

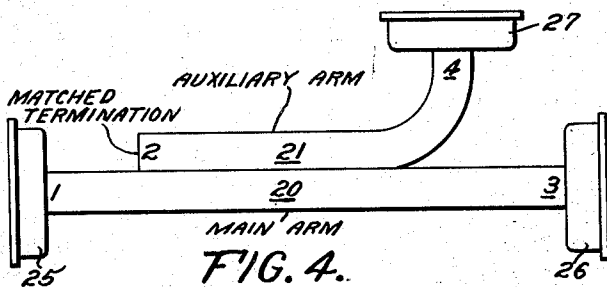
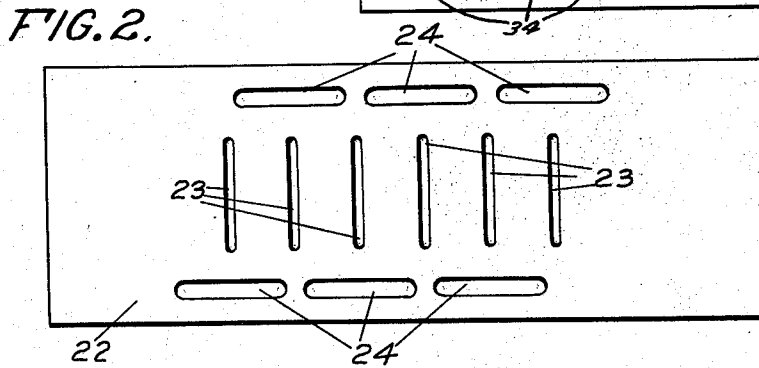
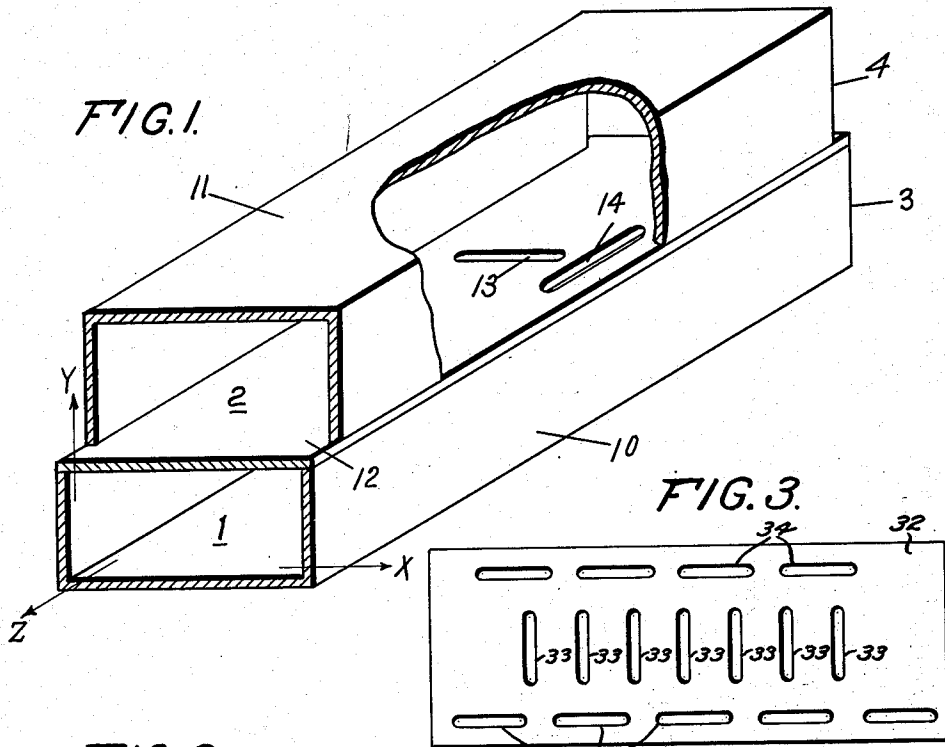
March 24, 1953

H. J. RIBLET
DIRECTIONAL COUPLER

2,632,809

Filed Nov. 5, 1947

8 Sheets-Sheet 1



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Filed Nov. 5, 1947

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FIG. 5a.

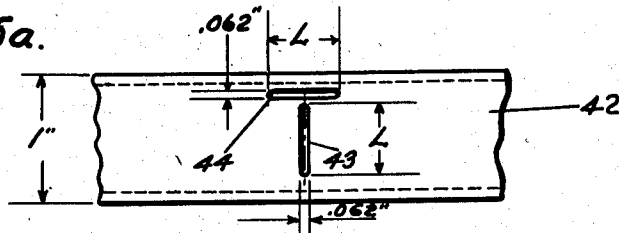
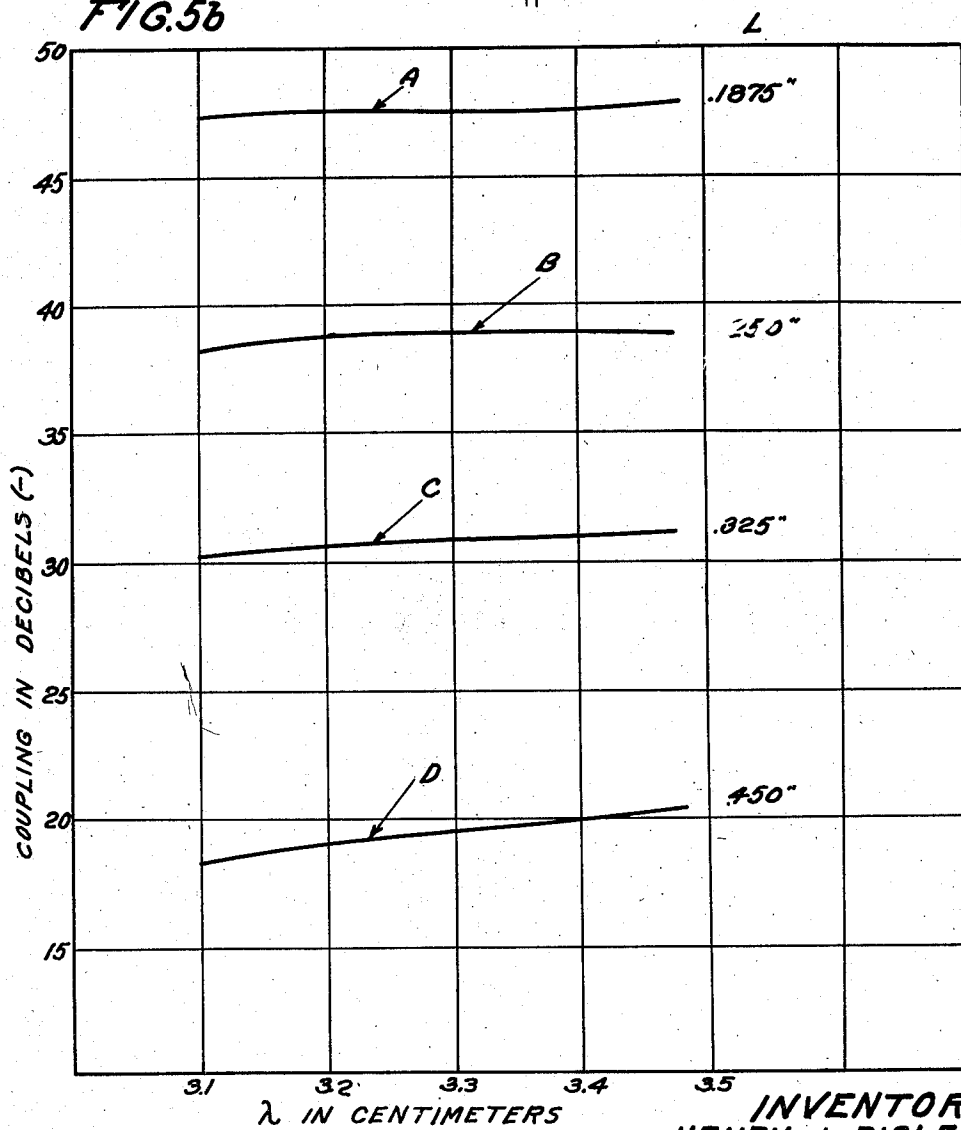


FIG. 5b



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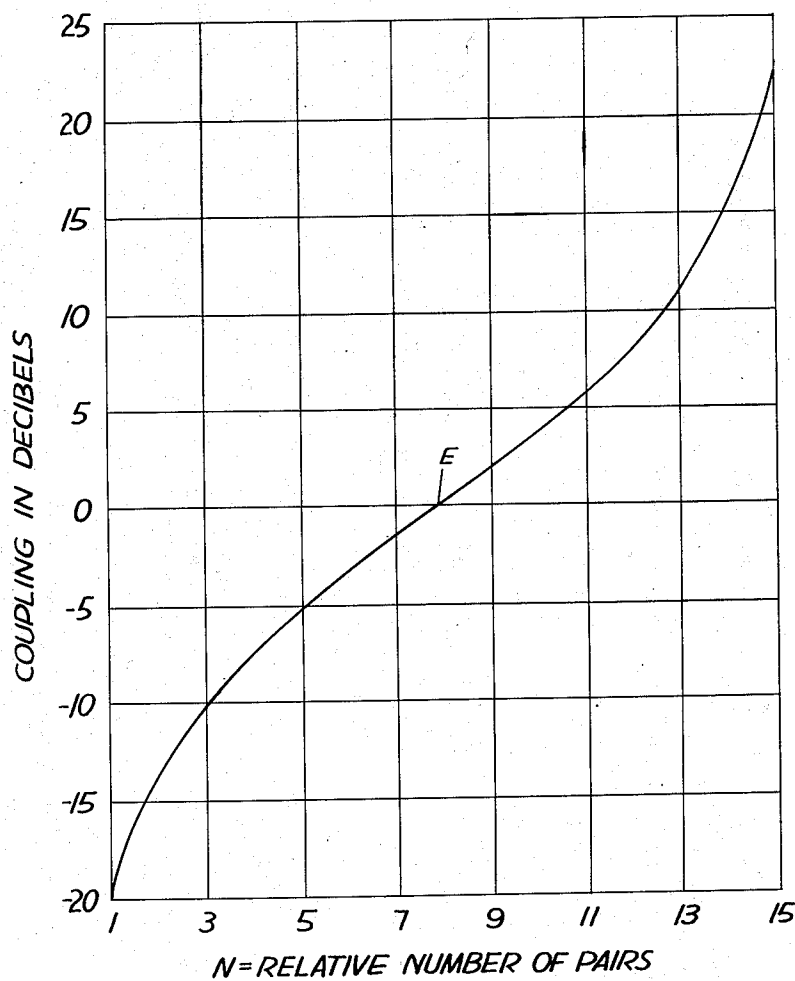
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FIG. 6



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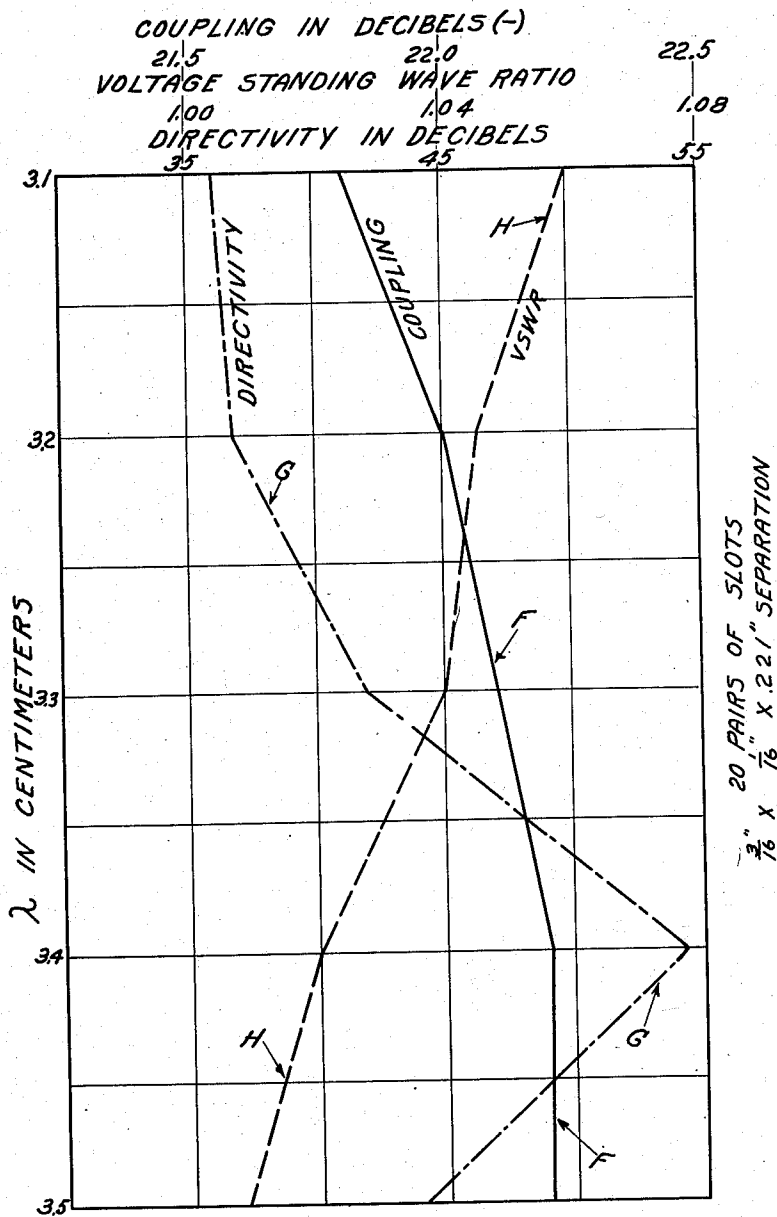
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FIG. 7.



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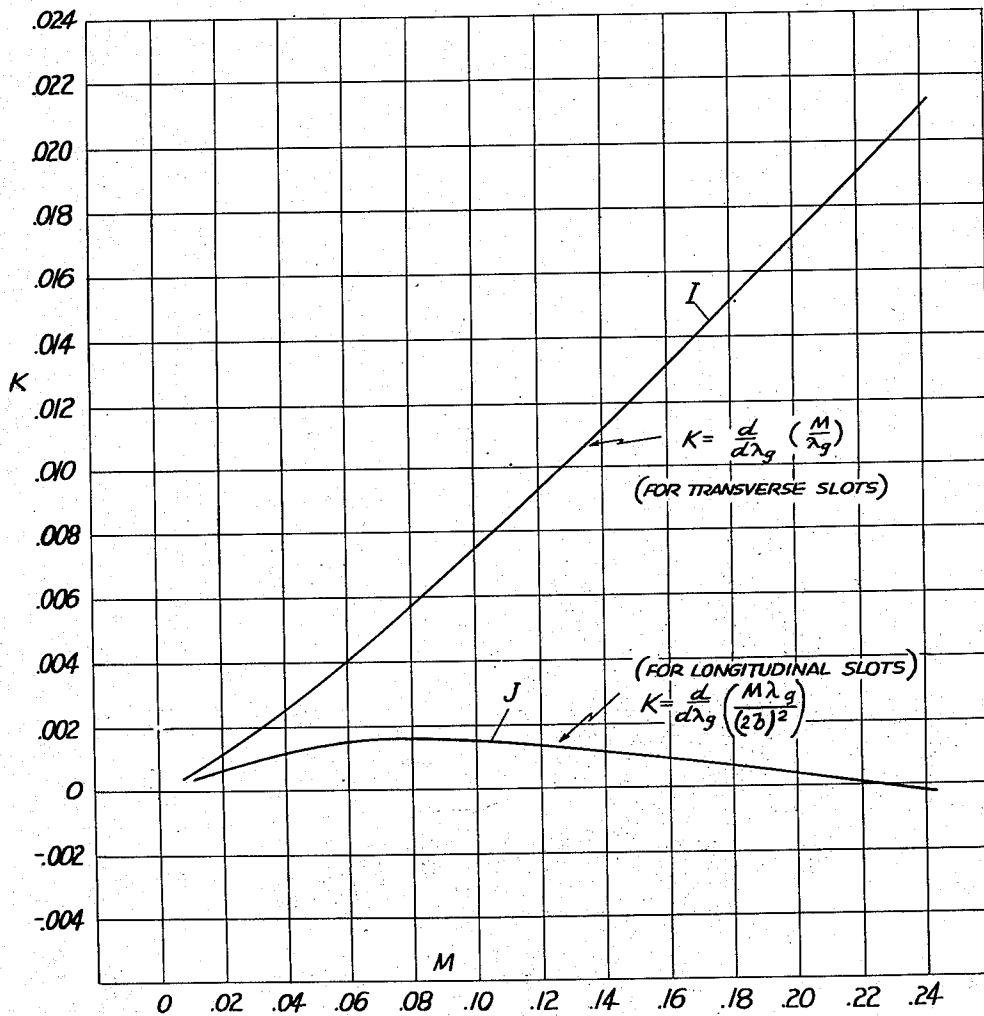
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FIG. 8



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FIG. 9a

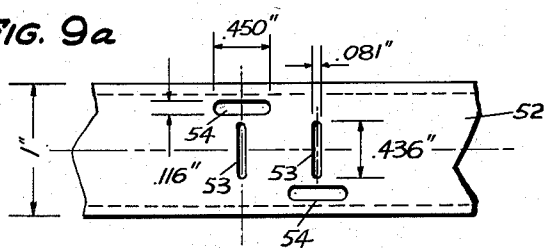
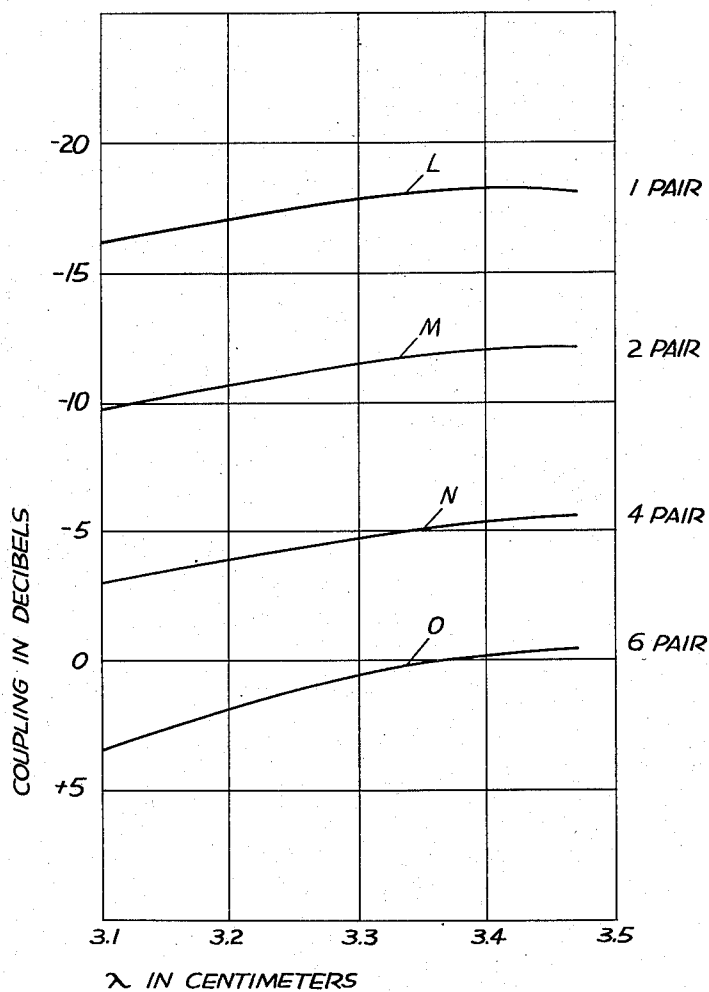


FIG. 9b



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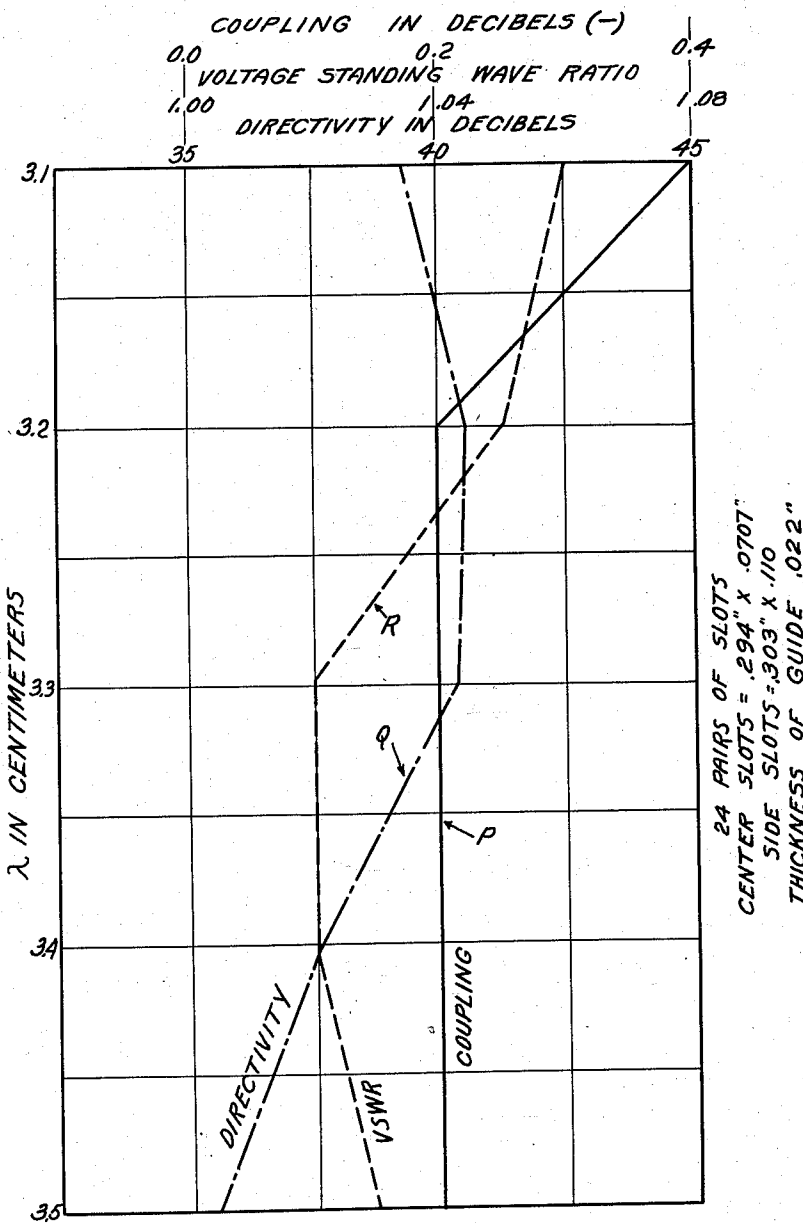
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FIG. 10



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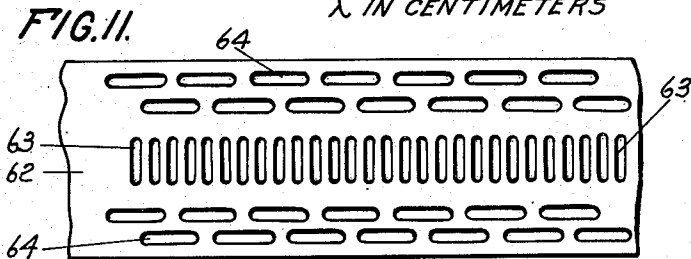
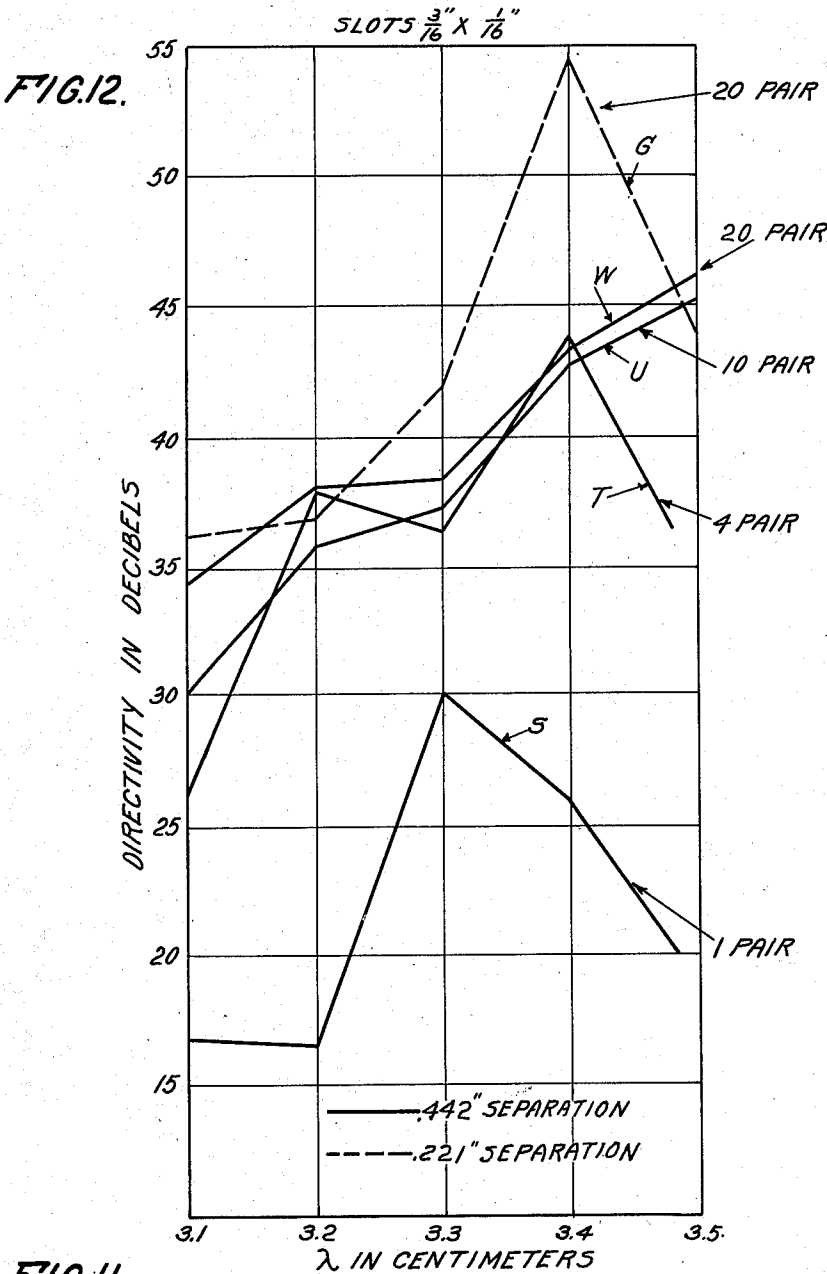
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DIRECTIONAL COUPLER

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8 Sheets-Sheet 8



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UNITED STATES PATENT OFFICE

2,632,809

DIRECTIONAL COUPLER

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Application November 5, 1947, Serial No. 784,277

13 Claims. (Cl. 178—44)

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The present invention relates in general to waveguide directional couplers, and in particular to a new type of directional coupler having improved performance and structural characteristics.

It is an object of the present invention to provide a waveguide directional coupler having a coupling characteristic which is substantially constant over a relatively wide band of operating frequencies.

It is another object to provide such a directional coupler wherein a coupling characteristic having a desired value lying between wide limits can be provided, and which can consequently be employed as a balanced bridge having the characteristics of a "magic T" or "rat race" bridge, without being frequency critical.

It is another object to provide such a directional coupler having high directivity, of the order of 40 decibels or more.

It is another object to provide such a directional coupler having a low input standing wave ratio, in the region of unity.

It is still another object to provide such a directional coupler wherein the structural requirements to provide broad band characteristics are easily arrived at and simple to satisfy.

It is a further object of the invention to provide a directional coupler having the foregoing advantages which occupies a relatively small space as compared with prior directional couplers, and has the advantage of universal applicability.

To provide the foregoing and other advantages, the invention contemplates the provision, in a common wide wall between two waveguides of rectangular cross-section, for example, of individual energy-transferring slots having mutually perpendicular directions. Energy introduced into one end of one of the waveguides proceeds in part to the other end of that waveguide and in part into and to the corresponding end of the other waveguide, without change of direction, substantially no energy emerging from the remaining end of the other waveguide.

Other and further objects of the invention will become apparent from the description of certain embodiments thereof that follows, reference being made to the accompanying drawings, wherein:

Fig. 1 shows an isometric view partly broken away of a directional coupler in accordance with the present invention;

Fig. 2 shows a top plan view of another embodiment of the invention;

Fig. 3 shows a top plan view of still another embodiment of the invention;

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Fig. 4 shows a side view of a waveguide arrangement employing a directional coupler, illustrating a manner of employment of the present invention;

Fig. 5a is a fragmentary view of a particular embodiment of the invention;

Fig. 5b is a group of graphs illustrating the broad band coupling characteristics of directional couplers like that shown in Fig. 1 having the parameters as shown in Fig. 5a;

Fig. 6 is a graph illustrating the manner in which the coupling characteristic of the invention can be altered with constructions like those shown in Figs. 2 and 3;

Fig. 7 is a composite group of graphs illustrating the overall performance characteristics of a particular directional coupler, made of elements like those shown in Fig. 1, over a wide band of operating frequencies;

Fig. 8 is a graph illustrating certain characteristics of slot arrangements according to Fig. 2 which are employed to provide uniform coupling over wide operating frequency bands;

Fig. 9a is a fragmentary view of another particular embodiment of the invention;

Fig. 9b is a group of graphs illustrating the broad band coupling characteristics of certain directional couplers in accordance with Fig. 2 and having the parameters as shown in Fig. 9a;

Fig. 10 is another composite group of graphs similar to Fig. 7 for a coupler designed in accordance with Figs. 2 and 8;

Fig. 11 shows a top plan view of still another embodiment of the invention; and

Fig. 12 is a group of graphs illustrating the high directivity characteristic of directional couplers of the present invention.

Referring now to Fig. 1, a first waveguide 10 and a second waveguide 11 are joined together to provide a four terminal waveguide network. The waveguides may be constructed, as shown in Fig. 1, of a pair of rectangular U-channels, each of which provides one wide wall and both narrow walls of one waveguide, disposed with the free ends of their respective legs confronting and a plate 12 providing the common wide wall positioned between them. Electrically and mechanically satisfactory joints between the ends of the legs and the long edges of the plate 12 are accomplished by soldering, for example. The precise manner in which the two waveguides are constructed is not material to the invention, however. The parts shown in Fig. 1 may be bolted or riveted together, or, if desired, two conventional waveguides may be electrically joined together at their wide walls. As will appear be-

low, it is desirable that the common wide wall 12 shall have a minimum thickness, and, for this and other reasons, such as ease of construction of the invention, and smooth finish of the completed article, the construction shown in Fig. 1 is preferred.

The two waveguides 10 and 11 are operated in the lowest or $TE_{0,1}$ mode, which, as is well known, is characterized by current flow in the wide walls which is largely in the direction of the longitudinal axis of the waveguide along and near the longitudinal center line, and largely in a direction perpendicular thereto in the region of the narrow or side walls.

The common wide wall 12 is provided with a transversely directed slot 13 in the region of the longitudinal center line and preferably centered thereabout as shown, and a longitudinally directed slot 14 near a side edge thereof. In the embodiment of the invention shown in Fig. 1, the center points of the two slots lie along a common transversely directed line (not shown), but this is not essential to the invention, as will appear in the discussion of Fig. 3. When one of the waveguides, which will be called the "main waveguide," is energized in the $TE_{0,1}$ mode, the two slots being advantageously positioned to interrupt current flow in the wide wall 12, substantial electromagnetic fields are built up about them and energy is thereby coupled into the other waveguide, which will be called the "auxiliary waveguide." The slots may be of the same dimensions or, as will be discussed in detail below, they may be different. They should preferably not be of such size, however, as to become resonant to the waves being carried, for the coupling characteristic of the coupler (which will be defined below) changes rapidly with frequency when the slots are resonant to these waves.

Denominating the open ends of the first waveguide 10 as terminals 1 and 3, respectively, and those of the second waveguide 11 as terminals 2 and 4, respectively, with terminals 1 and 2 at one end and terminals 3 and 4 at the other end of the network, the network of Fig. 1 functions as a directional coupler if power incident on terminal 1 divides in some ratio between terminals 3 and 4 without reaching terminal 2, while power incident on terminal 3 divides between terminals 1 and 2 without reaching terminal 4, assuming matched output terminals. When the power incident, for example, at terminal 1, is divided evenly between terminals 3 and 4, the directional coupler is called a "bridge circuit."

Denominating power introduced at any terminal as P_i , and power out at terminals 1, 2, 3 and 4 as P_1 , P_2 , P_3 , and P_4 , respectively, the performance of the directional coupler may be specified in terms of the coupling, the directivity, and the input voltage standing wave ratio. Where P_1 is at terminal 1, these terms are defined as follows:

$$\text{coupling} = \frac{P_4}{P_3}$$

$$\text{directivity} = \frac{P_4}{P_2}$$

The input voltage standing wave ratio (VSWR) is defined, in the usual manner, as

$$\frac{V_{\max}}{V_{\min}}$$

at the input terminal, where V designates voltage.

The network of Fig. 1 with the single pair of

separate and mutually perpendicular slots 13 and 14 may be considered to be a basic form of directional coupler constructed in accordance with the invention when the output terminals are properly matched. Fig. 2 illustrates how these pairs of slots may be cascaded to provide a more complex directional coupler. A plate 22, which is to be employed, like the plate 12 in Fig. 1, as the common wall between two waveguides, is provided with a plurality of transversely directed slots 23 spaced apart along the center line of the plate, and a plurality of longitudinally directed slots 24, arranged in two opposing endwise rows near the long edges of the plate.

Individual transverse slots of one alternate series are aligned with the centers of respective individual slots of one row of longitudinal slots, while the remaining transverse slots, of a second alternate series, are individually aligned with the centers of individual transverse slots of the other row, providing, in effect, two series of alternately disposed pairs of slots, interdigitally arranged. As will be shown below, increasing the number of pairs of slots increases the coupling ratio, and, to a certain extent, the directivity. It will also be shown that, as long as the slot pairs are intrinsically reasonably directive, the spacing between sets of pairs is not critical as far as the coupling ratio is concerned. Hence the spacing between slot pairs can easily be chosen to minimize the length of the coupler, and the interdigital arrangement of Fig. 2 is valuable to this end. In the embodiment of Fig. 2, the transverse slots 23 are narrower than the longitudinal slots, illustrating a practical embodiment that has worked well, as will be discussed in detail below.

Fig. 3 illustrates an embodiment of the invention similar to that of Fig. 2 except that the transverse and longitudinal slots do not have their centers aligned to form particularly defined pairs of slots. The transverse slots 33 and the longitudinal slots 34 are provided in a plate 32 similar to the plate 12 of Fig. 1, the transverse slots being arranged along the center line of the plate, and the longitudinal slots being arranged in two endwise rows along both long edges of the plate.

Fig. 4 shows a manner of employment of directional couplers of the invention, wherein the main arm 20 is provided at its terminals 1 and 3 with waveguide coupling joints 25 and 26, respectively, which may be of any known type, for connection at terminal 1 to a source of power (not shown) and at terminal 3 to a utilization circuit (likewise not shown). The auxiliary arm 21 is provided interiorly at terminal 2 with a matched termination, in accordance with known practices, and at terminal 4 with another coupling joint 27, for connection to a second utilization circuit (not shown). By suitable design, power introduced at terminal 1 can be divided in a large variety of desired ratios between the utilization circuits connected to terminals 3 and 4, due to the fact that the coupling ratio P_4/P_3 can be altered between wide limits by varying the number of slot pairs and their size.

The mathematical considerations involved in determining the behavior of a single pair of slots, for example, the slots 13 and 14 of Fig. 1, are as follows.

Where X , Y and Z represent mutually perpendicular coordinates of a three-coordinate system, and correspond, respectively, to the directions of the width, thickness, and longitudinal axis of the waveguide under consideration, the

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field distribution for the TE_{0,1} mode propagating in the positive Z-direction is:

$$E_x = j\sqrt{\frac{\mu}{\epsilon}} \frac{2b}{\lambda_0} H_0 \sin \frac{\pi Y}{b} e^{j\left(\omega t - \frac{2\pi}{\lambda_0} Z\right)} \quad (Relation 1)$$

$$H_Y = j\frac{2b}{\lambda_0} H_0 \sin \frac{\pi Y}{b} e^{j\left(\omega t - \frac{2\pi}{\lambda_0} Z\right)} \quad (Relation 2)$$

$$H_Z = H_0 \cos \frac{\pi Y}{b} e^{j\left(\omega t - \frac{2\pi}{\lambda_0} Z\right)} \quad (Relation 3)$$

where:

μ =permeability,

ϵ =dielectric constant,

$j=\sqrt{-1}$,

b =the wide cross-sectional dimension of the waveguide,

a =the narrow cross-sectional dimension of the waveguide,

λ_0 =the free-space wavelength of the energy being transmitted,

λ_g =the wavelength of the energy in the waveguide,

H_0 =the magnetic field parallel to the Z-axis at the side wall of the waveguide,

$\omega=2\pi f$,

t =time,

E_x =the electric field along the X-axis, and H_Y and H_Z are the magnetic fields along the Y and Z axes respectively.

These relations follow the notation of J. C. Slater, "Microwave Transmission," McGraw-Hill Book Company, New York and London, 1942, chapter III (see particularly page 134, equations 15.12), except that in said book

$$\gamma = j\frac{2\pi}{\lambda_g}$$

The power flow in the positive Z-direction along the wave guide is:

$$S = \frac{1}{2} \int (E_x \bar{H}_Y) ds = \sqrt{\frac{\mu}{\epsilon}} \frac{(2b)^2 ab}{\lambda_g \lambda_0^4} H_0^2 \quad (Relation 4)$$

where the integration is taken over the cross section of waveguide, and

$$\bar{H}_Y$$

is the complex conjugate of H_Y .

The theory of the coupling of waveguides by means of small holes in an infinitesimally thin common wall between them is developed in reports by H. Bethe, entitled "Lumped Constants for Small Irises," Radiation Laboratory Report 43-22, March 1943, and "Theory of Side Windows in Waveguides," Radiation Laboratory Report 43-27, April 1943, at page 19 and following. From these discussions of Bethe, it follows that for a single hole the amplitude factor, A, of the lowest mode wave travelling, for example, to the right in the second or auxiliary waveguide 11 in Fig. 1, when excited by a wave of unit amplitude factor travelling in the same direction in the first or main waveguide 10, is

$$A = \frac{jk}{2Sa} (PE_X^{(1)} E_X^{(2)} - M_1 H_Y^{(1)} H_Y^{(2)} - M_2 H_Z^{(1)} H_Z^{(2)}) \quad (Relation 5)$$

while the amplitude factor, B, of the similar

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mode wave travelling to the left in the auxiliary waveguide 11 is given by

$$B = \frac{jk}{2Sa} (PE_X^{(2)} E_X^{(1)} + M_1 H_Y^{(2)} H_Y^{(1)} - M_2 H_Z^{(2)} H_Z^{(1)}) \quad (Relation 6)$$

where:

$$E_X^{(1)}$$

$E_X^{(1)}$ is the magnitude of the X component of a unit amplitude electric field as defined in Relation 1 in the first waveguide 10 evaluated at the center of the hole, and

$$E_X^{(2)}$$

$E_X^{(2)}$ is the same term evaluated for unit amplitude electric field in the second waveguide 11.

$$H_Y^{(1)}, H_Y^{(2)}, H_Z^{(1)} \text{ and } H_Z^{(2)}$$

have similar definitions.

P, M_1 , and M_2 are positive real numbers, called "polarizabilities," and are determined by the shape of the hole. They are independent of the wavelength for small holes of which no dimension is greater than $\lambda/4$. M_1 and M_2 are more particularly called the "principal magnetic polarizabilities" of the hole, whose axes of symmetry are supposed to lie parallel to the X- and Z-direction, while P is the "electric polarizability" of the hole. Sa as used by Bethe is $2S$ as defined above, and

$$k = \frac{2\pi}{\lambda_0}$$

The effect of a common wall, for example, the common wall 12, of finite thickness is not considered in the reports by Bethe, but may be treated by including in each term of each of Relations 5 and 6 a factor which expresses the voltage attenuation experienced by a mode of the given type travelling below cutoff, a distance equivalent to the thickness of the wall.

As may be seen, consideration of physical arguments indicate that for a narrow slot in a waveguide wall the only exciting field which need be considered is one which gives rise to a current tending to flow across the long dimension of the slot. With this fact in mind, it will be seen that each of the slots 13 and 14 in Fig. 1 couples the two waveguides 10 and 11 in only one way. The amplitudes A_t and B_t of the waves excited by the centrally disposed transverse slot 13 are then proportional respectively, to the second terms on the right-hand side of each of Relations 5 and 6, or proportional to $-M_1$ and M_1 , respectively. The first and last terms on the right-hand side of each of these relations may be neglected in the consideration of the transverse slot. Similarly the amplitudes A_L and B_L of the waves excited by the longitudinally disposed slot 14 are both proportional to

$$-M_2 \left(\frac{\lambda_g}{2b}\right)^2$$

In this case, the first and second terms on the right-hand side of each of Relations 5 and 6 may be neglected. The pair of slots 13 and 14 has infinite directivity when the condition

$$B_L + B_t = 0$$

is fulfilled, that is, when there is no energy coupled into the auxiliary waveguide 11 from the

main waveguide 10 in the direction reverse to

that of the input energy to the main waveguide. This condition is

$$M_1 = M_2 \left(\frac{\lambda_g}{2b} \right)^2 \quad (\text{Relation 7})$$

For slots of equal size, $M_1 = M_2$, and consequently $\lambda_g = 2b$, which is the wavelength of the cutoff frequency for the $TE_{0,1}$ mode. In $1'' \times \frac{1}{2}''$ waveguide with 0.050" wall thickness this predicts that infinite directivity occurs, theoretically, at a wavelength of 3.25 centimeters. How this condition is modified, in the event that the slots are of different sizes, or are placed in the waveguide so that the transverse slot 13 does not lie along the center line thereof and/or the longitudinal slot 14 does not lie adjacent to the side wall of the waveguide, is deducible from the foregoing discussion of general principles, and will be discussed below in connection with certain of the graphical data in the drawings.

The power flow from the main waveguide 10 into the auxiliary waveguide 11 through a pair of slots, 13 and 14, for example, as a function of frequency is calculated as follows.

Recalling that, from Relation 5, it was deduced that, for a transverse slot,

$$A_t = \frac{-j k}{28a} M_1 H_y^{(1)} H_y^{(2)}$$

and substituting the value of H_y as defined in Relation 2 as a definition of unit magnetic field in both waveguides, it follows that:

$$A_t = \frac{-2j\pi}{ab} \sqrt{\frac{\epsilon}{\mu}} \frac{1}{\lambda_g} M_1 \quad (\text{Relation 8})$$

This is the amplitude factor of the wave coupled by the transverse slot 13 and travelling to the right in the auxiliary waveguide 11 when the main waveguide is excited at terminal 1. Similarly, from the deduction from Relation 5, made above, that, for the longitudinal slot:

$$A_L = \frac{-j k}{28a} M_2 H_z^{(1)} H_z^{(2)}$$

with the substitution from Relation 3 of the value of H_z as the unit magnetic field in both waveguides, it follows that:

$$A_L = \frac{-2j\pi}{ab} \sqrt{\frac{\epsilon}{\mu}} \frac{\lambda_g}{(2b)^2} M_2 \quad (\text{Relation 9})$$

A_L is here the amplitude factor of the wave coupled by the longitudinal slot 14 and also travelling to the right in the auxiliary waveguide 11. The total amplitude factor is $A_t + A_L$ since the mutual coupling of the two slots 13 and 14 is zero. The field in the auxiliary waveguide is then $A_t + A_L$ times the respective expressions given in Relations 2 and 3. The ratio of power out of the auxiliary waveguide (P_4) to that entering the main waveguide (P_1) is then as follows:

$$\frac{P_4}{P_1} = (A_t + A_L)^2$$

whence

$$\frac{P_4}{P_1} = \frac{4\pi^2}{a^2 b^2} \frac{\epsilon}{\mu} \left(\frac{M_2}{\lambda_g} + \frac{M_2 \lambda_g}{(2b)^2} \right)^2 \quad (\text{Relation 10})$$

If M_1 and M_2 are independent of frequency, this ratio has a stationary value, and therefore the coupling is stationary, when

$$M_1 = M_2 \left(\frac{\lambda_g}{2b} \right)^2$$

which is Relation 7, the condition for maximum directivity. Thus the condition for maximum directivity is also the condition for a stationary value of coupling. Also, it will be seen that one way to obtain directional couplers which maintain reasonably constant coupling over a wide frequency band is to use small slots, for M_1 and M_2 are independent of frequency for small slots.

Referring now to Figs. 5a and 5b, the graphs there shown illustrate the manner in which the coupling varies with frequency over the band from 3.1 to 3.5 centimeters, for a single pair of slots 43 and 44, cut in the common wall 42 of a directional coupler constructed in accordance with Fig. 1, of $1'' \times \frac{1}{2}''$ waveguides. The slots are each 0.062" wide, and have the same lengths. Curve A shows that, with slot lengths of 0.1875", the coupling was very nearly constant over the band, at a value of approximately -47 db. This means that, with power in at terminal 1,

$$\frac{P_4}{P_3} = -47 \text{ db}$$

Curve B illustrates that, with slot lengths increased to 0.250", the coupling increased to approximately -39 db, but was slightly less stationary in value over the frequency band. Curve C illustrates that the coupling can be still further increased in value by increasing the slot length to 0.325", with a little greater sacrifice in constancy over the frequency band, and curve D shows that, when the slot lengths were increased to 0.450", the coupling increased to approximately -20 db, but suffered a variation of approximately 3 db over the frequency band. The separation between the two slots did not appear to be critical in value as far as the coupling was concerned. Thus the theoretical conclusion that the employment of small slots provides constant coupling over a wide frequency band is borne out by experiment, but the amount of power coupled by a pair of such slots is low.

Referring now to Fig. 6, the single curve E there shown illustrates the manner in which the coupling varies when slot pairs like those of Fig. 1 are cascaded, in a manner shown, for example, in Fig. 2. Again, with power in at terminal 1, the coupling is defined as

$$\frac{P_4}{P_3}$$

The slot pairs investigated to provide curve E constituted each a coupler wherein the coupling

$$\frac{P_4}{P_3} = -20 \text{ db}$$

and the curve illustrates that, when fifteen such slot pairs were cascaded, the coupling increased to +23 db (approximately).

In general, it may be stated that, when the coupling of each slot pair is weak, as here, doubling the number of directional couplers, or slot pairs, increases the coupling by 6 db, approximately. The coupling varies essentially as the cotangent of the number of slot pairs. In practice, curve E has permitted prediction, within a few tenths of a decibel, of the coupling to be expected of a cascade of known slot pairs.

The curves shown in Fig. 7 illustrate the overall performance of a directional coupler having twenty slot pairs, made of identical $\frac{1}{8}'' \times \frac{1}{8}''$ slots, with 0.221" separation between the centers of transverse slots of adjacent pairs. The coupler was investigated over the band 3.1 to 3.5 centimeters, and it was found from curve F that

the coupling varied by less than 0.5 db, and was centered about -22 db. Curve G illustrates the directivity characteristic, which it will be noted is about 40 db. The input voltage standing wave ratio (VSWR), shown by curve H, generally diminished as the directivity increased, as was to be expected. Curve G will be discussed in detail below in connection with Fig. 11.

Recalling that a directional coupler constitutes a bridge circuit when

$$\frac{P_4}{P_3} = 1 = 0 \text{ db}$$

it is seen from curve E that approximately 7.7 directional couplers of the -20 db variety must be cascaded in order to obtain a bridge circuit. In many applications, such an arrangement is impractical because the length required is excessive, although the resultant bridge is electrically quite satisfactory.

Generally, the amount of energy coupled by a slot increases as the size of the slot is increased. In particular, from Fig. 5b, it has been shown that the value of the coupling

$$\frac{P_4}{P_3}$$

increases toward unity as the slot lengths are increased, but that the relative constancy of this ratio over a wide frequency band is simultaneously diminished. As the length of a slot approaches

$$\frac{\lambda_g}{2}$$

its polarizability M increases rather rapidly. The problem of designing broad band bridge circuits with longer slots and thereby providing acceptably short lengths is thus the problem of choosing a longitudinal slot having a length such that the change in

$$\frac{M_2 \lambda_g}{(2b)^2}$$

with frequency is compensated for by the change in

$$\frac{M_1}{\lambda_g}$$

as determined by the length of the transverse slot. From Relation 10 it will be seen that a condition for such compensation is that the slope of the tangent to the curve

$$\frac{M_1}{\lambda_g}$$

shall be the negative of the slope of the tangent to the curve

$$\frac{M_2 \lambda_g}{(2b)^2}$$

That is

$$\frac{d}{d\lambda_g} \left(\frac{M}{\lambda_g} \right)$$

for the transverse slots shall be equal in magnitude and opposite in sense to

$$\frac{d}{d\lambda_g} \left(\frac{M \lambda_g}{(2b)^2} \right)$$

for the longitudinal slots.

Referring now to Fig. 8, curves I and J illustrate, respectively, the slopes K of the change with respect to frequency of transverse and longitudinal slots of various sizes as a function of the respective polarizabilities M . Curves I and

J may be obtained by plotting the values of A_t and A_L against λ_g in a given frequency range in Relations 8 and 9, for each value of M along the ordinate in Fig. 8, and then plotting the slopes of the resultant curves for each value of M against the value of M . The values of M_1 and M_2 that are being dealt with are also known from Relations 8 and 9, for A_t and A_L are measurable voltage or powers, related to a unit input voltage or power, λ_g is readily measurable, and the remaining quantities are known constants. Thus for each slot size investigated, the values of M can be determined initially by measurement and calculation. It will be seen from the curves that for small values of M_1 (transverse slots) it is possible to choose for each M_1 a value of M_2 (longitudinal slots) such that the values of the slopes K are equal and opposite, but that, for values of M_2 greater than approximately 0.22, this is no longer possible. For each smaller value of M_2 , however, there is a value of M_1 which provides frequency compensation to the coupling, and it will be noticed that in all cases the polarizability M_2 of the longitudinal slots will have a larger value than the polarizability M_1 of the transverse slots. The polarizability of either slot can be increased by increasing the length of the slot, as shown in Fig. 5.

Referring now to Figs. 9a and 9b, the curves L, M, N and O shown in Fig. 9b illustrate the variation of coupling with frequency for 1, 2, 4 and 6 pair of slots, respectively, of the sizes shown in Fig. 9a. The slots are cut in a wall 52, of 1" x 1/2" waveguide. Each longitudinal slot 54 is 0.450" long and 0.116" wide. Each transverse slot 53 is 0.436" long and 0.081" wide. The curves L, M, N and O show what is already known from Fig. 6, namely, that the coupling is increased when the number of pairs of slots is increased, but it should be noted in Fig. 9b that each pair of slots provides a -17 db (approximately) coupler, and only 6 pair are required to provide a bridge, while in Fig. 6, 7.7 of the -20 db pair are required to accomplish the same result. The curves in Fig. 9b illustrate also the fair amount of constancy of coupling versus frequency change that may be attained with the slot arrangement shown.

Fig. 10 illustrates the performance of a directional coupler designed in accordance with the foregoing discussion with relation to Fig. 8. Twenty-four pairs of slots were employed, the center transverse slots being 0.294" long and 0.0707" wide, and the longitudinal side slots being 0.303" long and 0.110" wide. Curve P shows that the coupling was for all practical purposes perfectly constant from 3.2 to 3.5 centimeters, being centered at -0.2 db, which is nearly the condition for bridge circuit. The directivity, curve Q, was flattened out at about 41 db, between 3.2 and 3.3 centimeters, and the VSWR, curve R, was at all times below 1.06. As in all the foregoing examples, all measurements were made on 1" x 1/2" waveguide. Comparison of Fig. 10 with Fig. 7 substantiates the predictions of improved performance attendant upon the discussion in connection with Fig. 8.

Although the theory developed and verified experimentally above is predicated on a single pair of slots which are aligned as in Fig. 1, when a plurality of slots are employed, as in Figs. 2 and 3, there is an averaging of the effects of individual slots, and as a result the alignment of slot pairs becomes increasingly unimportant as the number of slots is increased. Fig. 3 illus-

trates one embodiment of the invention wherein the slots are not aligned in pairs and Fig. 11 illustrates another. In Fig. 11, the wide wall plate 62 shown has a plurality of transverse slots 63 which are spaced very closely together, the separating metal between them being of the order of half as wide as the slots themselves. There are also a plurality of longitudinal slots 64, arranged in rows along the long side of the plate 62. The longitudinal and transverse slots are not related in pairs. The staggered relation of adjacent rows of longitudinal slots does not appear to have electrical significance; it was employed for ease in cutting the slots. With the embodiment of Fig. 11, the length of the coupler for a desired coupling ratio was greatly reduced. The sizes of the individual longitudinal and transverse slots were chosen in accordance with the principles set forth above in connection with Fig. 8, and the results were substantially as predicted.

Fig. 12 shows the directivity versus frequency curves S, T, U, W and G for 1, 4, 10, 20 and 20 pair, respectively, of $\frac{1}{16}$ " x $\frac{1}{16}$ " slots cut in the wide wall of 1" x $\frac{1}{2}$ " waveguide. It may be noted that, for a single pair of slots, maximum directivity occurred at 3.3 centimeters, whereas it is theoretically predicted from Relation 7 that this shall occur at 3.25 centimeters. This discrepancy may be attributed to the proximity of the longitudinal slots to the side wall of the waveguide. It may be noted from these curves that the directivity was increased greatly by cascading four pairs of slots, but that there was no substantial change of directivity within the major portion of the frequency range investigated for 10 and 20 pairs, respectively, as shown by curves U and W. However, there was another marked increase in directivity when the separation between slot pairs was reduced from 0.442" to 0.221" as in Fig. 7, and shown by curve G. On the other hand, it was found that, as long as the slot pairs each possessed reasonable directivity in itself, the spacing between pairs was not critical with respect to coupling. For example, the couplings of the two twenty-pair directional couplers that provided curves W and G were identical. It should be remembered, from the discussions of Figs. 7 and 10, that when high directivity, for example 20 db, or higher is obtained, it results in a correspondingly lower input voltage standing wave ratio.

In summarizing, it may be pointed out that, as far as directivity and input VSWR are concerned, the directional couplers of the present invention are very uncritical. No more than ordinary care is required in the machining or assembly of the parts. On the basis of experience, as set forth in detail herein, the problem of constructing a directional coupler with 30 db of directivity over a 12% band, and having any desired coupling, is a fairly simple matter. In fact, the present invention can provide a directional coupler having 20 db of directivity over frequency bands approximating the useful range of the waveguide itself.

Since numerous variations and applications within the scope of the invention will occur to those skilled in the art, it is intended that the appended claims shall be given a broad interpretation commensurate with their scope within the art. The term "common wall" in the claims that follow shall be taken to mean either a single wall shared by two waveguides or two closely adjacent walls of two separate waveguides through

which they are coupled in the manner taught herein. It will be remembered in this connection that the passage through a slot is in a sense a waveguide operated beyond cut-off and that these passages should be maintained as short as possible to avoid excessive attenuation of energy passing through the slot. However, it is realized that the invention could be practiced by providing slot-like passages of other than the shortest possible length between two adjacent walls of two separate waveguides.

Having now described my invention, I claim:

1. A waveguide directional coupler comprising a pair of waveguides adapted to convey electromagnetic wave energy and having a common wall, a plurality of transversely directed slots in said common wall spaced apart along the longitudinal center line thereof, and a plurality of separate longitudinally directed slots in said common wall spaced apart along a side edge of said wall, said transversely directed slots being parallel to each other and substantially perpendicular to said longitudinally directed slots and being disposed in said wall so that a line drawn across said common wall which line passes through a transversely directed slot and is parallel to the long dimension of said slot also crosses a longitudinally directed slot, the slots in each plurality being spaced substantially closer together than one-quarter of the wavelength in said waveguides of electromagnetic wave energy intended to be conveyed.

2. A waveguide directional coupler comprising a pair of rectangular waveguides adapted to convey electromagnetic wave energy and having a common wide wall, a transversely directed slot in said wide wall located substantially uniformly about the longitudinal center line thereof, and a separate longitudinally directed slot in said wide wall located near a narrow wall, said slots having portions lying substantially in the same plane transverse to the direction of energy propagation in said waveguides, the size of the latter slot being greater than that of the former slot, and the relative slot lengths being so proportioned with respect to wavelengths in the operating frequency range that for a particular change in operating frequency the changes in the quantities of energy coupled by the individual slots are equal in magnitude and opposite in sense, whereby the coupling is maintained substantially constant over the operating frequency range.

3. A waveguide directional coupler comprising a pair of similar rectangular waveguides having a common wide wall, a transversely directed slot in said wide wall located substantially uniform about the longitudinal center line thereof, and a separate longitudinally directed slot in said wide wall located near a narrow wall, the sizes of said slots being so chosen that their principal magnetic polarizabilities, M_1 and M_2 , respectively, are related by the relation

$$M_1 = M_2 \left(\frac{\lambda_g}{2b} \right)^2$$

where λ_g is the wavelength of electromagnetic waves which may be transmitted in the waveguides at a particular operating frequency, b is the wide cross-sectional dimension of the waveguides, M_1 is defined by a second relation

$$A_1 = -\frac{2j\pi}{ab} \sqrt{\frac{\epsilon}{\mu}} \frac{1}{\lambda_g} M_1$$

and M_2 is defined by a third relation

$$A_L = \frac{-2j\pi}{ab} \sqrt{\frac{\epsilon}{\mu}} \frac{\lambda_g}{(2b)^3} M_2$$

where A_t is the fraction of a unit of input voltage to one of said waveguides which is coupled into the other of said waveguides by said transversely directed slot, A_L is the fraction of said unit of input voltage to said one waveguide which is coupled into said other waveguide by said longitudinally directed slot, $j = \sqrt{-1}$, μ = permeability of the transmission medium, ϵ = dielectric constant of said transmission medium, and a is the narrow cross-sectional dimension of said waveguides.

4. A waveguide directional coupler comprising a pair of similar rectangular waveguides having a common wide wall, a transversely directed slot in said wide wall located substantially uniformly about the longitudinal center line thereof, and a separate longitudinally directed slot in said wide wall located near a narrow wall, the sizes of said slots being so chosen that their principal magnetic polarizabilities, M_1 and M_2 , respectively, are so related that

$$\frac{d}{d\lambda_g} \left(\frac{M_1}{\lambda_g} \right)$$

is substantially equal in magnitude and opposite in sense to

$$\frac{d}{d\lambda_g} \left(\frac{M_2 \lambda_g}{(2b)^2} \right)$$

within a predetermined operating frequency band where M_1 , M_2 , λ_g , and b are as is defined in claim 3.

5. A waveguide directional coupler comprising a pair of parallel rectangular waveguides adapted to convey electromagnetic wave energy and having a common wide wall, a plurality of transversely directed slots in said wide wall closely spaced along the longitudinal center line thereof, the space between slots being of the order of one-half the slot widths, and a plurality of separate longitudinally directed slots in said wide wall arranged in rows in the long side areas thereof, said transversely directed slots being parallel to each other and substantially perpendicular to said longitudinally directed slots and being disposed in said wall so that a line drawn across said common wall which passes through a transversely directed slot parallel to the long dimension thereof also crosses a longitudinally directed slot.

6. A waveguide directional coupler comprising a pair of parallel rectangular waveguides adapted to convey electromagnetic wave energy and having a common wide wall, a plurality of parallel transversely directed slots in said wide wall arrayed substantially along the center line thereof, and a plurality of separate longitudinally directed slots in said wide wall each having its center along the axial line of a different one of said transversely directed slots, said longitudinally directed slots being arranged alternately adjacent to one or the other of the side edges of said wide wall.

7. A waveguide directional coupler comprising a pair of rectangular waveguides adapted to convey electromagnetic wave energy and operative above the cut-off frequency for the $TE_{0,1}$ mode and having a common wide wall, a transversely directed slot of length less than one half a wavelength at said cut-off frequency in said wide wall centered substantially at the transverse voltage maximum for said mode, and a longi-

tudinally directed slot in said wide wall disposed near a long edge thereof, said slots having portions lying substantially in the same plane transverse to the direction of energy propagation in said waveguides, the latter slot being longer than the former but less than said one half wavelength long, the relative slot lengths being adjusted to provide that with increasing operating frequency within a given frequency range, the increase in power coupled from one waveguide to the other through the transversely directed slot is substantially compensated by a corresponding decrease in coupled power through the longitudinally directed slot.

8. A waveguide directional coupler comprising a pair of waveguides having a common wall, and first and second groups of separate mutually perpendicularly directed slots in said common wall, each slot being located to be substantially perpendicular to the current component which may exist in the part of said common wall where said slot is located during passage through either waveguide of electromagnetic waves of a prescribed mode, the slots of said first group being parallel to each other and arrayed side by side along a line parallel to the long dimension of said waveguides, and the slots of said second group being arrayed collinearly in rows on either side of said line.

9. A waveguide directional coupler comprising a pair of waveguides adapted to convey electromagnetic wave energy and having a common wall, and a plurality of pairs of separate mutually perpendicularly directed slots in said common wall, the slots of the first group being arranged side-wise parallel to each other and perpendicular to the direction of propagation of said energy and the slots of the second group being arrayed end-wise parallel to each other and parallel to the direction of propagation of said wave energy, each slot being located to be substantially perpendicular to the current component which may exist in the part of said common wall where said slot is located during passage through either waveguide of electromagnetic waves of a prescribed mode, each slot being short with respect to the wavelength of said waves at the operating frequency and non-resonant thereto, and coupling a certain small fraction of the total available power, the number of pairs of mutually perpendicular slots in the coupler being chosen to provide a desired degree of coupling in accordance with the rule that doubling the number of said pairs increases the coupling by approximately six decibels.

10. A waveguide directional coupler comprising a pair of waveguides having a common wall, and first and second groups of separate mutually perpendicularly directed slots in said common wall, each slot being located to be substantially perpendicular to the current component which may exist in the part of said common wall where said slot is located during passage through either waveguide of electromagnetic waves of a prescribed mode, the slots of said first group being parallel to each other and arrayed side by side along a line parallel to the long dimension of said waveguides, and the slots of said second group being arrayed collinearly in rows on either side of said line, the space between the slots of said first group being of the order of one-half the width of said slots.

11. A waveguide directional coupler comprising a pair of parallel directed similar waveguides having a common wide wall, and a plurality of

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pairs of separate mutually perpendicularly directed slots in said common wall, said pairs being arrayed parallel to the longitudinal direction of said waveguides, each slot being located to be substantially perpendicular to the current component which may exist in the part of said common wall where said slot is located during passage through either waveguide of electromagnetic waves of a prescribed mode, each slot being short with respect to the wavelength of said waves at the operating frequency and non-resonant thereto, and coupling a certain small fraction of the total available power, the number of pairs of mutually perpendicular slots in the coupler being chosen to provide a desired degree of coupling in accordance with the rule that doubling the number of said pairs increases the coupling by approximately six decibels.

12. A waveguide directional coupler comprising a pair of similar rectangular waveguides operative in the $TE_{0,1}$ mode and having a common wide wall, a transversely directed slot in said wide wall centered substantially at the transverse voltage maximum for said mode, and a longitudinally directed slot in said wide wall near the transverse voltage minimum for said mode, the sizes of said slots being so chosen that their principal magnetic polarizabilities M_1 and M_2 , respectively, are related by the relation

$$M_1 = M_2 \left(\frac{\lambda_g}{2b} \right)^2$$

where λ_g is the wavelength of electromagnetic waves of said mode in the waveguides at a particular operating frequency, b is the wide cross-sectional dimension of the waveguides, M_1 is defined by a second relation

$$A_t = \frac{-2j\pi}{ab} \sqrt{\frac{\epsilon}{\mu}} \frac{1}{\lambda_g} M_1$$

and M_2 is defined by a third relation

$$A_L = \frac{-2j\pi}{ab} \sqrt{\frac{\epsilon}{\mu}} \frac{\lambda_g}{(2b)^2} M_2$$

where A_t is the fraction of a unit of input voltage to one of said waveguides which is coupled into the other of said waveguides by said transversely directed slot, A_L is the fraction of said unit of input voltage to said one waveguide which is coupled into said other waveguide by said longitudinally directed slot, $j = \sqrt{-1}$, μ = permeability of the transmission medium, ϵ = dielectric constant of said transmission medium, and a is the narrow cross-sectional dimension of said waveguides.

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13. A waveguide directional coupler comprising a pair of similar rectangular waveguides operative in the $TE_{0,1}$ mode and having a common wide wall, a transversely directed slot in said wide wall centered substantially at the transverse voltage maximum for said mode, and a longitudinally directed slot in said wide wall near the transverse voltage minimum for said mode, the sizes of said slots being so chosen that their principal magnetic polarizabilities M_1 and M_2 , respectively, are so related that

$$\frac{d}{d\lambda_g} \left(\frac{M_1}{\lambda_g} \right)$$

is substantially equal in magnitude and opposite in sense to

$$\frac{d}{d\lambda_g} \left(\frac{M_2 \lambda_g}{(2b)^2} \right)$$

within a predetermined operating frequency band, where λ_g is the wavelength of electromagnetic waves of said mode in the waveguides at a particular operating frequency, b is the wide cross-sectional dimension of the waveguides, M_1 is defined by a second relation

$$A_t = \frac{-2j\pi}{ab} \sqrt{\frac{\epsilon}{\mu}} \frac{1}{\lambda_g} M_1$$

and M_2 is defined by a third relation

$$A_L = \frac{-2j\pi}{ab} \sqrt{\frac{\epsilon}{\mu}} \frac{\lambda_g}{(2b)^2} M_2$$

where A_t is the fraction of a unit of input voltage to one of said waveguides which is coupled into the other of said waveguides by said transversely directed slot, A_L is the fraction of said unit of input voltage to said one waveguide which is coupled into said other waveguide by said longitudinally directed slot, $j = \sqrt{-1}$, μ = permeability of the transmission medium, ϵ = dielectric constant of said transmission medium, and a is the narrow cross-sectional dimension of said waveguides.

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