FERRITE PHASE SHIFTERS

Phase shifters are used extensively in the microwave and millimeter-wave region primarily as array elements in phased array antennas. The first application of ferrite phase shifters in antenna arrays was during the decade of the 1960s. Since then growth has been dramatic with military applications being the motivating force. The air-defense systems of the former Soviet Union are designed and built around ferrite phase shifting devices as are several of the ground-based, naval and airborne systems of the US. The article describes the evolution of ferrite phase shifters which have made the transition from the research laboratory to the production floor. Wherever possible the author has identified the systems which use a specific type device.

Ferrite phase shifters are two port devices operating in the microwave and millimeter frequency range between 1.4 GHz and 100 GHz. A variable insertion phase between input port and output port is accomplished by varying the bias magnetic field of the ferrite material. The insertion phase of a phase shifter is the phase delay experienced by a radio-frequency (RF) signal propagating between port 1 and port 2 and is the angle of S21, the transmission coefficient from port 1 to port 2. If the angle of S21 equals the angle of S12, the transmission coefficient from port 2 to port 1, the phase shifter is *reciprocal,* while if these two angles are not equal the device is *nonreciprocal.* The phase shifter consists of (1) a microwave circuit containing magnetized ferrite whose purpose is to provide a variable insertion phase to the RF signal and (2) an electrical circuit containing electronic components whose purpose is to vary the magnetic bias of the ferrite and control the amount of variable insertion phase. Because the state-of-the-art of electronic control circuits changes rapidly depending upon device availability, the focus of the following discussion will be on the microwave portion of the ferrite phase shifter and the electronic control techniques will be limited to basic principles.

The use of magnetized ferrite to provide variable phase shift was recognized as early as 1953 (1). Phase shifter applications were stimulated by the discovery of the reciprocal, ferrite phase shifter in 1957 (2) and the latching ferrite phase shifter in 1958 (3). During the 1960s, major efforts were undertaken on phase shifter development, and the toroid phase shifter (4) and dual-mode phase shifter (5) evolved into their present configurations during this decade. The rotary-field phase shifter was reported in the early 1970s (6).

Although they find application in many areas, the major use of ferrite phase shifters are as phase shifting elements in electronic scanning antennas where the data rate is high enough to preclude the use of a mechanical scanning antenna or where the aperture must be shared by several functions requiring the antenna have an agile beam shape. Antennas used for systems tracking large numbers of targets such as the AWACS require data rates not attainable with mechanical scanning antennas. A ground-based air defense system such as the Patriot must track a particular target while continuing to search for other threats necessitating an electronic scanning system. Ferrite phase shifters are also used as feed elements for reflector antennas where the pattern of the reflector may be changed by changing the feed pattern providing different coverages. Electronic control is desirable since the system may be located in space and the reliability of mechanical switches is not adequate. Other antenna feeds use four phase shifters to provide a variable phase to each quadrant of the antenna resulting in a conical scanning beam for the antenna. A third use is as the variable element in microwave circuits used for high-power switches and variable-power dividers and combiners. Because of the low insertion loss and excellent phase accuracy attainable with ferrite phase shifters, high-power electronic switches with insertion loss as low as 0.5 dB and with isolations approaching −40 dB may be realized. A circuit providing variable phase shift in each leg of a bridge circuit has been used to combine the azimuth and elevation difference signals from a monopulse antenna and by properly phasing the signals compensate electronically for aircraft roll. Finally, ferrite phase shifters have been used as Doppler simulators, frequency translators, and so on.

FERRITE MATERIALS AND PROPERTIES

A material is called *magnetic* if it exhibits a magnetic moment in the absence of an applied magnetic field. The magnetic moment is due to the presence in the material of at least two different electronic spin systems. If these spin systems are equal and parallel, the material is ferromagnetic; if the spin systems are equal and antiparallel, the material is antiferromagnetic; and if the spin systems are unequal and antiparallel, the material is ferrimagnetic and is generically referred to as ferrite. Ferrite materials are ionic crystals with no free electrons, resulting in high resistivity and making them potentially useful for application in the microwave and millimeter frequency ranges. Two types of ferrites both with cubic crystalline structure but one (spinels) having structure similar to spinel and the other (garnets) having the garnet structure have been used for phase shifter fabrication. A sample of ferrite material of a size required for microwave components usually does not exhibit a net magnetic moment in the absence of an external bias field. The material is composed of magnetic domains; each of these exhibits a net magnetic moment but is randomly aligned, resulting in zero net magnetic moment when summed over the sample. Application of an external magnetic bias field rotates the domains which align with the bias field and produce a net magnetization. When all domains in a sample are aligned, the material is saturated and the magnetization is called the *saturation magnetization,* $4\pi M_S$. A virgin sample of material exhibits a magnetization curve similar to that of iron.

When the magnetizing current is removed, some magnetic flux may remain in the sample, and a current in the opposite direction must be applied to reduce this flux to zero. This phenomenon is called *hysteresis.* A ferrite material formed in a closed loop exhibits a hysteresis loop similar to that shown in Fig. 1, with the squareness of the loop being a function of the chemical composition of the material. The magnetic field intensity required to reduce the magnetic flux density to zero is called the *coercive force,* H_c, while that magnetic flux density remaining after the magnetic field intensity has been reduced to zero is called the *remanent flux density,* B_r. Magnetic material properties are sensitive to temperature; and above a certain temperature, called the *Curie temperature,* the magnetic properties vanish.

Ferrite phase shifters require values of saturation magnetization ranging from approximately 200 gauss to 5500 gauss (the maximum attainable value with commercially available materials). By substituting aluminum ions for ferric ions in YIG, the saturation magnetization may be reduced from 1780 gauss (the value for pure YIG) to about 175 gauss. For the

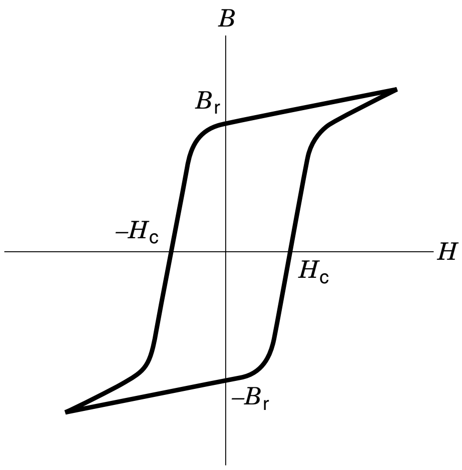

Figure 1. Ferrite hysteresis loop for a square loop material defining the remanent magnetization, B_r, and the coercive force, H_c.

lithium spinel family the substitution of titanium ions for ferric ions is used, and both aluminum and zinc separately or in combination have been used to vary the saturation magnetization for the magnesium–manganese ferrite family and the nickel ferrite family. In general, when substitution is made the Curie temperature is lowered from that of the unadulterated material. Doping with rare earth ions may be used to increase peak power capacity, although the insertion loss may increase slightly.

Phase shifters providing variable values of insertion phase operate with the ferrite partially magnetized. The ferrite exhibits a tensor permeability whose on-diagonal elements, μ, vary slightly as a function of the applied magnetization. The off-diagonal elements of the tensor, $\pm j\kappa$, are equal but of opposite sign, leading to the nonreciprocal behavior of ferrite devices. These off-diagonal elements are in phase quadrature with the on-diagonal elements and are proportional to the ratio of applied magnetization to saturation magnetization. If the RF energy is circularly polarized, the effective permeability of the ferrite medium is equal to $(\mu + \kappa)$ for one sense of circular polarization and $(\mu - \kappa)$ for the other sense of circular polarization, both of which are dependent upon the applied magnetization through the off-diagonal element of the permeability tensor. The permittivity of the ferrite is scalar with a dielectric constant in the range 10–18. The dielectric loss tangent of ferrite is about 0.0002 for garnets, 0.0003 for magnesium spinels, 0.0005 for lithium spinels, and 0.001 for nickel spinels.

Phase shifter characteristics determined by the microwave circuit are the mode of operation, either reciprocal or nonreciprocal; operating frequency; instantaneous and tunable bandwidth; polarization of the input and the output signals; peak and average RF power; insertion loss and modulation of the insertion loss; and return loss. Parameters determined by the microwave circuit and the electrical control circuit are phase quantization, phase accuracy, switching time, switching rate, and control power. Physical parameters of the phase shifter include size; weight; cooling requirements; input interfaces for RF signal, data, and control power; and output interfaces for RF signal and built-in-test. The phase shifter must conform with environmental requirements such as operating and storage temperature range; operating and transportation shock; operating and transportation vibration; and operating and storage humidity. Finally, requirements generally exist for the reliability, interchangeability, and maintainability of the phase shifter.

TYPES OF FERRITE PHASE SHIFTERS

Many ferrite phase shifters are described in the literature, but only three types have been produced in quantity and deployed in the field in various antenna systems. The one characteristic shared by these three different devices is an insertion loss less than 1 dB. System and antenna designers are unwilling to use devices with higher loss because of reduction in antenna gain and cooling problems associated with dissipation of the transmitter power in the antenna.

The J-STARS airborne surveillance system, the Patriot mobile, ground-based air-defense system, and the Aegis naval-based air-defense system use variations of the nonreciprocal toroidal phase shifter. This device operates in a nonreciprocal mode, requiring that the phase shifter be switched immediately after the transmitter pulse to provide the proper phase shift for propagation in the receive direction. The phase shifter is switched again just prior to the next transmitter pulse, resulting in a switching rate twice the pulse repetition rate of the radar. Switching time is a few microseconds depending upon operating frequency. This type of phase shifter may be designed to have extremely wide operating bandwidth approaching two octaves in some cases.

The second type of phase shifter, also nonreciprocal, consists of a longitudinally magnetized ferrite rod located on the axis of either square or circular waveguide. Several of the ground-based, mobile air-defense systems of the Confederation of Independent States use these phase shifters in antennas, radiating one sense of circular polarization and receiving the orthogonal sense of circular polarization—the "single bounce" return. An adaptation of the phase shifter which provides reciprocal phase shift is referred to as the "dual-mode" device and has been successfully employed in several antenna designs most notably the multimode offensive radar systems of the B-1B. Switching times for these phase shifters are in the tens of microseconds depending upon the frequency of operation. Operating bandwidth is more modest than the toroid phase shifter, typically being 10 to 15%, although 40% bandwidth has been achieved for experimental devices.

The phase shifters described above provide a variable insertion phase by varying the magnitude of the bias magnetic field, resulting in a variation in the equivalent inductance of the waveguide and yielding a variable propagation delay through the device. The final phase shifter described in this section does not use this phenomenon but rather makes use of the variation in the direction of the bias magnetic field to effect change in insertion phase with no change in the propagation delay. Because of the similarity of the phase shifter to the rotary-vane (7) mechanical phase shifter, it has been called the *rotary-field phase shifter.* The rotary-vane device uses a dielectric vane to realize a half-wave plate which can be rotated about the axis of a circular waveguide housing. A circularly polarized RF signal receives phase shift when passing through the half-wave plate equal to twice the mechanical angle of rotation of the half-wave plate. Substitution of a

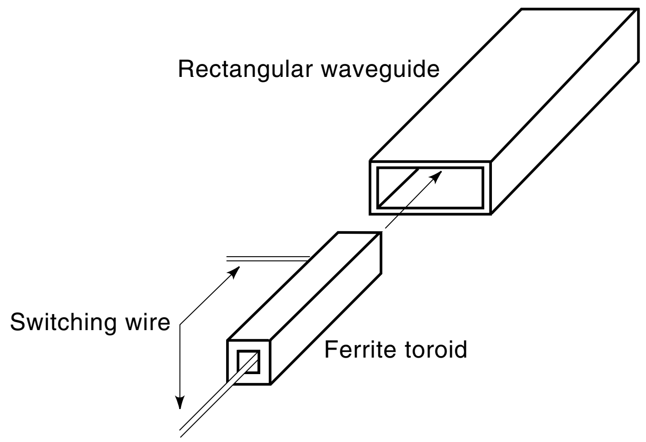

Figure 2. Prototypical toroidal phase shifter. First described in the 1950s, this device was the first latching, ferrite phase shifter. By pulsing the switching wire the flux may be latched to either $+B_r$ or $-B_r$. Sustaining drive current is not required.

transversely magnetized ferrite rod for the dielectric half-wave plate results in an electrically variable version of this phase shifter. This phase shifter has been employed in a single-axis scanning configuration for the antenna for the AWACS surveillance aircraft and for several single-axis scanning, ground-based, mobile air-defense systems. The switching time for the device is of the order of hundreds of miroseconds, and the operating bandwidth is about the same as that of the dual-mode phase shifter.

Toroidal Phase Shifters

The toroidal phase shifter consists of one or more ferrite toroids inserted into a rectangular waveguide as shown in Fig. 2. The cross section shown in Fig. 3a is the original version of the toroidal phase shifter reported by Truehaft and Silber (3) in 1958. The toroid is fabricated from a material with a square hysteresis loop. Current flowing in the switching wire induces a magnetic flux in the toroid which remains after the current is removed. The phase shifter is said to be "latched"; operation in this mode is desirable since control energy is required only when the phase shifter is set to a new state. The magnetic field intensity of the TE10 mode in a rectangular waveguide is circularly polarized in a longitudinal plane parallel to the narrow wall of the waveguide and located a distance from the waveguide centerline which makes the longitudinal magnetic field intensity equal in magnitude to the transverse magnetic field intensity. The opposite sense of circular polarization exists in the longitudinal plane located the same distance on the other side of the waveguide centerline. If a sample of magnetized ferrite is placed in the region of circular polarization, a strong interaction between the RF and the ferrite will occur provided that the direction of the bias field is interchanged on either side of the waveguide centerline.

The geometry shown in Fig. 3b makes more efficient use of the ferrite toroid and provides more total phase shift than the geometry of Fig. 3a at a minimal increase in insertion loss by loading the "window" in the toroid with a dielectric. The dielectric loading effect of the ferrite toroid and dielectric used to load the toroid window distorts the behavior of the fields of the waveguide mode so that the region of circular polarization no longer lies in the same plane as that of the air-filled waveguide. Computer-aided analyses programs have been evolved (8,9) to predict the performance of the phase shifter as a function of toroid placement and dielectric loading. A disadvantage of the geometries shown in Fig. 3a and Fig. 3b is the excitation of the TEM mode which is easily established by the switching wire coupling to the rectangular waveguide. Two toroids separated by a dielectric slab spacer as shown in Fig. 3c reduce this coupling by concentrating the RF energy in the region adjacent to the dielectric slab and locating the switching wires in regions of very low RF energy. This geometry is referred to as the *dual toroid* and has come to be the preferred realization for this class device.

The ferrite–dielectric composite is housed in a rectangular waveguide which typically has a smaller cross section than the connecting waveguide because of the dielectric loading. Quarter-wave transformers are used to match into and out of the ferrite–dielectric composite. These transformers increase the length of the device but do not contribute significantly to the insertion loss. When the connecting transmission line is a TEM-type line such as microstrip, a high dielectric constant ($\approx$100) material may be used as the dielectric spacer to reduce the cross-sectional dimensions of the phase shifter and

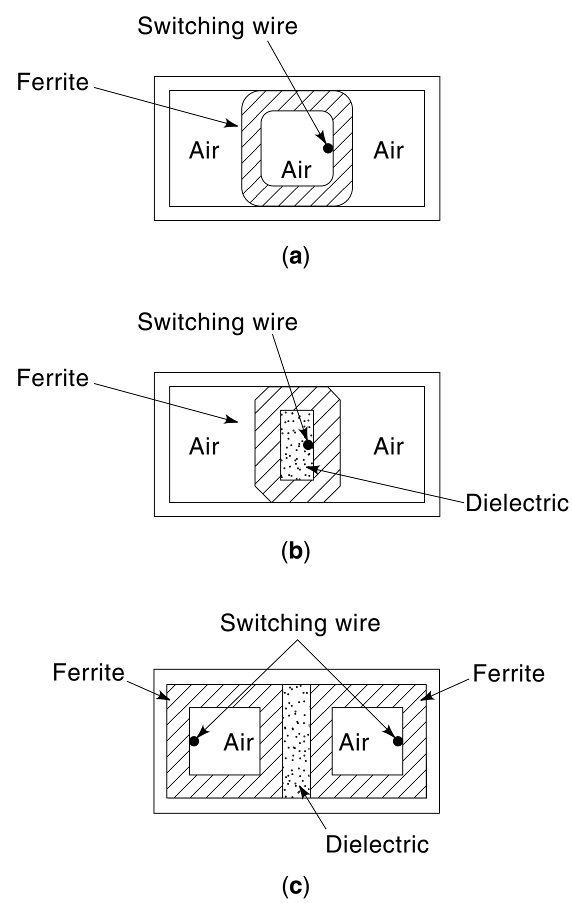

Figure 3. Evolution of the toroidal phase shifter into the twin-toroid device. The window inside the toroid is loaded with high dielectric material in order to improve the phase shifter RF performance in (b) while in (c) another toroid is added which greatly decouples the switching wires from the RF field.

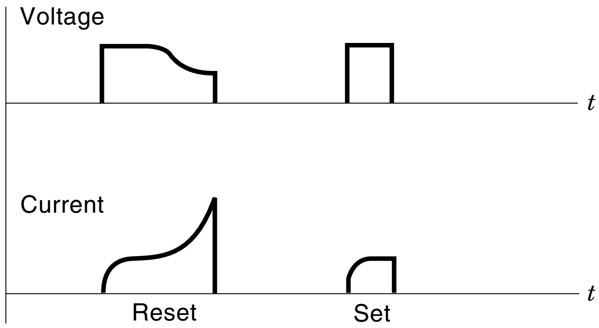

Figure 4. Switching waveforms of the latching phase shifter when driven from a constant voltage source. The voltage remains approximately constant during switching until the ferrite saturates. Saturation of the core to obtain a stable reset state is exhibited by the abrupt rise in the current in the reset waveform. The area under the voltage waveform for the set pulse determines the amount of flux switched into the ferrite core and hence the amount of phase shift.

lower the characteristic impedance level to around 50 Ω. This has the added benefit of reducing the length of the device because of the increase in electrical length caused by the dielectric loading. The ferrite toroids are bonded to the high dielectric constant rib, and the composite is coated with a conducting material to form the waveguide. Connection to the TEM-line may be made with a short length of wire with a chip capacitor located at the point of connection of the wire to the phase shifter in order to resonate the inductance of the wire loop.

In order to establish a reference condition for the phase shifter the toroid is *reset;* that is, a voltage pulse of magnitude and duration sufficient to saturate the toroidal core is applied to the control wire. The current in the control wire remains roughly constant until the core saturates, at which time the current increases sharply. Sensing the current and removing the drive voltage when a predetermined current has been attained allows the core to relax to the remanent flux and establishes a stable reference point. The magnitude of the voltage pulse is not critical for the reset operation. The *set* operation establishes a flux level in the core corresponding to a given value of phase shift. Faraday's law states that the change of flux is equal to the time integral of the applied voltage; a variable flux level may be set by using a variable amplitude voltage pulse for a fixed time duration or a fixed amplitude voltage pulse for a variable time duration. If either the voltage or the pulse width varies substantially from that used to calibrate the phase shifter, the error in setting the flux may be excessive and resort to more complicated methods such as integration of the voltage pulse may be required. Typical switching waveforms are shown in Fig. 4.

During switching, the toroidal core presents a resistive load to the source. Application of a voltage pulse to the control wire results in a current pulse whose amplitude is determined by Ampere's law, $NI = \int H\,dl$. The magnetic field intensity is constant and equal to the coercive force, the number of turns is unity, and the integral of dl is equal to the mean length around the ferrite toroid. Thus $I = H_c l$. The flux change from one remanent state to the other remanent state is $2B_rA$, where B_r is the remanent flux density and A is the cross-sectional area of the toroid normal to the direction of flux. For a constant voltage V applied to the core for a time T, $VT = 2B_rA$, yielding a switching time $T = 2B_rA/V$. This is the maximum value of the time to establish the reset condition; the total switching time would be at least twice this value. Increasing the applied voltage reduces the switching time and increases the dynamic core resistance, which is given by $R = 2B_rA/(TH_cl)$.

Dual-Mode Phase Shifters

Latching operation of the ferrite rod phase shifter is realized by filling the waveguide completely with ferrite and providing a magnetic return path for the bias flux through the use of external ferrite yokes as shown in Fig. 5. The control power is furnished by a coil which is wound around the waveguide. Again the insertion phase of the device is dependent upon the value of magnetic flux existing in the ferrite rod, and variable phase is realized by changing this value. The RF energy propagating through the ferrite rod must be circularly polarized, which may require the input polarization be converted from linear polarization to circular polarization. Each sense of circular polarization receives a different value of insertion phase when propagated through the device, and these values are interchanged when either the direction of propagation or the direction of magnetization is reversed. However, if an antenna uses these phase shifters and receives the "single bounce" return, transmitting right-hand circular and receiving left-hand circular or vice versa, switching between transmit and receive is not required.

The adaptation of the ferrite rod phase shifter to the reciprocal dual-mode phase shifter is illustrated schematically in Fig. 6, and the physical realization of the phase shifter is shown in Fig. 7. Nonreciprocal circular polarizers (NCP) located on either end of the ferrite rod function as the circulators shown in the schematic diagram converting linearly polarized RF energy into circularly polarized RF energy and vice versa. The NCP physically consists of a section of the ferrite rod which is transversely magnetized with a four-pole bias field by a permanent magnet located exterior to the microwave circuit. This four-pole bias field provides a differential phase shift of 90° to cross-polarized signals. If the input to the

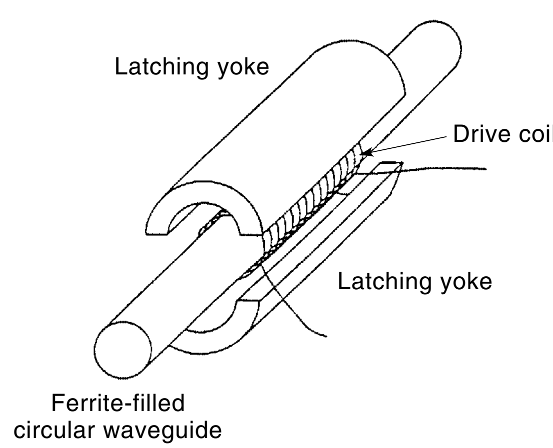

Figure 5. The Faraday rotation phase shifter. The ferrite-filled circular waveguide provides the signal path for the RF energy. Longitudinal magnetization is obtained using a drive coil wrapped around the ferrite rod. Latching operation is realized using latching yokes for a return path for the bias magnetic flux.

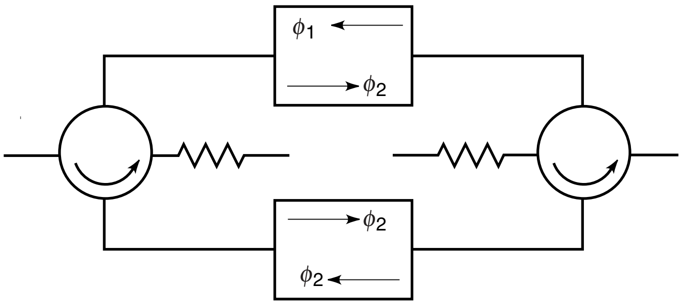

Figure 6. A reciprocal phase shifter realized using four nonreciprocal components. The two circulators and two nonreciprocal phase shifters provide port-to-port reciprocal behavior.

NCP is linearly polarized at an angle of 45° with respect to the axis of the NCP, the output will be circularly polarized with the sense of circular polarization depending upon the orientation of the input linear polarization. For a circularly polarized input signal, the output of the NCP will be linearly polarized with orientation depending upon the sense of the circularly polarized input signal. The NCP on the left side of the device in Fig. 7 converts input linear polarization into right-hand circular polarization in the ferrite rod section when RF energy is propagated from left to right. This circularly polarized energy receives a variable value of insertion phase dependent upon the magnitude of the remanent bias flux density in the ferrite rod. The circular polarization is then restored to linear polarization by the NCP on the right side of the figure. For propagation from right to left, the RF energy in the ferrite rod is converted to left-hand circular polarization by the NCP on the right side of the figure, resulting in the signal receiving the same value of variable insertion phase irrespective of the direction of propagation through the device. The signal is restored to linear polarization by the NCP located on the left side of the device.

The electronic control of the dual-mode device is similar to that used for the toroid, but two major exceptions exist. The drive coil is almost always a multiturn coil which results in the apparent resistance and inductance of the ferrite core being increased by the square of the number of turns of the drive coil. Second, the waveguide walls do not enclose the magnetic circuit in its entirety. The magnetic flux cuts through the waveguide walls as it passes from the ferrite rod and is returned through the external yokes resulting in an induced voltage in the waveguide walls whenever the flux is changed. Since the waveguide walls are made of low-resistivity material, a low-resistance path allows eddy currents to flow in the waveguide walls and produces the phenomenon called *shorted-turn damping.* This effect may be modeled by including a parallel resistance due to this damping in the equivalent circuit of the phase shifter.

Rotary-Field Phase Shifters

The geometry of the rotary-field phase shifter is shown in Fig. 8. A composite ferrite–dielectric rod is metallized with a thin metallic coating to form the microwave portion of the circuit. This is inserted into a laminated steel yoke which provides the variable magnetic bias field. The rod–yoke assembly is housed in a two-piece metallic housing which interfaces to standard rectangular waveguide. Two interlaced windings wound on the multislot yoke generate the four-pole bias field. Dielectric quarter-wave plates on either end of the ferrite rod convert linearly polarized RF energy to circularly polarized energy, and vice versa, for propagation through the ferrite half-wave section. The linearly polarized RF input signal is converted to circularly polarized energy by means of the dielectric quarter-wave plate. This circularly polarized energy passes through the ferrite half-wave plate and receives a variable phase shift dependent upon the orientation of the ferrite half-wave plate. At the output of the ferrite half-wave plate the sense of circular polarization is reversed, allowing the

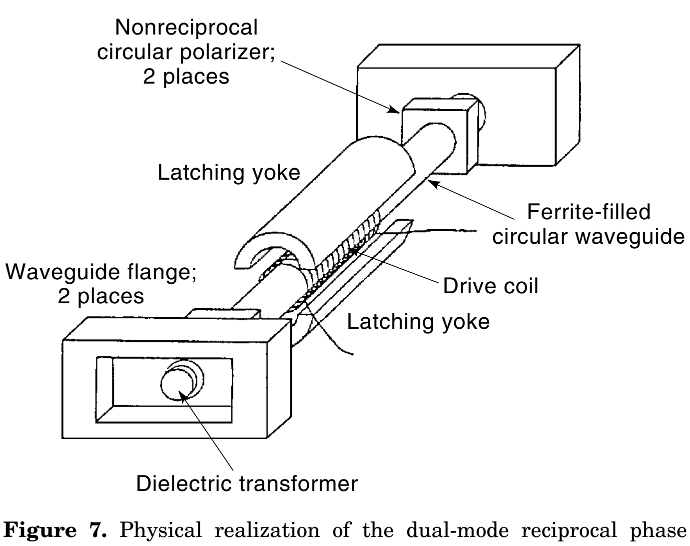

Figure 7. Physical realization of the dual-mode reciprocal phase shifter. This compact realization of the schematic shown in Fig. 6 has proven to be compatible with the packaging requirements for electronic scanned phased array antennas with wide scan angle requirements.

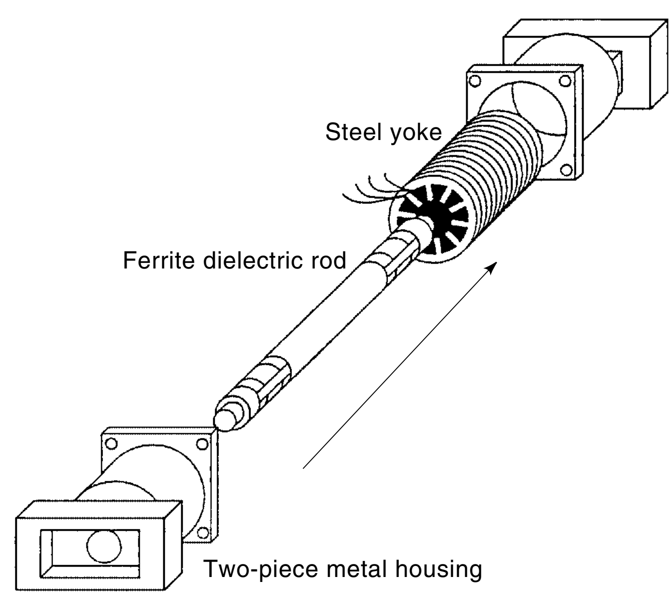

Figure 8. The rotary-field phase shifter. This device provides excellent phase accuracy and is capable of relatively high values of RF power.

output dielectric quarter-wave plate to reconstitute the same sense of linear polarization as the input polarization. The phase shift through the device is the same for either direction of propagation so that it is referred to as a *reciprocal device.* In the strictest sense it is nonreciprocal since a fixed 180° phase shift exists between signals propagating through it in opposite directions.

Latching operation of the rotary-field device has only recently been reported (10) and units presently deployed operate with continuous holding current, resulting in a substantial dc power supply for array applications. This has limited the device to single-axis electronic scanning antenna applications such as the surveillance antenna for the AWACS aircraft. Typically the electronic control for these devices are two parallel drivers to control the two independent windings on the yoke, with the control current on one winding set proportional to the cosine of the desired phase angle and the control current on the remaining winding set proportional to the sine of the desired phase angle.

PHASE SHIFTER CHARACTERISTICS

Most phase shifter designs are custom designs having been developed for specific purposes and programs. Specific operating parameters will not be provided, but rather general electrical and physical characteristics will be discussed. Finally, typical numbers are provided for the reliability of the devices.

Electrical Characteristics

Electrical characteristics of importance are the operating mode (reciprocal/nonreciprocal), the operating frequency, the instantaneous bandwidth, the tunable bandwidth, the input polarization, the output polarization, the peak and average RF power, the insertion loss and the insertion loss modulation, the return loss, the quantization of the phase shift, the phase accuracy, the switching time, the switching rate, and the control power. Although it would seem that reciprocal operation would be preferred over nonreciprocal operation, there are many more nonreciprocal phase shifters deployed than reciprocal ones. The interaction of ferrite with RF energy is nonreciprocal and historically the earlier successful phase shifters were the nonreciprocal toroidal types. The choice of operating mode is generally dictated by system requirements; and in several cases such as communication satellites, nonreciprocal operation is not a handicap.

The operating frequency is another choice of the system designer with phase shifters having been developed from 1.4 GHz to 94 GHz. The instantaneous bandwidth refers to the frequency band over which the phase shift remains within specified tolerances, while the tunable bandwidth refers to the frequency band over which the phase shifter may be adjusted to bring the phase shift within the specified tolerance. The nonreciprocal toroidal phase shifter has been designed to yield two octaves of instantaneous bandwidth, while the dual-mode phase shifter and the rotary-field phase shifter yield instantaneous bandwidths in the 2 to 4% range with tunable bandwidth of the order of 15%.

The input and output polarization depends upon the application for which the phase shifter is intended and may be either linear or circular or switchable between the various linear and circular polarizations. The nonreciprocal toroidal phase shifter operates in a linearly polarized waveguide mode so that the input and output polarizations are linearly polarized. The dual-mode phase shifter may use circularly polarized input and output polarization operating in the nonreciprocal mode or linearly polarized input and output polarizations when operating in the reciprocal mode. This phase shifter lends itself well to incorporating polarization switching so that various output polarizations are available even when the phase shifter is excited with a linearly polarized input. The rotary-field phase shifter usually uses linearly polarized input and output signals, although this is not required.

The peak RF power capacity of a ferrite phase shifter is determined by the choice of ferrite used to realize the phase shifter. If the RF magnetic field intensity exceeds a threshold value, excitation of spin waves results and the RF insertion loss increases substantially. Doping of garnet material with rare earth ions may be used to increase the threshold value, but at the expense of increased low power insertion loss. The average RF power capacity of a phase shifter is determined by the mechanical design and may only be increased by improving the heat flow path away from the ferrite.

The insertion loss of the phase shifter, as mentioned previously, should be below 1 dB in order to merit consideration from antenna designers. Of the phase shifters discussed, the rotary-field device has the lowest loss with values as low as 0.3 dB obtained in production quantities for a device operating in the 5 GHz frequency range. The toroidal phase shifter and the dual-mode phase shifters have insertion loss in the range from 0.6 to 1.0 dB. The variation of the insertion loss as a function of the insertion phase of the device is greatest for the reciprocal devices, generally being of the order 0.2 to 0.4 dB, while the toroidal device has loss modulation less than 0.1 dB.

The return loss of the ferrite phase shifters depend upon the RF input and output connections, and values cited will be for linearly polarized input and output configurations. The toroidal phase shifter generally has a maximum value of return loss of −20 dB, while the reciprocal phase shifters have maximum values of return loss of the order of −14 to −17 dB.

Ferrite phase shifters are generally designed to provide 360° of electrical phase shift. Early ferrite phase shifters were realized using discrete lengths of ferrite to provide quantization of the phase shift in steps of 180°, 90°, 45°, and 22.5°. This method results in a simple electronic driver design but a complicated microwave structure. Modern ferrite phase shifters are realized using a continuous piece of ferrite in order to minimize the cost of the microwave structure, resulting in a continuous range of phase shift. Quantization is provided by the electronic driver. Since the driver commands are distributed over the total range of phase shift which is often greater than 360°, the final quantization is 1 bit less than that provided by the electronic driver; that is, an 8-bit driver command results in 7-bit phase shift quantization. Quantization levels greater than this are found in the control electronics of variable power dividers/combiners but rarely are used in other phase shifter applications.

The phase accuracy of the phase shifter refers to the precision with which the insertion phase of the device may be set. For the toroid phase shifter, this parameter is a function of the stability of the reset state, the operating frequency, and the operating temperature, and accuracies of the order of 2° to 3° rms error can be achieved. Improvements in the accuracy can be achieved at the expense of added calibration. For the dual-mode phase shifter the alignment of the nonreciprocal polarizer magnets is another source of phase error, and accuracies of the order of 3° to 4° rms error are common with this device. The rotary-field phase shifter may be set very accurately since the insertion phase is proportional to the ratio of the two currents which control the rotation angle of the magnetic bias field. Typical phase accuracies for this device are in the range 1° to 1.5° rms and are not particularly sensitive to frequency and/or temperature.

The switching time of the phase shifter is the time required to establish a new insertion phase state and includes the times for resetting and setting the toroid and dual-mode phase shifter. The switching time is a function of the operating frequency since the size of the phase shifter is dependent upon the frequency. Typical switching times for a toroid phase shifter range from about 20 μs at 2 GHz operating frequency to about 5 μs at 20 GHz. Typical switching times for a dual-mode phase shifter range from about 200 μs at 5 GHz to about 50 μs at 20 GMz. The nonlatching rotary-field phase shifter requires switching times ranging from 200 μs at 3 GHz to about 100 μs at 10 GHz but requires a high-voltage boost circuit in order to attain these speeds. The switching rate of the phase shifter is generally determined by system requirements, with the control power being directly proportional to the switching rate.

Physical Characteristics

Important physical characteristics of the phase shifter are the size, the weight, the cooling requirements, and the physical location of the input and output interfaces. The size is dictated by the operating frequency, average power requirements, and type of phase shifter. In general the toroid phase shifter has the smallest cross section, and the rotary-field phase shifter has the largest cross section with the dual-mode somewhere between the two. The weight of the phase shifter is proportional to size: The toroid phase shifter is generally the lightest weight unit, the rotary field the heaviest, and the dual-mode in between the two. The RF interfaces are the input and output RF ports, which may be coaxial cable, microstrip transmission line, rectangular waveguide, radiating elements into free space, or any combination of these. Electrical interfaces consist of the input data and any output data, such as built-in-test, control, power, and ground.

The electrical and mechanical design must be such that the phase shifter meets the specified values over operating temperatures ranging from −40 to +95°C. In many cases a reduced temperature range for full performance with degraded performance over the temperature extremes is allowed. Nonoperating temperatures normally range from −55 to +125°C. Operating shock and vibration requirements are determined by the mechanical design of the system and the phase shifter mounting.

The reliability of the phase shifter as measured by the mean time before failure (MTBF) is an important consideration. The microwave portion of the phase shifter has high reliability since it is composed of a ferrite core and associated windings. The overall reliability is generally determined by the electronic driver with values of roughly 200,000 h for the latching phase shifters and values of 50,000 h for the nonlatching phase shifters because of the requirement for continuous drive current.

FUTURE DEVELOPMENTS

Two developments in waveguide devices offer promise. The first is an attempt to provide a reciprocal phase shifter using the toroid phase shifter in a geometry similar to the dual-mode device but using microstrip circulators. The difficulty with this approach is that the microstrip circulator is realized naturally as a three-port device and the schematic diagram of Fig. 6 requires a four-port circulator to adequately isolate the input and output ports. Work continues in this development. The second development in the waveguide area is the latching rotary-field phase shifter which has been reported in the literature (6) but has not been deployed in the field. Data taken on experimental units are very encouraging.

There is a continuing effort to develop a ferrite phase shifter in a planar geometry suitable for integration with microstrip transmission line. The literature contains many references to these devices, but the insertion loss continues to be a drawback to deployment. The textbook cited in the reading list contains several examples of planar phase shifters as well as many references.

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Reading List

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FERRITES, HARD. See PERMANENT MAGNETS.

FERROELECTRICS. See MICROWAVE FERRITE MATERIALS.

FERROELECTRIC THIN FILMS. See THIN FILMS.

FERRO-, PYRO-, AND PIEZOELECTRICITY IN ELECTRETS. See ELECTRETS.