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D'Antonio

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[54] **DIGITALLY CONTROLLED PHASE SHIFT NETWORK**

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[51] **Int. Cl.**... **H03k 17/66,** H03k 17/14, H01p 1/32

[58] **Field of Search**..... 307/101, 273, 314; 328/155; 333/24.1, 31 A

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Primary Examiner—Paul L. Gensler

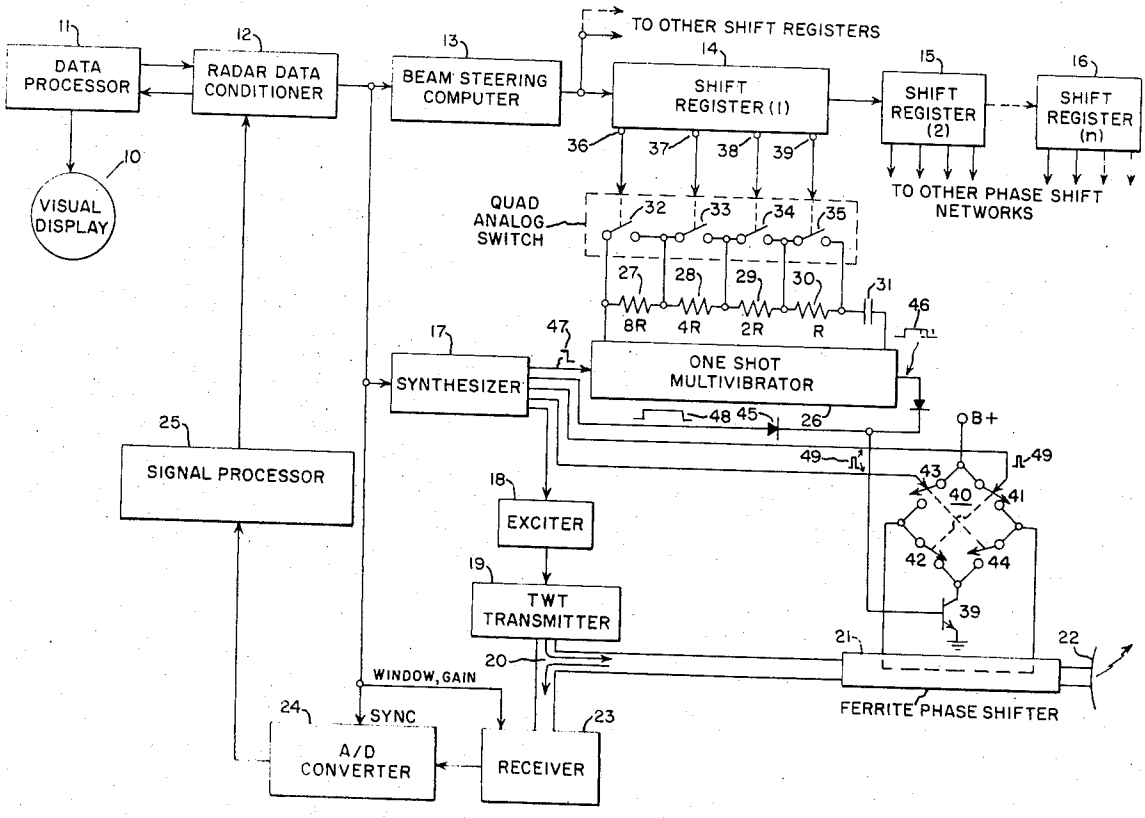
Attorney, Agent, or Firm—Richard V. Lang; Carl W. Baker; Frank L. Neuhauser

[57] **ABSTRACT**

The present invention relates to a digitally controlled phase shift network for use with an individual antenna element, as would form a part of a phased array radar system wherein a directional beam is formed and electrically scanned by control of the phase of each individual antenna element. The phase shift network here described is responsive to a computed digital signal which it converts in an electrically switched resistance-capacitance timing network to a pulse whose duration is an analog quantity stepped in equivalence to the digital input. The variable duration pulse is used to control the volt time area of a source of magnetizing energy to achieve stepped remanent states in the ferrite phase shifters corresponding to stepped angles of phase shift. A direct conversion of a digital signal into an analog phase shift angle is achieved while also providing electronic compensation for nonlinearity in the magnetization characteristics of the ferrite and for temperature drift.

The invention herein described was made in the performance of a contract with the Department of the Army.

9 Claims, 5 Drawing Figures



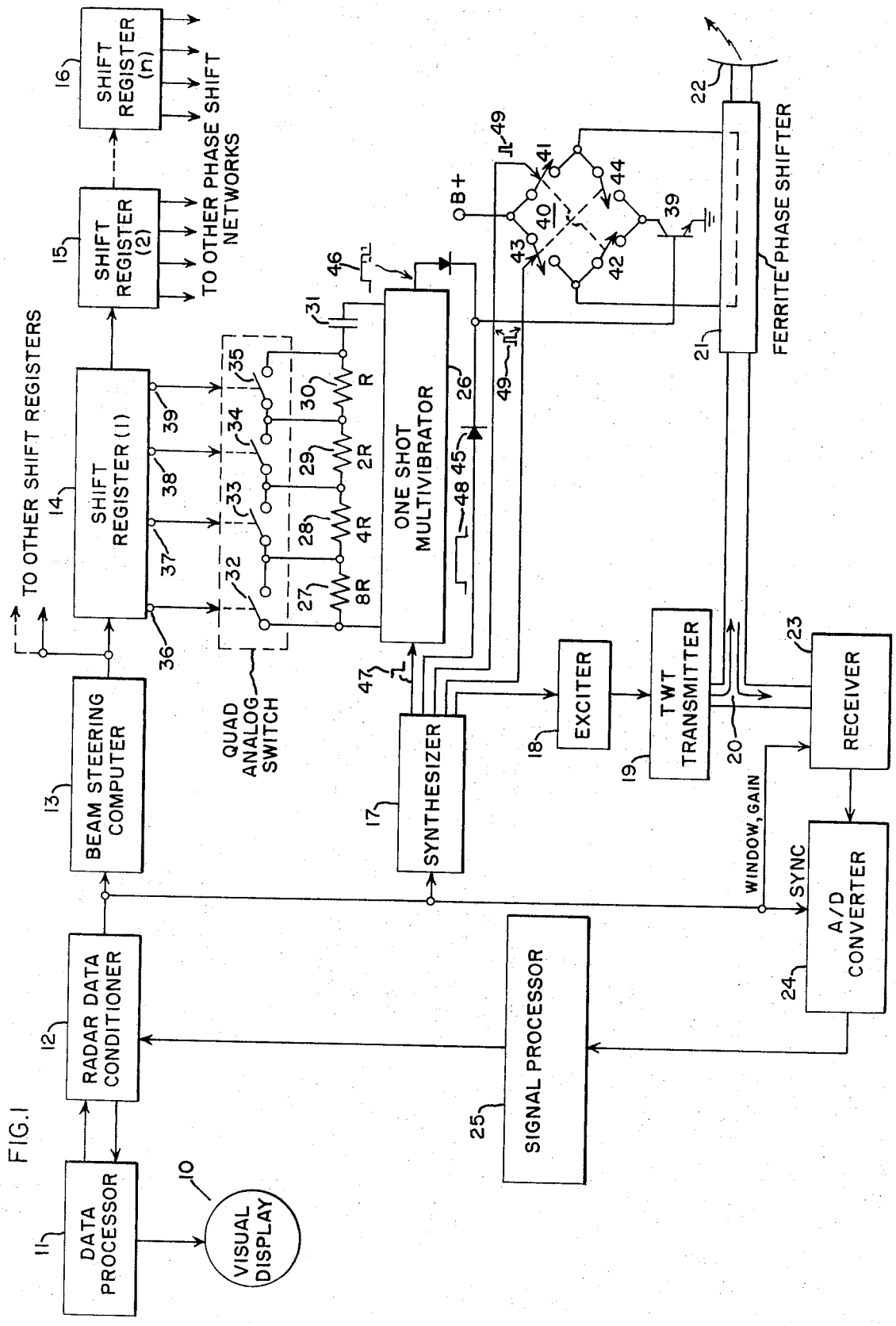

DATA PROCESSOR
VISUAL DISPLAY
RADAR DATA CONDITIONER
BEAM STEERING COMPUTER
SHIFT REGISTER (1)
SHIFT REGISTER (2)
SHIFT REGISTER (n)
TO OTHER SHIFT REGISTERS
TO OTHER PHASE SHIFT NETWORKS
QUAD ANALOG SWITCH
ONE SHOT MULTIVIBRATOR
SYNTHESIZER
EXCITER
TWT TRANSMITTER
RECEIVER
A/D CONVERTER
SIGNAL PROCESSOR
FERRITE PHASE SHIFTER
B+
WINDOW, GAIN
SYNC
R
2R
4R
8R

FIG. 1

FIG.4

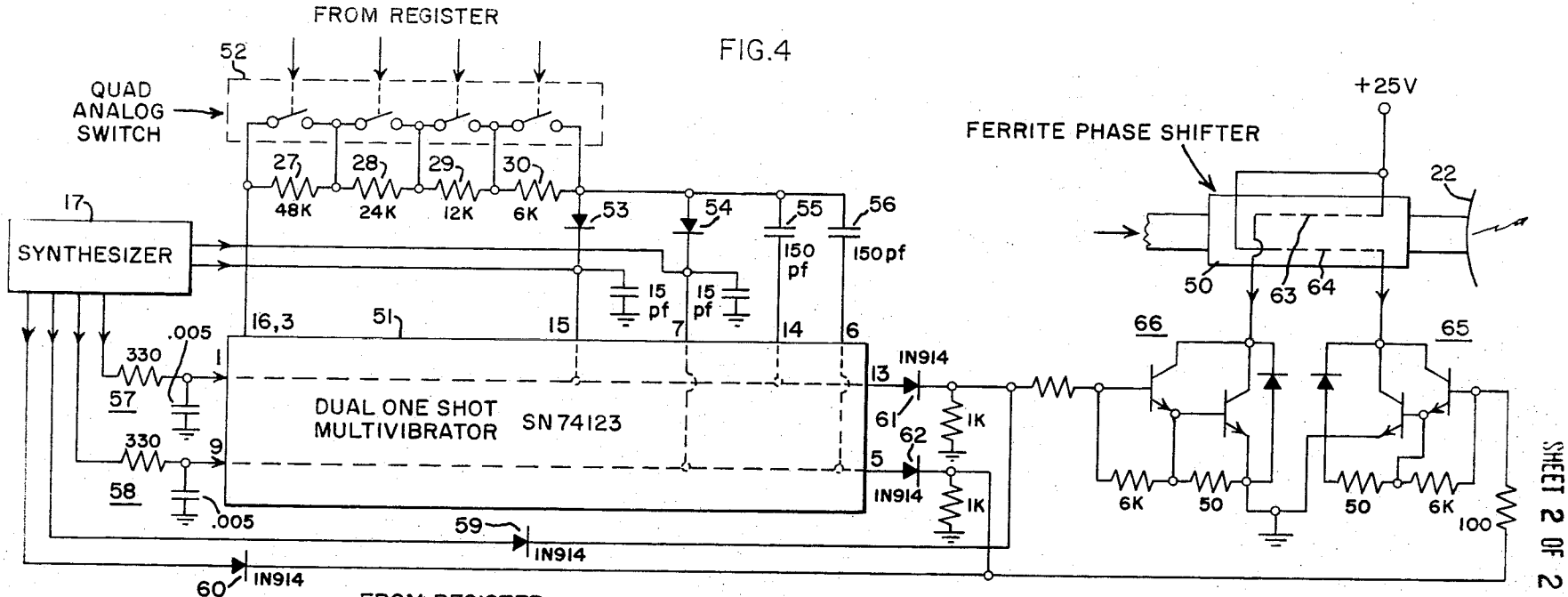


FIG.2

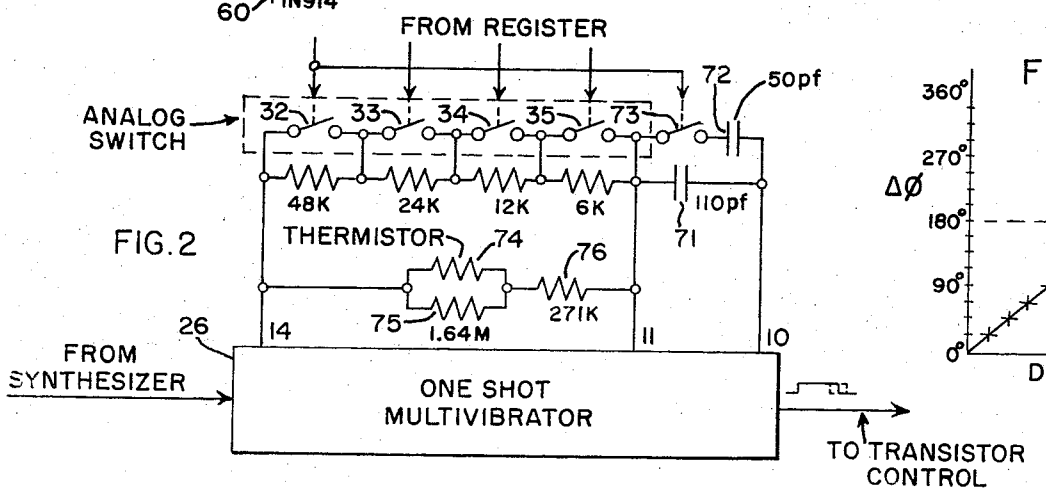


FIG.3b

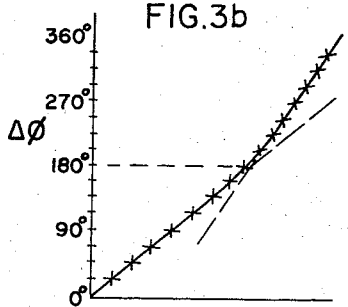
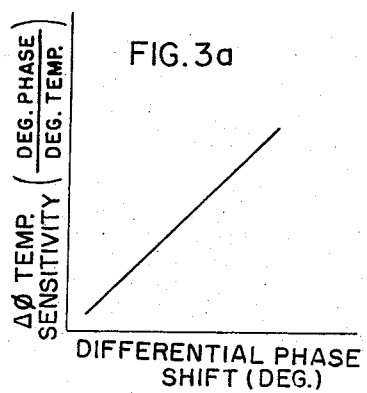


FIG.3a



DIGITALLY CONTROLLED PHASE SHIFT NETWORK

BACKGROUND OF THE INVENTION

1. Field of the Invention:

The present invention relates to phased array radar systems wherein individual antenna elements are subject to individual phase adjustment. The invention also relates to networks designed to produce stepped phase shift angles in ferrite phase shifters in response to digital control signals. The invention further relates to the compensation for nonlinearity in the magnetization of such ferrite phase shifters and for temperature induced drift.

2. Description of the Prior Art:

Phased array radar systems are well known and in their most important form consist of large numbers of like antenna elements, each operating in predetermined phases. The phases are often varied in phase intervals stepped a simple fraction of 180°. Such intervals have been 90°; 60°; 45°; 30°; 22.5°; 15°, etc. The approaches to producing such phase shifts have been divided between diode switching arrangements and ferrite devices to which the present invention pertains. In ferrite phase shifters, a ferrite having a square loop characteristic is used and magnetized to a remanent state producing a desired phase shift. In recent systems, the need has developed for phase shift devices which are capable of larger numbers of remanent states. Typically, from eight to 32 remanent levels are now of interest. In the typical application, a phase shifter exhibiting 16 remanent states would produce phase shifts in angular increments of 22.5° embracing a range of from 0° to 337.5° of total phase shift. Because of the nonreciprocal nature of the magnetization, a given remanent state is always achieved by starting from reverse saturation and then applying a drive signal having a given volt time area to reach the desired remanent state. Since the phase shifters are used in both transmission and reception and since forward and reverse passage of the signal through the ferrite phase shifter produces opposite but equal phase shift, it has been customary to operate the phase shifter in the reception mode with the magnetization in one sense and during transmission with an equal magnetization in the other sense. If the hysteresis properties of the core, as between forward and reverse hysteresis, are symmetrical, the like phase shifts would be achieved in both reception and transmission.

The preferred quantization of the magnetization levels is one producing phase shifts occurring in equal angular steps. A number of ways have been proposed to produce equality in the stepping angles and at the same time insure that the steps remain accurate in the presence of temperature drift. Since ferrites have tended to have nonlinearly spaced remanent states as a function of the volt time area of the drive signal, a number of techniques have been introduced to correct this nonlinearity. These techniques have involved extreme care in the design and construction of the magnetic and associated waveguide structures. These techniques have generally involved high degrees of mechanical precision to insure not only that individual phase shifters meet absolute specifications but that they be interchangeable with one another. In general, the use of large numbers of these phase shifters has multiplied the severity of tolerance control. In addition to the matter of control of the magnetization characteristics, all ferrite devices

have been subject to temperature induced drift. A common technique for avoiding such drift has been to establish the devices in a temperature controlled environment. Ideal mechanical solutions to both of the foregoing problems have been prohibitively expensive in large arrays and costs have set definite limitations upon phase accuracies that could be expected.

In addition to the matter of individual device accuracy, the circuitry used to produce stepped remanent states has tended to be overly complicated. Because large numbers of individual circuits have been required, circuit improvement has been particularly important. In the prior art, the achievement of stepped analog angles under the control of a digital computer has been achieved through use of a digital to analog converter producing a voltage which is then used to control the frequency of a gated voltage controlled oscillator to achieve a variable time period which is then used to control the volt time area of ferrite magnetization circuitry. The indirect conversion has been complicated and objectionable when large numbers of like equipments have been needed.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide an improved digitally controlled phase shift network.

It is another object of the invention to provide a digitally controlled phase shift network having improved temperature compensation means.

It is a further object of the invention to provide a digitally controlled phase shift network wherein stepped remanent states of a ferrite element are utilized, having improved phase shift linearity in successive remanent states.

It is still another object of the invention to provide a digitally controlled phase shift network wherein successive remanent states of a ferrite element are utilized, having improved means for converting a digital signal into an analog time quantity for controlling the magnetization of the ferrite.

These and other objects of the invention are achieved in a digitally controlled phase shift network comprising a source of a digital electrical quantity, typically a shift register, which electrical quantity is representative of a desired phase shift angle. Means are provided for producing a pulse whose duration is an analog function of the registered electrical quantity. These means comprise a monostable multivibrator whose output pulse duration is proportional to an associated controllable resistance element, the controllable resistance comprising "N" serially connected resistances having consecutive values corresponding to the place significance of successive positions on the register and further comprising a like number of switches responsive to the successive registered quantities and shunting each serially connected resistance. The resulting controllable resistance has a value which is the analog equivalent to the registered digital electrical quantity. The network further comprises a ferrite phase shifter, and a power switch responsive to the variable duration pulse for coupling electrical energy to the phase shifter for a period equal to the pulse duration to produce an analog phase shift corresponding to the digital electrical quantity.

In accordance with other aspects of the invention, the digital source employs binary coding and the indi-

vidual resistances are scaled to have consecutive values of approximately R, 2R, 4R, etc. In order to provide compensation for temperature drift at all settings of the controllable resistance, a negative temperature coefficient resistance is provided in an electrical path which shunts the serially connected resistances and which is physically disposed in the same temperature environment as the core of the phase shifter. To effect a more accurate compensation of thermal drift, the negative coefficient resistor may be provided with serial and shunt compensating resistances to adjust both the curvature and the slope of the compensation and thereby provide essentially three points of a precise compensation.

In accordance with another aspect of the invention, a controllable capacitance is coupled in series with the serial resistance elements whose value decreases at higher phase shifts, the prior and subsequent capacitances being selected to linearize the phase shift. Additional capacitance is normally switched out in synchronism with the switch corresponding to the highest place significant terminal in order to reduce the capacitance near the middle of the phase shift range.

In accordance with additional aspects of the invention, the resistances are offset from precise binary scaling in order to further compensate for nonlinearity in the magnetic properties of the ferrite core. Should the ferrite cores have nonreproducible properties, then the resistances are made adjustable about the binary value.

BRIEF DESCRIPTION OF THE DRAWING

The novel and distinctive features of the invention are set forth in the claims appended to the present application. The invention itself, however, together with further objects and advantages thereof may best be understood by reference to the following description and accompanying drawings in which:

FIG. **1** is an illustration principally in block diagram form of a phased array radar system incorporating a digitally controlled phase shift network in accordance with the invention;

FIG. **2** is a circuit diagram of a portion of the digitally controlled phase shift network including two modes of compensation;

FIG. **3**(*a*) is a graph illustrative of the phase shift temperature sensitivity in degrees phase per degrees temperature as a function of the differential phase shift required, and

FIG. **3**(*b*) is a plot of the differential phase shift as a function of the volt-time area of an applied rectangular pulse; and

FIG. **4** is an illustration of an embodiment of a phase shift network modified for use with a phase shifter having separate transmitting and receiving windings.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. **1**, there is shown a phased array radar system incorporating a plurality of digitally controlled phase shift networks in accordance with the invention. A phased array radar system is a target location system in which a beam of radio energy is directed toward a target and an echo received, and which uses an antenna which is electrically, as opposed to mechanically, scanned. The antenna, which is normally used for both transmission and reception, is formed of a plurality of individually excited radiating elements disposed in a stationary array, the phase of the energy flowing out of and into each element of the array being controlled in such a manner as to synthesize a directional beam and to provide for its scanning.

The phased array radar system of FIG. **1** is of a generally conventional configuration. It comprises a data processor **11** which is the central control system computer and to which target data such as azimuth, elevation and range is continuously supplied. The interface between the central control system computer **11** and the radar is provided by a radar data conditioner **12** which in turn feeds data into the beam steering computer **13.** The beam steering computer is designed to provide the electrical values to the phase shifters for individual elements of the array in performance of the scanning function. It also provides reference timing. The output of the beam steering computer **13** is supplied to a series of "N" registers **14, 15** and **16** each assigned to an element of the array, the illustrated series of shift registers being a single row, or a block of elements, in the array. Other series of shift registers corresponding to other portions of the array are not illustrated, but would be present in the total system. The radar data conditioner **12** is also coupled to a synthesizer or waveform generator **17** which establishes the transmitted pulse width and triggers the exciter **18** used to drive the traveling wave tube transmitter **19.** The transmitter **19** is shown coupled by a waveguide through a directional coupler **20** and a ferrite phase shifter **21** to an individual array element **22.** The phase shifter **21** has a single control winding shown as a dotted line symbolizing a single turn and has a core of square loop material exhibiting a succession of stable remanent states.

A conventional array may be quite large, using many of the same elements repetitively. It must be organized for efficient distribution and collection. A conventional array may have a large number of radiating elements as, for instance, 100 × 100 or 10,000 elements. Each array element has its own phase shifter and a separate phase shift network for that phase shifter. Directional couplers, which are a part of the power distribution network, are normally shared with other elements of the array. During transmission, the power distribution network (not shown) distributes the power available at high power levels at the transmitter to the individual array elements which operate at relatively low power. During reception, the power distribution network must be designed to collect the received signal from individual elements of the array and to apply it to the receiver (**23**) at a reasonably low signal to noise ratio.

The phased array radar system of FIG. **1** also functions in a generally conventional manner. In transmission, the transmitting pulse passes successively through elements **19, 20, 21** and **22.** In reception, the return signal is coupled from the array element **22** to the phase shifter **21.** The return signal is then directed through directional coupler **20** to a receiver **23.**

Completing the operational description, the receiver **23** demodulates the radar return received by the array and couples the demodulated signals first to an A/D converter **24** and then to a signal processor **25.** The processor **25** couples the processed data to the radar conditioner **12,** which couples the data to the data processor **11** so as to apply fresh target data on azimuth,

elevation and range for updating the visual display, shown at **10.**

The foregoing elements of the system may be of conventional design. The novelty of the system lies in the measures, which will now be described, for controlling the individual ferrite phase shifters in accordance with digital information applied to the shift registers.

The phase shift network associated with a single array element comprises a one shot multivibrator **26,** which produces a pulse **46** of controllable duration in accordance with digital numbers stored in a shift register **14**; a timing network associated with the multivibrator comprising the resistive and capacitive elements **27–31** and switches **32–35**; diode **45**; and a power switching network **39–44** for applying a timed power pulse to an individual phase shifter.

The timing network produces a time constant which establishes the duration of the multivibrator output pulse at an analog value equivalent to the digital number stored in the shift register. The timing network comprises a series of binary scaled resistances **27, 28, 29, 30** serially connected with one another and to a capacitor **31.** The series circuit (**27–31**) is connected between the timing input terminals of the one shot multivibrator **26** so as to control the duration of the output pulse. The resistances **27, 28, 29, 30** are each shunted by a switch **32, 33, 34, 35.** Each switch is responsive to the state of the shift register **14** at a corresponding stage **36, 37, 38** and **39.** Information from the beam steering computer is applied to the shift register, with the most significant data to the left and the least significant data to the right as seen in FIG. **1.** The resistances are scaled **8R, 4R, 2R** and **1R** in the same left to right order. In this manner the place significance of digits stored at successive stages of the register correspond to the scaling of the resistances. When a digital number having a decimal value of from 0–15 is stored in the register, it will control the operation of the switches **32-35** to produce a corresponding analog value in the resulting serial resistance of the timing network. Since the time constant of the timing network is proportional to the resulting resistance, the duration of the multivibrator pulse is also proportional to the digital number stored in the shift register.

The one shot multivibrator **26** and associated switching circuitry are available in the form of relatively inexpensive integrated circuit modules. A satisfactory multivibrator is Texas Instrument SN74121. The individual switches **32** through **35** of FIG. **1** are also available in a single integrated circuit module called a "quad analog switch," National Semiconductor Type AH0015 being suitable. The module, as the name implies, consists of four individual switches, each having a differential amplifier input stage, whose input is externally available for coupling to the output terminal of the shift register **14.** The output of each differential amplifier is internally connected to the gate of a field effect transistor (MOSFET), used as the switching element of the module. The individual timing resistances **27, 28, 29, 30** are each coupled between the externally available source and the drain electrodes of an associated field effect transistor. A field effect transistor used in this manner is well suited for this switching application because of its low impedance when it is on, because of its nearly infinite impedance when it is off, because of its high speed, and finally because of its bidirectional conductivity.

The variable duration output pulse **46** of the one shot multivibrator **26** controls the power switching network which in turn controls the application of power to the individual ferrite phase shifter **21.** The power switching network comprises a high β, high current transistor control **39,** and a bridge **40** consisting of four electronic switches **41–44.** The multivibrator pulse **46** is applied to the input terminal of the transistor control **39.** The output terminals of the control are coupled respectively between the lower terminal of the bridge (as seen in FIG. **1**) and ground. The upper terminal of the bridge is coupled to a source of positive voltage. In low power applications, the transistor control **39** may be a single transistor as illustrated. The multivibrator pulse is applied to the base, positive voltage is applied to its collector through the bridge **40,** and the emitter is grounded. In moderate or high power applications, where the multivibrator has insufficient drive for controlling substantial amounts of power in a single transistor, a buffer amplifier may be introduced between the output of the multivibrator and the control transistor. A particularly satisfactory configuration is a Darlington configuration, which requires relatively little drive, and is capable of switching as much as 10 amperes of current. A suitable type is an integrated circuit module by Unitrode, Type U2T101.

The bridge **40,** under the control of synthesizer **17,** consists of four SCR devices arranged to conduct the "drive command" current applied to the phase shifter and to reverse it as between transmission and reception. This permits use of a phase shifter (**21**) with a single rather than a double control winding. The synthesizer **17** controlling each switch (**41–44**) causes conduction of one diagonal pair of switches for transmission (**41, 42**) and conduction of the other diagonal pair (**43,44**) for reception. The pulses which adjust the phase shifters are timed to precede signal transmission and signal reception. Assuming that the switch elements **41** and **42** are conductive, current flows through the element **41** to the right terminal (as seen in FIG. **1**) of the phase shifter to its left terminal and thence through the switching element **42** into the collector of the control **39** and thence to ground. Assuming that the foregoing direction of conduction is suitable for transmission, the condition of the bridge is reversed for reception with the switches **43** and **44** being turned on and the elements **41** and **42** being turned off. The current path is then reversed through the phase shifter with the current passing from the left hand terminal to the right hand terminal. The switching elements (**41–44**) may take several forms but a particularly satisfactory type are silicon controlled rectifiers of the fast turn off variety of which RCA Type 40554 is suitable.

The digitally controlled phase shift network uses certain conventional practices for obtaining accurately stepped magnetization levels in the ferrite phase shifter while at the same time embodying certain improvements not in conventional use.

In accordance with convention, the synthesizer **17** prepares the ferrite phase shifter for magnetization to a specific remanent level by generating a clearing pulse **48** in advance of the quantized drive command pulse. The clearing pulse is sufficiently long to saturate the phase shifter core in the opposite direction to that produced by the quantized pulse. The clearing pulse, which is of a positive polarity, is coupled by the diode

45 from the output of the synthesizer 17 to the base of the transistor control 39. The leading edge of the clearing pulse has no effect on the one shot multivibrator 26 which (in this design) responds to a negative edge pulse as shown at 47. The positive pulse 48 then turns on the transistor control 39. At the same time that the transistor control 39 is being turned on, a short trigger pulse 49 is applied from synthesizer 17 to the switching bridge 40 to turn on SCR switches 43, 44. With both the transistor control 39 and the bridge 40 turned on, a flow of magnetizing current is applied to the ferrite phase shifter 21 having a sufficient volt time area to saturate it.

After the ferrite phase shifter has reached saturation, the clearing pulse 48 from the synthesizer terminates and the negative, trailing edge of the clearing pulse may be used to start the multivibrator in generating the quantized pulse 46. Normally, the start of the quantized pulse is delayed a short time with respect to the trailing edge of the clearing pulse by an RC network either at the input of the multivibrator or in synthesizer 17. During this delay, the control transistor 39, to which both the clearing and quantized pulses are applied, is nonconductive and interrupts the energization of the switching bridge 40. The duration of the interruption is chosen to be long enough to allow the stored charge in the junctions of the SCRs 43 and 44 to be swept out for full turn off. Any stored charge in the gate region of the SCRs is minimized by using minimum duration trigger pulses for turning them on.

During application of the quantized command pulses to the ferrite phase shifter, a similar control sequence to that during reset occurs. As the multivibrator starts the generation of its quantized drive command pulse (46), the transistor control 39, which responds to the amplitude of the pulse is turned on. The transistor control 39 and the SCR switches 41 and 42 are turned on simultaneously. The magnetizing current then flows from the d.c. source through the bridge 40, through the core winding, and through the transistor control 39 throughout the duration of the quantized command pulse. As the pulse 46 terminates, the current through the control transistor 39 terminates, cutting off the current path for the SCRs 41 and 42. In the time that it takes the stored charge to be swept out, the SCRs become nonconductive and current flow to the ferrite phase shifter is terminated. As noted with respect to the clearing pulse, the SCRs 41 and 42 are preferably turned on by a short duration trigger pulse (49) which does not persist into the conduction period. Thus, charge storage is minimized and the accuracy and the duration of the current flows are determined primarily by the lengths of the quantized command pulse 46 applied to the transistor control.

Since the magnetization of the ferrite phase shifter produces an angular phase shift proportional to the volt time area of an applied pulse, and since the pulse duration occurs in quantized steps corresponding to the digital information at the shift register, the phase shift produced by the phase shifter also becomes a stepped quantity.

Using a large clearing pulse insures that the quantized drive command pulse will always commence from a reverse saturation condition, and avoids any error in the final remanent state, due to the open loop or nonreciprocal nature of the ferrite. While described in connection with setting up the magnetic state of the phase shifter for transmission, the same sequences of clearing and quantizing pulses are repeated during reception, with the switches 41, 42 now being used in clearing, and the switches 43, 44 being used to achieve the quantized magnetic state.

In summary, the phase shift network directly converts the information available in binary digits at successive stages of the shift register 14 into an analog electrical quantity having discrete values. The digital information is initially translated into the total external resistance associated with the multivibrator 26. The resistance in turn determines and represents the time constant that this resistance produces in combination with capacitor 31. The time constant of the external network then determines the duration of the pulse generated by the one shot multivibrator. The pulse, whose duration is adjustable in 15 steps, then controls the duration of application of voltage to the core of the ferrite phase shifter.

The FIG. 1 arrangement, without further modification, produces accuracies of about (±3°) for 225° steps over a range of 337.5°. If greater accuracy is sought, the present conversion technique is adaptable to further refinement. In particular, the arrangement lends itself to compensation for both temperature induced drift and inaccuracy in the magnetization curve.

The measures for producing these compensations are illustrated in FIG. 2 which repeats only that portion of the phase shift network of FIG. 1 which involves the one shot multivibrator 26 and its associated resistance and capacitance matrix. Using the same reference numerals applied in FIG. 1 to repeated elements, the one shot multivibrator 26 is provided with shunting resistances 27, 28, 29, 30, and analog switches 32, 33, 34, 35 as before, but it is modified to include one pair of capacitances 71, 72 and an additional analog switch 73 synchronized with switch 32, and a temperature compensation network comprising resistances 74, 75 and 76.

The temperature compensation network includes a thermistor 74 with curve shaping resistances 75 and 76, respectively, coupled in shunt and in series with it. The compensation network is connected in shunt with serial resistances 27 through 30. The termistor 74 has a negative temperature coefficient and the curve shaping resistances 75 and 76 provide for more accurate thermal compensation. The termistor has a predetermined slope and substantial initial curvature. In the initial calculation, the value needed for two point compensation at the upper and lower limits of the expected temperature range is calculated. If the mid-point of the range is displaced from the ideal linear characteristic, the curvature of the thermistor characteristic is reduced by adding a suitable amount of shunt resistance. The serial resistance gives an additional degree of freedom in the adjustment. In this way, three point curve fitting is available.

For good temperature compensation, the thermistor should be exposed to the same temperature environment as the ferrite core of the phase shifter that it compensates. Normally, this will entail the application of the thermistor to a metal part encasing the ferrite, where it is isolated from the r.f. fields traversing the waveguide but in good thermal contact through the encasing metal parts with the ferrite core.

The foregoing temperature compensation remains accurate for all 0–15 values of the resistance matrix.

This may be appreciated in an intuitive fashion. As resistance of the matrix is increased to maximum values, the effect of a predetermined change in the resistance of the correction network in shunt therewith will be increased proportionately. Similarly, if the serial resistance of the matrix is decreased, the relative effect of a predetermined change in resistance in the correction network will be decreased. To compensate the network against temperature changes, it is necessary that a greater absolute correction be achieved for higher resistance values than for lower resistance values. The proposed configuration is in accord with these requirements. A computer calculation shows that the temperature compensation can be made to a degree of perfection which surpasses the other inaccuracies of the overall network. The component values indicated on FIG. **2** contemplate a temperature range of from 25° to 70°C and achieves an accuracy of ± 0.75°. The thermistor is a type NL4D051 having values of 164K at 25°C, 66K at 45°C, and 23K at 70°C.

For compensation of nonlinearity in the magnetization curve, the capacitors **71, 72** in series with the resistive elements are provided with a switch **73** which permits reduction of the capacitance at mid-range. The magnetization of the ferrite is approximated by the solid line illustrated in FIG. **3**(*a*) The line has an initial slope which is less than the terminal slope, with the most significant change in slope occurring, and being confined to, near the mid-range of the ferrite. The switch **73** is synchronized with the switch **32** corresponding to the most significant digit, so that the capacitance over the initial half of the range is that of **C1** and **C2,** while the upper half range is that of **C1** alone. If the capacitor values of **C1** and **C2** are suitably chosen (110 pf, 50 here), the nonlinearity exhibited by the magnetization curve may be exactly fitted at two points in the range, and in practice a very close approximation to the desired linear phase shift characteristic may be achieved over the entire range. Phase inaccuracies of less than ± 1° in a system employing 15 steps of 22.5°, and embracing a range of 337.5° may be achieved by this correction. If a less carefully tailored phase shifting element, having a more generally curved magnetization characteristic is used, near perfect compensation may still be achieved using a third capacitor switched out in synchronism with the switch, normally at the next most significant position.

FIG. **4** illustrates an embodiment in which the phase shifter (**50**) has separate transmit and receive windings and in which the phase shift network is suitably adapted. When separate transmit and receive windings are used, the switching bridge **40** of FIG. **1** is not required, but separate transistor controls and separate multivibrators for the transmit and receive function are required.

The phase shift network of FIG. **4** comprises a dual one shot multivibrator **51** having a switched resistance matrix comprised of resistances **27, 28, 29, 30**; a quad analog switch **52**; gating diodes **53, 54** coupled to the timing terminals of the separate multivibrators within the module; separate timing capacitors **55** and **56** also connected to the timing terminals of the separate multivibrators; a pair of input RC delay networks **57, 58**; reset diodes **59, 60**; and output steering diodes **61, 62.**

In operation, one section of the one shot multivibrator **51** controls the transmit winding **63** of the ferrite phase shifter and the other section of the multivibrator controls the receive winding **64.** The initial control pulses are coupled from the synthesizer **17** through the delay network **57** to one section of the one shot multivibrator. The resistance matrix **27–30** is active, with the diode **53** being turned on by a control pulse from **17** so as to connect the resistance matrix in circuit with the first multivibrator section. The capacitor **55** is connected by a separate terminal with the same section. The duration of the multivibrator output pulse is controlled by these elements. The multivibrator output pulse is coupled through the steering diode **61** to the input connection of the Darlington control **66.** The control **66** is inserted between the transmit winding **63** of the phase shifter and ground. During transmission, the variable width drive command pulse from the first multivibrator section controls the duration of conduction of transistor control **66** and, by energizing the transmit coil **63** for a metered volt-time area, steps the core to a predetermined remanent state.

During reception, the second multivibrator section is active. The output from the synthesizer **17** is coupled to delay network **58** at the input to the second multivibrator section. The diode gate **54** is turned on, coupling the resistance matrix **27, 28, 29, 30** into the timing terminals of the second section of the multivibrator. The separate capacitor **56** is coupled to the second section. The second section output pulse, whose duration is timed by these impedances is then coupled through the steering diode **62** to the input of the second Darlington transistor control **65.** The transistor control **65** is coupled between the reception coil **64** of the phase shifter and ground, and steps the core to a pre-assigned remanent state corresponding to that during transmission.

The reset diodes **59** and **60** associated with the separate multivibrator sections, functions in the same manner as the reset diodes of FIG. **1.** They permit the resetting of the core to a reverse saturation remanent state prior to stepping to an intermediate level.

The resistance matrix in the FIG. **4** arrangement, including the analog switches **52** may be used for both transmission and reception even though separate multivibrator sections are employed. Since it is desired that the phase delays for transmission and reception be alike, this removes that source of error. The problem of obtaining identical magnetizations for transmission and reception then depends upon the ferrite phase shifter, wherein the geometry of the double control windings, and their relationships to the core and waveguide must be kept symmetrical by tight mechanical tolerance control. The arrangement of FIG. **2,** wherein the same winding is used for both transmission and reception, uses the intrinsic reciprocal properties of the single winding to reversed signal currents to preserve like phase delay for transmission and reception. Both arrangements use a switched resistance matrix which permits correction of nonlinearity in the magnetization curve and temperature drift of the ferrite phase shifter by simple resistance and capacitance adjustments. Thus, the arrangement permits one to achieve higher phase delay accuracies while at the same time relaxing the tolerances, mechanical and electrical, placed upon the phase shifter.

The direct conversion of the digital drive command signal in the register to a variable width pulse, timed by an electrically switched resistance matrix, thus provides a particularly advantageous method for control-

ling the stepped remanent states of the ferrite phase shifter in a phased array.

In solving the problem of inaccuracy in the stepped phase angles produced, the use of binary scaled, serially connected resistances is particularly advantageous. As additional resistances are successively connected or disconnected, the resistance progression steps linearly. Using the binary scaled serial resistances with a single capacitor as in FIG. 1, an accuracy of ±4° in the phase shift angles is typical. This error is primarily the result of the normal nonlinearity in the magnetization characteristics of ferrite materials. If it is desired to reduce the inaccuracy to below ±2°, then the measures illustrated in FIG. 2 will normally be required. The capacitor value is stepped down at mid-range, or in more severe cases of ferrite nonlinearity, it is stepped a second time. If ±2° accuracy is sought in a conventional thermal environment, the thermal drift requires compensation. If inaccuracies under ±1° are sought, then, depending upon the expected magnetic characterization of the ferrite, the resistance elements themselves may be individually tailored. In this event, each of the four binary scaled resistances may have values lying within a small range above or below the natural value. If the magnetic characterization of the ferrite is reproducible, then fixed resistances at these slightly offset values may be used. If the phase shifters have differing characterizations however, individual compensation with a practical minimum of adjustment may be achieved by using four adjustable resistances.

The serially stepped resistance matrix appears to be unique in that a comparable shunt configuration has a nonlinear progression curving in a direction counter to that exhibited by the ferrite materials and thereby making precise compensation substantially more difficult.

In practice, the resistance adjustments and capacitance herein taught are considerably simpler than most mechanical measures. In addition to achieving close compensation for variability in the magnetic properties of the ferrites, the selection of four binary scaled resistances provides an optimum configuration for temperature compensation. The compensation is practically perfect in the indicated FIG. 2 arrangement since it normally falls below other errors. The configuration is much simpler than arrangements providing individual temperature compensation for each of a plurality of resistances, each of which must be in the temperature environment of the ferrite. In any arrangement requiring a large number of resistances per phase shifter element, the temperature compensation would be complicated in proportion to the number of resistances requiring individual compensation. Thus, the temperature compensation herein taught which requires only a single thermistor per ferrite element and which is effective at a large number of resistance settings is particularly advantageous.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. A digitally controlled phase shift network comprising

A. a source of a digital electrical quantity available on N output terminals of consecutive place significance and representative of a desired analog phase shift,

B. means for producing a pulse whose duration is an analog function of said digital electrical quantity comprising:

1. a monostable multivibrator whose output pulse duration is proportional to a resistance element,
2. a resistance element of controllable value coupled to said monostable multivibrator comprising:
   a. N serially connected resistances having consecutive values corresponding approximately to said place significance, and
   b. N switches shunting each of said serially connected resistances and responsive to the quantity of the corresponding place significant terminal of said digital source to produce a resultant resistance whose value is the analog equivalent of said digital electrical quantity,

C. a ferrite phase shifter having a core of square loop material exhibiting plural magnetic states and whose phase angle is substantially proportional to the time of an applied pulse of constant voltage, and

D. a power switch responsive to said output pulse of said monostable multivibrator for coupling electrical energy to said phase shifter for a period corresponding to said pulse duration to produce an analog phase shift corresponding to said digital electrical quantity.

2. A temperature compensated phase shift network as set forth in claim **1** wherein

said pulse duration is proportional to the time constant of said resistance element and a serially connected capacitor and having in addition thereto

a negative temperature coefficient resistance provided in an electrical path which shunts said serially connected resistances and which is physically disposed in the same temperature environment as the core of said phase shifter.

3. The combination set forth in claim **2** wherein said negative temperature coefficient resistance is in circuit with a compensating resistance to provide curvature and slope control, the compensating element being selected to provide the resistance sought at the two extremities and a mid-point of the operating temperature range of the phase shifter.

4. The combination set forth in claim **1** wherein said pulse duration is porportional to the time constant of said resistance element and a controllable capacitance in series therewith, said capacitance having a reduced value for higher phase shifts, said prior and subsequent capacitance being selected to match the magnetization curve of said ferrite phase shifter.

5. The combination set forth in claim **1** wherein

said pulse duration is proportional to the time constant of said resistance element and a pair of capacitances in series circuit therewith, and having in addition thereto

a switch operated in synchronism with the switch corresponding to the highest place significant terminal for reducing the capacitance for higher phase shifts, said capacitance values being selected to match the slopes of the upper and lower portions of the magnetization curve of said ferrite phase shifter.

6. The combination set forth in claim **1** wherein

said pulse duration is proportional to the time constant of said resistance element and a pair of capac-

itances in series circuit therewith, and having in addition thereto

a negative temperature coefficient resistance provided in a path which shunts said serially connected resistances and which is disposed in the same temperature environment as the the core of said phase shifter, and

a switch operated in synchronism with the switch corresponding to the highest place significant terminal for reducing the capacitance for higher phase shifts, said capacitance values being selected to match the slopes of the upper and lower portions of the magnetization curve of said ferrite phase shifter.

7. The combination set forth in claim **1** wherein said N output terminals correspond to binary coding and said resistances are scaled to have consecutive values of approximately R, **2R**, **4R**, etc.

8. The combination set forth in claim **7** wherein said resistances are individually adjustable about said binary scaling in order to compensate for nonlinearity in the magnetic properties of said ferrite core.

9. The combination set forth in claim **7** wherein said resistances are offset from precise binary scaling in order to compensate for nonlinearity in the magnetic properties of said ferrite core.

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