Oct. 6, 1959 L. C. VAN ATTA 2,908,002

ELECTROMAGNETIC REFLECTOR

Filed June 8, 1955 3 Sheets-Sheet 1

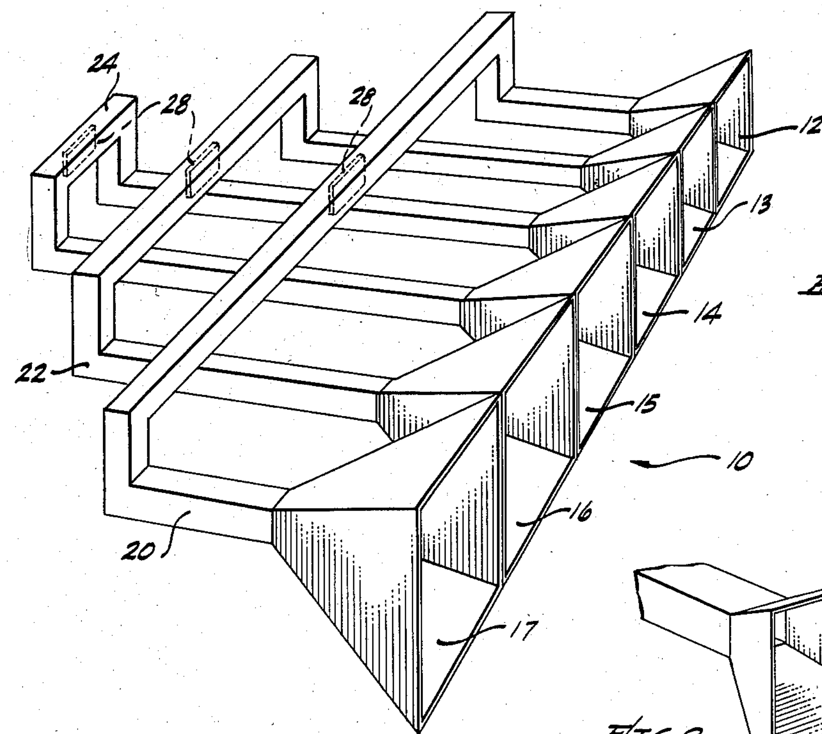


FIG. 3.

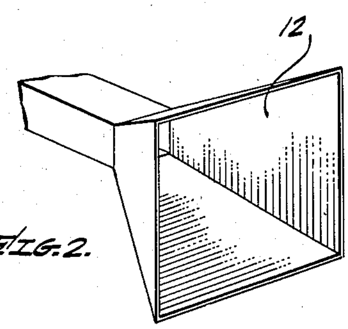
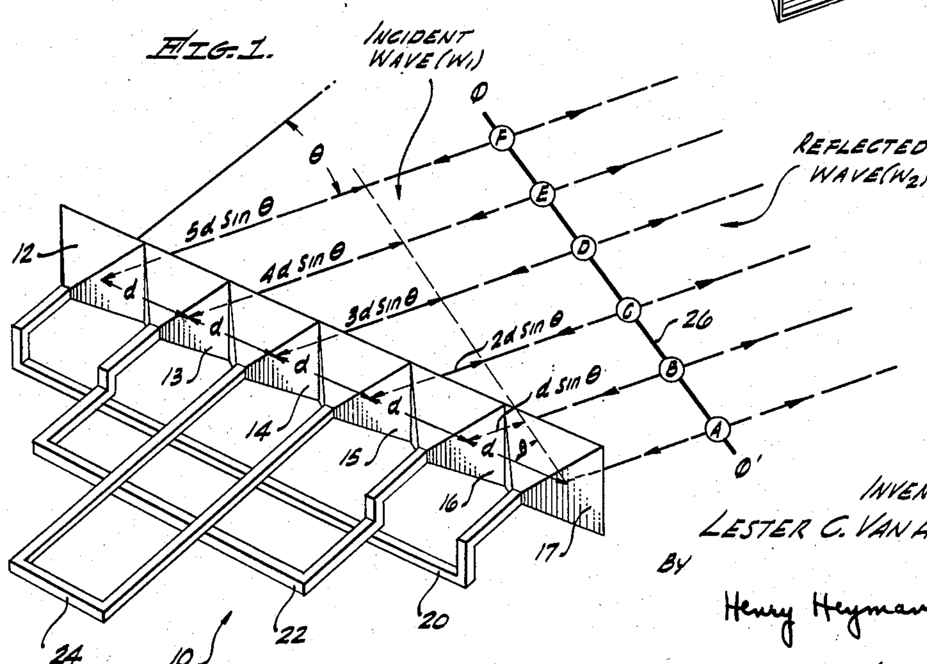


FIG. 2.

FIG. 1.



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ELECTROMAGNETIC REFLECTOR

Filed June 8, 1955 3 Sheets-Sheet 2

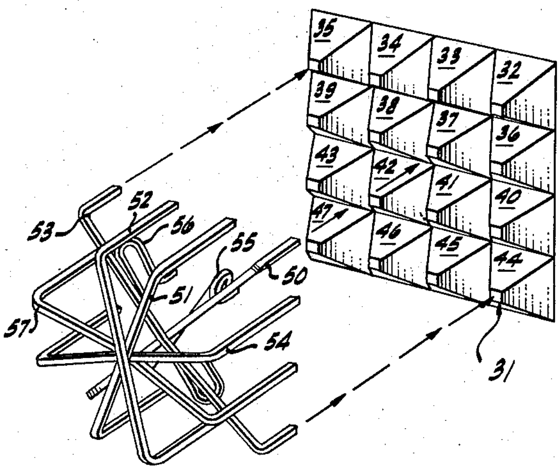


FIG. 5b.

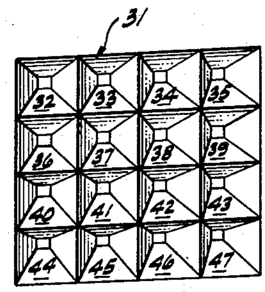


FIG. 5a.

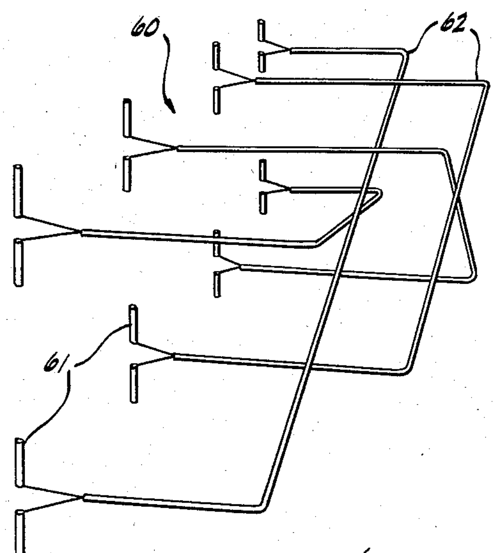
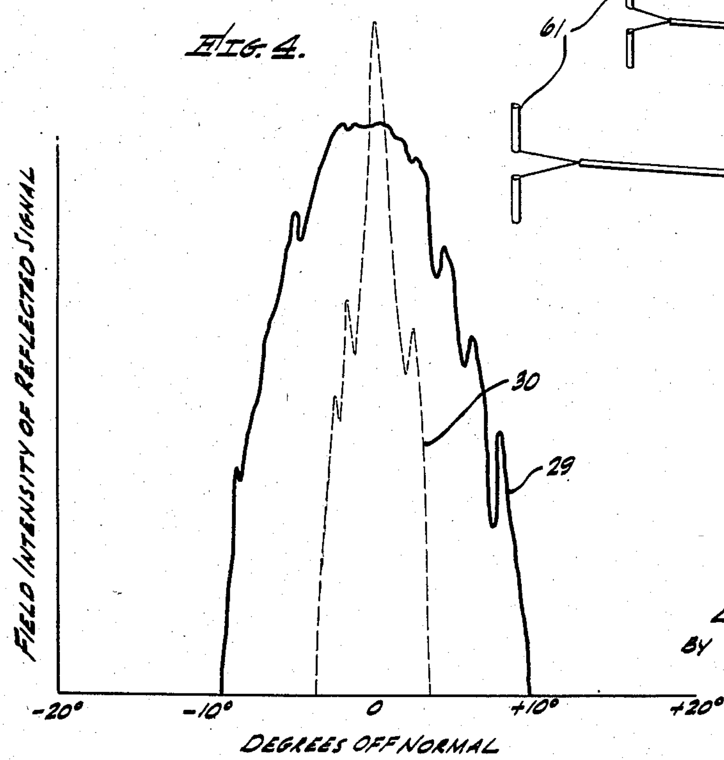


FIG. 6.

FIG. 4.



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Filed June 8, 1955 3 Sheets-Sheet 3

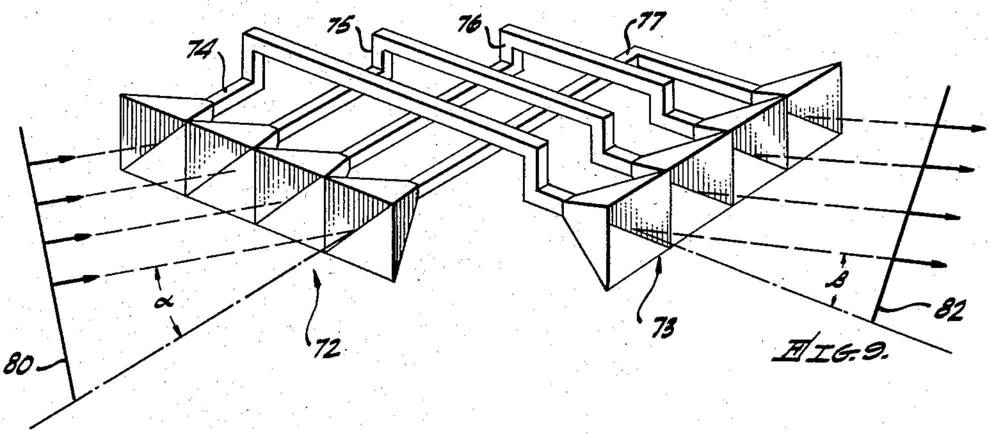


FIG. 9.

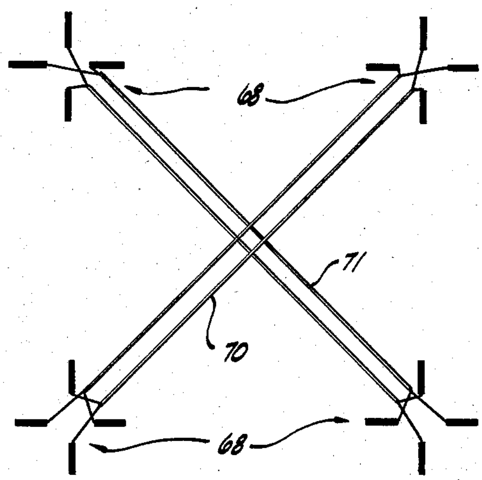
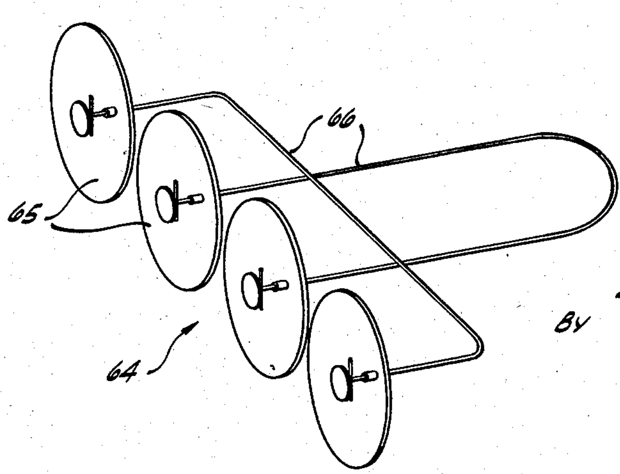


FIG. 7.

FIG. 8.



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ELECTROMAGNETIC REFLECTOR

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3 Claims. (Cl. 343—776)

This invention relates to apparatus for reflecting an electromagnetic wave, and more particularly to an array of antennas for reflecting an incident wave in a predetermined direction with respect to the angle at which the wave was incident on the array.

Several types of electromagnetic reflectors are presently in use, among which are the corner reflector having two plane surfaces at right angles or, more commonly, having three plane surfaces at right angles. Corner reflectors of this type, however, have several disadvantages, namely, if a large frontal area is required, great depth with a concomitant large volume must be utilized. Also, the two-surface corner reflector is effective in only one plane, it being effectively a plane surface in the other plane. The three-surface corner reflector, on the other hand, has a poor form factor and a low efficiency for most applications, i.e., it is not readily adapted to round, square, or rectangular apertures.

In accordance with one embodiment of the present invention, a plurality of antennas are disposed symmetrically with respect to a geometrical center to form a linear or two-dimensional array. The symmetrically disposed antennas are interconnected with transmission lines of equal electrical length, in which case an incident electromagnetic wave is reflected back in the same direction from whence it came. Any conventional type of antenna may be employed such as, for example, dipoles, crossed dipoles, horns, or paraboloids. The directivity of the individual antenna is chosen to cover the angular region over which reflection is required. Transmission line best suited for use with the particular array of antennas is used. This may be a two or four-wire line, rectangular waveguide, square waveguide, coaxial line, or other structure equivalent to a transmission line and capable of providing an electromagnetic path. In operation, energy incident on each antenna of the array is transmitted to a symmetrically disposed associated antenna by transmission lines of equal electrical length interconnecting associated pairs of antennas. Therefore, inasmuch as the delay provided by each transmission line is equal, received energy will be radiated from antennas of the array that are symmetrically disposed with respect to the receiving antennas in the same succession as received. In this manner, the radiated energy forms a wavefront that propagates back in the direction from whence the incident wave came. It is noted that when a linear array is used, the directional characteristics of this reflection occur only in a single plane, whereas when a two-dimensional array is used, the directional characteristics occur in three dimensions.

In an alternative embodiment of the invention, the antennas of a first array are interconnected with their symmetrically or similarly disposed antennas of a second similar array with transmission lines of equal electrical length. In this device, the angle at which the incident wavefront impinges on the first array determines the angle at which an electromagnetic wave is radiated from the second array. Apparatus of this type is particularly useful where a radar receiving station, for example, is located at a position other than that of its associated transmitter. Such apparatus may be used to enable analysis of existing atmospheric conditions or to improve communication signals passing between transmitting and receiving points which are otherwise blocked from each other.

Some advantages of the device of the present invention over devices of the type presently in use are that there is considerable flexibility in adapting its design to a variety of aperture shapes such as, for example, round, square, or rectangular, thus achieving greater efficiency with regard to space requirements. In addition, the arrays of the present invention may be adapted to operate at increased efficiencies at all angles of incidence, particularly at wide angles of incidence by using small antennas. This is because the control of the angular region over which reflection is obtained is determined by the directive characteristics of the individual antennas of the array. Also, the array of antennas together with the connecting transmission lines does not require great depth, nor does the depth need to increase appreciably as the aperture increases. In view of the above, it is evident that the arrays of antennas herein described are of a type that is particularly adapted to ship and aircraft installations. In addition to the above advantages, it is to be noted that the effect of the devices of the present invention on the polarity of the reflected wave relative to that of the incident wave is that it may be retained the same, rotated 90°, changed from linear to circular, or from right circular or elliptical to left circular or elliptical polarization, respectively.

It is therefore an object of this invention to provide an improved passive apparatus for reflecting an electromagnetic wave back in a predetermined direction with respect to its original angle of incidence on the apparatus.

Another object of the invention is to provide an improved passive apparatus for reflecting an incident electromagnetic wave back in the same direction from whence it came.

Still another object of the invention is to provide an array of antennas for reflecting an incident electromagnetic wave back in a predetermined direction that is capable of operating at wide angles of incidence.

A further object of the invention is to provide an array of antennas for controlling the polarity of an incident electromagnetic wave reflected back in a predetermined direction.

A still further object of the invention is to adapt an antenna array for reflecting an incident electromagnetic wave back in a predetermined direction with respect to the angle of incidence of the electromagnetic wave to efficiently utilize any type of aperture, such as round, square, or rectangular aperture in a manner such that the array requires very little depth.

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

Fig. 1 is a perspective view of a linear array of horn antennas with waveguide interconnections and, in addition, showing the manner in which an incident electromagnetic wave will be reflected;

Fig. 2 is an enlarged perspective front view of one of the horn antennas in the array of Fig. 1;

Fig. 3 is a linear array of horn antennas including a phase shifter in one of the interconnections;

Fig. 4 illustrates experimental results obtained from the device of Fig. 1;

Figs. 5*a* and 5*b* are perspective views of a two-dimensional array of antennas with interconnections;

Figs. 6, 7 and 8 are views of the antenna array of the present invention as adapted to employ dipoles, paraboloid antennas, and crossed dipoles, respectively; and

Fig. 9 is a perspective view of two linear arrays of horn antennas with interconnections in accordance with the present invention.

Referring now to the drawings, Fig. 1 illustrates an embodiment of the invention comprising a linear array **10** of horn antennas **12**, **13**, **14**, **15**, **16**, and **17** disposed so that the adjacent sides of the front apertures thereof immediately adjoin each other. A perspective view showing the front of horn **12** is illustrated by way of example in Fig. 2. The horn antennas **12** to **17** are symmetrical horns made of conductive material each of which has a square aperture which tapers down to a square opening at its vertex, as clearly shown in Fig. 2. As is generally known, square horns are suitable for receiving and transmitting horizontal, vertical or circularly polarized electromagnetic waves and may be designed to operate over a wide angle of incidence by keeping their apertures small. The square openings at the vertices of horn antennas **12**, **17**, disposed at opposite extremities of the linear array **10**, are interconnected with a section **20** of square waveguide. Similarly, the horn antennas **13**, **16** and **14**, **15**, which are symmetrically disposed with respect to the geometrical center of array **10**, are interconnected with sections **22** and **24**, respectively, of square waveguide. The sections **22** and **24** are of the same electrical length as the section **20** connecting the horns **12**, **17** at the extremities of the array **10**.

It is to be noted that in the positioning of the horns **12**—**17**, it is only necessary that the horns **12**, **17**; **13**, **16**; and **14**, **15** be disposed symmetrically with respect to a geometrical center which, in the present case, is the mid-point of the array **10**. In view of this, it is apparent that the horns **14**, **15** could be separated any arbitrary distance apart and, if desired, an additional odd horn having a shorted waveguide section of one-half the length of sections **20**, **22** or **24** disposed at the geometrical center.

In operation, an electromagnetic wave W_1 having an associated phase front $\varphi\varphi'$, represented by line **26**, is incident on the array **10** at an angle θ with respect to a normal through the array. Portions of the phase front $\varphi\varphi'$ of wave W_1 that will impinge on the antennas **17**, **16**, **15**, **14**, **13**, and **12** are designated as A, B, C, D, E, and F, respectively. It can be shown that the time required for each portion of the wave W_1 to progress to the array **10** and back to the phase front represented by line **26** is the same. In this event, the reflected energy is reinforced along the phase front $\varphi\varphi'$ to form a reflected wave W_2 which will retrace the path of the incident wave, W_1.

More particularly, the above relations may be made more apparent by a geometrical consideration in view of the fact that a wave will be reflected in the direction from whence the incident wave arrived provided that the phase front of the reflected wave coincides with that of the incident wave, say at $\varphi\varphi'$. This will occur if all the path lengths for each portion of the wave to the array **10** and back to the phase front $\varphi\varphi'$ are equal. Since the apertures of the horns of array **10** are of equal size, the distances between their adjacent centers are also equal and hence may all be designated by d. Therefore, if the transmission line length plus twice the distance that the portion A must travel to the horn **17** from the phase front $\varphi\varphi'$ be subtracted from the length of the "round-trip" path traveled by the portion A of the wave, in going from the phase front $\varphi\varphi'$ to the array and back again, it is seen that the remaining distance is $[(0+5)d \sin \theta]$. Similarly, the remaining distances traveled by the portions B, C, D, E, and F when a like amount is subtracted from the length of their respective round-trip paths from and to the phase front $\varphi\varphi'$ is $[(1+4)d \sin \theta]$, $[(2+3)d \sin \theta]$, $[(3+2)d \sin \theta]$, $[(4+1)d \sin \theta]$ and $[(5+0)d \sin \theta]$, respectively. Therefore, it is evident that the distance traveled to and from the array **10** with respect to the phase front $\varphi\varphi'$ represented by line **26** is the same for each portion of the incident wave, W_1. It is thus apparent that the reflected portions of the wave will reinforce along the same phase front $\varphi\varphi'$ to form the reflected wave, W_2, which will retrace the path of the incident wave, W_1 insofar as electromagnetic energy in a plane normal to and passing through the length of the array **10** is concerned.

Under some circumstances it may be desirable to change the polarization of the reflected wave W_2. In this case, the polarization may be rotated 90° by twisting the square waveguide sections **20**, **22**, and **24** one-quarter of a turn between connections to their associated horns. Alternatively, it may be desirable to change from a right circular or elliptical polarization to a left circular or elliptical polarization, respectively. This may be accomplished by inserting a phase shifter **27**, **28**, and **29** in each of the interconnecting waveguide sections **20**, **22**, and **24**, respectively of the array **10** as shown in Fig. 3. As is generally known, a circular or elliptically polarized wave may be resolved into two linear components in quadrature with each other. Thus, the phase shifters **28** may comprise, for example, a sheet of dielectrics disposed across the central portion of the waveguide and extending a sufficient distance therealong to delay one of the linear components of the circular or elliptically polarized wave by 180°. Under these circumstances, a right circular or elliptical polarization will be changed to a left circular or elliptical polarization, respectively. Thus, for proper operation, it is only necessary that the phase shifters **28** be capable of shifting the phase of one linear component of the transmitted wave by 180° in each of the interconnecting transmission lines. Similarly, other polarization changes could be effected, if desired.

An example of the operation of the device of the present invention is illustrated in Fig. 4. In this figure the relative field intensity of a reflected signal versus the angular deviation from normal incidence is plotted for a four-horn array of the type shown in Fig. 1 and for a reflecting sheet of the same area. In this respect the solid line **29** indicates the relative intensity of a signal reflected from a four-horn linear array connected in accordance with the present invention whereas the dashed line **30** represents the relative intensity of a signal reflected from a conductive sheet of the same area as the aperture of the array. The difference in the peak values of these curves is not significant. As shown in the figure, the four-horn array reflects over an angle of approximately 20° whereas the conductive sheet reflects over an angle of only 6°. It is to be noted that the directivity or wide-angle scattering is governed by the elemental antennas of the array. Thus, in order to reflect over a wide angle of incidence the apertures of the horns **12**—**17** of the array **10** of Fig. 1 should be kept small. Therefore, it is possible to achieve a large array area while still retaining the angular coverage of a single elemental antenna by using a number of elemental antennas in a rectangular array. Also, the use of small horns enables good matching to be achieved without prohibitive size.

An alternative embodiment of the present invention is shown in Figs. 5*a* and 5*b*. In these figures there is illustrated a two-dimensional array **31** of horn antennas which is capable of controlling the direction of reflection of an incident electromagnetic wave in three dimension, i.e., in two planes in quadrature and normal to the plane of the array. Two-dimensional array 31 comprises sixteen horn antennas 32—47 which are similar to the horn antennas 12—17 constituting the array 10. Horn antennas 32—47 are disposed with their apertures in a common plane and arranged to form a square having four antennas across and four in a vertical direction as shown in the drawing. In accordance with the invention, the horns are symmetrically disposed with respect to the geometrical center of the array 31 and the selected pairs of horns are connected together by means of sections of transmission line of equal electrical length. More particularly, antennas horns 32, 47 are connected together with waveguide section 50; horns 33, 46 with waveguide section 51; horns 34, 45 with waveguide section 52; horns 35, 44 with waveguide section 53; horns 36, 43 with waveguide section 54; horns 37, 42 with waveguide section 55; horns 38, 41 with waveguide section 56; and horns 39, 40 with waveguide section 57. As in the case of the array 10, an odd horn having a shorted section of waveguide one-half the length of the sections 50—57 may be disposed at the geometrical center of the array. The two-dimensional array 31 operates in controlling the polarization and the direction of reflection in two planes in the same manner as the linear array 10 shown in Fig. 1 operates in one plane.

As previously specified, the device of the present invention is not restricted to any particular type of antenna or transmission line. Referring to Fig. 6 there is shown a two-dimensional array 60 of dipole antennas which are interconnected in accordance with the present invention. That is, symmetrically disposed dipole antennas 61, disposed in two parallel rows of four dipoles each, are connected together with equal lengths of two-wire transmission line 62. On the other hand, there is illustrated in Fig. 7, a linear array 64 of four paraboloid antennas 65. Symmetrically disposed paraboloid antennas 65 are connected together with equal lengths of coaxial line 66. It is to be noted that the device of the present invention will not operate over a wider angle of incidence than that for which a single antenna is adapted to operate. In the present case, paraboloid antennas may be adapted to operate over a wide angle of incidence by making the diameter of the paraboloids comparatively small. For example, a paraboloid having a diameter approximately equal to two free-space wavelengths at the operating frequency will operate over an angle of incidence of the order of 30°. Still further, each antenna may constitute an individual array 68 of crossed-dipoles. In this case the symmetrically disposed individual arrays 68 are interconnected with four-wire transmission lines 70, 71. Desired changes in the polarization of the reflected wave may be achieved by appropriate connections with the four-wire transmission lines 70, 71 and the individual elements of the crossed-dipole arrays 68 or by the addition of appropriate phase shifters. For example, the polarization of a horizontally or vertically polarized wave may be rotated 90° by interconnecting the horizontal elements of one individual array 68 to the vertical elements of its associated individual array 68. Also, right circular or elliptical polarization may be transformed to left circular or elliptical polarization, respectively, by inserting a phase shifter in one pair of the four-wire transmission lines sufficient to delay the phase of the associated linear component by approximately 180°.

As stated above, it is sometimes desirable to reflect an incident electromagnetic wave in a predetermined direction with respect to its original angle of incidence. A device for accomplishing this result in accordance with the present invention is shown in Fig. 9. Referring to

this figure, the device comprises first and second linear arrays 72 and 73, respectively, of horn antennas. The arrays 72 and 73 are of the type shown and described in connection with Figs. 1 and 2. The antenna horns of array 72 are each connected to either similarly or symmetrically disposed antenna horns of the array 73 with transmission lines 74—77 of equal electrical length.

In operation, a wave W_3 having a phase front represented by line 80 is incident on the array 72 at an angle α. In that the antennas of the arrays 72, 73 are interconnected with transmission lines of equal electrical length, it is evident that the portions of the phase front 80 of a wave W_3 received by the array 72 will be radiated by the corresponding antennas of array 73 in the same sequence as received. Thus the energy radiated by the antennas of array 73 will reinforce along a phase front represented by a line 82 to form a reflected wave W_4 which will leave the array 73 along a path at an angle β therewith which is equal to the angle α i.e., the angle at which the wave W_3 was incident on the array 72. The angle β, of course, may be made positive or negative dependent upon whether the antennas of array 72 are connected to similarly or symmetrically disposed antennas of array 73. Also, since the flow of energy through the waveguide sections 74—77 is uni-directional in this device, it is evident that amplifiers of uniform gain and phase delay may be inserted in the waveguide sections 74—77 without departing from the spirit and scope of the invention.

What is claimed is:

1. A passive electromagnetic device for receiving an incident electromagnetic wave and transmitting said wave back in the direction from whence it came, said device comprising a linear array of no less than four antennas, and means providing electromagnetic paths of equal length between antennas disposed symmetrically with respect to a geometrical center of said linear array.

2. A passive electromagnetic device for receiving an incident electromagnetic wave and transmitting said wave back in the direction from whence it came, said device comprising a two-dimensional array of no less than four antennas, and means providing electromagnetic paths of equal length between antennas of said two-dimensional array that are symmetrically disposed about a geometrical center of said array.

3. A passive electromagnetic device for receiving an incident electromagnetic wave and retransmitting said wave in a direction related to the direction of incidence, said device comprising an antenna array having a plurality of pairs of antennas, the antennas in each of said pairs being symmetrically disposed about a common geometric center point of said array, a plurality of substantially electrically identical transmission paths, the antennas in each of said pairs being interconnected with each other by means of one of said transmission paths whereby a portion of an incident wave received at one section of said antenna array will be retransmitted from another section of said array which is symmetrically disposed about said geometrical center point, each of said transmission paths includes means for delaying the phase of one of the linear components of an elliptically polarized incident wave by approximately 180° so as to reverse the polarization of the retransmitted wave.

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