

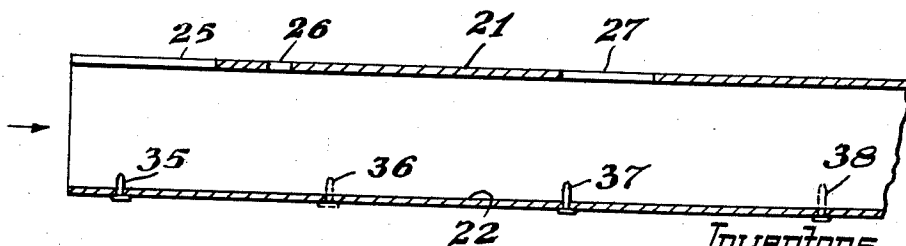
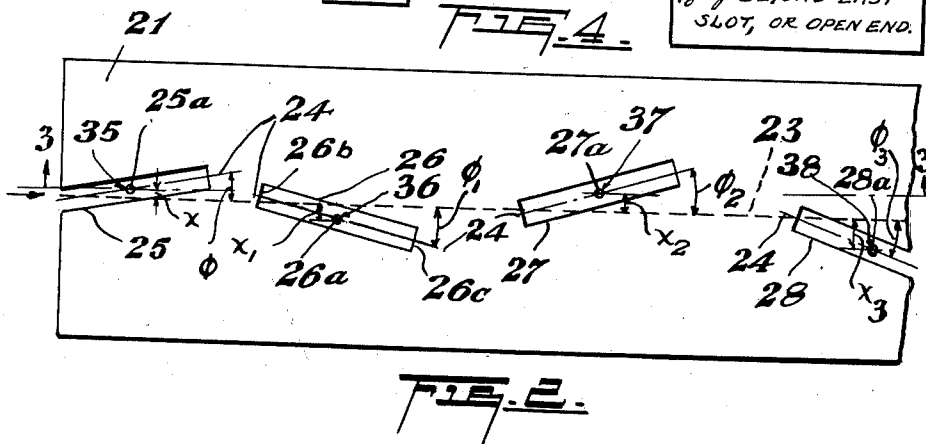
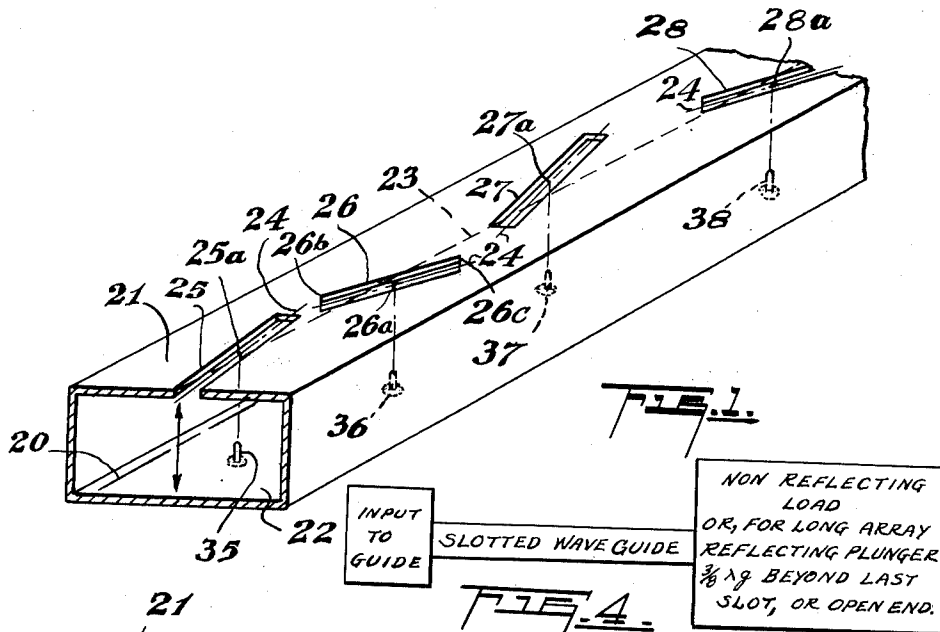
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DIRECTIVE ANTENNA FOR MICROWAVES

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DIRECTIVE ANTENNA FOR MICROWAVES

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

The present inventors have previously proposed in application Serial No. 626,738, filed November 5, 1945 (Patent No. 2,573,746 granted November 6, 1951), the production of antennas comprising wave guides formed with arrays of radiators consisting of slots in special arrangements. The antennas described in this previous application have many advantages over any microwave antennas previously used, but they are limited in the range of frequencies to which they will respond satisfactorily. An array according to the prior application, in which the slots are spaced at intervals of half the wave length in the guide (λ_g), is particularly sensitive to changes of frequency, but even one in which the slots are arranged at off half-wave spacing is limited by the fact that the frequency must not alter either to such an extent as to bring the slots effectively to half-wave spacing or to such an extent as to bring the slot spacing above seven-eighths of the wave length in free space (λ_s).

According to the present invention these difficulties are avoided by providing an array which will operate equally satisfactorily whether the slots are at half-wave spacing or at off half-wave spacing. This results from the discovery that if an appropriate combination of a slot and a probe is made in a guide which is terminated by its characteristic conductance, this conductance is transformed unchanged by the combination. For this purpose the slot must be of such a length that when it is inclined at an appropriate angle to the longitudinal centre line of the broad face of a rectangular wave guide fed with a microwave of a given wave length and its centre is displaced by an appropriate distance from this line, it will transform the characteristic conductance of the guide to an admittance composed of a conductance having a value equal to the characteristic conductance of the guide and of a susceptance. A slot of such a length is termed in this specification a purely reactive slot, since its net effect, when the guide beyond it is terminated by the characteristic conductance, is to alter the input admittance solely by the addition of an imaginary quantity.

According to the invention a directive antenna for microwaves comprises a wave guide formed with an array of slots substantially purely reactive for a microwave of a given wave length and of substantially greater length than width. The

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centres of the slots are spaced along the length of the guide at intervals of less than substantially seven-eighths of said wave length in free space. The centres of alternate slots along the length of the guide are displayed on opposite sides from a line at which the transverse current flow along the guide wall is zero in the absence of electrical discontinuities when the guide is fed with a microwave. All the slots, moreover, are inclined with respect to the line in question. The angle of inclination of each slot and the distance of displacement of the centre of each slot is such that the slot will radiate substantially no power when it is shunted by a susceptance of a sign appropriate to the direction of inclination of the slot and of a value equal to the value of the characteristic admittance of the guide. If the direction of inclination of the slot is such that the end nearest the input end of the guide is closest to the line of zero transverse current flow referred to, the appropriate susceptance is negative, and if the slot is inclined in the opposite direction, the appropriate susceptance is positive. Inside the guide and associated with at least each group of consecutive slots which radiate substantially one-fifth of the total power supplied to such group are means for introducing a susceptance of substantially the same value as but of opposite sign to the susceptance resulting from such group when the guide beyond such group is terminated by the characteristic admittance.

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 previously known 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 electrical dimension being well under λ_s and well over $\frac{1}{2}\lambda_s$, generally about $\frac{3}{4}\lambda_s$, and the minimum electrical 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 electrical dimension in one direction is substantially greater than the maximum electrical dimension in a direction at right angles thereto, both dimensions

being of the order of λ s, 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.

In a guide of such cross section the line of zero transverse current flow referred to is the longitudinal centre line of each broad face. The slots are, accordingly, cut in a broad face of the guide at angles to its longitudinal centre line, and the centres of alternate slots along the length of the guide are displaced on opposite sides of this line. The means associated with the slots for introducing susceptance may, if the required susceptance is positive, as is preferred, consist of probes of appropriate length extending from the inner surface of the opposite broad face opposite the centres of the slots. If the required susceptance is negative, the means in question may consist of flat irises, i. e. thin metal sheets, extending an appropriate distance from the inner surfaces of the narrow faces of the guide.

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

Figure 1 is a perspective view of a section of a slotted wave guide constructed according to the invention,

Figure 2 is a top plan view of portions of the upper broad face of a guide of the kind illustrated in Figure 1,

Figure 3 is a longitudinal section on the line 3-3 of Figure 2, and

Figure 4 is a schematic illustration of a slotted wave guide with its input and termination.

In the guide illustrated in the drawings the longitudinal axis is shown at 20, the upper broad face at 21, the lower broad face at 22, and the longitudinal centre line of the broad face 21 at 23. The direction of the electric vector is illustrated by the arrow in Figure 1, the wave being a transverse electric wave. All the slots shown are of substantially greater length than width, and have longitudinal axes denoted by the numeral 24. Wherever the direction or inclination of a slot is referred to, the direction or inclination of this longitudinal axis is meant. In Figure 1 the near end of the section illustrated is assumed to be nearest to the input end of the guide, and in Figures 2 and 3, the ends towards which the arrows point are assumed to be nearest to the input end of the guide.

The guide section illustrated in Figure 1 has four slots 25, 26, 27 and 28, the centres of which are displaced alternately on opposite sides from the centre line 23 of the face 21. As illustrated, the centres 25a and 27a of slots 25 and 27 respectively are displaced from the centre line 23 to the left hand side, and the centres 26a and 28a of slots 26 and 28 are displaced from this line to the right hand side, the centres of the slots being at increasing distances x , x_1 , x_2 , and x_3 , from this line. All the slots are inclined to the centre line 23, with the ends facing the input end of the guide, for example the end 26b, of the slot 26 closer to this line than the opposite ends, for

example the end 26c of the slot 26. The four slots illustrated are inclined at successively greater angles ϕ , ϕ_1 , ϕ_2 and ϕ_3 . The displacements and angles are considerably exaggerated in the drawings in order to illustrate the principle.

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 the array of the present invention, a slot of a length equal to half the wave length in free space of the microwave whose frequency corresponds to the mean frequency of the band for which the array is designed is in practice satisfactory. The exact length for a purely reactive slot must be determined separately for every 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 one-half the wave length in free space and at a substantial angle which has an appropriate relation to the displacement as discussed below, and then lengthening this slot by successive increments until standing wave measurements show that the slot fulfils the required condition.

In any given wave guide, the best length for a purely reactive slot 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 centre 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 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 purely reactive as to be quite satisfactory in practice. As an aid in estimating the proper slot length, 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 mm., an internal width of 7.2 cms. and an internal height of 3.4 cm. the length of a rectangular purely reactive slot near the centre line of the broad face of the guide is 2 inches.

The displacement and angle of each slot must be such that the slot will radiate substantially no power when it is shunted by a susceptance of a sign appropriate to the direction of inclination of the slot and of a value equal to the value of the characteristic admittance of the guide, that is, when it is shunted by a reflecting plunger $\frac{3}{8}\lambda g$ or $\frac{5}{8}\lambda g$, as the case may be, away from its centre. In the case of the slots illustrated, the ends of which nearest the centre line 23 are those nearest to the guide input, the appropriate susceptance is negative so that the slots should be put out of action by a reflecting plunger $\frac{5}{8}\lambda g$ (equivalent in operation to $\frac{1}{8}\lambda g$) away from their centres. For all cases in which the angles and displacements are small, as is the case for all but possibly a few terminal slots in most arrays, the angle of a slot which is to be displaced by a given distance from the centre line should be the angle of a resonant series slot, according to our said prior application, cut in the broad face of the guide with its centre on the longitudinal centre line of that face and presenting a resistance of a value equal to the value of the conductance presented by a resonant shunt slot according to that application cut

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in the broad face of the guide parallel with the longitudinal centre line of that face and with its centre displaced from that line by the distance in question. A series slot according to the said prior application is one whose longitudinal axis has projections extending transversely to the longitudinal current in the guide and which is excited solely by those currents. The loads presented by a number of such slots are added according to the laws of series combination. The shunt slot according to the said prior application is one whose longitudinal axis has projections extending transversely to the transverse currents in the guide and which is excited solely by those currents. The loads presented by a number of such slots are added according to the laws of shunt combination. It should be noted that all measurements of resistances, conductances, etc., in this specification are expressed as fractions of the characteristic resistance, conductance, etc., of the guide.

The centres of alternate slots along the length of the guide are displaced on opposite sides from the centre line 23 of the broad face in order that adjacent slots should be coupled in reversed phase relation and thus radiate in phase if the slots are at half wave spacing, or nearly so if they are at off half wave spacing.

The slots may be arranged at any spacing less than about $\frac{1}{2}\lambda_g$, which their geometry will allow. Generally it is preferable to arrange them at a spacing of $\lambda_g/2$ at the centre of the band of frequencies to which the array is to respond, in order that the beam should, at the median frequency, be normal to the axis of the array. The more the spacing departs from $\lambda_g/2$ the more the angle of the beam to the axis of the array departs from a right angle.

Associated with each of the slots illustrated is a means for introducing a susceptance of the same value as but of opposite sign to the susceptance resulting from the slot when the guide beyond the slot is terminated by a match, i. e. the characteristic admittance. These means, in the case of the slots illustrated, are probes 35, 36, 37 and 38 associated with the slots 25, 26, 27 and 28 respectively. The probes are mounted in the lower broad face 22 directly underneath the centres of the slots with which they are associated and may conveniently be short metal rods of about $\frac{1}{8}$ " in diameter, for example of silver, inserted through the broad face 22. The length of each probe is determined by the susceptance which it must cancel, this susceptance for any given slot being given for practical purposes by the formula

$$\frac{2\alpha}{1+\alpha}$$

where α is the value of the conductance which would be presented by a slot of the same dimensions and same displacement as the given slot but lying parallel to the centre line of the broad face of the guide. The appropriate probe length for the susceptance required for any given guide may easily be found by a series of experimental measurements. The susceptance introduced by a long probe is measured and the length of the probe then reduced by successive small increments, the susceptance being measured each time so that a graph of probe length and susceptance for the given guide is established.

There need not be a probe for every slot in an array, but there should be one for every group of consecutive slots which radiates sub-

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stantially one-fifth of the power supplied to such group. Thus, with the usual gabling, i. e. distribution of the excitation along the array there might be no probe until the tenth slot from the input end of the guide and this probe would be of a length such as to introduce a susceptance substantially compensating the susceptance resulting from the first ten slots. As the load end of the array is approached, the probes must become more frequent as the slots are radiating a larger fraction of the power supplied to them. The groups of slots thus become smaller until, near the load end, they consist of one slot. In a fifty slot array, the last five to ten slots would be likely each to require a probe.

When the inclination and displacement of a slot is small, as is true of most of the slots of a practical array, it is not essential that the probe be directly underneath the centre of the slot, provided that it is in the same transverse plane of the guide as the slot centre. Accordingly, construction of an array in practice may be facilitated by placing all the probes, except from the slots near the terminal end which radiate a substantial fraction of the power supplied to them, along the centre line of the lower face of the guide.

If the slots are inclined in the opposite direction to that shown, i. e. with their ends which are furthest from the input end of the guide nearest to the longitudinal centre line of the broad face, then the sign of the susceptances resulting from them is reversed, and these susceptances can be cancelled, by means of irises projecting into the guide from the narrow faces in the same transverse plane of the guide as a slot centre. There appears, however, to be no advantage in such an arrangement, and that shown is accordingly preferred.

The power radiated by any given slot arranged according to the invention is determined for practical purposes by the product

$$\frac{2\alpha}{(1+\alpha)^2}$$

where α is the value of the conductance which would be presented by a slot of the same dimensions and same displacement as the given slot but lying parallel to the centre line of the broad face of the guide.

Each slot-probe combination results in a phase retardation of the wave in the guide by approximately an angle of which the tangent is

$$\frac{\alpha}{1+\alpha^2}$$

(where α has the same meaning as indicated above). For slots near the input end of the guide α is so small that the phase retardation is unimportant, but near the load end, where each slot is relatively substantially displaced from the longitudinal centre line of the broad face, the angle of phase retardation becomes appreciable. The spacing of the slots must accordingly be reduced by an appropriate amount at least near the load end of the guide in order to maintain throughout the length of the guide the same effective spacing in terms of the wave length in the guide.

The formulae given for the calculation of susceptance to be cancelled by a probe, the power radiated by a slot and the phase retardation resulting from a slot-probe combination are substantially accurate for all slots which ex-

tract less than about one-fifth of the power supplied to them. In most practical arrays this is true of all slots. For any array in which the last two or three slots may extract more than one-fifth of the power supplied to them, the necessary calculations for these slots may be made with quite satisfactory practical accuracy by one or two experimental measurements and extrapolation of the curves given by the formulae through the points determined by these measurements.

As is shown schematically in Figure 4, any array of slots according to the invention may be terminated by a non-reflecting load, for example a conventional sand and graphite load. A long array of about fifty slots or more, in which the last slot radiates about one third or more of the power supplied to it, can, at some slight sacrifice of band width, be very conveniently terminated by a reflecting plunger arranged $\frac{3}{8}\lambda_g$ beyond the centre of the last slot. Another alternative for a long array in which the power passing the last slot is a very small fraction, say 1% of the input power, may be simply to allow the power passing the last slot to be radiated into space from the end of the guide.

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, if the inclination of the slots to the centre line 23 is small, as it is in practice for long arrays of about fifty elements or more, the radiation from the array is polarized mainly with the electric vector perpendicular to the axis of the array.

What we claim as our invention is:

1. A directive antenna for microwaves, comprising a wave guide formed with an array of slots substantially purely reactive for a microwave of a given wave length and of substantially greater length than width, the centres of said slots being spaced along the length of the guide at intervals of less than substantially seven-eighths of said wave length in free space, said slots being inclined with respect to a line at which the transverse current flow along the guide wall is zero in the absence of electrical discontinuities when the guide is fed with a microwave, and the centres of alternate slots along the length of the guide being displaced on opposite sides from said line, the angle of inclination of each slot and the distance of displacement of the centre of each slot being such that the slot will radiate substantially no power when it is shunted by a susceptance of a sign appropriate to the direction of inclination of the slot and of a value equal to the value of the characteristic admittance of the guide, and means in the guide associated with at least every group of consecutive slots which radiates substantially one-fifth of the total power supplied to such group for introducing a susceptance of substantially the same value as but of opposite sign to the susceptance resulting from such group when the guide beyond such group is terminated by the characteristic admittance of the guide.

2. A directive antenna according to claim 1, in which the centres of the slots are spaced along the guide at intervals of half the wave length in the guide of the median wave length of the band of frequencies to which the antenna is designed to respond.

3. A directive antenna according to claim 1,

in which the array of slots is terminated by a non-reflecting load in the wave guide.

4. A directive antenna according to claim 1, in which the wave guide is formed with an array of at least about fifty slots inclined in a direction such that their ends nearest the end from which the guide is adapted to be fed with a microwave are nearest to the line of zero transverse current flow, and in which the last slot of the array radiates not less than about one-third of the power supplied to it, comprising a reflecting plunger arranged in the guide at a distance from the centre of said last slot equal to five-eighths of the wave length in the guide of the wave for which the slots are substantially purely reactive.

5. 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 an array of slots substantially purely reactive for a microwave of a given wave length and of substantially greater length than width, the centres of said slots being spaced along the length of the guide at intervals of less than substantially seven-eighths of said wave length in free space, said slots being inclined with respect to the longitudinal centre line of said broad face, and the centres of alternate slots along the length of the guide being displaced on opposite sides from said line, the angle of inclination of each slot and the distance of displacement of the centre of each slot being such that the slot will radiate substantially no power when it is shunted by a susceptance of a sign appropriate to the direction of inclination of the slot and of a value equal to the value of the characteristic admittance of the guide, and means in the guide associated with at least every group of consecutive slots which radiates substantially one-fifth of the total power supplied to such group for introducing a susceptance of substantially the same value as but of opposite sign to the susceptance resulting from such group when the guide beyond such group is terminated by the characteristic admittance of the guide.

6. A directive antenna according to claim 5, in which the centres of the slots are spaced along the guide at intervals of half the wave length in the guide of the median wave length of the band of frequencies to which the antenna is designed to respond.

7. A directive antenna according to claim 5, in which the array of slots is terminated by a non-reflecting load in the wave guide.

8. A directive antenna according to claim 5, in which the slots are inclined in a direction such that their ends nearest the end from which the guide is adapted to be fed with a microwave are nearest to the longitudinal centre line of the broad face of the guide, and in which the means for introducing susceptances consist of probes mounted in the opposite broad face of the guide to that in which the slots are formed, each of said probes being arranged in the same transverse plane of the guide as the centre of a slot.

9. A directive antenna according to claim 8, in which the wave guide is formed with an array of at least about fifty slots and the last slot of the array radiates not less than about one-third of the power supplied to it, comprising a reflecting plunger arranged in the guide at a distance from the centre of said last slot equal to five-eighths of the wave length in the guide

of the wave for which the slots are substantially purely reactive.

10. A directive antenna for microwaves, comprising a wave guide formed with an array of slots substantially purely reactive for a microwave of a given wave length and of substantially greater length than width, said slots being spaced along the length of the guide at intervals of less than substantially seven-eighths of said wave length in free space and inclined with respect to a line at which the transverse current flow along the guide wall is zero in the absence of electrical discontinuities when the guide is fed with a microwave, and the centres of alternate slots along the length of the guide being displaced on opposite sides from said line, the angles of inclination of successive slots and the distances of displacement of the centres of successive slots along said wave guide being of progressively increasing values in the direction of travel of waves in said guide, and means in the guide associated with at least every group of consecutive slots which radiates substantially one-fifth of the total power supplied to such group for introducing a susceptance of substantially the same value as, but of opposite sign to, the susceptance resulting from such group when the guide beyond such group is terminated by the characteristic admittance of the guide.

11. An antenna for microwaves comprising a wave guide of rectangular section having a plurality of slots of greater length than width formed in one broad face thereof, the centres of said slots being spaced at regular intervals along the length of said guide, alternate slots being oppositely inclined at acute angles to the center line of said broad face, and having their centers displaced on opposite sides of said center line, the angles of inclination of successive slots and the distances of displacement of the centres of successive slots along said wave guide being of progressively increasing values in the direction of travel of waves in said guide.

12. A directive antenna according to claim 1. in which the angles of inclination of successive slots and the distances of displacement of the centres of successive slots along the wave guide are of progressively increasing values in the direction of travel of waves in said guide.

13. A directive antenna for microwaves, comprising a wave guide formed with an array of

slots substantially purely reactive for a microwave of a given wave length and of substantially greater length than width, the centres of said slots being spaced along the length of the guide at intervals of less than substantially seven-eighths of said wave length in free space, and said slots being inclined with respect to a line at which the transverse current flow along the guide wall is zero in the absence of electrical discontinuities when the guide is fed with a microwave, and the centres of alternate slots along the length of the guide being displaced on opposite sides from said line, the angle to said line of zero transverse current flow of substantially every slot of which the centre is displaced by a given distance from said line being substantially the same as the angle to said line of a resonant series slot with its centre on said line and presenting a resistance of a value equal to the value of the conductance presented by a resonant shunt slot parallel to said line and displaced therefrom by said given distance, and means in the guide associated with at least every group of consecutive slots which radiates substantially one-fifth of the total power supplied to such group for introducing a susceptance of substantially the same value as but of opposite sign to the susceptance resulting from such group when the guide beyond such group is terminated by the characteristic admittance of the guide.

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