

May 29, 1956

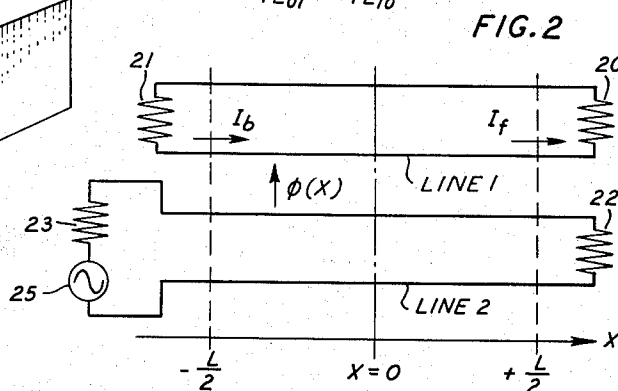
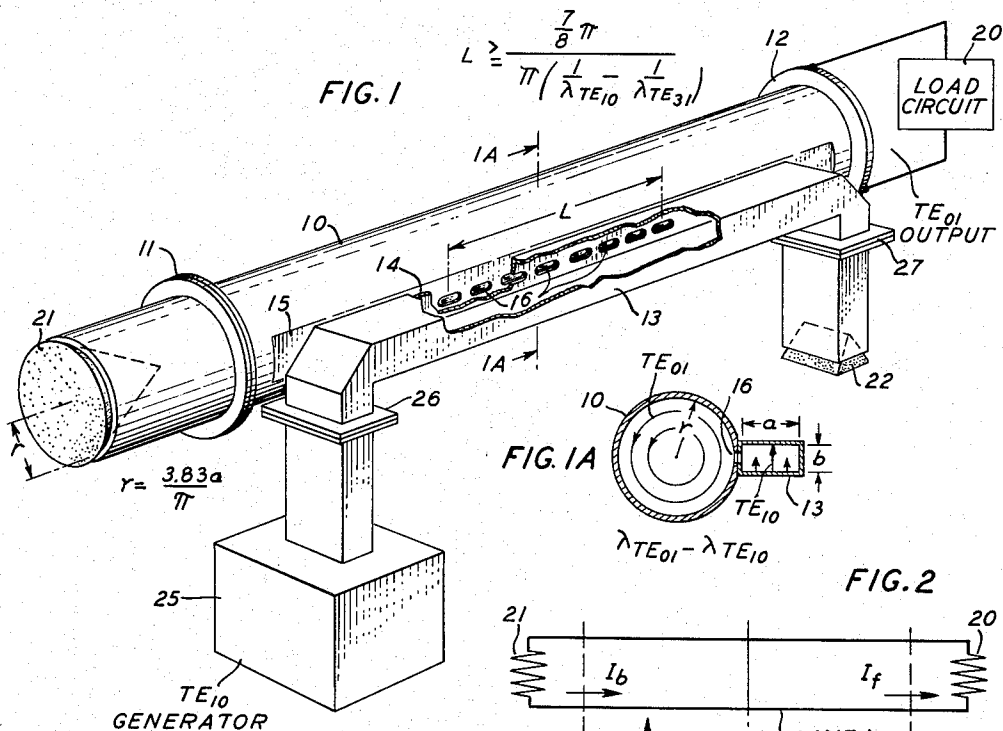
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ULTRA-HIGH FREQUENCY SELECTIVE MODE DIRECTIONAL COUPLER

Filed Sept. 5, 1951

4 Sheets-Sheet 1



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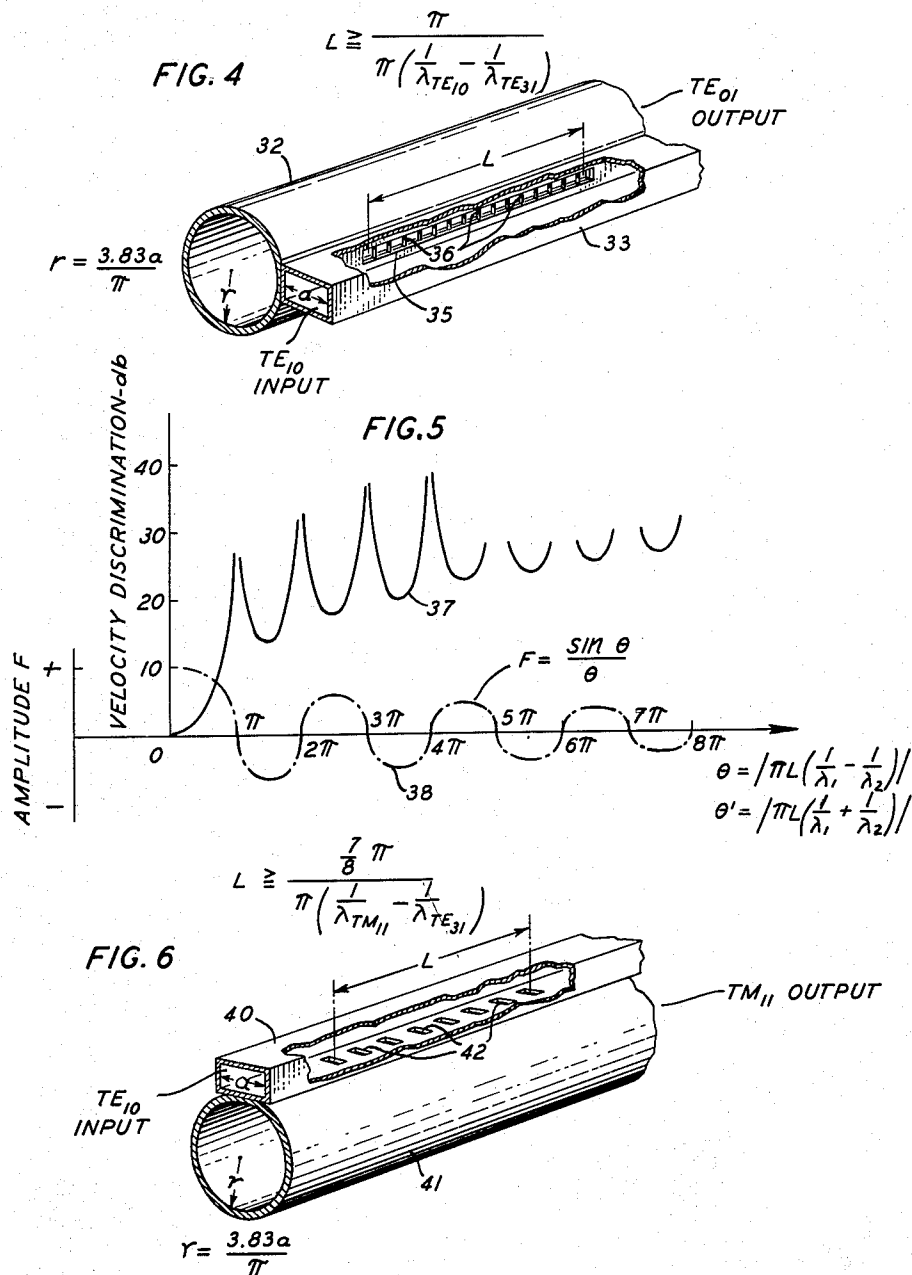
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4 Sheets-Sheet 3

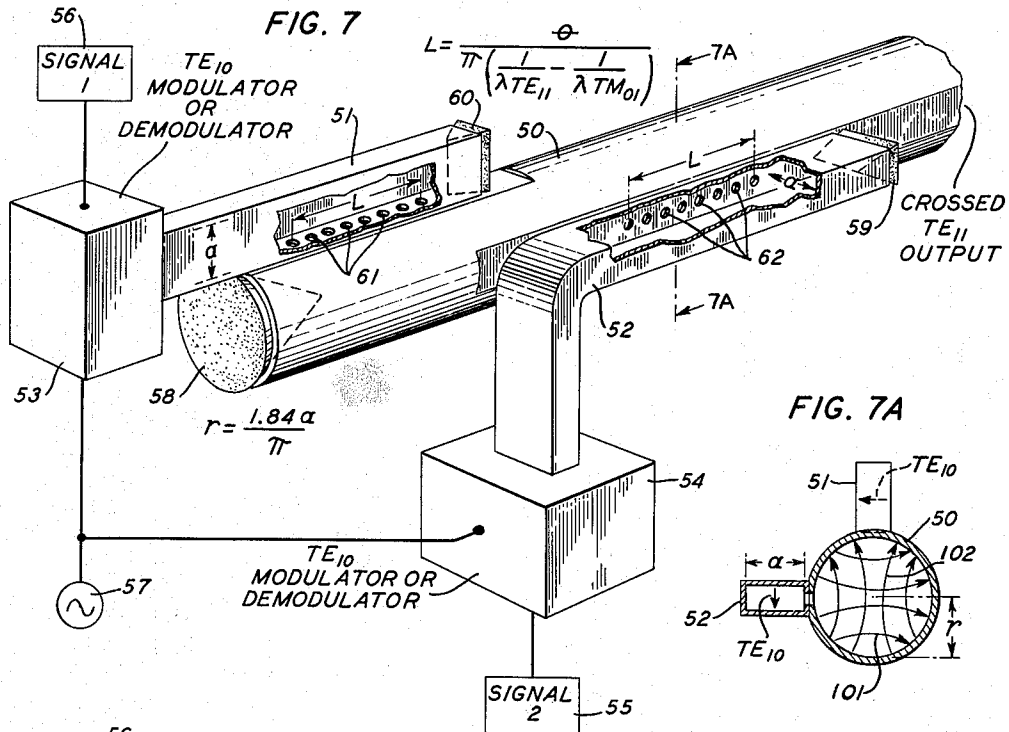
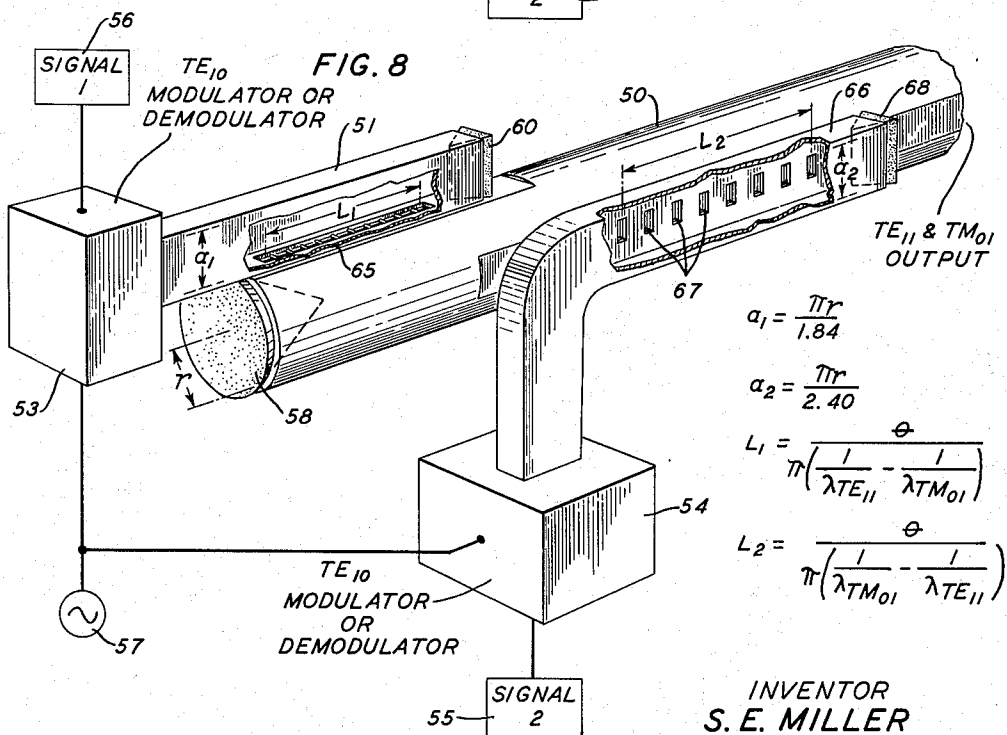
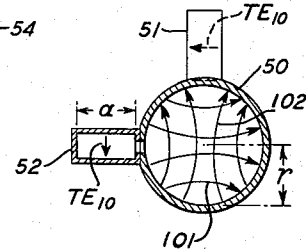


FIG. 7A



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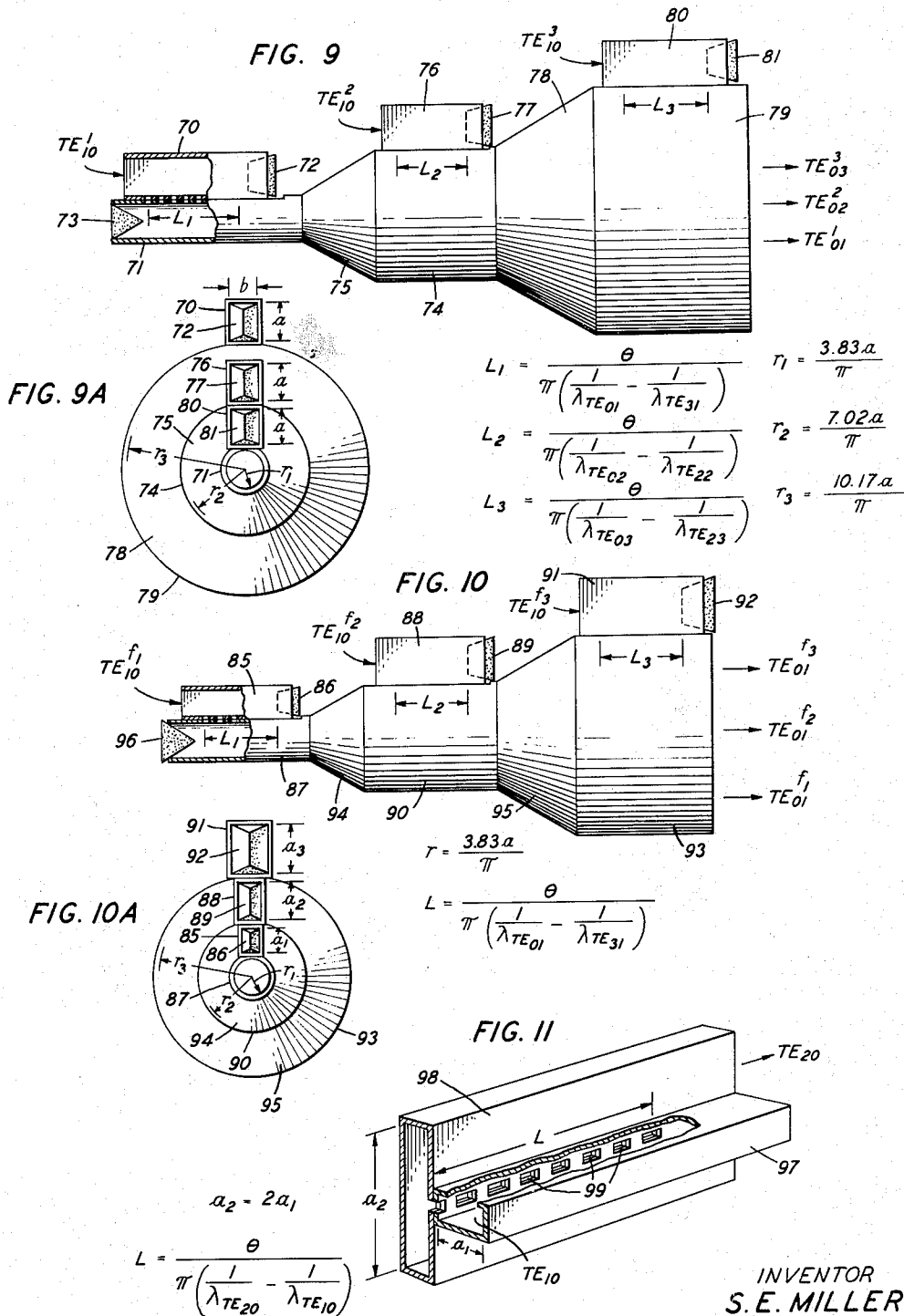
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4 Sheets-Sheet 4



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ULTRA-HIGH FREQUENCY SELECTIVE MODE DIRECTIONAL COUPLER

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Application September 5, 1951, Serial No. 245,210

34 Claims. (Cl. 333—10)

This invention relates to wave transmission systems for the transmission of electrical wave energy along multimode transmission lines and, more particularly, to devices having special transmission characteristics dependent upon the particular mode of transmission of said wave energy.

Such guided waves, as is well known in the microwave transmission art, are capable of transmission in an infinitely large number of forms or modes, each mode being distinguished by the characteristic configuration of the component electric and magnetic fields comprising the waves.

These waves have been divided into two broad classes. In one class the electric component of the wave is transverse to the metallic pipe guide, and at no point does it have a longitudinal component. The magnetic component, on the other hand, has both transverse and longitudinal components. This class has been designated as "transverse electric" waves or TE waves. In the other class, the magnetic component is transverse to the pipe and at no point does it have a longitudinal component, but the electric component has in general both transverse and longitudinal components. This class has been designated as "transverse magnetic" waves or TM waves.

The waves in each of these classes have been further identified and distinguished from each other by their mode or the pattern of wave energy distribution as it appears in the cross-section of the wave guide. A complete discussion of wave mode may be found in any standard textbook of microwaves and microwave guides. For the purpose of the present disclosure, the usual convention is herein adopted of designating a transverse electric wave TE_{mn} where, in a rectangular wave guide, m represents the number of half period variations of the transverse component encountered in passing across the width of the wave-guide cross-section, and n represents the number of half periods of transverse components encountered in passing across the height of the wave guide; and in a circular or cylindrical wave guide, m represents the number of whole periods of the transverse component encountered in running around the circumference of the cross-section, and n represents the number of half periods encountered in passing along the radius of the wave-guide cross-section.

For example, in a rectangular wave guide, TE_{10} represents a wave having a one-half electric period variation across the width of the guide, and, since the field is uniform, there is no variation across the height of the guide. This is commonly known as the dominant mode wave. Likewise, in a cylindrical wave guide, TE_{01} represents a wave whose electric field is wholly tangential and forms a series of circles concentric with the axis, and wherein no variations in the electric field are encountered around the circumference of the cross-section, but rather, a one-half period is encountered along the radius thereof. This latter wave mode is commonly known as a circular electric wave.

Each wave mode differs specifically from other modes in certain characteristics that render one mode particu-

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larly suitable for one use in electrical communication systems and another mode suitable for another use. For example, the circular electric wave, when propagated through a circular metal pipe of a given diameter, suffers progressively less attenuation as the frequency is increased. Because of this low attenuation, the TE_{01} wave is particularly adapted for long distance transmission systems. On the other hand, the TE_{10} wave or dominant mode wave is easily generated by presently known generators, does not easily degenerate into other modes, and in addition, is most favorable for amplification, modulation or demodulation. Similar advantages and disadvantages might be cited for other modes.

It is, therefore, an object of the present invention to transfer wave power of a given mode in a first transmission line, suitable for one purpose therein, from said first line and to launch it as wave power of another mode suitable for another purpose in a second transmission line.

Another object of the invention is to transfer a predetermined portion or the entire portion of energy in the first mode into energy in the second mode.

As is well known, the size of a shielded transmission line may be so chosen that the line will support only one mode, usually the dominant mode of propagation. However, as the size of the line is increased, it becomes multimode and may support simultaneously wave energy in a plurality of modes of propagation.

It is an object of the present invention to launch wave energy of only specifically selected mode configuration in a multimode transmission line.

It is a further object of the present invention to select or filter wave energy having specifically selected mode configurations in a multimode transmission line from energy having other mode configurations.

It has been determined, in accordance with the invention, that when two transmission lines of uniform characteristics are coupled, in the particular manner to be described, over a longitudinal length thereof, that wave energy will be transferred between the lines when the velocity of propagation of the wave energy in each of the two lines is equal. It has further been determined that when the velocities of propagation of wave energy in the two lines are unequal, no energy will be transferred between the lines when the length of the coupling interval bears the particular relation to be hereinafter specified, to the difference between the velocities in the two lines and to the Fourier transform of the particular coupling distribution. Inasmuch as the velocity of propagation of wave energy in any particular mode is uniquely determined by the physical dimensions of the transmission line, these physical dimensions and the length of the coupling distribution are chosen in accordance with the invention to couple, reject, filter or select any desired mode or modes of wave energy propagation.

Certain classes of modes have individual mode configurations for which the velocity of propagation is the same as a corresponding individual mode configuration in another class of modes. Special features of the invention reside in the means provided to separate modes by classes and therefore to separate the individual mode configurations having like velocities of propagation.

Further features of the invention reside in combination of two or more specifically chosen mode transducers to launch two or more intelligence-bearing signal waves in different modes of propagation for transmission simultaneously in a single wave-guide system.

Other objects, aspects and features of the invention will be apparent from the following detailed description when read in conjunction with the accompanying drawings in which:

Fig. 1 shows in pictorial representation a high fre-

quency selective mode transducer, in accordance with the invention;

Fig. 1A is a cross-sectional view of the transducer of Fig. 1 taken as indicated;

Fig. 2 is a diagrammatic representation of the transducer of Fig. 1, given for purposes of illustration;

Fig. 3 is a representation of certain critical characteristics of the transducer of Fig. 1, given for purposes of illustration;

Fig. 4 shows a modified embodiment of the transducer of Fig. 1;

Fig. 5 is a representation of certain critical characteristics of the transducer of Fig. 4, given for purposes of illustration;

Fig. 6 illustrates a modification of the selective mode transducer of Fig. 1, whereby dominant mode TE₁₀ wave energy in a rectangular guide is transformed into TM₁₁ wave energy in a circular guide;

Fig. 7 shows a multichannel transducer, whereby two or more signal channels may be transmitted or received in a single round wave guide by cross-polarized TE₁₁ wave energy;

Fig. 7A is a cross-sectional view of Fig. 7, taken as indicated;

Fig. 8 shows a multichannel transducer, whereby two or more signal channels may be transmitted or received in a single round wave guide by energy in the TE₁₁ and TM₀₁ modes;

Fig. 9 shows a multichannel transducer, whereby each of a plurality of signal channels may be transmitted or received in one of the lower order circular electric wave modes;

Fig. 9A is a left-hand end view of Fig. 9;

Fig. 10 shows a multichannel transducer in accordance with the invention whereby a plurality of dominant mode TE₁₀ signal channels of different frequencies may be transmitted or received as TE₀₁ circular electric signals at corresponding frequencies;

Fig. 10A is a left-hand end view of Fig. 10; and

Fig. 11 shows a further alternative embodiment of the invention employing the rectangular wave-guide modes.

In more detail, Fig. 1 shows a high frequency selective mode transducer, in accordance with the invention, for transforming dominant mode TE₁₀ wave energy in a rectangular wave guide into TE₀₁ circular electric wave energy in a circular wave guide. The transducer of Fig. 1 comprises a first section 13 of shielded transmission line for guiding wave energy which is, as shown on the cross-sectional view of Fig. 1A, a dominant mode rectangular wave guide having an internal wide dimension a and a narrow dimension b . Wave guide 13 is provided with terminal flange connections 26 and 27 at each of its ends bent at right angles to the guide for convenience in mechanical assembly. Located adjacent to wave guide 13 and having a portion of its length contiguous to a portion of guide 13 is a second shielded transmission line 10 for guiding wave energy, which is a circular cross-sectional wave guide of radius r , having terminal connections 11 and 12 at each of its ends for mechanical assembly. The reverse end, toward terminal 11, of guide 10 is terminated in a reflectionless manner by its characteristic impedance as indicated diagrammatically by termination 21 of electrical high loss material. The forward end, toward terminal 12, of guide 10 is connected to a load circuit 20 adapted to utilize the generated TE₀₁ wave energy. This load 20 may represent, for example, a long distance circular transmission line. A source 25 of TE₁₀ dominant mode electromagnetic wave energy is shown connected to terminal 26 of guide 13. The other end of guide 13 is terminated in a reflectionless manner by its characteristic impedance as indicated diagrammatically by termination 22 of electrical high loss material.

Guides 10 and 13 are coupled in their contiguous portion by like equally sized and equally spaced apertures 16 extending through the wall 14 of rectangular guide 13

and the adjacent wall portion 15 of guide 10. The wall thickness of guide 10 is cut away along the portion thereof contiguous to guide 13 so that portion 15 is flattened to fit snugly against wall 14 of the rectangular guide 13.

The coupling apertures 16 are distributed along a total array length L measured along the longitudinal length of the guides from the centers of each of the end apertures. The apertures 16 are illustrated as elliptically shaped; however, within the limits set by the considerations to be detailed hereinafter, the shape of these apertures may be of any shape consistent with good coupling.

The relative cross-sectional dimensions of guides 10 and 13 are chosen so that the guide wavelength of TE₀₁ wave energy in guide 10 is equal to the guide wavelength of TE₁₀ wave energy in guide 13. The significance of this relation will be brought out fully in the discussion which follows. In this connection it should first be noted that the guide wavelength λ_g for a particular mode of wave energy propagation in any guide depends directly upon the cut-off wavelength λ_c of the guide in accordance with the following relation:

$$\lambda_g = \frac{\lambda_0 \lambda_c}{\sqrt{\lambda_c^2 - \lambda_0^2}} \quad (1)$$

where λ_0 is the free space wavelength. It is thus seen that if the cut-off wavelength for a particular mode in each of two guides is made equal, the guide wavelength of wave energy in the two guides will be equal, regardless of the particular frequency of the energy. These considerations are fully discussed in any standard textbook on wave-guide transmission, such as Southworth, "Principles and Applications of Waveguide Transmission," 1950.

It should further be noted that the cut-off wavelength λ_c in a rectangular guide for any TE_{mn} or TM_{mn} wave mode depends upon the physical dimensions of the wave guide and may be expressed:

$$\lambda_c = \frac{2ab}{\sqrt{m^2 b^2 + n^2 a^2}} \quad (2)$$

in which either m or n may be zero. Thus, for the TE₁₀ wave in which m equals 1 and n equals zero, the cut-off wavelength $\lambda_c = 2a$ and the guide wavelength λ_g is accordingly proportioned by Equation 1.

In circular wave guides, the cut-off wavelength λ_c for a particular mode is determined by the radius r of the guide and is expressed:

$$\lambda_c = \frac{2\pi r}{k_{mn}} \quad (3)$$

in which k_{mn} is the Bessel function constant for the particular mode of transverse magnetic or transverse electric waves. A complete discussion of the Bessel function and its derivation may be found in any standard textbook on wave-guide transmission, but it will suffice here to give the values of k_{mn} for the lower order modes.

For transverse magnetic waves:

$k_{01}=2.40$	$k_{02}=5.52$	$k_{03}=8.65$
$k_{11}=3.83$	$k_{12}=7.02$	$k_{13}=10.17$
$k_{21}=5.14$	$k_{22}=8.42$	$k_{23}=11.62$

For transverse electric waves:

$k_{01}=3.83$	$k_{02}=7.02$	$k_{03}=10.17$
$k_{11}=1.84$	$k_{12}=5.33$	$k_{13}=8.54$
$k_{21}=3.05$	$k_{22}=6.71$	$k_{23}=9.97$
$k_{31}=4.20$	$k_{32}=8.02$	$k_{33}=11.35$

Thus for the TE₀₁ wave,

$$\lambda_c = \frac{2\pi r}{3.83}$$

and the guide wavelength λ_g is accordingly proportioned by Equation 1. In order then that the TE₀₁ wave in guide 10 have the same cut-off wavelength, and there-

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fore, the same guide wavelength as the TE₁₀ wave in guide 13, the radius r of guide 10 must equal

$$\frac{3.83a}{\pi}$$

This proportion is indicated on Fig. 1. In accordance with usual practice for rectangular wave-guide cross-sections, the dimension b of guide 13 may be equal to

$$\frac{a}{2}$$

Having thus proportioned the physical dimensions of guides 10 and 13 so that the guide wavelength for the TE₀₁ mode in guide 10 is equal to the guide wavelength for the TE₁₀ mode in guide 13, at least the energy coupled through each of the coupling apertures which happens to appear in guide 10 in the TE₀₁ mode will add in phase for transmission to load 20, as will be demonstrated hereinafter, regardless of the aperture spacing or the length of the coupling array. But since the necessary dimensions of guide 10 render this guide multimode and, in all practical cases, capable of supporting all of five other modes in addition to the desired TE₀₁ mode, it would be expected that a substantial portion of the original TE₁₀ energy would appear in unwanted spurious modes in guide 10. An inspection of the above table of Bessel function constants will show that these five possible spurious modes would be the TM₀₁, TM₁₁, TE₃₁, TE₂₁ and TE₁₁.

Reserving special consideration of the TM₁₁ mode for full treatment hereinafter, all of the remaining spurious modes are substantially suppressed in the forward direction of transmission, in accordance with the invention, by making the length L of the coupling array at least equal to substantially a certain length determined by the coupling distribution and the phase velocity difference between the desired mode and the modes to be discriminated against. This relation is

$$L = \frac{\theta}{\pi \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)} \quad (4)$$

Wherein λ_1 is the guide wavelength of the desired mode, in this case the TE₀₁ wave, wherein as will be shown, θ is at least the value of the periodic angle of the Fourier transform for the particular coupling distribution employed at which the characteristic of the transform first passes through zero, and wherein λ_2 is the guide wavelength of the spurious mode having the wavelength nearest to, but not equal to, the guide wavelength of λ_1 . The quantity

$$\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

while not strictly a velocity quantity is proportional to the velocity difference between the waves λ_1 and λ_2 and for convenience herein will be referred to as the velocity difference function. In the particular embodiment of Fig. 1, λ_2 is the guide wavelength of the TE₃₁ wave calculated in accordance with Equations 1 and 3, and θ is equal to

$$\frac{7\pi}{8}$$

radians, as will be shown, for a coupling distribution comprising eight equal point couplings. This particular relation is indicated by the expression on Fig. 1.

The reasons underlying the choice of these particular dimensions for the selective mode transducer of Fig. 1 will most easily be understood upon a consideration of the diagrammatic representation of this structure in Fig. 2. On Fig. 2 are shown two identical transmission lines 1 and 2 corresponding, respectively, to lines 10 and 13 of Fig. 1. These transmission lines are assumed parallel and the direction of propagation is along the x -axis. The region in which coupling exists, corresponding to the array

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length L of apertures 16, is designated in Fig. 2 by the interval from

$$-\frac{L}{2} \text{ to } +\frac{L}{2}$$

The coupling distribution, or the variations of coupling between the lines in the interval

$$-\frac{L}{2} \text{ to } +\frac{L}{2}$$

is described by the function $\varphi(x)$. Assume further that the exciting wave generated by source 25 is traveling to the right in line 2, and that the fraction of this energy transferred to line 1 is negligible. Thus, the voltage wave on line 2 is

$$E_2 = e^{-i\frac{2\pi}{\lambda_2} \left(\frac{L}{2} + x \right)} \quad (5)$$

in which the phase reference is taken as that at

$$x = -\frac{L}{2}$$

The voltage $E(x)$ in series with line 1 due to the coupling represented at any distance x intermediate

$$-\frac{L}{2} \text{ and } +\frac{L}{2}$$

by $\varphi(x)$ is

$$B(x) = \varphi(x) E_2 = \varphi(x) e^{-i\frac{2\pi}{\lambda_2} \left(\frac{L}{2} + x \right)} \quad (6)$$

The effect of $E(x)$ will be to send a current I_f forward into the termination at

$$x = \frac{L}{2}$$

and a current I_b backward to the termination at

$$x = -\frac{L}{2}$$

Referring all current elements of I_f to the point

$$x = +\frac{L}{2}$$

$$dI_f = \frac{E(x)}{2Z} e^{-i\frac{2\pi}{\lambda_1} \left(\frac{L}{2} - x \right)} \quad (7)$$

Combining Equations 7 and 6, and summing the elements of I_f leads to

$$I_f = k \int_{-\frac{L}{2}}^{\frac{L}{2}} \varphi(x) e^{i2\pi \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) x} dx \quad (8)$$

where

$$k = \left[\frac{2Z}{e^{-i\pi L \left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2} \right)}} \right]^{-1}$$

The term Z represents a normalized characteristic impedance of either line, its terminal impedances 21 and 22, and the internal impedance 23 of source 25.

Thus, when $\lambda_1 = \lambda_2$, the condition established above for the TE₀₁ and TE₁₀ waves by the physical dimensions of the coupled wave guides, the forward current is maximum and becomes

$$I_f = k \int_{-\frac{L}{2}}^{\frac{L}{2}} \varphi(x) dx \quad (9)$$

When λ_1 and λ_2 are not equal, the condition necessarily found between the desired wave and the spurious mode

waves in Fig. 1, the forward current may not be maximum. Substituting

$$-\frac{\theta}{L} = \pi \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \quad (10)$$

in Equation 8, the relation

$$I_f = k \int_{-\frac{L}{2}}^{\frac{L}{2}} \varphi(x) e^{\frac{-j2\theta}{L} x} dx \quad (11)$$

is obtained.

The expression of Equation 11 is seen to be in the form of a Fourier transform, i. e., the forward current is equal to the constant k times the evaluation of the integral for the particular coupling distribution $\varphi(x)$ (which evaluation is the Fourier transform of the coupling distribution). The quantity θ is the periodic angle of the Fourier transform, and when θ is such that the value of the transform is zero, the forward current will be zero.

For a specific example, consider the coupling distribution of Fig. 1 which comprises eight equal strength point couplings distributed over a total array length L . The Fourier transform with this distribution is well known to be

$$F = \cos \frac{\theta}{7} + \cos \frac{3\theta}{7} + \cos \frac{5\theta}{7} + \cos \theta \quad (12)$$

The characteristic of Equation 12 is plotted as curve 30 on Fig. 3, and it is seen to be a periodic function which passes through zero at specific values of θ , for example $\frac{7}{8}\pi$, $1\frac{3}{4}\pi$, and $2\frac{5}{8}\pi$. These values, therefore, define the specific relationships between the coupling length L and the phase velocity difference function

$$\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

for which the forward current of Equation 11 will be zero for the particular coupling distribution, in other words, the relationships for which maximum velocity discrimination is obtained against the wavelength λ_2 . Infinite velocity discrimination is obtained, therefore, when

$$L \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

is equal to $\frac{7}{8}$, $1\frac{3}{4}$, $2\frac{5}{8}$, et cetera. Lesser values of discrimination are obtained at intermediate relationships. The over-all velocity discrimination characteristic of the transducer of Fig. 1 is most conveniently shown by the decibel ratio of the forward current when λ_1 is equal to λ_2 (Equation 9), to the forward current when the wavelengths are different (Equation 11), plotted versus

$$\theta = \left| \pi L \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \right|$$

This velocity discrimination characteristic is shown as curve 31 on Fig. 3.

In every case the most critical spurious mode to be discriminated against is that mode which may be supported by the transducer multimode line which mode has a guide wavelength or a phase velocity nearest to, but not equal to, the guide wavelength or phase velocity of the desired mode. Of the spurious modes noted above for the embodiment of Fig. 1, the guide wavelength in guide 10 of the TE₃₁ mode is the nearest to the guide wavelength of the TE₀₁ mode. Thus, the coupling length L is chosen with λ_2 equal to the guide wavelength of the TE₃₁ mode, to place the discrimination against this mode at the first point of infinite decibel discrimination, i. e., at $\theta = \frac{7}{8}\pi$. For a specific embodiment in accordance with Fig. 1, in which the mid-band operating frequency is 24,000 megacycles in a rectangular wave guide having an inside wide dimension 0.359 inch, the remaining parameters calcu-

lated in accordance with the equations given above would be: $r = \frac{7}{16}$ inch

$$\lambda_{TE_{10}} = 0.676 \text{ inch}$$

5 and

$$\lambda_{TE_{31}} = 0.747 \text{ inch}$$

For eight couplings with $\theta = \frac{7}{8}\pi$, the coupling length L would be 6.26 inches or in the order of 10 times the TE₀₁ wavelength. All other spurious modes having less critical velocity differences will fall upon larger values of θ and will likewise be discriminated against, as shown by curve 31 of Fig. 3, so long as the mode possessing the greatest velocity difference does not cause θ , for the particular coupling distribution of Fig. 1, to assume a value much greater than 6π and to fall within the region of the second major lobe centered around 7π .

Special consideration has been reserved for the TM₁₁ mode. An inspection of the table of Bessel functions given above will indicate that the TM₁₁ mode has the same guide wavelength as the TE₀₁ mode. These waves are known in the art as degenerate pairs. Other degenerate pairs in circular wave guides are seen to be the TM₁₂ and TE₀₂, the TM₁₃ and TE₀₃. Degenerate pairs are also found in rectangular wave guides as will be seen from inspection of Equation 2. Since each wave of a degenerate pair has the same guide wavelength, something more than velocity discrimination is required to discriminate between these waves. In the embodiment of Fig. 1, apertures 16 will excite all transverse electric modes in guide 10 but will excite no TM modes. Thus, the coupling mechanism itself discriminates against the TM mode in a circular wave guide.

In this respect several general comments can be made with regard to the mode discrimination effects of a rounded aperture coupling mechanism. When a rounded aperture is placed in the side wall of the rectangular guide, it will couple any TE_{0m} mode in rectangular guide to any TE wave in the circular guide, and conversely any TE round to TE_{0m} in rectangular, but will discriminate against TM circular guide modes because the rectangular guide will not respond to longitudinal voltages impressed on the side wall. When placed in the center of the wide side of a rectangular guide, a rounded aperture will couple any TE mode of round guide (except TE₀₁) to TE_{0m} in rectangular guide, and will couple any TM mode of round guide to any TE_{0m} in rectangular guide if m is odd. For TE₀₁ in a circular guide, TE₁₀ will not be excited but TE₂₀ will be excited in rectangular guide. This type of coupling is therefore favorable for discriminating against TE₀₁ power in round wave guide if the TM₁₁ is desired in the circular guide.

Thus, when degenerate pairs are involved, the coupling mechanism is chosen to couple to or from the desired mode of the pair and to discriminate against the undesired mode of the pair. For the particular pair involved in Fig. 1, any coupling mechanism which is responsive to at least the TE₁₀ wave in rectangular guide, excites at least the TE₀₁ wave in the circular guide, and discriminates against at least the TM₁₁ in the circular guide, will be satisfactory. Other cases illustrating the choice of the particular coupling in accordance with the invention will be demonstrated hereinafter with specific reference to Figs. 4, 6 and 8.

While the primary considerations of the invention are directed to energy transferred in the forward direction in line 10 to load circuit 20, it is of interest to consider the character of the energy appearing at terminals 11 and 27. Clearly, all energy which is not transferred from guide 13 to guide 10 will be absorbed by termination 22. The exact amount of the energy which will be transferred into guide 10 is yet to be considered in detail. Likewise, energy transferred into guide 10 in the backward direction will be absorbed by termination 21. However, since it is desirable to convert the maximum amount of energy in

line 10 into the TE₀₁ mode for delivery to load 20, it is desirable that the backward current be made as small as possible. Referring again to the diagrammatic representation of Fig. 2, all elements of the backward current I_b may be referred to the point

$$x = -\frac{L}{2}$$

as

$$dI_b = \frac{E(x)}{2Z} e^{-\frac{j2\pi}{\lambda_1} \left(x + \frac{L}{2}\right)} dx \quad (13)$$

Combining Equation 13 with Equation 6 leads to

$$I_b = k \int_{-\frac{L}{2}}^{+\frac{L}{2}} \varphi(x) e^{-j2\pi \left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right) x} dx \quad (14)$$

Making the substitution

$$\frac{\theta'}{L} = \pi \left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2} \right) \quad (15)$$

an equation identical to Equation 11 above is obtained. Thus, the velocity discrimination characteristic of Fig. 3 serves also as a representation of the directivity of the transducer of Fig. 1 except that θ' is a sum function of the relative velocities

$$\frac{1}{\lambda_1}$$

and

$$\frac{1}{\lambda_2}$$

It is thus seen that, insofar as conduction in the backward direction in guide 10 is concerned, the transducer of Fig. 1 possesses certain multimode directional coupling characteristics and that minor backward currents are inherently obtained when the coupling interval L is sufficiently long.

The particular coupling distribution of Fig. 1, comprising eight equal strength and equally spaced apertures, has been chosen to illustrate the principles of the invention because of its simplicity and because it serves to illustrate many of the necessary considerations. It should be noted, however, that any number of apertures, spaced equally, unequally, or spaced according to some predetermined function; of equal, unequal or tapered strength, may be used. In each and every case the same considerations set forth above apply since each coupling distribution involves a Fourier transform from which the particular value of θ is obtained. It should be noted that when n equal strength and equally spaced apertures are employed, the value of θ for which the Fourier transform first passes through zero will always be

$$\frac{n-1}{n} \pi$$

Thus, as has been demonstrated above for eight equally spaced and equal strength apertures, this value of θ becomes $\frac{7}{8}\pi$.

The number of coupling points, however, will determine the position of the second major lobe, shown on Fig. 3 as centered about 7π . As more coupling points are employed, the position of this lobe moves to larger values of θ . Consequently, when a very large velocity difference between any spurious mode to be discriminated against and the desired mode exists, it is desirable to employ an increased number of coupling points.

The number and amplitude strength of the couplings is of principal importance in determining the TE₁₀ power transferred from line 13 into TE₀₁ power in line 10. Thus, energy transferred from line 13 to line 10 through

the first left-hand aperture 16 experiences a 90 degree phase delay. This energy travels in the TE₀₁ mode to the right along line 10 to the second coupling aperture 16 and part of this energy returns to line 13 with the further phase delay of 90 degrees. Thus, energy which goes from line 13 to line 10 and back to line 13 at a later coupling point arrives in line 13 out of phase with the TE₁₀ energy which travels straight through line 13. A summation of such components eventually results in cancellation of the TE₁₀ wave in line 13.

Designating the magnitude of the coupling through each of the apertures 16 as C, and assuming unit applied voltage at terminal 26, the voltage V₁ in line 10 after the first coupling point may be expressed

$$V_1 = C \quad (16)$$

and the voltage E₁ in line 13 as

$$E_1 = \sqrt{1-C^2} \quad (17)$$

Upon passing the second coupling unit, these voltages become, respectively

$$V_2 = \sqrt{1-C^2} V_1 + C E_1 = 2C \sqrt{1-C^2} \quad (18)$$

and

$$E_2 = \sqrt{1-C^2} E_1 - C V_1 = 1 - 2C^2 \quad (19)$$

Employing the transformation

$$C = \sin w \quad (20)$$

Equations 18 and 19 may be expressed after n coupling units as

$$E_n = \cos nw \quad (21)$$

$$V_n = \sin nw \quad (22)$$

Equations 21 and 22 may be rewritten in the form

$$E_n = \cos (n \sin^{-1} C) \quad (23)$$

$$V_n = \sin (n \sin^{-1} C) \quad (24)$$

Thus, the required number n of identical coupling units having a coupling factor C may be determined for any required ratio in the voltages E_n and V_n. The desired ratio of power division would, therefore, be the square of the voltage expression. On the other hand, the desired relation between voltage or power may be obtained by a fixed number of coupling units having the required coupling factor C. In either case complete power transfer of all TE₁₀ energy will take place between the lines when the quantity $n \sin^{-1} C$ is equal to

$$\frac{m\pi}{2}$$

where m is any odd integer.

It is desirable in certain applications, as pointed out above, to utilize a coupling array employing a plurality of apertures having different coupling factors. The desired power division may then be determined as

$$E = \cos (n_1 w_1 + n_2 w_2 + n_3 w_3 + \dots n_k w_k) \quad (25)$$

$$V = \sin (n_1 w_1 + n_2 w_2 + \dots n_k w_k) \quad (26)$$

where E and V are the voltages in line 13 and line 10, respectively, at the end of the series of couplings, and there are employed:

- n_1 apertures of individual coupling C₁
- n_2 apertures of individual coupling C₂
- n_3 apertures of individual coupling C₃
- n_k apertures of individual coupling C_k

and the transformation

$$C_1 = \sin w_1$$

$$C_2 = \sin w_2$$

$$C_k = \sin w_k$$

has been employed in writing the above expression for

E and V. Equations 25 and 26 may be rewritten in the form

$$E = \cos (n_1 \sin^{-1} C_1 + n_2 \sin^{-1} C_2 + n_3 \sin^{-1} C_3 + \dots n_k \sin^{-1} C_k) \quad (27)$$

$$V = \sin (n_1 \sin^{-1} C_1 + n_2 \sin^{-1} C_2 + n_3 \sin^{-1} C_3 + \dots n_k \sin^{-1} C_k) \quad (28)$$

Again complete power transfer of TE₁₀ energy to TE₀₁ energy between the lines will take place when the expression in the parenthesis of Equation 28 is equal to

$$\frac{m\pi}{2}$$

in which m may be any odd integer.

It should be noted that the transducer of Fig. 1, like all of the transducers to be disclosed herein, is bilateral, i. e., the same power transfer will take place from line 10 to line 13 as has been described as taking place from line 13 to line 10. Assuming that load circuit 20 is therefore a transmission system delivering a plurality of modes including the TE₀₁ mode to terminal 12 of line 10, only that energy in the TE₀₁ mode will be transferred into guide 13, appearing therein in the TE₁₀ mode, while energy in the other modes in line 10 will be delivered to and absorbed by termination 21. Similarly, if source 25 is replaced by a system delivering a large number of modes to terminal 26 of guide 13, and guide 13 is assumed to have such initial dimensions as to support these modes, only that power appearing in guide 13 in the TE₁₀ mode will be transferred to the TE₀₁ mode in line 10.

In Fig. 4, a modification of the transducer of Fig. 1 is shown in which coupling between the lines is provided by a divided aperture 35. The exact nature and the coupling characteristics to be expected from a divided aperture such as 35 is fully disclosed and claimed in the copending application of A. G. Fox, Serial No. 236,556, filed July 13, 1951, now United States Patent No. 2,701,342, granted February 1, 1955, and in my copending application, Serial No. 216,132, filed March 17, 1951, now United States Patent No. 2,701,340, granted February 1, 1955. It is sufficient to state here that aperture 35 is an elongated rectangular aperture of length L extending through the contiguous walls of guides 32 and 33, as shown, and is termed "divided" since extending parallel across the transverse or narrow dimension of aperture 35 is a grid, comprising a plurality of dividers or wires 36. The dimensions and spacing of wires 36 are set forth in detail in the above-mentioned copending applications. This divided aperture provides a current coupling between lines 32 and 33 which is effectively distributed to a substantial degree along the length L of the aperture. The Fourier transform for such a coupling distribution is known to be

$$F = \frac{\sin \theta}{\theta} \quad (29)$$

in which θ is the periodic angle of the transform and is equal to

$$\pi L \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

as originally defined herein by Equation 4. The characteristic of this transform is plotted as curve 38 on Fig. 5 and it is seen that $F=0$ for all multiples of π . Thus, infinite discrimination is obtained for the TE₃₁ mode when

$$L = \frac{\pi}{\pi L \left(\frac{1}{\lambda_{TE_{01}}} - \frac{1}{\lambda_{TE_{31}}} \right)} \quad (30)$$

The total velocity discrimination characteristic for all modes is shown as curve 37 on Fig. 5. It will be noted that this coupling distribution produces no subsequent major lobes but rather the velocity discrimination char-

acteristic continues to increase as the velocity difference between the desired mode and the spurious modes increases.

The same principles apply with corresponding advantages to each of the various geometric shapes of divided apertures disclosed in my above-mentioned copending application. These principles apply to each of the composite geometric shapes disclosed therein as well as to the basic geometric shapes of which the uniform rectangular coupling of Fig. 4 is an example.

When distributed coupling is employed in the mode transducer, such as the coupling provided by aperture 35 of Fig. 4, or when such a large number of discrete coupling points is employed that the coupling may be considered as substantially distributed, the criteria for complete power transfer between the desired modes is more conveniently expressed by the relations now to be defined.

Consider again, therefore, Fig. 2 and particularly the TE₀₁ current transmitted in the forward direction in line 1 and within a length interval so small that negligible power is transmitted between the lines 1 and 2. The envelope of the traveling wave in line 2 may be expressed

$$\frac{dE_1}{dx} = -\alpha E_1 + \alpha E_2 \quad (31)$$

and the traveling wave in line 1 may be expressed as

$$\frac{dE_2}{dx} = -\alpha E_2 + \alpha E_1 \quad (32)$$

wherein α represents the continuous coupling per unit length between the lines. Assuming a TE₁₀ wave of magnitude unity impressed on line 2, Equation 31 becomes

$$E_1 = \frac{1}{2} (1 + e^{-2\alpha L}) \quad (33)$$

and Equation 32 becomes

$$E_2 = \frac{1}{2} (1 - e^{-2\alpha L}) \quad (34)$$

wherein L represents the distance over which the coupling is maintained.

Since the coupling length L of Fig. 4 is fixed, being determined for maximum velocity discrimination against the spurious modes, it is seen that the TE₁₀ wave magnitude in line 33, represented by Equation 33, declines cosinusoidally and the TE₀₁ wave magnitudes in line 32, represented by Equation 34, increases sinusoidally as the distributed coupling strength α is increased. Complete power transfer from the TE₁₀ mode in line 33 to the TE₀₁ mode in line 32 takes place when the product $2\alpha L = m\pi$ radians, where m is any odd integer, and repeats cyclically as α is further increased. In other words, the TE₁₀ power in line 33 and the TE₀₁ power in line 32 will be divided in accordance with the ratio

$$\frac{TE_{10}}{TE_{01}} = \frac{\cos^2 2\alpha L}{\sin^2 2\alpha L} \quad (35)$$

As fully disclosed in the above-mentioned copending applications, the current coupling factor α is directly dependent upon the transverse dimension of the divided aperture. Thus, this transverse dimension is chosen with respect to the already fixed longitudinal dimension L to provide any desired ratio of mode conversion. For complete conversion of all power, the transverse dimension is chosen to make α equal to

$$\frac{m\pi}{2L}$$

m being any odd integer.

The divided aperture 35 of Fig. 4, like the rounded apertures of Fig. 1, discriminates against the TM₁₁ mode of the degenerate pair TE₀₁ and TM₁₁. In general, the mode discrimination characteristics of divided aperture 35 are identical to those of an undivided rectangular aperture of the same shape and position. Thus, an un-

divided rectangular aperture, long dimension parallel to the circular guide axis and placed in the narrow side of the rectangular guide, will couple TE_{no} modes in rectangular guides to any TE wave of the round guide. Round guide TM waves will be discriminated against. When such a rectangular aperture is placed in the center of the wide side of the rectangular guide it will tend to couple TE round guide modes to the TE₂₀ rectangular guide mode. The rectangular guide TE₁₀ modes are discriminated against by virtue of the hole placement in the center of the wide side of rectangular guide, while the round guide TM modes are discriminated against by virtue of the long narrow hole width which fails to intercept the longitudinal round guide currents.

It should also be noted that the mode coupling characteristics of a coupling probe are similar to, but not identical with, those of the rectangular aperture. For example, a probe, radial in the circular guide and in the center of the wide side of the rectangular guide, will respond to any wave in the round guide except TE_{0n} and will excite only dominant wave TE₁₀ in the rectangular guide even if the TE₂₀ mode could exist. Conversely, the probe will respond to the TE₁₀ mode in the rectangular guide and will excite all modes in the round guide, except TE_{0n}, since here, as in each case, the reciprocal relationship exists.

Fig. 6 illustrates a selective mode transducer, in accordance with the invention, in which the dominant mode TE₁₀ wave energy in rectangular guide 40 is transformed into TM₁₁ wave energy in circular guide 41. The relative dimensions of guides 40 and 41 are identical to the relative dimensions of guides 13 and 10, respectively, of Fig. 1. The length of the coupling interval L is the same in both transducers. The principal difference exists in the coupling means employed in Fig. 6 which discriminates against the TE₀₁ mode of the degenerate pair TE₀₁ and TM₁₁. This coupling comprises a plurality of rectangular apertures 42, specifically eight as also employed in Fig. 1 for illustration, disposed with the long dimensions thereof perpendicular to the axis of guide 41 and in the wide wall of guide 40. Such an aperture will couple any mode of circular wave guide except the TE_{0n} modes to the TE₁₀ mode in the rectangular guide. It should be noted that a rectangular aperture, long dimension perpendicular to the round guide axis and placed in the small side of the rectangular guide, tends to have weak coupling for all modes because the longitudinal round guide currents do not sufficiently excite the rectangular guide.

Having thus described the basic principles and construction of the selective mode transducer with reference to several illustrative embodiments, several specific and useful applications of the transducers in accordance with the invention will now be described. One such application, given here for purposes of illustration, is in the multichannel intelligence transmission systems. It has heretofore been demonstrated that a multimode transmission line may be used to transmit simultaneously a plurality of intelligence-bearing signal channels, each channel being transmitted by energy in different modes or each in the same mode with different guide excitation polarities.

In Fig. 7 is illustrated a particularly interesting example of the latter, wherein two signal channels are transmitted in a single round wave guide by cross-polarized TE₁₁ wave energy. Cross-polarized TE₁₁ waves comprise, as shown in the cross-sectional view of Fig. 7A, two electric fields 61 and 62 of TE₁₁ energy polarized at right angles to each other. These waves have been demonstrated to be stable and not undesirably subject to cross-talk between their respective modulating signals. Thus, in Fig. 7, a first modulating signal from source 56 is impressed upon a carrier signal from source 57 in a modulator 53 and launched as TE₁₀ dominant mode energy in guide 51. A second modulating signal from source 55 is similarly

impressed upon the carrier from source 57 by modulator 54 and launched as TE₁₀ energy in guide 52. A portion of a narrow wall of guide 51 is coupled by a plurality of apertures 61 distributed over the interval L to the circular multi-mode guide 50 in a manner substantially identical to that already illustrated with reference to Fig. 1. Guide 52 is similarly coupled by apertures 62 to guide 50 along a line displaced 90 degrees around the circumference of guide 50 from the line of coupling of guide 51. The unused forward ends of guides 51 and 52 are terminated in a reflectionless manner by terminations 60 and 59, respectively, each of electrical high loss material. The reverse end of guide 50 is similarly terminated in a reflectionless manner by termination 58. The relative cross-sectional dimensions of guides 51 and 50 and guides 52 and 50 are chosen in accordance with the invention so that the guide wavelength of the TE₁₁ wave energy in guide 50 is equal to the TE₁₀ guide wavelength in both guides 51 and 52. In accordance with the considerations already noted with reference to Equations 1, 2 and 3, this requires the radius r of guide 50 to be

$$\frac{1.84}{\pi}$$

times the wide dimension a of guides 51 and 52 in which the factor 1.84 is the Bessel function constant for the TE₁₁ wave tabulated above.

All spurious or undesired modes which would ordinarily be capable of being supported in guide 50 are substantially suppressed by proportioning the length L of the coupling interval in accordance with Equation 4 above. Inasmuch as the TM₀₁ mode would have a guide wavelength or a phase velocity most nearly equal to, but not the same as, the guide wavelength or phase velocity of the TE₁₁ mode, the velocity difference function of Equation 4 is determined by the guide wavelengths of the desired TE₁₁ mode and the TM₀₁ mode, as indicated by the relation shown on Fig. 7. Thus, the modulated TE₁₀ energy in guide 52 will be transferred to a vertically polarized TE₁₁ wave 102 in guide 50, as may be seen on the cross-sectional view Fig. 7A, and the modulated TE₁₀ energy in guide 51 will be transferred to a horizontally polarized TE₁₁ wave 101 in guide 50.

At the receiving end of guide 50 a receiving station of structure identical to that of Fig. 7 will serve to separate and demodulate the two cross-polarized TE₁₁ components. Assuming such a station, the location and orientation of the rectangular guides 51 and 52 around the circumference of the circular guide 50 serves to separate the two TE₁₁ waves from each other; the velocity discrimination of the particular coupling intervals will serve to mitigate against coupling into unwanted modes. It should further be noted that the structure of Fig. 7 may serve for simultaneously transmitting and receiving. If, for example, modulator 53 is a demodulating apparatus, the vertically polarized TE₁₁ energy 62 will serve for transmission of an intelligence signal to the station represented by Fig. 7, while the horizontally polarized TE₁₁ energy 61 will serve for transmission away from the station represented by Fig. 7.

In Fig. 8, a multimode channel system is illustrated in which the TE₁₁ and TM₀₁ modes are employed to transmit and/or receive separate intelligence-bearing signals. The TE₁₁ and TM₀₁ modes are of interest since they are the lowest order circular wave-guide modes. The overall system of Fig. 8 is substantially similar to the system shown in Fig. 7 and corresponding reference numerals have been employed to designate corresponding components. Guides 51 and 50, having the same relative cross-sectional dimensions a_1 and r , respectively as corresponding guides of Fig. 7, are coupled, for the sake of variety of illustration, by a divided aperture 65 substantially identical to the divided aperture 35 of Fig. 4, having a length L₁.

The TE₁₀ output of modulator 54 is applied to guide 66 having the wide dimension a_2 thereof coupled to guide 50 along a longitudinal length L_2 by rectangular apertures 67 substantially identical to apertures 52 of Fig. 6. Guide 66 is terminated in a reflectionless manner by termination 68. The dimension a_2 of guide 66 is proportioned with respect to the radius r of guide 50 so that the guide wavelength of the TE₁₀ wave energy in guide 66 will equal the guide wavelength of TM₀₁ wave energy in guide 50. Thus, in accordance with Equations 1, 2 and 3, the dimension a_2 is equal to

$$\frac{\pi}{2.40}$$

times the radius r of guide 50 in which the factor 2.40 is the Bessel function constant for the TM₀₁ mode. As has already been noted in connection with Fig. 6, rectangular apertures, such as apertures 67, having the long dimension thereof perpendicular to the axis of guide 50, may excite TM modes including the TM₀₁ mode in circular guide 50.

In determining the lengths L_1 and L_2 of each of the coupling distributions, the velocity difference function of Equation 4 in each case are the same since aperture 65 must discriminate between the desired TE₁₁ mode and the undesired TM₀₁ mode, while the array comprising apertures 67 must discriminate between the desired TM₀₁ mode and the undesired TE₁₁ mode. However, L_1 is not equal to L_2 since the value of θ in each case is different. If divided aperture 65 is of the shape illustrated in the drawing, θ will be equal to π radians, as demonstrated with reference to Fig. 4. On the other hand, the value of θ for the array comprising apertures 67, assuming eight equal apertures, will be equal to $7/8\pi$ radians, as demonstrated with reference to Fig. 1. The general expressions for the lengths L_1 and L_2 are indicated on Fig. 8. Thus, the selective mode transducer comprising guides 51 and 50 may serve to launch modulated TE₁₁ wave energy in guide 50 for a transmitting operation or to select the TE₁₁ wave energy from other mode energy in guide 50 for a receiving operation. Likewise, the mode transducer comprising guides 66 and 50 may serve to launch or select TM₀₁ wave energy for either transmitting or receiving operations, respectively.

It should be noted that while in Fig. 8 guides 51 and 66 are illustrated as being coupled to guide 50 along different longitudinal lines, this particular relationship is not necessary. If guide 51 is moved to couple along the same longitudinal line as guide 66, a TE₁₁ mode having a polarity at right angles to the mode illustrated would be launched in guide 50. In some respects, this modification is preferable since the spurious TE₁₁ mode which apertures 67 tend to introduce must then be of different polarity from the desired TE₁₁ modes introduced by aperture 65, and a possible source of cross-talk is thereby eliminated.

In Fig. 9 is shown a multimode transducer by which each of a plurality of intelligence-bearing signals may be launched in one of the lower order circular electric wave modes. For example, on Fig. 9, three modulated TE₁₀ waves, designated, respectively TE₁₀¹, TE₁₀² and TE₁₀³, are to be launched in a single circular wave guide 79 for long distance transmission in the TE₀₁¹, TE₀₂², and TE₀₃³ modes, respectively. The TE₀₁ portion of the transducer of Fig. 9 comprises a rectangular guide 70 coupled in the manner heretofore described with reference to Figs. 1 or 4 over an interval L_1 to a circular guide 71 of radius r_1 . The forward end of guide 70 and the backward end of guide 71 are terminated in a reflectionless manner by terminations 72 and 73, respectively. The circular guide radius is increased from the radius r_1 of guide 71 to the radius r_2 of guide 74 by a linear taper section 75. A second rectangular guide 76, terminated in a reflectionless manner at its forward end by termination 77, is coupled to guide 74 over an interval L_2 , as heretofore described.

Guides 76 and 74 comprise the TE₀₂ section of the transducer. Similarly, the radius of the transducer is again expanded by section 78 to the radius r_3 of section 79 which comprises, together with rectangular guide 80, coupled thereto over an interval L_3 , the TE₀₃ section of the transducer. The forward end of guide 80 is terminated in a reflectionless manner by termination 81.

Each of the rectangular guides 70, 76 and 80 have equal wide dimensions a , chosen to support the dominant TE₁₀ wave energy applied thereto. The radius r_1 of guide 71 is chosen in accordance with considerations already fully detailed hereinbefore to render the guide wavelength of the TE₀₁ mode therein equal to the wavelength of the TE₁₀ mode in guide 70. Similarly, the radius r_2 of guide 74 is chosen to render the guide wavelength of the TE₀₂ energy therein and the radius r_3 of guide 79 is chosen to render the wavelength of the TE₀₃ energy therein, equal to the guide wavelength of the TE₁₀ wave energy in guides 76 or 80, respectively. Thus, in accordance with Equations 1, 2 and 3:

$$\begin{aligned} r_1 &= \frac{3.83a}{\pi} \\ r_2 &= \frac{7.02a}{\pi} \\ r_3 &= \frac{10.17a}{\pi} \end{aligned}$$

In guide 71 the mode having the nearest phase velocity to the desired TE₀₁ mode and, therefore, the critical mode in the determination of the velocity discriminating length L_1 , is the TE₃₁ mode. Similarly, in guides 74 and 79, the critical spurious modes are the TE₂₂ and the TE₂₃ modes, respectively. The critical mode is in each case determined by an inspection of a portion above and below the listing of the desired mode on the Bessel function tables set out hereinbefore. Thus, the lengths L_1 , L_2 and L_3 , of the coupling distributions between guides 70 and 71, 76 and 74, and 80 and 79, are proportioned according to Equation 4 to have the relations set out on Fig. 9 and to therefore discriminate between each desired mode and its critical spurious mode.

In Fig. 10, an alternative mode multiplex system is shown in which a plurality of dominant mode TE₁₀ modulated signals of different frequencies are transformed to TE₀₁ circular electric wave signals at corresponding frequencies. Thus, a first modulated TE₁₀ wave at a first frequency, designated on Fig. 10 as TE₀₁¹, is transformed into a first modulated TE₀₁ wave at the same frequency, designated on Fig. 10 TE₀₁¹. Similarly, dominant mode waves at frequencies f_2 and f_3 are converted into circular electric waves. The f_1 portion of the transducer comprises a rectangular guide 85, having a wide dimension a_1 , terminated at its forward end by termination 86, and coupled over a longitudinal length L_1 to guide 87 of radius r_1 . Guide 87 is terminated in its backward direction by termination 96. The f_2 portion of the transducer comprises a rectangular guide 88, having a wide dimension a_2 , terminated at its forward end by termination 89, and coupled over a longitudinal length L_2 to guide 90 of radius r_2 . The f_3 portion of the transducer comprises a rectangular guide 91, having a wide dimension a_3 , terminated at its forward end by termination 92, and coupled over a longitudinal length L_3 to guide 93 of radius r_3 . The transition between radius r_1 of guide 87 to radius r_2 of guide 90 is accomplished by linear taper portion 94. A similar linear taper portion 95 is provided between guides 90 and 93. The dimensions a_1 , a_2 and a_3 for rectangular guides 85, 88 and 91 are chosen to support the TE₁₀ energy at the frequencies f_1 , f_2 and f_3 in each, respectively. In the illustration of Fig. 10 f_1 is assumed to be a frequency higher than f_3 and therefore the dimension a_1 of guide 85 is substantially smaller than the dimension a_3 of guide 91. For each frequency section of the transducer, the radius of the circular guide member is

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chosen to render the wavelength of the TE₀₁ energy therein at the particular frequency equal to the wavelength of the TE₁₀ energy in the corresponding rectangular guide. Therefore, in each frequency section the ratio of the radius r to the wide dimension a is the same, namely,

$$r = \frac{3.83a}{\pi}$$

in which the quantity 3.83 is the Bessel function constant for the TE₀₁ wave. Again the length L for each frequency section of the transducer is chosen to discriminate between the desired TE₀₁ wave in the circular guide of that section and the critical spurious mode TE₃₁ therein. Therefore, the lengths of L_1 , L_2 and L_3 will be equal when measured in wavelengths but unequal in actual physical dimensions, since the relative guide wavelengths of the TE₀₁ and TE₃₁ waves will be different at the frequencies f_1 , f_2 and f_3 .

While the principles of the invention have herein been demonstrated with reference to systems in which one guide is rectangular and the other is circular, inasmuch as present commercial interest appears to be directed to such systems, the principles of the invention are by no means limited to coupling between these particularly shaped wave guides. The related guides may be of the same geometrical cross-section. Any or all of these may well be elliptical, triangular, square, or of any other shape, as is well known in the art.

For example, Fig. 11 illustrates a selective mode transducer, in accordance with the invention, in which the dominant mode TE₁₀ wave energy in a rectangular guide 97 is transformed into TE₂₀ wave energy in a second rectangular guide 98. The relative wide dimensions of guides 97 and 98 are chosen in accordance with Equation 2 above so that the cut-off wavelength for the TE₁₀ mode in guide 97 equals the cut-off wavelength for the TE₂₀ mode in guide 98. This requires the wide dimension a_2 of guide 98 to equal twice the wide dimension a_1 of guide 97. The narrow dimension of the guides may be equal.

The center of the narrow wall of guide 97 is coupled by a plurality of rectangular apertures 99, each disposed with the long dimension thereof parallel to the axis of the guide 97, to the center of the wide wall of guide 98. The apertures 99 are distributed along the length L chosen in accordance with Equation 4 above to discriminate between the desired TE₂₀ mode in guide 98 and the undesired spurious TE₁₀ mode therein. As in the examples illustrated hereinbefore, the value of θ depends upon the exact number and strength of such apertures.

Apertures 99 will couple between the TE₁₀ mode in guide 97 and the TE₂₀ mode in guide 98 and since the apertures 99 are located substantially exactly on the center line of the wide wall of guide 98, very little coupling will exist between the TE₁₀ mode of guide 97 and the TE₁₀ mode of guide 98. Thus, the velocity discrimination as hereinbefore described is enhanced by the aperture coupling discrimination to make possible a very high degree of mode purity in the transfer of power from guide 97 to guide 98.

Several general comments can be made with regard to mode discrimination effects of aperture coupling between rectangular guides. If the guides of Fig. 11 were coupled by apertures in a common narrow wall, the TE₁₀ mode of guide 97 would couple to both TE₁₀ and TE₂₀ modes in guide 98. If the guides were coupled by apertures on the center line of a common wide wall, the TE₁₀ mode of guide 97 would couple only to the TE₁₀ mode of guide 98.

While the invention has been illustrated with reference to shielded transmission lines, specifically of the wave-guide type, the principles of the invention apply to each type of electrical transmission system known in the art, including for example, the coaxial transmission line or the open two-wire transmission line. In each case the coupling between the related lines is obtained over the

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length specified herein by the particular coupling means typically employed for and in each of these transmission systems. The velocity of propagation of wave energy along any of these systems is regulated by the means known for each system for controlling the value of effective distributed inductance and capacitance of the lines in the same way that these parameters are controlled by the physical dimensions of the wave-guide transmission lines herein illustrated.

In all cases, it is understood that the above-described arrangements are simply illustrative of 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. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line having a transverse cross-section, said line adapted to support wave energy in a plurality of modes of propagation including a first mode, said line having a guide wavelength λ_1 for said first mode, a second transmission line located adjacent said first line and coupled with a given coupling distribution to said first line over a longitudinal length of said lines, said second line having a transverse cross-section of dimensions different from those of said first line cross-section, said dimensions of said second line providing a guide wavelength for a second mode of propagation therein substantially equal to said λ_1 , said first mode and said second mode being different modes of wave energy propagation, said longitudinal length of coupling being substantially equal to

$$\frac{\theta}{\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)}$$

wherein θ is at least the value of the periodic angle of the Fourier transform of said coupling distribution at which the characteristic of the transform first passes through zero, wherein λ_2 is the guide wavelength of a mode of said plurality nearest said λ_1 , whereby wave energy propagated in said second mode in said second line will be transferred to said first mode in said first line and all other modes of said plurality will be suppressed in said first line.

2. A selective mode transducer for multimode high frequency electrical transmission systems comprising a main wave-guide transmission path for said energy, a plurality of auxiliary wave-guide transmission paths, each of said auxiliary paths being coupled with a given coupling distribution to a portion of said main path over a longitudinal length of said main path, each portion of said main path over which an auxiliary path is connected having a transverse cross-section and a given guide wavelength for a predetermined mode of wave energy propagation, each of said auxiliary paths having a transverse cross-section of dimensions different from and adapted to support wave energy in a particular mode of propagation different from the transverse cross-section of and the predetermined mode in the portion to which that auxiliary path is coupled, each of said auxiliary paths having a guide wavelength for said particular mode of propagation therein substantially equal to said guide wavelength of said predetermined mode in the portion to which that auxiliary path is coupled, said longitudinal length of coupling for each portion being substantially equal to

$$\frac{\theta}{\pi \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)}$$

wherein θ is at least the value of the periodic angle of the Fourier transform of said coupling distribution at

which the characteristic of the transform first passes through zero, wherein λ_1 is said given guide wavelength for that portion, and wherein λ_2 is the guide wavelength of a mode of propagation in that portion of said main path nearest said λ_1 , whereby wave energy propagated in one of said particular modes in each of said auxiliary paths is transferred to one of said predetermined modes in said main path and all other modes in said main path are suppressed.

3. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first transmission line, said line having a given guide wavelength for a first mode of wave energy propagation, a second transmission line coupled to said first line over a longitudinal length of said lines, said second line adapted to support wave energy in a plurality of modes including a second mode of propagation different from said first mode, said second line having a guide wavelength for said second mode substantially equal to said guide wavelength of said first mode in said first line.

4. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first transmission line, said line adapted to support a plurality of modes of wave energy propagation, said line having a guide wavelength λ_1 for predetermined one of said modes, a second transmission line located adjacent said first line and coupled with a given coupling distribution to said first line over a longitudinal length of said lines, said second line having a guide wavelength for a mode of propagation therein substantially equal to said λ_1 , said longitudinal length of coupling being substantially equal to

$$\frac{\theta}{\pi \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)}$$

wherein θ is at least the value of the periodic angle of the Fourier transform of said coupling distribution at which the characteristic of the transform first passes through zero, and wherein λ_2 is the guide wavelength of a mode of said plurality nearest said λ_1 .

5. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line having a transverse cross-section, said line adapted to support a plurality of modes of wave energy propagation, said line having a given guide wavelength for a predetermined one of said modes, a second shielded transmission line coupled to said first line over a longitudinal length of said lines, said second line having a transverse cross-section, the dimensions of said second line cross-section being different from the dimensions of said first line cross-section, said second line having a guide wavelength for a mode of propagation therein substantially equal to said guide wavelength of said first line.

6. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line having a transverse cross-section, said line adapted to support a plurality of modes of wave energy propagation, said line having a guide wavelength λ_1 for a predetermined one of said modes, a second shielded transmission line located adjacent said first line and coupled with a given coupling distribution to said first line over a longitudinal length of said lines, said second line having a transverse cross-section of dimensions different from those of said first line cross-section, said second line having a guide wavelength for a mode of propagation therein substantially equal to said λ_1 , said longitudinal length of coupling being substantially equal to

$$\frac{\theta}{\pi \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)}$$

wherein θ is at least the value of the periodic angle of the Fourier transform of said coupling distribution at which the characteristic of the transform first passes through zero, and wherein λ_2 is the guide wavelength of a mode of said plurality nearest said λ_1 .

7. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line having a circular transverse cross-section, said line adapted to support a plurality of modes of wave energy propagation, said line having a given cut-off wavelength for a predetermined one of said modes, a second shielded transmission line located adjacent said first line and coupled to said first line over a longitudinal length of said lines, said second line having a rectangular transverse cross-section, said second line having a cut-off wavelength for a mode of propagation therein substantially equal to said cut-off wavelength of said first line.

8. The combination according to claim 7 wherein the radial dimension of said first line is substantially

$$\frac{1}{\pi} \text{ to } \frac{2}{\pi}$$

times one transverse dimension of said second line.

9. The combination according to claim 7 wherein the radial dimension of said first line is substantially

$$\frac{2}{\pi} \text{ to } \frac{3}{\pi}$$

times one transverse dimension of said second line.

10. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first transmission line, said line having a given cut-off wavelength for the dominant mode of wave energy propagation therein, a second transmission line located adjacent said first line and coupled to said first line over a longitudinal length of said lines, said second line adapted to support wave energy in the circular electric mode of propagation, said second line having a cut-off wavelength for said circular electric mode substantially equal to said cut-off wavelength of said dominant mode in said first line.

11. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line having a circular transverse cross-section, said line adapted to support at least the TE_{01} and TM_{11} modes of wave energy propagation, said line having a given guide wavelength for said modes, a second shielded transmission line located adjacent said first line and coupled to said first line over a longitudinal length of said lines, said second line having a rectangular transverse cross-section, the wide dimension of said second line cross-section being substantially equal

$$\frac{\pi}{4} \text{ to } \frac{\pi}{3}$$

times the radial dimension of said first line cross-section whereby the guide wavelength for the TE_{10} mode of propagation in said second line substantially equals said given wavelength of said first line.

12. The combination according to claim 11 wherein said lines are coupled by means responsive to one of said modes in said first line and excluding the other of said modes therein.

13. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line having a circular transverse cross-section, said line adapted to support at least the TE_{01} and TM_{11} modes of wave energy propagation, said line having a guide wavelength λ_1 for said modes, a second shielded transmission line of rectangular transverse cross-section located adjacent said first line and coupled with a given coupling distribution to said first line over a longitudinal length of said lines, said second line having a guide wavelength for the TE_{10} therein substantially equal

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to said λ_1 , said longitudinal length of coupling being substantially equal to

$$\frac{\theta}{\pi \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)}$$

wherein θ is at least the value of the periodic angle of the Fourier transform of said coupling distribution at which the characteristic of the transform first passes through zero, and wherein λ_2 is the guide wavelength of the TE₃₁ in said first line.

14. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line, said line having a given cut-off wavelength for a first mode of wave energy propagation, a second shielded transmission line having a portion of its length contiguous a portion of said first line, means coupling said lines over a longitudinal length thereof comprising a common shield in said contiguous portion having aperture means therethrough, said second line adapted to support wave energy in a plurality of modes including a second mode of propagation different from said first mode, said second line having a cut-off wavelength for said second mode substantially equal to said cut-off wavelength of said first mode in said first line.

15. The combination according to claim 14 wherein said aperture means comprises a plurality of apertures distributed along a line parallel to the axis of said shielded lines.

16. The combination according to claim 14 wherein said aperture means comprises a plurality of apertures distributed along a line parallel to the axis of said shielded lines, and wherein each of said plurality of apertures is rectangular in shape and is positioned in said shield with the longer dimension of said rectangle parallel to the axis of said shielded line.

17. The combination according to claim 14 wherein said aperture means comprises a plurality of apertures distributed along a line parallel to the axis of said shielded lines, and wherein each of said plurality of apertures is rectangular in shape and is positioned in said shield with the longer dimension of said rectangle perpendicular to the axis of said shield.

18. The combination according to claim 14 wherein one of said lines is rectangular in cross-section and wherein said common shield portion includes the narrower wall of said rectangular line.

19. The combination according to claim 14 wherein one of said lines is rectangular in cross-section and wherein said common shield portion includes the wider wall of said rectangular line.

20. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line, said line adapted to support a plurality of modes of wave energy propagation, said line having a guide wavelength λ_1 for a predetermined one of said modes, a second shielded transmission line having a portion of its length contiguous a portion of said first line, means coupling said second line with a given coupling distribution to said first line over a longitudinal length L of said lines, said coupling means comprising a common shield in said contiguous portion having aperture means therethrough, said second line having a guide wavelength for a mode of propagation therein substantially equal to said λ_1 , said longitudinal length of coupling being substantially equal to

$$\frac{\theta}{\pi \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)}$$

wherein θ is at least the value of the periodic angle of the Fourier transform of said coupling distribution at which the characteristic of the transform first passes through zero, and wherein λ_2 is the guide wavelength of a mode of said plurality nearest said λ_1 .

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21. The combination according to claim 20 wherein said aperture means comprises n apertures distributed along a line parallel to the axis of said shield and wherein θ is substantially equal to

$$\frac{n-1}{n} \pi$$

22. The combination according to claim 20 wherein said aperture means is a divided rectangular aperture and wherein θ is substantially equal to π .

23. The combination according to claim 20 wherein said aperture means provides a substantially distributed coupling per unit length along said length L equal substantially to

$$\frac{\pi m}{2L}$$

wherein m is any odd integer.

24. The combination according to claim 20 wherein said aperture means comprises

$$\frac{\pi \pi}{2 \sin^{-1} C}$$

coupling apertures each having substantially a coupling factor C , wherein m is any odd integer.

25. A selective mode transducer for multimode high frequency electrical transmission systems comprising a first shielded transmission line having a rectangular transverse cross-section, said line adapted to support a plurality of modes of wave energy propagation, said line having a given cut-off wavelength for a predetermined one of said modes, a second shielded transmission line located adjacent said first line and coupled to said first line over a longitudinal length of said lines, said second line having a rectangular transverse cross-section, the wider dimension of said first line cross-section being twice the wider dimension of said second line cross-section whereby said second line has a cut-off wavelength for a mode of propagation therein substantially equal to said cut-off wavelength of said first line.

26. A selective mode transducer for multimode high frequency electrical transmission systems comprising a main transmission path for said energy, a plurality of auxiliary transmission paths, each of said auxiliary paths being coupled to a portion of said main path over a longitudinal length of said main path, each portion of said main path over which an auxiliary path is coupled having a given cut-off wavelength for a predetermined mode of wave energy propagation, each of said auxiliary paths adapted to support wave energy in a particular mode of propagation different from the predetermined mode in the portion to which that auxiliary path is coupled, each of said auxiliary paths having a cut-off wavelength for said particular mode of propagation therein substantially equal to said cut-off wavelength of said predetermined mode in the portion to which that auxiliary path is coupled.

27. A selective mode transducer for multimode high frequency electrical transmission systems comprising a main shielded transmission line of circular cross-section, said line adapted to support a plurality of modes of wave energy propagation, a plurality of auxiliary shielded transmission lines of rectangular cross-section, each of said lines being coupled to a portion of said main line over a longitudinal length of said main line, said main line having given cut-off wavelengths for predetermined ones of said modes, each of said auxiliary paths adapted to support wave energy in a particular mode of propagation different from the predetermined modes in said main line, each of said auxiliary paths having a cut-off wavelength for said particular mode of propagation therein substantially equal to said cut-off of a predetermined mode in said main line.

28. The combination in accordance with claim 27 wherein said auxiliary lines are each coupled to said main line along lines displaced around the circumference of

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said main line whereby the same mode of wave energy is launched in said main line by each auxiliary line but with different relative polarities therein.

29. The combination in accordance with claim 28 wherein the radial dimension of said main line is substantially

$$\frac{1}{\pi} \text{ to } \frac{2}{\pi}$$

times one transverse dimension of an auxiliary line.

30. The combination in accordance with claim 27 wherein a part of said plurality is coupled to said main line by means responsive to one group of modes of wave energy propagation while excluding another group of modes, and wherein the remainder of said plurality are coupled by means responsive to a mode included in said other group and excluding a mode included in said one group.

31. The combination in accordance with claim 30 wherein the radial dimension of said main line is substantially

$$\frac{1}{\pi} \text{ to } \frac{2}{\pi}$$

times one transverse dimension of said part and substantially

$$\frac{2}{\pi} \text{ to } \frac{3}{\pi}$$

times one transverse dimension of said remainder.

32. A selective mode transducer for multimode high frequency electrical transmission systems comprising a main transmission path for said energy, said main path comprising a connected plurality of circular cross-sectional shielded transmission line portions, a plurality of auxiliary shielded transmission lines of rectangular cross-section, each of said auxiliary lines being coupled to a corresponding one of said main path portions over a longitudinal length of said portion, each portion of said main path having a given cut-off wavelength for a predetermined mode of wave energy propagation, each of said auxiliary lines adapted to support wave energy in a particular mode of propagation different from the prede-

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termined mode in its corresponding portion, each of said auxiliary paths having a cut-off wavelength for said particular mode of propagation therein substantially equal to said cut-off of said predetermined mode in its corresponding portion.

33. The combination in accordance with claim 32 wherein the wide dimensions of all of said auxiliary lines are substantially equal, wherein the radial dimension of one portion of said main path is substantially

$$\frac{3}{\pi} \text{ to } \frac{4}{\pi}$$

times said transverse dimension, and wherein the radial dimensions of subsequent portions of said main path are integral multiples larger than a value in said range of

$$\frac{3}{\pi} \text{ to } \frac{4}{\pi}$$

times said transverse dimension.

34. The combination in accordance with claim 32 wherein each of said auxiliary lines is adapted to support the dominant mode of wave energy at successively different frequencies and wherein the radial dimension of each portion of said main path is

$$\frac{3}{\pi} \text{ to } \frac{4}{\pi}$$

times one transverse dimension of its corresponding auxiliary line.

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