

Aug. 4, 1959

J. RUZE

2,898,593

ANTENNA ARRAY FOR COUNTERACTING THE EFFECT OF NULL REGIONS

Filed April 12, 1954

4 Sheets-Sheet 1

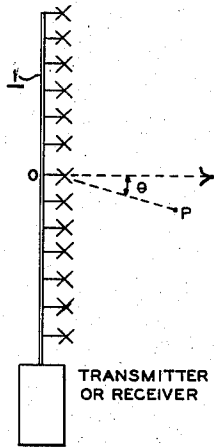


Fig. 1

PRIOR ART

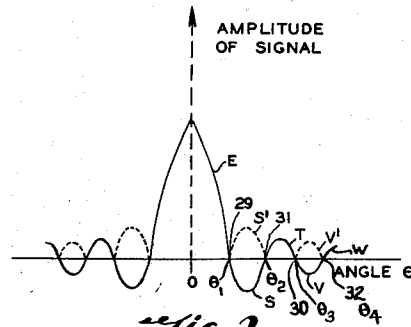


Fig. 2

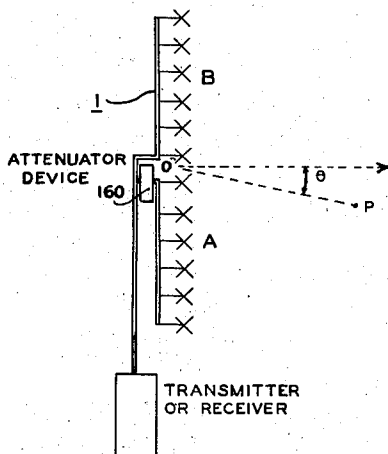


Fig. 3

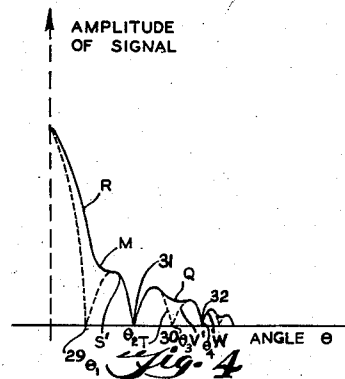


Fig. 4

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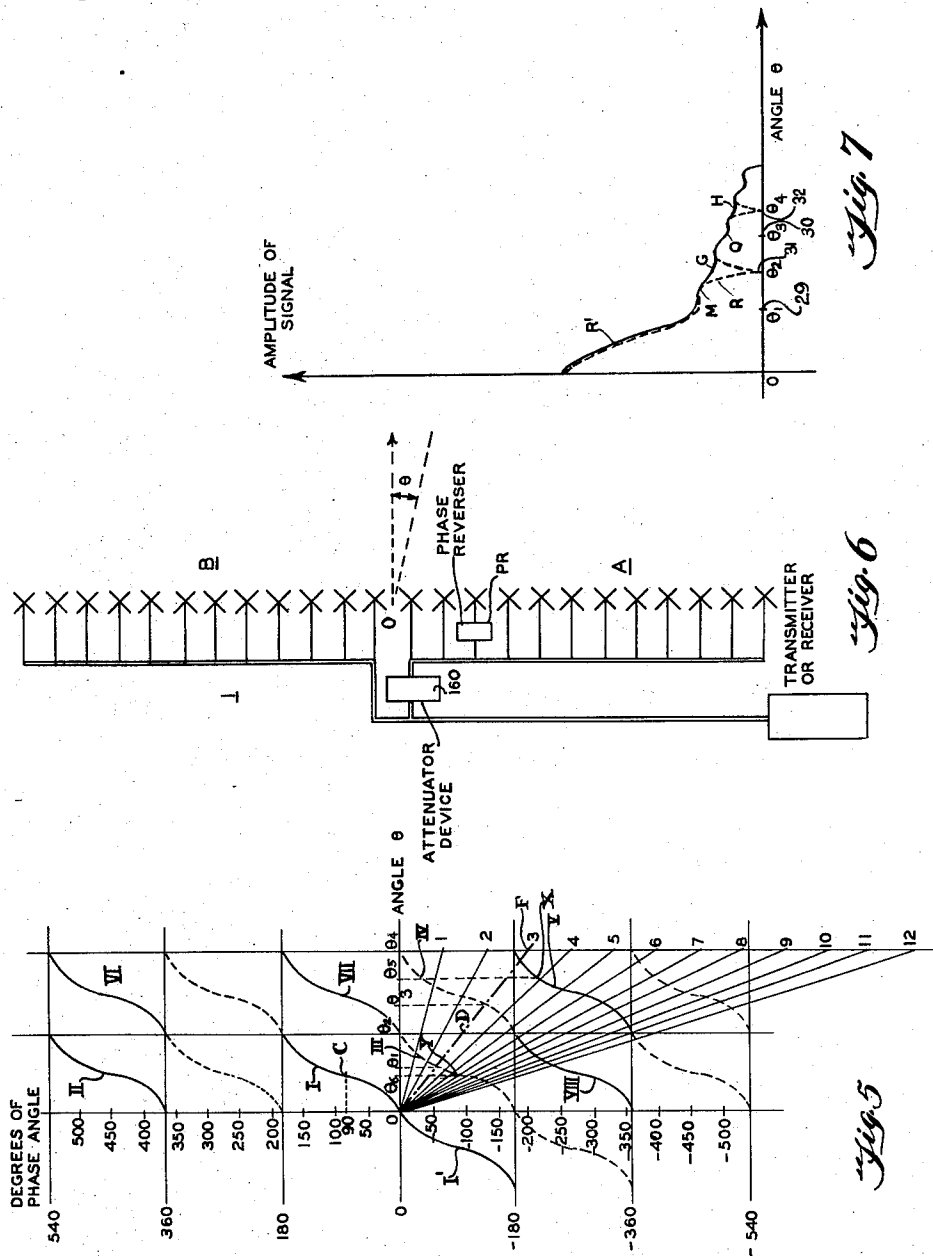
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4 Sheets-Sheet 2



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4 Sheets-Sheet 3

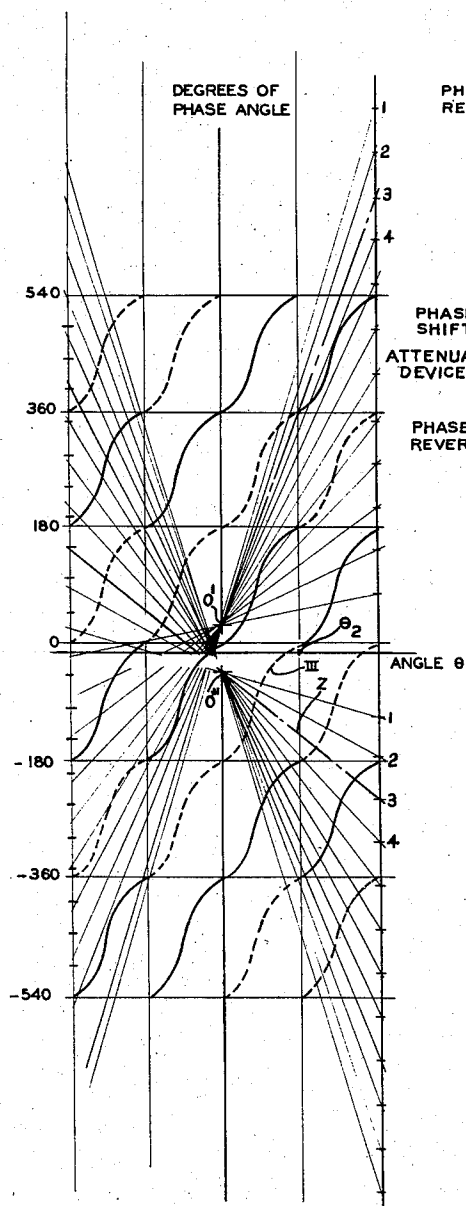


Fig. 8

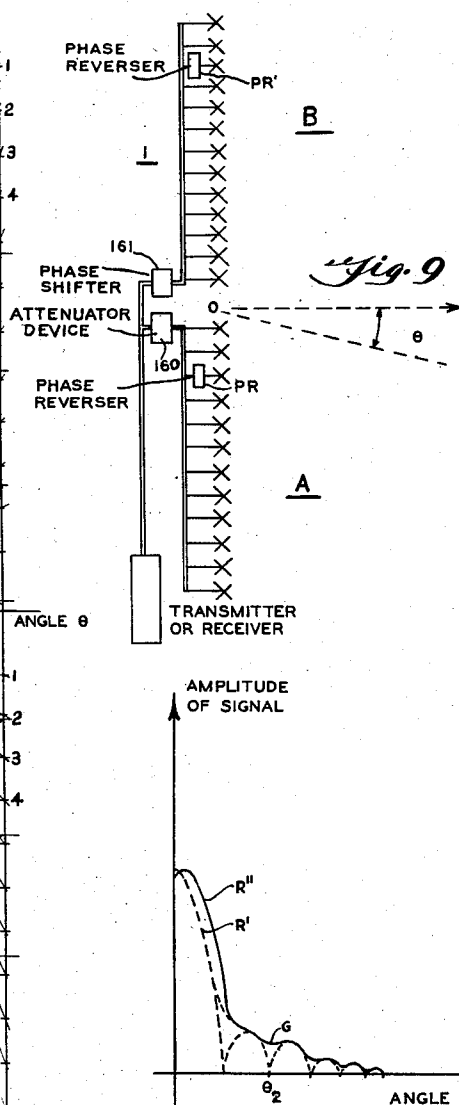


Fig. 10

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4 Sheets-Sheet 4

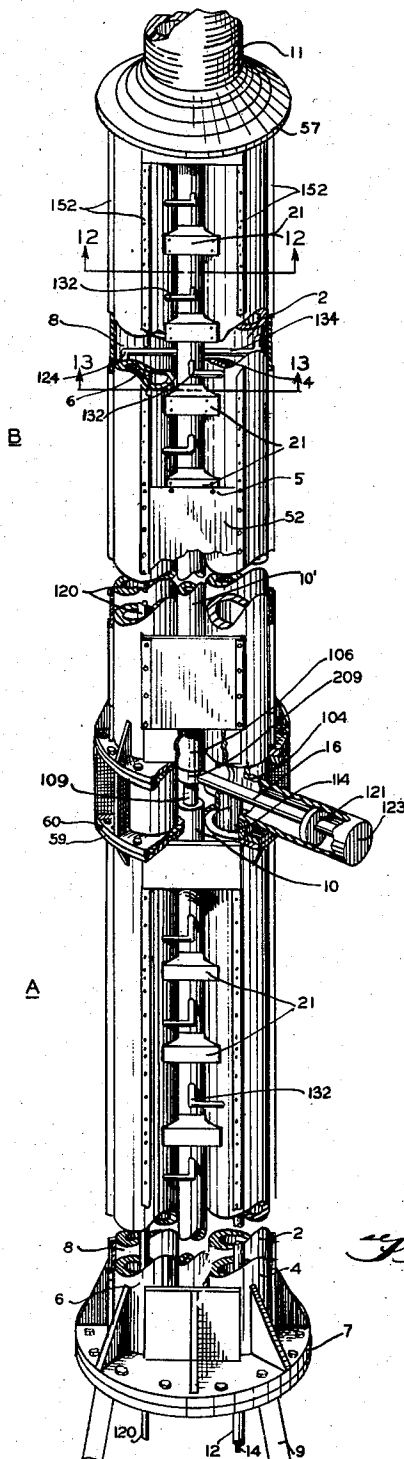


Fig. 11

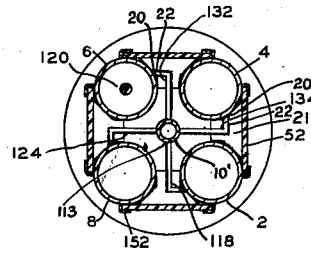


Fig. 12

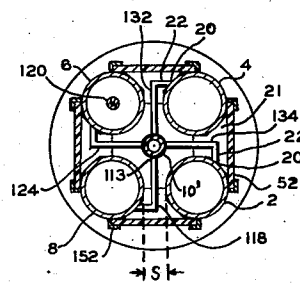


Fig. 13

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2,898,593

ANTENNA ARRAY FOR COUNTERACTING THE EFFECT OF NULL REGIONS

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Application April 12, 1954, Serial No. 422,524

17 Claims. (Cl. 343—853)

The present invention relates to antennas and methods of operating the same and more particularly to antenna structures particularly adapted for use in the ultra-high-frequency range.

In the broadcast or reception of radio waves by antennas located at predetermined points above the earth's surface, discontinuities in the radiation pattern or coverage of the antenna frequently introduce complications. A transmitting antenna, for example, is generally incapable of transmitting radiation uniformly at all angles of elevation in the vertical plane. The radiation pattern, to the contrary, is discontinuous, there being a principal direction of maximum radiation, termed the principal or main "lobe," and a plurality of secondary directions along which successively less quantities of radiation are produced, termed "secondary lobes." Between the successive lobes or directions of radiation transmission, in the vertical radiation pattern of the antenna, so-called "null regions" exist where substantially no radiation at all is transmitted. In those areas along the ground where the vertical-radiation pattern of the antenna has a null region, therefore, no signals can, of course, be received. This provides a serious obstacle to broadcasting stations. The same remarks apply, of course, to the discontinuities in the radiation-reception patterns of receiving antenna systems.

Various techniques have accordingly been evolved for attempting to obviate this difficulty. One proposal involves tilting the antenna to effect a corresponding tilt in the vertical-radiation pattern thereof in order to direct a radiation lobe to cover an otherwise blind spot. Such tilting technique, while it may serve to effect the propagation of some radiation at a place where a null previously existed, does not, however, actually eliminate the nulls between the lobes of the radiation pattern. It merely changes the direction of orientation of the lobes. A second proposal for counteracting the effect of null regions involves the employment in the antenna system of a further supplemental non-directional antenna, sometimes located centrally of the antenna system, to produce at least some radiation in the null regions of the antenna system. Not only does this proposal require careful adjustments, additional radio-frequency feed lines and phase-shifting networks, but the energy that is used up in the supplemental antenna represents energy that would otherwise have been available for the antenna system itself.

In the microwave field, this problem has been somewhat overcome by shaping the antennas and reflectors so as to produce vertical-radiation patterns that substantially follow a so-called cosecant-squared law. At broadcast frequencies, whether for radio, television or other purposes, however, to space antennas non-uniformly and to arrange complicated feeding devices in order to effect such a cosecant-pattern would be prohibitively complicated, expensive and impractical.

A very successful solution to a particular phase of this problem is described in a copending application of John Ruze, Serial No. 341,231, filed March 9, 1953, in accord-

2

ance with which the amplitude of the voltage fed to successive sets of antenna elements in, for example, a vertical antenna array is varied in steps of successively increasing amplitude. This, as later explained, has been found partially to fill in the null regions in the vertical-radiation pattern. This proposal is extremely useful, also, where it is only desired to fill in, say, the first, third and fifth null regions in the vertical-radiation pattern. The successive steps of increasing amplitude, as explained in the said copending application, may then be two in number.

Occasions have arisen, however, where it is necessary, also, to provide radiation in the second and fourth nulls. It would again be theoretically possible to effect such a result with intricate phasing networks or supplementary antennas or other complexities. In accordance with the present invention, on the other hand, the problem of filling in the second and fourth null regions has been solved with but a single minor mechanical change in the antenna system.

From a more particular aspect, an object of the present invention is to provide a new and improved method of altering the resultant radiation pattern of an array of similarly phased antenna elements at any predetermined angle off the radiation axis of the array. This result is effected through the selection of that antenna element of the array that, of itself, would transmit or receive radiation in a phase having a particular predetermined phase relation to the phase of the resultant radiation transmitted or received by the antenna array at the said angle. It is then merely necessary to effect a simple mechanical change, such as the reversal of the connections to or from the thus selected antenna element, to achieve the desired result.

A further object of the present invention is to provide a novel antenna and a method of operating the same in accordance with which the radiation at any predetermined angle may be increased by the mere reversal of phase of the feed to or from one particular antenna element of the array.

An additional object is to provide an antenna and a method of operating the same in accordance with which the radiation transmitted or received by the array at any predetermined angle may be decreased by the sole expedient of reversing the phase of the feed of a different particular antenna element of the array.

Other and further objects will be hereinafter explained and will be more particularly pointed out in the appended claims.

The invention will now be described in connection with the accompanying drawings—

Fig. 1 of which is a diagrammatic representation of a prior-art transmitting or receiving antenna array that is subject to the disadvantages obviated by the present invention;

Fig. 2 is a graph representing the variation of signal amplitude with angle in the vertical radiation pattern of the antenna of Fig. 1, and illustrating the detrimental null features before discussed;

Fig. 3 is a view similar to Fig. 1 illustrating a technique for partially filling in some of the nulls in the radiation pattern of Fig. 2;

Fig. 4 is a graph similar to Fig. 2, illustrating the vertical radiation pattern of the antenna of Fig. 3;

Fig. 6 is a diagram similar to Figs. 1 and 3, upon a somewhat larger scale, illustrating the application to the antenna array of Fig. 3 of the techniques of the present invention;

Figs. 5 and 7 are graphs illustrating, respectively, various phase and amplitude characteristics of the antenna system of Fig. 6;

Fig. 9 is a view similar to Fig. 6 of a modification;

Figs. 8 and 10 are graphs similar to Figs. 5 and 7, respectively, illustrating the phase and amplitude characteristics of the antenna system of Fig. 9;

Fig. 11 is a fragmentary perspective of a preferred embodiment of the present invention with parts being shown broken away to illustrate details of construction;

Fig. 12 is a section taken upon the line 12—12 of Fig. 11, looking in the direction of the arrows; and

Fig. 13 is a section taken upon line 13—13 of Fig. 11, looking in the direction of the arrows.

For purposes of illustration, the antenna elements of a vertically oriented antenna array 1 comprising a plurality of in-line uniformly fed and similarly phased antenna elements, are schematically represented in Fig. 1 by crosses. This representation is intended to connote that the antenna elements may take any desired form. They may, for example, be dipoles, linear elements, surface elements, wave guides, horns or slots, to mention but a few illustrations. In the case of television transmitting antennas, such an antenna array is customarily provided with antenna elements that are capable of radiating in all directions of azimuth. A preferred antenna of this character is later described in connection with the embodiment of Figs. 11 to 13. Though the horizontal radiation pattern may thus be substantially uniform, the vertical-plane radiation pattern is constituted of the lobes and nulls previously discussed. The center or axis of the antenna array 1 is represented by the dotted horizontal axis line O. Radiation is produced above and below the axis O at positive and negative angles of elevation θ . The variation of the amplitude or size of the radiation signal at points P located along angles θ from the axis O, may be plotted in graphic form to illustrate the nature of the vertical radiation pattern. Such a graph is shown in Fig. 2 where the amplitude of the signal is plotted along the dotted vertical ordinate line O, and the angle of elevation θ is plotted along the horizontal abscissa, labeled "Angle θ ." Negative angles θ , below the horizontal axis O in Fig. 1, are plotted in Fig. 2 to the right of the vertical ordinate line thereof, and the angles θ plotted to the left of the ordinate line of Fig. 2 represent positive angles θ above horizontal axis line O of Fig. 1. The solid-line curve E represents the variation of signal amplitude in the vertical plane along the different angles θ . It will be observed that maximum radiation occurs along the vertical ordinate O of Fig. 2, corresponding to the horizontal axis O of Fig. 1. This is the previously referred to principal or main lobe. For present purposes, it is sufficient to consider the radiation below the horizontal axis O of Fig. 1, or to the right of the ordinate in Fig. 2, since this is the radiation that is received at ground receiving stations. The discussion will hereinafter be limited, therefore, to this lower quadrant, although the remarks are equally applicable to the radiation in the upper quadrant above the radiation axis O.

At the point 29 in Fig. 2, the radiation pattern E drops to zero value. This point 29 represents the first angle θ_1 along which no radiation is transmitted by the antenna array 1. The amplitude of radiation then increases, in the opposite sense, providing the first secondary lobe S of radiation. A second null is produced at the angle θ_2 represented by the point 31. The radiation amplitude then again increases to provide a second secondary lobe T, and then a third null at an angle θ_3 represented by the point 30, after which the radiation again increases to provide a third secondary lobe V. The lobe V is followed by a fourth secondary lobe, part of which is shown at W, with a null 32 therebetween at angle θ_4 ; and so on, each successive lobe being of successively less signal amplitude. Instead of plotting the secondary lobes S and V below the horizontal abscissa axis, they may be equally well plotted above the abscissa for purposes of convenience, as shown by the dotted lobes S' and V', respectively, though it is to be understood that each time the

radiation pattern reaches the abscissa, as at 29, 31, 30 and 32, the phase of the radiation in the next following lobe changes by 180 degrees from the phase of the radiation of the preceding lobe. Thus the radiation in lobes E, T and W is all in the same phase, but it is, in turn, out-of-phase with the radiation in lobes S' and V'.

The prior-art transmitting or receiving antenna 1 of Fig. 1, therefore, inherently produces these undesirable null regions, 29, 31, 30, 32, etc. which provide blind spots in the radiation coverage.

By the before-mentioned expedient described in the said copending application, the lower section A of the array may be fed with a signal amplitude less than that applied to the upper section B, as with the aid of an appropriate transformer or attenuator device 160. The remarkable phenomenon that follows is illustrated in Fig. 4, where it will be observed that a new radiation pattern R is produced in the vertical plane that removes some of the nulls of the radiation pattern E of Fig. 2. In place of the null 29, the pattern R provides substantial radiation as shown at M. In place of the null 30, the pattern R provides radiation as shown at Q. But in the second and fourth null regions between the respective pairs of secondary lobes S' and T and V' and W, there still remain the nulls 31 and 32. As explained in the said copending application, this envelope R is entirely satisfactory for many purposes, particularly where the filling of the first null 29 is the only serious problem. Where, as before stated, however, continuous coverage is desired in the vertical radiation pattern with the type of antenna array 1 of Fig. 3, resort may be had to the techniques underlying the present invention to eliminate the second and fourth nulls 31 and 32. While, as before stated, one may obtain any desired radiation pattern by adding appropriate supplemental antennas or utilizing special phasing networks or other complicated equipment, in accordance with the present invention no such supplemental or complicated equipment is required. It is therefore in order to explain, first, the theory underlying the invention.

Referring to the graph of Fig. 5, the ordinate, labelled "Degrees of Phase Angle," plots the phase angle of the radiation from the antenna array 1 of, for example, Fig. 3, in units of degrees, ranging from 0 to 540 degrees. Along the abscissa, labelled "Angle θ ," the angle θ of elevation with respect to the radiation axis O of the antenna 1 is plotted. Any point in the graph, therefore, may be defined in terms of an angle θ off the axis O of the antenna 1, and a radiation phase angle along that angle θ . The S-shaped solid-line curves in Fig. 5 represent the nature of the variation in phase of the radiation transmitted by the complete antenna 1 with successively different angles θ of elevation. When the unequal upper and lower array feeding of Fig. 3 is not employed, as in Fig. 1, the S-shaped curve degenerates into a rectangular or step curve, not shown. Inspecting the S-shaped curve I, for example, it will be observed that at zero angle of elevation, $\theta=0$, the antenna 1 of Fig. 3 produces radiation of zero phase; that at successively increasing angles of elevation θ , the phase of the radiation produced by the antenna array 1, starts to increase along the S-shaped curve I, becoming 90 degrees at the center C of the S-shaped curve I, and then 180 degrees at the upper end of the S-shaped curve I. At the angle θ_2 , the radiation pattern reaches the abscissa axis, as shown in Fig. 4, where, as before stated, the phase of the radiation in the next lobe T changes or jumps through 180 degrees. This change is illustrated by the vertical phase-jump or phase-transition line between the upper point of the S-shaped curve I of Fig. 5 at coordinates θ_2 , 180, and the point at coordinates θ_2 , 360. From θ_2 to θ_4 , the radiation phase follows a further S-shaped curve VI. By the same token, the phase of the radiation decreases from zero to -180 degrees along a similar S-shaped curve I' for angles of elevation plotted to the left of the zero point

O of the graph. The curve I may also be represented by the S-shaped curve II shown plotted from a point along the ordinate labelled 360 degrees, upward to 540 degrees of phase angle. The curves I and II may really be considered as the same curve since they merely differ in starting and stopping points by 360 degrees, which is the same as zero degrees. By the same token, a whole family of S-shaped curves is plotted in Fig. 5 to represent the phase of the radiation produced by the antenna 1 at different angles of elevation off the radiation axis O of the antenna 1. The solid-line S-shaped curves may be supplemented, moreover, by dotted-line S-shaped curves, such as III and IV, which represent phase angles that are actually 180 degrees out of phase with the solid-line curves—so-called "out of phase" curves.

Superimposed upon the S-shaped curves of Fig. 5 is another family of phase curves comprising straight lines drawn from the origin O at successively different acute angles with respect to the abscissa, and numbered O-1, O-2, O-3 . . . O-12. These straight-line plots O-1 through O-12 represent the phase of the radiation that is produced by each of the antenna elements of the antenna array 1 by itself. Thus, for example, the straight-line curve O-1 represents the variation of phase of the radiation with varying angles θ that is produced by the first antenna element of the array 1. It will be observed that each of these individual straight-line curves O-1, O-2, O-3 . . . O-12 intersects one or more of the S-shaped curves. It is from certain points of intersection that information may be obtained on the basis of which to practice the present invention. This may best be illustrated by way of a specific example.

In Fig. 6, an antenna array 1 is shown comprising upper and lower sections A and B. For purposes of illustration, each section A and B is shown having twelve radiating or receiving antenna elements. The array 1 is otherwise of the same nature as shown in Fig. 3, having a resultant vertical radiation pattern R of the type shown in Fig. 4 and reproduced in dotted lines R in Fig. 7. This pattern R, as before described in connection with Fig. 4 is subject to the defect that it has a null 31 at a certain angle θ_2 and a further null 32 at the angle θ_4 . In accordance with the present invention, it is first necessary to determine which S-shaped curve is intersected near a predetermined region by one of the straight-line phase curves of Fig. 5 at the null angles θ_2 and θ_4 . Referring to Fig. 5, it will be evident that at the null angle θ_2 the straight-line phase curve O-3 intersects the vertical phase-jump or transition line between coordinates θ_2 , O and θ_2 , -180 at substantially its center or midpoint D. The point D has the coordinates θ_2 , -90, so that at this point of intersection D the phase is 90 degrees different from or in phase-quadrature with respect to the phase of the radiation at immediately adjacent angles just above and just below the angle θ_2 . The radiation at an angle just greater than the angle θ_2 , for example, has a phase angle of substantially 0 degrees, as shown at the left-hand end of the S-shaped curve VII. The phase at an angle just less than the angle θ_2 , however, is -180 degrees, as shown at the upper right-hand end of the S-shaped curve VIII. The phase at the point D is -90 degrees, which is 90 degrees different from or in phase-quadrature with the 0 and -180 degrees of phase at angles just above and just below the angle θ_2 .

It has been discovered that by selecting that particular antenna of the array the straight-line phase curve of which intersects the phase-jump or phase-change transition between successive S-shaped curves, preferably at substantially its center point, and by then reversing the phase of the voltage fed to that particular antenna of the array, radiation is provided at the null angle corresponding to the point of intersection. Thus, since the curve O-3 intersects the vertical phase-jump or transition between the S-shaped curves VIII and VII at the center region D, following the teaching of the present invention, it

is merely necessary to reverse the phase of the antenna number 3 down from the center of the array, corresponding to curve O-3, in order to provide radiation at the null angle θ_2 where the null 31 had previously existed. The phase reversal is shown effected in Fig. 6 by the device "PR," which may, in practice, entail merely reversing the transmission-line connections to the antenna element. By effecting such a phase reversal of the appropriately selected antenna, namely, number 3 in the example given, a new resultant vertical radiation pattern R' is produced, shown in solid lines in Fig. 7, providing radiation of amplitude G in the previous null region 31 at the angle θ_2 .

While the phase-quadrature relation of the radiation of the reversely fed antenna number 3 provides for the most effective null filling, if the antenna phase curve intersects the phase-jump or transition at a different intermediate point than the midpoint D, some null-filling radiation will still be produced. This is because the phase at the point of intersection will at least have a component that is in phase quadrature that can contribute to the null filling. Thus the line O-3 intersects the phase-jump line between coordinates θ_4 , -180 and θ_4 , -360 at an intermediate point F of phase angle of about -210 degrees. This phase angle differs from the phase angle of -180 degrees by 30 degrees. The 30 degrees of phase angle, of course, can be resolved into a 0-degree component and a 90-degree component, the latter of which contributes at least some radiation for filling in the null at the angle θ_4 . Thus, in Fig. 7, this partial fill-in is illustrated at H. The resultant pattern R' can thus be made to approximate the cosecant-squared pattern merely by the reversal of the feed to antenna number 3.

A generalized summary of these criteria required for null filling may be expressed as follows: first, select that antenna of the array that of itself would transmit or receive radiation in a phase between $n\pi$ and $(n\pm 1)\pi$, preferably substantially at a phase $n\pi \pm \pi/2$, where n is any integer including zero, and π represents 180 degrees of phase, by determining the intersection of the phase characteristic of such an antenna with the phase characteristic of the complete antenna array intermediate the region of phase-jump or transition between S-shaped phase curves, from $n\pi$ to $(n\pm 1)\pi$; and secondly, reverse the phase of the feed to the selected antenna.

The invention is of broader scope, however, than has previously been described. From a generic point of view, null-filling entails the increasing of the amount of radiation at a particular region. The invention is also useful, however, to reduce the radiation at any desired angle, if such reduction should be desired.

As an illustration, were one to select an antenna element whose straight-line phase characteristic intersects a solid S-shaped curve at any desired point, indicating in-phase radiation with the radiation of the complete antenna array, and then to reverse the phase of the feed to such an antenna element, a decrease, not an increase, in radiation would be produced at the angle θ corresponding to the point of intersection. Thus, were one to reverse the phase of antenna number 4 down from the center O of the antenna 1 of Fig. 6, since the straight-line curve O-4 of this fourth antenna intersects the solid-line S-shaped phase curve V and X, the radiation would be reduced at the angle θ_5 determined by the projection of the point X upon the abscissa.

The radiation-increasing, like the radiation-decreasing may also be effected at any desired angle θ , though it has before been described only in connection with null angles. By reversing the phase of an antenna the phase characteristic of which intersects a dotted S-shaped curve at any desired angle θ , indicating an out-of-phase relationship with the radiation of the complete array, a radiation increase will be produced at that angle θ . As an illustration, the phase characteristic of the sixth antenna down, O-6, intersects the dotted out-of-phase S-shaped

curve III at point Y. Reversal of phase of this sixth antenna will increase the radiation at the angle θ_0 corresponding to the point of intersection Y.

It is thus evident that, in accordance with the present invention, one may at will alter or modify the resultant radiation transmitted or received by an antenna array of substantially similarly phased antenna elements at any desired angle off the radiation axis of the array. The necessary criteria have before been explained to demonstrate how either an increase or a decrease in the amount of radiation at any such angle may be effected. The mere reversing of the feed of a particular antenna, of course, can easily be done in the field or in the production line without the necessity for additional or special parts and without involved adjustments. If the antenna is fed from a transmission line, for example, it is merely necessary to reverse the terminal connections of the line to the selected antenna. This is to be contrasted with prior-art pattern-changing proposals involving the before-mentioned special phasing networks, supplementary antennas and other complex devices and critical adjustments.

In view of the simplicity of the techniques of the present invention, it is possible to attain further advantages unattainable with prior-art devices. One may, if desired, shift the resultant radiation pattern R' , Fig. 7, to increase or decrease the radiation at any desired angle θ merely by tilting the antenna pattern along a line at a slight angle to the vertical. Such tilting, however, still maintains the complete vertical pattern R' null-free. This tilting may be resorted to when, for example, it is desired that maximum energy be transmitted in a slightly different location than would normally be the case were the antenna maintained vertical. Thus, in Fig. 10, the pattern R' is shown slightly shifted to the right, as at R'' . This result may be obtained with the aid of the antenna array 1 of Fig. 9 in which the pattern tilting is effected by advancing the phase of the energy fed to the upper array B over that of the energy fed to the lower array A. This phase advance may be effected by a phase-advancing device 161 which may merely be an additional section of transmission line in the feed to the upper array B. The family of S-shaped curves of Fig. 8 is similar to that discussed in connection with Fig. 5, as in the corresponding family of straight-line antenna phase curves. In view of the electrical tilting of the pattern of the antenna of Fig. 9, however, the straight-line curves of the individual antennas of the upper and lower arrays A and B will not pass through the same origin, as at O in Fig. 5, but will, on the contrary, pass through different origins O' and O'' located at points above and below the abscissa, as determined by the amount of the phase advancement of the energy fed to the upper array B. Again it happens that the third antenna down in the lower array A is provided with a phase-reversal connection PR since the line $O''-3$, representing the phase of the radiation radiated by this antenna immediately intersects the phase-jump or transition line between coordinates θ_2 , O and θ_2 , -180 at point Z. Thus at the angle θ_2 the radiation amplitude G is produced, as described in connection with Fig. 7. An inspection of Fig. 10 discloses that the antenna of Fig. 9 produces a resultant radiation pattern R'' that is very similar to the radiation pattern R' of Fig. 7 except that it is shifted to the right, indicating that the pattern is tilted slightly downward from the horizontal.

The preceding discussion has not been confined to any particular type of radiating or receiving antenna. To the contrary, the discussion is entirely general and applicable to any type of antenna. For purposes of illustration, however, the principles of the present invention will now be described as applied to a preferred television or other UHF transmitting antenna structure, capable of transmitting substantially uniformly in all directions

of azimuth. The horizontal radiation pattern of such an antenna is therefore usually referred to as omnidirectional or circular, though the vertical pattern would normally be subjected to nulls before described. In Fig. 11, vertically arranged spaced tubular columns are shown at 2, 4, 6 and 8 comprising a lower antenna array or section A. The columns 2, 4, 6 and 8 are symmetrically disposed with respect to a preferably substantially parallel centrally disposed transmission-line conductor 10 and with substantially equal spacing S, Fig. 13, between the adjacent tubular columns. The centers of the columns thus form a square. The tubular columns are connected together at the bottom of the antenna by an end plate 7, as by welding or with the aid of bolts. The columns 2, 4, 6 and 8 of the array in section A continue above sandwich-type supporting-plate conductive connectors 59—60 to form the upper array or section B. A platform 57 may be welded or otherwise secured to the top of the antenna for supporting a beacon light 11, the power cables 120 of which are shown carried upward through one of the tubular columns, such as the column 6.

The tubular columns 2, 4, 6 and 8 and the inner conductor 10 of the lower section A are electrically connected to the base plate 7. The outer conductor 12 of a coaxial feed system 12—14, from, for example, a television transmitter, not shown, is also connected to the base plate 7, and the inner conductor 14 thereof is extended, as at 114, upward within the tubular column 4. At the midway junction between the antenna sections A and B, formed by the before-mentioned sandwich-type supporting-plate conductive connectors 59—60, the inner conductor extension 114 branches right-angulantly, as at 16, and connects at 209 with the bottom of a central conductor 10' of the upper array B and the top of the central conductor 10 of the lower array A. Appropriate power division to achieve a two-step amplitude feed that provides greater power in the upper array B than in the lower array A is effected with the aid of different transformers 109 and 106 interposed between the connection 209 and the central conductors 10 and 10' of the lower and upper arrays A and B, respectively. This corresponds to the element 160 of Figs. 3, 6 and 9. Proper matching may be achieved through the movement of the capacitive plunger 121 in the stub section 123 formed by the portion of the branch 16 to the right of the conductor 114 and the outer sleeve 104 connected with and branching from the tubular conductor 4. The capacitive plunger 121 may, if desired, be omitted if satisfactory matching is obtained without the same. Proper phasing is achieved by providing a greater path length to the lower section A than to the upper section B.

Along the transmission-line conductors 2, 4, 6, 8 and 10 of the lower and upper arrays A and B, several sets of branch-conductor groups are provided each comprising four branch conductors, such as 118, 124, 132 and 134, disposed in substantially parallel planes preferably substantially normal to the transmission-line conductors and spaced therealong vertically at intervals corresponding substantially to the predetermined wavelength with which the antenna is to operate.

The branch conductors 118, 124, 132 and 134 are connected at one of their ends to the centrally disposed transmission-line conductor 10 or 10', as at 113; extend, in part, radially outward; and then preferably extend at right angles, as shown at 22. At their other ends, the branch conductors are connected to preferably co-planar points along the outside surfaces of the respective tubular column transmission-line conductors 2, 8, 6 and 4 by the preferably horizontally disposed connecting portions 22, as at points 20. Each branch conductor, such as, for example, the branch conductor 118, becomes one element of a further three-element branch transmission line the

other two elements of which comprise the side of the tubular column conductor to which it is connected, such as the right-hand side of the tubular column conductor 2, and the side of the adjacent tubular column conductor, such as the left-hand side of the tubular column conductor 8. Current then flows outward along the branch conductor 118 and back in the opposite direction along the right-hand side of the tubular column conductor 2, but in the same direction along the left-hand side of the tubular column conductor 8 as along the conductor 118. The appropriate impedance adjustment for this unbalanced three-conductor feed may be effected by adjusting the position of the point 20 along the right-hand side of the tubular column conductor 2. For the purposes hereinafter described, it has been found advantageous to locate the point 20 right near the outer edge of the tubular column conductor, as shown. If desired, a stub, not shown, may be used at the top of the array for assisting in matching the complete array. The location of the points 20 along one of the side edges of each tubular column may also be adjusted to effect desired phase relationships. The spacing S between the parallel sides of adjacent columns and the spacing from the inner conductor 10 may also be varied to effect desired impedance and phase relationships without the necessity for utilizing special lines, networks or other devices.

With such an arrangement, moreover, the rectangular wave-transmission loops or frames formed by the outer rims or edges of the transmission lines 2, 4, 6, 8 and preferably conductive spacers 21 dividing the successive groups of branch conductors, are provided with long sides such as 4, 6, about a wavelength in length, shorter sides 21 less than a half-wavelength in length, and since only essentially the outer rims or edges are effective, an effective depth or thickness of negligible dimensions. The feed system embodying the exciters, 118, 124, 132, 134, moreover, with the end portions 22 substantially in the plane of the loop or frame, may be oriented substantially parallel to the shorter sides, formed by the spacers 21, and thus insuring excitation by radio-frequency energy of polarization perpendicular to the plane of the longer sides, such as 4, 6, of the frame.

While the length of the branch conductors 118, 124, 132 and 134 can be made small, consistent with preventing the short-circuiting of the energy that is passed upward along the five-conductor transmission lines 2, 4, 6, 8, 10, and outward to the outer edges of the tubular column conductors 2, 4, 6 and 8, it cannot be made too large without producing sharp lobes in the radiation pattern of the antenna that destroy the circularity of the desired omni-directional radiation pattern. The overall width or diameter of the antenna array, on the other hand, must be large enough to support the necessary structure. If the degree of circularity or omni-directionality of the horizontal field pattern produced by the antenna, defined in terms of the maximum-to-minimum field intensity ratio in the pattern, is to be very great, the length of the branch conductors 118, 124, 132 and 134 should be substantially equal to or less than about the quarter-wavelength of the radio energy. The spacing S between the parallel side surfaces of the adjacent beam conductors 2, 4, 6, and 8, furthermore, is preferably adjusted to a value considerably less than the length of the branch conductors in order to maintain the omni-directional radiation pattern characteristic. An antenna particularly suited for the ultra-high-frequency range of from about 500 to about 890 megacycles per second, for example, having branch conductors 118, 124, 132, 134 of length about four and one-half inches, tubular columns of diameter about four inches and a spacing S between the parallel sides of adjacent angular beams of about one inch, has been found to produce a remarkable degree of circularity in the omni-directional horizontal pattern. For antennas designed for operation with different predetermined wavelengths in the said 500 to 890 megacycle range, the length

of the branch conductors may vary from about three and one-half to about six inches; the diameter of the tubular column conductors, from about three to about six inches; and the spacing S, from about one-half inch to about two inches.

An array of this character, about ten to twenty wavelengths long, will produce sufficient directivity and gain in the vertical plane for the television purposes before mentioned. A twelve-wavelength array, for example, has been found to produce a half-power vertical principal lobe angle of about 4.2 degrees. A high gain of 11 decibels over a tuned dipole was achieved, with a power gain of 14 and a voltage standing-wave ratio of less than 1.1 to 1.

It will be observed, however, that, the third group of branch conductors 118, 124, 132 and 134 down from the top of each antenna section A and B, is not connected in the same way as the other groups of branch conductors. The branch conductor 118 of this third group, for example, as more particularly shown in Fig. 13, is connected to the column 8, and not to the column 2; the branch conductor 124, to the column 6 and not to the column 8; the branch conductor 132, to the column 4, and not to the column 6; and the branch conductor 134, to the column 2, and not to the column 4. This simple reversal of connection accomplishes the phase reversal connection PR of Fig. 9, producing the pattern R' of Fig. 7.

Plexiglass, polyvinyl chloride or similar radio-wave transparent sheet material, such as the flat strips 52, may be inserted within guides 152 and secured, as by screws 5 or other means, to the edges of the spacers 21, to close off the space between the parallel sides of the adjacent angular beam transmission-line conductors to the effects of the atmosphere.

Further modifications will occur to those skilled in the art and all such are considered to fall within the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. An antenna system comprising an array of at least three separate antennae provided with means for feeding radio-frequency energy to or from all but one of said antennae with substantially the same phase, the said one antenna being that one of the array that of itself would transmit or receive radiation at a predetermined angle off the radiation axis of the array in a phase substantially equal to the phase of the resultant radiation transmitted or received by the array at the said angle $\pm n\pi$, where n is any integer including zero and π is 180 degrees of phase, and means for feeding radio-frequency energy to or from the said one antenna in anti-phase with the other antennae of the array.

2. The antenna system of claim 1, comprising two such arrays arranged in succession.

3. The antenna system of claim 1, said one antenna being that one of the array that of itself would transmit or receive radiation at a predetermined null angle off the radiation axis of the array at which the phase of the resultant radiation transmitted or received by the array changes from $n\pi$ to $(n\pm 1)\pi$.

4. The antenna system of claim 1, said feeding means transmitting to or receiving from one group of the antennae of the array a greater magnitude of energy than another group in order to fill a first null in the pattern of the resultant radiation transmitted or received by the array at a first predetermined angle off the radiation axis of the array; said one antenna being that one of the array that of itself would transmit or receive radiation at a second predetermined null angle off said radiation axis at which the phase of the resultant radiation changes from $n\pi$ to $(n\pm 1)\pi$, whereby the feeding of radio-frequency energy to said one antenna in anti-phase with the other antennae of the array fills said second null at said second predetermined angle.

5. The antennae system of claim 1, a second array of

antennae adjacent the first array, and means for feeding radio-frequency energy to or from the antennae of the second array in a phase different from the phase of the energy fed to the first array in order to tilt the radiation axis of the system.

6. The antenna system of claim 1, said feeding means comprising a transmission line and a plurality of conductors respectively connecting all but said one antenna to said transmission line to excite those antennae in said same phase and a further conductor connecting said one antenna to said transmission line to excite said one antenna in said anti-phase.

7. An antenna system for transmitting radio-frequency energy of a predetermined wavelength comprising a plurality in excess of two of substantially parallel transmission-line conductors of length several times the said predetermined wavelength, one of the transmission-line conductors being disposed symmetrically with respect to the other transmission-line conductors, means for energizing the said one transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the said other transmission-line conductors in anti-phase therewith, a plurality of branch-conductor groups each comprising a plurality of branch conductors equal in number to one less than the plurality of transmission-line conductors, the branch-conductor groups being disposed within the space between the transmission-line conductors and the branch conductors of each group except at least one group being connected at one of their ends to the said one transmission-line conductor and at their other ends to points disposed along the outer surfaces of the respective other transmission-line conductors and each of length not greater than approximately one-half the said predetermined wavelength, the branch conductors of the said one group being connected at one of their ends to the said one transmission-line conductor and at their other ends to points disposed along the outer surfaces of conductors of the said other transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the other of the plurality of branch-conductor groups are connected.

8. An antenna system for transmitting radio-frequency energy of a predetermined wavelength comprising a plurality in excess of two of substantially parallel transmission-line conductors of length several times the said predetermined wavelength, one of the transmission-line conductors being disposed symmetrically with respect to the other transmission-line conductors, means for energizing the said one transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the said other transmission-line conductors in anti-phase therewith, a plurality of branch-conductor groups each comprising a plurality of branch conductors equal in number to one less than the plurality of transmission-line conductors, the branch-conductor groups being disposed within the space between the transmission-line conductors and the branch conductors of each group except at least one group being connected at one of their ends to the said one transmission-line conductor and at their other ends to points disposed along the outer surfaces of the respective other transmission-line conductors and each of length not greater than approximately one-half the said predetermined wavelength, the branch conductors of the said one group being connected at one of their ends to the said one transmission-line conductor and at their other ends to points disposed along the outer surfaces of conductors of the said other transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the other of the plurality of branch-conductor groups are connected, and means for feeding different amplitudes of the radio-frequency energy to the said other transmission-line conductors at different branch-conductor groups.

9. An antenna system for transmitting radio-frequency energy of a predetermined wavelength and at a pre-

terminated angle off the radiation axis of which the resultant radiation suffers a phase reversal that gives rise to a null, comprising a plurality in excess of two of substantially parallel transmission-line conductors of length several times the said predetermined wavelength, one of the transmission-line conductors being disposed symmetrically with respect to the other transmission-line conductors, means for energizing the said one transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the said other transmission-line conductors in anti-phase therewith, a plurality of branch-conductor groups each comprising a plurality of branch conductors equal in number to one less than the plurality of transmission-line conductors, the branch-conductor groups being disposed within the space between the transmission-line conductors and the branch conductors of each group except at least one group being connected at one of their ends to the said one transmission-line conductor and at their other ends to points disposed along the outer surfaces of the respective other transmission-line conductors and each of length not greater than approximately one-half the said predetermined wavelength, the position of the said one group of branch conductors along the antenna system being selected so that the radiation that would be transmitted from the portion of the antenna system at the said one group of branch conductors itself would be of phase intermediate the phase of the said resultant radiation transmitted by the antenna system at angles immediately adjacent to the said predetermined angle off the radiation axis, and the branch conductors of the said one group of branch conductors being connected at one of their ends to the said one transmission-line conductor and at their other ends to points disposed along the outer surfaces of conductors of the said other transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the other of the plurality of branch-conductor groups are connected, thereby to produce radiation at the said predetermined angle.

10. An antenna system for transmitting radio-frequency energy of a predetermined wavelength and at a predetermined angle off the radiation axis of which the resultant radiation suffers a phase reversal that gives rise to a null, comprising a plurality in excess of two of substantially parallel transmission-line conductors of length several times the said predetermined wavelength, one of the transmission-line conductors being disposed symmetrically with respect to the other transmission-line conductors, means for energizing the said one transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the said other transmission-line conductors in anti-phase therewith, a plurality of branch-conductor groups each comprising a plurality of branch conductors equal in number to one less than the plurality of transmission-line conductors, the branch-conductor groups being disposed within the space between the transmission-line conductors and the branch conductors of each group except at least one group being connected at one of their ends to the said one transmission-line conductor and at their other ends to points disposed along the outer surfaces of the respective other transmission-line conductors and each of length not greater than approximately one-half the said predetermined wavelength, the position of the said one group of branch conductors along the antenna system being selected so that the radiation that would be transmitted from the portion of the antenna system at the said one group of branch conductors itself would be of phase intermediate the phase of the said resultant radiation transmitted by the antenna system at angles immediately adjacent to the said predetermined angle off the radiation axis, and the branch conductors of the said one group of branch conductors being connected at one of their ends to the said one transmission-line conductor

and at their other ends to points disposed along the outer surfaces of conductors of the said other transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the other of the plurality of branch-conductor groups are connected, thereby to produce radiation at the said predetermined angle, and means for feeding different amplitudes of the radio-frequency energy to the said other transmission-line conductors at different branch-conductor groups.

11. An antenna system for transmitting radio-frequency energy of a predetermined wavelength comprising a plurality in excess of two of substantially parallel transmission-line conductors of length several times the said predetermined wavelength, all but one of the transmission-line conductors comprising tubular columns symmetrically disposed with respect to the said one transmission-line conductor, means for energizing the said one transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the said other transmission-line conductors in anti-phase therewith, and several branch-conductor groups each comprising a plurality of branch conductors equal in number to one less than the plurality of transmission-line conductors, the branch-conductor groups being disposed within the space between the transmission-line conductors in substantially parallel planes substantially normal to the transmission-line conductors spaced therealong at intervals corresponding substantially to the said predetermined wavelength, the plurality of branch conductors of each group except at least one group being connected at one of their ends to the said one transmission-line conductor and at their other ends to substantially co-planar points disposed along the outer surfaces of the respective tubular column transmission-line conductors and each of length not greater than approximately one-half the said predetermined wavelength, the branch conductors of the said one group being connected at one of their ends to the said one transmission-line conductor and at their other ends to points disposed along the outer surfaces of conductors of the said other tubular transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the other of the plurality of branch-conductor groups are connected.

12. An antenna system for transmitting radio-frequency energy of a predetermined wavelength comprising five spaced substantially parallel transmission-line conductors of length at least equal to several times a predetermined radio-frequency wavelength, four of the transmission-line conductors comprising tubular columns of substantially circular cross-section symmetrically disposed with respect to the fifth transmission-line conductor with substantially equal spacing between the adjacent tubular column transmission-line conductors, means for energizing the fifth transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the tubular column transmission-line conductors in anti-phase therewith, and several branch-conductor groups each comprising four branch conductors, the branch-conductor groups being disposed in substantially parallel planes substantially normal to the transmission-line conductors spaced therealong at intervals corresponding substantially to the said predetermined wavelength, conductive supporting plates connected between adjacent tubular column transmission-line conductors substantially mid-way between successive groups of branch conductors, the four branch conductors of each group except at least one group being connected at one of their ends to the fifth transmission-line conductors, extending radially between the adjacent tubular column transmission-line conductors, extending near their other ends at right angles to the said radial extensions and connected at their said other ends to substantially co-planar points disposed along the outer surfaces of the respective four tubular

column transmission-line conductors near the outermost portions thereof and each of length not greater than approximately one-half the predetermined wavelength, the branch conductors of the said one group of branch conductors being connected at one of their ends to the fifth transmission-line conductor, extending radially between adjacent tubular column transmission-line conductors, extending near their other ends at right angles to the said radial extensions but in the opposite direction to the right-angular extensions of the corresponding branch conductors of the other of the several branch-conductor groups and connected at their said other ends to substantially co-planar points disposed along the outer surfaces of conductors of the said four tubular column transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the several branch-conductor groups are connected.

13. An antenna system for transmitting radio-frequency energy of a predetermined wavelength comprising five spaced substantially parallel transmission-line conductors of length at least equal to several times a predetermined radio-frequency wavelength, four of the transmission-line conductors comprising tubular columns of substantially circular cross-section symmetrically disposed with respect to the fifth transmission-line conductor with substantially equal spacing between the adjacent tubular column transmission-line conductors, means for energizing the fifth transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the tubular column transmission-line conductors in anti-phase therewith, and several branch-conductor groups each comprising four branch conductors, the branch-conductor groups being disposed in substantially parallel planes substantially normal to the transmission-line conductors spaced therealong at intervals corresponding substantially to the said predetermined wavelength, conductive supporting plates connected between adjacent tubular column transmission-line conductors substantially mid-way between successive groups of branch conductors, the four branch conductors of each group except at least one group being connected at one of their ends to the fifth transmission-line conductor, extending radially between the adjacent tubular column transmission-line conductors, extending near their other ends at right angles to the said radial extensions and connected at their said other ends to substantially co-planar points disposed along the outer surfaces of the respective four tubular column transmission-line conductors near the outermost portions thereof and each of length not greater than approximately one-half the predetermined wavelength, the branch conductors of the said one group of branch conductors being connected at one of their ends to the fifth transmission-line conductor, extending radially between adjacent tubular column transmission-line conductors, extending near their other ends at right angles to the said radial extensions but in the opposite direction to the right-angular extensions of the corresponding branch conductors of the other of the several branch-conductor groups and connected at their said other ends to substantially co-planar points disposed along the outer surfaces of conductors of the said four tubular column transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the several branch-conductor groups are connected, and means for feeding different amplitudes of the radio-frequency energy to the tubular column transmission-line conductors at different branch-conductor groups.

14. An antenna system for transmitting radio-frequency energy of a predetermined wavelength comprising five spaced substantially parallel transmission-line conductors of length at least equal to several times a predetermined radio-frequency wavelength, four of the transmission-line conductors comprising tubular columns of substantially circular cross-section symmetrically disposed with respect

to the fifth transmission-line conductor with substantially equal spacing between the adjacent tubular column transmission-line conductors, means for energizing the fifth transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the tubular column transmission-line conductors in anti-phase therewith, and several branch-conductor groups each comprising four branch conductors, the branch-conductor groups being disposed in substantially parallel planes substantially normal to the transmission-line conductors spaced therealong at intervals corresponding substantially to the said predetermined wavelength, conductive supporting plates connected between adjacent tubular column transmission-line conductors substantially mid-way between successive groups of branch conductors, the four branch conductors of each group except at least one group being connected at one of their ends to the fifth transmission-line conductor, extending radially between the adjacent tubular column transmission-line conductors, extending near their other ends at right angles to the said radial extensions and connected at their said other ends to substantially co-planar points disposed along the outer surfaces of the respective four tubular column transmission-line conductors near the outermost portions thereof and each of length not greater than approximately one-half the predetermined wavelength, the branch conductors of the said one group of branch conductors being connected at one of their ends to the fifth transmission-line conductor, extending radially between adjacent tubular column transmission-line conductors, extending near their other ends at right angles to the said radial extensions but in the opposite direction to the right-angular extensions of the corresponding branch conductors of the other of the several branch-conductor groups and connected at their said other ends to substantially co-planar points disposed along the outer surfaces of conductors of the said four tubular column transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the several branch-conductor groups are connected, and means for feeding different amplitudes of the radio-frequency energy to the tubular column transmission-line conductors at different branch-conductor groups, the phase of the feed to a group of the branch-conductor groups being advanced to tilt the radiation axis of the radiation transmitted by the antenna system.

15. An antenna system for transmitting radio-frequency energy of a predetermined wavelength and at a predetermined angle off the radiation axis of which the resultant radiation suffers a phase reversal that gives rise to a null, comprising five spaced substantially parallel transmission-line conductors of length at least equal to several times a predetermined radio-frequency wavelength, four of the transmission-line conductors comprising tubular columns of substantially circular cross-section symmetrically disposed with respect to the fifth transmission-line conductor with substantially equal spacing between the adjacent tubular column transmission-line conductors, means for energizing the fifth transmission-line conductor with radio-frequency energy of the said predetermined wavelength and the tubular column transmission-line conductors in anti-phase therewith, and several branch-conductor groups each comprising four branch conductors, the branch-conductor groups being disposed in substantially parallel planes substantially normal to the transmission-line conductors spaced therealong at intervals corresponding substantially to the said predetermined wavelength, conductive supporting plates connected between adjacent tubular column transmission-line conductors substantially mid-way between successive groups of branch conductors, the four branch conductors of each group except at least one group being connected at one of their ends to the fifth transmission-line conductor, extending radially between the adjacent tubular column transmission-line conductors,

extending near their other ends at right angles to the said radial extensions and connected at their said other ends to substantially co-planar points disposed along the outer surfaces of the respective four tubular column transmission-line conductors near the outermost portions thereof and each of length not greater than approximately one-half the predetermined wavelength, the position of the said one group of branch conductors along the antenna system being selected so that the radiation that would be transmitted from the portion of the antenna system at the said one group of branch conductors itself would be of phase intermediate the phase of the said resultant radiation transmitted by the antenna system at angles immediately adjacent to the said predetermined angle off the radiation axis, and the branch conductors of the said one group of branch conductors being connected at one of their ends to the fifth transmission-line conductor, extending radially between adjacent tubular column transmission-line conductors, extending near their other ends at right angles to the said radial extensions but in the opposite direction to the right-angular extensions of the corresponding branch conductors of the other of the several branch-conductor groups and connected at their said other ends to substantially co-planar points disposed along the outer surfaces of conductors of the said four tubular column transmission-line conductors different from those to which the said other ends of the corresponding branch conductors of the several branch-conductor groups are connected, thereby to produce radiation at the said predetermined angle.

16. An array of antenna elements provided with means for feeding radio-frequency energy to or from all but one of the antenna elements with substantially the same phase; the said one antenna element being that element of the array that of itself would transmit or receive radiation at a predetermined null angle off the radiation axis of the array, at which the phase of the resultant radiation transmitted or received by the array changes from $n\pi$ to $(n\pm 1)\pi$, where n is any integer including zero and π represents 180 degrees of phase, in a phase substantially midway between $n\pi$ and $(n\pm 1)\pi$; and means for feeding radio-frequency energy to or from the said one antenna element in anti-phase with the other antenna elements of the array, said array comprising twelve antenna elements successively spaced at intervals of substantially one-wavelength of the said radio-frequency energy, and the said one antenna element is the third from one end of the array.

17. An array of antenna elements provided with means for feeding radio-frequency energy to or from all but one of the antenna elements with substantially the same phase; the said one antenna element being that element of the array that of itself would transmit or receive radiation at a predetermined null angle off the radiation axis of the array, at which the phase of the resultant radiation transmitted or received by the array changes from $n\pi$ to $(n\pm 1)\pi$, where n is any integer including zero and π represents 180 degrees of phase, in a phase substantially midway between $n\pi$ and $(n\pm 1)\pi$; and means for feeding radio-frequency energy to or from the said one antenna element in anti-phase with the other antenna elements of the array, said array comprising upper and lower twelve antenna-element sections, the successive elements of each section being spaced at intervals of substantially one-wavelength of the said radio-frequency energy, and the said one antenna element is the third from the upper end of the lower section.

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