IV-3. FERRITE DIGITAL PHASE SHIFTERS

D. R. Taft, J. W. Simon, and J. D. Sweeney

Sperry Microwave Electronics Company, Clearwater, Florida

Recent phased array system requirements for fast switching, latching type phase shifters have prompted considerable interest in the non-reciprocal ferrite phase shifter using a toroidal geometry. The use of the toroidal geometry permits the ferrite to be permanently magnetized in the circumferential direction by passing a current pulse through the toroid. The basic ferrite and driving configuration are shown in Figure 1.

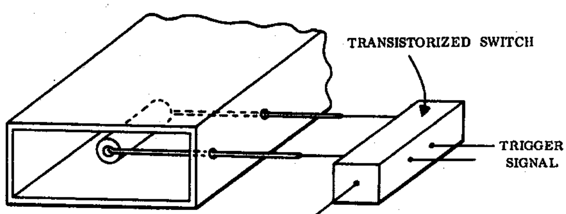

Figure 1. Basic Toroidal Ferrimagnetic Core in Rectangular Waveguide with Typical Switch Configuration

The single turn of wire coaxial to this tube provides a path for the current pulses which magnetize the ferrite to either of two remanent states, ($+M_r$ or $-M_r$). Corresponding to these states are phase shifts $+\phi_r$ and $-\phi_r$ and their difference, $\Delta\phi_r$, which represent the differential, phase shift of the ferrite "bit." In this device several bits of different electrical length can be used in cascade to achieve step variable, or digital, phase shift by activating the appropriate combination of bits; the other bits are left in the inactive or "reference" state.

Of great importance in the development of a ferrite digital phase shifter are the properties of the ferrite material, as well as the characteristics of the electronic driver used for switching between the two states. This paper defines the problems in each of these three general areas (ferrite material, phase shifter, electronic driver), and describes the efforts and results required for their respective solutions.

Materials from the garnet family $3\left[(1-x)\,Y_2O_3\cdot xGd_2O_3\right]\cdot 5\left[w A\ell_2O_3\cdot(1-w)\,Fe_2O_3\right]$ have been investigated for use in relatively low power latching type digital phase shifters. At room temperature, as x and w varied from 0 to 0.30, the electrical properties of these materials varied in the following manner:

Saturation Magnetization	$(4\pi M_s)$	- 1780 to 500 Gauss
Resonance Linewidth	(ΔH)	- 33 to 200 Oersteds
Remanence Ratio, R_r	(B_r/B_s)	- 0.90 to 0.65
Coercive Force	(H_c)	- 0.50 to 2.00 Oersteds
Switching Constant	(S_w)	- 0.50 to 1.00 usec-Oersted

By proper choice of x and w, some of these properties can be made quite insensitive to temperature and power variations over wide ranges. It was found that, although H_c and R_r tend to undergo large unfavorable changes with x and w, they could be controlled by increasing the average size of the crystallites. The ceramic processing techniques found to improve the square loop properties most have been longer ball milling times and high temperature annealing after machining of the ferrites.

The parameters affecting the selection of $4\pi M_s$ and linewidth are shown in Figure 2. The factor Y depends upon squareness because of domain formation and line broadening in the remanent state, and has been estimated to be approximately 3.

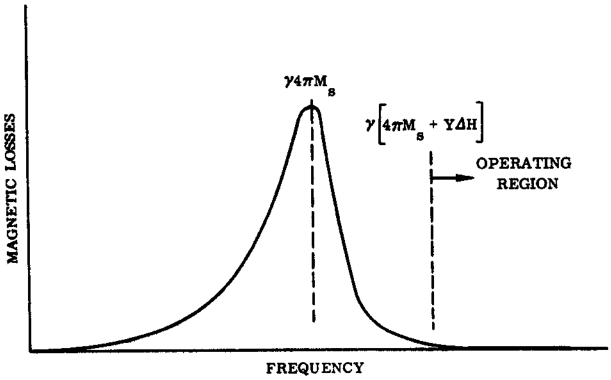

Figure 2. Criterion for Selection of $4\pi M_s$

For phase shifters in the indicated operating region, the conditions for subsidiary resonance are of primary concern. This subsidiary resonance which increases very abruptly above the threshold power level will deteriorate phase shifters by increasing their insertion loss. Nonlinear effects associated with resonance may also be troublesome in some cases at the lower frequencies. The resonance peak generally broadens above the threshold which could cause changes in the amount of phase shift obtained as well as increase the insertion loss of the device. These effects can be substantially reduced by properly choosing the ferrite compositions. The series of tests shown in Figure 3 illustrates the effectiveness of small substitutions of dysprosium in a material used in an S-band high power phase shifter. Similar results have been observed in C- and X- band. The improvements in power capacity were achieved without materially affecting the other microwave characteristics of the phase shifter.

The power consumed in the ferrite core by switching it once around the hysteresis loop (assuming a square loop) can be calculated on the basis of the area within the loop and is:

$$P \text{ (watts)} = 4 H_c M_r V R \times 10^{-7},$$

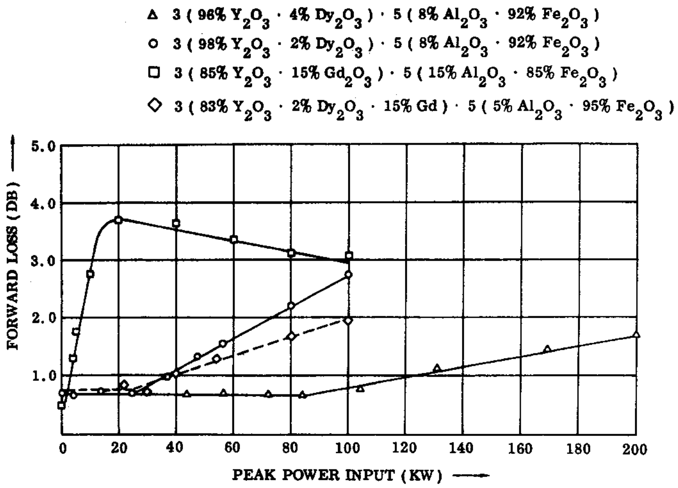

Figure 3. Insertion Loss versus Peak Power for S-Band Phase Shifter (2.9 gc)

where

H_c = the coercive field in oersteds

$4\pi M_r$ = remanence magnetization in gauss

V = volume of the core in cm^3

R = switching rate in cps.

Therefore, from a switching standpoint, H_c, $4\pi M_r$ and core volume should be as low as possible, consistent with the desired microwave operating characteristics. Typical H_c and $4\pi M_r$ values derived at Sperry for operation in C-band yield an energy product of 150μ joules per switching operation for 180 degrees of differential phase shift.

A typical circuit used for switching the ferrite toroids is shown in Figure 4. The positive gate pulses fire the left bank of transistors and cause current to flow through the toroid in the downward direction. Similarly, negative gate pulses fire the right bank of transistors which causes current to flow upward. Current flows only during the gate pulse. Transistors are presently available which switch 15 amperes in less than 0.5μ seconds. It has been experimentally determined that 15 amperes through one turn is sufficient to saturate most materials and geometries used in C- and X-band. This, of course, is dependent upon having materials with reasonably low coercive fields ($H_c < 0.8$ oersteds).

The switching magnetic interaction between the ferrite bits has been found to be minimized by forming the charging wire so as to "enclose" the in.ended bit. A further reduction in interaction can be obtained by spacing the bits so that stray fields are too weak to disturb the "unintended" bits. A spacing of 0.050 inches was found to be adequate at C-band.

The ferrite geometry found to give best results was a rectangular toroid placed at the center of a reduced width waveguide. The width is reduced in order to suppress the propagation of spurious dielectric modes which would give rise to anomalous insertion loss and phase shift peaks. This configuration can be dielectrically loaded in various ways to increase $\Delta\phi_r$, or the filling factor of the toroid itself can be made great enough so that it effectively provides the enhancement necessary to yield a large differential phase shift per unit length. Dielectric step transitions are utilized at the input and

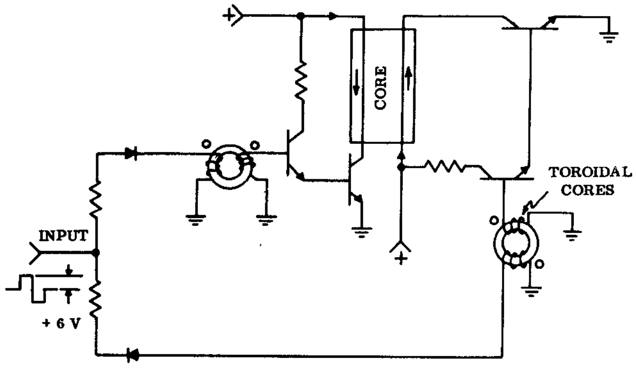

Figure 4. Core Driver Circuit

output of the device which provide approximately a 4:1 transformation ratio. The advantages and disadvantages of other possible geometries are discussed with the idea of forming a basis for choosing a geometry which will be most likely to result in sufficient differential phase shift per unit loss and which minimizes the energy required for switching.

ACKNOWLEDGMENT

This work was sponsored in part by the Advanced Research Projects Agency, Order No. 550, and the Rome Air Development Center under Contract AF30(602)3490. The authors are indebted to the assistance and encouragement of Mr. J. Brown.