

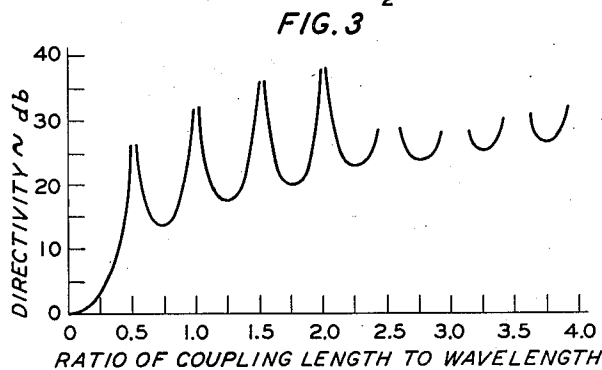
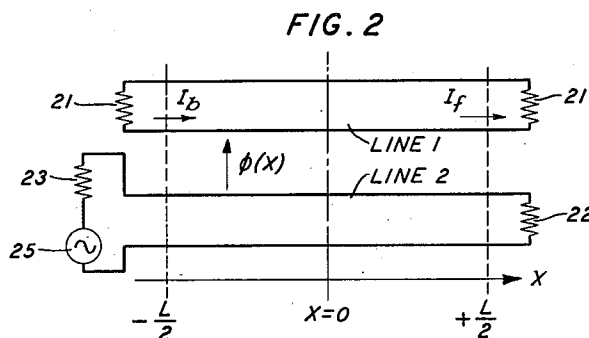
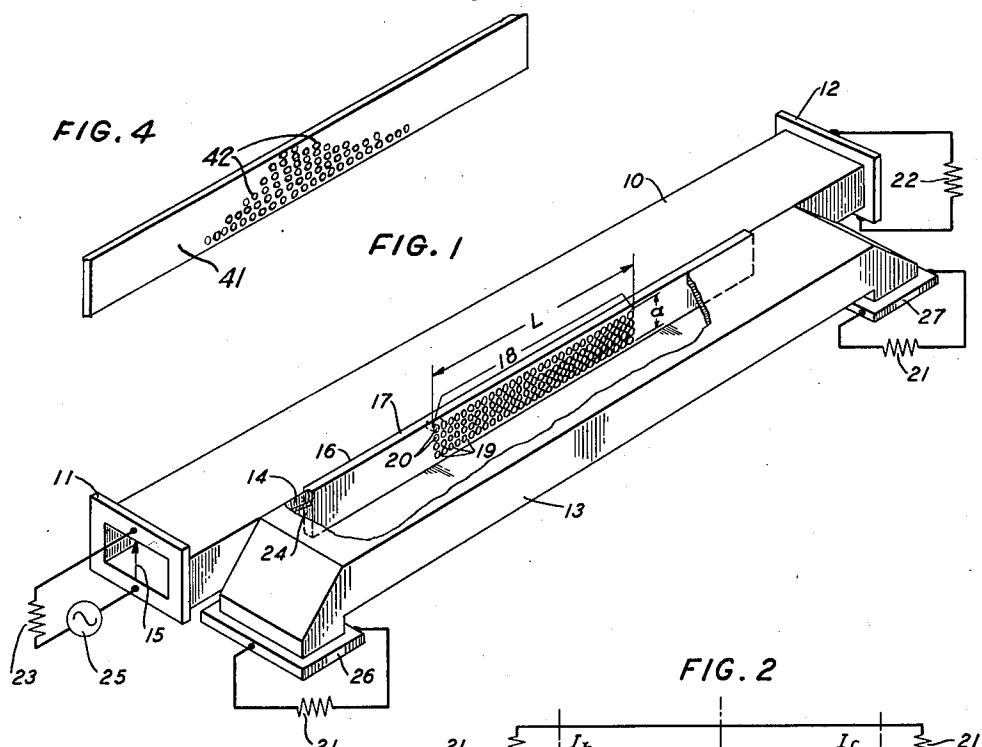
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A. E. BOWEN ET AL

2,701,341

HIGH-FREQUENCY DIRECTIONAL COUPLER

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A. E. BOWEN DECEASED  
INVENTORS: VIRGINIA C. BOWEN, HIS EXECUTRIX  
W. W. MUMFORD

BY

H. O. Wright  
ATTORNEY

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2,701,341

## HIGH-FREQUENCY DIRECTIONAL COUPLER

Arnold E. Bowen, deceased, late of Fair Haven, N. J.,  
by Virginia C. Bowen, executrix, Bloomfield, and Wil-  
liam W. Mumford, Atlantic Highlands, N. J., assignors  
to Bell Telephone Laboratories, Incorporated, New  
York, N. Y., a corporation of New York

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1 Claim. (Cl. 333—10)

This invention relates to electrical wave transmission systems and, more particularly, to improved electro-magnetic wave energy couplers providing a directional coupling characteristic between two transmission lines, such as wave guides, coaxial lines or the like.

More specific types of energy couplers are disclosed and claimed in the copending application of S. E. Miller, Serial No. 216,132, filed March 17, 1951, and A. G. Fox, Serial No. 236,556, filed July 13, 1951, which types are in certain respects based upon the principles to be disclosed herein.

One of the early practical types of directional couplers was described in an article in the Proceedings of the Institute of Radio Engineers, February 1947, vol. 35, pages 160 to 165 by W. W. Mumford. The couplers there disclosed are now well known in the art, and countless uses and applications thereof have been described in the published art. In general, all presently known directional couplers are formed by a short section of main transmission line coupled to a short section of auxiliary line. The coupling between the two sections is arranged so that an electromagnetic wave traveling in a single direction along the main line induces a principal secondary wave, known as the forward wave, traveling in a single direction along the auxiliary line. Likewise, this coupling operates so that a wave traveling in the opposite direction in the main transmission line induces a principal secondary wave traveling only in the opposite direction in the auxiliary line.

In most practical directional couplers there is also an induced or secondary wave traveling in the opposite direction from each forward wave, known as the backward wave. The forward and the backward waves are desirably greatly unequal in strength. Their relative strength is called the directivity of the coupler and is usually expressed as the decibel ratio of the forward wave current to the backward wave current. The strength of the desired induced forward wave in the auxiliary line to the inducing wave in the main line is called the "coupling loss" and is also expressed as the decibel ratio of the desired or forward induced wave to the inducing wave in the main line. This "coupling loss" is actually the transfer ratio between the two lines and there is no power dissipated in the structure. The performance of a directional coupler may be described in terms of this directivity and coupling. To operate satisfactorily, the directivity of a coupler must exceed some minimum design value at all frequencies within its operating range. Thus, the plot of directivity versus the operating frequency or wavelength of the coupled energy is known as the directivity characteristic of the coupler and will be so designated herein.

The coupler, as disclosed in one embodiment by Mumford in the above-mentioned publication, consists of a short section of auxiliary wave guide located contiguous to the main wave guide. Coupling is provided between the main wave guide and the auxiliary wave guide by a pair of longitudinally spaced holes in a common side wall. A traveling wave in the main guide will induce a traveling wave in the auxiliary guide traveling in the same direction and, since the path length of the energy coupled through each of the holes is equal, no electrical interference in the forward direction results. The path lengths of the oppositely directed or backward waves induced through the two holes into the auxiliary guide are unequal and, due to the spacing of one-quarter wavelength between the holes, cancellation results and no resulting wave will be induced in the auxiliary guide in the backward direction or in a

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direction opposite to that of the wave in the main guide.

This results in the directivity of the coupler being frequency sensitive since the desired high directivity occurs only at the frequency at which the coupling holes are separated by one-quarter wavelength. This frequency is known as the design or center frequency. At frequencies slightly higher and slightly lower than the design frequency the directivity decreases, giving a finite operating range over which the directivity exceeds the minimum design value.

It is shown in the above-mentioned publication that the frequency range over which the directivity exceeds a minimum design value may be broadened by employing an increased number of coupling elements which are still spaced one-quarter wavelength apart, but which have their coupling effects related to each other in accordance with the coefficients of a binomial expansion. Other coupler designs have been disclosed in which the frequency range of directivity has been increased by providing an infinite series of couplings or a distributed coupling between the two guides. This has in general been provided either by a plurality of probes or by a long narrow slot. This coupling is located in either case in a side of the guide walls which is perpendicular to the electric vector of the wave energy, that is, a wider wall assuming dominant mode energy, and provides coupling extending over an unusually long distance which must exceed several wavelengths at the operating frequency.

It is an object of the present invention to improve the directivity characteristic of directional couplers by increasing the directivity over a substantially increased operating frequency range.

It is a further object to shorten the wavelength distance over which coupling is required for improved directivity and thereby decrease the physical size of directional couplers.

It has been determined, in accordance with the invention, that when the particular type of coupling, known as divided aperture coupling, to be described with reference to specific embodiments hereinafter, is employed to relate the two transmission lines, the directivity characteristic of the coupler is directly related by a Fourier transform equation, to the shape of the plot of the magnitude of distributed coupling versus the coupling distance along the region of distributed coupling. In other words, the directivity is the transform of the shape of the coupling distribution, and conversely, the coupling distribution shape is the transform of the directivity.

These and other objects, the nature of the present invention, and its various features and advantages, will appear more fully upon consideration of the various specific illustrative embodiments, shown in the accompanying drawings and in the following detailed description of these embodiments.

In the drawings:

Fig. 1 illustrates a specific embodiment of a microwave directional coupler in which directional coupling is provided by a rectangular divided aperture in accordance with the invention;

Fig. 2, given by way of illustration, is a diagrammatic representation of the coupler of Fig. 1; and

Fig. 3, given by way of illustration, is a directivity characteristic of the type to be expected for the coupler of Fig. 1.

Fig. 1 shows a directional coupler in accordance with the invention, comprising a main section 10 of shielded transmission line for guiding wave energy, which may be a rectangular wave guide, as shown, having terminal connections 11 and 12 at each of its ends. Located adjacent main line 10 and having a portion of its length contiguous to a portion of main line 10, is an auxiliary shielded transmission line 13 for guiding wave energy, which may be a rectangular wave guide as shown, having terminal connections 26 and 27 at each of its ends. A portion of the adjacent walls 14 and 24 of the two guides 10 and 13, respectively, which walls are parallel to the electric vector 15 of wave energy in the guides or the narrower wall thereof, assuming normal dominant mode excitation, has been removed providing a slot 16 between the guides when viewed from the direction of the wider wall side. Into slot 16 is placed an insert 17 which forms the common

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wall between the adjacent wave guides 10 and 13. Each end of auxiliary guide 13 is terminated in its characteristic impedance as indicated diagrammatically by impedances 21. A source 25 of dominant mode electromagnetic microwave energy having a polarization of vector 15 is shown connected to terminal 11 of main wave guide 10. The internal impedance of source 25, indicated diagrammatically by impedance 23, is equal to the characteristic impedance of guide 10. The other end of guide 10 is terminated in its characteristic impedance as indicated diagrammatically by impedance 22.

Insert 17 is provided with a divided rectangular aperture 18 having a longitudinal dimension  $L$  and a transverse dimension  $a$  and provides the coupling between guides 10 and 13. The coupling means 18 is termed a "divided aperture" because it is, in fact, a composite of many smaller holes or undivided apertures 20 placed in insert 17 and distributed over the rectangular area  $aL$ . The holes 20 remain separate, being separated or divided from each other by small remaining portions 19 of insert 17. The preferable number of holes 20, their dimensions, and their spacing and distribution within the area  $aL$  will be discussed in detail hereinafter.

Divided aperture 18, representing the collective effect of the multiplicity of undivided apertures 20, provides a current coupling between lines 10 and 13 which is effectively distributed to a substantial degree along the length  $L$  of the divided aperture in the manner to be described. The magnitude of current coupling at each point along the length of divided aperture 18 is uniform and is proportional to the transverse dimension  $a$ , as will be pointed out in detail. A simple undivided rectangular aperture of the same size and shape as the divided aperture 18 does not provide this desired substantially distributed coupling. To the contrary, the undivided aperture behaves as a resonant transmission line independent of either of the adjacent wave guides. This is true no matter how thin the common wall thickness is made, since a standing wave is produced in the undivided aperture as a result of the high coefficient of reflection at the aperture ends. Such an aperture indeed behaves substantially as a resonant single point coupling and will, therefore, not have the particular attributes, including particularly distributed coupling, to be described in detail hereinafter, which attributes are necessary to the practice of the present invention.

With the divided aperture of Fig. 1, the standing waves which otherwise would tend to form in an undivided aperture of the same size and shape as divided aperture 18, are localized in each of the holes 20 and destroyed if the dimensions of the holes 20 are chosen in accordance with the following considerations. Generally speaking, if the largest dimensions of holes 20 are less than one-half wavelength, the holes will be non-resonant and no standing waves can be supported therein. Thus, each hole tends to produce a single discrete coupling located at its center point. However, since the amount of departure from the desired continuous coupling is inversely related to the number of such discrete couplings per wavelength along the length  $L$ , it is necessary that many small holes 20 be employed. It has been determined that if the number of holes 20 is in the range of five or more per wavelength along the length  $L$ , the desired continuous coupling assumed in the mathematics to follow is actually justified.

The number of holes 20 along a transverse cross section of divided rectangular aperture 18 determines the power coupling from main line 10 to auxiliary line 13. It may be easily shown that the power transferred through this path varies substantially as the total area included by all of the holes 20. Since this is so, the current coupling through the divided aperture of a given length varies directly as the divided aperture transverse dimension  $a$ .

Holes 20 are illustrated in Fig. 1 as circular since this is the simplest structure to obtain in an actual physical embodiment of the invention by drilling or punching the holes through a blank insert, but it should be apparent that holes 20 may be squares, rectangles or any other geometrical shape, so long as they may be closely fitted together to cover the major portion of the area  $aL$ .

The width of the dividers or portions 19, i. e., the distance between the perimeters of adjacent holes 20, does not affect the directivity within reasonable limits. In the preferred embodiment of the invention as shown in Fig. 1, this dimension of dividers or portions 19 is comparable to and perhaps somewhat less than the common wall

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thickness between guides 10 and 13, but the operable minimum dimension thereof is principally controlled by physical considerations such as rigidity of the insert 17 in the area of the divided aperture 18. The width of the portions 19 may be increased substantially beyond the thickness of the common wall without causing any substantial departure from the desired continuous coupling discussed above. The power transferred through the divided aperture, however, is affected by the dimensions of the dividers. For example, if the dimension of dividers 19 is increased in the plane of the aperture, i. e., decreasing the area of the holes 20, the power transferred is reduced. For this reason the ratio of the total portion of area  $aL$  included by all of the holes 20 to that portion of the area  $aL$  taken up by the dividers 19 should be made as large as possible for good power transfer. This means that distance between the perimeters of adjacent holes 20 should be less than the dimensions of holes 20.

As pointed out above, and as shown in Fig. 1, the divided aperture 18 is located in a common wall of the two rectangular guides 10 and 13 which wall is in the case of both guides parallel to the electric vector of wave energy in the guide. As stated above, in this position the current coupling between the guides at each point along the aperture 18 is proportional to the transverse dimension of the divided aperture 18. It should be noted, however, that this current coupling relation obtains if the divided aperture 18 is located in a common wall parallel to the electric vector in only one guide, that is, assuming dominant mode excitation, if the common wall includes only the narrower wall of one wave guide. The relation also obtains if the divided aperture is located in a common wall which is perpendicular to the electric vectors in both guides, provided that the aperture is displaced from the center line of the wider wall in both guides.

The manner in which directional coupling operation is obtained from the structure 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 13 and 10 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 divided aperture coupling in the structure of Fig. 1, is confined to the interval length  $L$  and is designated on Fig. 2 by the interval from

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

The coupling distribution or the variation 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 the source 25 is traveling to the right in line 2. When all the forward current elements are summed and referred to the plane of

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

the equation

$$I_f = kF \int_{-\frac{L}{2}}^{+\frac{L}{2}} \varphi(x) dx \quad (1)$$

is obtained in which the factor  $F$  is expressed

$$F = \frac{e^{-i(2\pi L/\lambda)}}{2Z}$$

The term  $Z$  represents the characteristic impedance of either line and its terminal impedances 21, 22 and 23. The term  $\lambda g$  represents the guide wavelength of electromagnetic energy.

The factor  $k$  represents the fraction of the total induced current which travels forward in the auxiliary line 1. The factor  $k$  is thus a measure of the directionality of the coupling on a differential length basis. If all the backward current elements are summed and referred to the plane

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

the equation

$$I_b = (1-k)F \int_{-\frac{L}{2}}^{+\frac{L}{2}} \varphi(x) e^{-i\frac{4\pi}{\lambda g}x} dx \quad (2)$$

is obtained. The ratio of the forward current (Equation 1) to the backward current (Equation 2) is the directivity of the coupler defined above. So long as the phase of the coupling function  $\varphi(x)$  does not change between

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

the forward current elements all add in phase in line 1. However, the backward current elements add in a form of destructive interference. The backward current expression (Equation 2) is in the form of a Fourier transform. Thus, the discrimination characteristic is directly related to the coupling distribution  $\varphi(x)$  by the Fourier transform. Theoretically, then, it is possible to design a coupling distribution which would produce any desired directivity characteristic.

For specific example, the coupling characteristic of the divided rectangular aperture 18 of Fig. 1 is a rectangular wave, i. e., the magnitude of the current coupling at each point along the length of the aperture is uniform over the coupling interval  $L$ , the length of aperture 18, and the magnitude is zero outside this interval. The exact manner in which this characteristic is obtained by a divided rectangular aperture such as 18 has been explained in detail hereinbefore. In terms of the notations used above, the function  $\varphi(x)$  for the coupling characteristic is equal to unity as  $x$  varies from

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

Equations 1 and 2 above may therefore be easily evaluated for this coupling function. In each equation the factor  $k$  becomes  $\frac{1}{2}$  since, as demonstrated by Mumford in the above publication, one-half of the current coupled by an aperture in the side wall of a wave guide will travel in each direction. The forward current expression of Equation 1 becomes

$$I_f = \frac{FL}{2} \quad (3)$$

The backward current expression of Equation 2 when evaluated for the rectangular coupling distribution of Fig. 1 is the known Fourier transform of a rectangular wave; that is, the backward current is a constant times the Fourier transform of the coupling distribution and becomes

$$I_b = \frac{FL}{2} \frac{\sin u}{u} \quad (4)$$

in which

$$u = \frac{2\pi L}{\lambda g} \quad (5)$$

and where  $\lambda g$  is the guide wavelength of the electromagnetic energy in both guides. Thus, the directivity is given by the ratio of the forward current to the backward current or the ratio

$$\text{Dir.} = \frac{u}{\sin u} \quad (6)$$

This function is plotted on Fig. 3, in which the ordinate represents the directivity in decibels and the abscissa represents the ratio of the coupling length  $L$  to the wavelength  $\lambda g$ . It will be noted that perfect directivity, i. e., infinite decibel discrimination in a backward direction, is found in all regions in which the coupling length  $L$  is an integral number of half wavelengths of the guide wavelength  $\lambda g$ . It will be noted the minima of directivity fall off as the ratio

$$\frac{L}{\lambda g}$$

With a coupling interval of approximately three wavelengths broad band directivity of the order of 25 decibels is obtained.

The nature of the coupling in accordance with the invention as thus described, and the particular character-

istics of this coupling may well be summarized at this point, to provide a firm foundation from which to proceed to the appended claims. Thus, the coupling is provided by what has been termed, and will continue to be termed hereinafter in the appended claim, a "divided aperture." A "divided aperture" may be considered as an original opening, the perimeter of which defines a given geometric shape, but which original opening has been broken down into many smaller openings or spaces. On the other hand, it may be considered as a composite aperture which has been built up or simulated by the many smaller openings or spaces. If the number of smaller spaces is large, their exact individual size and shape need not be considered, but rather attention should be directed to the size and shape defined by the perimeter of the original opening or the "divided aperture." This shape will in general be designated as having a "basic geometric shape." The magnitude of current coupled at any point through the divided aperture, located as described, is directly proportional to the transverse dimension of the divided aperture so that the distribution along the aperture of the coupled current is identical to the physical shape of the divided aperture. This current characteristic will be designated as a "basic geometric distribution." The Fourier transform of the basic geometric distribution, and therefore, the transform of the basic geometric shape is the characteristic of the backward current in the auxiliary transmission line which characteristic is directly related to the directivity of the coupler. The total current coupled, which determines the coupling loss in the forward direction, depends upon the magnitude of the transverse dimension of the divided aperture. So long as this magnitude is varied without altering the shape of the divided aperture, the coupling loss may be independently chosen by the transverse dimension without affecting the directivity characteristics.

All of this has been demonstrated herein with reference to a single basic geometric shape as the shape defining the perimeter of the divided aperture. The shape thus chosen for illustration of the invention was the rectangular shape or the shape defined by a square wave form. The same principles of analysis apply in determining the backward current expression and thus the directivity characteristic of a directional coupler having divided aperture coupling of other basic geometrical shapes. Particularly outstanding and useful examples of these other basic shapes for which the Fourier transforms are well known in the art include a triangular wave, a one-half period of a cosine wave, a whole period of a cosine wave measured from one minimum point to another and which is mathematically the same as one-half period of a  $\sin^2$  wave, and positive and negative exponential waves. In the case of the triangular wave form, for example, Fig. 4 shows an insert 41 which may replace the insert 17 of Fig. 1, and which has a triangularly shaped divided aperture therein built up from a plurality of holes 42, like the holes 20 in Fig. 1, distributed over an area of insert 41. The shape defining the perimeter of the divided aperture is made triangular and a backward current would be expected which would equal the Fourier transform for a triangular shape times a determinable constant. This, of course, is the mathematical evaluation of Equation 2 hereinbefore for a triangular coupling distribution.

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 said principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

Directional coupling apparatus for electromagnetic wave energy comprising a main hollow conductor rectangular wave guide having unequal transverse cross-sectional dimensions for guiding said energy, an auxiliary hollow conductor rectangular wave guide having unequal transverse cross-sectional dimensions and having a wall thereof in common with a wall of said main guide, said common wall being the narrow wall of at least one of said guides, said common wall having a multiplicity of closely spaced openings extending through said common wall and distributed over a geometrical area of said common wall, the geometrical perimeter of said area defining the shape of a coupling distribution characteristic that varies in

coupling strength along the longitudinal dimension of said area, the maximum longitudinal dimension of said area extending at least more than one-half wavelength of said energy along the longitudinal dimension of said guides, the maximum transverse dimension of said area extending at least along a major portion of the transverse dimension of said narrow wall, the dimension of each of said openings along said longitudinal dimension being no greater than the dimension of said opening along said transverse dimension, the concentration of said openings along said longitudinal dimension being at least five per wavelength to provide a substantially distributed coupling between said guides along said longitudinal dimension.

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