections B and C, and the curved and straight sections of the uniform guide of Fig. 2 are seen to be equivalent to the situation portrayed in Fig. 3 where a second order mode can exist in A₂ over a narrow range of frequencies, but not in B₂ or C₂. Where, as is often the case, the length *l*A of the section A in Fig. 2 is sufficiently close to an integral number of half wavelengths at the same time that the cut-off wavelength is proper for the higher order mode to exist in A and not in B or C, vigorous resonance oscillations will build up in this "ringing cavity."

To remedy the above situation the arc length *l*A of the curved structure of Fig. 2 can be chosen such that even though the troublesome mode can exist in the curved section of the guide, the reflections caused thereby will not reinforce each other. A length which differs from an integral number of half wavelengths by approximately 20 to 50 per cent of a half wavelength should be sufficient to prevent the build-up of strong resonant conditions in the bend, all wavelengths being measured in terms of the higher order waves capable of being propagated in the bend.

However, a more positive way of suppressing undesired reflections in wave-guiding bends is to prevent the existence of higher order transmission modes in the bends for those operating frequencies at which the modes cannot exist in the

straight sections of the guide. By increasing the cut-off frequency in the bends an amount which will cause the bends to exhibit the same cut-off properties to higher order modes as the main sections of the guide, the effect of the bend heretofore described may be overcome. This may be accomplished most effectively as suggested by constricting the width of the bend a few per cent throughout its entire length as determined from Equation 1. It should be appreciated, however, that other means which affect the characteristics of the bend in the manner described are also capable of adaptation. As long as the bend exhibits a cut-off frequency for higher order waves which is at least as high as the corresponding cut-off frequency of the main sections of the guide in which the bend is to be used, it is apparent that the higher order mode cannot be propagated in the bend without also being propagated in the other portions of the guide and the blocking or "ringing cavity" phenomenon exhibited by the guide structure of Fig. 2 will not be encountered.

The extent of the constriction or reduction in the width of the bend depends on the abruptness or curvature of the bend as brought out by Equation 1. For most purposes the constriction will be of the order of 2 per cent and within the range of $\frac{1}{2}$ to 5 per cent of the width of the unrestricted guide. Since abrupt bends are often desired and since wave-guiding structures are often operated in that range of frequencies where the dimensions of the guide correspond to the wavelength of the waves propagated therethrough, the wave-guiding elbows described herein are of practical importance.

Although the invention has been described as applied to a curved rectangular wave-guiding structure propagating waves in the principal or TE₁₀ mode, it will be understood that the invention is capable of general application to wave-guiding structures.

What is claimed is:

1. In combination, a wave guide, and means to excite electromagnetic waves in said guide for transmission therethrough in a first mode, said guide comprising a pair of substantially straight portions of uniform cross section joined by a curved portion that tends to generate a second transmission mode, the said waves occupying a frequency range that includes the transmission cut-off frequency of said straight portions for said second mode; and said curved portion having a different cross-sectional construction than said straight portions, having a cut-off frequency for said second mode that is at least as high as said first-mentioned cut-off frequency, and having a cut-off frequency for said first mode below the frequency of the electromagnetic waves excited in said guide.

2. A combination in accordance with claim 1 in which the two said cut-off frequencies for said second mode are equal.

3. A combination in accordance with claim 1 in which a cross-sectional dimension of said curved portion controlling the cut-off frequency thereof is uniformly constricted over the greater portion of its length relative to a corresponding dimension of said substantially straight portions.

4. In combination, a hollow-pipe wave guide of rectangular cross section and means to excite in said guide electromagnetic waves of dominant mode, said guide including two substantially straight portions interconnected by a contiguous curved portion that tends to generate a mode of

higher order, said waves occupying a frequency range that extends up to at least the cut-off frequency of said straight guide portions for said higher-order mode; and said curved portion having a different cross-sectional construction than said straight portions, having a cut-off frequency for said higher-order mode that is at least as high as said first-mentioned cut-off frequency, and having a cut-off frequency for said dominant mode below the frequency of the electromagnetic waves excited in said guide.

5. A combination in accordance with claim 4 in which the two said cut-off frequencies for said higher-order mode are equal.

6. A combination in accordance with claim 4 in which said mode of higher order is the TE₂₀ mode and in which a cross-sectional dimension of said curved portion is from about one-half to five per cent less than the corresponding dimension of said substantially straight portions.

7. In combination, a conductive-walled wave guide and means to excite in said guide for propagation therethrough in a first mode electromagnetic waves occupying a predetermined band of frequencies, said guide comprising three successive sections of which the intermediate section generates a second, higher-order transmission mode, the transmission cut-off frequencies of the end sections for said second mode being equal to each other and lying within said frequency band, the cross section of said intermediate section being constricted relative to that of the end sections, and said intermediate section having its transmission cut-off frequency for said second mode equal to that of said end sections and its transmission cut-off frequency for said first mode lower than the lowest frequency in said band of frequencies.

8. In combination, a wave guide elbow joining two straight, angularly disposed hollow-pipe guides, means to supply to said guides electromagnetic waves having a predetermined mode and extending over a predetermined band of frequencies, said elbow generating waves of a second mode from the waves of the said first mode supplied to it, the cut-off frequency of said straight guides for said second mode lying within said frequency band whereby at frequencies above said cut-off frequency wave power in said second mode is liable to be trapped within said elbow, said elbow having a different cross-sectional construction than said straight guides and having a cut-off frequency for said second mode that is at least as high as said first-mentioned cut-off frequency whereby said elbow suppresses waves in said second mode of any transmitted frequency that cannot pass freely from said elbow into said straight guides, and said elbow having a cut-off frequency for said predetermined mode which is lower than the lowest frequency in said band of frequencies.

9. A hollow-pipe wave guide of rectangular cross section supplied with electromagnetic waves in dominant mode occupying a predetermined band of frequencies, said guide comprising two substantially straight portions of the same uniform cross section having a cut-off frequency for the TE₂₀ mode that lies within said band; and a curved portion joining said straight portions having a different cross-sectional construction than said straight portions, having a substantially uniform cross section throughout its length, having a cut-off frequency for the TE₂₀ mode that is at least as high as said first-mentioned cut-off frequency, and having a cut-off frequency

for said dominant mode lower than the lowest frequency in said band of frequencies.

10. In an ultra-high frequency electromagnetic wave transmission system, a pipe-like wave-guiding conductor of rectangular cross section comprising two substantially straight sections connected by a curved section that has a different cross-sectional construction than said straight sections and has the same cut-off frequency as the straight sections for guided waves of the TE₂₀ mode.

11. In combination, two straight sections of wave guide having a given cut-off frequency for a first and a higher cut-off frequency for a second mode of transmission, means exciting electromagnetic waves in one of said straight wave guide sections in said first mode and over a frequency band including said cut-off frequency for said second mode, and a curved wave guide section which tends to generate said second mode of transmission joining said two straight sections, said curved wave guide section having a different cross-sectional construction than said straight sections and having a cut-off frequency for said second mode of transmission at least as high as that of the straight sections, said curved section also having a cut-off frequency for said first mode of transmission lower than the lowest frequency in said frequency band.

12. The combination as set forth in claim 11 in which the curved wave guide section has a uniform cross section over the greater portion of its length.

13. In combination, a hollow pipe wave guide of rectangular cross section including two substantially straight portions, said straight portions having a first cut-off frequency for the dominant mode of electromagnetic waves and a second cut-off frequency for a second order mode, a high frequency energy source generating a signal in a frequency band including said second cut-off frequency, means exciting said wave guide in the dominant mode with the output from said generator, and a curved hollow pipe wave guide portion having a different cross-sectional construction than the said straight portions contiguously interconnecting said two straight portions, said curved portion tending to generate second order modes, but having a cut-off frequency for said second order modes at least as high as that of said straight portions, said curved portion also having a cut-off frequency for said dominant mode which is less than the lowest frequency in said frequency band.

14. In combination, two straight sections of rectangular wave guide having a given cut-off frequency for a first and a higher cut-off frequency for a second mode of transmission, means exciting electromagnetic waves in one of said straight wave guide sections in said first mode and over a frequency band including said cut-off frequency for said second mode, and a curved

wave guide section of rectangular cross-section which tends to generate said second mode of transmission joining said two straight sections, said curved wave guide section being of uniform width over the greater portion of its length and having the width of its wave guiding passageway determined by the following relationship;

$$\frac{J_0\left(\frac{2\pi a}{\lambda}\right)}{N_0\left(\frac{2\pi a}{\lambda}\right)} = \frac{J_0\left(\frac{2\pi b}{\lambda}\right)}{N_0\left(\frac{2\pi b}{\lambda}\right)}$$

where λ is the cut-off wavelength in the straight wave guide sections, a and b are the respective radii of curvature of the two curved walls of said wave guiding passageway, and J_0 and N_0 are the zero order Bessel and Neumann functions, respectively.

15. In an ultrahigh frequency electromagnetic wave transmission system, two straight wave guides of rectangular cross-section, a curved section of wave guide of rectangular cross-section interconnecting said two wave guides, the width of the wave guiding passageway in said curved wave guide section being determined by the following relationship:

$$\frac{J_0\left(\frac{2\pi a}{w}\right)}{N_0\left(\frac{2\pi a}{w}\right)} = \frac{J_0\left(\frac{2\pi b}{w}\right)}{N_0\left(\frac{2\pi b}{w}\right)}$$

where w is the width of the passageway in said rectangular wave guides, a and b are the radii of curvature of the two curved walls of the wave guiding passageway of said curved wave guide section, and J_0 and N_0 are the zero order Bessel and Neumann functions respectively.

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