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RECIPROCAL MICROWAVE PHASE SHIFTER HAVING TWO MAGNETIZING
CONDUCTORS AND ONE RESET CONDUCTOR

Filed April 21, 1967

4 Sheets-Sheet 1

Fig. 1a

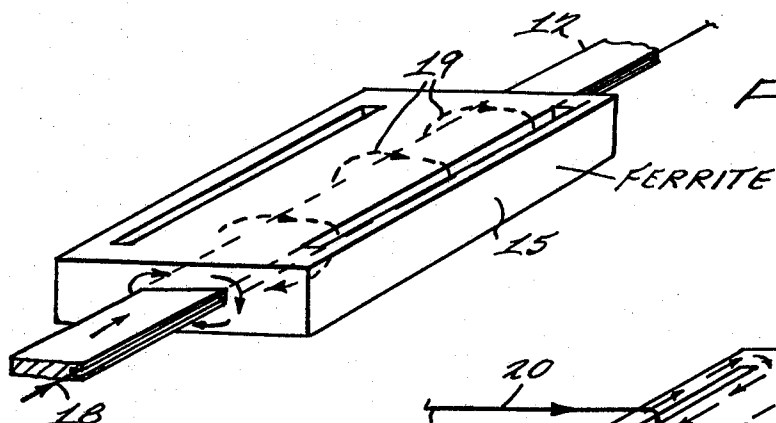
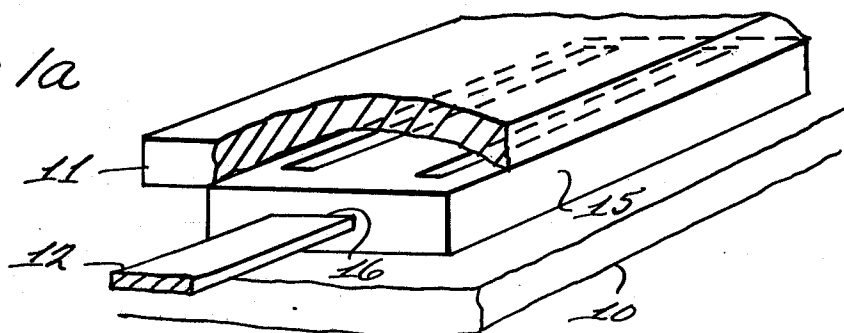


Fig. 1b

Fig. 1c

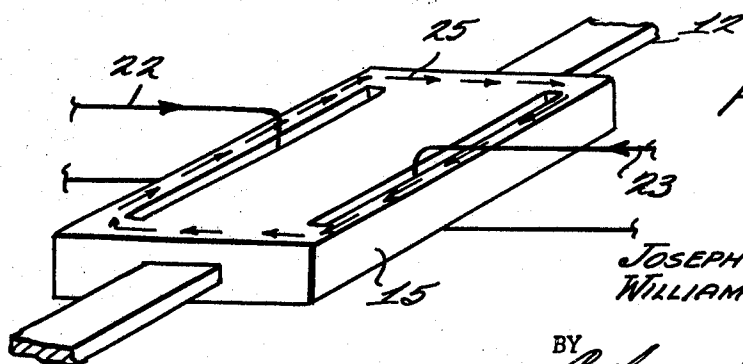
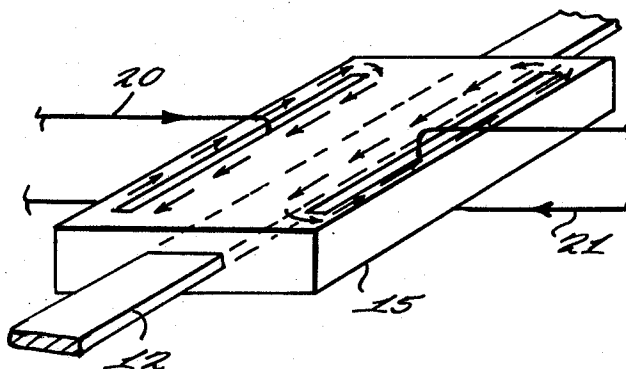


Fig. 1d

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4 Sheets-Sheet 2

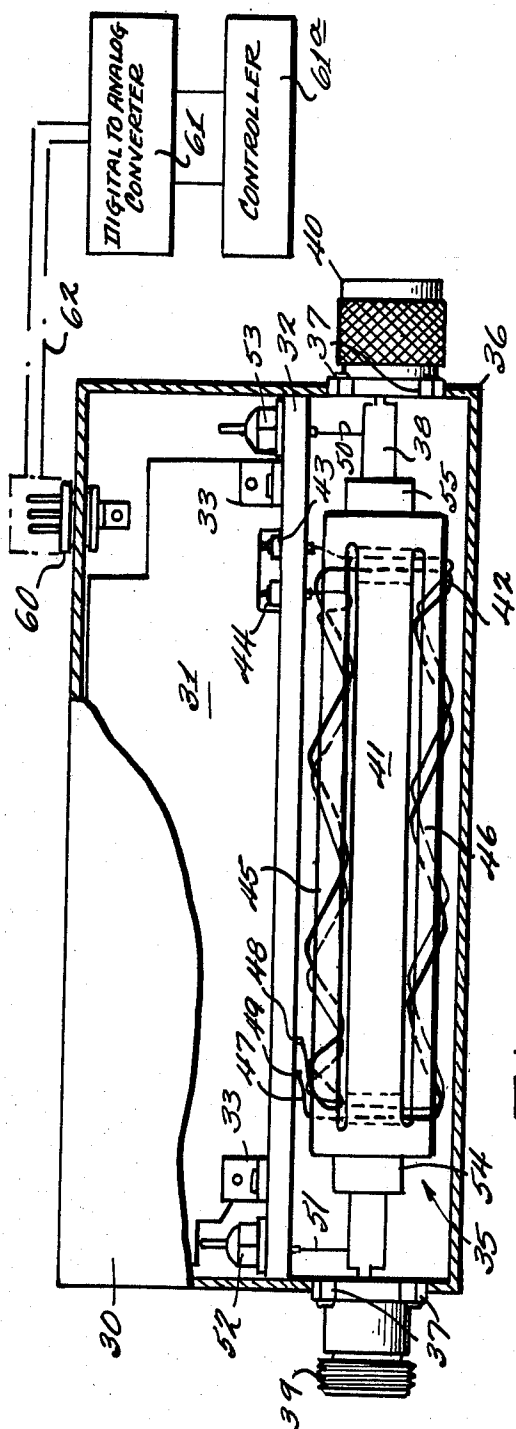


Fig. 2

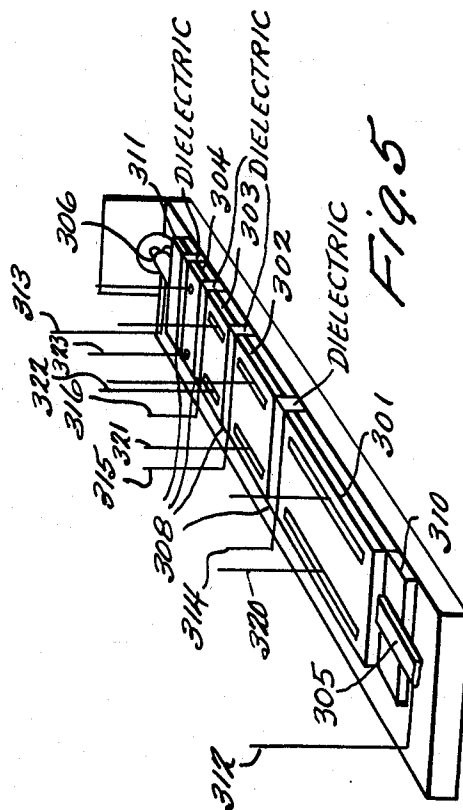


Fig. 5

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4 Sheets-Sheet 3

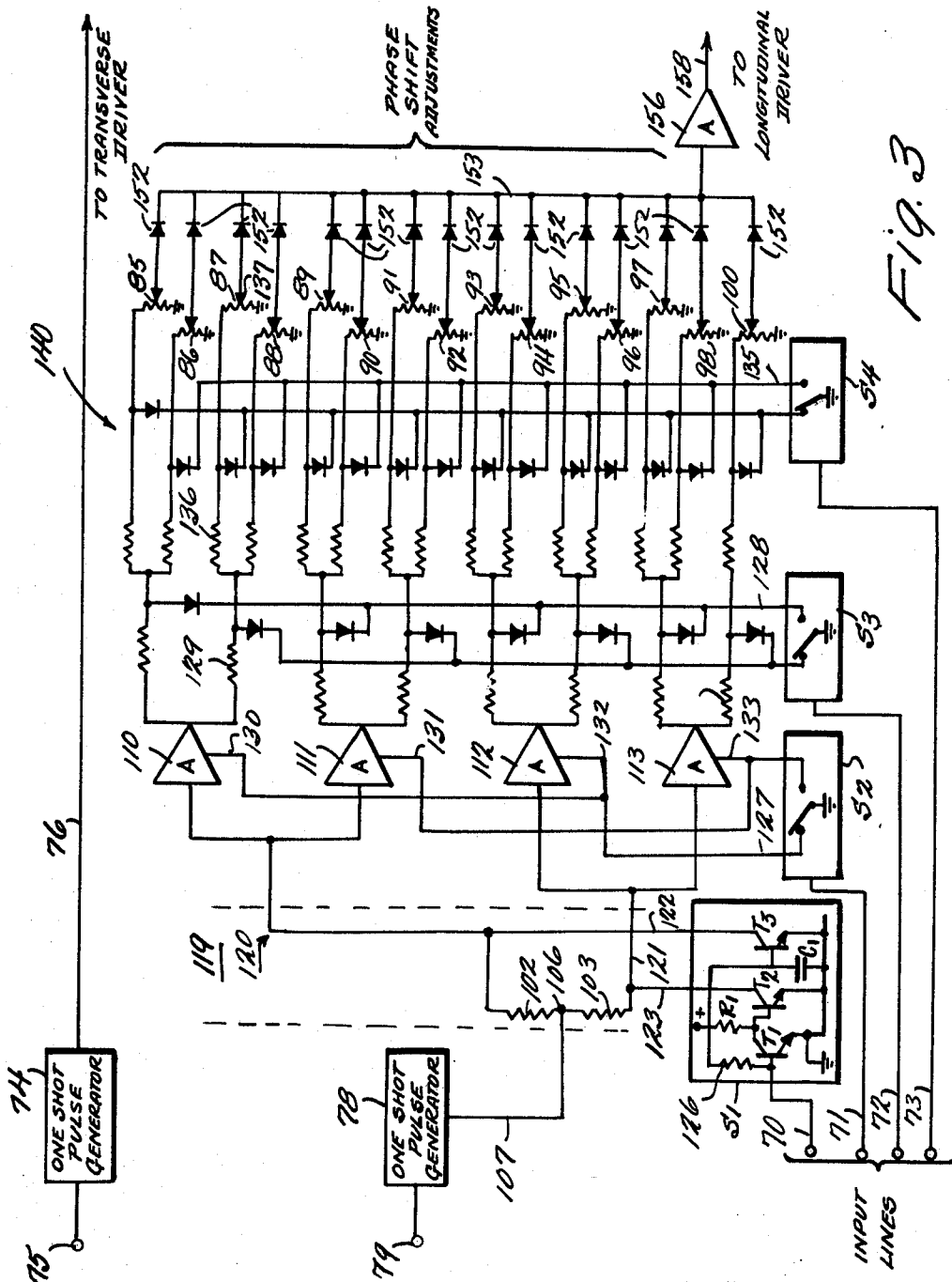


FIG. 3

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4 Sheets-Sheet 4

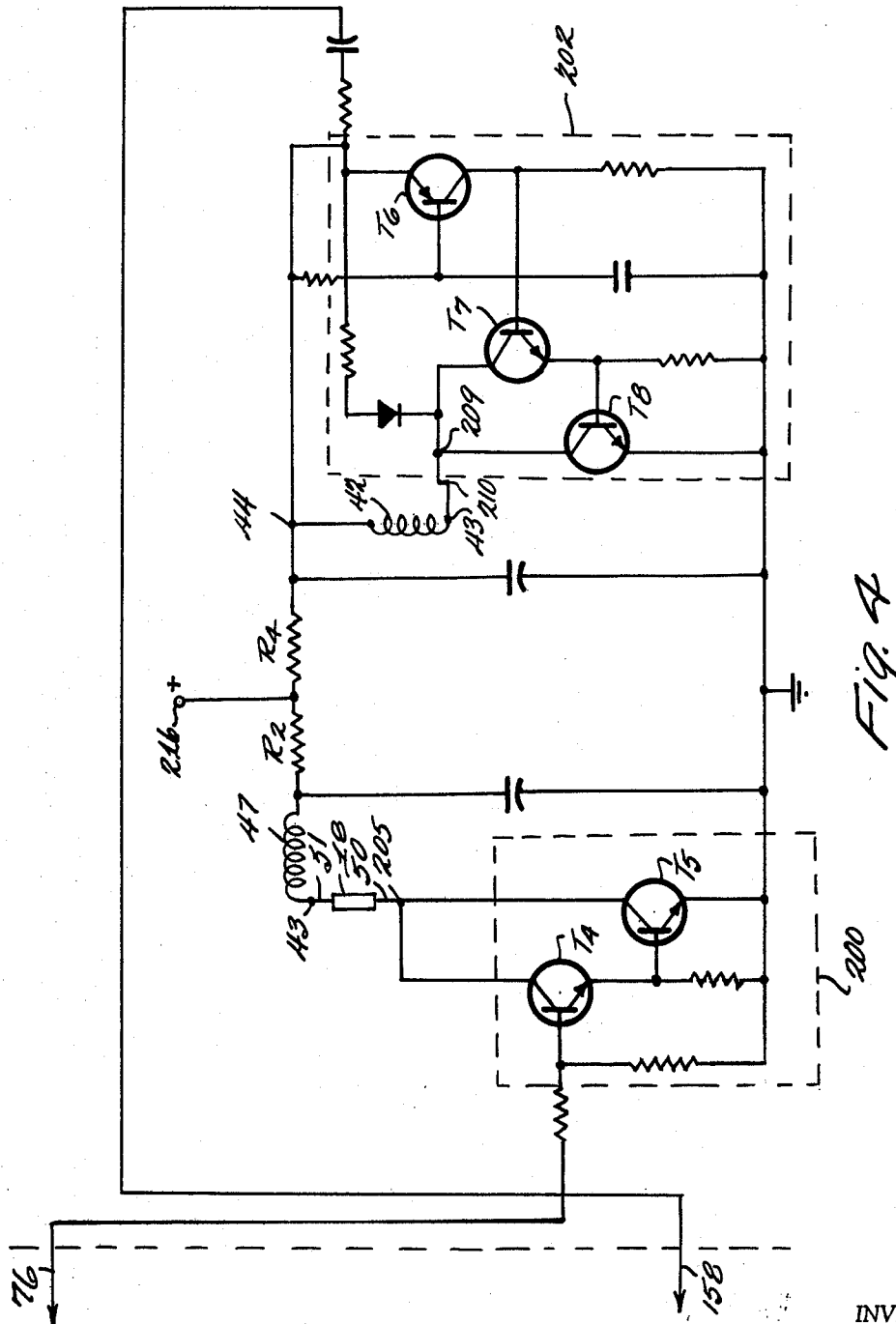


Fig. 4

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RECIPROCAL MICROWAVE PHASE SHIFTER HAVING TWO MAGNETIZING CONDUCTORS AND ONE RESET CONDUCTOR

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14 Claims

ABSTRACT OF THE DISCLOSURE

A reciprocal microwave phase shifter in the form of a strip transmission line having a ferrite element in the shape of a double toroid longitudinally disposed between the ground planes and magnetizing conductors associated with the ferrite element. Control circuitry associated with said magnetizing conductors for selectively switching said ferrite element between two orthogonal states of remanent magnetization, one of said states being parallel to the direction of propagation through the transmission line, said control circuitry being effective to control the degree of phase shift by selectively varying the magnitude of remanent magnetization parallel to the direction of propagation.

The instant invention pertains to the field of microwave phase shifter. More specifically, the invention concerns reciprocal, ferrite loaded microwave phase shifters suitable for use in phased array radar systems.

In a phased array radar system many phase shifting elements capable of assuming multi-stable states of phase shift are required in order to achieve adequate scanning of the radar beam. In view of this requirement for plural phase shifting elements, it would be advantageous to employ individual phase shifters which consume a minimum amount of power during switching, and which are capable of switching times between the various stable states on the order of 1 to 10 microseconds in order to reduce the overall power consumption of the scanning phase shifters as well as the overall time required to scan the entire beam. In view of the premium placed on switching time, it is further desirable to employ a reciprocal type of switch of phase shifter, in view of the fact that non-reciprocal phase shifters require switching during both transmitting and receiving modes whereas reciprocal phase shifters need be switched only when the beam is scanned. The non-reciprocal phase shifter must be switched between each transmitted pulse, whereas the reciprocal phase shifters need be switched only when the scan position is changed.

Known reciprocal phase shifters have usually taken the form of a portion of a waveguide having a ferrite element longitudinally disposed therein with a magnetizing coil wound about the waveguide. Current passing through the waveguide coil is effective to create a longitudinal magnetic field within the ferrite, which thereby affects the permeability of the ferrite and, in turn, alters the propagation constant of the material for a wave propagating through the guide. The change in the propagation constant is proportional to the change in the current flowing through the coil, and therefore the phase of a propagation wave may be controlled by varying the current.

This type of phase shifter consumes considerable power during operation due to the fact that it is necessary to maintain constant current through the magnetizing coil in order to maintain a particular degree of phase shift. The switching time of these known reciprocal phase shifters is limited due to the fact that the waveguide is disposed within the magnetizing coil, which produces high eddy current losses and increases the switching time.

The present invention suggests a reciprocal microwave phase shifter having a relatively fast switching time, in the order of 10 microseconds, and a switching energy requirement significantly lower than the above described known reciprocal phase shifters. The instant invention further suggests suitable control circuitry for differentially varying the amount of phase shift.

The phase shifter of the present invention comprises a TEM strip transmission line having a ferrite phase shifter element disposed between the ground planes. The center conductor of the transmission line passes through the center of the ferrite which is in the shape of a rectangular double toroid and is selected to have a relatively high remanence ratio i.e., a good square hysteresis loop.

The ferrite element is magnetized in a direction parallel to the direction of propagation through the transmission line by applying a pulse of current to magnetizing coils wound about the outer legs of the double toroid. This pulse of current is of short duration and places this ferrite in a state of remanent magnetization determined by the magnitude of the pulse. In this manner the ferrite is switched to a longitudinal state of magnetization in a latching fashion i.e., after the pulse is removed the ferrite remains in a magnetized state. Latching type switching of the ferrite eliminates the requirement for maintaining a constant current as in known reciprocal devices. The fact that the coil is wound directly about the ferrite also enables a rapid switching time using low energy drive because all the flux generated passes through the ferrite, and large eddy currents are not generated due to flux being switched through a metallic material. In order to reset the ferrite to enable accurate repeatability to differential phase shifts, a current pulse is passed through the center conductor, or a wire parallel thereto to magnetize the ferrite, in a latching fashion, in a state of remanent magnetization perpendicular, or transverse, to the direction of propagation of the TEM wave.

In accordance with the instant invention, a suitable electronic circuitry is provided to supply pulses to the various magnetizing wires. This circuitry comprises, in addition to a transverse pulse generator, a digital-to-analog converter for supplying a pulse to the longitudinal magnetizing coils, having a magnitude determined by a digital input signal. In this manner the phase shifter of the instant invention can be differentially shifted in discrete steps in accordance with the output of a digital computer, programmed to effect the scanning of a phased array radar beam.

The invention may be better understood by referring to the following detailed description taken together with the drawings wherein:

FIGURES 1a, 1b, 1c and 1d are schematic illustrations of the theory employed in the instant invention;

FIGURE 2 is a side elevation with parts broken away of a phase shifter constructed in accordance with the present invention;

FIGURE 3 is a schematic diagram of a suitable digital-to-analog converter for use in the present invention;

FIGURE 4 is a schematic diagram of a linear amplifier driver circuit used in the instant invention which is adapted to be connected to the output of this digital-to-analog converter of FIGURE 3; and

FIGURE 5 illustrates an alternate embodiment of the invention in accordance with the teachings of this application.

In FIGURE 1 a ferrite loaded strip transmission line is schematically illustrated and comprises a pair of parallel ground planes 10 and 11 and a center conductor 12. A ferrite element 15 is longitudinally disposed between the ground planes and has a longitudinal aperture 16 therein, through which the center conductor passes. Suitable, well-known strip launchers (not shown) are adapted

to be connected to both ends of the transmission line in order to couple microwave energy to, or from, the transmission line. Strip transmission lines of this type are capable of transmitting microwave energy in the TEM, or Quasi TEM mode to the exclusion of any higher order modes, provided that the spacing between the ground planes is less than one-half of the wave length of the propagating wave in an unbounded isotropic medium having a relative dielectric constant equal to that of the ferrite. Strip transmission lines of this type are also capable of shifting the phase of electromagnetic energy whenever a longitudinal magnetic field exists in the ferrite element.

For the purposes of further description of the instant invention, the term "transverse magnetization" refers to the state of remanent magnetization depicted in FIGURE 1b wherein a current pulse applied to conductor 18 is effective to magnetize the ferrite in a closed loop about the center conductor as shown by arrows 19. The term, "longitudinal magnetization," refers to the state of remanent magnetization shown in FIGURE 1c. Here, a pulse of current applied to the windings 20 and 21 in the direction shown leaves the remanent magnetization in the vicinity of the center conductor parallel to the direction of propagation. FIGURE 1d shows a pair of reset windings 22 and 23 wound about the outer legs of the ferrite element 15. Current passing through these reset windings, in the direction shown, is effective to magnetize the external legs of the ferrite in a circular direction around the outside of the complete toroid as shown by arrows 25.

In order to predict the operation of a strip transmission line as shown in FIGURE 1a, when the ferrite element is either transversely or longitudinally magnetized it would be necessary to set forth a rigorous and complicated derivation of the propagation constant of the device in both states of magnetization. While this will not be carried out in detail, it suffices to point out that the relative permeability in the transversely magnetized state is approximately equal to one (a simple dielectric), and when in the longitudinal magnetized state, the relative permeability is less than one by an amount determined by the magnitude of the longitudinal magnetization. Since the propagation constant is proportional to the square root of the relative permeability, it can be seen that by switching between these orthogonal states of remanent magnetization a change in the phase of a propagating wave can be effected. Furthermore, the phase of the propagating wave may be differentially shifted by alternatively switching between the transverse state of magnetization and a differentially controllable state of longitudinal magnetization. The double toroid shape of the ferrite not only enhances the squareness of the hysteresis characteristic but also renders the device reciprocal in both states of remanent magnetization.

In actual practice it has been found that the outer legs of the ferrite element will remain in a longitudinally magnetized state even after the application of a current pulse to the transverse magnetizing conductor and these outer legs will tend to remagnetize the center leg of the ferrite element in a longitudinal direction which detrimentally affects the device performance. This tendency to revert to a state of longitudinal magnetization may be eliminated by applying a pulse to the reset windings as shown in FIGURE 1d simultaneously with the application of a transverse magnetizing pulse to the conductor 18 shown in FIGURE 1b.

FIGURE 2 is a side elevation with parts broken away, of a preferred embodiment of a phase shifter constructed in accordance with the instant invention. The housing 30 contains a linear amplifier driver circuit for controlling the magnitude of the phase shift and is schematically represented here by a printed circuit board 31. The printed circuit board is mounted on a feed-through plate 32 by brackets 33. The feed-through plate is suitably secured to the housing 30 and is effective to shield the control

circuitry from the electromagnetic waves propagating through the strip transmission line 35 which is mounted in lower housing 36. The lower housing is secured to housing 30 as by screws 37. The strip transmission line comprises a center conductor 38 connected at either end to strip launchers 39 and 40. The ferrite element 41 is in the shape of a double toroid as shown in FIGURES 1a-1d and is arranged so that a center conductor passes through a longitudinal aperture (not shown) therein. The ground planes of this strip transmission line, which are disposed on either side of the ferrite element in planes parallel to the broad face of the ferrite, as shown in FIGURE 1a, have not been shown in FIGURE 2 so that the magnetizing coils may be more clearly illustrated.

A longitudinal magnetizing conductor 42 is connected between terminals 43 and 44 and is wound about the outer legs 45 and 46 of the ferrite element in such a sense that current passing through this conductor will create a magnetic flux in the ferrite in the manner shown in FIGURE 1c. Reset conductor 47 is connected between terminals 48 and 49 and is also wound about the outer legs of the ferrite element. The sense of these reset windings is such that current passing through this conductor will cause a magnetic flux pattern as shown in FIGURE 1d. A transverse magnetizing conductor (not shown) is disposed within a slot in the longitudinal edge of the center conductor as shown in FIGURE 1b. Wires 50 and 51 electrically connect this transverse magnetizing conductor to terminals 52 and 53. Terminals 43, 44, 48, 49, 52 and 53 are in the form of feed-through capacitors and are adapted to connect their respective magnetizing conductors to the control circuitry. The feed-through capacitor feature is effective to short out any RF energy which may be induced in the magnetizing conductors by a microwave propagating through the transmission line. Further RF decoupling may be achieved by selecting the length of the transverse magnetizing conductors, between the feed-through capacitors and the center conductor, to be approximately equal to $n/4$ when n is the wave length of the microwave energy for example at a frequency of 5.7 GHz. Elements 54 and 55 are conventional quarter wave dielectric transformers which are employed as impedance matching element in a well known manner.

An input terminal 60 is mounted in the top of housing 30 and is adapted to connect control signals from the digital-to-analog converter 61 to the control circuitry 31 through a cable 62. The digital-to-analog converter is in turn connected to a programmable controller 61(a). In accordance with a preferred embodiment of this invention, controller 61(a) is a digital computer programmed to effect a predetermined sequence of differential phase shifts.

The operation of the phase shifter shown in FIGURE 2 can best be understood by reference to FIGURES 3 and 4 which are schematic circuit diagrams of the control circuitry of FIGURE 2.

In FIGURE 3 there is shown a digital-to-analog converter which is adapted to convert a digital input signal from computer 61(a) (FIGURE 2) on binary input leads 70, 71, 72 and 73 to a fixed width pulse, the magnitude of which being determined by the particular digital input signal.

The digital-analog converter comprises two single-shot pulse generators 74 and 78. Pulse generator 74 is effective to generate a transverse magnetizing pulse in response to periodic trigger pulses from computer 61(a) on input terminal 75. Single-shot pulse generator 78 has an input terminal 79 for receiving periodic trigger pulses from computer 61(a). A steering matrix is effective to "steer" a pulse from generator 78 to one of fifteen independently adjustable potentiometers 85-100 in accordance with the digital input signal. The steering matrix comprises a first voltage divider 119 having a pair of resistors 102 and 103 connected in series, the

junction 106 thereof being connected to the pulse generator 78 by lead 107. The other end of resistor 102 is connected to the inputs of amplifiers 110 and 111 by lead 120, and the other end of resistor 103 is similarly connected to the inputs of amplifiers 112 and 113.

Lead 120 and therefore the input to amplifiers 110 and 111 are connected to a solid state single pole double throw switch S1 by lead 122. The inputs to amplifiers 112 and 113 are similarly connected to switch S1 via lead 123. Switch S1 is effective to connect either lead 122 or 123 to ground which thereby clamps the input of amplifiers 110 and 111 or 112 and 113, respectively, to ground. Switch S1 comprises a first transistor T1 having its base connected to binary input lead 70 and its emitter connected to ground. The collector of T1 is connected to the base of a second transistor T2 and to a source of DC bias voltage (not shown) through a resistor R1. The emitter of T2 is connected to ground and its collector is connected to lead 123. The base of a third transistor T3 is connected through a resistor to the binary input lead 70 and to ground through a capacitor C1. The emitter of T3 is connected to ground and its collector is connected to lead 122. In this manner, when no voltage appears on binary input lead 70, representing a binary "0," transistors T1 and T3 are non-conductive and transistor T2 is biased into saturation by the DC bias source. The input to amplifiers 112 and 113 are therefore effectively clamped to ground. A voltage exceeding a predetermined minimum on lead 70, representing a binary "1," is effective to turn on transistors T1 to thereby ground the base of T2, to cut-off conduction therein. This binary "1" is also effective to turn on T3 to thereby ground the inputs to amplifiers 110 and 111.

Amplifiers 110, 111, 112 and 113 are effective to amplify a pulse at their input only when their respective ground terminals 130, 131, 132 and 133 are connected to ground. Ground terminals 130 and 132 of amplifiers 110 and 112 are ganged together and connected to a switch S2 which is the same as S1 as described hereinbefore. The ground terminals of amplifiers 111 and 113 are also ganged together and connected to S2. The switch S2 is schematically illustrated as connecting the lead 127 to ground when a binary zero is present on line 71. The outputs of amplifiers 110 to 113 are connected to a conventional two-stage diode steering matrix 140 which is controlled by switches S3 and S4. These switches are the same as S1 and are illustrated in the position caused by a binary "0" on leads 72 and 73 respectively, by the schematic single pole double throw switches shown thereon.

The outputs of the diode steering matrix are connected to the fifteen adjustable potentiometers. The voltage taps of these potentiometers are connected through diodes 152 to a common output amplifier 156 by common output lead 153. The output of the amplifier 156 is connected to a driver circuit (FIGURE 4) by lead 158.

The driver circuit shown in FIGURE 4 comprises a first amplifier 200 comprising transistors T4 and T5 and a second amplifier 202 comprising transistors T6 and T7 and T8.

The transverse magnetizing conductor 18, the reset winding 47 and a decoupling resistor R2 are connected in series between the output terminal 205 of the amplifier 200 and a terminal 216 which is connected to a suitable DC source (not shown). Elements common to both FIGURES 2 and 4 have been identified with the same numbers in both figures.

The output amplifier 156 (FIGURE 3) is connected to the input of a linear pulse amplifier 202 of well known construction. The output of this amplifier at 209 is connected to terminal 43 by lead 210. One end of the longitudinal magnetizing conductor 42 is connected to terminal 43 and the other end is connected to terminal 44. The DC source mentioned hereinbefore is connected to terminal 44 through decoupling resistor R4.

The operation of the instant invention may best be understood from the following example. Assume that the ferrite element is in a given state of longitudinal magnetization which causes a particular degree of phase shift, and it is desired to change the phase shift to say 67.5° . Further assume that potentiometer 87 of FIGURE 3 is set to attenuate the pulse from generator 78 an amount such that when the pulse is amplified by amplifier 202 (FIGURE 4) the ferrite will be placed in a state of remanent magnetization which will cause a 67.5° phase shift.

In order to accomplish this change of phase shift, the controller 61(a) of FIGURE 2 will trigger single-shot pulse generator 74. The pulse from generator 74 will be amplified by amplifier 200 (FIGURE 4) and fed to the reset winding 47 and the transverse magnetizing conductor 18 to place the ferrite in a state of transverse magnetization. The controller 61(a) will then generate a trigger pulse for pulse generator 78 and a digital signal "0011" which is applied to binary input leads 70 to 73 respectively. The pulse generator will generate a fixed width, fixed amplitude pulse at output 107, and the digital signal will set the steering matrix to steer the pulse from generator 78 to potentiometer 87.

The digital signal on binary input lead 70 is "0" and therefore the input to amplifiers 112 and 113 are grounded and the pulse is "steered" to amplifiers 110 and 111. The binary "0" on lead 71 causes S2 to ground lead 127 to thereby cause amplifier 110 to amplify the pulse. The binary "1" on lead 72 causes S3 to ground lead 128 to thereby steer the pulse through resistor 129 and the binary "1" on lead 73 switches S4 to ground lead 135 whereby the pulse is steered through resistor 136 to potentiometer 87.

The attenuated pulse on tap 137 passes through diode 152 and amplifier 156 to the linear amplifier 202 which amplifies the pulse and applies it to the longitudinal magnetizing conductor 42 to thereby place the ferrite in a state of remanent magnetization determined by the magnitude of the pulse. The setting of potentiometer is such that the pulse will drive the ferrite about the particular minor loop of the hysteresis characteristic that will yield a remanent magnetization of such a magnitude that will cause a phase shift of 67.5° relative to the 0° reference, or transverse magnetization, state.

In an actual device, the ferrite employed was a Trans-Tech ferrite TT 1-105 approximately 4.7 inches in length. This length yielded a phase shift of 400° (at 5.7 GHz.) between the transverse state of magnetization and the maximum longitudinal state of remanent magnetization which remains after the ferrite has been driven into saturation. The potentiometers 85 to 100 were set to provide successively decreasing values of attenuation, such that incremental phase shifts of 22.5° , from 0° in the transverse state of magnetization, to 337.5° of phase shift in the longitudinally magnetized state caused by a pulse steered through potentiometer 100, were available in response to the digital input signal.

In FIGURE 5 there is shown another embodiment of the instant invention which employs a plurality of ferrite elements 301, 302, 303 and 304, in the shape of double toroids instead of the single ferrite element described hereinbefore. The center conductor 305 passes through the center of each element and is connected at one end to strip launcher 306 and at the other end to a similar strip launcher (not shown). The ferrite elements are separated by dielectric spacers 308 in order to prevent magnetic interactions. Elements 310 and 311 are conventional dielectric impedance matching transformers employed to match impedance of the air line to the ferrite filled line. Due to the fact that each ferrite has two states of magnetization, each ferrite filled section has two possible values of characteristic impedance. The matching transformers are designed to match into the geometric

mean of these two impedances in order to minimize reflections.

A transverse magnetizing conductor (not shown) passes longitudinally through each ferrite element. Input leads 312 and 313 are connected to opposite ends of the conductor and intermediate input leads 314, 315 and 316 are connected to the conductor at points between adjacent ferrite elements. Longitudinal magnetizing conductors 320, 321, 322 and 323 are schematically illustrated as passing through the slots in each ferrite element whereby a current through these conductors is effective to longitudinally magnetize its respective ferrite element. In actual practice, conductors 320 to 323 would be wound about the outer legs of the ferrite elements.

The relative lengths of the ferrite elements 304, 303, 302 and 301 are approximately in the ratio of 1:2:4:8, respectively. In this manner, by selectively magnetizing the various ferrite elements in one of two orthogonal states of remanent magnetization, sixteen different values of phase shift are available.

Suitable means (not shown) may be provided to selectively switch each ferrite element from one state of magnetization to another in any desired sequence.

It will be apparent from the foregoing, to those skilled in the art that this invention is amenable to a variety of modifications with respect to mechanical components, circuitry, and electrical components and, hence, may be given embodiments other than those particularly illustrated and described herein without departing from the essential features of the present invention and within the scope of the claims appended hereto. For example, the particular transistorized switches herein disclosed could be, instead, comprised of vacuum tubes, relays or other equivalent components. The ferrite element herein disclosed may, instead, be fabricated from any suitable gyromagnetic material having the requisite square loop hysteresis characteristic and further may comprise two separate portions sandwiched together about the center conductor instead of being a solid rectangular element with a longitudinal aperture as shown. Other and further modifications may similarly be made without departing from the instant invention, the scope of which is to be determined by reference to the following claims.

What is claimed is:

1. A reciprocal microwave phase shifter comprising a strip transmission line having parallel ground planes and a center conductor, a gyromagnetic phase shifting element disposed between said ground planes, said phase shifting element being in the shape of a double toroid having a pair of outer legs and a center leg, said phase shifting element further having a longitudinal passage through said center leg, said passage receiving said center conductor, a transverse magnetizing conductor passing through said longitudinal passage, a reset conductor wound about said outer legs, and a longitudinal magnetizing conductor wound about said outer legs, whereby a pulse of direct current energy when applied to said transverse magnetizing conductor and said reset conductor is effective to place said gyromagnetic phase shifting element in a state of transverse magnetization and when applied to said longitudinal magnetizing conductor is effective to place said gyromagnetic phase shifting element in a state of longitudinal magnetization.

2. A reciprocal microwave phase shifter comprising a strip transmission line having parallel ground planes and a center conductor, a gyromagnetic phase shifting element disposed between said ground planes, said phase shifting element being in the shape of a double toroid having a pair of outer legs and a center leg, said phase shifting element further having a longitudinal passage through said center leg, said passage receiving said center conductor, a transverse magnetizing conductor passing through said longitudinal passage, a reset conductor wound about said outer legs, a longitudinal magnetizing conductor wound about said outer legs, first pulse pro-

ducing means connected to said transverse and reset magnetizing conductors, second pulse producing means connected to said longitudinal magnetizing conductor, said first and second pulse producing means being adapted to be selectively energized to thereby switch said phase shifting element between a transverse state of magnetization and a longitudinal state of magnetization.

3. The apparatus of claim 2 wherein said phase shifting element is a ferrite and wherein said element is comprised of two slabs each having a longitudinal channel therein, said slabs being sandwiched together about said center conductor, said longitudinal channels forming said aperture for receiving said center conductor.

4. The device of claim 2 wherein the spacing between said ground planes is less than one-half of the wavelength of the microwave energy being transmitted, in an unbounded isotropic medium having a relative dielectric constant equal to that of the phase shifting element.

5. The device of claim 2 wherein said reset conductor is wound about each of said outer legs in such a sense that the net magnetic flux through said center leg caused by current through said reset conductor is zero and wherein said longitudinal magnetizing conductor is wound about each of said outer legs in such a sense that a net magnetic flux in the center leg is caused by current through said longitudinal magnetizing conductor.

6. The apparatus of claim 5 wherein said second pulse producing means comprises a digital-to-analog converter adapted to receive a digital input signal, for generating fixed width pulse having an amplitude determined by said digital input signal.

7. The apparatus of claim 6 wherein said digital-to-analog converter comprises a single-shot pulse generator adapted to be triggered, a variable attenuator, and a linear amplifier, said variable attenuator being connected between said single-shot pulse generator and said linear amplifier, the value of attenuation introduced by said variable attenuator being determined by said digital input signal.

8. The device of claim 7 wherein said variable attenuator comprises a steering matrix, a plurality of variable potentiometers, and control means adapted to receive said digital input signal, for setting said steering matrix to connect said single-shot pulse generator to one of said plurality of potentiometers in accordance with said digital input signal.

9. A microwave phase shifter comprising a strip transmission line having parallel ground planes and a center conductor, a plurality of ferrite phase shifting elements, each of said phase shifting elements being in the shape of a double toroid having a pair of outer legs and a center leg and further having a longitudinal passage through each of said center legs said phase shifting elements being arranged in tandem with said center conductor extending through said longitudinal passages, means including at least a single longitudinal magnetizing conductor wound about said outer legs to selectively magnetize said phase shifting elements in a longitudinal direction, and means including a transverse magnetizing conductor passing through said passages and at least a single reset conductor wound about said outer legs to selectively magnetize said phase shifting elements in a transverse direction whereby a plurality of discrete values of phase shift may be obtained.

10. The apparatus of claim 9 further comprising dielectric spacers disposed between each of said plurality of phase shifting elements for preventing magnetic interaction therebetween.

11. The device of claim 9 wherein said means for transversely magnetizing said phase shifting elements comprises a conductor extending through said longitudinal passages, intermediate input leads connected to said conductor at points between adjacent phase shifting elements, and means to selectively apply a pulse of electrical energy between any two adjacent ones of said input leads.

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12. The device of claim 9 wherein said means for longitudinally magnetizing said elements comprises a plurality of magnetizing conductors, each of said conductors being wound about a different one of said phase shifter elements and means to selectively apply a pulse of electrical energy to each of said longitudinal magnetizing conductors.

13. A reciprocal microwave phase shifter comprising a strip transmission line having parallel ground planes and a center conductor, a gyromagnetic phase shifting element disposed between said ground planes, said phase shifting element being in the shape of a double toroid having a pair of outer legs and a center leg, said phase shifting element further having a longitudinal passage through said center leg, said passage receiving said center conductor, a transverse magnetizing conductor passing through said longitudinal passage, a reset conductor wound about said outer legs, and a longitudinal magnetizing conductor wound about said outer legs, whereby a pulse of direct current energy when applied to said transverse magnetizing conductor and said reset conductor is effective to place said gyromagnetic phase shifting element in a state of transverse magnetization, whereby said phase shifting element provides a closed toroidal path for said state of transverse magnetization so that

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said element remains in said state of transverse magnetization after said pulse applied to said transverse and reset conducting is removed, and whereby a pulse of direct current energy when applied to said longitudinal magnetizing conductor is effective to place said gyromagnetic phase shifting element in a state of longitudinal magnetization.

14. A phase shifter as in claim 13 whereby ferrite material completely encircles said center conductor to provide said closed path.

References Cited

UNITED STATES PATENTS

3,277,401	10/1966	Stern	333—24.1
3,316,508	4/1967	Jones et al.	333—24.2
3,332,042	7/1967	Parris	333—24.1 X
3,340,484	9/1967	Siekanowicz et al.	333—24.1 X
3,355,682	11/1967	Taft	333—24.1 X

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