Nov. 6, 1951 W. H. WATSON ET AL 2,573,746

DIRECTIVE ANTENNA FOR MICROWAVES

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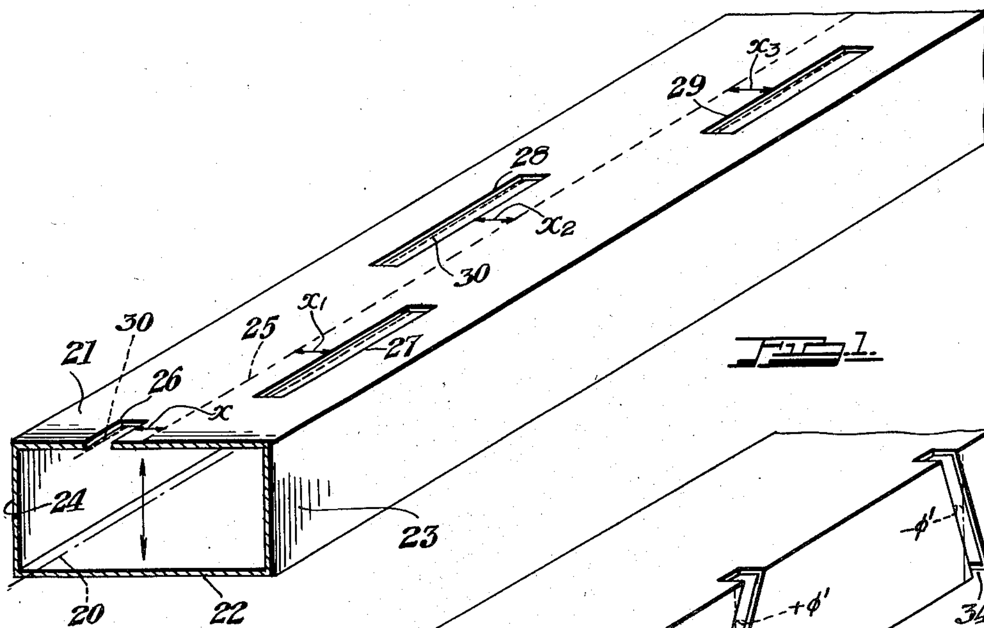

Fig. 1.

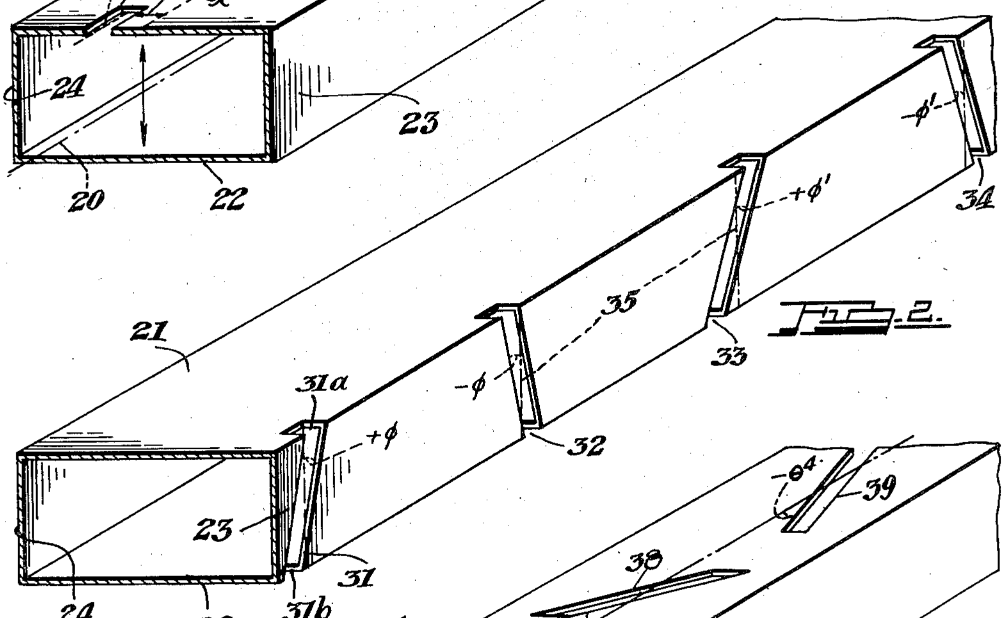

Fig. 2.

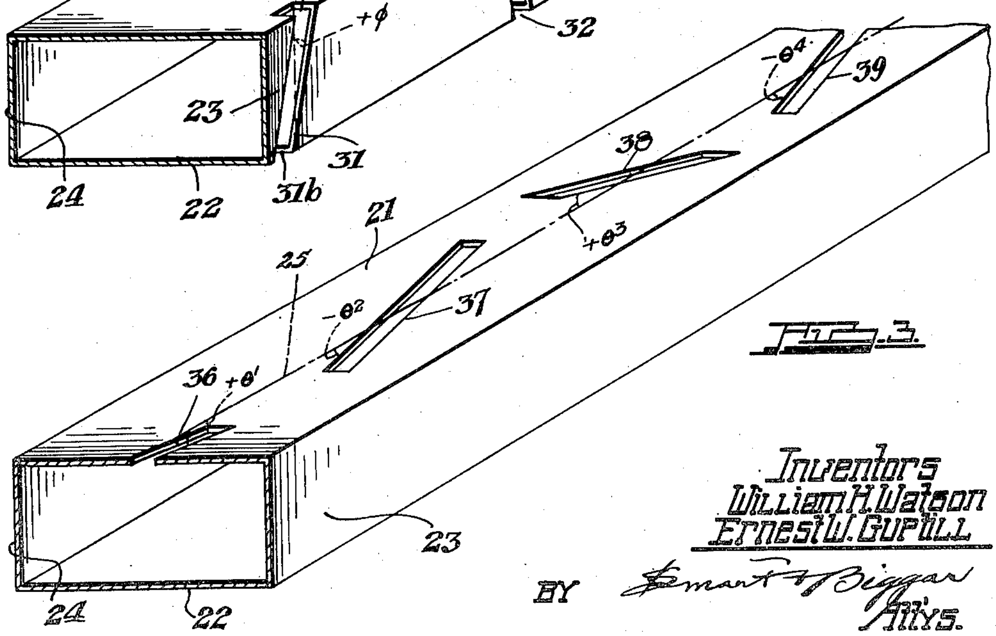

Fig. 3.

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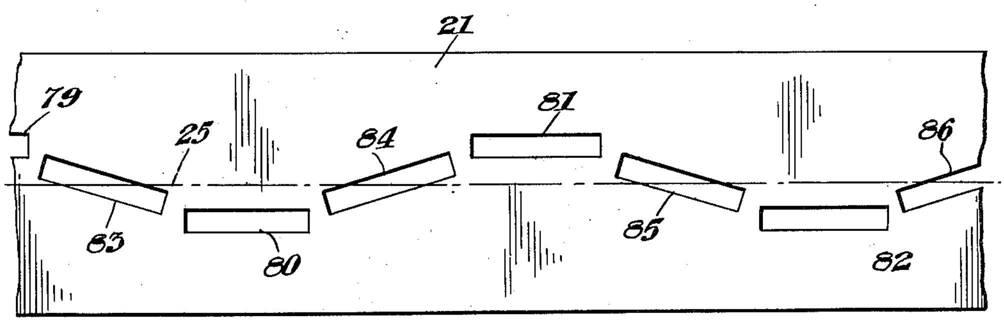


Fig. 4.

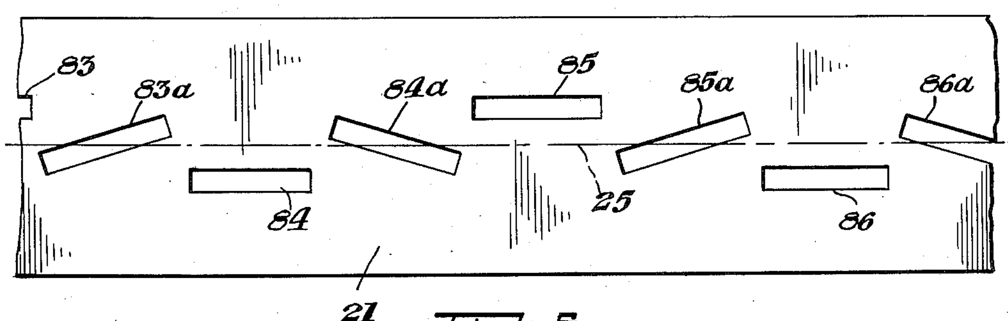


Fig. 5.

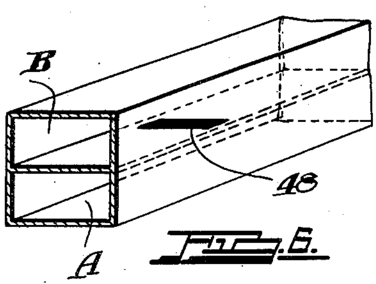


Fig. 6.

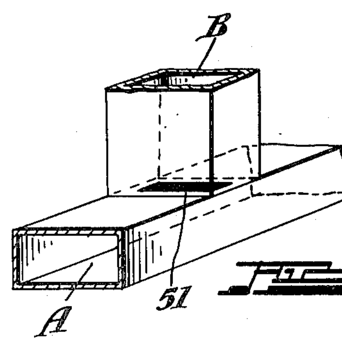
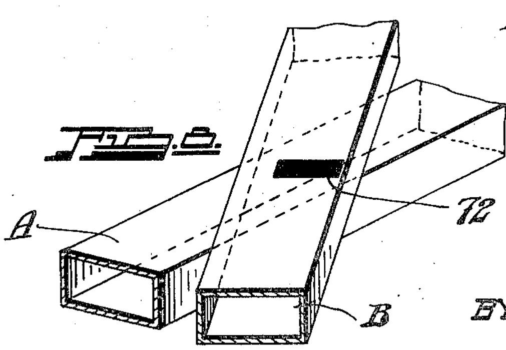


Fig. 7.

Fig. 8.



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DIRECTIVE ANTENNA FOR MICROWAVES

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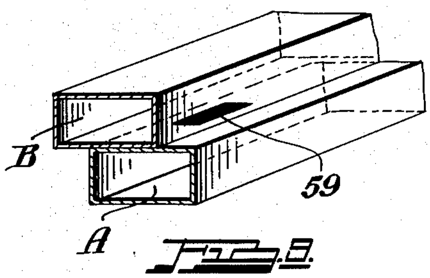

Fig. 9.

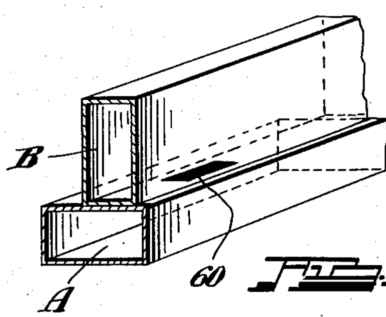

Fig. 10.

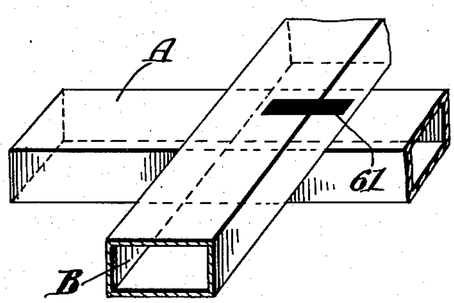

Fig. 11.

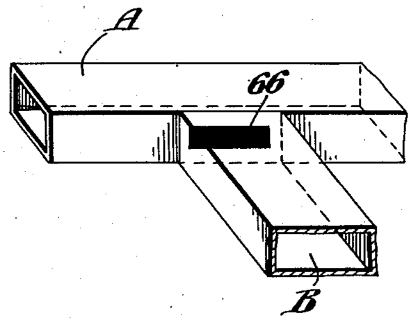

Fig. 12.

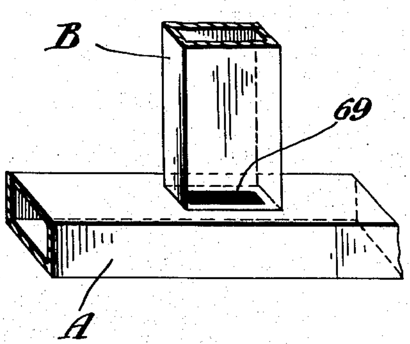

Fig. 13.

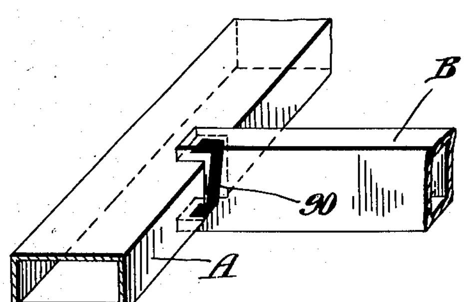

Fig. 14.

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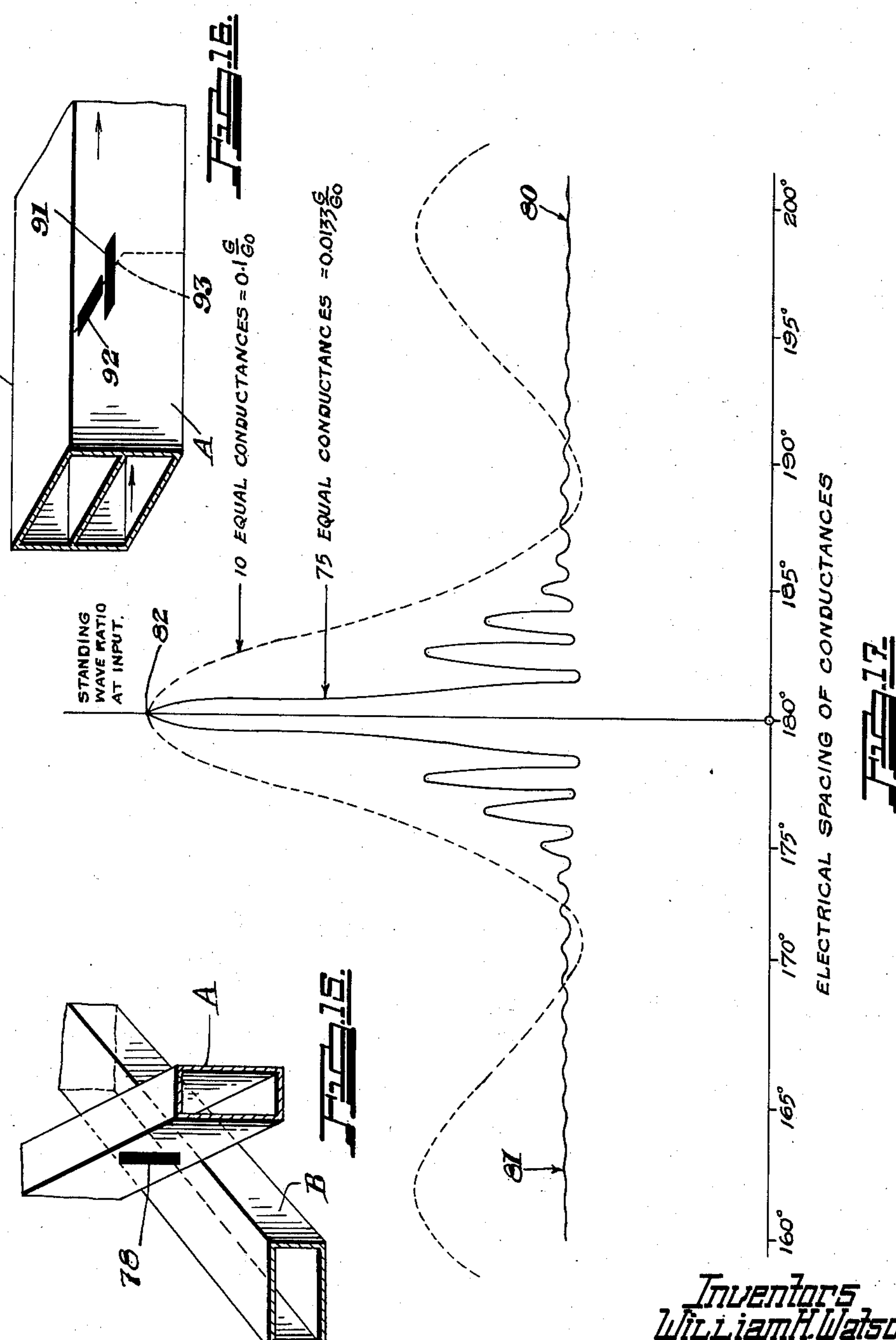

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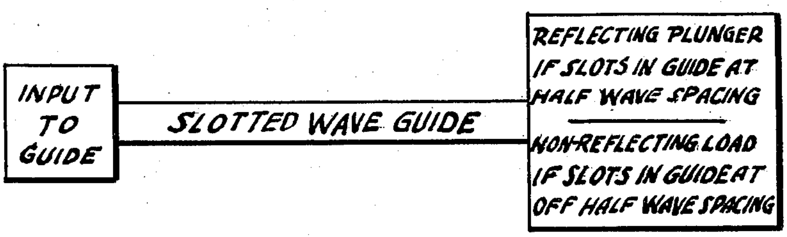

Fig. 18.

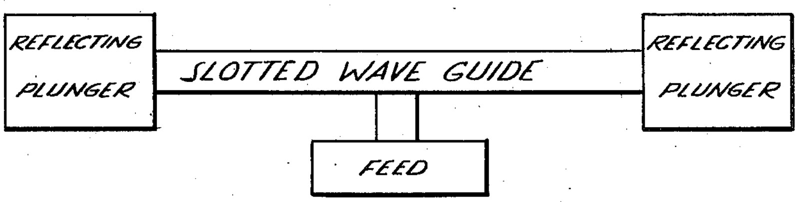

Fig. 20.

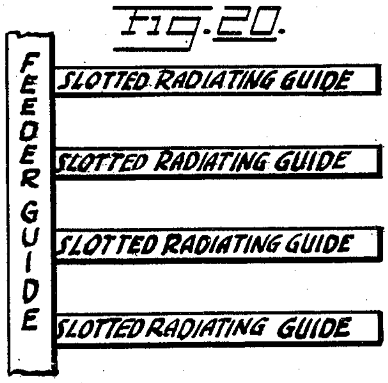

Fig. 19.

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UNITED STATES PATENT OFFICE

2,573,746

DIRECTIVE ANTENNA FOR MICROWAVES

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Application November 5, 1945, Serial No. 626,738
In Canada September 19, 1945

33 Claims. (Cl. 250—33.63)

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This invention relates to directive antennas for microwaves, that is, electromagnetic waves having a wave length in free space of less than one metre.

Before this invention an antenna of this type consisted generally of a wave guide feeding a linear array of radiators in the form of dipoles coupled to the guide by means of probes. Such radiators have numerous serious disadvantages but have nevertheless been used heretofore because only with them was it found possible to fulfil certain essential conditions of a practical array.

It is known that, in order to achieve a satisfactory radiation pattern with an array of radiators, the radiators should, if they radiate to any considerable extent longitudinally of the array, be spaced from each other at intervals of not over seven-eighths of the wave length in free space of the wave to be radiated, because at greater spacings the intensity of second order beams directed substantially at right angles to the first order beam increases very rapidly, being equal to that of the first order beam when the radiators are spaced at wave length intervals (see page 421, "Ultra High Frequency Techniques" by Brainerd et al., published in 1942 by D. Van Nostrand Co. Inc.). It is of course essential that there should be only one effective beam from the array, and it is also desirable that this beam should be substantially normal to the axis of the array, i. e. a straight line passing through all the radiators. In order that the beam should be normal to the axis of the array the radiators must radiate in phase. This could be achieved by spacing the radiators along the axis of the array at intervals equal to the wave length in the guide (λg) of the wave to be radiated, but, owing to the higher velocity of propagation in the guide, at least in the normal case where the dielectric is air, such a spacing would, in the normal case of a guide having a width of about three-quarters of the wave length in free space (λs), be equal to a spacing of about $1\frac{1}{2}\lambda s$ and would consequently be unsatisfactory from the point of view of the pattern of the radiation. The result can also be achieved by coupling adjacent radiators in reversed phase relation, i. e., in such a way that if the adjacent radiators were situated in the same transverse plane in the guide they would be excited by currents or voltages 180° out of phase with each other, and by spacing the radiators at intervals of $\frac{1}{2}\lambda g$. A spacing of $\frac{1}{2}\lambda g$ is, in the normal case of a guide of a width of about $\frac{3}{4}\lambda s$, equivalent to a spacing of about $\frac{3}{4}\lambda s$ and is consequently satisfactory from the point of view of the radiation pattern. When the spacing of radiators coupled in reversed phase relation is different from $\frac{1}{2}\lambda g$, the angle of the beam to the axis of the array becomes acute and decreases with increasing departure from $\frac{1}{2}\lambda g$ spacing, the beam being directed in the direction of wave propagation in the guide when the spacing is greater than 180° and in the opposite direction when the spacing is less than 180°.

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It was discovered that dipoles could be coupled alternately in reversed phase relation. Very little, however, was appreciated about the basis on which arrays of radiators operate so far as the loads which they present to the exciting wave in the guide are concerned. Attempts were first made to arrange dipoles at half wave spacing in the guide with a non-reflecting load at the termination. Such arrangements were, however, found impractical because there was always a standing wave at the guide input which increased as the number of radiators was increased, and it was thus, practically speaking, impossible to maintain a match between the guide and the oscillator feeding it. In view of this, dipoles were generally arranged at off-half wave spacing in such a way as to give as nearly as possible a pure travelling wave throughout the length of the guide. Such an arrangement required that the loads presented by the dipoles should gradually increase along the length of the guide. The achievement of this result was largely a trial and error process because the laws governing the abstraction of energy from guides by probe coupled dipoles, or in fact by any radiator of energy, were not known.

Quite apart from these difficulties, however, most dipole arrays which have been used have been unsatisfactory from the point of view of the radiation pattern which they give, because there is considerable radiation from exposed parts of the probes by which the dipoles are coupled to the guide. This radiation is directed in a plane other than that of the principal radiation from the dipoles themselves and is, moreover, polarized in a different direction.

Since dipoles and their coupling probes must be of precise small dimensions, their manufacture is difficult and expensive and becomes more so the shorter the wave length for which they are designed. The dipoles must be secured in position on the guide in some way, and the array will not continue to operate satisfactorily unless they remain in their exact positions under service conditions. The delicacy of the dipoles, the difficulties of maintainning them in satisfactory adjustment and their elaborate structure have inevitably resulted in more or less considerable alterations of their electrical properties under service conditions.

The radiation from a linear array of radiators extends in two dimensions. To concentrate it to a beam it has been the practice to arrange the dipoles along the focal axis of a parabolic cylindrical reflector so as to restrict the radiation from each dipole as far as possible to a direction normal to the axis of the array. Although in the technique of radiating waves of lower than microwave frequencies the restriction of the radiation to a beam by arranging a number of antennas side by side had been resorted to, the same technique was not followed in microwave radiation because no satisfactory way was known of splitting the energy of a wave between a number of wave guides.

Although it has been known that holes in metal would act as radiators, they have never been used as radiators in wave guides. Proposals have been advanced for making arrays of slots spaced at λg intervals and with so-called horns mounted around them on the outer face of the guide, these horns being apparently for the purpose of directing the radiation from each slot as far as possible normal to the surface of the guide, and so reducing the second order beams which would otherwise result from the spacing used. There was no suggestion of any way of coupling alternate slots to the guide in reversed phase relation or of any special dimensions for the slots. The proposals in question were never put to practical use.

The present inventors have succeeded in coupling slots to a wave guide in reversed phase relation and in coupling a number of wave guides to one wave guide in such a way as to divide the energy in the latter wave guide between the former guides in any predetermined manner. They have discovered that radiators, and slots in particular, present loads to a wave in a wave guide which behave in the same way as loads on an ordinary transmission line and may be series or shunt according to circumstances. They have succeeded in making, in wave guides, slots which present substantially no reactive load to the wave in the guide, and are thus substantially resonant for a given wave length, and they have discovered the laws by which the substantially pure resistance or conductance, which is presented by a slot in a given position in a given guide, may be predetermined. On the basis of their work the the inventors have constructed directive antennas consisting of both linear and two dimensional arrays of slots cut in wave guides.

According to the invention a directive antenna for microwaves comprises a wave guide formed with a series of slots which are substantially resonant for a wave of a given wave length in free space and are of substantially greater length than width. The centres of the slots of this series are spaced along the length of the guide at intervals of less than substantially ⅞ of the wave length in free space for which the slots are substantially resonant. Wherever longitudinal spacing of slots is hereafter referred to in this specification, the spacing of the centres of the slots is to be understood. All the slots are arranged in positions such that when the guide is fed with a microwave the current flow along the guide wall at these positions excites the slots, and each of substantially all the slots of the series is in sub-

stantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot with respect to a line on the guide wall across which, in the absence of any slots, there would be no current flow.

Wave guides of various shapes and cross sectional dimensions may be used. These have heretofore been the subject of considerable study, and various forms have been used or proposed to be used in connection with dipole arrays. The wave guide shape and cross section forms no part of the present invention. Substantially the same considerations apply to the selection of a suitable shape and cross section for a guide provided with an array of slots according to the present invention as for a guide provided with a dipole array. The cross sectional shape most generally used is rectangular but not square, the maximum dimension being well under λs and well over $\frac{1}{2}\lambda s$, generally about $\frac{3}{4}\lambda s$, and the minimum dimension being about half the maximum dimension. A rectangular wave guide of such cross sectional dimensions will effectively propagate only the lowest mode of a transverse electric wave. Other cross sectional shapes in which the maximum dimension in one direction is substantially greater than the maximum dimension in a direction at right angles thereto may be suitable. A circular or square cross section, unless a radial septum is provided, is apt to give such difficulties as to be unsuitable because the substantially equal dimensions in the two directions at right angles to each other tend to permit propagation with equal ease of modes polarized in either of these directions. Since the most usual cross section is a rectangular one with dimensions as indicated above and since the invention has been principally developed in connection with a guide of such a cross section, the description which follows will be based exclusively on a guide of that cross section.

A slot in a wave guide is excited by currents flowing along the guide wall transversely to the longitudinal axis of the slot or to a projection thereof. The inventors have discovered that the loads presented by a number of slots excited solely by the longitudinal currents in the guide, i. e. whose longitudinal axes have projections extending transversely to the longitudinal currents in the guide are added according to the laws of series combination; such slots being hereafter referred to in the disclosure and claims as "series coupled" slots. On the other hand, they have discovered that the loads presented by a number of slots excited solely by the transverse currents in the guide, i. e. whose longitudinal axes have projections extending transversely to the transverse currents in the guide are added according to the laws of shunt combination; such slots being hereafter referred to in the disclosure and claims as "shunt coupled" slots. Since the longitudinal and transverse currents are in phase quadrature with each other, a series coupled slot will be in phase quadrature with a shunt coupled slot cut with its centre in the same plane transverse to the guide when both are excited by a travelling wave.

In the case of series coupled slots a satisfactory arrangement is to have each slot formed with its centre on the longitudinal centre line of a broad face of the guide and its longitudinal axis at an angle to this centre line. The resistance presented by a slot so formed varies with the angle which its longitudinal axis makes with the centre line of the broad face. If the angles of the longitudinal axes of two slots with the centre line are of opposite sign, then these slots are coupled in reversed phase relation.

Shunt coupled slots may be arranged either on a broad face or a narrow face of the guide. If a slot is formed in a broad face to extend parallel to the longitudinal centre line of that face, then the conductance which it presents will depend upon the distance of its centre from the centre line of the broad face. If adjacent slots lie on opposite sides of the centre line, they are coupled in reversed phase relation. In the case of slots formed in the narrow face, the angle formed by the longitudinal axis of the slot with the height of the guide determines the conductance presented by the slot. If the angles of the longitudinal axes of two slots with the height of the guide are of opposite sign, then these slots are coupled in reversed phase relation.

Radiation from a slot is polarized with the electric vector at any point tangent to the surface of a cylinder coaxial with the slot (i. e. whose axis coincides with the longitudinal axis of the slot) and lying in a plane normal to the axis of such cylinder.

Thus, it will be seen that, in accordance with the principles of this invention, arrays of slots may be designed in which the distribution of radiated energy along the array, that is, the relative illumination of the slots; the angle of the radiated beam to the axis of the array; and the polarization of the radiation may all be predetermined.

The invention will be more fully described by reference to the attached drawings which illustrate several embodiments of it, and in which

Figure 1 is a perspective view of a section of a wave guide having shunt coupled slots formed in a broad face thereof,

Figure 2 is a similar view of a section of a wave guide having shunt coupled slots formed in a narrow face thereof,

Figure 3 is a similar view of a section of a wave guide having series coupled slots formed in a broad face thereof,

Figures 4 and 5 are partial plan views of the broad face of a guide showing portions of arrays consisting of a series of shunt coupled slots and a series of series coupled slots,

Figures 6 to 16 are diagrammatic views illustrating various ways in which two wave guides may be couped by means of slots in accordance with the invention,

Figure 17 is an indicative curve of standing wave ratios,

Figure 18 is a schematic illustration of a slotted wave guide with its input and termination,

Figure 19 is a schematic illustration of a directive antenna system comprising a feeder guide with a number of radiating guides coupled to it, and

Figure 20 is a schematic illustration of a slotted wave guide fed between the ends of the series of slots.

In all the wave guides illustrated in the drawings, the longitudinal axis is indicated at **20**, the upper broad face at **21**, the lower broad face at **22**, the right-hand narrow face at **23** and the left-hand narrow face at **24**, and the longitudinal centre line of the broad face **21** at **25**. The direction of the electric vector is illustrated by the arrow in Figure 1, the wave being a transverse electric wave. The slots in all the figures are of substantially greater length than width and have longitudinal axes denoted by the numeral **30**. Wherever the direction or the angle of a slot is referred to, the direction or angle of this longitudinal axis is meant.

Figure 1 shows a section of a wave guide in which four slots **26**, **27**, **28** and **29**, are cut in the broad face **21** to extend longitudinally thereof and parallel to the longitudinal centre line **25** alternately on opposite sides of the latter, which also constitutes the axis of the array. The slots are arranged, accordingly, in positions such that, when a microwave is fed to the guide, the transverse current flow along the interior surface of the guide wall at the slots is perpendicular to their longitudinal axes **30** while the longitudinal flow is parallel to the slot axes. The result is that the slots are excited solely by the transverse currents and are shunt-coupled to the guide.

It will be noted that the even numbered slots **26** and **28** occupy positions on one side of the centre line **25** and the odd numbered slots **27** and **29** positions on the opposite side of the centre line. The result of this arrangement is that the slots **26** and **28** are coupled in reversed phase relation to the slots **27** and **29**. Each slot is in substantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot with respect to the centre line **25**. The geometrical relation to the guide of one slot with respect to the centre line **25** is not exactly the same as that of the image of an adjacent slot because, as indicated, the centres of the slots **26**—**29** are at increasing distances x, x_1, x_2 and x_3 from the centre line **25**. In any array, however, the difference in these distances would be very small in the case of any two adjacent slots, and such slots are therefore in substantially though not always exactly image positions with respect to one another.

As the slots of Figure 1 extend longitudinally of the guide, the main radiation from an array of slots arranged according to Figure 1 will be polarized with its electric vector perpendicular to the axis of the array.

Various shapes of slots may be used, but the length of the slot must always be substantially greater than its narrowest width. The most usual shape is substantially rectangular with either straight or rounded ends. In order that a radiating slot in the arrangement of Figure 1 should present substantially no reactive load to the wave in the guide, i. e., that it should be substantially resonant to the wave, its length should generally be up to about 10% less than half the wave length in free space of that wave. The exact length for resonance must be determined separately for very different wave length and guide, though it depends primarily on the wave length and only secondarily on the guide dimensions. The determination may be effected by cutting a slot much shorter than $\frac{1}{2}\lambda s$; putting a reflecting plug in the guide $\frac{1}{4}\lambda g$ from the centre of the slot, as the latter is shunt coupled to the guide; determining by standing wave measurements where the point of minimum current is in relation to the centre of the slot; and lengthening the slot by successive increments until such measurements show that this point coincides with the centre of the slot.

In any given wave guide, the best length for resonance will vary slightly depending on the position of the slot in the guide. In the case of the arrangement of Figure 1 it increases as the distance of the slot from the longitudinal centre line increases. However, when the distance from the centre line is small, as it is for all slots in most arrays, the required difference in length for resonance is so small that it may be disregarded in practice, and all the slots may be made of the same length. In such a case they are all so nearly resonant as to be quite satisfactory in practice. As an aid in estimating the proper slot length for resonance, it may be indicated that for a wave length in free space of 10.7 cm., and for a rectangular guide having a wall thickness of 2.03 cm., an internal width of 7.2 cm. and an internal height of 3.4 cm. the length of a rectangular resonant shunt slot near the centre line of the broad face of the guide is 4.9 cm.

The width of the slot will depend on the amount of peak power which is to pass through the slot, the width being greater, the greater the amount of this power. The width need not be uniform along the length of the slot. The effective width is the width at the point at which the voltage per centimetre across the slot is a maximum. For any given form of slot this point is given by the point at which breakdown occurs when the power is sufficiently increased.

Figure 1 shows only a small section of a wave guide. Ordinarily a radiating array of slots would consist of a large number of slots, say between fifty and one hundred, cut in the guide along its length. The intervals at which the centres of these slots should be spaced longitudinally of the guide will depend on a variety of factors, of which the principal ones are the length of the array and the frequency stability of the oscillator feeding it. The longitudinal spacing of the slots will determine the direction of the radiation with respect to the axis of the array and the loads which the slots should present to the wave in the guide.

Other things being equal, it is desirable that the radiation from an array should be directed normal to the axis of the latter. As indicated above, such a direction of the radiation can be obtained only if all the radiators are radiating in phase with each other. Accordingly, the radiation from an array of slots arranged in accordance with Figure 1 will be directed normal to the axis of the array only if the slots are spaced at longitudinal intervals such that the distance along the guide between their centres is equal to $\frac{1}{2}\lambda g$, i. e. that they are at half wave spacing.

As is known, it is essential that at half wave spacing of the radiators the total load presented by the array as seen from the oscillator feeding it should be such that there is substantially no reflection and consequently substantially no standing wave at the input to the oscillator. Thus, in the case of shunt coupled slots as in Figure 1 it is essential, just as in the case of a pair of loaded transmission lines, that the input admittance of the array should substantially equal the characteristic admittance. With dipole arrays this condition was never achieved and consequently half wave spacing could not be used. According to the present invention this condition can be achieved by so choosing the length of the slots that they each present a substantially pure conductance to the wave in the guide and by terminating the array with a reflecting plunger, as indicated schematically in Figure 18, placed $\frac{1}{4}\lambda g$ from the centre of the terminal slot in the guide, i. e. the slot farthest from the point at which the guide is to be fed with a microwave. As the slots are at half wave spacing they are all electrically at the same position in the guide and as they are substantially pure conductances they can be made to present a total conductance substantially equal to the characteristic admittance which is a pure conductance. There is thus a large standing wave at the plunger end of the guide which is gradually reduced to substantially a travelling wave at the input. In the previous work with dipoles the necessity of a reflecting plunger was not appreciated, but even if such a plunger were used an array of dipoles could not be satisfactorily made at half wave spacing because no probe coupled dipoles were in use which presented a substantially pure conductance.

For short arrays of, for example, ten radiators, half wave spacing is the preferable spacing. However, an array of radiators at half wave spacing is sensitive to changes of frequency and this sensitivity increases fairly rapidly as the length of the array increases. It will be appreciated that if the frequency at which the array is fed changes, the slots are no longer at half wave spacing, with the result that there is a standing wave at the input, which may be considerable even for a very small change in frequency. The longer is the array the smaller is the change of frequency which will produce a large standing wave at the input.

This is illustrated by Figure 17 which shows indicative curves of input standing wave ratios plotted against slot spacing in terms of the wave length in the guide. The figure shows only the general nature of the curve, which can, however, be plotted accurately for any given set of circumstances from the following equation, provided that $\alpha s \ll 1$

$$W_0=\frac{-\omega^N\left(\sum_{S=1}^{S=N}\frac{\alpha s}{2}\omega^{-2s}\right)+\omega^{-N}\left(1-\sum_{S=1}^{S=N}\frac{\alpha s}{2}\right)W_T}{\omega^N\left(1+\sum_{S=1}^{S=N}\frac{\alpha s}{2}\right)+\omega^{-N}\left(\sum_{S=1}^{S=N}\frac{\alpha s}{2}\omega^{2s}\right)W_T}$$

in which W_T and W_0 (sometimes called the complex reflection coefficients) are the terminating and input values respectively of the complex variables represented by the impedance circle diagram; $\omega=\cos\theta+j\sin\theta$, where θ is the angular spacing of two consecutive loads; αs is the conductance or resistance, as the case may be, of the s element of the array; and N is the number of elements in the array.

For the case in question of a change in the frequency feeding an array designed for half wave spacing, the ratio shown in Figure 17 is assumed to be that of minimum voltage to maximum voltage and the peak is of course 1, since there is no standing wave at the input when the elements are effectively at half wave spacing. The full line curve is that for seventy-five slots presenting equal conductances, each of a value equal to 0.0133 G/G_0 (G/G_0 being the ratio of the sum of the conductances of all the slots to the characteristic admittance of the guide), and the dotted line curve is that for ten slots presenting equal conductances, each of a value equal to 0.1 G/G_0. It will be seen from a consideration of the figure that for a long array (which in this specification means an array of more than about 50 elements) a slight change in frequency, which may effectively change the spacing of the elements by only a degree or two, will cause a large change in the input standing wave ratio, while for a short array (which in this specification means an array of up to about 50 elements) the same slight change in frequency will cause much less change in that ratio.

Thus, although half-wave spacing is suitable for short arrays, a long array at half-wave spacing is too frequency sensitive for practical purposes. For long arrays, accordingly, off half-wave spacing, that is, a spacing of the slots different from $\frac{1}{2}\lambda g$, must be resorted to, the array being in this case terminated by a non-reflecting load, as indicated schematically in Figure 18, and the conductances given increasing values along its length. Since, as indicated in Figure 17, the variations of the standing wave ratio in the neighbourhood of half wave spacing are extremely sharp, it is necessary to select a spacing of the slots corresponding to a point in a relatively flat portion of the standing wave ratio curve of Figure 17, which in the case of off half wave spacing represents the ratio of maximum voltage to minimum voltage, this ratio attaining the value of unity in the level portions of the curve. Consequently, a spacing will be selected which is as close as possible to 180°, but is nevertheless on a flat part of the curve such as 80 or 81, the ratio at such a portion being arranged to be in the neighbourhood of 1, while that at the peak 82 is much higher. The spacing is preferably greater than 180°, since the radiation is directed more nearly normal to the axis of the array than when the spacing is correspondingly less than 180°. A spacing of 200° on the basis of the wave length in the guide, i. e. a spacing of $\frac{5}{9}\lambda g$ (corresponding to a point in the portion 80 of the curve) is in practice satisfactory. For the reasons given earlier, the spacing should in no event exceed substantially $\frac{7}{8}\lambda s$. Since there is practically no radiation from a slot in the direction of its longitudinal axis, it will be appreciated that in the arrangement of Figure 1, the second order beams at any given spacing are not as serious as indicated in the diagram on page 421 of the Brainerd book previously referred to, and that they do not increase quite as rapidly with increased spacing as there indicated. Accordingly, the spacing between slots arranged as in Figure 1 might, without danger of second order beams of seriously disturbing magnitude, be such that, for frequencies at the top of the frequency range to which the array is to respond, the effective spacing would be a few degrees over $\frac{7}{8}\lambda s$.

The slots in the case of off half wave spacing, as in the case of half wave spacing, should be resonant. If an array of slots at off half-wave spacing is fed from one end and terminated at the other end by a non-reflecting load, and the slots are arranged to present progressively increasing conductances to compensate for attenuation, and if the conductance of no slot exceeds $\frac{1}{10}$ of the characteristic conductance of the guide, the slots will be excited by a nearly pure travelling wave and the array will perform satisfactorily over the range of frequencies likely to be encountered with oscillators presently available. The radiation from such an array will be directed away from the normal to the axis of the array by an angle the sine of which is

$$\frac{\lambda s}{\lambda g}-\frac{\lambda s}{2d}$$

where d is the distance between slot centres. The progressive increase in conductances may, near the terminal end of the array, be effected with small groups of say, two or three slots instead of with single slots. Thus two or three slots might be cut at the same distance from the longitudinal centre line 25 and then the next group of two or three be cut at a greater distance.

The non-reflecting terminating load may be either any of those conventionally used, such as a sand and graphite load, or may consist, in the case of a long array, of a group of a few slots, say four, at $\frac{1}{2}\lambda g$ spacing and a reflecting plunger $\frac{1}{4}\lambda g$ from the centre of the terminal slot of the group. Such a terminating load is much easier to make than the conventional ones and offers the additional advantage of radiating the power which reaches it rather than dissipating such power uselessly. The number of slots in the terminating load should not exceed about 5% of the total number of slots in the array.

Obviously with a short array of slots at off half wave spacing with the guide terminated by the conventional non-reflecting load, the amount of power radiated compared to the amount of power supplied will necessarily be small. Moreover, as appears from the curve of Figure 17, the decrease in frequency sensitivity at off half wave spacing compared to that at half wave spacing is not nearly as marked with short arrays as with long arrays. Consequently, since with short arrays comparatively little advantage from the point of view of frequency sensitivity is gained by using off half wave spacing and a substantial proportion of power is wasted, half wave spacing is preferable for such arrays. As the length of the array increases, the relative frequency sensitivity at off half wave spacing decreases and the proportion of power effectively used increases, with the result that off half wave spacing becomes increasingly preferable.

While an array at off half wave spacing can be fed only from one end, because the angle of the radiation with the normal to the axis of the array changes sign as the direction of propagation in the guide changes, an array at half wave spacing may be fed at an intermediate point. In such a case it is terminated at both ends by a reflecting plunger placed $\frac{1}{4}\lambda g$ from the centre of the last slot (as illustrated schematically in Figure 20), and the conductances should be calculated to give the characteristic admittance as seen from the feeding point looking in either direction. The feeding may be effected in all cases by coupling the guide to a feeder guide by a non-reactive coupling slot as explained more fully below.

If the slot length in Figure 1 is so chosen that each slot radiating outside the guide presents to the wave for which it is designed a pure or substantially pure conductance, the value of this conductance, expressed as a fraction of the characteristic admittance of the guide, is given substantially by the equation

$$G=A\sin^2\frac{\pi x}{a}$$

where x is the distance of the centre of the slot from the centre line 25, a is the internal width of the guide perpendicular to the electric vector of the wave, and A is a constant which depends upon the frequency and guide cross section used.

It will be seen from the above equation that for a given frequency and given guide dimensions the conductance presented by the slot varies as the distance of its centre from the centre line 25 of the broad face. As shown, this distance is least in the case of the slot 26 and greatest in the case of the slot 29, so that the slot 26 presents the smallest and the slot 29 the greatest conductance of the four which are shown.

On the basis of this equation an array of slots arranged according to Figure 1 may be designed at half wave or off half wave spacing with the gabling, i. e. the distribution of the excitation along the array, appropriate for the radiation pattern which is desired. The relative amounts of energy to be radiated by the different slots having been determined on the basis of the gabling function, the distance of each slot from the centre line **25** may be determined on the basis of the above equation.

Figure 2 shows an alternative arrangement of shunt coupled slots, the radiation from which will be polarized with the electric vector parallel to the axis of the array rather than perpendicular thereto as in the case of an array according to Figure 1. In this arrangement the slots are cut in a narrow face of the guide at angles to the height of the latter. The admittance of a slot of this type depends on the value of its angle to the height of the guide, and the phase of radiation from it is reversed when the sign of this angle is changed. The section of the guide shown in Figure 2 includes four slots **31**, **32**, **33** and **34**, of which the first two are at angles of $+\phi$ and $-\phi$, respectively, to the height of the guide, indicated by the dotted line **35**, and the other two are at angles of $+\phi'$ and $-\phi'$ respectively to this height. Thus, all four slots are coupled to the guide in reversed phase relation, the positions of the slots **31** and **32** on the one hand and **33** and **34** on the other hand being exactly the images of each other with respect to the height of the guide, while the positions of the slots **32** and **33** are only substantially the images of each other because of the difference between the values of ϕ and ϕ'. This difference is much exaggerated in the drawings for clarity, but in practice the differences between the values of the angles for adjacent slots will be of the order of less than one degree.

Whereas in the slot arrangement of Figure 1 there will be practically no mutual action between adjacent slots, this is not the case in the arrangement of Figure 2. Here there is appreciable mutual action between the slots because, since the slots have their centres on the same line and are more or less parallel to each other, each slot is excited to an appreciable extent by radiation from nearby slots. The consequence of this is that, although a single slot of the type of Figure 2 may be of a length such that, alone, it presents a pure conductance to the wave in the guide, a group of identical slots of this length will present a reactive load. In the circumstances it will be appreciated that the determination of resonance for a single slot in the arrangement of Figure 2 has little practical significance.

The mutual admittance between two slots decreases as their distance from each other increases and, for practical purposes, becomes negligible when the distance is equal to about $7\lambda s$. This distance is equivalent, for the usual guide cross section to about ten times the longitudinal spacing between slots. Accordingly, the proper slot length in an array according to Figure 2 is determined on the basis of a group of ten slots rather than on the basis of a single slot as in the case of an array according to Figure 1. The determination may be made by cutting at the desired spacing a group of ten slots, each of which is substantially shorter than $\frac{1}{2}\lambda s$; measuring the conductance presented by this group; and lengthening all the slots equally by successive increments until as a group they present the maximum conductance. A further slot of the length thus determined added to the array will, for any given angle, increase the conductance by the maximum possible amount. This conductance will be termed the incremental conductance. A resonant slot in the case of Figure 2 is one of a length such that it presents the incremental conductance.

If the length of a resonant slot exceeds, as it generally will, $h \sec \phi$, h being the height of the guide, the slot is cut equally into the two broad faces of the guide. This is shown in Figure 2, where, for example, the slot **31** has portions **31***a* and **31***b* of equal depth extending respectively into the upper and lower broad faces **21** and **22** of the guide. In long arrays, where ϕ will be small, all the slots may in practice be cut to the same depth into the two broad faces in spite of the fact that this will result in some slots of which the angle ϕ is greater than that for the group of slots for which the resonant length was determined, having a length slightly greater than the resonant length. The difference is so slight as to be practically insignificant, and the fact that all slots can be cut to the same depth makes the production of the array easier.

The incremental conductance of a resonant slot in an array according to Figure 2 is given by the equation

$$G=K \sin^2 \phi$$

in which ϕ is the angle between the slot and the height of the guide, and K is a constant which depends upon the frequency and guide cross section used and also to a lesser extent on the spacing of the slots.

This equation gives the incremental conductance to a first approximation, sufficient for practical purposes, for values of ϕ up to about 15°. In practice the angle of any slot will almost never exceed about 15°.

What has been said above with regard to half-wave spacing in connection with the arrangement of Figure 1 applies generally to an arrangement according to Figure 2 except that it is necessary to arrange the terminating reflecting plunger or plungers at a distance from the centre of the terminal slot in the array different from $\frac{1}{4}\lambda g$ in order to tune out the susceptance introduced by the mutual action of the slots and present to the oscillator a load equal to the characteristic admittance of the guide.

At off half wave spacing the above equation for incremental conductance does not hold strictly good. However, it has been found that the appropriate angle of the slots may be calculated on the basis of it and that long arrays designed with slots at angles so calculated will perform satisfactorily. Otherwise, what has been said above in connection with Figure 1 with regard to off half-wave spacing applies to arrays designed in accordance with Figure 2, except that the maximum permissible longitudinal spacing, from the point of view of second order beams, is less in Figure 1 because the slots radiate longitudinally of the array.

If the angle ϕ is small, as it is for long arrays of about fifty or more elements because the conductance of each element is to be small, the main radiation from an array according to Figure 2 is polarized with the electric vector parallel to the axis of the array.

Figure 3 shows an array of series coupled slots, which, like the shunt coupled array of Figure 1, will radiate with the electric vector perpendicular to the axis of the array. In this arrangement the slots are cut in a broad face of the guide at angles to the longitudinal centre line of the latter. The impedance of a slot of this type depends on the value of its angle, and the phase of the radiation from it is reversed when the sign of the angle is changed. The section of the guide shown in Figure 3 includes four slots **36**, **37**, **38** and **39**, of which **36** and **38** are at angles of $+\theta_1$ and $+\theta_3$ respectively to the longitudinal centre line **30**, and **37** and **39** are at angles of $-\theta_2$ and $-\theta_4$ to that line. Thus adjacent slots are coupled to the guide in reversed phase relation, the position of one slot, e. g. **37**, differing, apart from longitudinal displacement, from the image position with respect to the centre line **25** of the adjacent slots, e. g. **36** and **38**, only by the differences between the angles at which the slots are cut. These differences are exaggerated in the drawing, but are in practice very small.

When a slot of Figure 3 is of resonant length it presents a resistance, expressed as a fraction of the characteristic impedance of the guide, determined substantially by the equation

$$R=B \sin^2\theta$$

in which θ is the angle between the centre line **25** and the longitudinal axis **30** of the slot, and B is a constant which depends upon the frequency and guide cross section used.

All that has been said in connection with Figure 1 regarding the design of arrays at half wave and off half wave spacing applies to the arrangement according to Figure 3, except that, as the slots in this case are series coupled, the reflecting terminating plunger for an array at half wave spacing must be placed $\frac{1}{2}\lambda g$ from the centre of the terminal slot of the array. If θ is small, as it will be for relatively long arrays of, say, fifty elements or more, the radiation from an array according to Figure 3 is polarized mainly with the electric vector perpendicular to the axis of the array.

Figures 4 and 5 illustrate two arrays, each of which consists of a series of shunt coupled slots and a series of series coupled slots, the shunt coupled slots alternating with the series coupled slots. In Figure 4 the shunt coupled slots are indicated at **79**, **80**, **81** and **82**, and the series coupled slots at **83**, **84**, **85** and **86**. In Figure 5 the shunt coupled slots are in the same positions as in Figure 4, but the signs of the angles of the series coupled slots **83a**, **84a**, **85a** and **86a** with the centre line **25** are changed with respect to the signs of the angles of the corresponding slots **83**, **84**, **85** and **86**, respectively, of Figure 4.

The arrangement of either of these figures, with the slots in each series at off half wave spacing, e. g. 200° spacing, might be resorted to for the purpose of obtaining some improvement in band width over the arrays of Figures 1 to 3. Since, in this case, adjacent slots of different series, e. g. **80** and **84**, are spaced apart only 100°, on the basis of the wave length in the guide, i. e. $5/18\lambda g$ it will be necessary, particularly in the case of the arrangement of Figure 4, either to choose the guide dimensions in such a way as to lengthen the wave length in the guide sufficiently to allow the slots to be cut at the required spacing on the basis of this wave length, or to use slots covered with a dielectric such as polystyrene, which results in a shortening of the resonant length.

As was indicated generally earlier in this specification, the inventors have succeeded in coupling guides to each other by means of slots in such a way that a predetermined proportion of the energy supplied to one guide may be transferred to the other in a known phase relation. Such couplings are of great value in the production of directive antennas consisting of two dimensional arrays of slots, and make it possible to dispense with the parabolic reflectors heretofore used. According to this feature of the invention, a feeder guide may be coupled to a number of guides, each provided with an array of slots as described above, such guides being termed hereafter "radiating guides." The energy supplied to the feeder guide may be distributed between the various radiating guides in accordance with any desired gabling pattern and the radiating guides may be spaced from each other by not more than $\frac{7}{8}\lambda s$ and nevertheless be fed in phase or nearly so.

The coupling of the guides is effected by means of registering slots cut in contiguous walls of the guides to be coupled. One of these slots must be of predetermined dimensions, the nature of which will be more fully indicated hereafter, and the other may be of the same size or larger, since it is the smaller of the two slots which controls the transfer of energy from one guide to the other. The registering slots behave as if they were a single slot cut in a wall common to the two guides and accordingly in the description and claims hereafter two such registering slots will be referred to as a coupling slot. At points of coupling there are impedances or admittances. As used in this specification, a terminating impedance or admittance at a point of coupling is the input impedance or admittance to the radiating guide concerned as measured at the point of coupling in the radiating guide in the absence of the coupling slot. There will be two terminating impedances or admittances for each point of coupling, one for each side of the point.

The coupling slot should be of such a length that it transfers to the feeder guide the sum of the terminating impedances or admittances in the radiating guide with their resistive and reactive components multiplied by the same real, as opposed to complex, quantity. Thus, the slot length should be such that, if, as seen from the centre of the slot, the terminating impedances or admittances in the radiating guide are pure resistances or conductances, the slot will present a pure resistance or conductance to the wave in the feeder guide. A coupling slot of such length will be termed a non-reactive coupling slot. The length may be determined in various ways, for example, by terminating the radiating guide with a non-reflecting load at one or both ends, depending on whether the guide is to be coupled at one end or between its ends, and adjusting the length of the coupling slot until it presents a pure resistance or conductance, as the case may be, to the feeder guide.

The way in which two guides are coupled by a coupling slot will depend upon the aspect of the slot to each guide, that is, upon the position of the slot in each guide. The coupling will be series-series if the slot is coupled in series aspect to both guides, shunt-shunt if it is coupled in shunt aspect to both, series-shunt if it is coupled in series aspect to the feeder guide and shunt aspect to the other guide, and shunt-series if it is coupled in shunt aspect to the feeder guide and series aspect to the other. All these forms of coupling are electrically equally satisfactory, and the choice of that to be used in any particular case will depend simply on the way in which, physically, it is desired to arrange the guides with respect to each other. Generally one type of coupling will be found most satisfactory for a given physical arrangement of the guides.

Various forms of coupling are diagrammatically illustrated in Figures 6 to 15, the couplings in Figures 6 to 8 being series-series, those in Figures 9 and 10 shunt-shunt, and those in Figures 11 to 15 being series-shunt or shunt-series depending on which guide is taken as the feeder guide. In each of these figures the feeder guide is indicated at A and the radiating guide at B.

In a series-series coupling, if Z′ is the sum of the terminating impedances in a radiating guide coupled between its ends or is the single terminating impedance in an end coupled radiating guide, then the impedance Z presented by a non-reactive coupling slot to the wave in the feeder guide at the same point is

$$z = \frac{Z'}{n}$$

where n is a real constant the value of which increases as the coupling of the coupling slot to the feeder guide becomes weaker, all other factors remaining constant, and is unity for identical guides coupled in identical aspect.

The case where $n=1$ is illustrated in Figure 6, in which the guides A and B are identical and the aspect of the slot **48** to both is the same, the slot being thus said to be coupled to both guides in identical aspect. The arrangement shown in Figure 7 is electrically equivalent to the arrangement of Figure 6 in which the guide B is terminated at one end by a reflecting plunger placed one-half wave length from the centre of the coupling slot. The difference in the physical relationship of the guides in the two figures will only negligibly affect the value of n, which is accordingly substantially 1 for the coupling illustrated in Figure 7. That is, as the strength of the series coupling of the slot **51** to both guides is substantially the same, the guides are coupled in substantially identical aspect. It should be noted that an end coupled guide, such as the guide B of Figure 7, need have no wall in its coupled end, being simply cut off and butted on to the other guide. In this case the current flow along the wall of guide A containing the slot **51** and the current flow along the end wall of the guide B (constituted by the portion of the wall of guide A onto which the guide B is butted) is at right angles to the coupling slot **51**. Figure 8 illustrates a case where $n>1$, as the slot **72** is more weakly coupled to guide A than to guide B, being transverse to the latter and at an angle of less than 90° to the axis of the former. In the converse case, where the coupling of the slot to the feeder guide is stronger than to the radiating guide, $n<1$.

In the case of a shunt-shunt coupling, if Y′ is the sum of the terminating admittances in the radiating guide as seen from the centre of the coupling slot, the admittance presented by a non-reactive coupling slot to the wave in the feeder guide at the same point is

$$Y = \frac{Y'}{n}$$

Two possible forms of such coupling are illustrated in Figures 9 and 10. In Figure 9 the slot **59** is coupled in identical aspect to both guides and n accordingly is unity. Figure 10 illustrates a case where the coupling slot **60** is more loosely coupled to the feeder guide A than to the radiating guide B, since in the feeder guide A its displacement from the centre line of the broad face is small, while in the radiating guide B it is in a narrow face and is transverse to the height of the guide.

In the case of a series-shunt coupling, if Y′ is the sum of the terminating admittances in the radiating guide as seen from the centre of the coupling slot, the impedance presented by a non-reactive coupling slot to a wave in the feeder guide at the same point is

$$Z = \frac{Y'}{p}$$

where p is a real constant the value of which increases as the coupling of the coupling slot to the feeder guide becomes weaker.

In the case of a shunt-series coupling, if Z′ is the sum of the terminating impedances or is the single terminating impedance in the radiating guide as seen from the centre of the coupling slot, the admittance presented by a non-reactive coupling slot to the wave in the feeder guide at the same point is

$$Y = \frac{Z'}{q}$$

where q is a real constant the value of which increases as the coupling of the coupling slot to the feeder guide becomes weaker.

For two systems which are identical except that the feeder and radiating guides are interchanged, the constants p and q above are the reciprocals of each other.

Various possible forms of shunt-series coupling are shown in Figures 11 to 15, though these figures can be used to illustrate a corresponding series-shunt coupling, if designation of the feeder guide A and radiating guide B are interchanged in each figure. In Figure 11, the coupling slot **61** is coupled in shunt aspect to the feeder guide A, as in Figure 1, and in series aspect to the radiating guide B. In Figure 13, the coupling slot **69** is shunt coupled to the feeder guide A, as in Figure 1, and, being formed in the end of the radiating guide B, is series coupled to the latter. There is the same similarity between the couplings of Figures 11 and 13 as there is between those of Figures 6 and 7. In Figure 12, the coupling slot **66** is strongly shunt coupled to the feeder guide A and is series coupled to the radiating guide B in the same way as in Figure 13. Figure 14 shows a coupling similar to that of Figure 12, but with the coupling slot **90** weakly instead of strongly coupled to the feeder guide A. In Figure 15, the coupling slot **78** is in shunt aspect to the feeder guide A, as in Figure 2, and in series aspect to the radiating guide B, as in Figure 3.

It should be pointed out that if the total thickness of the contiguous guide walls at the coupling slot is appreciable in proportion to the wave length for which the guides are designed, as is the case, for example, with guides designed for 1 cm. waves and having wall thickness of about 1 mm., it is impossible to make a coupling slot which is wholly non-reactive. However, the approach to this condition is sufficiently close to permit the above equations to be used for practical purposes in the designing of two dimensional arrays.

In designing a radiating guide which is to be coupled between its ends to a feeder guide, regard must be had to the type of coupling which is to be used. If the coupling slot is in series aspect to the radiating guide, there will be reversal of phase in that guide across the point of coupling, whereas if the coupling slot is in shunt aspect to the radiating guide, there will be no reversal of phase in that guide across the coupling. Thus, if a guide with an array of slots of the type illustrated in Figure 1 were to be coupled between its ends to a feeder guide by a coupling slot which was in series aspect to the radiating guide, the adjacent slots on either side of the coupling slot in the radiating guide would have to be cut on the same side of the longitudinal centre of the broad face of that guide.

The guide couplings described make possible the construction of directive antennas composed of a feeder guide with a number of radiating guides coupled to it and extending with their longitudinal axes parallel to each other to constitute a two dimensional radiating array, as indicated schematically in Figure 19. In order that adjacent radiating guides, the longitudinal axes of which should not be more than substantially $\frac{7}{8}\lambda s$ apart, may radiate substantially in phase with each other, these guides may either have their slots arranged identically and be coupled in reversed phase relation to the feeder guide, or they may have their slots so arranged that the array in one radiating guide is the image of the array in the other, and be coupled to the feeder guide in the same phase relation. So far as the longitudinal spacing of the coupling slots in the feeder guide is concerned, substantially the same considerations prevail as have been set out above in connection with the longitudinal spacing of radiating slots in a radiating guide. The spacing of the radiating guides from each other is subject to the same considerations, from the point of view of the appearance of second order beams in the radiation, as the spacing of slots along a radiating guide. Thus, radiating guides of the type of Figure 2 could, from this point of view safely be spaced somewhat further apart than radiating guides of the type of Figure 1.

A guide coupling of special properties may be obtained by the use of a pair of coupling slots. If two identical guides are coupled in identical or substantially identical aspect by two non-reactive coupling slots the centres of which lie in the same transverse plane but one of which is in shunt aspect to both guides and the other is in series aspect to both guides, radiation transfers completely from one guide to the other and continues in the latter in the same direction, regardless of the terminating impedance in the first guide and of the terminating impedance looking in the opposite direction in the other guide.

Such a coupling is illustrated in Figure 16, where the guides are coupled by the slots 91 and 92, the centres of which lie in the same transverse plane as indicated by the dotted line 93, the slot 91 being in identical shunt aspect to both guides and the slot 92 in identical series aspect to both guides. The direction of propagation in the feeder guide A is shown by the arrow. The pair of coupling slots 91—92 will cause radiation in the feeder guide A to transfer completely to the radiating guide B and to continue in the latter guide in the same direction as shown by the arrow. This result is quite independent of the terminating impedance in guide A as seen from the coupling slots looking to the right end of the terminating impedance in guide B as seen from the coupling slots looking to the left.

The utility of the guide coupling features of this invention is not limited to the production of two dimensional radiating arrays. Guide coupling might be useful in various devices in which the guide coupled to the feeder guide was not itself a radiating guide.

Antennas designed in accordance with the present invention are, of course, useful both for transmitting and receiving purposes.

What we claim as our invention is:

1. A directive antenna for microwaves, comprising a wave guide formed with at least one series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the guide at intervals of less than substantially seven-eighths of said wave length in free space and the slots being arranged in positions such that when the guide is fed with a microwave the current flow along the guide walls at such positions excites said slots, each of substantially all the slots of said series being in at least substantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot of said series with respect to a line on the guide wall across which in the absence of any slots there would be no current flow.

2. A directive antenna according to claim 1 in which the slots are series-coupled to the guide and the centres of the slots are spaced along the guide at intervals of half the wave length in the guide of the wave to which the slots are resonant, comprising a reflecting plunger arranged in the guide at a distance equal to one half of said wave length in the guide from the centre of the slot in the guide furthest from the point at which the guide is to be fed with a microwave.

3. A directive antenna according to claim 1 in which the slots are shunt coupled to the guide and the centres of the slots are spaced along the guide at intervals of half the wave length in the guide of the wave to which the slots are resonant, comprising a reflecting plunger arranged in the guide at a distance equal to one-quarter of said wave length in the guide from the centre of the slot in the guide furthest from the point at which the guide is to be fed with a microwave.

4. A directive antenna for microwaves comprising a wave guide of substantially rectangular cross-section with two opposite faces broader than the other two faces, said wave guide having formed in a broad face thereof a series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the guide at intervals of less than substantially seven-eighths of said wave length in free space, each of the slots of said series being formed with its length parallel to the longitudinal centre line of said face, adjacent slots lying on opposite sides of said line, and the distance from said line of substantially every slot being at least substantially the same as the distance from said line of either adjacent slot.

5. A directive antenna according to claim 4 in which the slots lie at distances from the centre line which vary along the length of the guide.

6. A directive antenna according to claim 4

in which the centres of the slots are spaced along the guide at intervals of half the wave length in the guide of the wave to which the slots are resonant, and comprising a reflecting plunger arranged in the guide at a distance equal to one-quarter of said wave length in the guide from the centre of the slot in the guide furthest from the point at which the guide is to be fed with a microwave.

7. A directive antenna for microwaves comprising a wave guide of substantially rectangular cross-section with two opposite faces broader than the other two faces, said wave guide having formed in a broad face thereof a series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the guide at intervals of less than substantially seven-eighths of said wave length in free space, each of the slots of said series being formed at an angle to the longitudinal centre line of said face and with its centre on said line, the angles to said line of alternate slots being of opposite sign, and the angle to said line of substantially every slot being at least substantially the same as the angle to said line of either adjacent slot.

8. A directive antenna according to claim 7 in which the slots lie at angles to the centre line which vary along the length of the guide.

9. A directive antenna according to claim 7 in which the centres of the slots are spaced along the guide at intervals of half the wave length in the guide of the wave to which the slots are resonant, and comprising a reflecting plunger arranged in the guide at a distance equal to one-half of said wave length in the guide from the centre of the slot in the guide furthest from the point at which the guide is to be fed with a microwave.

10. A directive antenna for microwaves comprising a wave guide of substantially rectangular cross-section with two opposite faces broader than the other two faces, said wave guide having formed in a narrow face thereof a series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the guide at intervals of less than substantially seven-eighths of said wave length in free space, each of the slots of said series being formed at an angle to the height of said face, the angles to said height of adjacent slots being of opposite sign, and the angle to said height of substantially every slot being at least substantially the same as the angle to said height of either adjacent slot.

11. A directive antenna according to claim 10 in which the slots lie at angles to the height of the narrow face of the guide which vary along the length of the guide.

12. A directive antenna according to claim 10 in which the centres of the slots are spaced along the guide at intervals of half the wave length in the guide of the wave to which the slots are resonant, and comprising a reflecting plunger arranged in the guide at a distance from the centre of the slot in the guide furthest from the point at which the guide is to be fed with a microwave such as substantially to tune out the susceptance introduced by the mutual action of the slots.

13. A directive antenna according to claim 10, comprising means for feeding the guide between the ends of the series of slots with a microwave having a wave length in free space to which said slots are resonant, and a reflecting plunger arranged in said guide at a distance from the centre of the terminal slot at each end of said series such as substantially to tune out the susceptance introduced by the mutual action of the slots.

14. A directive antenna for microwaves, comprising a wave guide formed with at least one series of slots substantially resonant for a wave of a given wave length and of substanially greater length than width, the centres of the slots of said series being spaced along the length of the guide at intervals of about five-ninths of the wave length in the guide of the wave to which said slots are resonant and the slots being arranged in positions such that when the guide is fed with a microwave the current flow along the guide walls at such positions excites said slots, each of substantially all the slots of said series being in substantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot of said series with respect to a line on the guide wall across which in the absence of any slots there would be no current flow, and comprising a non-reflecting terminating load arranged in the guide beyond the terminal slot in the guide furthest from the point at which the guide is to be fed with a microwave.

15. A directive antenna according to claim 14 in which the non-reflecting load consists of a group of series-coupled slots not exceeding about 5% of the total number of slots in the guide, the centres of the slots of said group of slots being spaced at intervals of one-half of the wave length in the guide of the wave to which the slots are resonant, and a reflecting plunger arranged in the guide at a distance from the centre of the last slot of said group equal to one-half of the said wave length in the guide.

16. A directive antenna according to claim 14 in which the non-reflecting load consists of a group of shunt coupled slots not exceeding about 5% of the total number of slots in the guide, the centres of the slots of said group of slots being spaced at intervals of one-half of the wave length in the guide of the wave to which the slots are resonant, and a reflecting plunger arranged in the guide at a distance from the centre of the last slot of said group equal to one-quarter of the said wave length in the guide.

17. A directive antenna according to claim 14, in which the slots are series coupled to the guide and present loads which progressively increase along the length of the guide towards the terminating load, and the maximum resistance presented by any slot is not over about one-tenth of the characteristic impedance of the guide.

18. A directive antenna according to claim 14, in which the slots are shunt coupled to the guide and present loads which progressively increase along the length of the guide towards the terminating load, and the maximum conductance presented by any slot is not over about one-tenth of the characteristic admittance of the guide.

19. A directive antenna for microwaves comprising a wave guide of substantially rectangular cross section with two opposite faces broader than the other two faces and formed in a broad face thereof with a series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the guide at intervals of about 200° on the basis of the wave length in the guide

of the wave to which said slots are resonant, said slots being arranged with their lengths parallel to the longitudinal centre line of said broad face, adjacent slots lying on opposite sides of said centre line, and comprising a non-reflecting terminating load arranged in the guide beyond the terminal slot in the guide furthest from the point at which the guide is to be fed with a microwave.

20. A directive antenna according to claim 19, in which the slots lie at distances from the longitudinal centre line of the broad face of the guide which progressively increase along the length of the guide towards the terminating load, and the maximum conductance presented by any slot is not over about one-tenth of the characteristic admittance of the guide.

21. A directive antenna for microwaves comprising a wave guide of substantially rectangular cross section with two opposite faces broader than the other two faces and formed in a broad face thereof with a series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the guide at intervals of about five-ninths of the wave length in the guide of the wave to which said slots are resonant, said slots being arranged with their centres on the longitudinal centre line of said face at angles to said centre line, the angles of adjacent slots to said centre line being of opposite sign, and comprising a non-reflecting terminating load arranged in the guide beyond the terminal slot in the guide furthest from the point at which the guide is to be fed with a microwave.

22. A directive antenna according to claim 21, in which the angles of the slots to the longitudinal centre line of the broad face of the guide progressively increase along the length of the guide towards the terminating load, and the maximum resistance presented by any slot is not over one-tenth of the characteristic impedance of the guide.

23. A directive antenna for microwaves comprising a wave guide of substantially rectangular cross section with two opposite faces broader than the other two faces and formed in a narrow face thereof with a series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the guide at intervals of about five-ninths of the wave length in the guide of the wave to which said slots are resonant, said slots being arranged at angles to the height of the said narrow face, the angles of the adjacent slots to said height being of opposite sign, and comprising a non-reflecting terminating load arranged in the guide beyond the terminal slot in the guide furthest from the point at which the guide is to be fed with a microwave.

24. A directive antenna according to claim 23, in which the angles of the slots to the height of the narrow face progressively increase along the length of the guide towards the terminating load, and the maximum conductance presented by any slot is not over about one-tenth of the characteristic admittance of the guide.

25. A directive antenna for microwaves comprising a wave guide of substantially rectangular cross section with two opposite faces broader than the other two faces and formed in a broad face thereof with two series of slots substantially resonant for a given wave length and of substantially greater length than width, the slots of one of said series being formed with their lengths parallel to the longitudinal centre line of said broad face, adjacent slots of said series lying on opposite sides of said centre line, and the slots of the other series being formed with their centres on said longitudinal centre line and at angles to said centre line, the angles of adjacent slots of said other series to said centre line being of opposite sign, the slots of one series alternating with slots of the other series along the length of the guide, and the centre of each slot being spaced from the centres of adjacent slots along the length of the guide at intervals of about five-eighteenths of the wave length in the guide of the wave to which the slots are resonant.

26. A directive antenna for microwaves, comprising a wave guide formed with a series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the guide at intervals of half the wave length in the guide of the wave to which the slots are resonant and being series coupled to the guide, each of substantially all the slots of said series being in substantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot of said series with respect to a line on the guide wall across which in the absence of any slots there would be no current flow, means for feeding the guide between the ends of said series of slots with a microwave having a wave length in free space to which said slots are resonant, and a reflecting plunger arranged in said guide at a distance from the centre of the terminal slot at each end of said series equal to one half of said wave length in the guide.

27. A directive antenna for microwaves, comprising a wave guide formed with a series of slots substantially resonant for a wave of a given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the guide at intervals of half the wave length in the guide of the wave to which the slots are resonant and being shunt coupled to the guide, each of substantially all the slots of said series being in substantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot of said series with respect to a line on the guide wall across which in the absence of any slots there would be no current flow, means for feeding the guide between the ends of said series of slots with a microwave having a wave length in free space to which said slots are resonant, and a reflecting plunger arranged in said guide at a distance from the centre of the terminal slot at each end of said series equal to one quarter of said wave length in the guide.

28. A two dimensional directive antenna for microwaves comprising a number of parallel radiating guides coupled to at least one feeder guide by means of coupling slots which are substantially non-reactive for a wave of a given wave length, each radiating guide being formed with a series of slots substantially resonant for a wave of said given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the radiating guide at intervals of less than substantially seven-eighths of said wave length in free space and said last mentioned slots being arranged in positions such that when the assembly is fed with a microwave the current flow along

the radiating guide walls at such positions excites said last mentioned slots, each of substantially all the slots of said series being in substantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot of said series with respect to a line on the guide wall across which in the absence of any slots there would be no current flow, said radiating guides being spaced with their longitudinal axes at intervals of less than substantially seven eighths of said wave length in free space, and said coupling slots being arranged in positions such that when the assembly is fed with a microwave the current flow along the feeder guide walls at such positions excites said coupling slots.

29. A directive antenna system for microwaves comprising a number of radiating guides coupled to a single source of microwaves by at least one feeder guide, said radiating guides being coupled to the feeder guide by means of coupling slots which are substantially non-reactive for a wave of a given wave length, each radiating guide being formed with a series of slots substantially resonant for a wave of said given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the radiating guide at intervals of less than substantially seven-eighths of said wave length in free space and said last mentioned slots being arranged in positions such that when the assembly is fed with a microwave the current flow along the radiating guide walls at such positions excites said last mentioned slots, each of substantially all the slots of said series being in substantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot of said series with respect to a line on the guide wall across which in the absence of any slots there would be no current flow, said coupling slots being arranged in positions such that when the assembly is fed with a microwave the current flow along the feeder guide walls at such positions excites said coupling slots.

30. A two dimensional directive antenna for microwaves comprising a feeder guide coupled to a number of radiating guides by means of coupling slots which are substantially non-reactive for a wave of a given wave length, each radiating guide being formed with a series of slots substantially resonant for a wave of said given wave length and of substantially greater length than width, the centres of the slots of said series being spaced along the length of the radiating guide at intervals of less than substantially seven-eighths of said wave length in free space and said last mentioned slots being arranged in positions such that when the assembly is fed with a microwave the current flow along the radiating guide walls at such positions excites said last mentioned slots, each of substantially all the slots of said series being in substantially the same geometrical relation to the guide, apart from longitudinal displacement, as the image of an immediately adjacent slot of said series with respect to a line on the guide wall across which in the absence of any slots there would be no current flow, the centres of said coupling slots being

spaced along the feeder guide at intervals of less than substantially seven-eighths of said wave length in free space and said coupling slots being arranged in positions such that when the assembly is fed with a microwave the current flow along the feeder guide walls at such positions excites said coupling slots.

31. A directive antenna system for microwaves according to claim 30, in which each of substantially all the coupling slots is in substantially the same geometrical relation to the feeder guide, apart from longitudinal displacement, as the image of an immediately adjacent coupling slot with respect to a line on the feeder guide wall across which in the absence of any slots there would be no current flow.

32. A directive antenna system for microwaves according to claim 30, in which the series of slots in each radiating guide is the image of the series of the slots in the adjacent radiating guides.

33. A directive antenna for microwaves comprising a wave guide of substantially rectangular cross section with two opposite faces broader than the other two faces and formed in a broad face thereof with two series of slots substantially resonant for a given wave length and of substantially greater length than width, the slots of one of said series being formed with their lengths parallel to the longitudinal centre line of said broad face, adjacent slots of said series lying on opposite sides of said centre line, and the slots of the other series being formed with their centres on said longitudinal centre line and at angles to said centre line, the angles of adjacent slots of said other series to said centre line being of opposite sign, the slots of one series alternating with slots of the other series along the length of the guide, and the centre of each slot being spaced from the centres of adjacent slots along the length of the guide at intervals of less than substantially seven-eighths of the wave length in free space of the wave to which the slots are resonant.

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