Design of Composite Magnetic Circuits for Temperature Stabilization of Microwave Ferrite Devices

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Abstract—**The magnetic flux density of unsaturated microwave ferrites can be made almost constant although microwave ferrite saturation magnetization, coercive force, and hysteresis loop shapes change substantially. Temperature stabilization of flux is achieved by a composite series magnetic circuit consisting of microwave, driver, and flux-limiter ferrites, and a control coil.**

The flux limiter constrains the circuit flux to an almost constant level throughout the operating temperature range, despite large changes in the size and shape of the microwave ferrite hysteresis loop. The driver ferrite supplies the MMF necessary to sustain the flux. Current impulses in the control coil energize and switch the circuit flux.

Estimates of the required lengths and cross-sectional areas of the circuit elements, and of the required switching field and energy for a waveguide remanence phase shifter are given, along with the effects of leakage and fringing fluxes.

Composite circuit techniques have been applied to an experimental remanence phase shifter. Unstabilized, a 16 percent loss of phase shift was incurred as a result of an 80°C rise in temperature. By applying composite circuit techniques, this value was reduced to less than 2½ percent for the same temperature range.

Introduction

THE MAGNETIZATION of most microwave ferrites is sensitive to temperature changes between −50° and 100°C. The transfer characteristics of microwave devices employing ferrite materials depend on magnetization which should therefore be held constant over the operating temperature range.

This paper describes a method of maintaining an almost constant flux level in an unsaturated microwave ferrite, despite large changes in the saturation magnetization and flux density-field intensity (BH) loop shape of the microwave ferrite. A temperature stabilizing circuit[1,2] suitable for microwave devices and, in particular, for remanent phase shifters, is also described. Because BH loops of commercially available microwave ferrites vary as much as 10 percent at a given temperature, a complicated but more accurate design procedure may not be any more precise than the simpler approximations used here.

Because of the deceptively simple concepts of this paper, it appears advisable to describe the topic from three viewpoints. First, the basic principles of composite circuits are described. Second, a graphical (but impractical) analysis of a circuit is given. Third, the design procedure used to build the actual circuits is developed and subsequently used to design a composite circuit for remanence phase shifters.

The major BH loop is defined as the loop obtained with a maximum drive-field intensity of at least five times the coercive force. The remanence flux of a composite magnetic circuit is defined as the flux obtained without control current. This flux level usually does not correspond to the intrinsic remanence fluxes of the magnetic circuit components.

Description

Composite Magnetic Circuit

Figures 1 and 2 show major BH loops of a typical microwave ferrite and of a driver-limiter ferrite at several temperatures. Note that the maximum flux, remanence flux, and coercive force all decline as temperature increases in the garnet, but the maximum and remanence flux of lithium ferrite (Fig. 2) hardly changes in the same temperature range.

In the series magnetic circuit (Fig. 3), flux is limited to a steady value by action of the temperature-stable flux limiter. The driver ferrite supplies the MMF that sustains the remanence flux throughout the circuit. The circuit is energized and switched with current impulses in the control coil. In order to prevent microwave losses, the driver and limiter ferrites and control coil are located external to the microwave circuit.

Flux-limiter action is illustrated (Fig. 4) in a simple composite circuit. The maximum flux of the major hysteresis loops of the microwave and limiter ferrites are shown as functions of temperature. Note the stability of the driver-limiter nickel ferrite flux and the temperature sensitivity of the *S*-band microwave ferrite flux. Since the remanence flux of the series composite circuit is limited to the lesser value of flux at any given temperature, the composite circuit flux is stabilized to the crossover temperature T_s.

For the magnetic circuit (Fig. 4), flux trajectories of the initially unmagnetized driver limiter and microwave ferrites are shown in Fig. 5. As control current is applied, microwave and driver ferrites follow their initial magnetic trajectories to the maximum flux. The microwave element establishes a minor BH loop, and the driver limiter the major BH loop. As the magnetizing current decreases from positive to negative values, microwave and driver-limiter ferrite trajectories extend into the second quadrant. The composite

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[1] E. Stern and A. Christopher, Microwave Chemicals Lab., M.I.T. Lincoln Lab., Lexington, Mass., Subcontract Final Rept. DDC 611557, May 1964.

[2] E. Stern and W. J. Ince, "Temperature stabilization of unsaturated microwave ferrite devices," *J. Appl. Phys.*, vol. 37, p. 1075, March 1966.

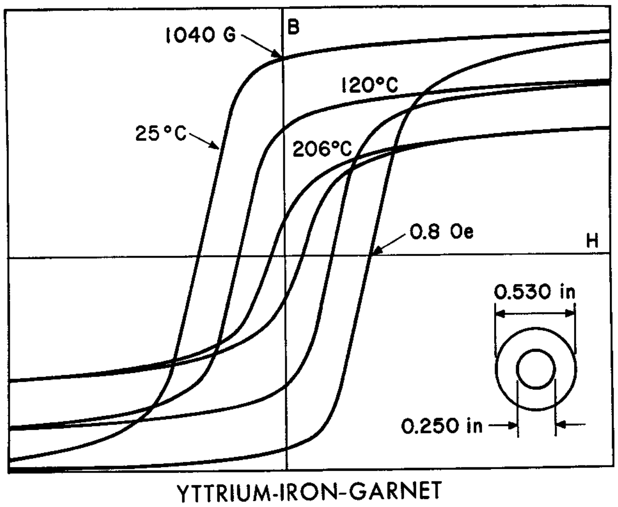


Fig. 1. Major BH loops of a typical microwave ferrite at several temperatures.

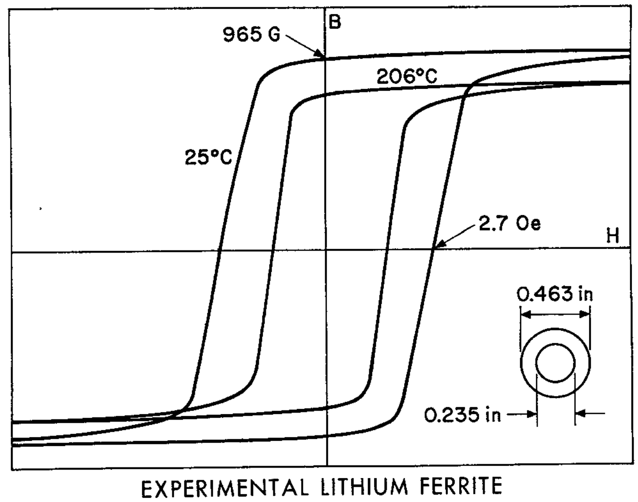


Fig. 2. Major BH loops of a lithium ferrite at two temperatures

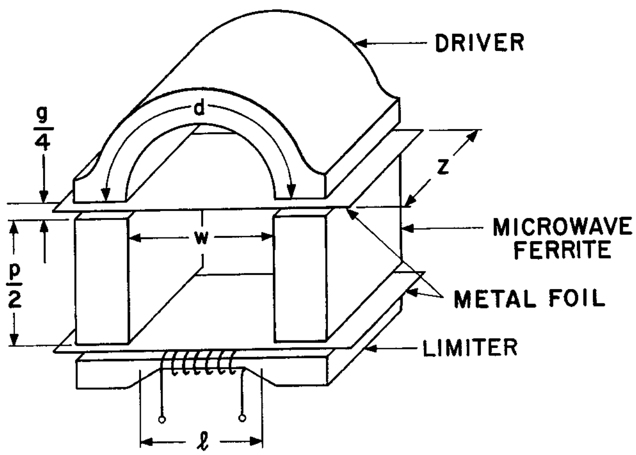


Fig. 3. Composite circuit for remanence phase shifter.

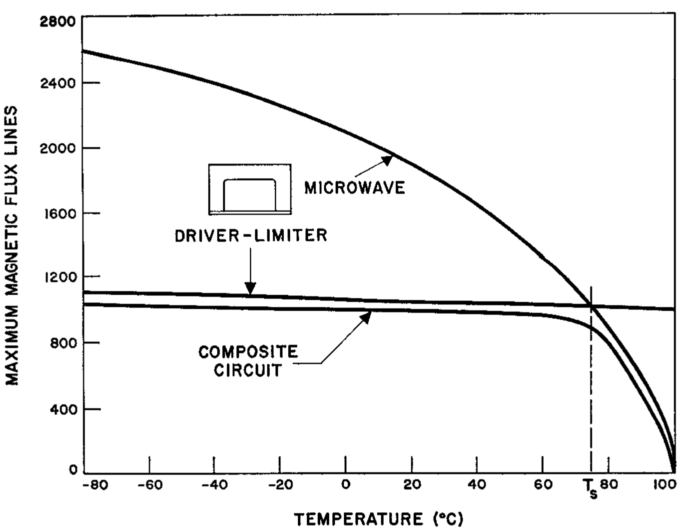


Fig. 4. Maximum flux of the driver limiter and microwave ferrites, and remanence flux of the composite circuit as a function of temperature.

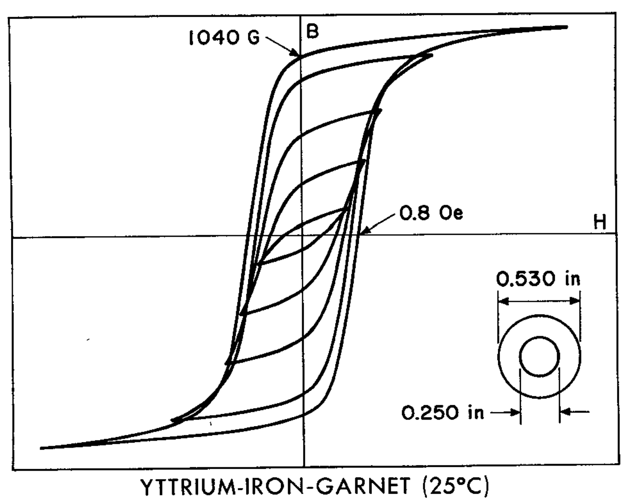
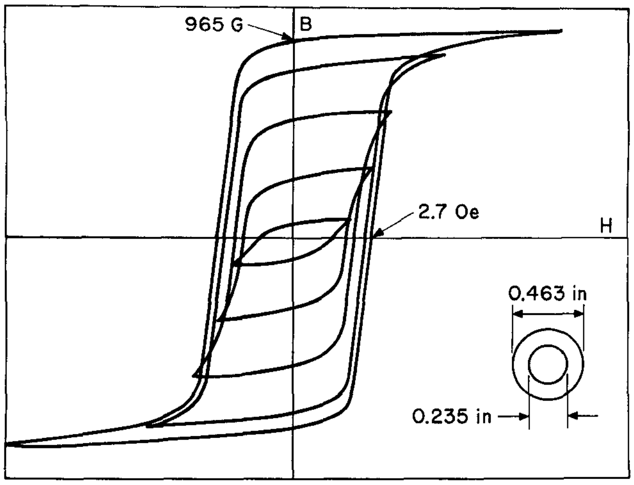


Fig. 5. Minor BH loops of a typical microwave ferrite.



EXPERIMENTAL LITHIUM FERRITE

Fig. 6. Minor BH loops of an experimental lithium ferrite.

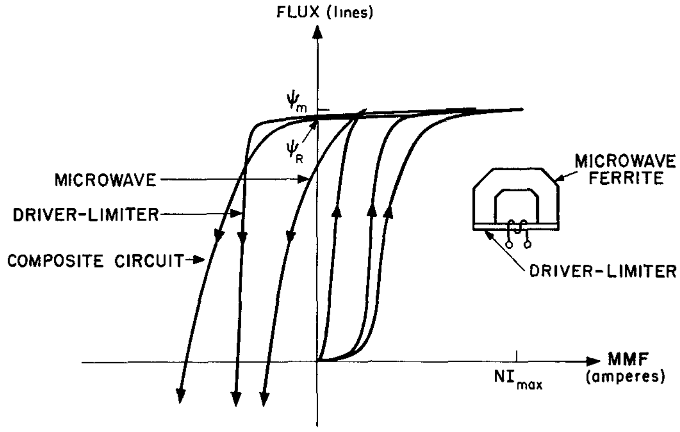


Fig. 7. Composite circuit flux trajectories. The circuit components are initially demagnetized.

circuit trajectory is constructed with the aid of the static field laws, div $\overline{B}=0$; $\oint$Hds$-NI=0$.

Typical examples of major and minor BH loops of microwave and driver-limiter ferrites are shown in Figs. 6 and 7. The major and larger minor loops of the lithium ferrite, a driver-limiter material, are squarer than all loops of the Yttrium-Iron-Garnet (YIG) microwave material. Under these circumstances, the remanence flux of the composite magnetic circuit (ψ_R on Fig. 5) may be substantially higher than the intrinsic remanence flux of the microwave ferrite. This potential increase of flux is frequently desirable in microwave devices because microwave activity is proportional to remanence flux density.

The flux trajectory is drawn for a particular minor loop at a given temperature for the microwave ferrite shown (Fig. 5). As the temperature rises, minor BH loops shrink in step with the major loop (Fig. 1). Therefore, a new graphical solution can be found at every operating temperature by selecting a particular minor loop whose maximum flux matches the maximum flux of the limiter ferrite.

If the driver ferrite is sufficiently long, however, the composite circuit trajectory is determined primarily by the driver ferrite, and relatively minor variations of microwave ferrite trajectories should have little effect on ψ_R, the composite circuit remanence flux. Under these circumstances, the temperature stability of the driver and limiter is imparted to the composite circuit flux. In particular, if the coercive force of the square loop driver material and the major loop maximum flux of the limiter material are insensitive to temperature changes, then the circuit can be made insensitive to temperature changes.

Circuit Design

Circuit Parameters

Because square loop ferrites can support a high level of magnetization in the presence of a negative field as large as the coercive force, an MMF as large as the driver coercive force times the driver length is available to sustain flux across gaps and in the limiter and microwave ferrites. In particular, the driver should develop fields at least as high as the coercive force in the limiter and microwave ferrites such that

$$dH_{CD} \geq pH_{CP} + lH_{CL} + gH_G \text{ amperes,} \tag{1}$$

where H_C is the coercive force and the mean flux path lengths are d, p, l, and g (Fig. 3). Subscripts D, L, and G refer to driver, flux limiter, and air gap. Equation (1) should be satisfied throughout the operating temperature range.

Limiting action is obtained if the major loop maximum flux of the limiter is less than the major loop maximum fluxes of driver and phaser ferrites throughout the operating temperature range. The cross-sectional areas of driver and limiter are selected to achieve limiting action, as

$$LB_{ML} \leq DB_{MD} \leq PB_{MP}\big|_{\min}, \tag{2}$$

where B_M is the maximum flux density of the major loop and L, D, and P are the cross-sectional areas normal to the flux direction.

Because remanence magnetization and BH loop shape in most ferrites are independent of drive field if the applied field is at least $5H_C$, the flux-limiter ferrite should have a field of at least $5H_{CL}$ applied to it. If (2) is satisfied, then microwave and driver ferrites are on minor loops, and the control current (I) required to achieve temperature-stable remanence

$$NI \geq [5lH_{CL} + gH_G + \lambda_D dH_{CD} + \lambda_P pH_{CP}] \text{ ampere-turns,} \tag{3}$$

where N is the number of turns; $\mu_0 GH_G = LB_L$; and the λ's are dimensionless constants. The field that establishes maximum flux of the circuit within a particular ferrite is equal to λH_C. For example, a maximum flux density equal to remanence flux of the major loop is established with a field of 2.3 H_C in a toroid of YIG (Fig. 5).

Because the limiter has a finite permeability μ_L at a field of $5H_{CL}$, current fluctuations produce a corresponding fluctuation of maximum flux density. If the driver and microwave ferrites are on minor BH loops, then most of the circuit reluctance is at the limiter, and most of the MMF drop appears there. The flux density variation

$$\Delta B_L \leq \mu_L N \Delta I / l. \quad (4)$$

Note that flux instability in the presence of control current fluctuations is inversely proportional to limiter length.

The hysteresis energy dissipated per cycle in a ferrimagnet is equal to the area of the BH loop times the ferrite volume. By assuming square loops for all circuit members, the ratio of hysteresis loss of the composite circuit to that of the microwave ferrite is equal to $2dH_{CD}/pH_{CP}$ if (1) is an equality.

Remanence Flux Level

If negligible leakage fluxes and uniform flux distributions are achieved in the series circuit shown in Fig. 3, then the static field equations of the composite circuit remanent state are

$$LB_L' = DB_D' = PB_P' = GB_G' = \psi_R$$
$$lH_L' + dH_D' + pH_P' + gH_G' = 0 \quad (5)$$

where H' is the internal field intensity, and B' is the flux density of the circuit elements during the remanent state of the composite circuit.

As seen in Figs. 5 and 6, the permeability μ_R of minor BH loops in the vicinity of remanence has a relatively constant value independent of minor loop size. Consequently, a reasonable linear approximation of minor BH loops at composite circuit remanence is

$$B' = B_m - \mu_R(H_C - H'), \quad (6)$$

where H_C is the major loop coercive force and B_m is the largest value of fluxing density attained on the given minor loop. The field intensity corresponding to B_m is approximately equal to H_C. When (6) is substituted in (5), the remanence flux of the composite circuit is

$$\psi_R = \psi_M - (1/\mathcal{R})[gH_G + dH_{CD} + lH_{CL} + pH_{CP}], \quad (7)$$

where

$$\mathcal{R} = d/D\mu_{RD} + p/P\mu_{RP} + l/L\mu_{RL} + g/G\mu_{RG}$$
$$\psi_M = LB_{ML},$$

where B_{ML} is the major loop maximum flux of the limiter.

Because it is frequently desirable to have the remanence flux ψ_R as close to the maximum ψ_M as possible, the reluctance $\mathcal{R}$ should be as large as possible. $\mathcal{R}$ of the composite circuit can be increased by selecting square loop driver materials with a low permeability μ_R at remanence. Note that the remanence flux cannot be increased appreciably by increasing the length of circuit members, because both the numerator and denominator of the second right-side term of (7) increase with length.

Leakage Fluxes

One of the principal causes of residual temperature sensitivity of the composite circuit shown in Fig. 3 is leakage flux between the microwave ferrite slabs. For example, the flux leakage ψ_{FP} between the microwave ferrites can be estimated for the remanent state as

$$\psi_{FP} \leq (\mu_0 z/w) \int_0^{p/2} (gH_G/2 + 2yH_{CP} - dH_{CD})dy, \quad (8)$$

where z and w are as shown in Fig. 3.

This leakage flux subtracts from the flux inside the microwave ferrite. Since H_{CD} and H_{CP} usually vary with temperature, a corresponding variation of leakage flux causes a change in microwave performance. If it is assumed that ψ_{FP} emerges uniformly along the microwave ferrite length, then the effective flux inside the microwave ferrite is roughly equal to $LB_{ML} - \psi_{FP}/2$. Consequently, if (1) is an equality, then the ratio of effective microwave ferrite flux over limiter flux is equal to

$$1 - \frac{1}{8} \frac{pz}{w} \frac{\mu_0(dH_{CD} + lH_{CL})}{LB_{ML}}. \quad (9)$$

The leakage flux between the ferrite slabs increases during the magnetizing interval and can be computed by replacing $-dH_{CD}$ with $+\lambda_D dH_{CD}$ in (8). If (1) and (3) are equalities and if $dH_{CD} \gg lH_{CL}$, then the dynamic leakage flux is approximately equal to $-(1+2\lambda_D)\psi_{FP}$. This rather large leakage flux can contribute to the premature saturation of circuit members below T_s.

If leakage fluxes are substantial, an attempt should be made to maintain uniform flux density in each member by tapering the cross-sectional areas appropriately. The leakage flux should be taken into account in (2). For example, in Fig. 3, if a large amount of leakage flux, ψ_{FD}, occurs across the driver ferrite, then the driver ferrite cross section is tapered toward the microwave ferrite, and D of (2) refers to the minimum driver cross section. The maximum driver cross section, equal to $(1+\psi_{FD}/LB_{ML})D$, is at the top of the structure of Fig. 3.

The coercive forces of the driver and limiter materials may be temperature sensitive; consequently, leakage flux varies and, thereby, phaser flux also varies with temperature below T_s. It is desirable to minimize the p/w ratio as much as feasible to achieve as little temperature sensitivity as possible.

The leakage flux across the limiter gap is relatively small in the remanent state and does not contribute directly to temperature sensitivity. It is minimized by distributing the current uniformly about the limiter.

Sample Calculations

The BH loop parameters of ferrites are ordinarily given in EMU (oersted and gauss). However, it is convenient in this example to use the mixed English system of units by multiplying gauss by 6.45 to obtain lines per square inch, and multiplying oersteds by 2.02 to obtain ampere turns per inch. The permeability of free space μ_0 is 3.192 lines per ampere turn per inch.

The composite circuit of Fig. 8 is suitable for X-band phase shifters. In the circuit, the function of driver and limiter have been combined, and the yoke is a magnetically soft, temperature-stable material. The microwave ferrite configuration is dictated by microwave requirements.[3] The magnetic parameters of the circuit elements are

B_{MP} = 9.0 kilolines per square inch at 170°C and at a field of $5H_{CP}$.
H_{CP} = 6.1 ampere turns per inch.
P = 0.05 square inch per running inch.
p = 0.8 inch.
μ_{RP}/μ_0 = 57, $\lambda_p = 2$.
B_{ML} or B_{MD} = 15 kilolines per square inch at a field of $5H_{CD}$.
H_{CD} or H_{CL} = 16 ampere turns per inch.
μ_{RD}/μ_0 = 12, $\lambda_D = 2.5$, $\mu_L/\mu_0 = 5$.
G = 0.10 square inch per running inch.
g = 0.002 inch.

The thickness of the driver limiter is obtained from (2), and

$$L \le PB_{MP}/B_{ML}|170°\text{ C} = 0.05 \times 9/15 = 0.03 \text{ in}^2 \text{ per running inch.}$$

The maximum flux per running inch of 0.03 and 0.033 inch thick driver limiter and of a 0.05 inch thick microwave ferrite slab is plotted as a function of temperature in Fig. 8. Note that a 10 percent increase of limiter thickness reduces the stabilized temperature from 160° to 100°C. In practice, the relevant flux values are not known with sufficient accuracy. It may be necessary to try several limiter thicknesses to obtain the desired temperature stability.

The field intensity in the air gap is

$$H_G = \frac{L}{G}\frac{B_{ML}}{\mu_0} = \frac{0.03}{0.10}\frac{15{,}000}{3.19} = 1410 \text{ ampere turns per inch.}$$

The minimum driver ferrite length is obtained with (1) as

$$d \ge \frac{1}{H_{CD}}[pH_{CP} + gH_G] = \frac{1}{16}[0.8 \times 6 + 0.002 \times 1410] = 0.475 \text{ in.}$$

A length of 0.6 inch was chosen to provide an adequate safety margin.

The minimum applied MMF is defined by (3) so that

$$NI \ge 5lH_{CL} + gH_G + \lambda_p pH_{CP} = 60.4 \text{ ampere turns.}$$

[3] W. J. Ince and E. Stern, "Waveguide non-reciprocal remanence phase shifters," Addendum to *Proc. IEE Internat'l Conf. on Microwave Behavior of Ferrimagnetics and Plasmas*, September 1965.

If current fluctuations of ±5 percent occur in the control coil, it is possible to estimate the variation of composite circuit remanence flux density due to these current fluctuations with (4), such that

$$\Delta B_L \le \mu_0 \times \mu_L/\mu_0 \times 0.05\, NI/l = 3.192 \times 5 \times (0.05 \times 60.4/0.6) = 80 \text{ lines per inch}^2.$$

These 80 lines represent about ½ percent of the circuit flux.

An alternative design might have employed a driver ferrite 0.6 inch long by 0.040 inch thick with a flux-limiter constriction 0.1 inch long by 0.030 inch thick. Under these circumstances, the required MMF would have been reduced to 39.4 ampere turns.

However, a five percent control current fluctuation would have produced a 2.1 percent variation of circuit flux. An estimate of the remanence flux is obtained with (7) such that

$$\mathcal{R} = \frac{1}{\mu_0}\left[\frac{d}{D}\frac{\mu_0}{\mu_{RD}} + \frac{p}{P}\frac{\mu_0}{\mu_{RP}} + \frac{g}{G}\right] = 0.482 \text{ ampere turns per line,}$$

$$\psi_R = B_{ML}L - \frac{1}{\mathcal{R}}[gH_G + dH_{CD} + pH_{CP}] = 450 - 36 = 414 \text{ lines per running inch.}$$

Experimental Verification

The magnetic circuit was built and assembled with 0.0005 inch copper foil between the microwave ferrites and the yoke, and between the driver and microwave ferrites. The gap w between the microwave ferrites was made as large as possible (0.200 inch) to minimize the leakage fluxes. Control current impulses of ten amperes were passed through the six-turn coil to magnetize and switch the circuit. The remanence flux of the composite circuit was measured as a function of temperature and the results are shown in Fig. 8. Note the close correspondence between composite circuit and driver-limiter fluxes to 160°C. The measured remanence flux at 160°C of 396 is close to the predicted value of 414 lines per running inch.

The composite circuit was placed in the microwave structure as shown in Fig. 9. The constraints of the microwave circuit required that w be equal to 0.07 inch. This reduced gap increased the leakage flux, which in turn may account for the droop of the differential phase shift characteristic versus temperature (Fig. 10). Despite the effects of leakage flux, the phase shift loss at 100°C has been reduced from 16 percent to 2½ percent.

An estimate of the maximum possible leakage flux, obtained from (9), indicates that the effective phaser flux can vary as much as 10 percent as a result of flux leakage. This potentially large leakage flux is undesirable. Unfortunately, if w and p are fixed, substantial reductions of leakage flux can only be achieved by reducing the driver MMF. Since the

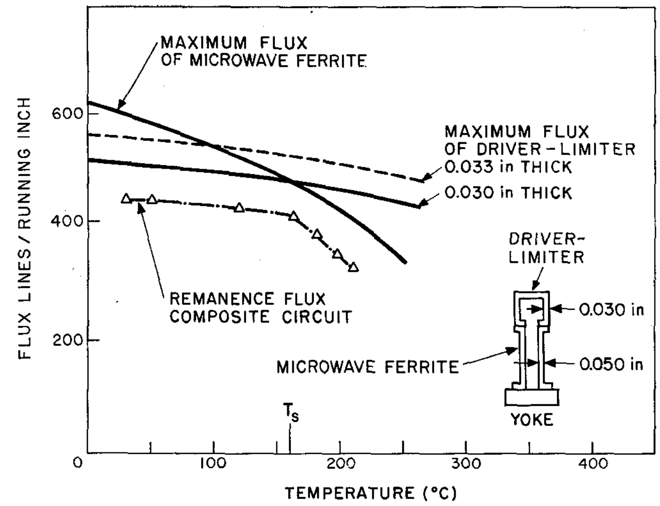


Fig. 8. Flux in magnetic circuit for a composite phase shifter as a function of temperature. The driver is a nickel-cobalt ferrite ($4\pi M_s=3000$ G) and the microwave ferrite is a magnesium-manganese ferrite ($4\pi M_s=2150$ G).

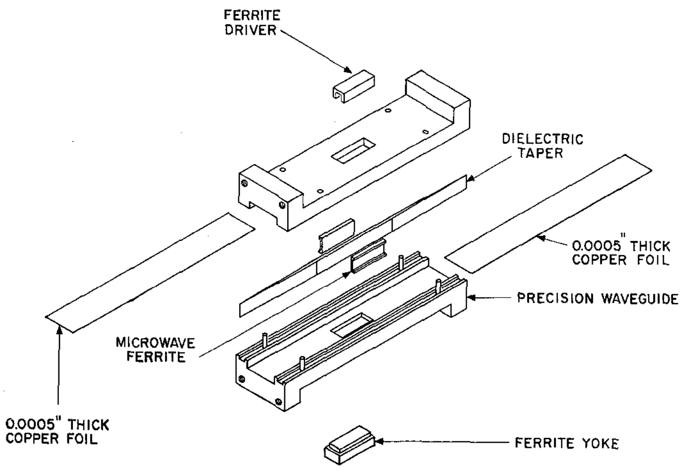


Fig. 9. Composite circuit phase shifter.

required driver MMF is determined primarily by the microwave ferrite [see (1)], a reduction in microwave ferrite coercive force H_{CP} is necessary to reduce the leakage flux.

The composite circuit technique has also been applied to a switching circulator by Betts et al.[4] The composite circuit for the circulator is shown in Fig. 11. The microwave energy is contained within 0.0002 inch tin films. An appreciable amount of switching energy is dissipated in the circulator and phase shifter by eddy currents in the foils if the switching time is less than 10 microseconds. Switching times on the order of a microsecond require higher resistivity foils with attendant higher microwave insertion loss.

[4] F. Betts, D. H. Temme, and J. A. Weiss, "A switching circulator: S-band; stripline; remanent; 15 kilowatts; 10 microseconds; temperature-stable," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-14, pp. 665–672, December 1966.

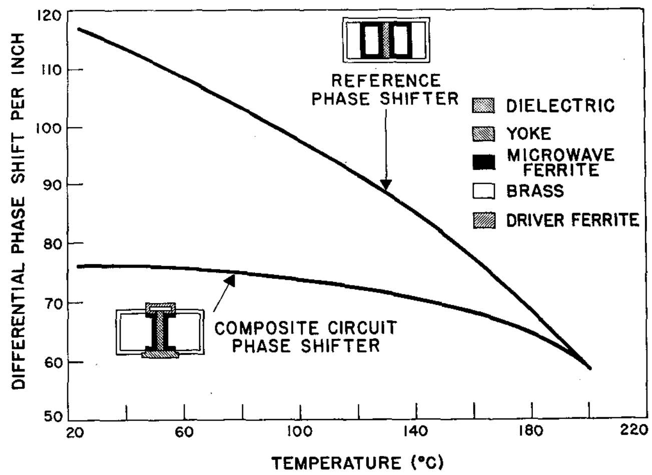


Fig. 10. Phase shift as a function of temperature of reference and composite circuit remanence phase shifter.

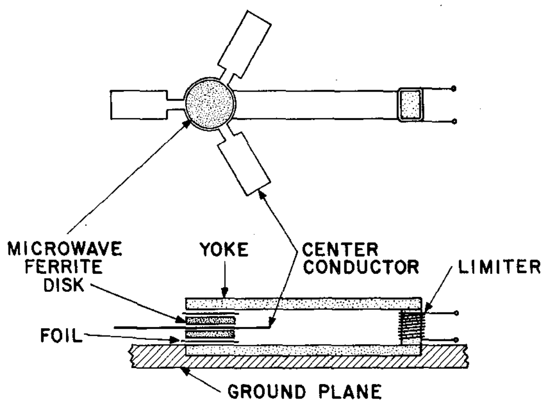


Fig. 11. Composite circuit switching circulator.

Conclusions

Remanent flux can be stabilized over a wide temperature range in composite circuits containing temperature-sensitive microwave ferrites. Although the specific examples used apply to remanence phase shifters and circulator switches, similar techniques can be used to stabilize junction circulators, field displacement isolators, gyrators, and any other microwave device where the microwave ferrite is weakly magnetized and a bi-stable composite circuit can be formed.

Acknowledgment

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