

July 18, 1961

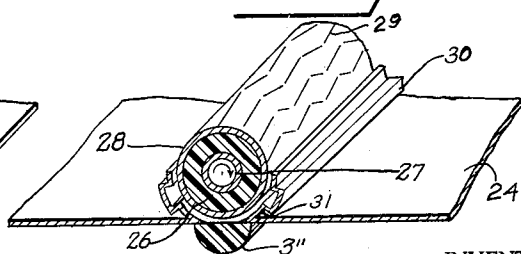
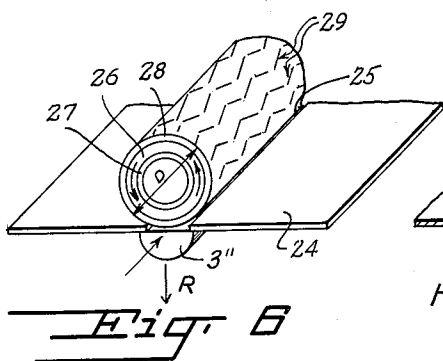
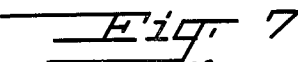
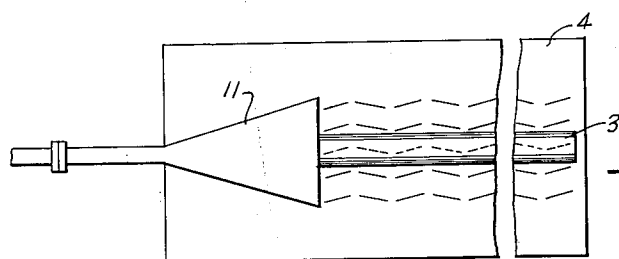
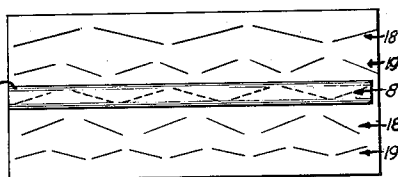
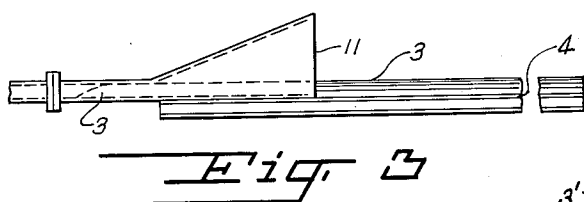
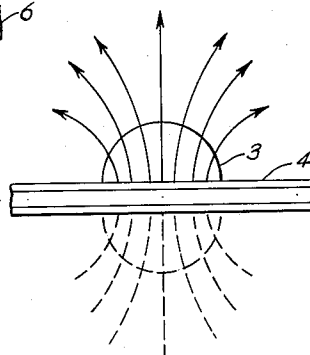
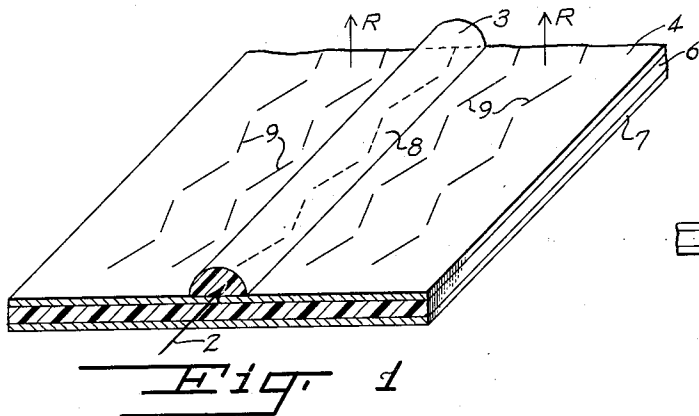
H. W. COOPER

2,993,205

SURFACE WAVE ANTENNA ARRAY WITH RADIATORS FOR
COUPLING SURFACE WAVE TO FREE SPACE WAVE

Filed Aug. 19, 1955

2 Sheets-Sheet 1



INVENTOR
Herbert Warren Cooper

Max L. Libman

BY

ATTORNEY

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H. W. COOPER

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2 Sheets-Sheet 2

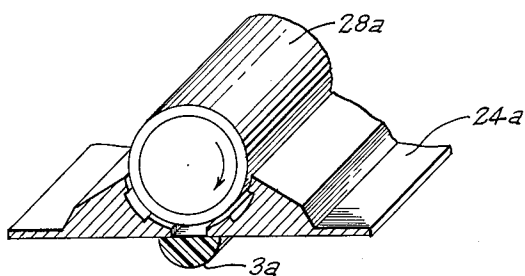


Fig. 7A

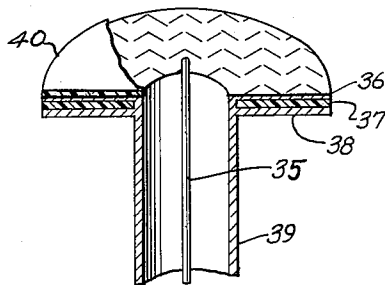


Fig. 7B

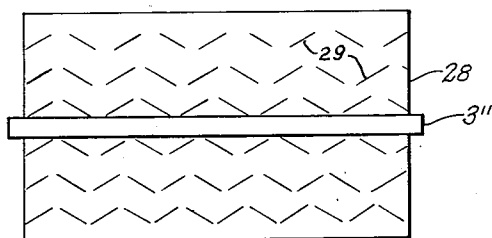


Fig. 10

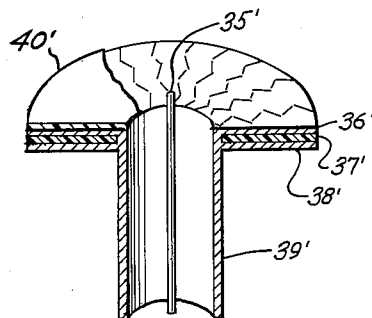


Fig. 8

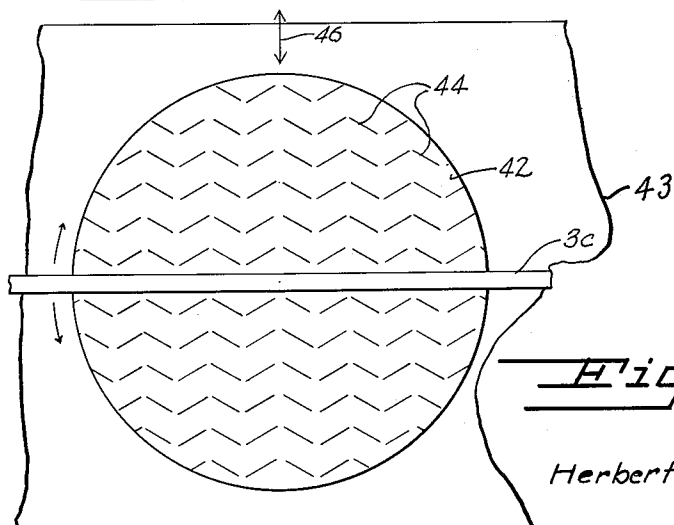


Fig. 11

INVENTOR

Herbert Warren Cooper

Max L. Libman

BY

ATTORNEY

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2,993,205

SURFACE WAVE ANTENNA ARRAY WITH RADIATORS FOR COUPLING SURFACE WAVE TO FREE SPACE WAVE

Herbert Warren Cooper, West Hyattsville, Md., assignor to Litton Industries of Maryland, Incorporated, a corporation of Maryland

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17 Claims. (Cl. 343-771)

This invention relates to high frequency antennas and particularly to microwave antennas employing a surface wave feed.

A major object of my invention is to provide a very efficient directional microwave antenna which is adaptable to printed circuit techniques. Printed circuit techniques have aroused great interest in recent years because of their obvious advantages from a tolerance and mass production standpoint. Most of the prior approaches to printed antennas have utilized more or less conventional techniques which are reproduced in printed or photo-etched circuit form. On the other hand, most of the surface wave antenna approaches have used corrugated surfaces with variations in the corrugations to effect a suitable character to the radiated pattern. The corrugations extend either the full width of the array or are in the form of concentric rings around a directional or omnidirectional exciting source. The present invention provides a new approach to which printed circuit techniques are applicable and which has wide application to the problem of antenna arrays and particularly to the problem of flush mounted antennas for aircraft.

According to a preferred form of the invention, the antenna array is fed by a dielectric line and particularly by a dielectric image line used as the transmission line to excite an array of a large number of slots in the ground plane of the dielectric image line. The dielectric image line, as reported for example by D. D. King in Journal Applied Physics, vol. 23, page 699, June 1952, is essentially a dielectric rod used as a waveguide on a conducting surface, the image plane, which may serve as the mechanical support for the dielectric line. It is a known advantage of the image plane that it replaces half the rod and surrounding space and so reduces the required cross section by one-half as well as largely eliminating mechanical support and shielding problems; according to the invention, further advantage is taken of the necessary presence of the ground plane to form an essentially two dimensional antenna array which is excited at high efficiency by the dielectric waveguide. A further advantage is that problems of feeders to separate antenna elements are also entirely eliminated. Still another advantage is that highly accurate antenna arrays of very close tolerance can be quickly and inexpensively reproduced.

The single dielectric image line may be utilized to excite arrays of about any desired length, which is a further advantage of the invention. Because the image line field extends over a large area transverse to the direction of the image line, either linear or mattress arrays may be excited by the image line. By suitable choice of and orientation of discontinuities the maximum of radiation may be directed at any angle in space not included in the image plane.

With the conventional methods, for example, the ordinary single mode waveguide excited slot or dipole array, a line source may be provided, but an array of these sources is required in order to provide the effective aperture in the other plane. At high microwave frequencies the problems of close tolerances required plus increasing losses render the conventional approaches impractical.

A further advantage of the invention as compared with

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the waveguide excited array lies in the fact that on a sufficiently small dielectric line there is essentially no dispersion with frequency, that is, the energy on the dielectric line propagates at essentially the velocity of free space propagation. Specifically, measurements at X-band on an array made in accordance with the invention indicate a velocity of propagation greater than 99 percent with a dielectric of moderate size (0.500" wide by 0.125" thick). With a dielectric of smaller cross section, the velocity of propagation would be even higher and the illumination in the transverse direction would be more uniform.

Another advantage that accrues to the dielectric image line antenna is that of flush mounting on aircraft surfaces. For example, it is possible to provide a total depth of array no greater than approximately 0.20 inch for the antenna plus feeder line, on the basis of experimental models, and it appears certain that much smaller dimensions could be obtained.

According to the invention, an array of slots or other electrical discontinuities on the central line of the dielectric waveguide may be provided, for example, by photo-etching in the image plane of a dielectric image line; secondary arrays may also be etched in the image plane symmetrically on both sides of the primary array or otherwise at suitable distances and spacings to produce a desired directional characteristic. As these secondary arrays also lie in a region of high field intensity produced by the dielectric line, there is good coupling and highly efficient antenna is thus produced.

It is also within the scope of the invention to use arrays of slots in a dielectric covered ground plane fed by the surface wave supported by this dielectric. The surface wave may be excited in the dielectric by terminating a conventional coaxial line in a radiating probe which will provide one means of launching a surface wave in the dielectric on the ground plane. By suitable disposition of the slots, this array can be made to radiate maximum energy normal to or almost parallel to the ground plane.

The specific nature of the invention, as well as other objects and advantages thereof, will clearly appear from a description of a preferred embodiment as shown in the accompanying drawings, in which:

FIG. 1 is a schematic diagram illustrating the principle of the invention;

FIG. 2 is an explanatory diagram illustrating the field distribution in a dielectric image line;

FIG. 3 is a side view of an antenna similar to that shown in FIG. 1, showing a method of supplying energy to the antenna;

FIG. 4 is a front view of the antenna shown in FIG. 3;

FIG. 5 is a front view of a broad band antenna array according to the invention;

FIG. 6 is a perspective view of a scanning type antenna according to the invention;

FIG. 7 is a sectional view of the same type of antenna shown in FIG. 6, with means for coupling it to a metallic panel;

FIG. 7A illustrates a modification similar to FIG. 7;

FIG. 8 illustrates a center-fed array according to the invention with parallel rows of slots;

FIG. 9 illustrates a similar center-fed array with radial rows of slots;

FIG. 10 is a developed view of the cylindrical antenna surface of FIG. 6; and

FIG. 11 illustrates a modified scanning antenna.

Referring to FIG. 1, microwave energy, for example in the K-band, is fed from any suitable source in the direction of the arrow 2 along dielectric rod 3 shown as having a semicircular cross section, although it will be understood that other cross sections may also be used

as described in the King article cited above. Rod 3 is located on and preferably in contact with image plane 4, which may be a sheet of any suitable conducting material. In practice, the image plane may be a thin layer of copper clad or deposited on heavier dielectric sheet 6, which provides the desired mechanical rigidity in a light weight, low cost structure and which lends itself readily to photo-etching of the metal surface 4. Where unidirectional radiation is desired, the other side 7 of sheet 6 may also be copper clad, thus providing a reflecting surface, which is required for unidirectional radiation only if the slots provide apertures completely through the sheet. In an apertured sheet without the reflecting surface, a bidirectional radiation occurs in which identical beams are radiated into both hemispheres. Alternatively, the slots may be photo-etched or otherwise fabricated in a thicker sheet of metal to a depth suitable for adequate coupling to the image line wave. This technique is applicable to antennas in the extremely high frequency band.

A primary antenna array of slots 8 is etched or otherwise fabricated in the material of image plane 4, each slot being one-half wavelength in length and the centers of the slots also spaced one-half wavelength apart. It will be understood that the slot sizes, slot configurations, spacing and arrangement shown are only exemplary and that other known spacings and arrangements, etc., may be employed.

Spaced on image plane 4 are parallel rows of secondary antenna arrays 9, similarly arranged to row 8. As indicated in FIG. 2, the semicircular dielectric rod 3 together with image plane 4 are equivalent to a full circular dielectric rod used as a waveguide, as is well understood. The type of array shown in FIG. 1 will produce a directional radiation pattern perpendicular to the image plane as indicated by the arrows R at the frequency for which the spacing between slots corresponds to one-half wavelength. The width of the beam will be determined largely by the number of rows of slots in the array. In practice, with the slots inclined at approximately 15° to the dielectric rod axis, and using six rows of slots on each side, each slot approximately $\frac{1}{8}$ inch wide, with sixteen slots in each row, a beam having a spread of 6° in the H-plane and 25° in the E-plane was radiated at right angles to the plane of array. The beam is radiated at right angles to the plane of the array only for the frequency for which the spacing between the centers of the slots in the direction parallel to the image line is one-half wavelength. If this spacing is greater than one-half wavelength, the radiated beam is tilted away from the launching horn, whereas, if the spacing between the slots is less than one-half wavelength the radiated beam is tilted towards the launching horn.

FIGS. 3 and 4 show one method of feeding the energy to the dielectric line by the use of a launching horn 11 conventionally fed from any suitable source of high frequency energy.

FIG. 5 shows a broad-band antenna arrangement according to the invention. For certain applications, one disadvantage of the simple ended surface wave type of array, as shown in FIG. 1, lies in the fact that the direction of the beam maximum in the direction of propagation of the energy on the dielectric image line shifts with frequency. That is, for alternate elements reversed in phase the beam is normal to the dielectric image line only for the frequency at which the spacing between the elements of the array is 180° . This limitation can be removed by including in close proximity several sets of slots dimensioned and spaced for different frequencies. In FIG. 5 the center rows of slots 8' are spaced for the mean frequency of the band to be radiated. The rows of slots 18, 18', etc., are dimensioned and spaced for lower frequencies and the rows of slots 19, 19', etc., are dimensioned and spaced for higher frequencies than that of row 8'.

At the frequency for which the slot spacing of row 8' is one-half wavelength, and the slot is a resonant length there is greatest coupling to the energy in the dielectric image line 3', and the principal portion of the energy of the band will thus be coupled into slot array 8' and be radiated at right angles from this array. In a similar fashion, energy in the dielectric image line at a somewhat higher and a somewhat lower frequency, corresponding to arrays 18 and 19 respectively, will be coupled to these arrays most effectively for radiation. In each case, the effect of the other rows of slots designed for slightly higher and slightly lower frequency will be to provide a slightly broader beam than for a single frequency array. Additional rows of slots 18' and 19', spaced respectively for still lower and higher frequencies, may be added to further increase the bandwidth or to otherwise modify the shape of the frequency or directional response curve of the antenna.

Optimum performance of the array over a particular frequency band may be obtained by adjusting the slot width to obtain a Q of the individual slot that is appropriate for the bandwidth under consideration.

FIG. 6 shows how a scanning type of radiated beam may be obtained, for example, a beam whose major direction is oscillated back and forth over an angle in a plane containing the image line so as to scan the sector included in that angle. Dielectric rod 3'' is excited as before with energy in the direction of the arrow. In this case, the ground or image plane may be a conducting sheet 24 sufficiently rigid and stiff to be self-supporting. The transverse dimensions of the sheet may be varied to cause shaping of the beam of radiated energy in the plane transverse to the image line. Directly opposite the rod 3'', however, there is a long axial slot 25 in the image plane. Extending into this slot but just out of contact with the image plane or the dielectric rod 3'' is a cylinder arranged for rotation about its axis by suitable mechanical means not shown. The cylinder may take either of two forms: first, it may be a metal cylinder with slots etched to a suitable depth in the metal, or, second, it may be a composite cylinder as shown comprised of an outer conducting coating of thin metal 28, a dielectric cylinder 26 and then an inner conducting coating of metal 27 to act as a reflector for the slots in the outer conducting coating. The outer conducting coating 28 is provided with axially extending rows of slots 29. These rows of slots are not uniformly spaced as in FIG. 1, but are as shown in FIG. 10. FIG. 10 represents a developed view of the cylinder and it is seen that the spacing between slots in the direction of propagation of energy on the dielectric line increases uniformly as the surface of the cylinder moves along a circumference. The variation in the slot-spacing will cause the direction of maximum radiated energy to vary away from the direction of the exciting source (considering the antenna as a transmitting antenna) as the spacing between slots increases. It is seen that, as the cylinder rotates, the direction of the radiated beam gradually moves from one extent of its scan to the other and then snaps back to its initial position and retraces the scan corresponding to a sawtooth scan. Other types of scan are possible, of course, with different variations in the slot pattern. Any reference to considering the antenna as a transmitting antenna is merely for the sake of illustration because, by the reciprocity theorem, the performance of the antenna as a receiving antenna is identical with that as a transmitting antenna with the exciting source replaced by the receiving source, and so on. Other details shown in FIG. 7A include a choke or contact finger arrangement to prevent the occurrence of undesired currents in the transverse plane on the under side of the ground plane 24a.

In FIG. 7, the ground plane 24 may be the metal skin of an airplane, on the outer side of which is dielectric rod 3'', as before, while on the inside is rotating cylinder

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surface 28 bearing slots 29, as in FIG. 6. In order to secure more effectively coupling to the ground plane, a broad band choke, consisting of quarter wavelength high impedance and low impedance sections 30, 31, respectively, in tandem, is provided to produce an effective short circuit connection to shunt the undesired transverse currents, as will be understood. The space between 30, 31, and the ground plane 24 may be filled with dielectric material, or may be an air space as shown. FIG. 7A shows a solid metallic version of the same concept.

FIG. 8 shows another form of antenna array according to the invention wherein a stub 35 is used to excite an array of slots arranged in a conducting plane 36 which may be either a solid metal sheet with slots etched to a suitable depth in it or which may be a thin metallic plane supported on a thin dielectric sheet or panel 37 backed by an additional ground plane 38. The ground plane 36 may be connected to the outer braid of a coaxial cable, sub 35 being coupled to the inner conductor of the coaxial cable. A surface wave is permitted to exist in a radial fashion over the ground plane by the presence of a thin dielectric sheet 40 over the top of the conducting plane 36. The probe 35 acts as a transducer to convert the TEM energy in the coaxial line to the radial cylindrical surface waves propagating on the surface of the ground plane. Other more efficient transducers may be used. By a suitable disposition of the slots in the conducting plane 36, the radiated field may take a variety of forms one of which is a pancake shaped field essentially circular in character with the probe as the axis of the pancake, in which case the maximum of radiation is nearly at right angles to the probe. By another arrangement of slots, as shown in FIG. 9, the maximum of radiation will be in the direction collinear with the probe. Also, by appropriate slot arrangement, the radiated polarization may be linear or circular. It will be understood that, in all cases in which the slots are inserted in a thin conducting sheet 36, the ground plane 38 is spaced from the plane of the slots by the thickness of the insulation. Mode suppressors may be required between the thin conducting sheet 36 and the ground plane 38 to prevent the propagation of undesired modes in this region. In this case and the previously discussed cases, the ground sheet 38 is effective as a reflector to keep the beam essentially unidirectional without introducing any other disturbances.

FIG. 11 shows another form of scanning arrangement. In this case, the dielectric line 3c passes over but out of contact with a circular conductive section 42 arranged to be rotated or oscillated in the ground plane 43. Arrays of slots 44 are provided in the circular section, and as section 42 rotates about its center, the radiated beam perpendicular to the ground plane will scan in a direction normal to the image line, as generally indicated by double-headed arrow 46.

It will be apparent that the embodiments shown are only exemplary and that various modifications can be made in construction and arrangement within the scope of my invention as defined in the appended claims.

I claim:

1. A directional microwave antenna comprising: means for providing a substantially smooth conducting surface; means for propagating a surface wave over said surface; and means including a plurality of electrical discontinuities arrayed in two dimensions in said surface for intercepting a portion of the energy in a surface wave propagating over said surface and radiating the intercepted energy in a direction having a vectorial component normal to said conducting surface, the size and position of said discontinuities relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

2. A directional microwave antenna comprising: a sheet of conducting material; means for launching a surface wave over said sheet; means for supporting and

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propagating a surface wave over said sheet; means including a plurality of electrical discontinuities arrayed in two dimensions in said sheet for intercepting at least a portion of the energy in a surface wave propagating over said sheet and for radiating intercepted energy in a direction having a vectorial component normal to said conducting sheet, the size and position of said discontinuities relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam, said sheet having slots extending completely through the sheet to form said discontinuities; and means providing a reflecting surface adjacent one side of said sheet.

3. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a dielectric element positioned adjacent said sheet for propagating a surface wave on said sheet; and means including a plurality of electrical discontinuities arrayed in two dimensions in said sheet for intercepting a portion of the energy in a surface wave propagating over said sheet and radiating the intercepted energy in a direction having a vectorial component normal to said conducting sheet, the size and position of said discontinuities relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

4. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a dielectric element positioned adjacent said sheet for propagating a surface wave on said sheet; and means forming a plurality of slots arrayed in two dimensions in said sheet, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

5. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a dielectric element positioned adjacent one side of said sheet for propagating a surface wave on said sheet; and means including a plurality of apertures in said sheet for intercepting a portion of the energy in a surface wave propagating over said sheet and radiating intercepted energy in a direction having a vectorial component normal to said sheet, each of said apertures being bounded by said sheet.

6. A directional microwave antenna comprising: a first sheet of conducting material having a relatively extensive area and substantially smooth first and second surfaces; a sheet of dielectric material having first and second sides, said first side of said dielectric sheet being positioned adjacent to said first surface of said first conducting sheet; a second sheet of conducting material positioned adjacent to said second side of said dielectric sheet; means including a dielectric element positioned adjacent said second surface of said first conducting sheet for propagating a surface wave on said sheet; and means forming a plurality of apertures in said first conducting sheet, each of said apertures being bounded by said sheet and being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said first conducting sheet.

7. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a substantially linear dielectric rod positioned adjacent said sheet for propagating a surface wave on said sheet; and means forming a plurality of slots arrayed

in two dimensions in said sheet, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

8. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a linear dielectric rod positioned adjacent said sheet for propagating a surface wave on said sheet; and means forming a plurality of slots arrayed in two dimensions in said sheet, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam, each of said slots being inclined at an angle to the axis of said dielectric rod.

9. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a linear dielectric rod positioned adjacent said sheet for propagating a surface wave on said sheet; means forming a plurality of slots arrayed in two dimensions in said sheet, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam; and means for rotating said sheet in its own plane with respect to said rod.

10. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a thin dielectric sheet positioned adjacent said conducting sheet for propagating a surface wave on said conducting sheet; and means forming a plurality of slots arrayed in two dimensions in said conducting sheet, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said conducting sheet and to radiate intercepted energy in a direction having a vectorial component normal to said conducting sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

11. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a dielectric element positioned adjacent said sheet for propagating a surface wave on said sheet; and means forming a plurality of slots arrayed in two dimensions in said sheet, the centers of said slots lying in a plurality of rows and a plurality of columns, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

12. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a dielectric element positioned adjacent said sheet for propagating a surface wave on said sheet; and means forming a plurality of slots arrayed in two dimensions in said sheet, the centers of said slots lying in

a plurality of rows and columns which are substantially at right angles to each other, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

13. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a dielectric element positioned adjacent said sheet for propagating a surface wave on said sheet; and means forming a plurality of slots arrayed in two dimensions in said sheet, the centers of said slots lying in a plurality of rows and a plurality of columns, each of said columns lying along a circle having a center common to and a radius different from that of every other column, and said rows extending radially from said center, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

14. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a dielectric element positioned adjacent said sheet for propagating a surface wave on said sheet; and means forming a plurality of slots arrayed in two dimensions in said sheet with their centers lying along a plurality of unequally spaced rows, each of said rows including a plurality of slots equally displaced with respect to each other, each of said slots being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said slots relative to each other being a function of the frequency of the microwave energy which is radiated and the characteristics of the radiated beam.

15. A directional microwave antenna comprising: a sheet of conducting material having a relatively extensive area and a substantially smooth surface; means including a dielectric element positioned adjacent one side of said sheet for propagating a surface wave on said sheet; means forming a plurality of apertures extending completely through said sheet, each of said apertures being bounded by said sheet and being operative to intercept a portion of the energy in a surface wave propagating over said sheet and to radiate intercepted energy in a direction having a vectorial component normal to said sheet; and means providing a reflecting surface adjacent a side of said sheet other than said one side.

16. In a directional microwave antenna, means providing a conductive surface having a relatively extended surface, means including a dielectric element positioned in proximity with said surface for propagating a surface wave on said surface, and means including a plurality of discontinuities arrayed in two dimensions on said surface for intercepting at least a portion of the energy in a surface wave propagating over said surface and radiating the intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said discontinuities relative to each other being a function of the frequency of microwave energy and the desired characteristics of the radiated beam.

17. In a directional microwave antenna, means providing a conductive surface having a relatively extended surface, means including a dielectric element positioned in proximity with said surface for propagating a surface wave on said surface, and means including an array of

discontinuities in said surface for intercepting at least a portion of the energy in a surface wave propagating over said surface and radiating the intercepted energy in a direction having a vectorial component normal to said sheet, the size and position of said discontinuities relative to each other being a function of the frequency of microwave energy and the desired characteristics of the radiated beam.

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