

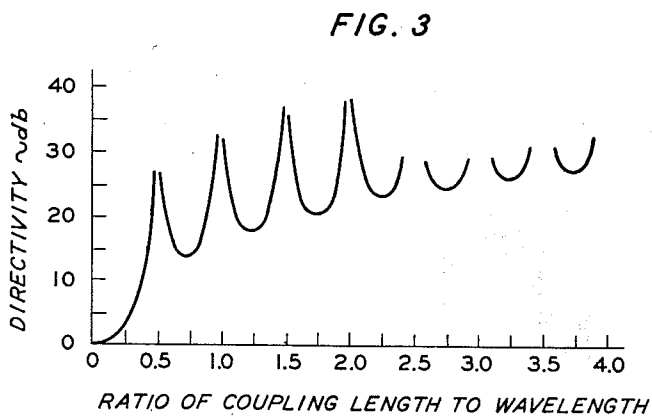
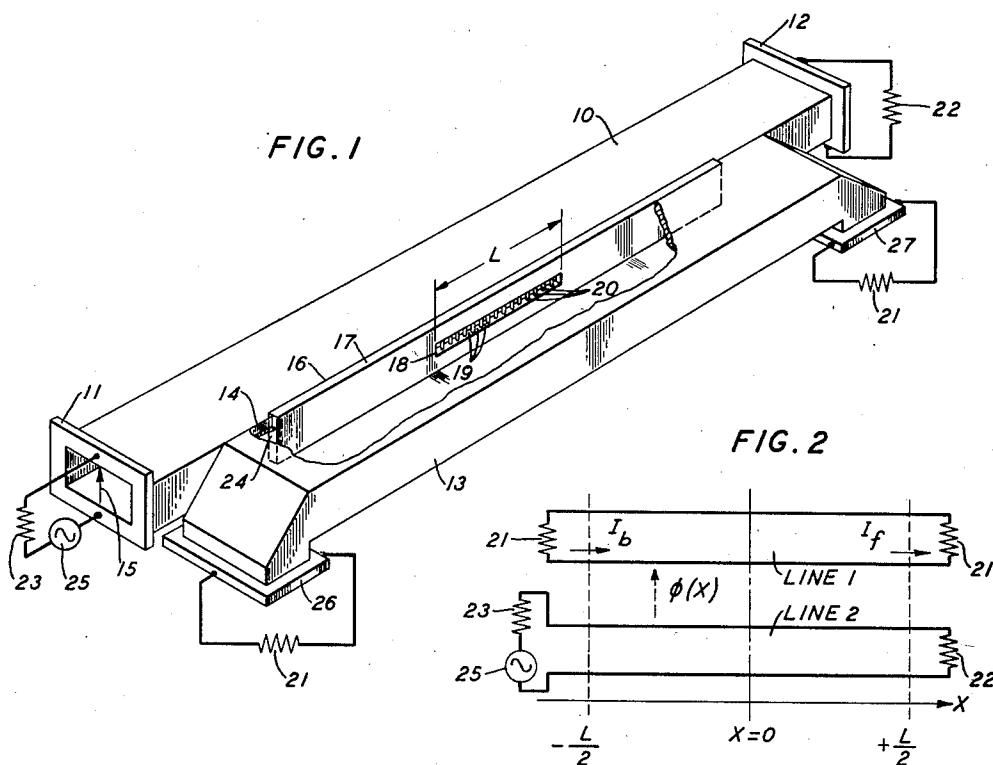
Feb. 1, 1955

A. G. FOX

2,701,342

HIGH-FREQUENCY DIRECTIONAL COUPLER

Filed July 13, 1951



INVENTOR
A. G. FOX
BY
H. O. Wright
ATTORNEY

1

2,701,342

HIGH-FREQUENCY DIRECTIONAL COUPLER

Arthur Gardner Fox, Eatontown, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application July 13, 1951, Serial No. 236,556

1 Claim. (Cl. 333—10)

This invention relates to electrical wave transmission systems and, more particularly, to improved electromagnetic wave energy couplers providing a directional coupling characteristic between two transmission lines, such as hollow conductor wave guides.

A related embodiment of the present invention is disclosed and claimed in the application of A. E. Bowen and W. W. Mumford, Serial No. 219,426, filed April 5, 1951, and the present embodiment is disclosed in an application of S. E. Miller, Serial No. 216,132, filed March 17, 1951.

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 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 power to the backward wave power. 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 inducing wave power in the main line to the desired or forward induced wave power in the auxiliary line. Although termed a "loss," there is customarily little or no power dissipated in the structure. The performance of a directional coupler may be described in terms of this directivity and coupling loss. 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 equal 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

2

backward direction or in a 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 effect 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, that is, a wider wall assuming the usual dominant mode propagation in rectangular wave guide, 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 hollow conductor rectangular wave guide, as shown, having terminal connections 11 and 12 at each of its ends. Located adjacent to the main line 10 and having a portion of its length contiguous to a portion of the main line, is an auxiliary shielded transmission line 13 for guiding wave energy, which may be a hollow conductor rectangular wave guide, as shown, and having terminal connections 26 and 27 at its respective ends. A portion of the adjacent walls 14 and 24 of each of the two guides 10 and 13, respectively, which walls are parallel to the electric vector 15 of the dominant wave, 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 a common wall between the adjacent wave guides 10 and 13. Insert 17 is provided with a divided rectangular aperture 18 providing coupling between guides 10 and 13. The exact dimensions of the divided aperture 18 will be given in detail hereinafter, but it may now be stated in general, that the longitudinal dimension L is greater than one-half wavelength, while the smaller dimension thereof is, in the usual case, considerably less than one-half wavelength. The aperture is termed divided since extending parallel across the transverse or narrower dimension of aperture 18 and dividing it longitudinally into a plurality of smaller spaces 19, is a grid comprising a plurality of dividers or wires 20. Wires 20 may be soldered into recesses placed in insert 17 along the edges of aperture 18 or the resulting structure may be stamped or punched from a blank insert. The preferable number of wires 20, their dimensions and the maximum size of spaces 19 will be discussed in detail hereinafter. Each end of main guide 10 and auxiliary guide 13 is shown terminated in its characteristic impedance as indicated diagrammatically by impedances 21 for guide 13, and 22 and 23 for guide 10. A source 25 of microwave energy is shown diagrammatically connected in series with impedance 23 to terminal 11 of main guide 10.

Divided aperture 18 provides a current coupling between the lines 10 and 13 which is effectively distributed to a substantial degree along the length L of the aperture. The magnitude of the current coupling is uniform along this length and is proportional to the transverse dimension of the aperture. A single undivided rectangular aperture of the same size and shape as the divided aperture 18 does not operate satisfactorily. This is because in addition to the desired coupling between waves in the two wave guides, there is also coupling with a wave traveling along the slot more or less as on a parallel wire transmission line. This "slot wave" travels at a lower phase velocity than the dominant wave in the separate wave guides and is totally reflected by the ends of the slot, thereby creating a standing wave along the slot. The standing wave due to the slot wave produces an undesired coupling in addition to the desired distributed coupling between the traveling waves in the two wave guides. As a result, the directivity may be greatly reduced. In order to avoid the spurious coupling, the aperture must be treated so as to prevent propagation of the slot wave. In accordance with the invention, this is done by providing shunt inductances in the form of wires 20 spaced along the slot as shown. When the reactance of each of these wires is smaller than the characteristic impedance of the slot for the slot wave, and when they are spaced closer together than one-quarter wavelength of the slot wave, the slot wave can no longer be propagated. More generally, when θ is the phase distance between wires for the slot wave, the inductive reactance of each of the wires must be less than

$$\frac{\sin \theta}{1 - \cos \theta} \quad (1)$$

in order to prevent the slot wave from propagating.

Such a divided aperture tends to produce a number of discrete couplings located midway between the wires 20. However, by reducing the spacing between wires and thereby increasing the number of discrete couplings, the electric field along the slot may be made to effectively approach the desired continuous distribution.

It has been determined that if the number of spaces 19 is in the range of three or more per wavelength, a useful approximation of continuous coupling is achieved, and if the number of spaces 19 exceeds eight or more per wavelength, the desired continuous coupling assumed as a basis for the mathematical analysis given hereafter is actually realized for all practical purposes.

The transverse dimension of the spaces 19, and therefore of divided aperture 18, is, of course, limited by the smaller of the transverse dimensions of the narrow walls 14 and 24 of the wave guides 10 and 13, respectively, and will therefore usually be less than one-half wavelength. The exact value of the transverse dimension of the divided rectangular aperture 18 determines the power coupling from the main transmission line 10 to the auxiliary transmission line 13. It may be easily shown that the transfer or power coupling loss through this path varies substantially as the square of the transverse dimension

of the aperture 18. This fact is a most important attribute of the divided aperture in the narrow wall, but the full significance of this fact will more readily be appreciated when certain of the embodiments to be described hereinafter are considered. It should be noted, however, that since the power transferred does vary as the square of the transverse dimension, the current coupling through the divided aperture varies directly as the transverse dimension.

The width of the dividers or wires 20, i. e., the diameter thereof if the dividers are wires of circular cross section, does not affect the directivity within reasonable limits. In the preferred embodiment of the invention as shown in Fig. 1, this dimension of the dividers, shown as wires 20, is comparable to and perhaps somewhat less than the common wall thickness between guides 10 and 13, but the operable minimum dimension thereof is principally controlled by physical considerations such as rigidity of the dividers 20. The width of the dividers 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 20 is increased in the plane of the aperture, i. e., decreasing the area of the spaces 19, or if the dimension of dividers 20 is increased in the direction of wall thickness which would not change the area of spaces 19, the power transferred is reduced. It is found that the width of spaces 19 changes the current transfer much more rapidly than linearly and as a consequence, for example, a given aperture when divided into ten spaces provides appreciably more power transfer than the identical aperture divided into twenty spaces.

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, assuming dominant mode propagation in rectangular wave guides, this current coupling relation obtains for any position of the slot in either wave guide, provided the slot is parallel to the axis of both wave guides and provided the slot is not centered in the wall which is perpendicular to the electric vector in either wave guide.

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

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

is obtained in which the factor F is expressed

$$F = \left[\frac{2Z}{e^{-i2\pi L/\lambda g}} \right]^{-1}$$

The term Z represents the characteristic impedance of either line and its terminal impedances 21, 22 and 23. The term λg 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

$$I_b = (1-k)F \int_{-\frac{L}{2}}^{+\frac{L}{2}} \varphi(x) e^{-i\frac{4\pi}{\lambda g}x} dx \quad (3)$$

is obtained. The ratio of the forward current (Equation 2) to the backward current (Equation 3) 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 3) 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 rectangular in form, 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 2 and 3 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 2 becomes

$$I_f = \frac{FL}{2} \quad (4)$$

The backward current expression of Equation 3 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

$$I_b = \frac{FL}{2} \frac{\sin u}{u} \quad (5)$$

in which

$$u = \frac{2\pi L}{\lambda g} \quad (6)$$

and where λg 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

$$\text{Dir.} = \frac{u}{\sin u} \quad (7)$$

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 λg . 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 λg . It will be noted the minima of directivity increase as

$$\frac{2\pi L}{\lambda g}$$

increases. 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 characteristics 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 claims, 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." The 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 characteristic 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 rectangular. 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 shape, a one-half period of a cosine function, one-half period of a $\sin^2$ function, and positive and negative exponential functions. In the case of the triangular shape, for example, 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 3 hereinbefore for a triangular coupling distribution.

The particular coupling distributions contemplated by the invention have been obtained in the preceding embodiments by varying the shape of the coupling aperture in a predetermined manner. However, a suitable coupling distribution may be obtained by varying the spacing of wires 20 placed across an aperture 18 of constant transverse dimension. For example, assume that a triangular distribution is desired. Then the spacing of the wires 20 will be chosen to render the areas between the wires 20 proportioned to substantially the square root amplitudes

of the coupling function at points along the aperture length which points correspond, respectively, to the centers of the spaces 19.

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 section of hollow conductor wave guide of uniform rectangular transverse cross-sectional dimensions for guiding said energy, an auxiliary section of hollow conductor wave guide of uniform rectangular transverse cross-sectional dimensions, said auxiliary guide 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 and having an elongated aperture therein which tends to act as a wave guiding path having a given characteristic impedance for standing waves set up within said aperture, the longitudinal dimension of said aperture being greater than one-half wavelength of said wave energy to provide a substantially distributed coupling between said guides in

addition to a spurious coupling resulting from said standing waves, and a plurality of conductive wires each having a shunt reactance that is smaller than said characteristic impedance extending across said aperture, said wires being spaced apart by the phase distance θ in the quantity

$$\frac{\sin \theta}{1 - \cos \theta}$$

10 which represents a reactance larger than the inductive reactance of each of said wires to prevent said standing waves from propagating in said aperture and to eliminate said spurious coupling.

References Cited in the file of this patent

UNITED STATES PATENTS

2,531,777	Marshall	Nov. 28, 1950
2,541,910	Bangert	Feb. 13, 1951
2,566,386	Varian	Sept. 4, 1951
2,568,090	Riblet	Sept. 18, 1951
2,575,571	Wheeler	Nov. 20, 1951
2,660,706	Hill	Nov. 24, 1953

FOREIGN PATENTS

657,826	Great Britain	Sept. 26, 1951
---------	---------------	----------------