March 15, 1960 K. C. KELLY 2,929,064

PENCIL BEAM SLOT ANTENNA

Filed Aug. 2, 1957 2 Sheets-Sheet 1

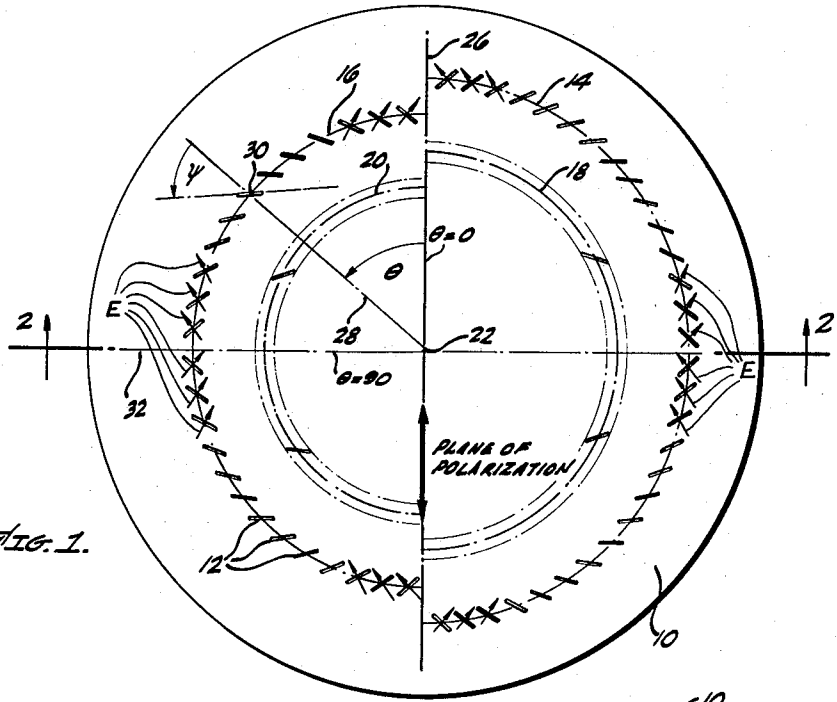


FIG. 1.

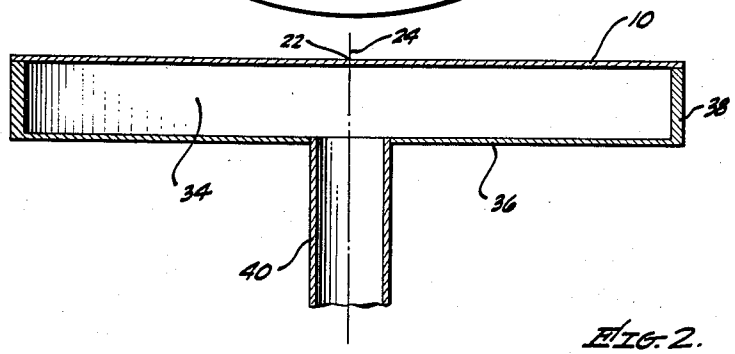


FIG. 2.

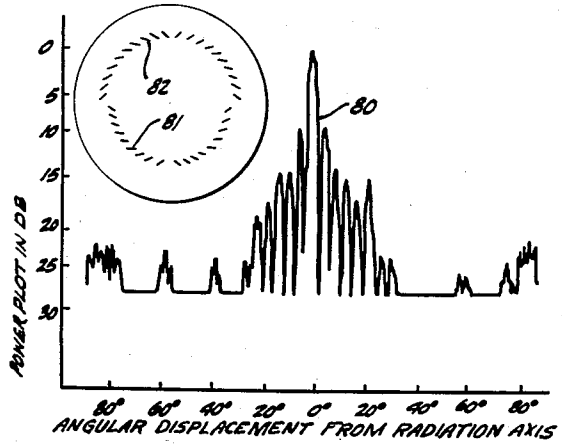


FIG. 5.

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FIG. 3.

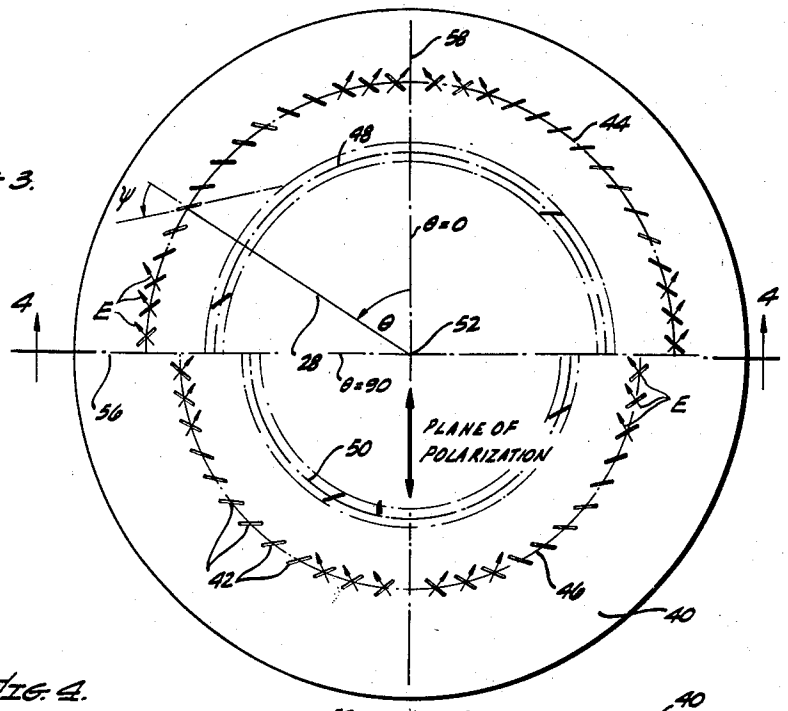
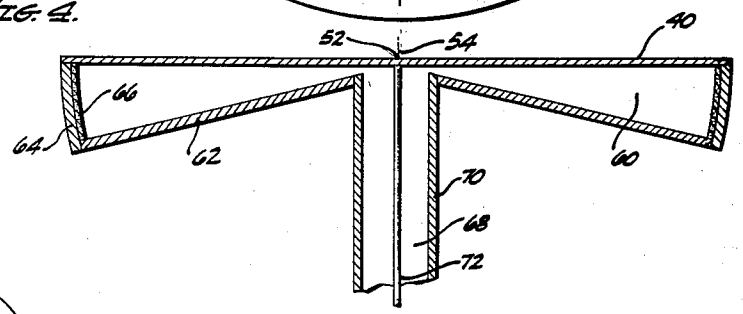


FIG. 4.



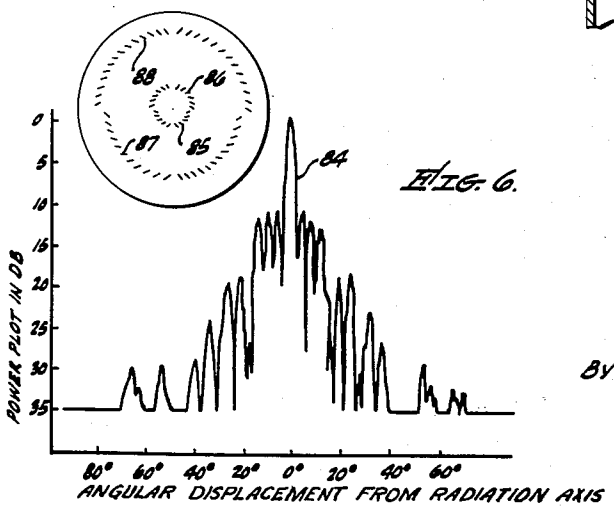


FIG. 6.

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PENCIL BEAM SLOT ANTENNA

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Application August 2, 1957, Serial No. 675,909

7 Claims. (Cl. 343—771)

This invention relates to wave energy radiators and more particularly to an antenna for radiating a plane polarized pencil beam.

Electromagnetic energy beams of circular cross section, which are commonly referred to as pencil beams, are extensively utilized for the location or tracking of reflecting objects, and for point-to-point microwave communication systems. Such beams may be plane or circularly polarized. Heretofore, plane polarized pencil beams have been obtained, for example, by combining a plane polarized electromagnetic wave point source with a beam shaping reflector. Such reflectors usually occupy a large volume, however, and therefore are not too desirable in systems where space is at a premium.

Another method which has been employed for the production of plane polarized pencil beams utilizes spatial arrays of plane polarized sources such as a plurality of dipoles or slots. Such systems may in some applications have the advantage of elimination of the space wasting reflector. However, these arrays are usually difficult to fabricate and, further, often require a complicated feed system imposing complex electrical requirements.

Radiating horns have also been utilized for the production of plane polarized pencil beams. While such horns have avoided the complicated feed system attendant in spatial arrays, they have in many cases required a great depth in the direction of the radiating beam and have been found unsuitable when space is at a premium. The same limitations are usually present in surface wave antennas which are also capable of producing plane polarized pencil beams. As is well known, a surface wave antenna suitable for the production of a plane polarized pencil beam requires very great length to sufficiently narrow the beam in a plane perpendicular to the surface.

Recent attempts to develop a radiator to produce a plane polarized beam have utilized annular slots excited by a structure setting up either radial or circumferential electric fields in the slots. Such systems overcome the objectionable depth of the antenna and the high cost attendant to its manufacture. The beams so produced are, however, elliptical in cross section along the radiator axis and the side lobe level varies with the plane of observation. Furthermore, there are directions in space in which prominent cross polarization exists.

It is therefore an object of this invention to provide an antenna for radiating a plane polarized pencil beam which is excited by a simple feed structure and which exhibits only a small amount of cross polarization.

It is also an object of this invention to provide a plane polarized pencil beam radiator which occupies a small volume and has a small depth.

It is a further object of this invention to provide a plane polarized pencil beam antenna which is simple to manufacture and which has a low side lobe level.

It is another object of this invention to provide an improved plane polarized pencil beam radiator which is simple in construction, reliable in operation, small in volume, light in weight and provides ease of aperture control to facilitate beam design.

In accordance with one embodiment of the pencil beam antenna of this invention, a conductive plate is perforated with a large number of slot-type radiation apertures disposed along a number of concentric semi-circles. Currents are induced into the plate by electromagnetic waves in such a manner that the gap produced by any radiation aperture intercepts a portion of the current and causes excitation of that aperture. The directions of the currents induced into the plate and the locations of the apertures in the plate are selected in such a manner that the electromagnetic waves radiated into space by each aperture are all substantially plane polarized along a common plane of polarization.

Plane polarization along a common plane is obtained in the selected embodiments of this invention by inducing a set of circumferential bands of radial or of circumferential current into the surface of the conductive plate. The slot-type radiation apertures are located in such a way as to intercept the induced current substantially in the same spatial direction and are inclined to radiate a component along the common plane of polarization.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which two embodiments of this invention are illustrated by way of example. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only, and are not intended as a definition of the limits of the invention.

Figs. 1 and 3 are plan views of different embodiments of the radiators of this invention;

Figs. 2 and 4 are cross-sectional views taken respectively along the lines 2—2 and 4—4 of the radiators of Figs. 1 and 3; and

Figs. 5 and 6 are illustrative radiation patterns of the radiator of Fig. 3 measured through a plane perpendicular to the aperture plane and containing the radiation axis.

Referring now to the drawings, in which like reference characters designate like parts, there is shown in Fig. 1 a planar conductive plate 10 perforated with a large number of radiation apertures 12 which have the shape of a short thin slot. The radiation apertures 12 are disposed within the plate along a plurality of semi-circles of which four are shown and designated by the reference characters 14, 16, 18 and 20. The semi-circles 14, 16, 18 and 20 are concentric and have a common geometrical center at a point 22. The point 22 lies on a radiator axis shown in Fig. 2 which is perpendicular to plate 10 and pierces plate 10 at the center point 22.

The semi-circles 14, 16, 18 and 20 differ in radius by one-half of a working wavelength or an odd multiple thereof. The term "working wavelength" will be defined in connection with the explanation of the operation of this invention. The semi-circles 14, 16, 18 and 20 are also disposed, in the order of increasing radial dimension, alternately to the right and to the left of a first diametrical plane 26 which first diametrical plane contains the radiation axis 24 (shown in Fig. 2).

The slots 12 are each inclined with respect to a radial line 28 drawn from the center point 22 to the center point 30 of each slot. This inclination depends upon an angle θ which the radial line 28 makes with the first diametrical plane 26. Angle θ is positive when measured in an anti-clockwise direction about center 22 from the plane 26. The inclination of a slot is measured by an angle ψ and is positive when measured in an anti-clockwise direction about the slot center 30 from the radial line 28.

For the purpose of describing the slot inclination without equivocation, the conductive plate **10** is divided into four quadrants by a second diametrical plane **32** perpendicular to the first diametrical plane **26** and intersecting the first diametrical plane along the radiator axis **24**. The first quadrant is defined by sweeping the radial line **28** through the angle θ between zero and 90 degrees. Similarly, the second, third and fourth quadrants are defined respectively for values of θ between 90 degrees to 180 degrees, 180 degrees to 270 degrees, and 270 degrees to 360 degrees. The inclination ψ of the slots **12** with the radial line **28** in the first and the third quadrant is preferably plus 45 degrees and in the second and fourth quadrant is preferably minus 45 degrees. For optimum condition of operation the inclination ψ should be as close as possible to 45 degrees.

The slots are approximately one-half of a free space wavelength in length and one-twentieth of a free space wavelength in width. The exact length and the number of the slots on each semi-circle depends on the fraction of the total power to be radiated by the slots lying on a given semi-circle. The fraction is determined, for each semi-circle by its relative position from the center point **22**. This is a matter of design and serves to control the side lobe level of the energy radiated from the radiator.

Referring now to Fig. 2, the conductive plate **10** is coupled to radial waveguide **34**. Radial waveguide **34** is utilized for the purpose of inducing currents into plate **10** for exciting the slots **12**. The radial waveguide **34** includes a lower conductive plate **36** and a cylindrical wall **38** substantially concentric with the radiator axis **24**. As will become more evident from a description of the operation of the radiator of this invention, the wall **38** terminating the radial waveguide **34** may be of a conductive material when it is desired to excite the slots **12** by standing wave fields. The slots may also be excited by travelling wave fields and for this embodiment the wall **38** may be of an absorptive material which will provide a termination of the radial waveguide **34** suitable for maintaining travelling wave fields. In other words, the conductive plate **10** may be excited by travelling wave fields or by standing wave fields and will, in either case, produce a plane polarized pencil beam.

The radial waveguide **34** may be excited by a feed means such as the circular waveguide **40** which is dimensioned for propagation for the TE_{01}-mode of the circular waveguide. The circular waveguide **40** is coupled to the radial waveguide **34** and disposed symmetrical with the radiation axis **24**.

The operation of the radiator shown in Figs. 1 and 2 will now be explained. The circular waveguide **40** being dimensioned for propagation of the TE_{01}-mode of the circular waveguide will excite the H_{01}-mode of the radial waveguide between the conductive plate **10** and the conductive plate **36** since the spacing of these plates is over one-half of a free space wavelength. If the wall **38** is made of a conductive material standing wavefields will be set up. If the wall **38** is made of an absorptive material, travelling wave fields will be set up in the radial waveguide **34**.

The waves of the H_{01}-mode of the radial waveguide, as is well known, induce circumferential bands of circumferential current into the conductive plate **10**. The term "circumferential band of circumferential current" is defined as an annular region of surface current in plate **10** in which all current lines flow in the same rotational sense which may be clockwise or counterclockwise. The intensities of the current lines in a band depends on the distance from center **22** at the instant under discussion. Each band starts and ends with zero intensity lines if the observer were moving in the radial direction with time standing still. The term "circumferential bands of radial current" to be used in conjunction with Figs. 3 and 4 are similarly described in that there are annular regions of surface currents except that the current lines are now directed along radii and the radial sense may be either inward or outward.

If the radial waveguide **34** is excited and the circumferential band of circumferential currents are induced into the plate **10**, the center of the current band is either stationary for standing wave fields or expanding for travelling wave fields. For standing wave fields, the center of a current band may be made to coincide with the semi-circle **14**. Since the radial separation between the semi-circles **14** and **16** is equal to one-half of a working wavelength or odd multiples thereof and the radial distance between the center of the current bands is likewise one-half of a working wavelength, the semi-circle **16** also coincides with the center of a current band. However, the direction of the circumferential current along semi-circle **16** is opposite to that of the current along the semi-circle **14**. The term "working wavelength" here used refers to the asymptotic value of the wavelength of the Hankel function which describes the radial dependence of waves in a radial waveguide.

The circumferential currents excite the short thin slots **12** by setting up an electric field across the narrow dimension thereof. The vectors designated by the reference character E (Fig. 1) represent an instantaneous condition for the direction and magnitude of the electric field across a selected few of the slots **12**. As can be seen from Fig. 1 when all the vectors E are added up with one another, a plane polarized wave having a plane of polarization parallel to the dimetrical plane **26** is obtained. Along the radiator axis **24** this polarization is substantially without any cross polarization. At a certain point not in the first or second diametrical plane a certain amount of cross polarization exists. The cross polarization which is defined as radiated wave energy having a plane of polarization perpendicular to the first diametrical plane has a maximum intensity of approximately 12 db below the main beam for one pair of semi-circles. This presents a marked improvement (about 4 db) over the annular slot type radiator previously mentioned. This cross polarization may be further suppressed by adding more semi-circles. Such suppression is not obtainable by adding annular rings to the annular slots antenna.

For traveling wave fields, the operation of the radiator of this invention is likewise described by the foregoing explanation. Instead of regarding the center of the current bands as fixed in space, the instantaneous position of the center of a current band is considered. At a given instant of time, the operation of the radiator is exactly the same. The difference over a time interval corresponding to a cycle at the operating frequency is that when standing waves are used to excite the radial waveguide **34**, the induced current band remains stationary and the current amplitude goes through a complete sinusoidal period. When travelling waves are used to excite the radial waveguide, the current bands travel across the semi-circles giving the identical effect.

Referring now to Fig. 3, there is shown a planar conductive plate **40** perforated with a large number of radiation apertures **42** which have the shape of short thin slots. Just like the slots **12** of Fig. 1, the slots **42** are disposed upon a plurality of semi-circles of which four are shown and designated by the reference numerals **44**, **46**, **48** and **50**. The radial dimensions and the relative locations of the semi-circles **44**, **46**, **48** and **50** are similar to those of the semi-circles **14**, **16**, **18** and **20** of Fig. 1. They are concentric about a point **52** through which the radiator axis **54** passes as shown in Fig. 4.

The essential difference between the conductive plate **10** of Fig. 1 and the conductive plate **40** of Fig. 3 is that the semi-circles of Fig. 3 are disposed about the second diametrical plane **56** which is perpendicular to the first diametrical plane **58**. The first diametrical plane **58** is defined as above as the direction of the plane of polarization of the waves radiated by the radiator.

The same nomenclature and geometry may be adopted to designate the inclination of the slots **42**. Therefore, the angle θ and the angle ψ are the same as defined in connection with Fig. 1 together with the designation of the four quadrants. The inclination of the slots **42** is therefore plus 45 degrees in the first and the third quadrant and minus 45 degrees in the second and fourth quadrant.

It is therefore seen that the inclination of the slots in the radiator of Fig. 3 is identical to the inclination ψ of the slots in the radiator of Fig. 1. However, the semi-circles upon which the slots are located are across different diametrical planes. The semi-circles of the radiator of Fig. 3 are located on opposite sides of a diametrical plane perpendicular to the direction of the plane of polarization whereas the semi-circles of the radiator of Fig. 1 are located on opposite sides of a diametrical plane parallel and coinciding with the plane of polarization.

Referring to Fig. 4, there is shown a preferred embodiment of an exciting means for the conductive plate **40**. The conductive plate **40** is coupled to a conical waveguide **60** which comprises a conical surface of revolution **62** oppositely disposed to and symmetric with plate **40**. The conical waveguide **60** is terminated. The termination may comprise a conductive circular wall **64** having an absorptive lining **66** for maintaining travelling wave fields with the conical waveguide **60**. The absorptive lining **66** may be dispensed with if standing wave fields are desired for exciting the slots **42**. As indicated previously, the conductive plate **40** may be excited with either standing waves or travelling waves, both methods of excitation will provide a plane polarized wave from the radiator of Fig. 4.

The conical waveguide **60** may be excited by a feed means such as a coaxial waveguide **68** having an outer conductor **70** and a center conductor **72**. The outer conductor is coupled to the conical surface of revolution and the inner conductor is connected to the plate **40**. The coaxial waveguide **68** is adapted to be excited in the TEM-mode of a coaxial waveguide and will excite the fundamental conical waveguide mode between the plate **40** and the conical surface of revolution **62**.

The operation of the radiator of Fig. 4 is in many respects similar to that of the radiator of Fig. 2. The major difference lies in direction of the currents induced into plate **40** by the fundamental conical waveguide mode. The fundamental mode induces circumferential bands of radial currents so that the direction of current flow in the plate **40** is radially inward or outward. The inclined slots **42** intercept, as before, a component of the current which is perpendicular to the long dimension of the slots. This intercepted component gives rise to an electric field across each of the slots **42** which are designated by vector E for a few of the slots.

The radial dimension of the semi-circles **44** and **46** differ by one-half of a free space wavelength since the fundamental mode is a TEM-mode. In the case of standing wave field excitation, the center of two adjacent current bands coincide with semicircles **44** and **46**. The radial direction of the current in the two bands is reversed and proper slot excitation is obtained giving rise to a plane polarized wave having a plane of polarization parallel to the first diametrical plane **58**.

The conical transmission line shown in Fig. 4 may be replaced by a radial waveguide or any symmetrical waveguide for that matter, as long as the distance between adjacent semi-circles is kept at one-half of a working wavelength at the particular radial dimension, and the mode used excites radial currents.

Figs. 5 and 6 respectively show the radiation pattern obtained with the radiator of Fig. 4. Fig. 5 shows the radiation pattern **80** which is obtained with a radiator having but two semi-circles as shown schematically by the two semi-circles **81** and **82**. Fig. 6 shows the radiation pattern **84** of a radiator having four semi-circles as shown by the semi-circles **85**, **86**, **87** and **88**.

A comparison between the pattern **80** and the pattern **84** shows the greater the number of semi-circles, the sharper is the radiation pattern along the radiator axis **54** which corresponds to zero degrees of the pattern plot. It further shows that the side lobe level is also decreased substantially by increasing the number of semi-circles.

There has been described a radiator which may be utilized for radiating a plane polarized pencil beam which essentially comprises a conductive plate perforated with a large number of thin short slots. Means are provided for exciting the conductive plate by circumferential bands of either radial or circumferential current. The thin short radiation slots are disposed within the conductive plate in such a manner as to increase the field contributions to the desired plane of polarization and reduce the contributions perpendicular thereto while causing an improvement of the shape of the main beam.

What is claimed as new is:

1. A radiator comprising a conductive plate having a plurality of radiating apertures therethrough, all of the apertures through said plate forming a pattern that is asymmetrical about a line extending diametrically across said plate, said pattern including a first row of apertures and a second row of apertures, all of the apertures in said first row being disposed a uniform distance from a common center located on said line, all of the apertures disposed said uniform distance from said center being disposed on one side of said line, all of the apertures in said second row being disposed a common distance from said center, all of the apertures disposed said common distance from said center being disposed on the opposite side of said line, said common distance and said uniform distance differing from each other by some predetermined amount, all of the radiating apertures on one side of said line having a distance from said common center differing from the distance from said center of all of the radiating apertures on the other side of said line, and means coupled to said plate for inducing a predetermined current therein for exciting said apertures whereby electromagnetic energy will be radiated therefrom.

2. A radiator comprising a conductive plate having a plurality of radiating apertures therethrough, all of the apertures through said plate forming a pattern that is asymmetric about a line extending diametrically across said plate, said pattern including a first group of apertures and a second group of apertures, all of the apertures in said first group forming semicircular rows that are disposed entirely one side of said line and are concentric about a point located on said line, all of the apertures in said second group forming semicircular rows that are disposed entirely on the opposite side of said line and are concentric about said point, the geometric centers of all of the apertures in any given row being disposed some predetermined radius from said point, all of the apertures having their geometric centers disposed at a given radius from said center being disposed on the same side of said line, the radius of any given row differing from the radius of any given row in the other group by a predetermined amount corresponding to an odd integer multiple of one-half a wavelength of the radiated energy, and means coupled to said plate for inducing a predetermined current therein for exciting said apertures whereby electromagnetic energy will be radiated therefrom.

3. A radiator for radiating electromagnetic energy along a radiation axis, said radiator comprising a conductive plate having a plurality of elongated radiating slots therethrough, all of the slots through said plate forming a pattern that is asymmetrical about a line extending diametrically across said plate, said pattern including a first row of slots disposed on one side of said line and a second row of slots disposed on the other side of said line, all of the slots in said first row having the geometric centers thereof disposed a uniform distance from a common point located on said line, all of the slots having the geometric centers thereof disposed said uniform distance from said point being disposed on the side of said line containing said first row, all of the slots in said second row being

disposed a common distance from said center, all of the slots disposed said common distance from said center being disposed entirely on the side of said line containing said second row, said common distance and said uniform distance differing from each other by an odd integer multiple of one-half a wavelength of the radiated energy, all of the radiating slots on one side of said line having a distance from said common point differing from the distance from said common point differing from the distance from said center of all radiating slots on the other side of said line, a second conductive plate spaced from said first plate so as to form a circular symmetrical waveguide, and means coupled to said waveguide for exciting a single wave energy mode therewithin that will excite said slots whereby electromagnetic energy will be radiated therefrom along said axis.

4. A radiator for radiating a beam of electromagnetic energy along a radiation axis, said radiator comprising a first conductive plate disposed normal to said radiation axis and having a plurality of elongated radiating slots therethrough, all of the slots through said plate forming a pattern that is asymmetrical about a line extending diametrically across said plate and intersecting said radiation axis, said pattern including a first row of slots disposed on one side of said line and a second row of slots disposed on the other side of said line, all of the slots in said first row having the geometric centers thereof disposed a uniform distance from the intersection of said axis and said line, all of the slots having the centers thereof disposed said uniform distance from said intersection being disposed on the same side of said line as said first row, all of the slots in said second row being disposed a common distance from said intersection, all of the slots disposed said common distance from said intersection being disposed on the same side of said line as said second row, said common distance and said uniform distance differing from each other by an odd multiple of one-half a wavelength of the radiated energy, all of the radiating slots on one side of said line having a distance from said intersection differing from the distance from said intersection of all the radiating slots on the other side of said line, the long dimensions of each of said slots being oblique to the radius extending between the geometric center of the slot and said intersection, a second conductive plate spaced from said first plate to form a waveguide symmetrical about said radiation axis, means coupled to said waveguide for exciting a single wave energy mode therewithin that will excite said slots whereby electromagnetic energy will be radiated therefrom along said axis.

5. A radiator for radiating a beam of electromagnetic energy along a radiation axis, said radiator comprising a first conductive plate disposed normal to said axis and having a plurality of elongated radiating slots therethrough, all of said slots forming a pattern that is asymmetrical about a line extending diametrically across said plate and intersecting said radiation axis, said pattern including a first group of slots and a second group of slots, all of the slots in said first group forming semicircular rows that are disposed entirely on one side of said line and concentric about the intersection of said line and said axis, all of the slots in said second group forming semicircular rows that are disposed on the other side of said line and are concentric about said intersection, all of the geometric centers of the slots in any given row being disposed at a predetermined radius from said intersection, all of the slots disposed at a given radius from said center being disposed on the same side of said line, the longest dimensions of one-half of the slots in each row intersecting the radius through the geometric center of the slot at a positive 45 degree angle, the longest dimensions of each of the remaining half of the slots intersecting the radius through the geometric center thereof at a negative 45 degree angle, the radius of any given row differing from the radius of any given row in the other group by an odd integer multiple of one-half a wavelength of the radiated energy, and means coupled to said plate for inducing a predetermined current therein for exciting said slots whereby a beam of electromagnetic energy will be radiated along said axis.

6. A radiator for radiating a beam of electromagnetic energy along a radiation axis, said radiator comprising a first conductive plate disposed normal to said axis and having a plurality of radiating apertures therethrough, all of the apertures through said plate forming a pattern that is asymmetrical about a line extending diametrically across said plate and intersecting said axis, said pattern including a first row of apertures and a second row of apertures, all of the apertures in said first row being disposed a uniform distance from said intersection, all of the apertures disposed said uniform distance from said intersection being disposed on one side of said line, all of the apertures in said second row being disposed a common distance from said intersection, all of the apertures disposed said common distance from said intersection disposed on the opposite side of said line, said common distance and said uniform distance differing from each other by some predetermined amount, all of the radiating apertures on one side of said line having a distance from said intersection differing from the distance from said intersection of all of the radiating apertures on the other side of said line, a second conductive plate having a conical shape juxtaposed to said first plate for forming a conical waveguide symmetrical about said radiation axis, and means coupled to said waveguide for exciting a single wave energy mode therewithin that will excite said apertures whereby a beam of electromagnetic energy will be radiated along said axis.

7. A radiator for radiating a beam of electromagnetic energy along a radiation axis, said radiator comprising a first conductive plate disposed normal to said axis and having a plurality of elongated radiating slots therethrough, all of said slots forming a pattern that is asymmetrical about a line extending diametrically across said plate and intersecting said radiation axis, said pattern including a first group of slots and a second group of slots, all of the slots in said first group forming semicircular rows that are disposed entirely on one side of said line and concentric about the intersection of said line and said axis, all of the slots in said second group forming semicircular rows that are disposed on the other side of said line and are concentric about said intersection, all of the geometric centers of the slots in any given row being disposed at a predetermined radius from said intersection, all of the slots disposed at a given radius from said center being disposed on the same side of said line, the longest dimensions of one-half of the slots in each row intersecting the radius through the geometric center of the slot at a positive 45 degree angle, the longest dimensions of each of the remaining half of the slots intersecting the radius through the geometric center thereof at a negative 45 degree angle, the radius of any given row differing from the radius of any given row in the other group by an odd integer multiple of one-half a wavelength of the radiated energy, a second conductive plate having a conical shape juxtaposed to said first plate for forming a conical waveguide symmetrical about said radiation axis, and means coupled to said waveguide for exciting a wave energy mode therewithin that excites said slots whereby a beam of electromagnetic energy will be radiated along said axis.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 2,929,064 March 15, 1960

Kenneth C. Kelly

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 7, line 9, strike out "from said common point differing from the distance".

Signed and sealed this 23rd day of August 1960.

(SEAL)
Attest:
KARL H. AXLINE
Attesting Officer

ROBERT C. WATSON
Commissioner of Patents