United States Patent

[11] **3,585,536**

[72] Inventors **Aleksander I. Braginski**
Pittsburgh;
Daniel C. Buck, Hanover, both of, Pa.
[21] Appl. No. **11,453**
[22] Filed **Feb. 16, 1970**
[45] Patented **June 15, 1971**
[73] Assignee **Westinghouse Electric Corporation**
Pittsburgh, Pa.

[54] RECIPROCAL, MICROSTRIP, LATCHED, FERRITE PHASE SHIFTER

6 Claims, 7 Drawing Figs.

[52] **U.S. Cl.** **333/31,** 333/24.1, 333/84
[51] **Int. Cl.** **H01p 1/18**
[50] **Field of Search** .... 333/24.1, 31, 84 M

[56] **References Cited**

UNITED STATES PATENTS

3,447,143	5/1969	Hair et al.	333/31 X
3,478,283	11/1969	Simon et al.	333/31

Primary Examiner—Eli Lieberman
Assistant Examiner—Paul L. Gensler
Attorneys—F. H. Henson, E. P. Klipfel and D. Schron

ABSTRACT: Described is a latching ferrite phase shifter for microstrip transmission lines compatible with integrated circuits and incorporating two ferrite materials deposited by vapor deposition techniques, one of the ferrite materials being in the path of the electromagnetic wave passing along the microstrip circuit and designed to control the amount of phase shift produced by the phase shifter, and the other of the ferrite materials exercising a magnetostatic interaction with the first or forming a connected magnetic circuit and having a coercive force greater than that of the first to hold the first in the magnetized state.

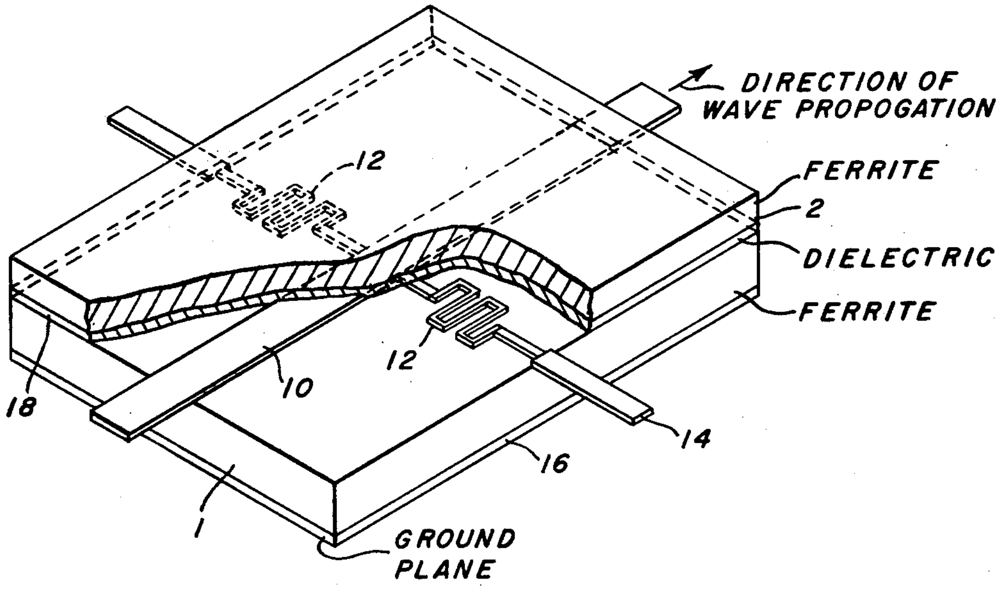


FIG. 1A.

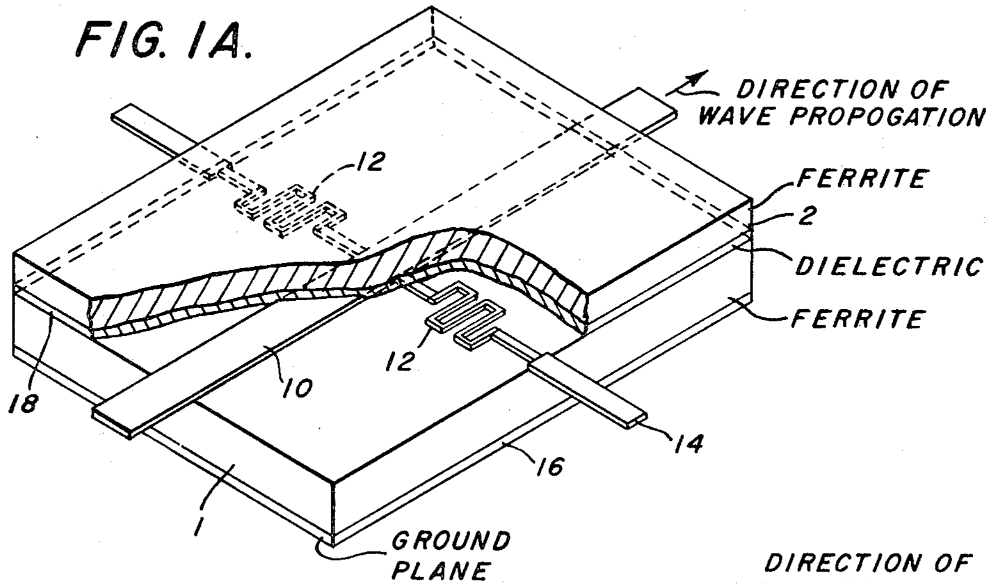


FIG. 1B.

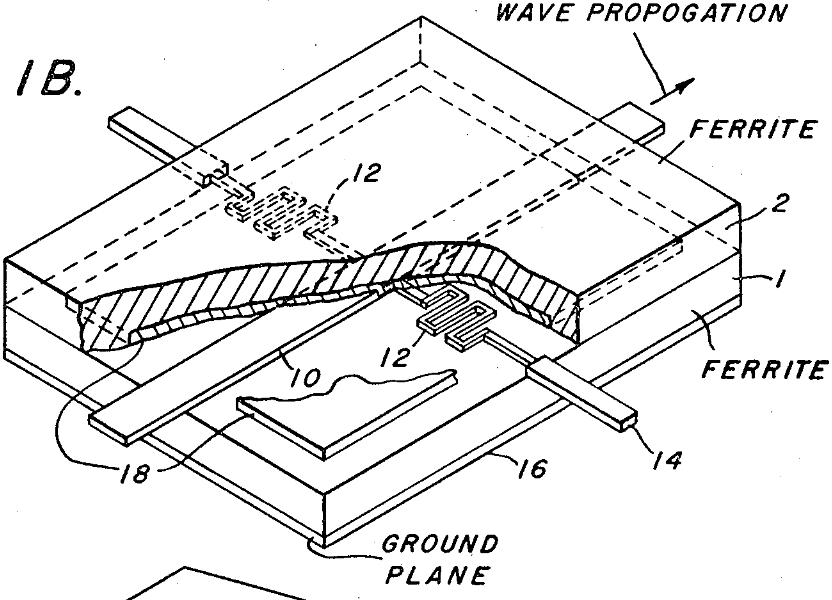


FIG. 2.

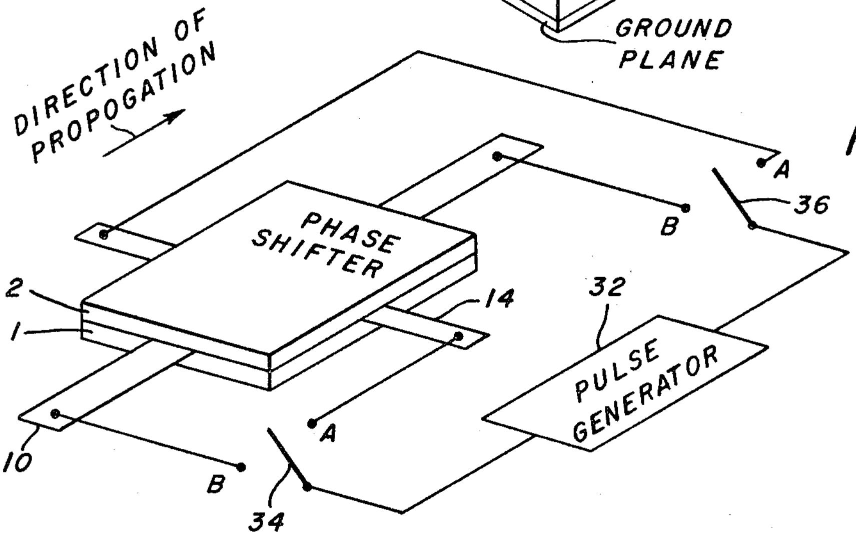


FIG. 3.

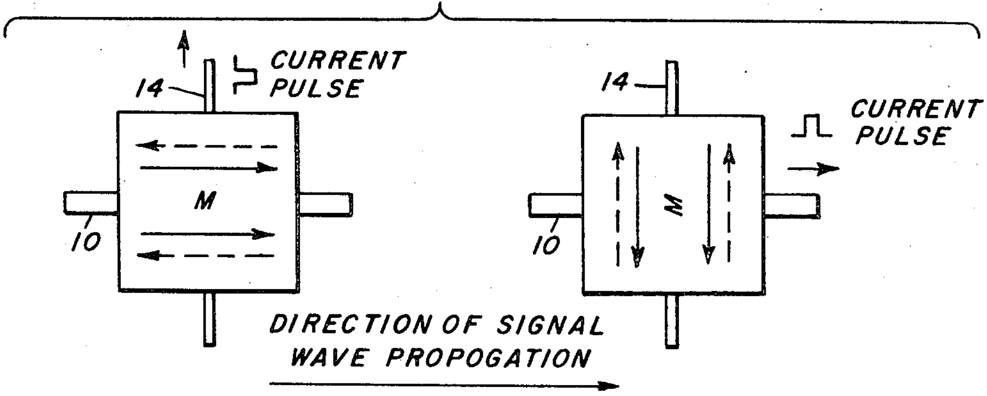


FIG. 4A

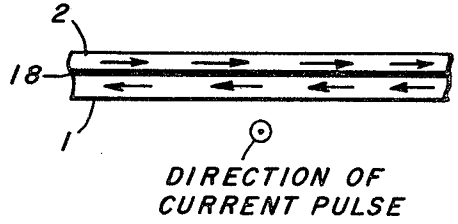


FIG. 4B.

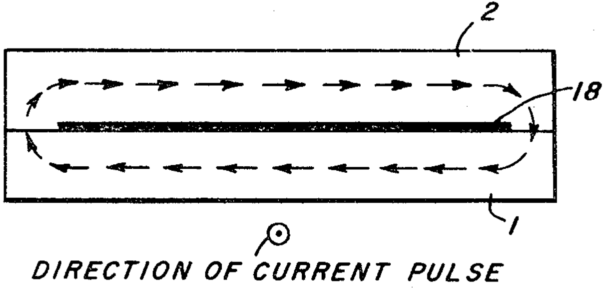
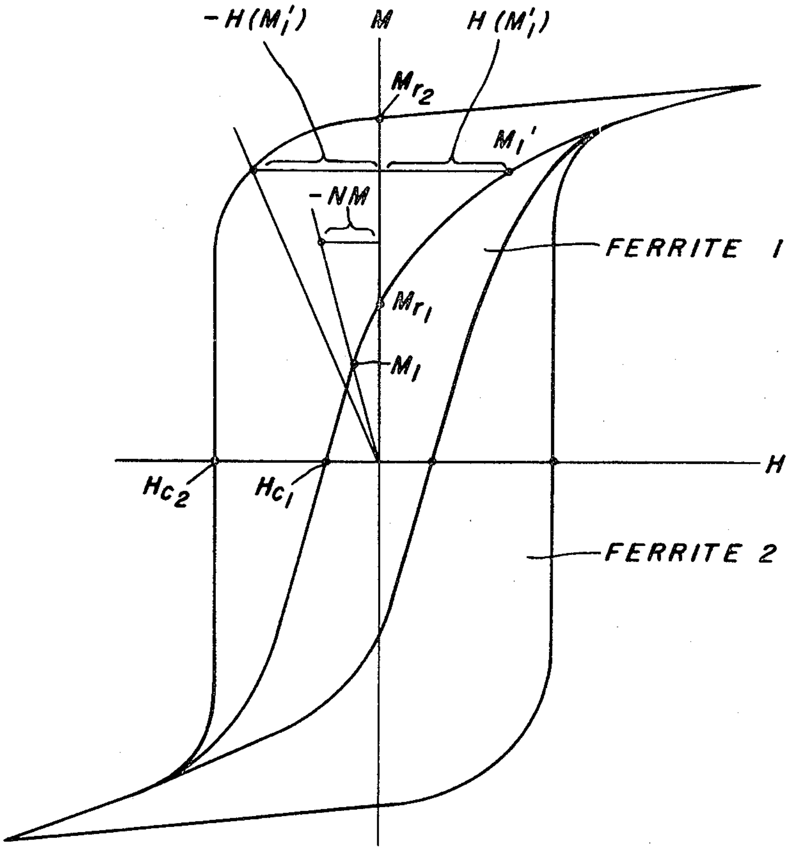


FIG. 5.



RECIPROCAL, MICROSTRIP, LATCHED, FERRITE PHASE SHIFTER

BACKGROUND OF THE INVENTION

As is known, most prior art ferrite phase shifters have utilized flat slabs of ferrite material together with a biasing direct current magnetic field. For switching, an electromagnet was sometimes used; but this resulted in relatively slow switching speeds. The development of digital latching phase shifters has eliminated the need for holding fields and has made possible submicrosecond switching speeds. In these designs, ferrite-magnetic toroids of various lengths are placed in a wave guide and latching wires passed through the centers of the toroids. By applying a current pulse of appropriate magnitude to the ends of the latching wire, the ferrite material can be driven close to saturation to effect a desired nonreciprocal phase shift and will remain in a remanent magnetized state until a pulse of the opposite polarity is applied across the ends of the latching wire to drive the ferrite material out of its magnetized state. The toroid configuration is used since, among other reasons, it forms a complete magnetic circuit which facilitates retention of remanent magnetization once the pulse is removed.

In many instances, it is desirable to obtain and control microwave signal phase in a reciprocal manner; i.e., the phase shift must be independent of direction of signal propagation. To achieve reciprocal ferrite phase shift, the applied direct current field must be parallel to the direction of signal propagation, and thus the latching wires should be perpendicular to it.

With the availability of microwave transistors and other semiconductor devices usable at microwave frequencies, the microstrip transmission line has found wide application because of its compatibility with the fabrication and installation of passive components and active devices on the same substrate with the transmission line in integrated circuits. Essentially, a microstrip transmission line is similar in operation to a coaxial TEM mode wave transmission line and consists of a strip of conductive material, corresponding to the center conductor of a coaxial transmission line, deposited on one side of a dielectric or semiconductive substrate, e.g., by photoresist techniques. The opposite side of the substrate is covered with a layer of conductive material comprising a ground plane and corresponding to the outer cylindrical conductor of a coaxial transmission line. With this configuration, and assuming that a source of signal wave energy is applied across the strip and ground plane on opposite sides of the substrate, an electromagnetic field pattern is established between the two.

In order to provide a latching phase shifter for such microstrip transmission lines, it is necessary to dispose the ferrite material in the space between the ground plane and the microstrip conductor itself, meaning that the thickness of the ferrite material has to be close to that of the integrated circuit substrate, a typical example being about 5 to 25 mils in the case of X-band and decreasing with increasing frequency. This poses a problem for latching ferrite phase shifters for two reasons. The first is that while the ferrite material can be driven into saturation by an appropriately applied pulse, difficulty is encountered in maintaining the flux density in the region of saturation. This may be due to one of two facts quoted below, or to both of them simultaneously:

1. The ferrite film does not form a complete magnetic circuit as is the case, for example, with toroids used in conventional wave guides, and the film thickness to surface area ratio is high enough to create a demagnetizing field which reduces the effective remanent state much below the true material remanence.
2. The film material while optimized for the microwave performance has an inadequate remanent magnetization much below that of the saturated state.

In the first case the demagnetization of the film should be removed by closing its magnetic circuit, or by subjecting it to a magnetizing field which would cancel the effect of demagnetization.

In the second case the magnetization of the film should be kept above the remanent value even after the magnetizing pulse is terminated.

SUMMARY OF THE INVENTION

As an overall object, the present invention seeks to provide a new and improved reciprocal latching ferrite phase shifter for microstrip transmission lines, which phase shifter is compatible with integrated circuits.

More specifically, an object of the invention is to provide a latching ferrite phase shifter of the type described, wherein difficulties encountered in maintaining a ferrite film in a magnetized condition are obviated by providing a second magnetic material in a magnetic circuit with the active ferrite film itself; this second material acting to insure that the active ferrite film will attain a desired degree of magnetization.

The reciprocal phase shift is given approximately by

(1)

$$\frac{\Delta\phi}{\phi_d}=1-\sqrt{\frac{1-\frac{f_m{}^2}{f}}{1-\frac{1}{2}\frac{f_m{}^2}{f}}}$$

where:

$\Delta\Phi$ = phase shift of the device,

Φ_d = phase shift of unmagnetized transmission line,

$f_m \cong (2.8\text{ MHz./gauss})\, x\, 4\pi M$

$4\pi M$ = magnetization component parallel to propagation direction in gauss, and

$f = X$ signal frequency.

The value of $4\pi M$, as defined above, can be varied by varying the angle of the magnetization to the strip conductor. This can be done by using two mutually perpendicular latching conductors in the plane of the ferrite, one of which is the microwave strip conductor and the other called a latching wire and provided with band rejection filters to prevent signal energy from leaking out of the latching circuit. The sign of the magnetization has no effect on the phase shift.

In accordance with the invention, a reciprocal ferrite phase shifter is provided comprising a film substrate of ferrite material, preferably formed by chemical vapor deposition techniques, having a metallic microstrip parallel to the direction of wave propagation and a latching wire perpendicular to it, deposited on the top face thereof, e.g., by vacuum deposition or thick film techniques. Conductive material is deposited also on the bottom side of the substrate film to form a ground plane. The microstrip conductor and the latching wire on the top face cover only a portion of the ferrite substrate which extends from either edge of the metal strips.

A subsequent nonmagnetic dielectric layer is deposited, e.g., by radio frequency sputtering on the top face of the substrate with the aforementioned conductors already plated. This dielectric layer separates partly or entirely the film substrate top face from a second magnetic film deposited over the dielectric layer. This second magnetic film may also be formed from ferrite and has a higher coercive force than the active ferrite between the ground and microstrip transmission line.

If the dielectric layer separates the two magnetic films over their entire surface area, they can be magnetostatically coupled, and the magnetization in the first will be antiparallel to the magnetization developed in the second. If the dielectric layer covers only a part of the substrate surface, the second magnetic film enters into direct contact with the uncoated part of the first, and they may form together closed magnetic circuits, where again magnetization in the first film will be antiparallel to the magnetization developed in the second with the exception of the direct contact area.

A pulse generator is connected to the latching wire and the transmission line on either side of the ferrite substrate. When a current pulse is applied through the latching wire perpendicular in the area of the ferrite substrate to the direction of wave propagation, a magnetic field parallel or antiparallel to the direction of propagation will be generated in both the ferrite substrate and the overlapping layer of magnetic material. As will be seen, the overlapping magnetic material of the second film, which requires a higher coercive force than that of the first to reduce flux density, guarantees a specified magnetization oriented in the direction of the field pulse in the active microstrip ferrite film itself.

Similarly, a pulse applied through the microstrip wire will generate in both films a magnetic field and orient the magnetization perpendicularly to the direction of propagation.

The ferrite substrate, in the usual case, will form a part of the nonmagnetic substrate of an integrated circuit and may be prepared by etching and deposition techniques, or by forming an opening in the main substrate and inserting a previously formed ferrite film. The method of mounting the phase shifter into the integrated circuit substrate is irrelevant to the present invention.

The above and other objects and features of the invention will become apparent from the following detailed description taken in connection with the accompanying drawings which form a part of this specification, and in which:

FIGS. 1A and 1B are perspective views of the ferrite phase shifter of the present invention in two possible variations:

1A with two ferrite films completely separated by the intermediate dielectric layer; and
1B with two ferrite layers separated only partly by the dielectric layer and forming closed magnetic circuits around the latching wire and around the microwave strip conductor;

FIG. 2 shows the manner in which a pulse generator is connected to the phase shifter;

FIG. 3 shows the orientation of magnetization in the film plane for the case of a pulsed latching wire and pulsed microstrip conductor;

FIGS. 4A and 4B give the schematic magnetization distribution in the phase shifter cross section in two possible variations:

4A when two magnetic films are completely separated by the intermediate dielectric layer and magnetostatically coupled; and
4B when two magnetic films form closed magnetic circuits around the latching wire and the microwave strip conductor; and

FIG. 5 illustrates the operation of the invention and comprises hysteresis curves of the active ferrite substrate material and the overlapping material which guarantees the desired state of magnetization in the substrate material.

With reference now to the drawings, and particularly to FIGS. 1A and 1B, the latching circuit in the phase shifter consists of a microwave strip conductor **10** plated on the surface of an active ferrite film **1** and aligned along the direction of signal wave propagation. A latching conductor **14** is perpendicular to the strip conductor **10**. To prevent leakage of the microwave energy, the latching wire **14** is endowed with two microwave band reject filters **12**, each on one side of the microstrip conductor and also plated on the top surface of ferrite film **1**. The bottom side of the ferrite film **1**, which forms the phase shifter substrate, is metallized to form a ground plane **16**. Deposited on the top of the ferrite film **1** and above the microstrip and latching conductors is a dielectric, nonmagnetic film **18** of alumina, magnesia silicate or beryllia. This dielectric film either covers the whole substrate surface as in FIG. 1A or leaves exposed portions of the substrate surface near all its edges as in FIG. 1B. Deposited on the top of the dielectric layer and on the remaining exposed substrate surface is a second ferrite film **2**, having a higher coercive force than the film of ferrite **1**. This second magnetic film can be either magnetostatically coupled to the first which corresponds to the case shown in FIG. 1A, or can form with the first film closed magnetic circuits through direct contact of films **1** and **2** on the exposed substrate surfaces **22** shown in FIG. 1B.

The complete, sandwichlike phase shifter can be mounted into a microwave microstrip circuit main substrate which, for example, may comprise alumina, beryllia or magnesia silicate. The mounting can be made by several different methods and is not directly relevant to the present invention.

The basic information on a reciprocal phase shifter and the relation between the ferrite magnetization and the phase shift have been the magnetization and the phase shift have been given above and are assumed here to be known. The operation of the invention can then be understood by reference to FIGS. 1A, 1B, 2, 3, 4A and 4B. The electromagnetic wave signal is propagating essentially between the ground plane **16** and the microwave strip **10** in the direction marked by the arrow in FIG. 1. It is thus mainly the magnetization of the ferrite film **1** which controls the phase shift in the microstrip. The ferrite film **2** separated by a dielectric layer from the main electromagnetic wave patch can contribute to the phase shift at a lesser but not negligible extent. The film **2** saturation magnetization, therefore, should not exceed that of film **1** because of the risk of excessive insertion loss. There are, however, less severe requirements as to the other microwave properties so that the material **2** can be optimized also with regard to the loop squareness and H_{c2} value.

The magnetization in the films **1**, **2** is controlled by the current pulse generator **32** and switches **34**, **36** connected to the microstrip conductor and to the latching wire as shown in FIG. 2. When both switches **34** and **36** are in position A, the current pulse passes through the latching wire **14**. When the switches are in position B, the current pulse passes through the microstrip conductor **10**. With the latching wire pulsed, the magnetic field induced in the films orients the magnetization M in both magnetic films parallel or antiparallel to the direction of signal wave propagation as shown in FIG. 3 and causes, therefore, the additional phase change Δ of the wave signal as indicated by Equation (1) given above.

FIGS. 4A and 4B illustrate the flux and magnetization distribution patterns in the phase shifter cross section at the end of a saturating pulse applied to the latching wire for two cases of:

A. magnetostatic interaction between adjacent completely separated thin magnetic films shown in FIG. 1A; and
B. a closed magnetic circuit around the latching wire formed by thick films 1 and 2 only partly separated by a dielectric layer as shown in FIG. 1B.

In both cases, the magnetizations of two films are mutually antiparallel and aligned in the direction of wave signal propagation.

When switches **34** and **36** are turned to position B in FIG. 2, and the microstrip conductor is pulsed, then the magnetic flux and the magnetization M will align in the new direction, now perpendicular to that of propagation. The flux and magnetization patterns in the films **1**, **2** at the end of the pulse are identical to the previous ones shown in FIGS. 4A and 4B, but now turned 90° in the plane of the films, as shown in FIG. 3. The additional phase shift in the microstrip, $\Delta\Phi$, caused by the preceding pulse through the latching wire is then removed because of zero magnetization component in the direction of wave signal propagation. This means that by using the film microstrip system shown in FIGS. 1 and 2, the phase shift in the microstrip can be latched between two discrete values by applying appropriate current pulses to either the latching wire or the microstrip conductor.

The application of the phase shifter requires, however, that the magnetization is properly aligned after the current pulse is terminated. It is a feature of the invention that this goal can be achieved owing to the presence of the second ferrite film located outside of the main electromagnetic wave path and having a saturation magnetization similar to that of the first, square material hysteresis loop and coercive force higher than that of the first film.

Let us refer to FIG. 5 and separately the cases of two magnetostatically coupled films and of the closed circuits formed by two connected films. The first case is of interest if the active film **1** is magnetically thin, i.e., its demagnetizing factor N is relatively small. In the absence of the second overlapping thin film **2**, the film **1** would be demagnetized by a small demagnetizing field (−NM) determined by the N factor and shown in FIG. **5**. At a low coercive force of film **1**, H_{c1}, this demagnetizing field may be, however, sufficient to drive the film **1** out of the material remanence M_{r1}, so that the effective remanent state M_1, also shown in FIG. **5** will be much lower: $M_1 < M_{r1}$. The second film of the same N added and coupled magnetostatically to the first prevents the demagnetization of the first by creating a magnetostatic field equal or bigger than $-NM_{r1}$. The loop of film 2 has to be more square and H_{c2} sufficiently higher than the coercive force H_{c1}. With the square loop of film 2 and its demagnetization field smaller than H_{c2}, the remanent value of magnetization M_{r2} is preserved. The magnetostatic interaction with the film **1** tends to preserve the antiparallel orientation of magnetizations in two films and, therefore, to magnetize the film **1** to a new state M'_1, higher than M_1 and approaching M_{r1}. The film **2** thus acts as a magnet or so-called "keeper" which keeps the magnetization of film **1** at the desired level until a next pulse through the microstrip conductor will reorient the "keeper" **2** and the active film **1**.

The second case of interest is that of closed magnetic circuits formed by two films. When the film **1** has a high thickness to surface area ratio and, therefore, a high demagnetizing factor N, the magnetostatic interaction between the films is too weak to orient the film **1** against the demagnetizing field (−NM). This field however, can be eliminated when closing the magnetic circuit as shown in FIG. **4B**. When the remanent magnetizations and thicknesses of both films are equal, i.e., $M_{r1}=M_{r2}=M_r$, the active film remains after the completed pulse in the M_r state. However, when the film **2** is thicker than the film **1** or has a higher remanent magnetization, $M_{r2}>M_{r1}$, then the active film **1** can be magnetized even above the material remanence state so that $M_1'>M_{r1}$. In this case the coercive force H_{c2} has to be greater than the field necessary to magnetize the film **1** from M_{r1} to M_1', $H(M'_1)$, which is equal to the internal demagnetizing field in the film **2**. The coercive force H_{c2} should then be greater than H_{c1}. This is illustrated again in FIG. **5**, where $M_{r2}>M_{r1}$.

In the case of X-band phase shifters, both films can be made of a magnesium-manganese ferrite, having a saturation magnetization of about 2,500 G. Film **1** can also be formed from aluminum substituted magnesium manganese ferrite. Typical coercive force figures will be H_{c1} equal to 1 oersted and H_{c2} equal to approximately 3 oersteds. The remanence of film **1** will be less than 0.5 M_s, but the remanence of film **2** will be about 0.8 M_s. The film **1** thickness in the X-band operation has to be 5 to 25 mils, and typical film area is of the order of 1 square inch or more. The demagnetizing factor is high in this case so that the phase shifter configuration depicted in FIG. **1B** is preferred. The dielectric layer separating the two films is typically 5 to 10 mils thick and made of alumina, magnesia silicate or beryllia. Of course, other different types of ferrites, dielectrics and film thicknesses could be substituted for those shown herein, depending on the frequency band in which the phase shifter operates. At frequencies above X-band, the magnetostatic film coupling configuration of FIG. **1A** can be used because of lesser film thickness.

Although the invention has been shown in connection with certain specific embodiments, it will be readily apparent to those skilled in the art that various changes in form and arrangement of parts may be made to suit requirements without departing from the spirit and scope of the invention.

We claim as our invention:

1. A reciprocal latching ferrite phase shifter comprising a substrate of ferrite material, a metallic microstrip conductor and a latching conductor coplanar with and perpendicular to the said microstrip conductor, both plated on the substrate surface so that portions of said surface are exposed on either side of the conductors, conductive material deposited on the other side of said substrate to form a ground plane, a dielectric nonmagnetic layer covering said conductors and at least a part of the ferrite substrate exposed surface, a second ferrite film deposited on the said dielectric layer and on the exposed substrate portions to form a magnetic circuit with the substrate, and means for connecting a source of pulsed electrical energy to the microstrip conductor and the latching conductor.

2. The phase shifter of claim **1**, wherein both of said magnetic films have the same or similar saturation magnetization and microwave properties acceptable in the frequency band of operation.

3. The phase shifter of claim **1**, wherein said second film of magnetic ferrite requires a square hysteresis loop and a greater coercive force to demagnetize it than said substrate of ferrite material in order to preserve the desired magnetization state of the substrate.

4. The phase shifter of claim **1**, wherein said second ferrite film is only partly separated from said substrate by means of said dielectric layer and forms with the substrate completely closed magnetic circuits around said latching conductor and around said microstrip conductor simultaneously.

5. The phase shifter of claim **1**, wherein said second ferrite film is entirely separated from said substrate by means of said dielectric layer and forms with the substrate a magnetostatically coupled magnetic circuit.

6. The phase shifter of claim **1**, wherein said dielectric, nonmagnetic and separating layer is selected from the group consisting of aluminum oxide, magnesia silicate or beryllium oxide.