March 26, 1957 M. T. WEISS 2,786,999

NON-RECIPROCAL DIRECTIVE ANTENNA ARRAYS

Filed May 5, 1953 2 Sheets-Sheet 1

FIG. 1

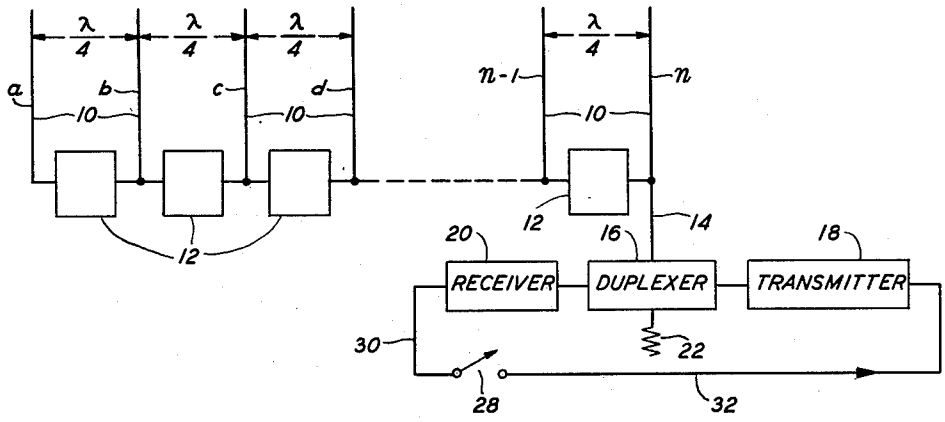
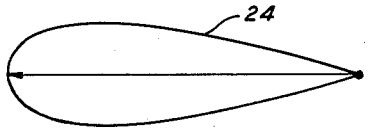
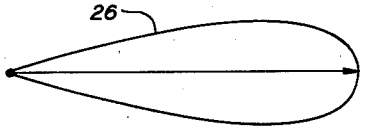


FIG. 1A



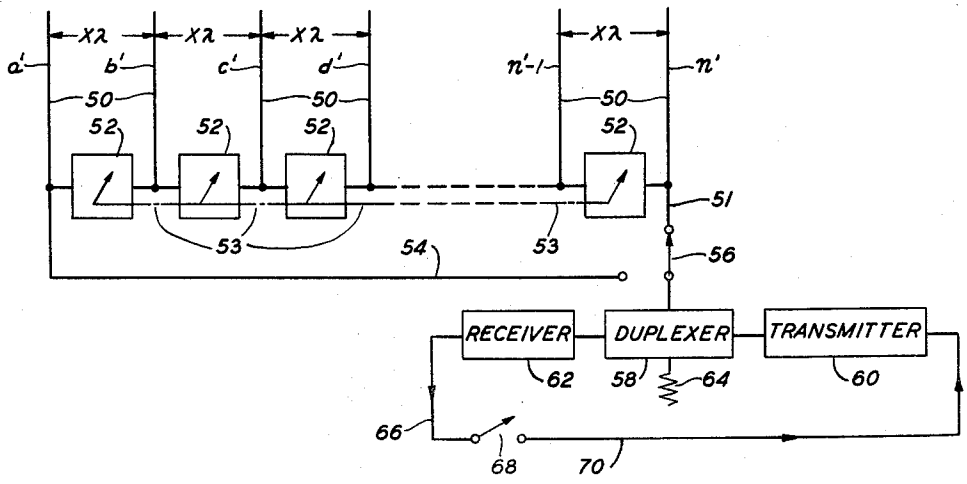
TRANSMITTING

FIG. 1B



RECEIVING

FIG. 2



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March 26, 1957 M. T. WEISS 2,786,999

NON-RECIPROCAL DIRECTIVE ANTENNA ARRAYS

Filed May 5, 1953 2 Sheets-Sheet 2

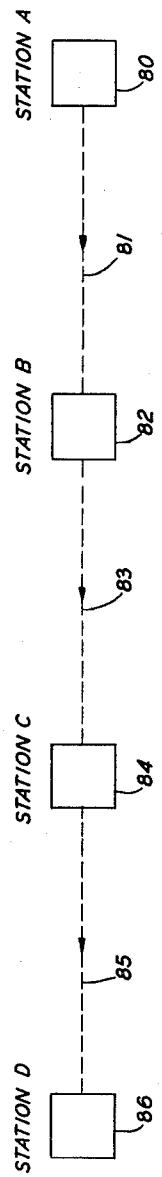

FIG. 3

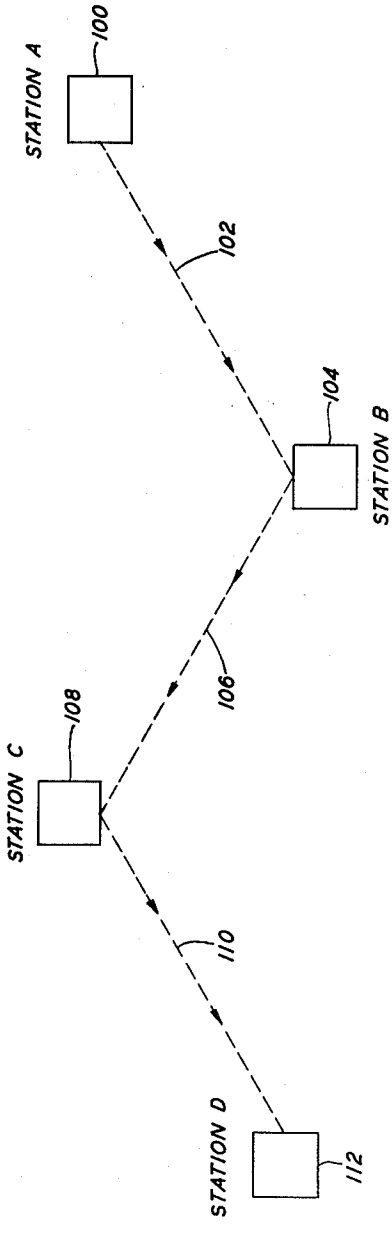

FIG. 4

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NON-RECIPROCAL DIRECTIVE ANTENNA ARRAYS

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Application May 5, 1953, Serial No. 353,188

6 Claims. (Cl. 343—853)

This invention relates to novel directive antenna arrays for high frequency, electromagnetic waves and to radio systems employing these arrays. More particularly, it relates to antenna arrays in which successive individual radiators or radiating units of an antenna array are interconnected by a non-reciprocal phase shifting device which imparts a different phase shift to energy passing through it in one direction than to energy passing through it in the opposite direction and to radio stations employing such arrays.

A radio system equipped with such an antenna array and suitably associated transmitting and receiving apparatus connected to a particular single point of the antenna array will, for each specific adjustment of the non-reciprocal phase shifters, both directively transmit energy in one particular predetermined direction and directively receive energy impinging upon the antenna array from a second different particular predetermined direction, without the necessity of making any apparatus adjustment to change from transmitting to receiving condition and without the necessity of using any complex circuital arrangement other than a conventional duplexing arrangement for connecting the transmitting and receiving apparatus to the single point on the antenna array.

Radio systems of the above-indicated type are useful, by way of example, in radio relay systems in which intermediate or relay stations are required to directively receive intelligence-bearing signals from a preceding station in the relay chain and to directively retransmit the received signals, after appropriate amplification, to the next succeeding station in the relay chain.

In view of the additional fact that the phase characteristics of certain non-reciprocal phase shifting devices can be conveniently varied over substantial ranges of phase, systems embodying arrangements of the invention employing such devices can be used to sweep a considerable area with an exploratory directive beam of transmitted energy or to directively receive signals arriving at the receiving stations from points at any direction within a like but, in general, differently directed area.

The addition of switching facilities for connecting the transmitting and/or receiving apparatus to any of two or more points of the antenna array affords an extremely flexible means for controlling the directivities of the overall system and/or of interchanging the transmitting and receiving directivity characteristics of the system.

A principal object of the invention is to provide a simple directive antenna array for radio systems, which systems, when equipped with said array, are, for each specific single point of connection to the array, adapted to receive energy from a first particular predetermined direction and to transmit energy in a second different particular predetermined direction without necessitating apparatus adjustment to change from transmitting to receiving condition and without necessitating the use of any complex circuital arrangements other than a conventional duplexing arrangement for connecting the transmitting and receiving apparatus to a single point on the antenna array.

A further object is to provide a simple antenna array for a radio relay station which relay station, when equipped with said array, will receive energy from a first predetermined particular direction, and after associated apparatus has amplified said energy, will retransmit the amplified energy in a second different predetermined particular direction.

A further object is to provide a simple antenna array for a radio system, the directive characteristics of which array are inherently different for the transmission of energy than for the reception of energy for each specific point of connection to the array, and which have inherently different receiving versus transmitting directive characteristics for each specific point of connection, which characteristics can be conveniently adjusted or swept through a considerable range of directions.

Other and further objects, features and advantages of the invention will become apparent from the following discussion of the principles of the invention and the accompanying detailed descriptions of specific illustrative embodiments, incorporating particular principles of the invention, as well as from the appended claims.

In the accompanying drawings,

Fig. 1 illustrates, in block schematic diagram form, a specific radio relay station system, including a simple straight-line antenna array, embodying certain of the principles of the present invention, in which energy will be received from a first particular predetermined direction and transmitted in a second particular predetermined different direction when conventional transmitting and receiving apparatus are both connected to any of a number of particular predetermined points of the array;

Figs. 1A and 1B indicate the directional characteristics of the system of Fig. 1 for transmitting and for receiving, respectively;

Fig. 2 illustrates, in block schematic form, a more generalized radio station system of the invention in which the directions for transmission and for reception, respectively, can be interchanged or can be adjusted, or, if desired, continuously swept through particular predetermined arcs;

Fig. 3 illustrates, in block schematic diagram form, a first radio relay system in which the stations can be of the general type illustrated in Fig. 1; and

Fig. 4 illustrates, in block schematic diagram form, a second radio relay system in which stations of the general type illustrated in Fig. 2 can be employed.

In more detail, in Fig. 1 a plurality of n individual radiating units **10**, designated a, b, c, d, . . . $n-1$ and n, respectively, aligned in a straight line and spaced apart a distance of one-quarter wavelength of the median operating frequency are shown. Each radiating unit can be, for example, a dipole or a dielectric rod or an array of dipole or dielectric rod elements. Each two successive radiating units are electrically connected together by an electrical path including a non-reciprocal phase shifter **12**. Non-reciprocal phase shifter **12** can, for example, be "the microwave gyrator" described in an article so entitled by C. L. Hogan, published in the Bell System Technical Journal, vol. XXXI, No. 1, for January 1952, pages 1 through 31, inclusive, see particularly Fig. 11 and description thereof starting at page 22. At one end of the array, a transmission line **14** connects the end radiating unit **10** to a duplexing arrangement **16**, as shown. A microwave transmitter **18** and a microwave receiver **20** are connected by duplexer **16** to the antenna lead **14** and a matching impedance termination **22** is connected to the fourth arm of the duplexer **16**.

The duplexer **16** can be, for example, a "polarization circulator" as illustrated and described, in several forms, in the above-mentioned article by C. L. Hogan at pages 25 and 26 and in the copending application of S. E. Miller,

Serial No. 263,600, filed December 27, 1951, which application is assigned to applicant's assignee. Alternatively, it can be a hybrid junction of the wave-guide magic-tee or wave-guide ring or coaxial ring varieties well known to those skilled in the microwave art.

In the specific arrangement of Fig. 1, the non-reciprocal, phase-shifting, devices **12** are designed to each have a phase shift which differs by 180 degrees for opposite directions of transmission of electro-magnetic wave energy therethrough, i. e., they can, for example, each have a phase shift of 360 degrees plus 90 degrees for transmission from lead **14** toward the opposite, or left end of the array of radiating elements, and 360 degrees minus 90 degrees for wave energy proceeding toward lead **14**. The resulting directional characteristics for transmitting and for receiving with the system of Fig. 1 are then those shown in Figs. 1A and 1B, namely, characteristics **24** and **26**, respectively, the included arrows indicating the directions of maximum gain.

A connection comprising leads **30**, **32** and switch **28** is provided so that energy received from the direction indicated in Fig. 1B may be amplified and retransmitted in the direction indicated by Fig. 1A, in which case the system of Fig. 1 represents a radio relay repeater station adapted to relay signals in a substantially straight line.

Except for the inclusion of the non-reciprocal phase-shifting devices **12**, the antenna array of Fig. 1 is, of coures, merely a special case of the general array type of antenna, comprehensive descriptions of which are to be found, for example, in United States Patent 1,738,522 granted to G. A. Campbell on December 10, 1929, as well as in substantially all modern texts on antennas. For example, see the text entitled, "Principles and Applications of Waveguide Transmission," by G. C. Southworth, published by D. Van Nostrand Co., Inc., New York, New York, 1950, at pages 389 through 401.

At page 400 of this text, the equation (10.0–20) is given for the directivity pattern of an array of N′ identical radiators with the phase difference B′ between adjacent radiators, and a spacing A′.

Obviously, if non-reciprocal phase shifters are interposed between each two successive radiators of the array, B′ will be different for transmitting than for receiving and the directional characteristic of the array for transmitting will usually be displaced substantially from that for receiving, as is illustrated, for example, by the extreme case of oppositely directed characteristics of Figs. 1A and 1B for the specific system of Fig. 1.

In Fig. 2, a more generalized arrangement of the invention is illustrated. This arrangement comprises a plurality of n' radiating units **50**, designated a', b', . . . n', respectively, spaced in a line with a separation $x\lambda$ between each two consecutive radiators, in which $x\lambda$ can be any predetermined spacing up to several wavelengths as required to afford the inherent directive characteristics desired. Each two consecutive radiating units are interconnected, as shown, by a variable (or adjustable) non-reciprocal phase shifter **52**, the controls of all the phase shifters **52** being connected together, or ganged, by connecting control means **53**, so that all may be adjusted, or varied, simultaneously throughout a predetermined range of phase shift. The values of phase shift for the phase shifters for each position of the common control are substantially identical to each other and the value of phase shift for each differs substantially for the two directions of transmission. Several forms of readily adjustable, or variable, non-reciprocal phase shifters, suitable for use in the over-all system illustrated in Fig. 2, are disclosed and explained in detail in the copending application of A. G. Fox, Serial No. 304,609, filed August 15, 1952, assigned to applicant's assignee. As explained in this copending application, the adjustment or variation of phase can be effected by either mechanical or electrical control means, suitable structures for each type of control means being fully described. The duplexer **58**, termination **64**, transmitter **60** and receiver **62** can be of the types mentioned above for duplexer **16**, termination **22**, transmitter **18** and receiver **20**, respectively, of Fig. 1.

In Fig. 2, a switch **56** is provided to connect the upper terminal of duplexer **58** to either lead **51** or lead **54** which leads, in turn, connect to the near end or far end, respectively, of the antenna array, i. e., to reciprocally related units of the array, as shown. This obviously permits interchanging the respective directions for transmission and reception of the antenna array. This simple arrangement, also, obviously permits reversing the direction of transmission between the successive stations of a relay chain of stations.

Furthermore, leads **66** and **70** and switch **68** provide for connecting the output of receiver **62** to the input of transmitter **60**, so that the received signals can be automatically retransmitted to a more distant relay or terminal station of a radio relay system, for example.

Fig. 3 shows in block schematic diagram form a radio relay system in which stations A, B, C and D (**80**, **82**, **84** and **86**, respectively), comprise a chain of stations interconnecting the terminal stations A (**80**) and D (**86**). In this figure, the stations are in a straight line so that antenna arrays of the type shown in Fig. 1 would be suitable for the relay stations B (**82**) and C (**84**), each station receiving from the next successive station to its right and transmitting the received signal on to the next successive station to its left. Terminal stations **80** and **86**, for the system shown, would, of course, require only suitably directive transmitting and receiving antenna arrays, respectively. The paths of transmission between successive stations are indicated by lines **81**, **83**, and **85**, respectively, as shown.

An objection to the system illustrated in Fig. 3 may arise in that one or both of the first two transmitters at stations A and B may "over-carry" and cause interference at stations C, or D, or both, with the signal as retransmitted from the immediately preceding station B or C, respectively, in the chain. To obviate any such interference, the successive stations of a radio relay system are usually not placed in a straight line but are rather arranged in some such fashion as that indicated in Fig. 4, in which transmission from any of the stations is directed only toward the next succeeding station in the chain. Clearly, in Fig. 4, the directions of transmission **102**, **106** and **110** are such that "over-carry" from a preceding station will not cause interference. The stations B and C (**104** and **108**) are preferably of the type illustrated in Fig. 2 with the directional phase shifters **52** adjusted to afford the desired directions of transmission and reception indicated. The terminal stations A and D, of course, would need only antenna arrays having appropriate directive transmitting and receiving characteristics, respectively.

As explained in detail in the above-mentioned patent to G. A. Campbell, arrays which have two or more receiving and/or transmitting lobes are readily designed so that a particular relay station could readily be designed in accordance with the principles of the present invention which would respond to any of two or more particular differently oriented distant transmitting stations and retransmit the signal received to several particular additional differently oriented distant receiving stations. Alternatively, the arrangements of the invention are obviously readily adaptable as switching facilities whereby any one of several transmitting stations can be connected to particular ones of a plurality of receiving stations by appropriate adjustment of the ganged adjustable non-reciprocal phase shifters. Further alternative arrangements, in accordance with the principles of the invention, in which differing directivities are obtained by connecting the receiving and/or transmitting apparatus to points intermediate the ends of the antenna array, can be readily devised by those skilled in the art. Also, numerous and varied other arrangements within the spirit and scope of the principles of the invention will readily occur to those

skilled in the art and no attempt has here been made to exhaustively cover all such arrangements.

What is claimed is:

1. An antenna array including in combination, a first radiating unit, a second radiating unit spaced from said first unit and a non-reciprocal phase shifter the phase shift of which for one direction of transmission is substantially different from the phase shift for the opposite direction of transmission, said non-reciprocal phase shifter being interconnected between said first and said second radiating units.

2. An antenna array, including in combination a plurality of radiating units, each radiating unit being spaced from the remainder of said units, a plurality of non-reciprocal phase shifters the phase shift of each of said phase shifters being substantially different for the opposite directions of transmission through it, each radiating unit being interconnected to at least one adjacent radiating unit through one of said non-reciprocal phase shifters.

3. An antenna array comprising a plurality of radiating units aligned at intervals, successive units being interconnected by an electrical circuit including a non-reciprocal phase shifter, the phase shift of said phase shifter being substantially different for transmission through it in one direction than for transmission through it in the opposite direction, whereby when a transmitter and a receiver are connected to a radiating unit of said array, energy will be transmitted in a first particular predetermined direction and received from a second particular predetermined direction, said first and second directions differing materially from each other.

4. The antenna array of claim 3, in which said non-reciprocal phase shifters are each adjustable over a particular predetermined range of phase shift and means for simultaneously adjusting all of said phase shifters to any value of phase shift within said range, whereby the directive transmitting and receiving characteristics of said array can be adjusted to any of a large number of directions.

5. A radio relay station comprising an antenna array consisting of a plurality of radiating units spaced at regular intervals, adjacent units being connected through non-reciprocal phase shifters, said phase shifters having a substantial difference in phase shift for one direction of transmission from that for the opposite direction of transmission, and transmitting apparatus and receiving apparatus interconnected to a unit of said antenna array but isolated from each other by a duplexing unit, and means for interconnecting the output of the receiving apparatus to the input of the transmitting apparatus, whereby signals directively received by said antenna array from a first predetermined direction will be directively retransmitted in a second predetermined direction substantially different from said first direction.

6. The station of claim 5 and switching means for connecting said transmitting and receiving apparatus to either of two reciprocally related units of said array whereby the directivity of the array for transmitting and receiving can be reversed.

References Cited in the file of this patent

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