Ferrite Rotary-Field Phase Shifters: A Survey of Current Technology and Applications

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Ferrite Rotary–Field Phase Shifters have been used for more than two decades in applications that require highly accurate phase control at moderate to high microwave power levels. During this period, work has been carried out continuously to improve the basic understanding and computational models for this class of device, as well as to extend its power handling capability and frequency regions of practicality. This paper reviews the progress that has been made in the past few years in selected topics, namely, understanding of the sources of phase error, switching considerations, especially "hot" switching with power applied, extending the region of applicability to the 1–2 GHz. band, and increasing the average power handling capability through improved heat transfer geometry.

I. Introduction

In 1947 Fox [1] described a microwave phase changer in circular waveguide, in which two 90° differential phase sections (quarter–wave plates) of fixed angular orientation were separated by a 180° differential phase section (half–wave plate) of rotatable orientation. In his paper, Fox presented a mathematical analysis of the operating principal, and pointed out that the approach was analogous to a well–known optical configuration of much earlier vintage. Cacheris [2] applied the concept to a ferrite–loaded waveguide and in 1954 showed experimental results for a device operating at X–Band; his configuration evidently used a rotatable two–pole transverse magnetic bias field to generate the required 180° differential phase section. A thorough analysis of the basic configuration was published in 1971 by Sultan [3], who calculated and plotted the amplitude and phase errors that would be expected as a result of deviations from optimum differential phase in the quarter–wave and half–wave plates. Sultan also showed measured data for a structure using a ferrite tube and a drive stator that did not permit continuous rotation of its fourpole bias field, and concluded that the probable insertion loss was about 0.4 dB.

Concurrent with (but unrelated to) the publication of Sultan's paper, the author's company began delivery of the first set of high–power S–Band phase shifters for use in the USAF/Westinghouse E–3A AWACS radar antenna. This design evolved over a period of about a year of concentrated effort, and was based on earlier work on the same generic type of configuration [4]. Data on the AWACS type duplexing phase control component were presented [5] in the following year. These included insertion loss and return loss envelopes of a phase–scanned unit, as well as a typical plot of phase deviation from command angle over a 450° phase range, showing the effect of hysteresis. Since that time, the geometry, which fits the descriptor "rotary–field" well, has been used in a number of antennas with single–axis phase scanning, where high phase accuracy and/or the ability to handle moderate amounts of r–f power is important. A summary of performance statistics on a group of medium power (40 KW. peak, 600W. average) S–Band rotary–field phase shifters is available from the literature [6]; these units operated with typical rms phase errors on the order of 0.75° and average insertion loss around 0.35 dB.

As with most human endeavor, arriving at a hardware realization of the rotary–field phase shifter was achieved only after dealing with a host of design parameters, each of which had to be optimized to some degree, in many cases compromising other parameters. In the original production design for the AWACS antenna, much of the optimization was done empirically, because of the novelty of the approach, the effective lack of computational models, and the program schedule demand for a timely solution. The success of that effort is measured by the fact that the design still remains at the state–of–the–art with respect to performance, and that virtually all of the hardware items delivered have remained in service without failure, in some cases for a period now exceeding twenty years. While r–f characteristics have not been substantially improved, understanding of the design considerations has increased very greatly, and some simple computational models have been developed for predicting the performance of trial designs. The material presented below discusses a few selected topics affecting performance, and also reviews the extensions in device application at lower frequencies and higher power levels that have recently been achieved through the use of filter–like geometries of alternating ferrite and ceramic dielectric disks in place of the simple ferrite rod half–wave plate.

II. Basic configuration

The basic configuration of the rotary–field phase shifter is sketched in Figure 1, and consists of a central ferrite cylinder which completely fills a circular waveguide and which is coupled at each end to ceramic dielectric assemblies that inhomogeneously fill the waveguide. These dielectric quarter–wave plate sections act to convert linear polarization incident at either end into circularly polarized TE_{11} mode waves at the ends of the ferrite half–wave plate section. Beyond the dielectric quarter–wave plates are transducers coupling the circular waveguide to single–mode rectangular guide, and at the same time absorbing any energy cross–polarized to the propagating wave orientation. Outside the metallic waveguide wall,

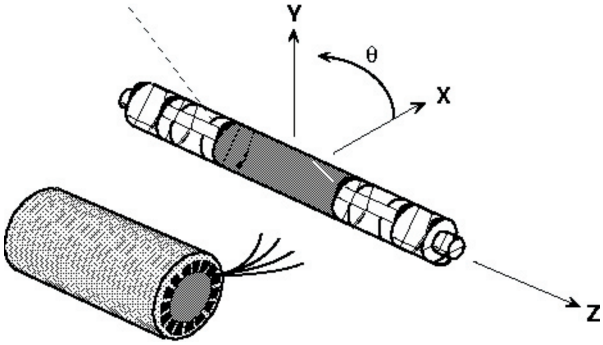

Fig. 1. Sketch of internal parts of a typical ferrite rotary–field phase shifter, showing drive stator with ferrite rod, dielectric quarter–wave plates, and transducers prior to metallization.

but in close proximity to the ferrite, is placed a frame that resembles a motor stator in its physical form, containing "sine" and "cosine" windings. Each winding produces a transverse fourpole magnetic field in the ferrite rod, and the windings are interlaced such that the principal axes of the fourpole bias field can be rotated to any arbitrary angle by proper setting of the currents in the two windings. Ideally, the sine winding is arranged to produce a radial magnetic field B_s around the periphery of the rod with a dependence

$$B_s = B_{s0} \sin(2\theta) \tag{1}$$

with the cosine winding field B_c as

$$B_c = B_{c0} \cos(2\theta). \tag{2}$$

Now define the electrical angle ϕ and let the magnitudes of B_{s0} and B_{c0} vary as $B_0 \sin(\phi)$ and $B_0 \cos(\phi)$, respectively. Neglecting nonlinear magnetic effects, the superposition of the fields for the two windings will be

$$B = B_0 (\sin(\phi)\sin(2\theta) + \cos(\phi)\cos(2\theta))$$

$$B = B_0 \cos(2\theta - \phi). \tag{3}$$

Thus a change ϕ_a degrees in the electrical angle parameter will cause a mechanical rotation of the ferrite half–wave plate fourpole transverse magnetic bias field by $\phi_a /2$ degrees. Since the r–f insertion phase changes by twice the rotation angle of the half–wave plate, it follows that changes in the winding current distribution angle parameter ϕ correlate exactly with the (r–f frequency independent) microwave insertion phase angle changes.

In its present realizations, the rotary–field phase shifter has a number of advantageous features, as well as a few noteworthy drawbacks. On the positive side are the excellent phase accuracy and high power handling noted above. The phase accuracy is a consequence of the fact that small internal errors in the quarter–wave plate and half–wave plate differential phase values mainly cause energy to be coupled at the output of the structure to a cross–polarized wave, which is absorbed in the transducer. Also, because the amount of ferrite needed is only enough to produce 180° of phase difference, the unit is capable of attaining low insertion loss. Low r–f power dissipation plus good heat transfer by conduction through the metal drive stator allow moderate average power handling without excessive temperature rise. The peculiar modulo–360° operation allows phase to be changed continuously and without limit in the same direction, so that small frequency offsets can be produced. (It is tempting to imagine phase shifters operating on the principal of altering the propagation constant in a structure as being analogous to a rubber band, in which only limited excursion is possible between the end points; in contrast, the rotary–field phase shifter would be analogous to a wheel, capable of traversing any desired distance.) Negative factors are the need for continuous biasing current, the significant size and weight of the drive winding stator, the bandwidth limitations resulting from frequency dispersion of the differential phase of the ferrite half–wave plate, and the difficulty of switching the bias field through the waveguide wall because of induced eddy currents. From elementary motor theory, the control power needed to develop a given mmf for the bias field is inversely proportional to the weight of copper in the windings, and therefore the stator size and weight are reduced only at the penalty of higher drive power. While steps can be (and are) taken to decrease the required mmf by reducing the demagnetizing effects of the air gap between the stator and the ferrite rod, the lowered mmf is attained only at the expense of greater hysteresis in the phase shift output (more about this phenomenon later). The eddy current problem can be reduced to an acceptable level by sputtering a thin film metallic waveguide wall directly onto the ferrite rod, allowing practical switching in 100μsec. or less to be achieved.

III. Phase error considerations

It is useful to classify phase errors, i. e. deviations of the actual insertion phase change from the commanded change, into four categories:

i. single cycle, in which the deviation forms a sine wave whose period equals 360° of command range,
ii. double cycle, in which the deviation forms a sine wave whose period equals 180° of command range,
iii. fast ripple, in which the amplitude of the deviation is irregular and the number of ripples increases in proportion to the number of teeth in the drive stator, and
iv. hysteresis, in which the insertion phase values for continuously increasing and continuously decreasing commands differ by a constant offset.

Figure 2 shows prototypes of these various error classes.

While the desired bias field is that of an ideal transverse fourpole, the actual distribution will deviate from ideal because of material inhomogeneities, because of misalignment between the drive stator and the ferrite rod, and because a finite number of stator slots are used for layup of the sine and cosine windings. The value of

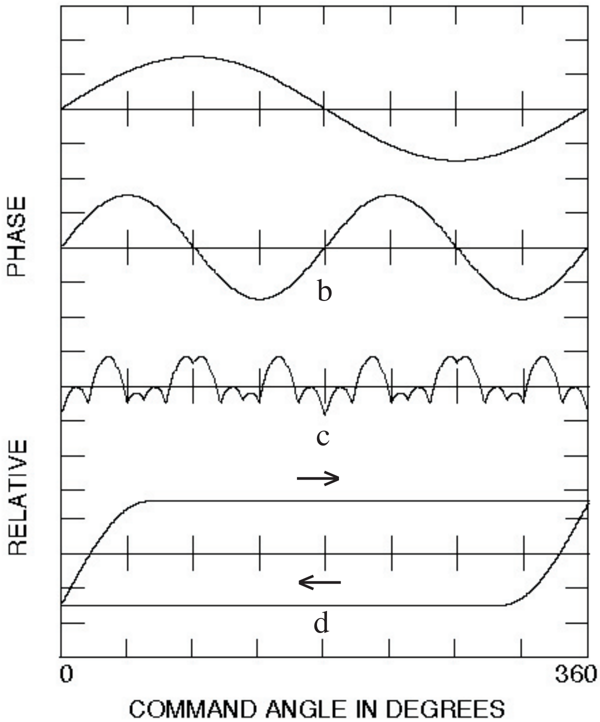

Fig. 2. Classification of microwave phase deviation from ideal control characteristics: a – single cycle; b – double cycle; c – fast ripple; d – hysteresis.

the radial component B_r of magnetic field at the surface of the ferrite may be expressed as a function of angular position θ around the rod circumference by a multipole Fourier series expansion:

$$B_r(\theta) = \sum_{n\ even} (a_n \sin(n\theta/2) + b_n \cos(n\theta/2)). \tag{4}$$

Except for the fourpole (n=4) case, nonreciprocal differential phase effects will cancel even when a_n and b_n are nonzero, leaving only the smaller reciprocal phase dependence on bias field amplitude. The fourpole field component has a relatively much stronger interaction with the ferrite and produces a nonreciprocal birefringence, in the sense that the principal axes of the differential phase are shifted by 90° between the two directions of propagation. Since insertion phase changes depend on the direction of rotation of the half–wave plate, the nonreciprocal nature of the interaction between the bias field and the ferrite rod does not alter the sense or reciprocity of phase changes. The primary consequence of the nonreciprocity is that in an ideal device the insertion phase of one direction of propagation always differs by 180° from the other.

The design, fabrication, and alignment of the drive stator are key to achieving low phase shift error. In general, the essential requirement is that the amplitude of the fourpole bias field should be kept as nearly constant as possible as the pattern is rotated in the transverse plane. Avoiding fourfold symmetry in the slot configuration and using a reasonably large number of slots both help in attaining this goal. Stators with eleven, thirteen, fifteen, and seventeen slots have been successfully employed in rotary–field phase shifter designs, the lesser numbers being important for higher frequencies of operation where the ferrite rod diameter becomes so small that the required tooth width for fifteen or seventeen slots is impractical. In addition, the winding pattern must be carefully selected to minimize amplitude variation of mmf as a function of command angle. Because each slot must contain an integral number of wires, a "quantization" error may occur, especially when the windings have few turns; choosing a poor winding pattern can lead to unfavorable levels of double cycle and fast ripple phase deviation. Most of the winding distributions of interest for stators of 11, 13, 15, and 17 slots have been mapped as the result of computer searches of the mmf amplitude variation over 360° of field rotation in 1° steps for incrementally increasing numbers of turns per magnetic pole. Albouy independently studied the winding problem at Thomson–CSF in Malakoff, France and noted [7] that mechanically shifting the orientation of a magnetic pole of the sine and cosine windings ±22.5° from the center of a stator tooth yields identical distributions for the two windings (displaced, of course, by 45°). This arrangement usually does not provide the smallest amplitude variation of the mmf versus field rotation, but the suggestion did stimulate incorporating the angular orientation of the winding magnetic poles to the stator slots as a parameter in the computer search for optimum distributions.

Hysteresis and single cycle error are associated with imperfections in the ferrite rod portion of the assembly. Any inhomogeneity that is localized with respect to a particular mechanical angle or angular region of the ferrite rod may cause single cycle error. Examples are lack of concentricity between the drive stator and the rod, localized porosity, cracks, or voids in the rod material, or even a break in the sputtered waveguide wall. Hysteresis arises from residual magnetization in the rod material, which causes the fourpole field pattern to be "dragged" along somewhat behind the forcing mmf pattern. As the demagnetizing effects of the air gap are reduced to minimize the control power needed to operate the phase shifter, the amount of hysteresis will increase. As long as the phase changes always occur in the same direction, the phenomenon of hysteresis will not affect the phase accuracy of the device; the discussion on switching below addresses techniques for achieving this condition. Finally, impedance mismatch at the various interfaces in the phase shifter will also produce double cycle phase error as a consequence of cancellation and reinforcing of reflections as the phase settings are changed.

It is evident from the discussion above that many potential sources exist for introducing error into the phase shift characteristics. Nevertheless, with careful attention to the design, fabrication, and assembly of rotary–field phase shifters, and with the fortuitous circumstance of obtaining ferrite material that is free from imperfections, it is possible to attain excellent phase accuracy. Figure 3 shows measured data on two different S–Band rotary–field phase shifters, one with mediocre and one with outstanding phase accuracy characteristics.

IV. Switching considerations

The sine and cosine winding distributions usually do

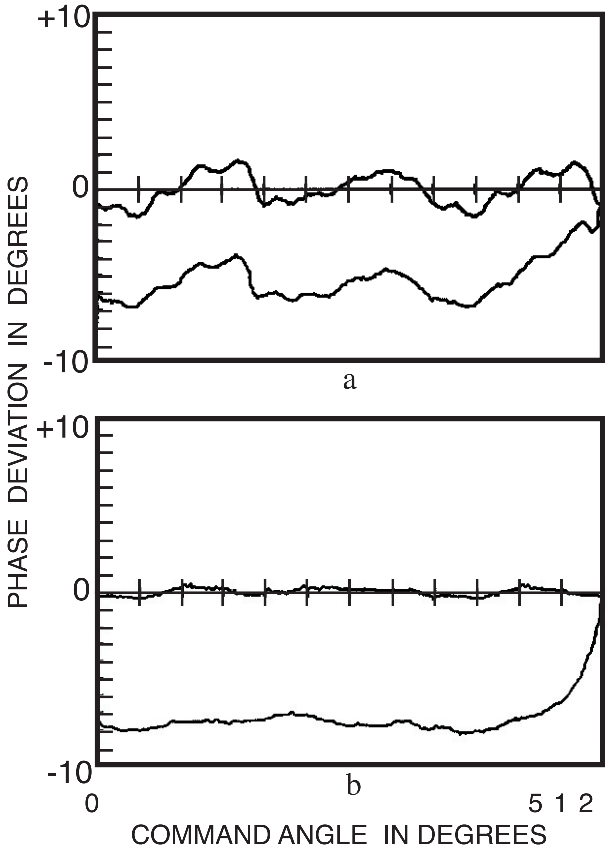

Fig.3. Phase deviation from commanded phase for two different S–Band rotary field phase shifters: a – mediocre performance; b – excellent accuracy. The reverse traces for commanded angles from 512° to 0° show the effect of hysteresis.

not contain more than a few hundred turns of fairly heavy (AWG 26–34) magnet wire each. Consequently the winding resistance will be in the range of several ohms to tens of ohms. The operating currents I_{sin} and I_{cos} to command a microwave angle setting of ϕ degrees will, from equation (3) above, be of the form $I_{sin} = I_{max}\ sin(\phi)$ and $I_{cos} = I_{max}\ cos(\phi)$, where I_{max} depends on the specific design but is typically in the range of 0.5 to 2.0 amperes. Under quiescent (nonswitching) conditions, the voltage V_{qmax} needed to maintain I_{max} current in a winding will be simply I_{max} times the winding resistance. The winding parameters are usually adjusted so that V_{qmax} will have a convenient value in the range of 8 – 10 volts. The need for both positive and negative supply voltages can be removed by placing the winding terminals in a bridge circuit, as shown in Figure 4. Here four low–power switching transistors control the direction of current flow, while the single high–power "pass" transistor controls the amount of current.

Under switching conditions, the time rate of change of the magnetic flux produced by the windings will be proportional to the available voltage, i. e. the voltage at the winding terminals after accounting for the resistive voltage drop. In order to achieve switching times in the 100μsec. range, it is necessary to impress a much larger voltage than the quiescent supply across the terminals of the windings, but only for the duration of the switching operation. A simple circuit of the configuration shown in Figure 5 has been used to "boost" the supply voltage during switching operations. Between switching operations, energy from the quiescent supply is stored in a capacitor C1 that is decoupled from the supply by a resistor. During the switching operation, transistor Q1 changes state from "open" to "closed", impressing nearly the full supply voltage across the primary coil of a ferrite toroid transformer that is initially set to full negative remanent magnetization. The applied voltage drives the toroid flux toward positive remanence, and causes a much larger voltage to appear across the transformer secondary winding, which has about four times the number of turns as the primary winding. This secondary voltage is connected in series with the quiescent supply voltage, and the combination drives the phase shifter windings. The ferrite transformer is designed such that the switching pulse ends before the condition of full positive magnetization is reached. At the end of the switching operation, transistor Q1 is opened, and the ferrite transformer secondary voltage drops below the quiescent supply voltage, then performs one half cycle, through negative values, of free oscillation at a frequency determined by the winding inductance and the combination of capacitor C2 in parallel with the interturn capacitance of the winding. This oscillation effectively resets the ferrite magnetization to the initial negative remanence state, ready for the next switching operation. As the secondary voltage attempts to oscillate into positive values, it is clamped to the quiescent supply voltage level and the oscillation ceases. With proper sizing of component values as well as the ferrite core magnetic properties, cross–section, and wire gauge, the "boost" circuit permits faster switching

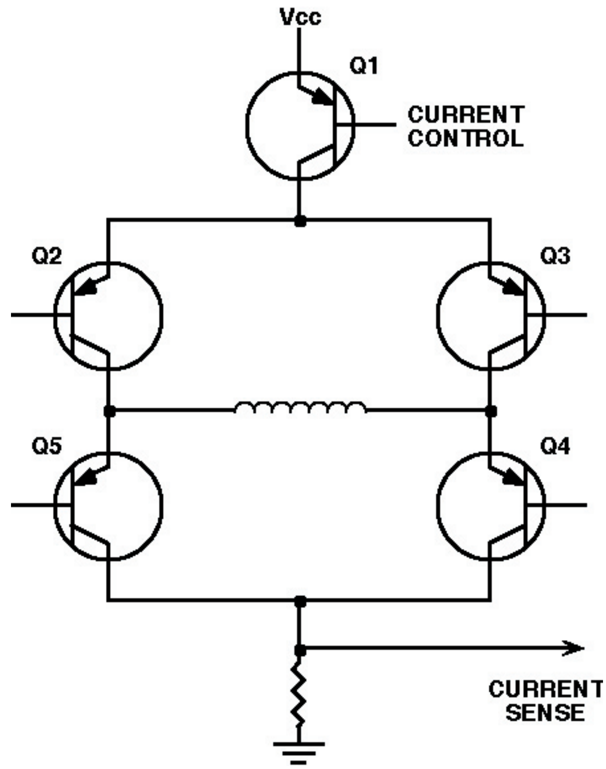

Fig.4. Bridge arrangement for controlling phase shifter winding current. Q1 is a "pass" transistor, Q2 – Q5 are switches. With Q2, Q4 ON and Q3, Q5 OFF, current flows from left to right; Q2, Q4 OFF and Q3, Q5 ON causes flow from right to left.

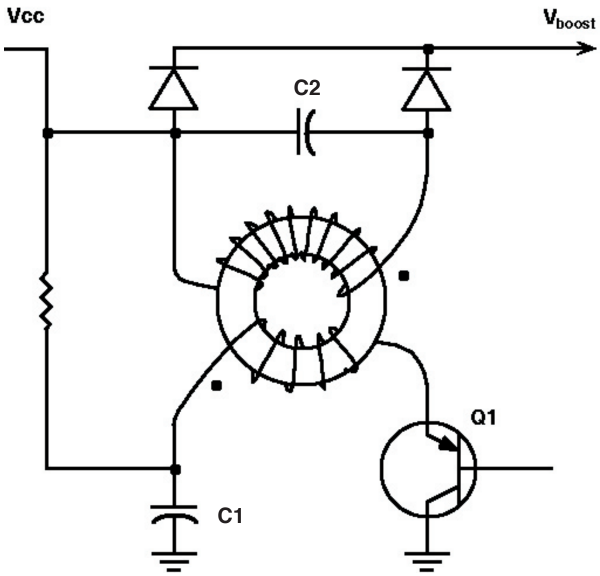

Fig. 5. Boost circuit for increasing the supply voltage during switching operations.

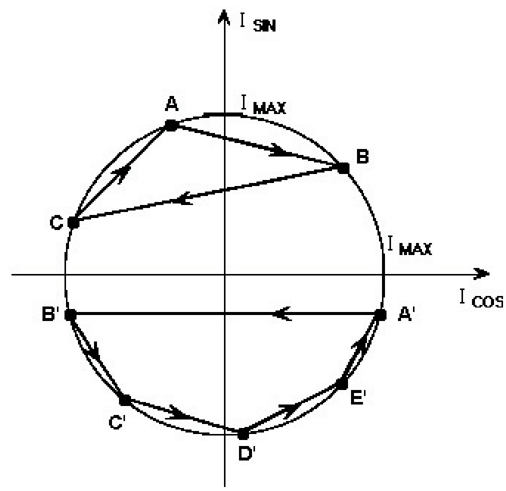

Fig. 6. Current trajectories during switching operations. Segments B→C→A illustrate hysteresis removal via two–step switching. Segments B'→C'→D'→E'→A' provide low insertion loss during the entire transition in case of "hot" switching.

without the necessity of additional power supplies or additional "pass" transistors.

As indicated above, bias field changes should be restricted to rotation in only one direction in order to remove the effect of hysteresis. In practice, this requirement is implemented by carrying out switching operations as a two–step process. Experience has shown that a rotation of the transverse fourpole bias field through a mechanical angle of about thirty degrees is sufficient to remove past history of the ferrite magnetization, and to ensure that the end state corresponds with one of the limits of the hysteresis characteristic. Therefore a two–step switching operation, in which the first step commands an electrical angle sixty degrees away from the final angle, and the second step commands the final angle, always arriving from the same direction, effectively removes hysteresis error from the microwave phase shift. The process is sketched in the upper part of Figure 6. This figure graphs the values of the sine and cosine winding currents, and shows the locus of quiescent operating points as the circle defined by $I_{sin}^{\ 2} + I_{cos}^{\ 2} = I_{max}^{\ 2}$. If the two winding currents are assumed to change at a linear rate and arrive at the end values simultaneously, the transition will follow a trajectory that lies along the chord connecting the two points on the circumference of the circle. Taking the direction of A→B as the standard, a two–step transition from B to A would be carried out with C as the intermediate point. Note, incidentally, that the locus of values for the quiescent currents implies that since the sine and cosine windings have about the same resistance, the quiescent control power is essentially independent of the angle setting.

The final discussion point on switching involves the microwave state of the phase shifter during the actual transient. Consider the transition A'→B' as shown in the lower part of Figure 6. In this case the sine current is held constant and the cosine current reverses direction between the start and end states. During the transition, the cosine current changes through zero, and at that point the bias field is much smaller than the amount needed to produce 180° of differential phase in the ferrite; consequently there will be a large component of cross–polarized energy at the output of the phase shifter and the insertion loss will increase significantly. This transient increase of insertion loss may be detrimental in the case of "hot" switching, i.e. switching while microwave power is being transmitted through the phase shifter. In particular, damage could be caused to the absorber of the cross–polarized wave if a large amount of power was incident as a result of a high switching rate and/or high peak power levels. Switching in smaller steps, as shown by the transition segments B'→C'→D'→E'→A' in Figure 6 keeps the bias field near the quiescent level throughout the switching operation and thereby eliminates the transient condition of high insertion loss. Figure 7 shows traces of the co–polarized and cross–polarized wave amplitudes as a function of time during switching operations corresponding to those described above. It is clear that the multi–step approach eliminates the loss "spike".

V. Periodically loaded ferrite sections

Conventional ferrite rotary–field phase shifters can be built to operate over bandwidths of about fifteen percent, at center frequencies extending from about 3 GHz. to 20 GHz. Below this range the diameter of the ferrite rod becomes uncomfortably large; for example, a conventional design centered at 1.3 GHz. would require a ferrite rod with a diameter of about 2.4 inches (6.1 cm.). The diameter can be reduced to practical dimensions through the use of a ferrite section that is periodically loaded with ceramic disks of high dielectric constant material. The ferrite is also shaped into disks, and the dielectric and ferrite sections alternate, the relative thicknesses chosen to provide a filter–like structure that propagates with low insertion loss in the desired frequency region. The general approach

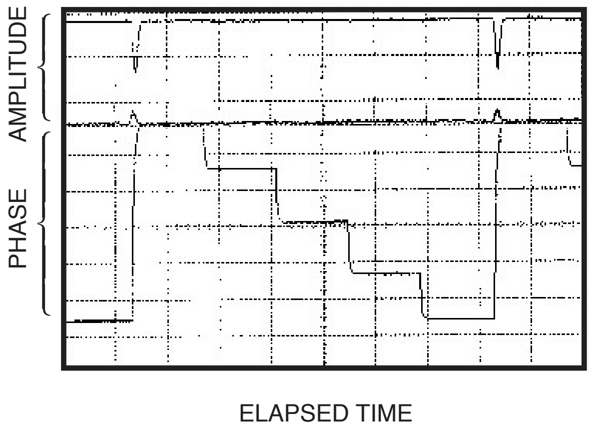

Fig. 7. Transient conditions for single step and multiple step switching. The upper trace shows the burst of energy coupled to cross–polarized output, the middle trace shows the corresponding increase of insertion loss (amplitude increases from top to bottom in these traces). The lower trace records the values of microwave phase setting, with a large step in phase causing a large transient coupling to cross–polarized output. The "staircase" multiple step switching back to the start point does not display significant cross–polarized output.

is illustrated by the sketch of Figure 8. The drive stator has the same form as that of a conventional rotary–field unit, and because both the biasing magnetic field and the ferrite–dielectric segment boundaries are transverse, no angle–dependent distortion of the fourpole bias field occurs. With the use of materials having relative dielectric constant on the order of 80, the diameter can be reduced to about half the value of a conventional solid ferrite rod design. A unit operating at the 1.3 GHz. band was reported in 1990 [8], and produced phase errors on the order of ±1° with an insertion loss below 1.0 dB.

Another use for periodic loading of the ferrite section is to increase the average power handling of the phase shifter type. Hord [9] studied a geometry in which ceramic disks of higher thermal conductivity were used as spacers between ferrite disks. Because the heat generation is primarily caused by magnetic loss in the ferrite, this approach has the benefits of spreading the loss over a longer waveguide section as well as providing a path for extraction of heat from the planar ferrite disk surfaces. In an experimental S–Band device, Hord was able to operate continuously at an average microwave power level of 3000 W. with forced air cooling; this compares with a maximum value of 800 W. average power for conventional air–cooled units. Furthermore, Hord's measurements indicated that the thermal gradients within his design were smaller than those of a solid ferrite rod by a factor of one–fourth to one–fifth. These results were achieved with no appreciable increase of insertion loss or phase error with respect to conventional (i.e. solid ferrite rod) rotary–field units operating in the same frequency band.

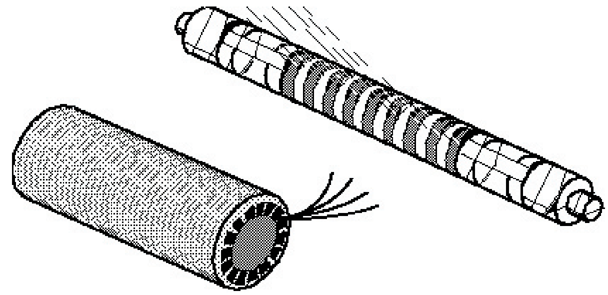

Fig. 8. Sketch of internal parts of a rotary–field phase shifter with periodically loaded ferrite section, prior to metallization.

VI. Acknowledgment

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