

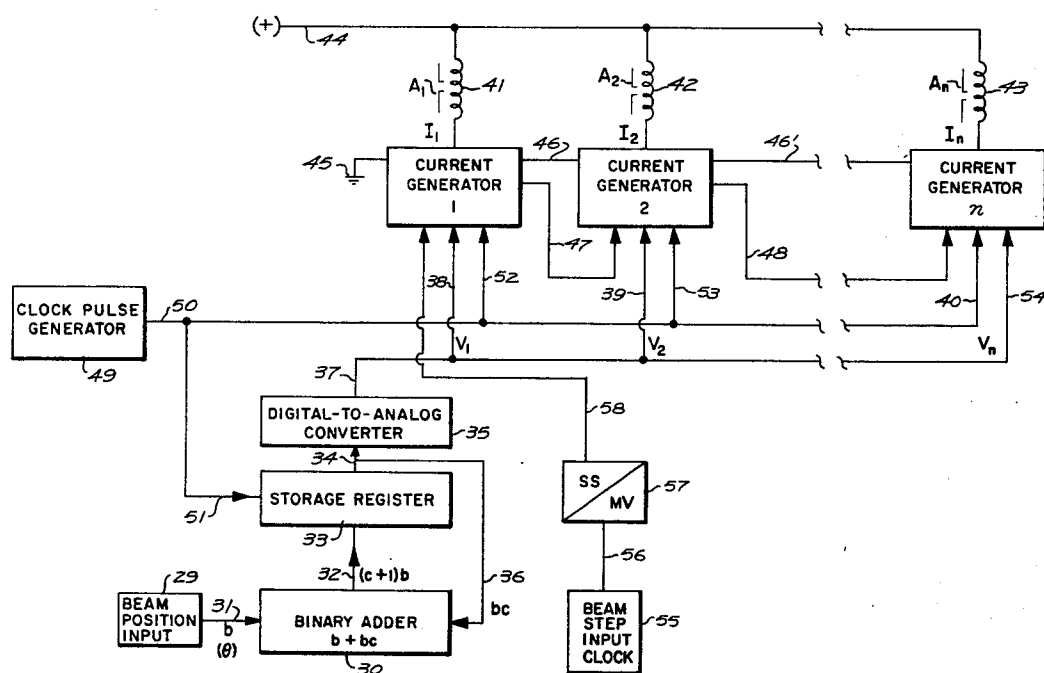
[11] 3,582,953

3,324,452	6/1967	Brightman et al.	343/854
3,387,301	6/1968	Blass et al.	343/854
3,500,412	3/1970	Trigon.....	343/854

**[54] CONTROL CIRCUIT FOR SETTING PHASE
SHIFTERS IN SCANNED ANTENNA ARRAY
7 Claims, 6 Drawing Figs.**

[56]	References Cited		
	UNITED STATES PATENTS		
3,205,501	9/1965	Kuhn.....	343/854

ABSTRACT: According to the present disclosure, apparatus and process is provided for controlling delay devices in antenna elements of antenna arrays for controlling the direction of propagation of electromagnetic radiation. An analog signal is developed from a digital signal and operates on a first control device in a predetermined manner. The analog signal is subsequently altered, as by altering the digital signal in a binary adder, and the altered analog signal operates on the next control device. The control devices are arranged in sequential relation and are successively operated by a clock.



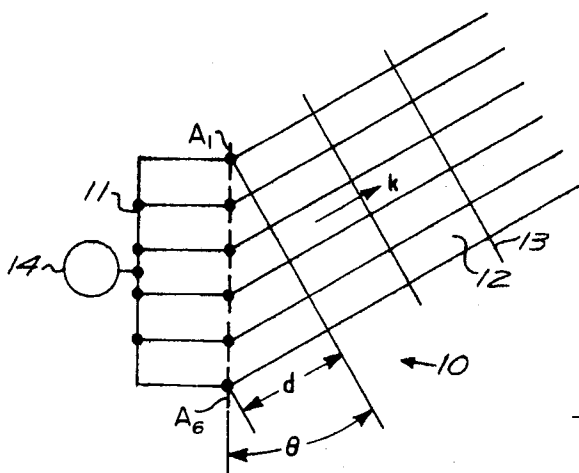


FIG 1

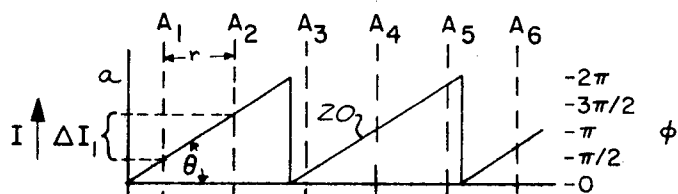


FIG 2a

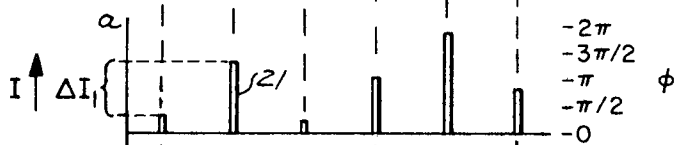


FIG 2b

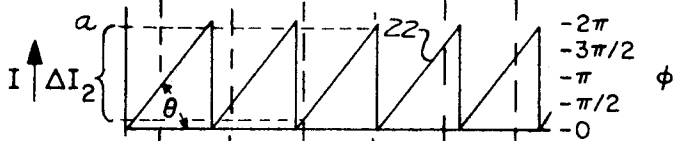


FIG 2c

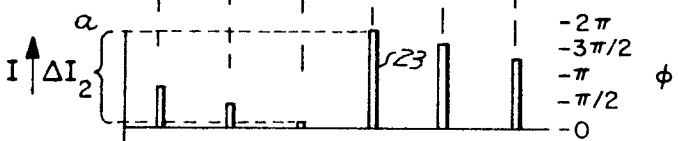
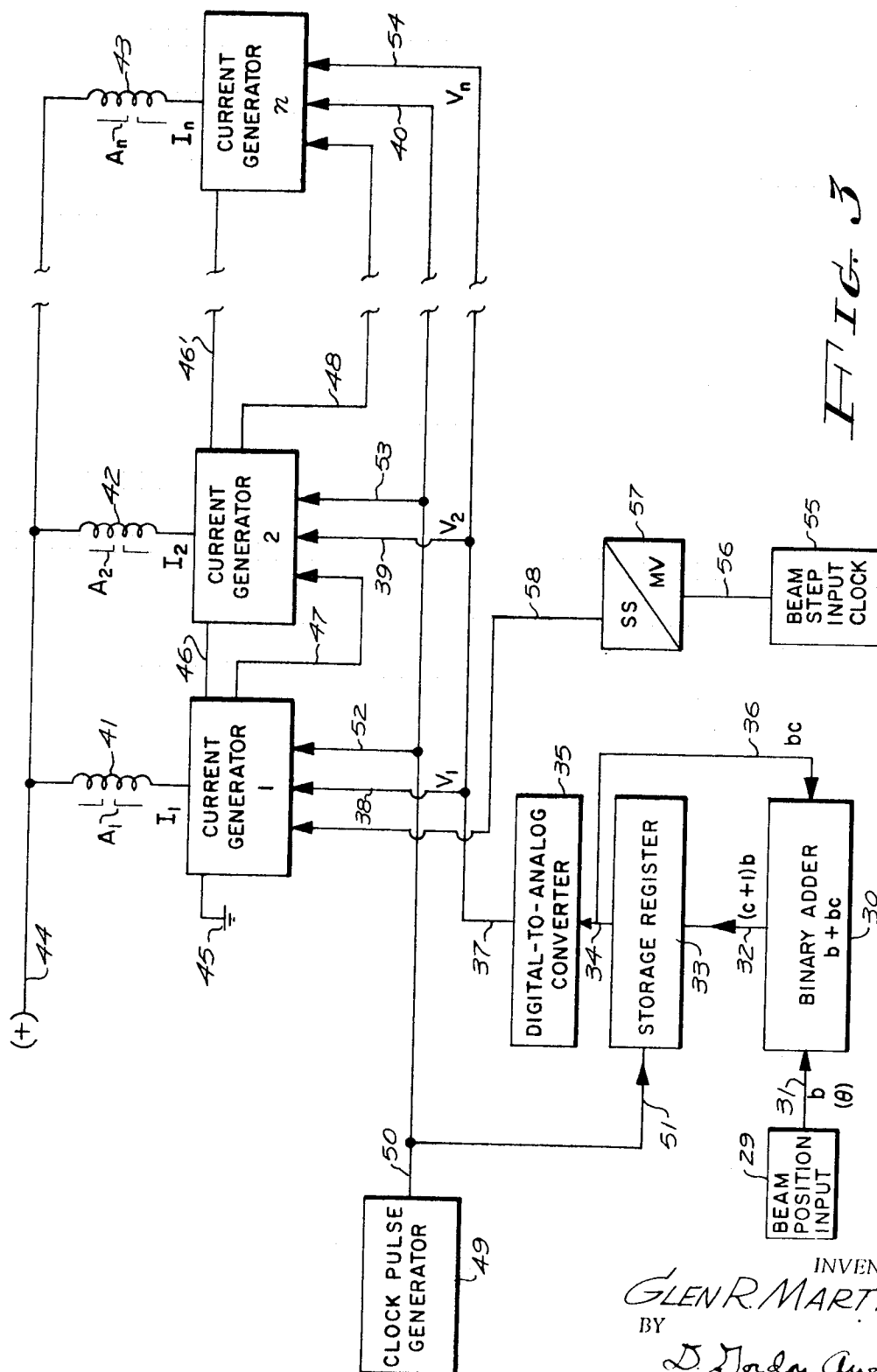


FIG 2d

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CONTROL CIRCUIT FOR SETTING PHASE SHIFTERS IN SCANNED ANTENNA ARRAY

This invention relates to control networks, and particularly to control networks for controlling current operable delay mechanisms for phase control antenna elements of antenna arrays.

If signals to be propagated are fed simultaneously to each antenna element of a linear array, each element will propagate electromagnetic radiation at the same phase as the radiation generated by every other element, and a narrow pencil-like beam of electromagnetic radiation having planar phase fronts will be propagated in a direction normal to the array. However, it is often desirable to shift the direction of propagation of such electromagnetic radiation so that it is oriented at some other angle to the array. Such directional controls are often performed by means of phase shifters or delay networks associated with each antenna element to delay the signal propagated by each element by an incremental amount so that the total propagated signal will be a narrow pencil-like beam of electromagnetic radiation having planar-phase fronts, but directed in a direction at some angle to the array. Heretofore, the phase shifters or delay networks have been current operable phase shifter coils, the control of which has ordinarily been accomplished by to provide control apparatus for antenna arrays whereby the current to each phase shifter is automatically controlled in accordance with the desired propagation direction.

Another object of the present invention is to provide apparatus for adjusting coil so that the phase shifter will shift the phase of the respective propagated signal by an amount dependent upon the current imposed on the shifter coil. The current for each phase shifter is ordinarily calculated by means of complex trigonometric calculations and was adjusted for each phase shifter separately. Since most antenna arrays have many elements and associated phase shifters, a considerable amount of time and equipment are required to adjust the current to each phase shifter for each desired beam position.

It is an object of the present invention is to provide apparatus for adjusting the phase shift of each of a plurality of phase shifters for an antenna array, which apparatus is capable of changing the direction of propagation of electromagnetic radiation from the array by means of a single adjustment.

In accordance with an optional desirable feature of the present invention the current generators are arranged to sequentially drive each other and a clock is provided so that the current will be regulated periodically.

According to another optional desirable feature of the present invention, the analog source comprises a digital-to-analog converter which is driven by a digital adding mechanism. A signal, whose value is dependent upon the desired direction of propagation, is imposed upon the digital adder which in turn drives the digital-to-analog converter. The relationship between the converter and the adder is cyclic so that the phase shifts will be sequentially correlated for each antenna element of the array.

The above and other features will be more fully understood from the following detailed description, and the accompanying drawings, in which:

FIG. 1 is an illustration of a typical linear antenna array for propagating electromagnetic radiation;

FIGS. 2a through 2d are illustrations of pulse signals which illustrate the principle of operation of the present invention; and

FIG. 3 is a schematic block diagram of a circuit in accordance with the presently preferred embodiment of the present invention.

The present invention is particularly useful in controlling the phase relationship between the phase shifters of each microwave antenna disclosed in the copending application of Chalfin et al., Ser. No. 792,070 for "Antenna Array" filed Jan. 17, 1969, and assigned the same assignee as the present invention. In the aforesaid copending patent application there is described an antenna array for propagating a narrow pencil-like beam of electromagnetic radiation in a desired direction

wherein a plurality of linear antenna arrays are mounted adjacent the rim of a lens so that upon rim-feeding the lens a fan beam of electromagnetic radiation is propagated to the linear antenna arrays. Each array includes phase-shift means for effectuating the desired phase shift for each radiating antenna element on the respective antenna array. The phase-shift means disclosed in said Chalfin copending patent application comprises a ferrite core disposed in a wave guide and a coil wrapped around each of the cores. A direct current of preselected magnitude is passed through the coils to alter the phase velocity of the electromagnetic radiation propagated by the waveguide. The present invention is directed particularly to the apparatus for selecting the magnitude of direct current for the coils for each ferrite phase shifter disclosed in said Chalfin et al. application. It is to be understood, however, that the present invention is useful for other types of current or voltage operable phase shifters.

In FIG. 1 there is illustrated a linear array 10 of antenna elements A to A_n. Each antenna element, which may, for example, be a dipole antenna, is connected by means of cable 11 to a suitable signal source 14. Each antenna element is capable of propagating electromagnetic radiation 12. As illustrated in FIG. 1 electromagnetic radiation 12 is being propagated in a direction *k* and contains planar phase fronts 13 disposed at an angle θ from the plane of the array. (It is to be understood that the direction *k* along which the electromagnetic radiation is propagated is also disposed at an angle θ from a line normal to the antenna array.) The distance between each phase front is illustrated by distance *d*.

For a linear array of antenna elements, it can be shown that

$d = n r \lambda \sin \theta$ (1) where λ is the wavelength of the propagated carrier signal, θ is the angle between the direction of propagation and a line normal to the array (also equal to the angle between the plane of the array and the plane of a phase front), *n* is an integer corresponding to the number of antenna elements from a given reference point, *r* is the number of wavelengths, λ , which can be confined between adjacent antenna elements ($n r \lambda$ being equal to the distance between elements *n* and the reference point), and *d* is the distance between element *n* and a phase front. The phase shift required for a given antenna element can be determined from the expression:

$$\lambda_n = k d \quad (2)$$

where Φ_n is the phase shift required for element *n* and

$$k = 2\pi/\lambda \quad (3)$$

Hence, from equations (1), (2) and (3),

$$\lambda = 2\pi n r \sin \theta \quad (4)$$

It can be shown that a trigonometric function of an angle which is greater than 360° (2 π radians) is equal to the trigonometric function of the amount by which the angle exceeds a multiple of 360°.

Put another way,

$$f(\alpha + 2m) = f(\alpha)$$

where *m* is an integer equal to the number of 2 π radians in the angle ($\alpha + 2m$). Applying this concept to the phase shift, it can be understood that if the phase shift exceeds 2 π radians, the phase shift necessary for each antenna element can be expressed by

$$\Delta\Phi_n = \Phi_n - 2\pi m \quad (5)$$

where *m* is the number of 2 π radians in Φ_n . Hence,

$$\Phi_n = 2\pi(n r \sin \theta - m). \quad (6)$$

Thus, if an array of nine antenna elements (numbered 0—8, element 0 being the reference point) are intended to

propagate a signal in a direction 30° from the normal to the array ($\theta=30^\circ$), and if the antennas are spaced one wavelength apart ($r=1$), from equations (4) and (6), the following can be tabulated:

TABLE I

$\phi_0=0$	$\Delta\phi_0=0$
$\phi_1=\pi$	$\Delta\phi_1=\pi$
$\phi_2=2\pi$	$\Delta\phi_2=2\pi$
$\phi_3=3\pi$	$\Delta\phi_3=\pi$
$\phi_4=4\pi$	$\Delta\phi_4=2\pi$
$\phi_5=5\pi$	$\Delta\phi_5=\pi$
$\phi_6=6\pi$	$\Delta\phi_6=2\pi$
$\phi_7=7\pi$	$\Delta\phi_7=\pi$
$\phi_8=8\pi$	$\Delta\phi_8=2\pi$

The current necessary to drive a phase shifter to obtain the desired phase shift can be determined by the following expression,

$$\frac{a\phi_n}{2\pi} \quad (7)$$

where I_n is the current driving element n , and a is the current necessary to obtain a 2π radian phase shift (expressed in milliamperes). In the example, the current necessary to drive each successive phase shifter may be determined from equation (7) as

TABLE II

$I_0=0$
$I_1=a/2$
$I_2=a$
$I_3=a/2$
$I_4=a$
$I_5=a/2$
$I_6=a$
$I_7=a/2$
$I_8=a$

If the antenna elements are 3 wavelengths apart ($r=3$), the phase and current relationship of element 0—8 are (for a 30° propagation angle):

TABLE III

$\phi_0=0$	$\Delta\phi_0=0$	$I_0=0$
$\phi_1=\pi/3$	$\Delta\phi_1=\pi/3$	$I_1=a/6$
$\phi_2=2\pi/3$	$\Delta\phi_2=2\pi/3$	$I_2=2a/6$
$\phi_3=\pi$	$\Delta\phi_3=\pi$	$I_3=a/2$
$\phi_4=4\pi/3$	$\Delta\phi_4=4\pi/3$	$I_4=4a/6$
$\phi_5=5\pi/3$	$\Delta\phi_5=5\pi/3$	$I_5=5a/6$
$\phi_6=2\pi$	$\Delta\phi_6=2\pi$	$I_6=a$
$\phi_7=7\pi/3$	$\Delta\phi_7=\pi/3$	$I_7=a/6$
$\phi_8=8\pi/3$	$\Delta\phi_8=2\pi/3$	$I_8=2a/6$

FIG. 2 is a graphic illustration of the relationship between the current necessary to drive the phase shifters and the angle of propagation θ . In FIG. 2a, there is illustrated the relationship between the propagation angle θ and the current necessary for obtaining the phase shift θ for angle θ for an antenna array having antenna elements A_1 through A_6 , to inclusive, spaced r distance apart. The current necessary to obtain a 360° (2π) phase shift for the particular phase shifters is a direct current having a value a . Heretofore, an antenna designer would use rectangular coordinate graph paper so sized as to relate the spacing between the antenna element to

the current necessary to obtain a 360° phase shift. The designer would plot the desired angle of propagation θ on the graph paper, in a repetition, sawtooth form 20 having its lowermost portion coincident with zero current and its peaks coincident with maximum current a . The point of intersection of graph 20 with the lines representing the position of the antenna elements A_1 through A_6 would then be related to the value of the current necessary to obtain the particular desired angle of propagation θ . The designer would then independently establish the desired current for the phase shifter associated with each antenna element, the representative currents being illustrated at 21 in FIG. 2b. The difference in current ΔI between successive phase shifters could likewise be obtained from the graph.

If the designer desired to alter the angle of propagation θ , he had to replot a sawtooth wave 22 at the new angle θ (FIG. 2c) and obtain the current values 23 as illustrated in FIGS. 2d.

The present invention is concerned with apparatus for automatically obtaining the current necessary for the phase shifters for such an antenna array. The apparatus in accordance with the preferred embodiment of the present invention is illustrated in FIG. 3, and includes a beam position input 29 connected to binary adder 30 through input 31. Adder 30 has an output 32 which provides an input to storage register 33. The output 34 from storage register 33 provides an input to digital-to-analog converter 35. Also, the output from storage register 33 is connected to input 36 of binary adder 30. The output 37 from digital-to-analog converter 35 is connected to the inputs 38, 39, 40, etc. of each current generator 1, 2, ... n . Each generator is operable to control the flow of direct current through a respective winding 41, 42, 43, etc. between positive lead 44 and ground 45. Each current generator is connected by means of lead 46, 46' to ground 45. The current generators 1, 2, ... n are arranged in a shift register-type circuit so that operation of current generator 1 provides a signal on lead 47 to enable operation of current generator 2, and operation of current generator 2 provides a signal on lead 48 to enable operation of the next current generator.

Clock-pulse generator 49 has its output 50 connected to input 51 of storage register 33. Also, the output of clock-pulse generator 49 is connected to inputs 52, 53, 54, etc. of the current generators.

A beam step input clock 55 is connected by means of lead 56 to single-shot multivibrator 57 which in turn is connected via lead 58 to the first current generator to enable operation of the current generator.

In operation of the circuit illustrated in FIG. 3, beam position input 29 provides a digital signal b whose value is indicative of the desired angle θ of propagation of electromagnetic radiation from the antenna elements A_1 and through A_n , inclusive. Signal b preferably comprises binary bits. Binary adder 30 adds the digital signals appearing at inputs 31 and 36 and delivers the resultant digital signal which may comprise binary bits, to storage register 33 by means of output 32. Clock pulse generator 49 produces a pulse to enable storage register 33 to accept and store the digital signal from adder 30. The digital signal stored in register 33 is delivered to digital-to-analog converter 35 through output 34. Digital-to-analog converter 35 produces, at output 37, a voltage having a value representative of the digital signal received from storage register 33. Also, the output from storage register 33 is applied to the input 36 of binary adder 30 so that binary adder 30 adds the signal bc (which, as will be more fully understood hereinafter, is a multiple of b) in storage register 33 to signal b from beam position input 29 and delivers the result to storage register 33. Hence, upon each clock pulse from clock pulse generator 49, signal bc is increased by the value of b .

Assuming there are six antenna elements A_1 through A_6 and hence six current generators, 1—6, the operation of establishing the current for shifters 41, 42, etc. may be explained. Beam position input 29 is adjusted to provide a digital signal b indicative of a desired angle of propagation θ . Signal b is applied to binary adder 30. Assuming that c is initially zero, bi-

binary adder 30 adds the binary signal b to zero and delivers the result (which is, of course b) to storage register 33. Clock pulse generator 49 operates to produce a pulse to input 51 of storage register 33 to enable storage register 33 to store the signal from adder 30. Digital signal b , stored in the register is applied through output 34 to digital-to-analog converter 35 which in turn produces a voltage V_1 which corresponds to digital signal b received from storage register 33.

At the same time, the signal b in storage register 33 is applied to binary adder 30 through input 36 and is added to signal b appearing at input 31. The result, $2b$ is applied to the input of storage register 33. Clock pulse generator 49 produces another clock pulse to enable storage register 33 to accept and store the new digital signal $2b$. Also, as will be more fully understood hereinafter, the same pulse from clock pulse generator 49 enables an appropriate one of the current generators to receive the voltage from digital-to-analog converter 35. Beam step input clock 55 produces a pulse to trigger single-shot multivibrator 57 which in turn produces a pulse at lead 58 to enable current generator 1 to receive a signal. Voltage V_1 appears at input 38 of current generator 1. During the next clock pulse from clock pulse generator 49, current generator 1 is enabled by the pulse appearing at input 52. Thus, when current generator 1 is enabled by a signal from clock 49 appearing at input 52, and is triggered by a signal from clock 55 appearing at input 58, the voltage V_1 occurring at input 38 operates on current generator 1 so that current generator 1 produces a current having a value proportional to the value of voltage V_1 . The current derived by the current generator flows between lead 44 and ground 45 through phase-shift coil 41. Thus, the phase shifter of antenna element A_1 of phase shifted by an amount dependent upon the value of voltage V_1 which in turn is dependent upon the beam position input binary signal, b . When current generator 1 is set, a signal is applied to lead 47 to enable current generator 2 to accept an input. Thus, digital-to-analog converter 35 will derive a new analog signal V_2 dependent upon the value of digital signal $2b$, which analog signal V_2 is applied to lead 37. During the next clock pulse from clock pulse generator 49, the digital signal appearing in storage register 33 is increased by b and current generator 2 is set through input 33 to receive voltage V_2 through input 39. Also, current generator 2 provides an output on lead 48 to enable the next current generator.

The cycle continues until all current generators 1—6 are set to provide the proper currents for the desired phase shifts.

From the foregoing, it can be understood that the binary signal stored in storage register 33 is of the general form bc , where c is an integer which increases by one for each cycle of clock pulse generator 49. Hence, binary adder 30 adds b to bc to derive $(c+1)b$; the $c+1$ becoming a new c .

Storage register 33 and binary adder 30 are designed to a capacity of the same number of bits. The voltage gain of the digital-to-analog converter is adjusted to a value so that when the maximum storage capacity of storage register 33 is reached, the voltage necessary to derive a 2π phase shift in each phase shifter is generated by generator 35. Hence, if adder 30 attempts to provide a digital signal having a number of binary characters which exceeds a 2π phase shift, only that much of the binary signal which exceeds the 2π equivalent will be transferred to the digital-to-analog converter. For example, assuming that a binary character of 1,000 (digital 8) would operate on digital-to-analog converter 35 to produce a voltage which, when applied to a current generator, would produce the current necessary for obtaining a 2π phase shift; and assuming b equaled binary 11 (digital 3), storage register 33 would attempt to store the following tabulated binary signals:

TABLE IV

A_1	00011	(3)
A_2	00110	(6)
A_3	01001	(9)
A_4	01100	(12)
A_5	01111	(15)
A_6	10010	(18)

However, if a binary signal of 1,000 (digital 8) will produce a 2π phase shift, which, of course is equal to a zero phase shift, a binary signal of 000 (digital 0) will produce the same results. Hence, in this case, the storage register could be constructed as to store only the last three binary bits (thereby dropping any binary number in excess of 111—digital 7). Hence, in the example, the values of A_1 — A_6 may be represented as follows:

TABLE V

A_1	011	(3)
A_2	110	(6)
A_3	001	(1)
A_4	100	(4)
A_5	111	(7)

A_6 010 (2) It is to be understood that although a binary signal of only three binary characters is used in the example, it is more likely that the binary signal would have more characters, for example, 10 characters. If binary signals containing more characters are utilized, a greater degree of accuracy and incremental variation may be obtained over the angle of propagation θ .

Since the ring or successive enabling relationship between current generator 1— n ends with current generator n , additional setting of the current generators is not effectuated by additional pulses from clock pulse generator. Hence, beam step input clock 55 periodically produces a pulse to enable current generator 1 to be reset. Beam step input clock 55 may be related to binary adder 30 so as to clear any input appearing at input 36 on each clock pulse from clock 55, so upon initiation of each setting cycle, by clock 55, binary adder, storage register, and digital-to-analog converter operate on the first current generator in identically the same manner as in the prior cycle.

Since clock 55 should operate at a rate less than the rate of the entire cycle, it is desirable that the frequency of clock 55 be less than or equal to $1/n$ times the frequency of clock pulse generator 49. Hence, in the case of six antenna elements, the frequency of clock 55 will be less than one-sixth the frequency of clock pulse generator 49.

The present invention thus provides a cyclic beam control circuit for controlling the propagation direction for an antenna array. The cyclic beam control network in accordance with the present invention is particularly useful for controlling the phase shifters described in the said Chalfin et al. application.

This invention is not to be limited by the embodiment shown in the drawings and described in the description, which is given by way of example and not of limitation.

What I claim is:

1. Apparatus for controlling a plurality of electrically controllable delay devices for an array of a plurality of antenna elements so that the antenna elements will propagate electromagnetic radiation in a desired direction, said apparatus comprising: adding means for adding digital signals, said adding means having a first input adapted to receive a digital signal representative of the desired direction of propagation of

electromagnetic radiation by said array of antenna elements, said adding means having a second input and having an output, said adding means being capable of adding a digital signal appearing at said first input to a digital signal appearing at said second input; clock means providing a periodic signal; storage means connected to the output of said adding means and to said clock means for storing the sum of the digital signals upon receiving a periodic signal; means connecting the output of said storage means to the second input of said adding means; converter means connected to the output of said storage means for converting the digital signal in said storage means to an analog signal; control means connected to said converter means for controlling each of said delay devices and means connecting said control means to said clock means to periodically and successively operate said control means upon each periodic signal to enable successive control of each of said delay devices.

2. Apparatus according to claim 1 wherein said control means comprises a plurality of control devices each having a first input connected to the output of said converter means, each of said control devices being operable to control a respective delay device by an amount dependent upon the analog signal from said converter means for successively operating the control devices.

3. Apparatus according to claim 2 wherein said last-named means comprises a first enable input to each of said control devices connected to said clock means, and a second enable input to each of said control devices, the second enable input to the first control device being connected to a control source and the second enable input to each successive control device being connected to an enable output of the previous control device so that each control device is enabled upon successful operation of the prior control device.

4. Apparatus according to claim 3 wherein said control

source comprises a second clock means.

5. Apparatus according to claim 4 wherein the delay devices are current-operable and said control devices are current generators.

6. Apparatus according to claim 4 wherein there are n number of delay devices and n number of control devices, said second clock means having a frequency not greater than $1/n$ times the frequency of the first clock means.

7. A control circuit for controlling a plurality of load devices comprising: a binary adder having a first input adapted to receive a digital signal indicative of a desired control function, a second input and an output, said binary adder being capable of adding a binary signal at the first input and applying the sum to the output; a storage register having an input connected to the output of said binary adder and having an output connected to the second input of said binary adder; a clock pulse generator connected to an input of said storage register to enable said storage register to store the binary signal from said binary adder; a digital-to-analog converter having an input connected to the output of said storage register and having an output; a plurality of current generators each having an input connected to the output of said digital-to-analog converter and each having a first enable input connected to said clock pulse generator and each having a second enable input, some of said current generators having an enable output; a source of clock pulses connected to the second enable input of one of said current generators, the second enable input of each successive current generator being connected to the enable output of the previous current generator whereby the current generators are arranged in ring relation; and means connecting the output of each current generator to a respective load device.

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