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Phelan

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[45] **Dec. 9, 1975**

[54] ANTENNA ARRAYS OF INTERNALLY PHASED ELEMENTS

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[73] Assignee: **Radiation Incorporated,** Melbourne, Fla.

[22] Filed: **Feb. 6, 1974**
[21] Appl. No.: **440,182**

Related U.S. Application Data

[63] Continuation of Ser. No. 192,869, Oct. 27, 1971, abandoned.

[52] **U.S. Cl.** **343/754;** 343/854; 343/895
[51] **Int. Cl.^{2}** **H01Q 19/00**
[58] **Field of Search** 343/754, 854, 895, 797

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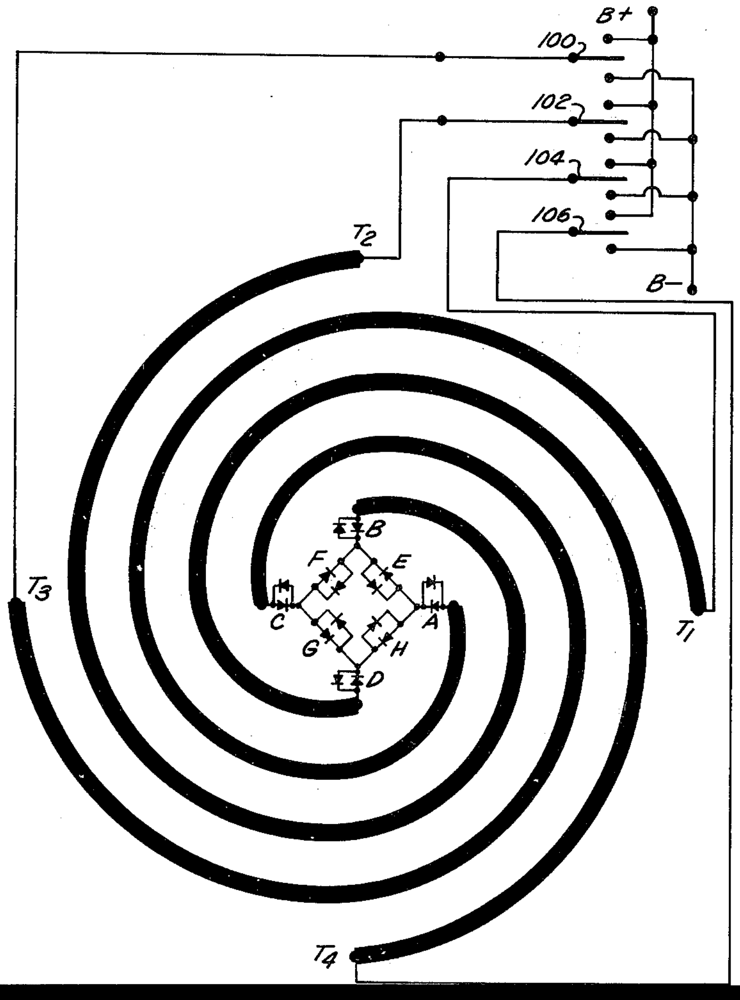
Primary Examiner—Eli Lieberman

[57] **ABSTRACT**

An antenna array which receives radio waves and reradiates them in a controllable direction. Direction of the reradiated wave is controlled by controlling the phase relationship between waves reradiated from individual antennas which are elements of the complete array assembly. Phase control of the individual element antennas is effected by altering the relative phase between the received wave and the reradiated wave for each individual element antenna. The phase of the received signal is controlled at terminals on the individual antennas at which that received signal arrives. The phase-altered signal is reapplied to those terminals to serve as an excitation signal for the antenna for causing a reradiated wave to be emitted. The difference between the direction of the reradiated wave and the direction of the received wave is controlled by diode switches or by varactor diodes (or by both) which can be mounted integrally with the individual element antennas of the array assembly.

30 Claims, 19 Drawing Figures



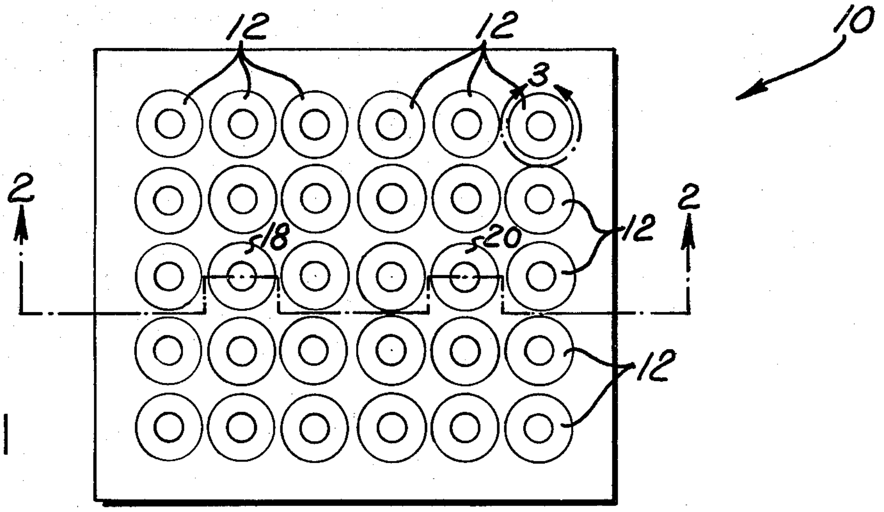


FIG. 1

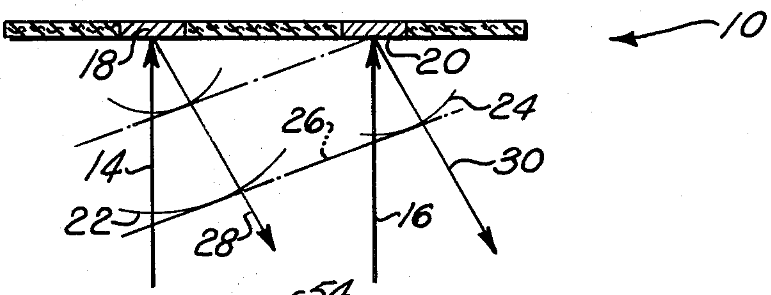


FIG. 2

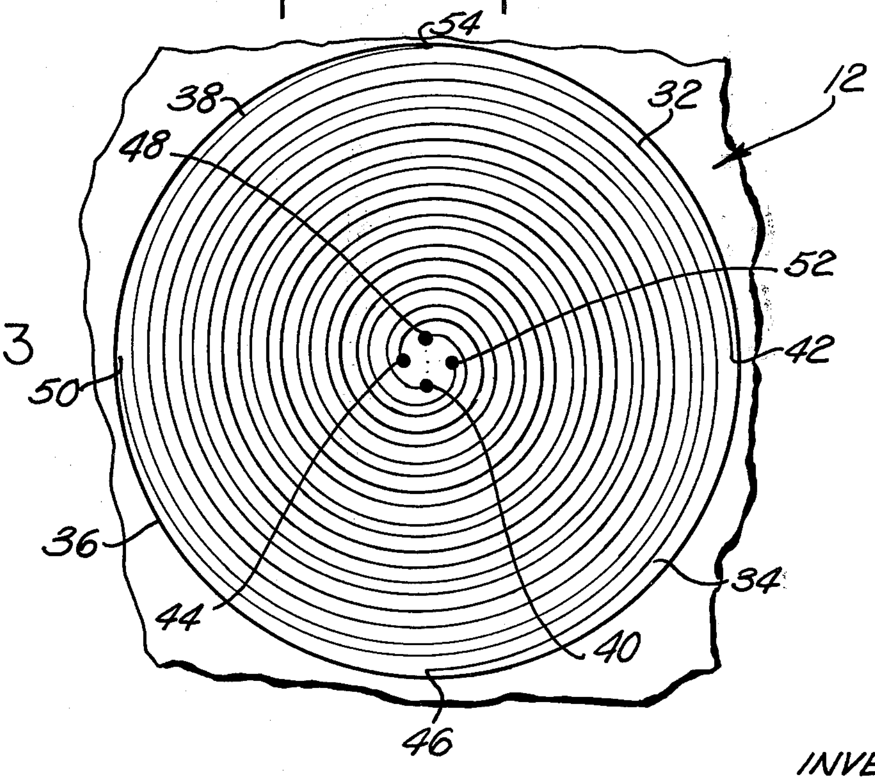


FIG. 3

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ATTORNEYS

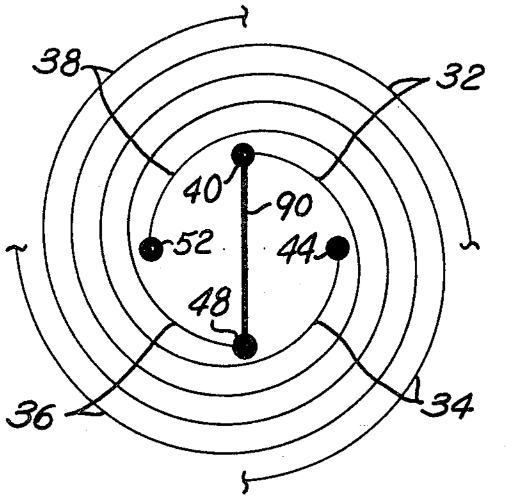

FIG. 4

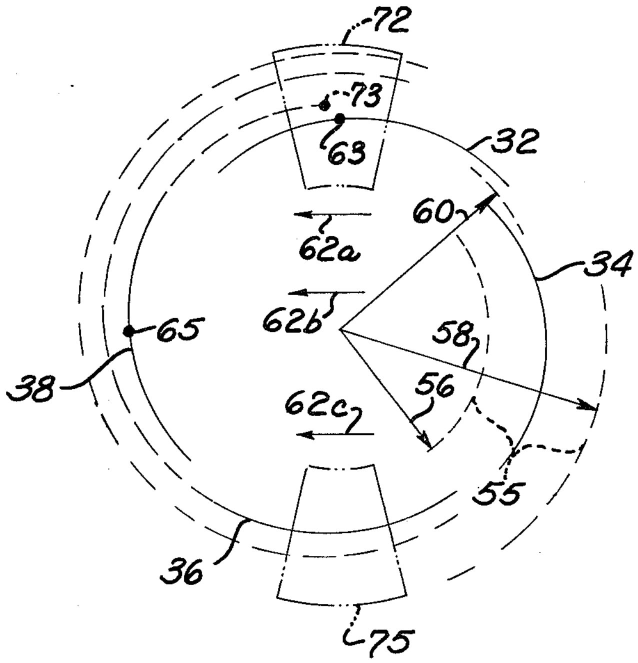

FIG. 5

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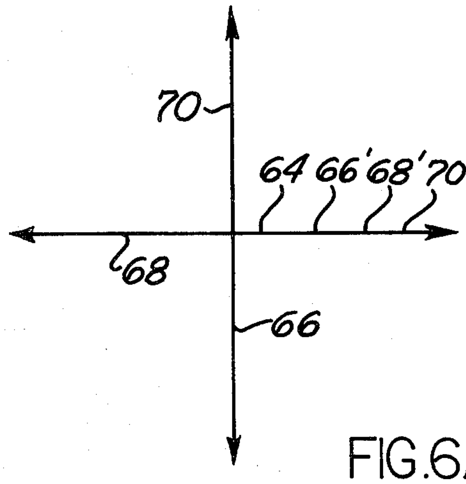


FIG.6A

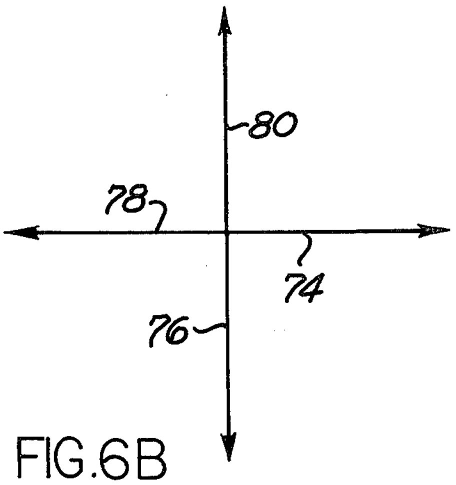


FIG.6B

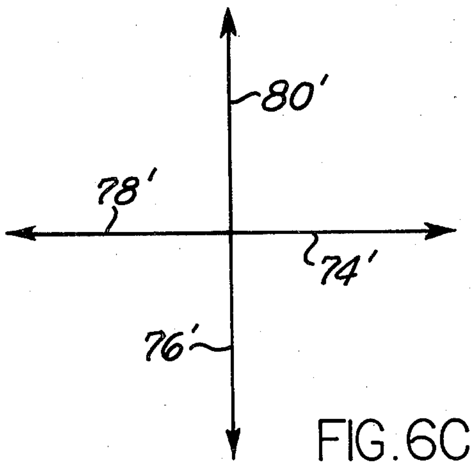


FIG.6C

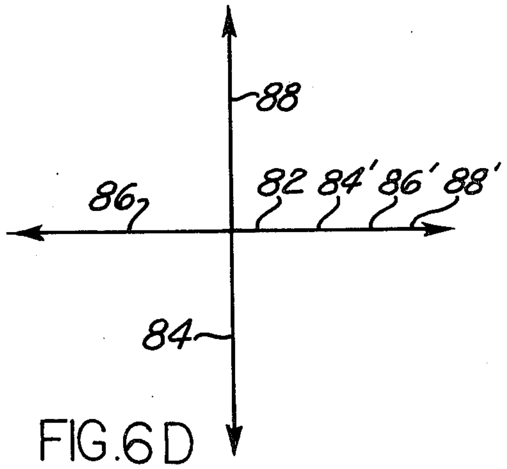
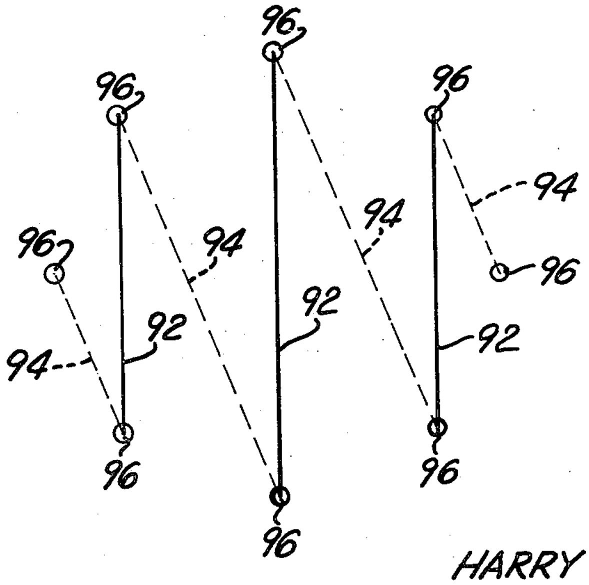


FIG.6D

FIG.7



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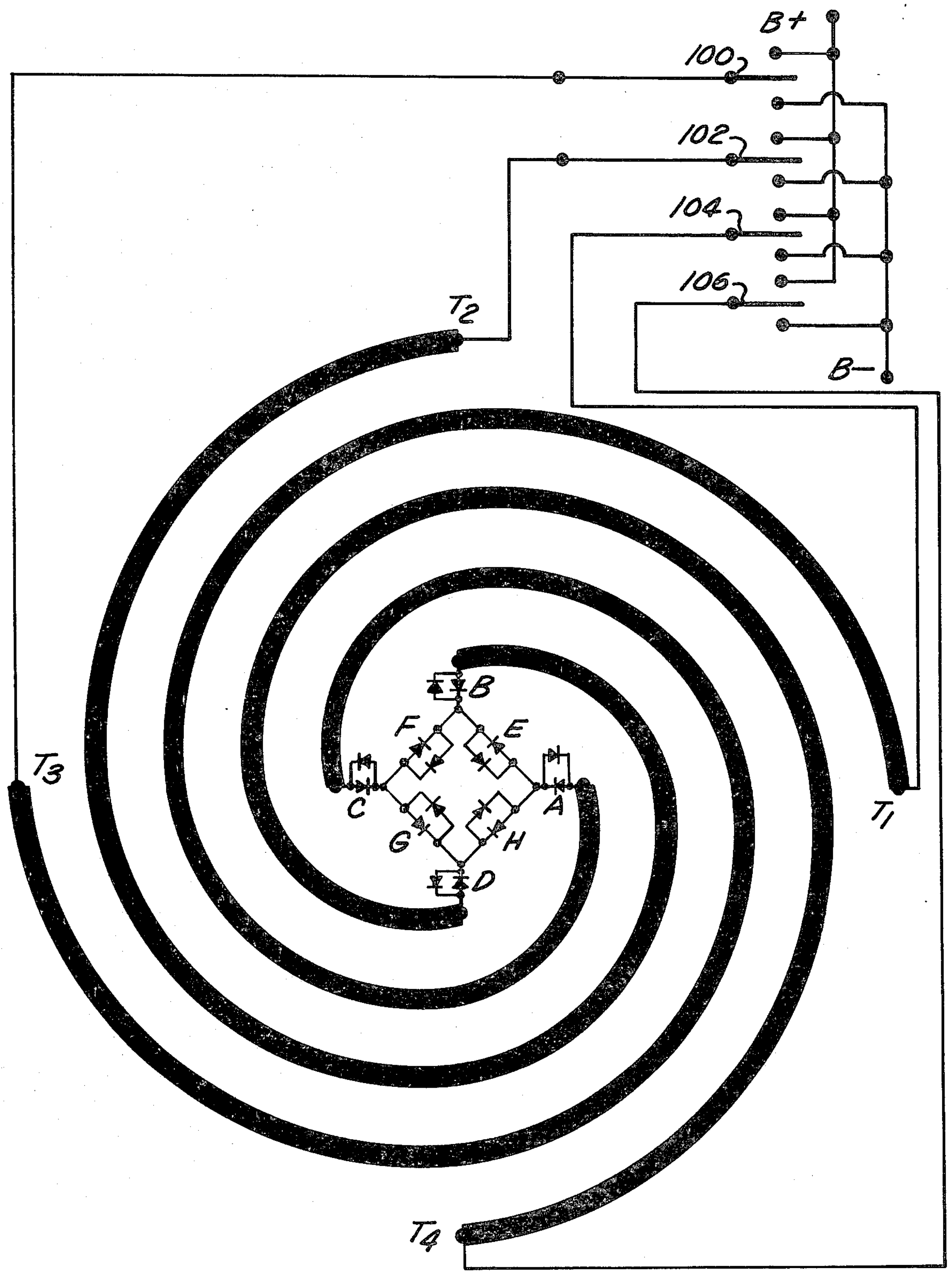

FIG. 8

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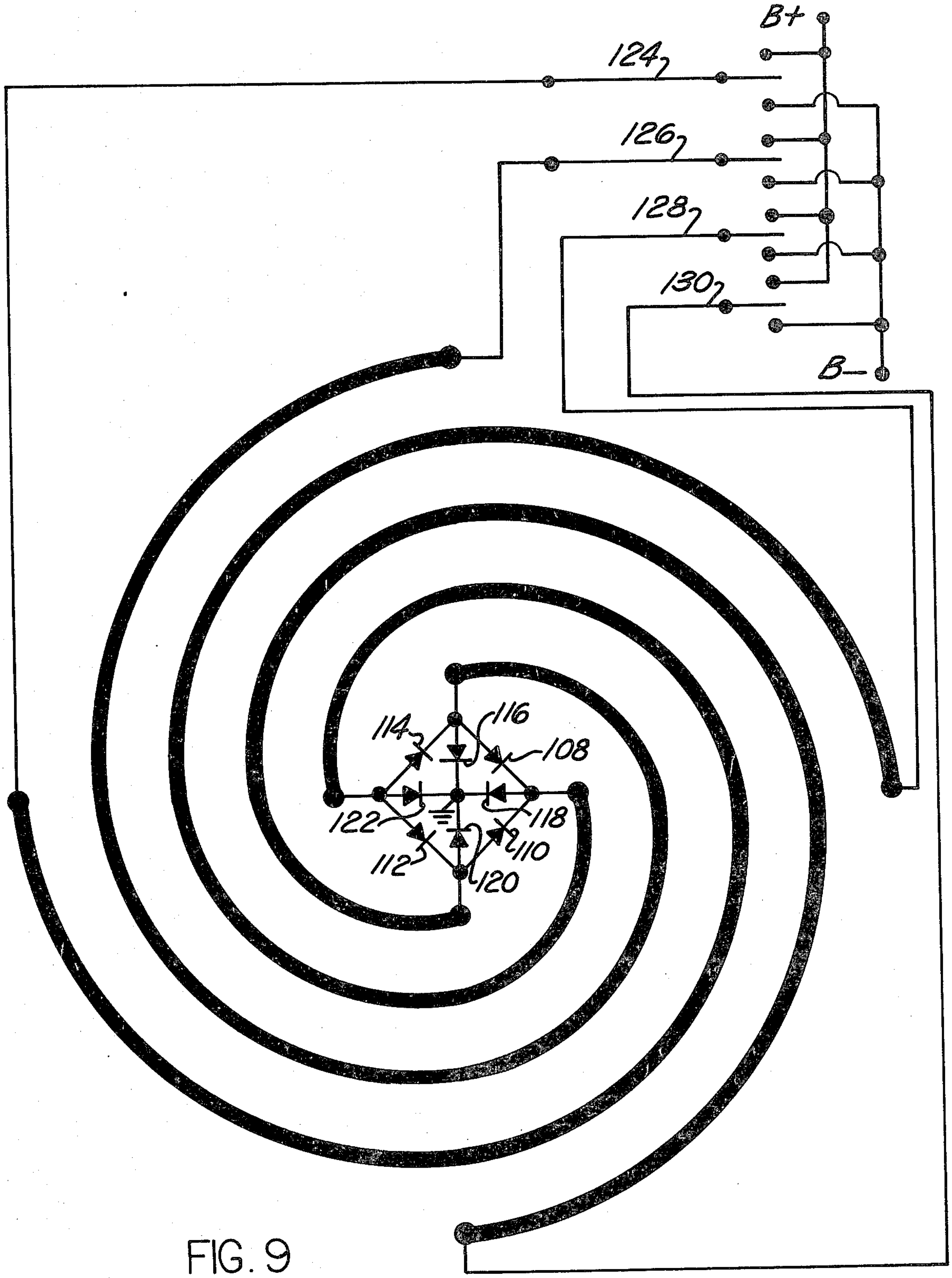

FIG. 9

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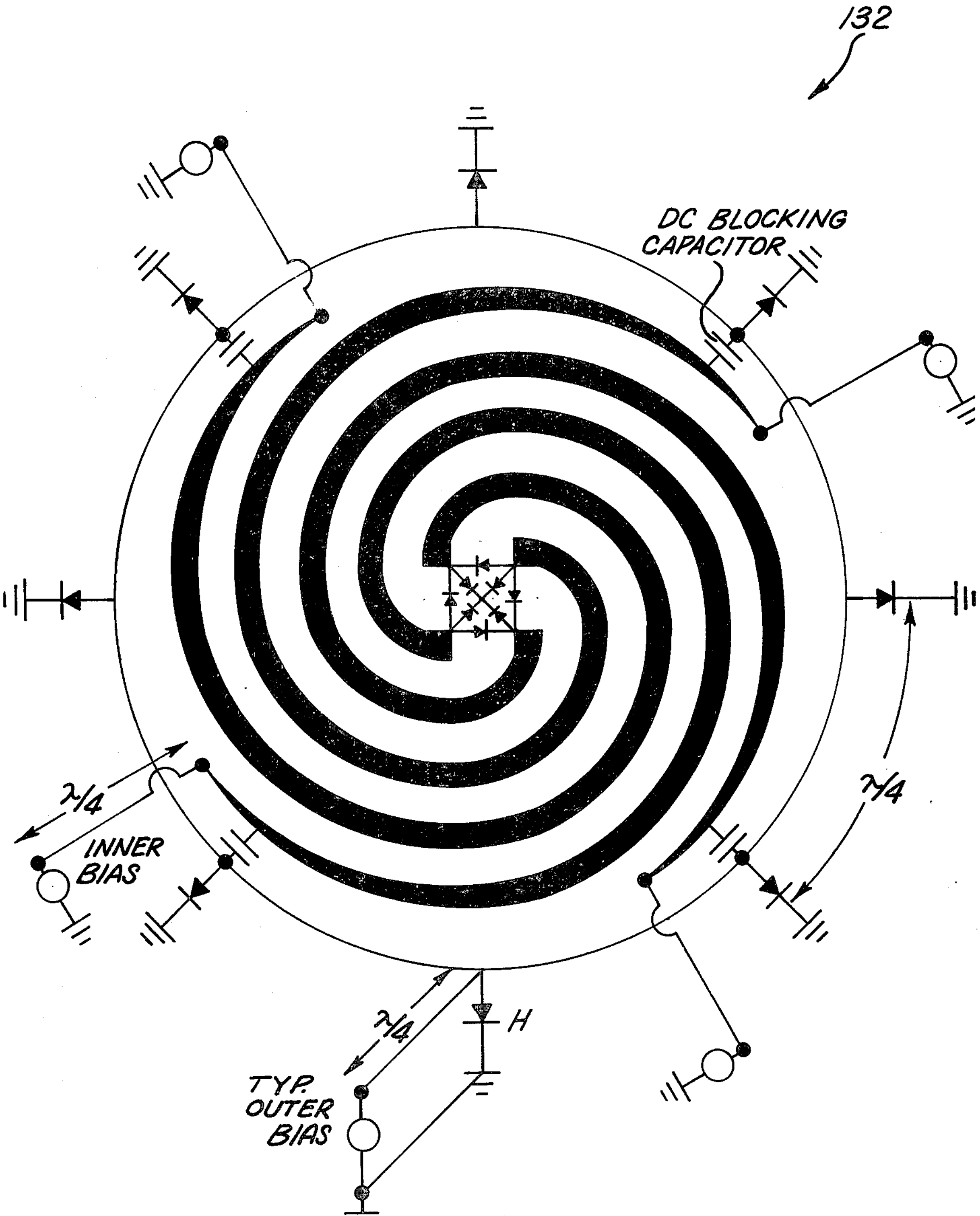

FIG.10

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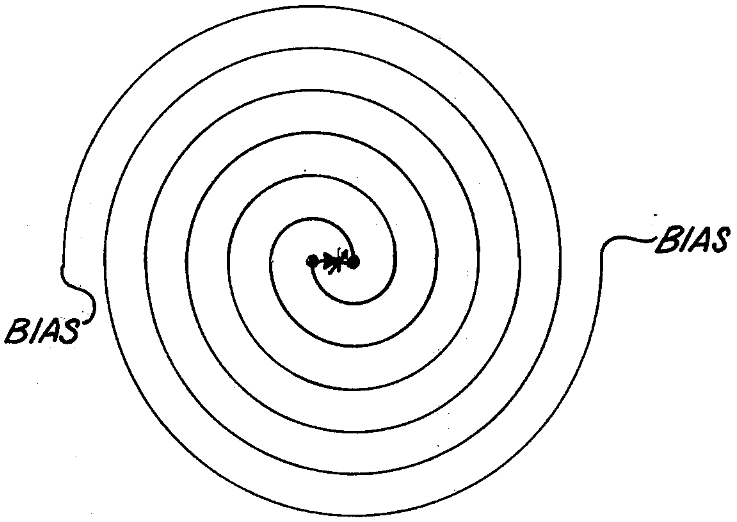

FIG. 11

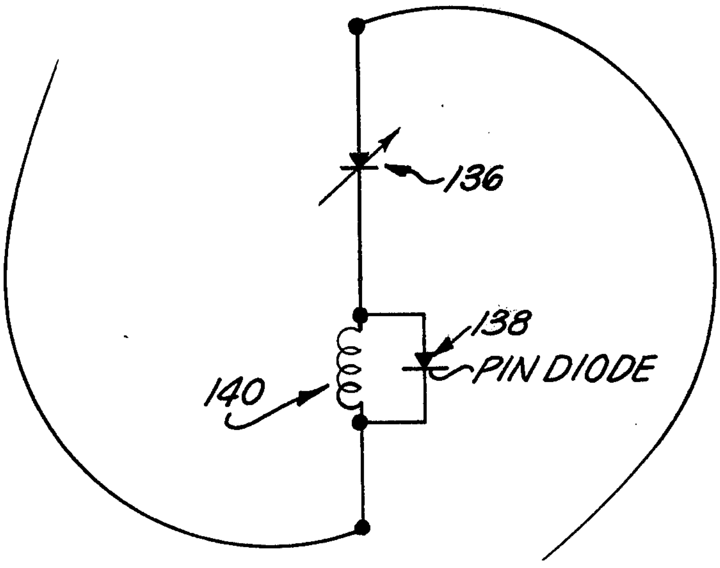

FIG. 12

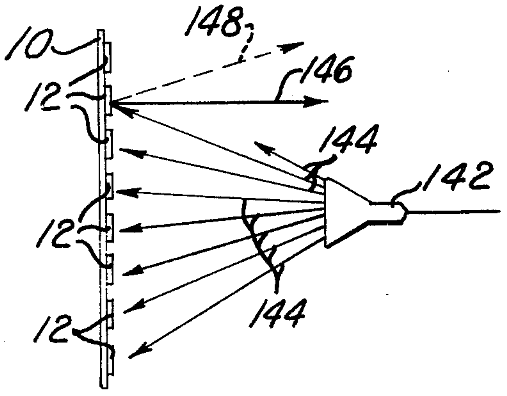

FIG. 13

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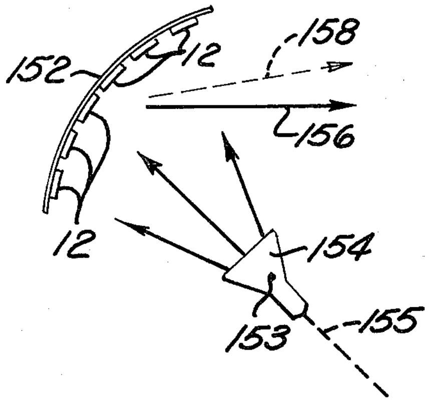

FIG. 14

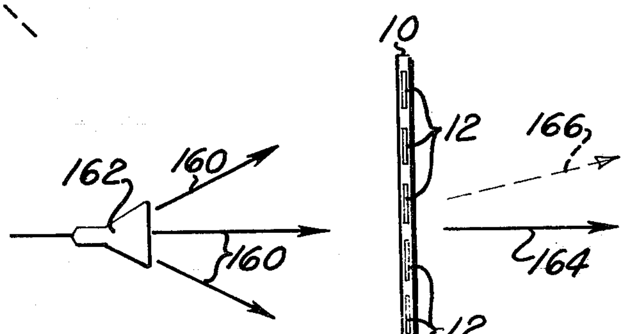

FIG. 15

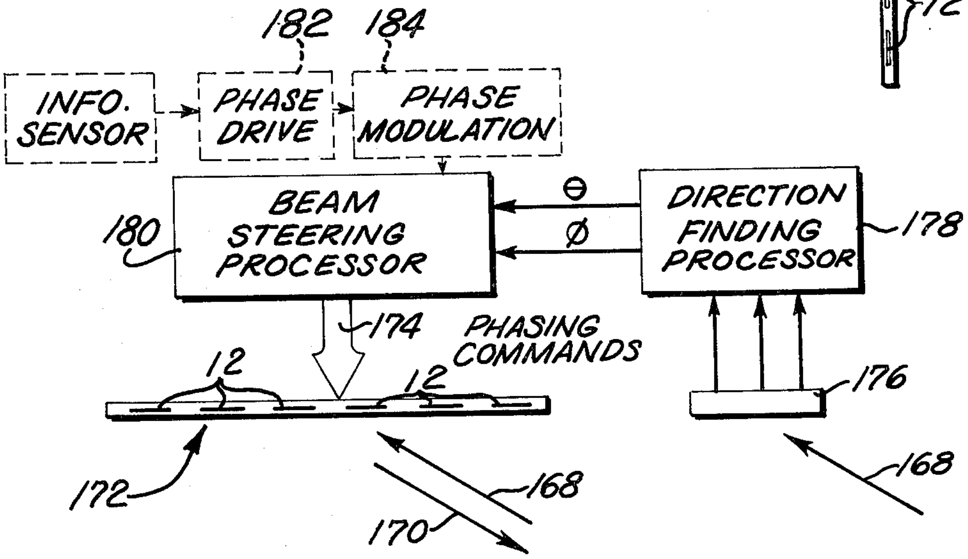

FIG. 16

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ANTENNA ARRAYS OF INTERNALLY PHASED ELEMENTS

This is a continuation of application Ser. No. 192,869, filed Oct. 27, 1971, now abandoned.

This invention relates to an antenna comprising a plurality of individual element antennas assembled in an array. It particularly relates to passive antenna applications in which no transmitter or receiver is connected directly to terminals of the array assembly, but rather in which the array assembly effectively reflects or redirects the radiant energy from a primary radiator. The direction of transmission of the reradiated wave is controllable, without the use of moving parts.

The antenna array assembly may be circularly polarized. It is suitable for reradiating, as a return signal, energy received from a distance source of radio transmission (retrodirective array); or for reradiating radio energy in a controlled direction from a nearby feed horn or other primary source of excitation in front of it, (reflectarray); or for reradiating in lens fashion a radio frequency wave which excites the array assembly from behind it (lens array).

Other antenna array assemblies capable of controlling the reradiation angle of an impinging radio wave are known in the prior art. One of them is an array of spiral individual antenna elements, each of which can be rotated about its individual principal axis perpendicular to the plane of the antenna in order to control the relative phases among reradiated waves from the element antennas of the array. The relative phases are changed by mechanically rotating the individual element antennas if they are circularly polarized.

In the present invention, no mechanical motion is required; instead the phase of the wave that is reradiated from an individual element antenna is changed by "electrically rotating" the antenna.

The basic scheme for controlling the amount of phase change accomplished within an individual element antenna between the received wave and the reradiated wave is to receive the wave on element antennas of a type having a plurality of arms, such as the arms of a spiral antenna. The arms must have a spatial configuration such that they receive signals differing in electrical phase from one another, although they are received from the same incoming wave.

each element antenna of the array assembly has several arms. The received signals on the various arms can be cross-connected to each other so as to interchange signals among the arms. As a result, the antenna arms have a different set of phase relationships to each other for reradiation purposes than they had when receiving the wave originally. The phase relationships among arms for reradiation are controllable with respect to those of the received signals so as to change the phase of the reradiated wave with respect to that of the received wave. Thus, for purposes of reradiation, signal phases exist on the arms that differ among the arms but which collectively are appropriate to reradiate a wave having a particular phase relationship to the received wave.

As alternatives, instead of having the phases of the arms interchanged by crossconnecting the arms, the signals can be individually phase shifted. Moreover, they can be both crossconnected and phase shifted.

Accordingly, it is a principal object of the present invention to provide an antenna capable of receiving a radio wave and reradiating it, in which the phase of the reradiated wave relative to the phase of the received wave is conveniently controllable.

Another object is to provide an antenna capable of operation over a wide range of frequencies without readjustment because of frequency differences, in which the phase of a reradiated wave relative to a received wave is simply and inexpensively controllable without the necessity for any mechanically movable parts.

Yet another object of the present invention is to provide a phase-adjustable antenna having a simple phase adjustment method and low insertion loss because of the elimination of extraneous transmission lines.

A further object is to provide an antenna that is capable of convenient deployment in an array with other like antennas for portable use because the array may be cut between any element antennas for folding and because the array is thin.

A further object is to provide a reflectarray type of antenna array that is steerable as to direction of reradiation by controlling externally applicable DC biasing voltages.

A still further object is to provide a retrodirective antenna array whose principal direction of radiation of a response signal is controlled by DC bias potentials.

And a still further object is to provide a lens antenna array whose direction of reradiation is easily steerable by means of bias potentials applied to it.

Other objects and features of the invention will become apparent upon aa consideration of the following description of a presently preferred embodiment taken in conjunction with the accompanying drawings wherein:

FIG. 1 is a view of an array assembly of element antennas suitable for use as part of either a retrodirective array or a reflectarray or a lens array;

FIG. 2 is an edge view of the array assembly which illustrates the steering of a reradiated radio beam by phasing of the element antennas;

FIG. 3 shows one individual element antenna of an array assembly, the element shown being a four-arm spiral antenna;

FIG. 4 is an enlarged view of the center of one element antenna with two of the four spiral arms connected together at their inner ends;

FIG. 5 shows an annular ring which is a portion called the active zone of an element antenna;

FIG. 6A is a phasor diagram showing relative phases of currents induced in arms of an element antenna at an active zone, by a received radio wave;

FIG. 6B is a phasor diagram showing relative phases of induced arm currents which have travelled spirally in an inbound direction, as they exist at the inner ends of the arms;

FIG. 6C is a phasor diagram showing the relative phases of currents reapplied to the inner ends of the arms for transmission out to the active zone;

FIG. 6D is a phasor diagram showing the relative phases of arm currents that cause reradiation of radio energy at the active zone of an element antenna;

FIG. 7 shows two connection plans for interconnecting the arms of an element antenna at the inner ends of the arms;

FIG. 8 shows an arrangement of switching diodes connected to the inner ends of a four-arm spiral antenna and provided with external means for switching DC biasing potentials to them via the outer ends of the spiral arms;

FIG. **9** is another possible arrangement of switching diodes connected to the inner ends of the arms of a spiral antenna;

FIG. **10** is a spiral antenna having diodes connected between outer ends of the spiral arms and ground terminals;

FIG. **11** illustrates the use of a varactor diode for phase shifting at the inner ends of spiral antenna arms;

FIG. **12** is yet another version of a phase control system showing the use of a varactor diode together with a PIN diode connected to ends of the spiral arms of an element antenna;

FIG. **13** shows a reflectarray antenna consisting of a primary radiator and a planar reflectarray utilizing the present invention;

FIG. **14** shows a version of the reflectarray, excited by a primary horn radiator, wherein the spiral element antennas are mounted so as to form a curved surface;

FIG. **15** is a lens antenna array illuminated from its back by a primary radiator; and

FIG. **16** is a retrodirective antenna system for radiating a return wave back to a remote transmitter from which a wave has been received.

The principle of the invention can be implemented structurally in one embodiment in the following way. A number of structural arms are provided on each element antenna, geometrically so arranged that a single incoming radio wave excites currents of differing electrical phase in the various structural arms. These received currents are routed, at terminals of the arms to different arms from those upon which they are received, but still within the same element antenna, or are reflected back along the same arm, so that a different set of phase currents appears on the structural arms for reradiation purposes. The current phases differ among the arms but they are nevertheless, as a set, appropriate for reradiating a single phase of wave because of the spatial relationship between the arms. By changing the selection of arms to which the received arm currents are routed for reradiation, the set of current phases on the structural arms can be changed, thereby altering the phase relationship of the reradiated wave to the received wave and making it different from previous values of that phase relationship. This control can be effected by diode switching or by varactor diodes, or by both, at the terminals of the structural arms.

FIG. **1** is a front view of one embodiment of an array assembly **10** suitable for use as either a reflectarray, a retroreflective array or a lens array. It is illustrated herein as a planar structure, although other structures are contemplated, consisting of a number of rows and columns of individual element antennas. The individual element antennas are multiple-arm spiral antennas suitable for transmitting and receiving circularly polarized radio waves. When a radio wave is arriving from, for example, the front of the array assembly **10**, energy is being received by the element antennas **12**. The portion of the energy which the element antennas **12** accept is conducted through their spiral arms to ends of the arms, usually the inside ends, and then flows back along the arms to the same portion of each antenna at which it was received, that is, to the same annular ring region. There they reradiate radio energy so as to launch a wave that propagates outward from the array assembly. All of the element antennas of the array operate in this manner at the same time, and collectively they cause a single electromagnetic wave to be reradiated from the array assembly as though it had been reflected from the array assembly.

The angle of departure of the reradiated wave from the array assembly depends upon the angle of arrival of the incident wave and upon the control settings of external DC biasing means which controls switching diodes or phase shifters located near the center of each element antenna. Changing the phase relationships among element antennas of an array assembly causes a wave to be radiated in a different direction. In FIG. **2** an array assembly **10** is shown in edge view. It consists of a number of element antennas **12** deployed over a planar surface in a grid arrangement or any other pattern in which the individual element antennas are close enough together to give a suitably smooth antenna radiation pattern as measured in the far field. A planar electromagnetic radio wave symbolized by the vectors **14** and **16** is shown impinging normally on the array assembly, having been propagated there from some transmitting antenna not shown.

The energy represented by vector **14** is received by an element antenna **8** lying in the surface of the array assembly, and is reradiated on a wave front **22.** Similarly, energy captured by an individual element antenna in the region of vector **16** is reradiated in a hemispherical contour represented by the circle arc **24.**

If the phase of wave **22** that is reradiated from element antenna **18** leads the phase of wave **24** which is reradiated from element antenna **20,** the instantaneous phase of the radiated wave at circle arc **22** will be the same as the phase at that instant of the wave at circle arc **24,** but the wave from element antenna **20** has not then propagated outward as great a distance as has that from element antenna **18.** Consequently, the dotted line **26** represents an advancing phase front of a resultant wave being reradiated from element antennas **18** and **20** together. If all of the element antennas across the face of the array assembly are properly phased so as to act in concert, they collectively create a wave front such as that shown by dotted line **26** across the entire face of the array assembly, which advances from the array assembly in a direction shown by **28, 30** normal to that wave front line.

The direction of the reradiated wave can be controlled by controlling the relative phases of excitation of the individual element antennas of the array assembly.

One type of element antenna that is suitable for the array assembly of this invention is a multiple-arm spiral such as that shown in FIG. **3.** This antenna consists of four spiral arms **32, 34, 36** and **38,** all electrically insulated from each other. It may be constructed by printed circuit techniques wherein the four individual arms are conductive copper strips on the surface of a plastic substrate. The arm **32** has an inner end **40** and an outer end **42.** The inner and outer ends of arms **34, 36** and **38** are designated by numbers **44** and **46, 48** and **50, 52** and **54,** respectively, as shown in FIG. **3.**

As element antenna **12** is performing its receiving function currents are induced in each of its four arms in a portion of the arms at a distance from the center which depends upon the frequency of the radio wave received. With a particular direction of rotation of circular polarization of the received wave, the induced current travel inwardly along the spiral arms which serve as transmission line until they arrive at the inner ends having terminals **40, 44, 48** and **52** of the arms.

As the antenna is performing its transmitting function, antenna excitation currents enter the arms at the same terminals **40, 44, 48** and **52** and are transmitted in spiral paths outwardly along the arms until they arrive at a place on the antenna which is suitable for radiating waves of the frequency of the excitation employed, as described in more detail below. The receiving and transmitting functions can occur continuously and simultaneously.

FIG. **4** shows one manner connecting the inner terminals of an element antenna. The conductive link **90** between terminals **40** and **48** can, in practice be a switching diode. Another switching diode can be provided to connect terminals **44** and **52** together at times when link **90** is opencircuited, to create a **180°** different phase shift than that which exists when link **90** is conductive. The **180°** phase shift occurs because changing the diode states effectively rotates the antenna **90°** because the phase shift realized is equal to twice the effective mechanical rotation. More details of the switching of links are given later.

Energy is received on each spiral antenna and reradiated from a portion of the antenna called the active zone, whose position varies depending upon the frequency of the radiation. FIG. **5** shows an annular ring **55** which represents one portion of an individual element antenna **12;** its boundaries are circles of radii **56** and **58.** The active zone or sensitive zone is not sharply defined; instead the sensitivity of the antenna progressively increases with increasing radius and then progressively decreases with further increasing radius and has a maximum sensitivity at some radius such as **60** on FIG. **5,** which is termed the mean radius of the active zone herein. Portions of the spiral arms of the antenna having smaller radial locations than radius **56** or larger radial locations than radius **58** do not radiate or receive energy very efficiently at the particular frequency under discussion. Those portions do not serve as an efficient coupling mechanism between the conductive circuit of the antenna arms and the wave transmission medium, so that radiation from such areas outside the active zone is negligible.

FIG. **5** is useful for describing electrical and structural phase relationship among the currents on the arms. Portions within the active zone of all four arms of a fourarm antenna are shown in FIG. **5;** other portions of these arms are omitted from FIG. **5** for simplicity. When this antenna is receiving a circularly polarized electromagnetic wave that falls upon it, the electric field vector of the received wave at the plane of the antenna may be represented at one instant of time by vectors **62***a*, **62***b* and **62***c*. Electric field vector **62***a* induces a counterclockwise current in spiral arm **32** within the active zone and vector **62***c* induces a clockwise current or negative current in arm **36** within the active zone. The current induced by transverse vector **62***b* in arm **38** and **34** at that instant is negligible at mean radius **60.**

The current induced in the active zone portion of arm **32** propagates spirally inward along arm **32** to its inner terminal **40.** At the same time and at the same velocity of propagation, the negative current induced in the active zone portion of arm **36** by electric field vector **62***c* propagates inwardly along spiral arm **36.** It arrives at the inner terminal **48** of arm **36** at the same time that the current induced in arm **32** by electric field vector **62***a* arrives at terminal **40.** Since the current directions induced in arms **32** and **36** were opposite in sense, the arriving currents are **180°** out of relative phase at terminals **40** and **48.** Currents at terminals **44** and **52,** which are the inner terminals of arms **34** and **38,** respectively, are 9° out of phase with the currents at terminals **40** and **48.**

Because the received electromagnetic wave is circularly polarized, the electric field vectors **62***a*, **62***b* and **62***c* rotate so that the maximum value of induced current of one polarity is induced sequentially in arms **32, 38, 36** and **34,** for one sense of rotating polarization. The maxima of current waves that are induced arrive sequentially at the terminals **40, 52, 48** and **44** and, therefore, those terminals have a rotating phase sequence of received currents.

The relative phases of currents in the antenna at the active zone are shown in FIG. **6A.** Phasor **64** represents a current at a point **63** on arm **32** where arm **32** crosses the mean circle **60** of the active zone, and serves as a reference phasor for this diagram. Current phaser **66** represents a current in arm **38** at a point **65** where arm **38** spirally crosses the mean circle **60** of the active zone. Similarly, the phasors **68** and **70** represents currents induced in arms **36** and **34** at points where those arms cross the mean radius circle of the active zone.

The circumference of the mean circle of the active zone is approximately one wave length of the waves being propagated along the arms, this wave length being slightly greater than a free space wave length because the velocity of propagation on the arms is slightly smaller than the free space velocity. In the active zone, there is approximately a **360°** phase shift standing on any arm of the spiral antenna around one complete loop of the spiral at one instant of time.

If the currents within one angular sector, such as sector **72** of FIG. **5** are examined as to phase, all portions of all arms therein are found to have approximately the same phase of current, in and near the active zone. Phasor **66,** which represents the phase of the current on arm **38** at the mean circle of the active zone, lags by **90°** the phase of current at a point **73** on arm **38** within the angular sector **72,** because point **73** is displaced **90°** structurally clockwise around the spiral from the point **65** where phasor **66** exists. Thus, the current in arm **38** at point **73** can be represented in FIG. **6A** by phasor **66′** which is leading the current phasor **66** by **90°.** Phasor **66′** is seen to be in phase with current phasor **64** of arm **32,** within the angular sector **72.**

Similarly, the current on arm **36** within angular sector **72** is leading phasor **68** by **180°** and can therefore be represented by phasor **68′**, which is in phase with phasor **64.** In the same way, the current on arm **34** within the angular sector **72** can be represented by pahsor **70′** which is leading phasor **70** by **270°** because of the structurally-caused phase difference along arm **34,** spanning the three-fourths of a full turn from the point on arm **34** where it crosses the mean circle of the active zone, to the point where that arm is within sector **72.** All of the current within sector **72** are therefore seen to be of the same phase, such as would be induced by a single electric field vector **62***a*.

Moreover, for radii within the active zone, each arm may be contributing to the effective coupling of energy from space from the antenna by more than merely that portion of the arm which crosses the mean radius of the active zone. Other convolutions of each arm at smaller and larger radii within the active zone contribute somewhat also, although they are not quite as effective in contributing to the operation of the antenna as is the particular convolution which crosses the mean radius of the active zone.

FIG. **6B** shows that current induced in the arms **32, 38, 36** and **34** of the spiral antenna differ in phase by progressive **90°** steps at the inner ends **40, 52, 48** and **44** of those arms, as shown by phasors **74, 76, 78** and **80,** respectively, of FIG. **6B,** which represent the received currents at those terminals. This relative phase relationship is the same as the phase relationship between currents on the respective four arms at the places where those four arms cross the means circle of the active zone, because all four currents travel inward along the spiral conductors with the same propagation velocity from the active zone to the inner terminals of the antenna.

When the spiral antenna element is considered as a transmitting antenna, its operation is similar to that described above for receiving purposes, except that the direction of propagation of energy is outward along the spiral transmission lines from the inner terminals to the active zone. The four phasors **74', 76', 78'** and **80'** of FIG. **6C** represent currents applied to the terminals **40, 44, 48, 52,** respectively, of the antenna for purposes of radiating energy into space. It should be noted that phasor **76'** is applied to terminal **44,** not to terminal **52.** The sequence of events is as follows: The currents at the inner terminals which are in **90°** clockwise phase progression with respect to each other around the four terminals, propagate outward, each along its own arm, at equal propagation velocity. They arrive simultaneously at the mean radius **60** of the active zone of the antenna and have, at the radius, a relative phase relationship shown by phasors **82, 84, 86** and **88** in FIG. **6D.** These are the relative phases at the active zone of currents on the four arms **32, 34, 26** and **38,** respectively. Tracing a wave clockwise around the active zone on, for example, arm **38,** whose current on the mean radius is represented by phasor **88,** there is seen to be a **90°** phase lag in traversing the structural quarter-circle from point **65** to point **73** in zone **72.** Consequently, the phase of the current on arm **38** within sector **72** is represented by phasor **88'**, which is seen to be in phase with the current **82** on arm **32** within that angular sector. Arms **36** and **34** contribute currents **86'** and **84'** in zone **72,** which are also in phase with current **82.**

It can be shown in a similar manner that all four arms contribute currents of mutually reinforcing phase at a sector **75** diametrically opposite sector **72** in the active zone. Those currents are instantaneously **180°** out of phase electrically with the currents in sector **72.** However, because the portions of the arms in sector **75** are mechanically pointing in an opposite direction from their direction within sector **72,** the structural phase reversal due to this change in mechanical direction of the arms cancels the **180°** electrical phase reversal. As a result, the currents in sector **75** travel in the same space direction as those in sector **72** so that they cooperate with the currents in sector **72** to induce an electromagnetic wave in space. That is, because the currents in angular sectors **72, 75** are instantaneously in the same space direction, for example, from left to right, they reinforce each other in producing an electromagnetic wave for propagation into space from the antenna.

When an element antenna such as **12** is utilized in the present invention as an element of an array, it must function as both a receiving antenna and a transmitting antenna. The manner in which the spiral antenna functions as a receiving antenna was described above, culminating in currents at the inner terminals of the arms **40, 44, 48** and **52.** The transmitting mode of operation of the antenna was also described, starting with the application of currents to the inner antenna terminals **40, 44, 48** and **52** and culminating in the radiation of an electromagnetic wave from the antenna because of resulting currents in the active zone. Although the receiving and transmitting functions of an element antenna were described above as occurring in a time sequence, they can be contemporaneous and continuous, and therefore reception and re-radiation can occur simultaneously.

In the antenna of the present invention, the currents which are applied to the terminals **40, 44, 48** and **52** for transmitting purposes can be the same currents which are received at those terminals from the same group of antenna arms in the receiving mode, but shifted as to phase by a greater or less amount either by phase shifting devices or by swapping currents among the arms by interconnections. Phase changing can be accomplished in a variety of ways, one of which is simply to leave inner terminals **44** and **52** open-circuited, and to connect terminals **40** and **48** together by a link **90,** as shown in FIG. **4.** Then current waves that propagate inward along the spiral arms reflect when they encounter the opencircuited terminals **40** and **48,** and cause current waves to start to propagate outward along the same spiral arms. The received current of arm **34** becomes, when it reaches the inner terminal **44,** the negative of the transmitting current of that same arm. In the same way, the transmitting current of arm **38** is simply the negative of the received current of arm **38.** The negative relationship exists at the central terminals and may be somewhat different at the active zone.

The received current from arm **32** at terminal **40** is connected through a conductive link **90** to terminal **48** of arm **36** so that the received current of arm **32** becomes a transmitting current of arm **36** and conversely the received current of arm **36** becomes a transmitting current of arm **32.** There is a current cross-over between the two arms through the link **90,** which can be a switching diode.

The direction of sequential phase rotation of transmitting currents among the terminals is the reverse of the direction of phase rotation of the received currents, as it must be if it is to radiate when it reaches the active zone. When the outward propagating wave arrives at the active zone of the antenna, it causes radiation, and the originally impinging radio wave appears to have reflected from the antenna. Reconnecting the link **90** across termianls **44** and **52** instead of across terminals **40** and **48** would cause a different phase shift between receiving and transmitting currents, differing by **180°** from its previous value.

Alternatively, two of the inner terminals could be short-circuited to a small ground plane or common tie point at the center of the element antenna, in which case the currents propagating outward along the short-circuited arms would have the same polarity at their starting terminals as have the received currents.

The relative phase between inward-propagating currents when they originate in the active zone, and outward-propagating when they arrive back at the active zone, is a function of the round trip distance from the active zone in to the inner terminals and back along the spiral arms, and can be expressed in wavelengths on the line. This phase difference between the received wave and the reradiated wave can be altered by changing the connections at the inner terminals **40, 44, 48, 52,** as just described. The phase of the reradiated wave can therefore be made different as between different individual element antennas of an array assembly, even though all of those element antennas are excited by the same received radio wave, by simply making different connections at the antenna terminals **40, 44, 48, 52** of the different element antennas of the array. Not only may the reradiated wave be changed in phase by **180°**, as shown above, but by appropriate connections of the inner terminals, other amounts of phase shift can be accomplished.

FIG. **7** shows, by solid lines **92**, conections that would give a particular phase relationship between received and reradiated waves in an antenna having eight spiral arms. The dotted lines **94** show different connections at the same inner terminals **96** of the antenna arms, which would result in a different phase shift for the same eight-arm spiral antenna.

In a preferred embodiment of the present invention connections between the various arms at their inner terminals are made by means of diode switching. FIG. **8** shows a four-arm spiral antenna with diodes connected to its inner terminals, having capability for applying by means of external switches various positive or negative DC biasing currents to the outer ends of the spiral arms. By selective operation of the switches **100, 102, 104,** and **106,** various diodes can be rendered conductive by being forward biased, thereby effectively connecting together the inner terminals of certain spiral arms. Other connections can be effectively opened by means of voltage back-biasing of their switching diodes, or even by applying zero bias voltage to them, which is insufficient to cause efficient conduction of small signals.

In FIG. **8,** when terminal **T2** receives a positive voltage by having switch **102** in its upper position, and terminal **T4** is given a negative voltage by having switch **106** in its lower position, and terminals **T1** and **T3** have no bias voltage applied because switches **104** and **100** are in their center positions, the following diode pairs are conductive for samll signals: B, D, E, F, G, H. Diode sets A and C do not conduct then. The relative phase of the group of transmitting currents for this condition can be arbitarily called **0°**, so that this is a reference phase condition.

When only terminal **T1** is made positive and only **T3** is negative, only diode pairs B, D are nonconductive. The relative phase of the transmitting currents is then **180°**.

When **T1** and **T4** are positive and **T3, T4** are negative, only diode pairs F and H are nonconductive (because they have zero bias), and the relative transmitting phase is **90°**.

When **T1** and **T2** are positive and **T3, T4** are negative, only diode pairs E and G are nonconductive; the relative transmitting phase is then **270°**.

By operating switches **100, 102, 104, 106** to achieve various biases as just described, the phase of the reradiated wave can be changed in **90°** steps.

FIG. **9** shows another embodiment in which, instead of the inner ends of the spiral arms being selectively connected only to each other, they may either be connected to another arm or connected to a common ground point near the center of the element antenna. Diodes **108, 110, 112** and **114** are employed to connect antenna arms together, while diodes **116, 118, 120** and **112** are used to connect arms to a common ground point. The switches **124, 126, 128** and **130** may be used selectively to control the bias voltages on the various diodes.

The electromechanical switches represented by reference numerals **100, 102, 104, 106, 124, 126, 128, 130** are merely symbolic of any means of controlling the potentials to be applied to the spiral antenna arms and therefore to the switching diodes or varactor diodes. In practice, these potentials would more probably be controlled by static switching circuits and possibly by circuits under computer control.

Digitally switched embodiments of the invented antenna are frequency independent in their performance, because the phase differences among the currents originate in frequency independent structural phase differences among the arms at the active zone. For operation at a lower frequency, the active zone automatically moves out to a greater radius of the element antennas.

When a counterclockwise-rotating circularly polarized wave is received in the active zone shown in FIG. **5,** the received signal propagates inward along the spiral arms because of the manner in which the received wave couples to all of the arms and reinforces the flow of current induced in those arms throughout all of the convolutions of those arms in the active zone. On the other hand, a clockwise-rotating circularly polarized wave impinging upon the element antennas causes outwardly propagating spiral waves which travel along the spiral arms to their outside ends. FIG. **10** shows an embodiment in which diodes H are connected from the outside ends of the antenna **132** to ground. When the antenna receives a circularly polarized wave having such direction of circular polarization as to cause the induced currents to propagate outwardly from the active zone to the outside ends of the spiral arms, certain of the diodes can be biased to conduction to cause currents of the same polarity as the received currents to reflect back inwardly along the spiral arms. The diodes may be switched by application of DC potentials to forward-bias or back-bias the diodes, thereby changing the phase shift. This embodiment is frequency-dependent. The usefulness of this technique is that both senses of circular polarization may be operated on simultaneously and independently.

In another frequency-dependent version of the invented antenna, the switching diodes may be varactor diodes, as seen in the simplified sketch of FIG. **11,** and the capacitance of the diodes may be altered by applying different DC potential biases to them. The phase shift encountered by a current that propagates along an arm to the diode and is then reflected, can be varied by varying the capacitance of the diode under control of the DC potential bias. In this way, the phase shift of the element antenna can be controlled as to the reradiated wave.

FIG. **12** is a combination of an analog and digital form of phase control at terminals of a spiral antenna. Element **136** is a varactor diode and element **138** is a PIN diode which can be either forward-biased to short-circuit the reactance **140** or else back-biased to permit reactance **140** to come into play.

FIG. **13** shows a planar array assembly **10** of the type shown in FIG. **1** utilized in a reflectarray antenna wherein the array assembly is illuminated electromagnetically by a primary radiator such as a circular horn **142** having a circularly polarized element in its throat. Power represented by the vectors **144** strikes element antennas **12** of the array assembly and is reradiated. The direction of reradiation is that shown by arrow **146** for one phasing condition of the element antennas **12.** The wave is reradiated in a different direction **148** when the element antennas **12** are phased in a different manner, by application of a different set of DC potential biases to their diode switches as described above.

In an embodiment employing multi-arm spirals, the spiral elements can be nominally 0.5 wavelength in diameter at the lowest operating frequency and spaced 0.25 wavelength above a continuous reflecting ground plane. The diameter of the reflectarray is related to the antenna gain and beamwidth desired. For example, if a 1° antenna beamwidth is required, the reflectarray aperture must be approximately 70 wavelengths in diameter. If D is the reflectarray diameter and *f* is the distance from the reflectarray to the feed horn, typical useful values of the ratio *f*/D are 0.5 to 1.0. The feed horn is typically 1 to 2 wavelengths in diameter.

FIG. **14** shows a curved version **152** of a reflectarray antenna, in which the element antennas **12** are placed so as to form a contour especially suitable for collimating energy that is radiated upon it from a focus **153** by a nearby feedhorn or other primary radiator **154** on an axis of geometric symmetry **155.** When the contour is parabolic and the element antennas **12** are a frequency-independent type, such as spiral antennas, and the aperture of the array is large in terms of wavelengths, e.g., 5 or more wavelengths, the collimation that is realized is independent of frequency. The reradiated wave can be made to propagate in a direction shown by the vector **156,** for one set of phase shifting conditions within the element antennas, or to propagate in a different direction **158** for a different set of internal phase shifts. The array is suitable for both transmitting and receiving, as are the other antennas described herein.

FIG. **15** is a lens array antenna which is yet another embodiment of this invention. An array assembly **10** comprising element antenna **12** is subjected to radiation **160** from a feed device such as horn **162** mounted behind it. The array **10** behaves as though it were refracting the received wave and directs it forward in a direction such as is represented by Poynting vectors **164** or **166.** The direction is controlled by DC biasing potentials on the phase-shifting diodes of element antennas **12,** with no moving mechanical parts.

A retrodirective application of the invented antenna is shown in FIG. **16.** The purpose of this antenna is to receive a wave **168** from a remote source and send it back in the reverse direction **170** as that from which it came. The reflection behavior of the antenna array assembly **172** is, as in the other embodiments, controlled by phase-shifting the reradiated wave from the various element antennas. The phase-shifting is, as before, under the control of DC potential biases **174** which affect switching diodes or analog phase shifters such as varactor diodes at points connected to either the inner ends, outer ends, or both ends of the spiral arms of each element antenna. The direction in which the reradiated wave is to be transmitted is ascertained with a direction-finding antenna **176** which is shown separated from the retrodirective array antenna **172,** although conceivably their functions could be combined in a single antenna. A direction-finding processor **178** controls the DC potential biases by means of a beam steering processor **180,** to establish the desired direction of reradiation.

Another feature of the retrodirective version is that relative phase shift between elements may be used to steer the direction of reradiation, while the absolute phase of all elements may be used to phase modulate the retrodirected signal. A typical application is one in which some desired information is sensed near the retrodirective antenna, converted to voltage sufficient for phase drive and applied to the retrodirective antenna phase modulator and then to processor **180.** Phase drive and modulation equipment **182, 184** are in dotted lines in FIG. **16.** The sensed information may be obtained by addressing the antenna from a distance with an RF transmitter, receiver, and antenna.

Although the invention has been described by examples of circularly polarized embodiments, it is equally applicable to elliptically and linearly polarized antennas of types having individual arms in which are induced, from a single received radio wave, currents having differing electrical phases. Expressing this requirement in terms applicable to a transmitting mode of operation, the invention is applicable to antennas whose radiated wave is created by simultaneous cooperation of arms or sub-elements whose instantaneous exciting currents are distributed in phase, preferably over some appreciable fraction of **360°** or more. Antennas of this type permit current signals that are received on their arms to be interconnected among themselves to other such arms, and/or phase shifted, and thereby to serve as transmitting antenna currents, with the manner of interconnecting the various antenna arms to each other being used to control the phase of the reradiated wave.

What is claimed is:

1. A passive antenna for receiving and reradiating electromagnetic waves comprising:

at least three electrically conductive arms each having an inner end and an outer end,

said arms being spaced apart and symmetrically arranged in a plane and having a common center such that AC electrical signals are induced in said arms by a received electromagnetic wave and in such a manner that said respective signals differ in phase among said arms, and

interconnecting means located proximate to said inner arm ends at said common center and in said plane for connecting a selected pair of said inner arm ends together with essentially a short circuit for reapplying said phase differing signals to the interconnected arms in such a manner that an electromagnetic wave radiates from the antenna with a phase relationship with respect to the received electromagnetic wave that is determined by the selected interconnections of said inner arm ends.

2. An antenna as set forth in claim **1** wherein the interconnecting means comprises a plurality of switching diodes, and means for selectively actuating said diodes into conduction or nonconduction so that the relative phases of the reapplied signals are determined by a choice made among received signals of differing phases to be reapplied to the arms by the switching diodes.

3. An antenna as set forth in claim **2** wherein said plurality of electrically conductive arms comprises frequencyindependent antenna means having a frequency-independent phase shift between said received electromagnetic wave and said received signals and between said reapplied phase-differing signals and said radiated electromagnetic wave, whereby said phase relationship between said received and radiated electromagnetic waves is independent of frequency of the waves over a range of frequencies.

4. An antenna as set forth in claim **2** wherein the means for actuating said diodes comprises static switching means.

5. An antenna as set forth in claim **1** wherein the interconnecting means comprises a plurality of switching means, and means for selectively actuating said switching means so that the relative phases of the reapplied signals are determined by a choice made among received signals of differing phases to be reapplied to the arms by the switching means.

6. A passive antenna for receiving radiated electromagnetic waves and reradiating them, comprising:

a plurality of electrically conductive arms in which A.C. electrical signals are induced by a received electromagnetic wave, and

means for selectively changing the relative phases among the arms of the signals and for reapplying the phase-differing signals to the arms, by transmission and reflection, whereby the phase-differing signals in the arms induce an electromagnetic wave that radiates from the antenna with a phase relationship with respect to the received electromagnetic wave that is affected by the changes in the phases of the signals, said electrically conductive arms being arms of a multi-arm spiral antenna, and the means for selectively changing the relative phases and reapplying the signals are proximate to the inner ends of the spiral arms, and are controlled by a further element, namely, control means connected proximately to the outer ends of the conductive arms.

7. A passive antenna for receiving radiated electromagnetic waves and reradiating them, comprising:

a plurality of electrically conductive arms in which A.C. electrical signals are induced by a received electromagnetic wave, and

means for selectively changing the relative phases among the arms of the signals and for reapplying the phase-differing signals to the arms, by transmission and reflection, whereby the phase-differing signals in the arms induce an electromagnetic wave that radiates from the antenna with a phase relationship with respect to the received electromagnetic wave that is affected by the changes in the phases of the signals, said electrically conductive arms being arms of a spiral antenna, and the means for selectively changing the relative phases and reapplying the signals are proximate to the outer ends of the spiral.

8. A passive antenna for receiving radiated electromagnetic waves and reradiating them, comprising:

a plurality of electrically conductive arms in which A.C. electrical signals are induced by a received electromagnetic wave, and

means for selectively changing the relative phases among the arms of the signals and for reapplying the phase-differing signals to the arms, by transmission and reflection, whereby the phase-differing signals in the arms induce an electromagnetic wave that radiates from the antenna with a phase relationship with respect to the received electromagnetic wave that is affected by the changes in the phases of the signals, said electrically conductive arms being arms of a multiple-arm spiral antenna, and some of the means for selectively changing the relative phases and reapplying the signals are proximate to the inner ends of the spiral arms for affecting received signals having one direction of rotation, and others of such means are proximate to the outer ends of the spiral arms for affecting received signals having the opposite direction of rotation.

9. A passive antenna array for receiving radiated electromagnetic waves and reradiating them, comprising:

a plurality of electrically conductive arms spaced from each other and oriented relative to each other such that A.C. electrical signals are induced in said arms by a received electromagnetic wave and in such a manner that said respective signals differ in phase among said arms, and

phase shifting means for selectively changing the relative phases of said signals among the arms and including interconnecting means for selectively interconnecting selected ones of the arm ends of the same sense for selectively reapplying the phase-differing signals to the arms, by transmission and reflection, in such a manner that an electromagnetic wave radiates from the antenna with a phase relationship with respect to the received electromagnetic wave that is determined by the selected interconnection of said arm ends,

an array of said element antennas wherein the impinging wave strikes the array of element antennas on the same side of the array as that from which the resultant reradiated array wave leaves the antenna for propagation principally in the controllable directions,

each of said element antennas comprises frequency-independent antenna means having a frequency-independent phase shift between said impinging wave and said received A.C. signals and between said reapplied A.C. signals and said reradiated elemental antenna waves, and wherein the array of element antennas forms a parabolic contour having a focus for one of said impinging and reradiating waves on the geometric axis of symmetry of said contour, and the array's dimensions transverse to the axis of the parabolic contour are at least as great as five wavelengths of the A.C. signals, whereby said reradiated wave when propagating externally from said array remains collimated substantially independently of the frequency of the A.C. signals.

10. A passive antenna array for receiving electromagnetic waves and reradiating them in a controllable direction, comprising:

a plurality of element antennas that receive A.C. signals from an impinging wave, and

means for reapplying the received A.C. signals to the element antennas with signal phases that differ controllably among the element antennas, to excite the element antennas to reradiate elemental antenna waves having signal phases that differ among themselves by amounts that cause a resultant reradiated array wave which the elemental antenna waves cooperate to form, to propagate principally in controllable directions from the array, under control of the means for reapplying the received A.C. signals, said element antennas being multiple-arm spiral antennas, and the means for reapplying the received A.C. signals are proximate to the inner ends of the spiral arms, and are controlled by a further element, namely, control means connected proximately to the outer ends of the conductive arms.

11. A passive antenna for receiving radiated electromagnetic waves and reradiating them, comprising:

a plurality of electrically conductive arms spaced from each other and oriented relative to each other such that A.C. electrical signals are induced in said arms by a received electromagnetic wave and in such a manner that said respective signals differ in phase among said arms, and

phase shifting means for selectively changing the relative phases of said signals among the arms and including interconnecting means for selectively interconnecting selected ones of the arm ends of the same sense for selectively reapplying the phase-differing signals to the arms, by transmission and reflection, in such a manner that an electromagnetic wave radiates from the antenna with a phase relationship with respect to the received electromagnetic wave that is determined by the selected interconnection of said arm ends,

said received and the reradiated electromagnetic waves have rotating polarization and wherein said electrically conductive arms are arms of a multi-arm spiral antenna, and wherein said interconnecting means includes means proximate the inner ends of the arms.

12. A passive antenna for receiving radiated electromagnetic waves and reradiating them, comprising:

a plurality of electrically conductive arms spaced from each other and oriented relative to each other such that A.C. electrical signals are induced in said arms by a received electromagnetic wave and in such a manner that said respective signals differ in phase among said arms, and

phase shifting means for selectively changing the relative phases of said signals among the arms and including interconnecting means for selectively interconnecting selected ones of the arm ends of the same sense for selectively reapplying the phase-differing signals to the arms, by transmission and reflection, in such a manner that an electromagnetic wave radiates from the antenna with a phase relationship with respect to the received electromagnetic wave that is determined by the selected interconnection of said arm ends,

said received and reradiated electromagnetic waves have rotating polarization and wherein said electrically conductive arms are arms of a multi-arm spiral antenna and said interconnecting means include means proximate the outer ends of the arms.

13. A passive antenna for receiving radiated electromagnetic waves and reradiating them, comprising:

a plurality of electrically conductive arms spaced from each other and oriented relative to each other such that A.C. electrical signals are induced in said arms by a received electromagnetic wave and in such a manner that said respective signals differ in phase among said arms, and

phase shifting means for selectively changing the relative phases of said signals among the arms and including interconnecting means for selectively interconnecting selected ones of the arm ends of the same sense for selectively reapplying the phase-differing signals to the arms, by transmission and reflection, in such a manner that an electromagnetic wave radiates from the antenna with a phase relationship with respect to the received electromagnetic wave that is determined by the selected interconnection of said arm ends,

said received and reradiated electromagnetic waves are rotationally polarized waves and wherein said plurality of spaced apart electrically conductive arms comprises a plurality of rotationally angularly spaced apart electrically conductive arms for receiving and reradiating said rotationally polarized waves, whereby a change in said phase relationship effectively electrically rotates the antenna for said reradiated signals.

14. A passive element antenna comprising:

a plurality of electrically conductive spiral arms spaced from each other, said arms having a common axis of rotation, each said arm having inner and outer ends, said inner ends being rotationally displaced about said axis relative to each other by a given angle to achieve a given rotational phase progression about said common axis; and

phase control means for effectively electrically rotating said spiral arms about said axis to control the phase relationship of electromagnetic energy to be radiated from said element antenna comprising interconnecting means for interconnecting at least one pair of said inner arm ends together so that electrical signals in said respectively interconnected pair of arms are interchanged from one arm to the other thereof with a relative phase change dependent upon the rotational phase relationship between said interconnected inner arm ends.

15. An element antenna as set forth in claim **14** for use in receiving and reradiating electromagnetic waves and wherein said arms are oriented such that AC electrical signals are induced in said arms by a received electromagnetic wave in such a manner that the respectively induced signals differ in phase among said arms whereby the electromagnetic energy reradiated from said element antenna exhibits a phase relationship with respect to the received electromagnetic energy that is determined by said interconnected inner arm ends.

16. An element antenna as set forth in claim **14,** wherein said plurality of spiral arms includes a plurality of pairs of said arms and said interconnecting means includes means for selectively interconnecting the inner arm ends of at least one said pair of arms.

17. An element antenna as set forth in claim **16** wherein said interconnecting means includes switching means located proximate to said inner arm ends.

18. An element antenna as set forth in claim **17** wherein said plurality of arms and said switching means define a coplanar structure.

19. An element antenna as set forth in claim **14** wherein said plurality of spiral arms includes N pairs of arms, wherein N is at least one, and said interconnecting means includes switching means arranged to selectively interconnect at least one of N pairs of said inner arm ends, whereby said element antenna is selectively operable at one of 2^N phase states.

20. An element antenna as set forth in claim **19,** wherein said switching means is proximate to said inner arm ends.

21. An element antenna as set forth in claim **20** wherein said switching means and said N pairs of arms define a coplanar structure.

22. A passive element antenna comprising:

at least three elongated electrically conductive arms;

said arms being spaced from each other, said arms having inner and outer ends, said inner arm ends being rotationally displaced about a common axis of rotation by a given angle to achieve a given rotational phase progression about said axis so that AC electrical signals are induced in said arms from received electromagnetic energy such that the respective signals in the plurality of arms differ in phase from each other in accordance with said phase progression; and

control means for controlling said element antenna to reradiate electromagnetic energy phase relationship with respect to the received electromagnetic energy and comprising interconnecting means located proximate to said inner arm ends for interconnecting selected ones of the inner arm ends with essentially a short circuit so that at least one pair of said inner arm ends is interconnected by essentially a short circuit so that the phase differing signals in the two interconnected arms of said at least one pair are interchanged from one arm to the other thereof such that an electromagnetic wave radiates from the element antenna with a phase relationship relative to said received energy in dependence upon the selected interconnection.

23. An element anntenna as set forth in claim **22** wherein said arms extend outwardly of said common axis from said inner arm ends to said outer arm ends.

24. An element antenna as set forth in claim **23** wherein said arms are coplanar.

25. A passive element antenna comprising:

at least three electrically conductive arms spaced from each other, said arms being rotationally displaced from each other about a common axis of rotation, each said arm having inner and outer ends, said inner ends being rotationally displaced about said axis relative to each other by a given angle to achieve a given rotational phase progression about said common axis, and

control means for effectively electrically rotating said arms about said axis to control the phase relationship of electromagnetic energy to be radiated from said element antenna comprising interconnecting means located proximate to said inner arm ends for interconnecting at least one pair of said inner arm ends together with essentially a short circuit so that electrical signals in said respectively interconnected pair of arms are interchanged from one arm to the other thereof with a relative phase change dependent upon the rotational phase relationship between said interconnected inner arm ends.

26. An element antenna as set forth in claim **25**, wherein said arms are spiral arms of the same winding sense.

27. A element antenna as set forth in claim **25**, wherein said arms are of like configuration.

28. An element antenna as set forth in claim **25**, wherein said arms are of like configuration both in shape and size.

29. An element antenna as set forth in claim **28**, wherein said arms are spiral arms of the same winding sense.

30. An element antenna as set forth in claim **28**, wherein said arms and said interconnecting means are coplanar.

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