

Jan. 12, 1971

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3,555,463

RECIPROCAL MICROWAVE PHASE SHIFTER HAVING A PLURALITY OF
LONGITUDINAL AND TRANSVERSE ENERGIZING CONDUCTORS
PASSING THROUGH THE FERRIMAGNETIC MATERIAL

Filed Oct. 17, 1968

2 Sheets-Sheet 1

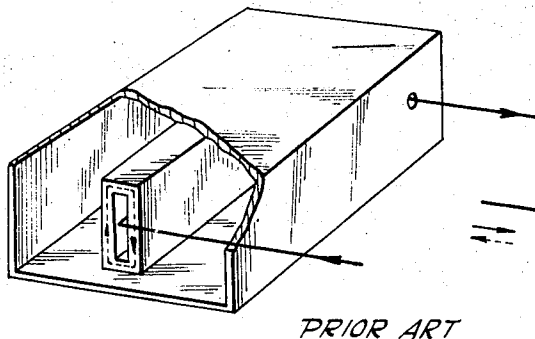


FIG. 1

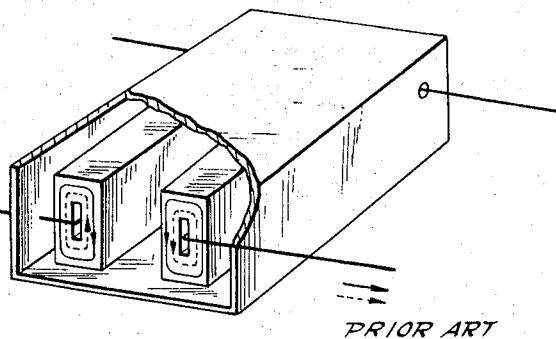


FIG. 2

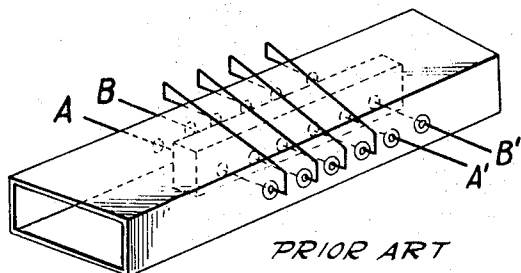


FIG. 3a

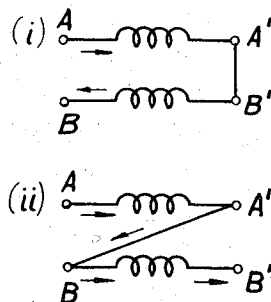


FIG. 3b

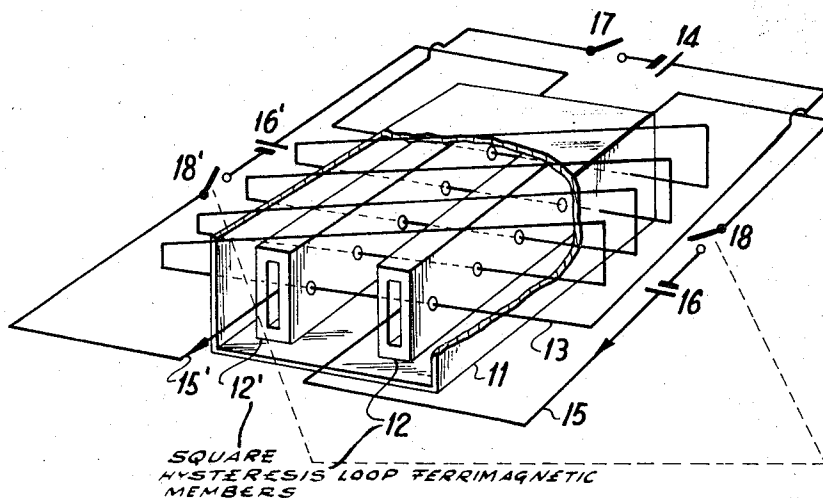


FIG 4

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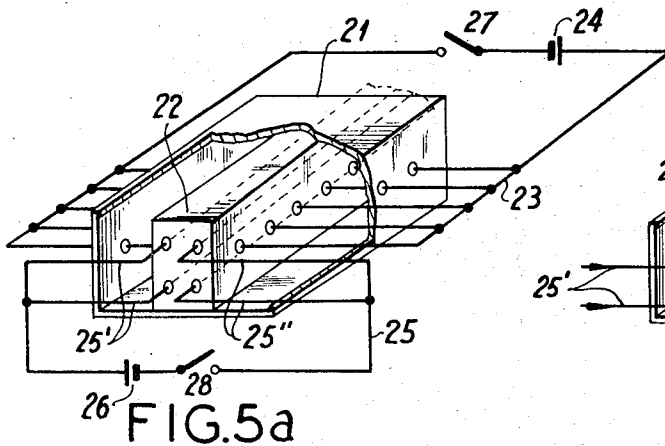
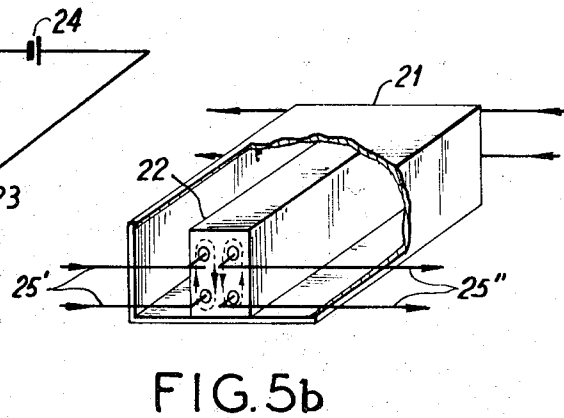
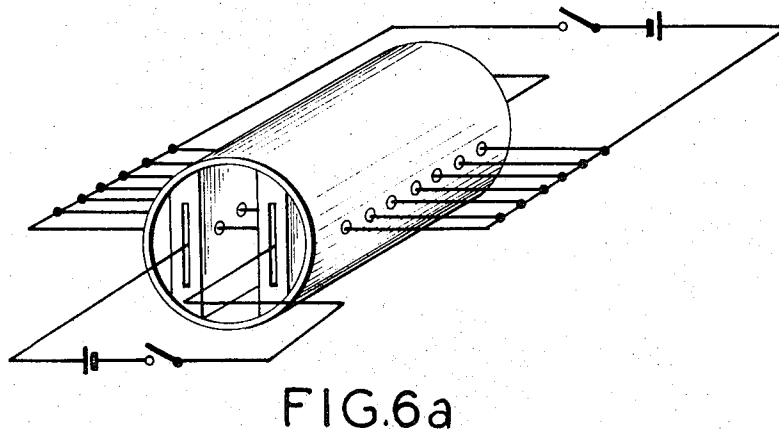
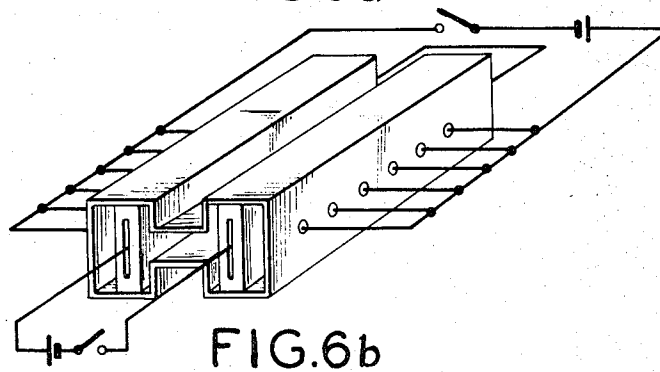
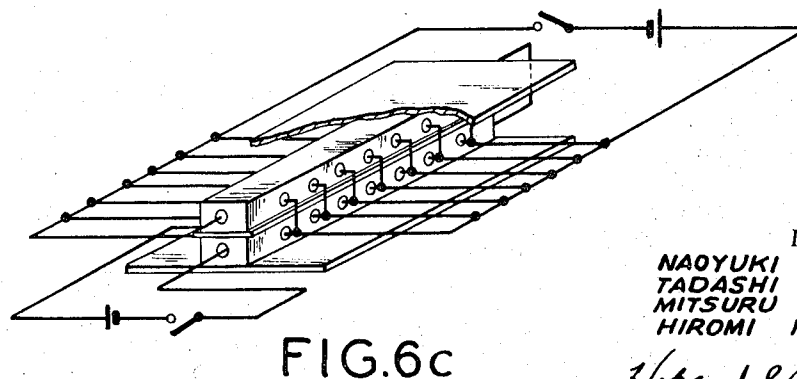
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RECIPROCAL MICROWAVE PHASE SHIFTER HAVING A PLURALITY OF LONGITUDINAL AND TRANSVERSE ENERGIZING CONDUCTORS PASSING THROUGH THE FERRIMAGNETIC MATERIAL

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Filed Oct. 17, 1968, Ser. No. 768,408
Claims priority, application Japan, Oct. 21, 1967,
42/67,689

Int. Cl. H01p 1/18

U.S. Cl. 333—31

11 Claims

ABSTRACT OF THE DISCLOSURE

A reciprocal microwave phase shifter is described wherein a ferrimagnetic material is disposed along an electromagnetic energy guiding path. The ferrimagnetic material is provided with longitudinal and transverse oriented bores to accommodate correspondingly oriented conductors which are so interconnected and energized to form the desired reciprocal phase shifting performance.

This invention relates to a reciprocal microwave phase shifter for controlling the phase of the electromagnetic waves in the microwave band.

Conventional microwave phase shifters are mostly of the nonreciprocal type. Reciprocal phase shifters are known but have not been fully satisfactory for some applications. One of such applications is the use of a plurality of electrically controllable phase shifters for controlling the phase of the electromagnetic waves at the plane of a radar antenna array. It has been known that this kind of application is the most desirable in effecting high speed scanning of the radar beam. High speed scanning was made feasible by appearance of a non-reciprocal microwave phase shifter comprising a waveguide and a member which is made of ferrite or other ferrimagnetic material having rectangular magnetization characteristics and which is disposed in the waveguide. This phase shifter is excellent because of its simplicity of construction, its ability to operate at a high speed, and its capability of withstanding the high powers used in the radar transmitter. Such a non-reciprocal phase shifter, however, is not desirable because it must be interswitched on turning the radar equipment from the transmitting operation to the receiving operation and vice versa and the resulting complexity of the equipment. A reciprocal phase shifter completely eliminates the last-mentioned demerits but has not yet been put to practical use because it has still had certain defects such as a poor standing wave ratio, a large insertion loss, and requires complicated circuit if the maximum amount of phase shift is to be obtained. It should be noted here that microwave means electromagnetic waves that can be propagated by a waveguide or by a pair of strip conductors.

It is therefore an object of this invention to provide a reciprocal microwave phase shifter which does not deteriorate the standing wave ratio.

It is another object of the invention to provide a reciprocal microwave phase shifter which has little insertion loss.

It is still another object of the invention to provide a reciprocal microwave phase shifter by which the maximum phase shift is attained without any complicated circuit.

According to this invention there is provided a reciprocal microwave phase shifter comprising a path for guiding the electromagnetic energy, a member of ferrimagnetic material having rectangular magnetic characteristics and which is disposed along the longitudinal axis of said path, a first set of conductors disposed transverse to said longitudinal axis, a second set of conductors disposed substantially parallel to said longitudinal axis, and means for selectively energizing one of said first set and said second set of conductors.

Now the invention will be described with reference to the accompanying drawings, in which:

FIG. 1 is a perspective view of a conventional non-reciprocal microwave phase shifter;

FIG. 2 is a similar view of another phase shifter of the kind;

FIG. 3(a) is a similar view of a conventional reciprocal microwave phase shifter;

FIG. 3(b) shows the manner of connecting the conductors of the phase shifter illustrated in FIG. 3(a); and
FIGS. 4, 5 and 6 are perspective views of certain embodiments of this invention.

Referring to FIG. 1, a conventional non-reciprocal microwave phase shifter comprises a rectangular waveguide and a ferrimagnetic member disposed along the longitudinal axis of the waveguide. The ferrimagnetic member is made of ferrimagnetic material having rectangular magnetization characteristics and is formed into a generally rectangular cylinder having a hollow inner space of the generally rectangular prism shape. The phase shifter further comprises a conductor generally extended through the hollow inner space. Electric current caused to flow through the conductor in the sense shown by arrow heads creates within the body of the ferrimagnetic member closed magnetic lines of forces illustrated by a broken line having arrow heads. The electromagnetic wave travelling through the waveguide in the fundamental mode (TE₁₀ mode) in one sense is thereby polarized into positive circularly polarized wave (whose electric vector rotates in the same sense as the spin magnetic moment of the ferrimagnetic material), while the electromagnetic wave travelling through the waveguide in the reversed sense is polarized into negative circularly polarized wave (whose electric vector rotates in the sense opposite to the sense of rotation of the spin magnetic moment). The arrangement thus serves as a non-reciprocal microwave phase shifter.

Referring to FIG. 2, another microwave phase shifter comprises a ferrimagnetic member which is different from the corresponding member in the phase shifter shown in FIG. 1 in that the member of the example of FIG. 2 is composed of two separate parts or elements. Each ferrimagnetic element is substantially identical to the ferrimagnetic member described with reference to FIG. 1 and is accompanied by a conductor. When electric currents are caused to flow through the respective conductors in the senses shown by broken-line arrows, the operation is similar to that of the example depicted in FIG. 1. When electric currents are caused to flow in the senses illustrated by solid-line arrows, it has empirically been confirmed that the arrangement of FIG. 2 displays reciprocal characteristics or, more particularly, propagates the electromagnetic wave in the fundamental mode as though the ferrimagnetic member were not in the magnetized state. It is believed that this phenomenon results because the phase shifts caused by the respective ferrimagnetic elements in one and the other sense cancel each other and because no non-reciprocal phase shift is accordingly observed from the outside.

Referring to FIG. 3(a), a conventional reciprocal phase shifter is shown having generally similar components as

the phase shifters of FIGS. 1 and 2, except that in the phase shifter of FIG. 3(a) a pair of conductors A-A' and B-B' are wound around a half of the arrangement. More particularly, conductor portions lying on the central plane of the waveguide are substantially perpendicular to the longitudinal axis of the waveguide and thread through the waveguide and the ferrimagnetic member. The remaining portions run outside the waveguide along the walls thereof.

Referring to FIGS. 3(a) and (b), the arrangement of FIG. 3(a) shows reciprocal phase shift when connection of the conductors A-A' and B-B' is interswitched between the S connection shown in FIG. 3(b)(i) and the P connection illustrated in FIG. 3(b)(ii). With this arrangement, the maximum phase shift is attained when the ferrimagnetic member is brought from the entirely demagnetized state to the fully magnetized state or vice versa. When switched to the S connection, the arrangement provides a phase shift whose amount is smaller than the amount attainable by inter-switching between the P connection energization and the entirely demagnetized state. With the S connection, the arrangement is apt to deteriorate the standing wave ratio and to increase the insertion loss. Incidentally, demagnetization of the ferrimagnetic member, if to be effected at a high speed, requires a complicated circuit.

Turning now to FIG. 4, a first embodiment of this invention comprises a rectangular waveguide 11 and a ferrimagnetic member composed of two ferrimagnetic elements 12 and 12'. Each ferrimagnetic element is made of ferrimagnetic material having rectangular magnetic characteristics and is formed into a generally rectangular cylinder having a hollow inner space of the generally rectangular prism shape. The ferrimagnetic elements 12 and 12' are disposed within the waveguide 11 along the longitudinal axis thereof on both sides of a plane passing through the center lines of the broad walls of the guide 11. A set of opposite walls of each ferrimagnetic element is in the proximity of the broad walls. The embodiment further comprises a set of transverse conductors 13 penetrating the narrow walls of the waveguide 11 and the other set of walls of the individual ferrimagnetic elements 12 and 12'. These conductors 13 are connected at the outside of the waveguide 11 in the manner shown and provided with a D.C. power source 14. The embodiment still further comprises a set of longitudinal conductors 15 and 15' generally extended through the spaces of the ferrimagnetic elements 12 and 12', respectively, and brought out of the waveguide 11. These longitudinal conductors 15 and 15' are provided with D.C. power sources 16 and 16', respectively. The D.C. power source 14 supplies a D.C. control pulse to each of the transverse conductors 13 each time a switch 17 is closed. Likewise, the D.C. power sources 16 and 16' supply D.C. control pulses to the longitudinal conductors 15 and 15', respectively, every time ganged switches 18 and 18' are closed.

When the transverse conductors 13 are energized by a D.C. control pulse, the phase shifter is brought into the same state as the conventional reciprocal phase shifter of FIG. 3(a) with the P connection. The electromagnetic wave travelling through the phase shifter therefore undergoes reciprocal phase shift of a certain amount as compared with the phase of the wave propagated in the fundamental mode. When the transverse conductors 13 are deenergized and the longitudinal conductors 15 and 15' are instead energized by a pair of D.C. control pulses flowing through the respective conductors 15 and 15', the phase shifter is brought into the same state as the conventional non-reciprocal phase shifter of FIG. 2 with the conductors supplied with electric current flowing in the sense illustrated by the solid-line arrows. The electromagnetic wave is therefore propagated in the fundamental mode. Thus, the embodiment of FIG. 4 serves as a reciprocal microwave phase shifter.

Referring to FIG. 5(a), a second embodiment of this

invention comprises a waveguide 21 and a ferrimagnetic member 22 disposed along the longitudinal axis of the guide 21. The member 22 is made of ferrimagnetic material having rectangular magnetic characteristics into a generally rectangular prism having four longitudinal holes and a plurality of transverse holes, each hole running through the body of the member 22. Preferably, the longitudinal holes are distributed symmetrically with respect to the plane passing through the center lines of the broad walls of the guide 21. A set of opposite surfaces of the ferrimagnetic member 22 are in contact with the inside surfaces of the broad walls. The embodiment further comprises a set of transverse conductors 23 put through the respective transverse holes and through the narrow walls of the waveguide 21. The transverse conductors 23 are connected together at their respective ends put out of the waveguide 21 and are provided with a common D.C. power source 24. The embodiment still further comprises a set of longitudinal conductors 25 disposed within the respective longitudinal holes of the ferrimagnetic member 22. A first subset 25' of the longitudinal conductors 25 are connected together at the outside of the waveguide 21 and connected with one of the terminals of a D.C. power source 26. A second subset 25'' of the longitudinal conductors 25 are likewise connected together and brought into connection with the other terminal of the power source 26. Switches 27 and 28 are provided to supply, upon closure, D.C. control pulses to the respective sets of conductors 23 and 25.

When the switch 27 is closed to supply a D.C. control pulse to each of the transverse conductors 23, the phase shifter is brought into the same state as the conventional reciprocal phase shifter of FIG. 3(a) with the P connection. When the switch 27 is opened and the switch 28 is instead closed to supply a D.C. control pulse to each of the longitudinal conductors 25, the ferrimagnetic member 22 is magnetized in the manner shown in FIG. 5(b). This state of magnetization is equivalent to that illustrated in FIG. 2 with the solid-line curves having arrow heads. The second embodiment therefore serves as a reciprocal microwave phase shifter.

A phase shifter of the construction shown in FIG. 5(a) wherein the dimensions of the broad wall and the narrow wall of the waveguide 21 and of the width (parallel to the broad wall), the height (parallel to the narrow wall), and the length of the ferrimagnetic member 22 are 12 mm., 5 mm., 6 mm., 5 mm., and 40 mm., respectively, provided a phase shift of 110° at the 9 GHz. band.

Referring finally to FIGS. 6(a), (b) and (c) there are illustrated further embodiments of this invention wherein the paths for guiding the electromagnetic energy are a circular waveguide, a ridge waveguide, and a pair of strip lines, respectively. The operation does not differ in principle from that of the first and the second embodiments.

As is understood from the description, this invention makes it possible, without any complicated demagnetization control but only with simple pulse control, to put a phase shifter into each of two states between which the maximum phase shift is attained. Furthermore, this invention raises the overall characteristics because no use is made of the magnetization state which deteriorates the standing wave ratio and increases the insertion loss.

What is claimed is:

1. A reciprocal microwave phase shifter comprising a path for guiding the electromagnetic energy, a member of ferrimagnetic material having rectangular magnetization characteristics and disposed along the longitudinal axis of said path, a first plurality of conductors disposed transverse to said longitudinal axis, passing through said ferrimagnetic material, and being connected in parallel with one another, a second plurality of conductors disposed substantially parallel to said longitudinal axis and passing through said ferrimagnetic material, and means

5

for alternately energizing said first and said second plurality of conductors.

2. The device as recited in claim 1 wherein said ferrimagnetic material has a plurality of longitudinal and transverse bores, with said first set of transverse conductors being passed through the transverse bores and with a first subset of longitudinal conductors being passed through a first subset of longitudinal bores and a second subset of longitudinal conductors being passed through a second subset of longitudinal bores, with the ferrimagnetic member and the first and second subset of longitudinal bores located in selective position relative to a plane passing through the longitudinal axis.

3. The device as recited in claim 1 wherein the path for guiding the electromagnetic energy comprises a rectangular waveguide having a pair of parallel broad walls and a pair of parallel narrow side walls with the ferrimagnetic material positioned being of rectangular form and positioned in symmetrical relationship with an axial plane passing through the center of the broad walls, said ferrimagnetic material being provided with transverse bores aligned along a plane substantially parallel to the broad walls with the transverse conductors passing through the transverse bores and protruding from the narrow side walls of the waveguide.

4. The device as recited in claim 3 wherein the ferrimagnetic material is provided with a plurality of longitudinal bores through which the longitudinal conductors are passed, with first and second subsets of longitudinal bores arranged in symmetry relative to the axial plane, and with longitudinal conductors passing through the first subset of longitudinal bores electrically connected in parallel, and with the longitudinal conductors passing through the second subset of longitudinal bores electrically connected in parallel.

5. The device as recited in claim 4 wherein the ferrimagnetic material is sized to contact the broad walls of the rectangular guide.

6. The device as recited in claim 1 wherein said path of guiding electromagnetic energy is a cylindrical waveguide.

7. The device as recited in claim 1 wherein said path of guiding electromagnetic energy is a ridged waveguide.

6

8. The device as recited in claim 1 wherein the path of guiding electromagnetic energy is a strip line.

9. A reciprocal microwave phase shifter comprising a path for guiding the electromagnetic energy, ferrimagnetic material having rectangular magnetization characteristics and disposed along the longitudinal axis of said path, a first plurality of conductors disposed transverse to said longitudinal axis, passing through said ferrimagnetic material, a second plurality of conductors disposed substantially parallel to said longitudinal axis and passing through said ferrimagnetic material, means for alternately energizing said first and said second plurality of conductors, said ferrimagnetic material comprising first and second longitudinal rectangular shaped ferrimagnetic members having longitudinal bores extending there-through, with said second plurality of conductors being passed through said longitudinal bores, said first and second longitudinal members further being provided with a plurality of transversely extending bores, with the first and second members positioned along the longitudinal axis of the electromagnetic axis with their transverse bores in registration to align said first plurality of conductors substantially transverse to said axis.

10. The device as recited in claim 9 wherein said longitudinal bores are rectangular shaped and wherein said first and second members are positioned in symmetry relative to a plane including the longitudinal axis and substantially transverse to the first set of transverse conductors.

11. The device as recited in claim 9 wherein the transverse conductors are electrically parallel connected to one another.

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U.S. Cl. X.R.

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