Short Papers

On the Latching of Ferrite Microwave Devices

R. S. MUELLER, MEMBER, IEEE, AND
F. J. ROSENBAUM, SENIOR MEMBER, IEEE

***Abstract*—Empirical relations are given for the hysteresis (*B–H*) loop of microwave ferrite toroids in terms of their measured properties (B_r, B_m, and H_c) and for the trajectory that *B* follows when flux drive latching is used. These relations also apply to minor loop switching. Finally, an idealized analysis of flux drive latching is presented and is shown to compare well with experiments for the number of voltage pulses of fixed width and amplitude needed to reverse the remanent flux.**

INTRODUCTION

The magnetic remanence properties of closed magnetic paths are often used to provide the internal magnetic field needed to bias ferrite phase shifters [1]–[9] and switchable circulators [10]–[15]. In such devices the ferrite is part of the closed magnetic path, often in the form of a toroid, some portion of which interacts with the microwave fields of the device. These components may be characterized as "latching" devices since the internal magnetization of the ferrite may be driven around its hysteresis loop to the desired magnetic state by applying a pulse of current (or equivalently of magnetic flux) [7], [8], and then allowing the magnetization to relax to some remanent (or latched) value.

To date, the design of these devices has been largely experimental owing to the difficulty in modeling the relationship between the drive applied to the ferrite and the resultant latched magnetization obtained. In this short paper an empirical relation for the hysteresis loop (*B–H* loop) of a ferrite is presented along with an analysis of the latching properties of a ferrite phase shifter.

B–H LOOPS

The hysteresis properties of a ferrite toroid are described by the relation between the magnetic induction *B* and the magnetic field intensity *H*. The major *B–H* loop is composed of an upper curve $B_+(H)$, which describes the magnetic state for decreasing field intensity, and a lower curve $B_-(H)$, for increasing field intensity, as shown in Fig. 1, for a typical microwave ferrite, TT1-390.® These curves cross the abscissa at $H = \pm H_c$, the coercive force. For $|H| \gg |H_c|$, the ferrite saturates and the upper and lower curves asymptotically approach the maximum induction B_m. Conventionally, B_m is measured with $H = 5H_c$. If the applied magnetic field is removed, the induction becomes B_r, the maximum remanent induction.

If the ferrite is magnetized along its major hysteresis loop, but not to saturation, it will relax to some value of remanent induction smaller than B_r when the applied field is removed. In fact, any value of remanent induction B_p between $+B_r$ and $-B_r$ can be reached. The toroid is then "latched" at this value. Based on Frolich's equation [16], an approximate expression for the major *B–H* loop can be found in terms of the measured parameters of the given ferrite

$$B_\pm = (H \pm H_c) + \frac{B_m(H \pm H_c)}{\left(\dfrac{B_m}{B_r} - 1\right) H_c + |H \pm H_c|}. \quad (1)$$

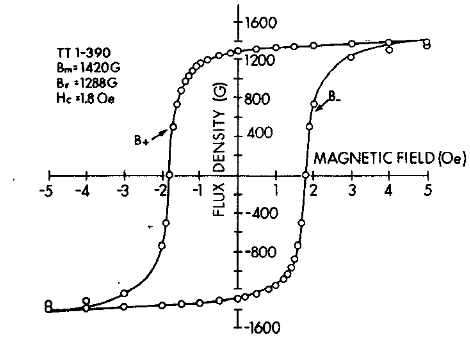

Fig. 1. Major hysteresis loop for microwave ferrite TT1-390, taken from manufacturer's data. Points ⊙ represent approximation from (1).

Values of $B_\pm$ obtained from (1) are shown in Fig. 1 as the circled points using the manufacturer's published data for both the ferrite parameters and the *B–H* loop of TT1-390, a MgMn ferrite. The *B–H* loops of several other ferrites in this family were also found to be in good agreement with the results of (1).

The toroid can be brought to any magnetic state interior to the major *B–H* loop. Approximate contours followed by the induction as a function *H* are given by

$$B_{p\pm} = (H \pm H_{c\pm}') + B_{p\pm}' + \frac{B_{m\pm}'(H \pm H_{c\pm}')}{\left(\dfrac{B_{m\pm}'}{B_{r\pm}'} - 1\right) H_{c\pm}' + |H \pm H_{c\pm}'|} \quad (2)$$

where

$$H_{c\pm}' = \left(\frac{B_r \pm B_p}{B_m \pm B_p}\right)\left(\frac{B_r + B_m}{2B_r}\right) H_c$$

$$B_{m\pm}' = \tfrac{1}{2}(2B_m - B_r \pm B_p)$$

$$B_{r\pm}' = \tfrac{1}{2}(B_r \pm B_p)$$

$$B_{p\pm}' = \tfrac{1}{2}(B_p \mp B_r).$$

The point $(0,B_p)$ is the magnetic induction intercept for both curves $B_{p\pm}$. The approximate contours that are followed for increasing fields, $B_{p-}(H)$, begin on the upper major loop, $B_+(H)$, and curve upward to level off at B_m. Reflecting all these curves through the origin gives the contours for decreasing magnetic field, $B_{p+}(H)$.

With knowledge of the original state of the ferrite, the history of the applied field, and the just-mentioned parametric curves it is possible to trace out a path to its final state. Such a magnetic path is sketched in Fig. 2 which starts from the lowest remanent state at Ⓐ. An initial current pulse applied to the toroid drives the induction along the path Ⓐ Ⓑ. It then relaxes to Ⓒ and remains latched there until a second pulse is applied. The

Manuscript received June 16, 1975; revised January 2, 1976. This work was supported by the Air Force Avionics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, OH, under Contract F33615-72-C-1034.
R. S. Mueller was with the Department of Electrical Engineering, Washington University, St. Louis, MO 63130. He is now with Emerson Electric Co., St. Louis, MO.
F. J. Rosenbaum is with the Department of Electrical Engineering, Washington University, St. Louis, MO 63130.
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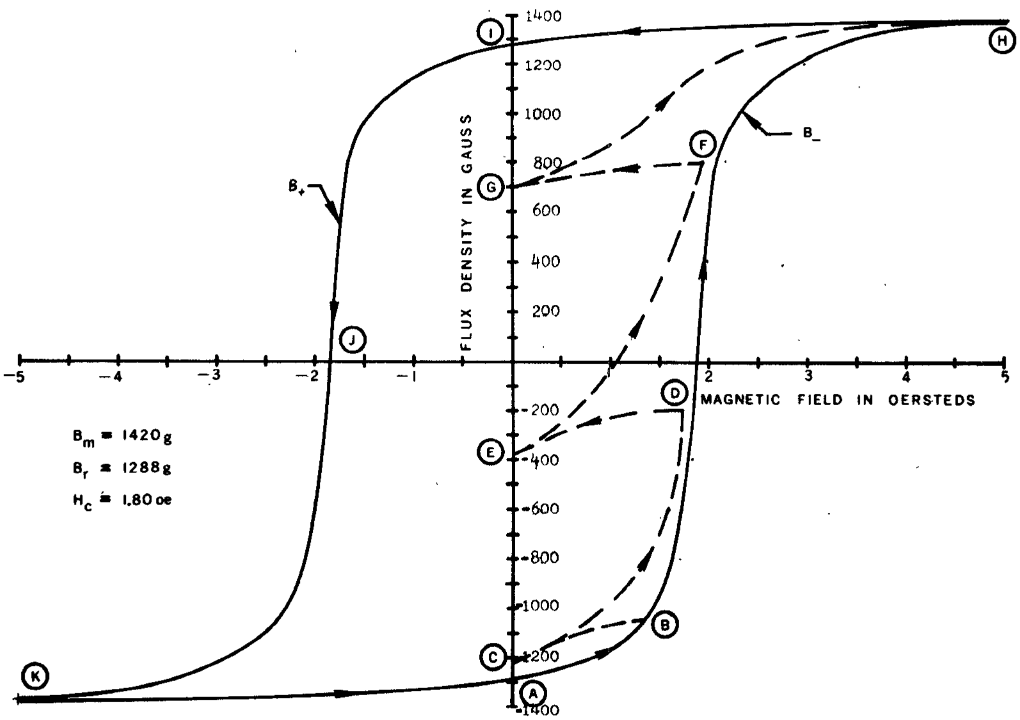

Fig. 2. Hysteresis loop of TT1-390 showing magnetizing path from negative saturation to positive saturation when four current pulses are applied sequentially.

trajectory Ⓒ Ⓓ Ⓔ is then followed. Subsequently, pulses drive the toroid into saturation and finally to the upper remanent state at Ⓘ. A saturating negative reset pulse returns the toroid to A via the path Ⓘ Ⓙ Ⓚ Ⓐ.

Minor hysteresis loops can be described by (2) if symmetrical values $\pm B_p$ and $\pm H$ are used. The temperature performance of latching devices also can be modeled if the temperature dependence of B_m, B_r, and H_c is incorporated in (1) or (2). These quantities are usually presented on manufacturers' data sheets.

Latching experiments were performed with thin rectangular and square toroids of Arc Plasma Sprayed [17] TT1-390 ferrite deposited onto a ceramic backing. Coplanar waveguide [18] (CPW) phase-shifter structures were used to examine the microwave performance of this material [19]. A typical CPW phase shifter is shown in Fig. 3. The dimensions of two experimental structures are given in Table I. The ferrite thickness is b.

The magnetic path length along a constant magnetostatic field line is $2(l_1 + l_2 + 2\pi r)$ where $r_1 < r < r_2$. With N turns wound around one of the legs of the toroid, the magnetic field generated by a current i is

$$H(r) = \frac{0.497Ni}{2(l_1 + l_2 + 2\pi r)} \text{ Oe.} \tag{3}$$

The factor 0.497 allows H to be given in oersteds, i in amperes, and l_1, l_2, and r in inches.

A solution to the latching problem can be formulated as follows. Fig. 4(a) shows a zero impedance voltage pulse generator in series with the coil on the toroid and a current-limiting resistor R. The voltage around the loop is

$$V_t = N\frac{d\phi}{dt} + Ri \tag{4}$$

where the flux through the coil in webers is

$$\phi = 6.45 \times 10^{-8} b \int_{r_1}^{r_2} B\{H(r)\}\, dr \tag{5}$$

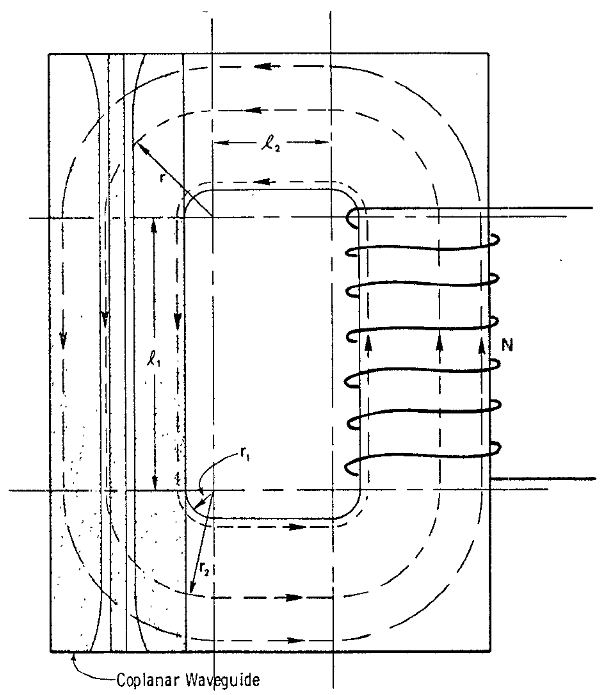

Fig. 3. Ferrite toroid used for the substrate of the coplanar waveguide phase shifter.

TABLE I
DIMENSIONS OF FERRITE TOROIDS IN INCHES

	Square	Rectangular
r_1	0.03125	0.03125
r_2	0.3330	0.2250
ℓ_1	0,3305	0,5400
ℓ_2	0.2965	0.0400
b	0.0250	0.0246

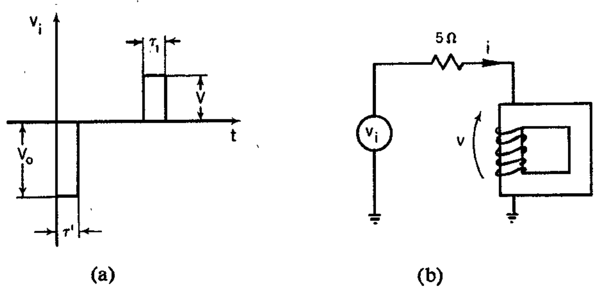

Fig. 4. Latching circuit and voltage waveforms.

and the magnetic field is given by (3). It may be assumed that the initial magnetic state of the toroid is $(0,-B_r)$ and that a voltage pulse of width τ and height V is applied to the circuit of Fig. 4. With $V_i = V$ during the pulse, (2)–(5) can be used to find a temporal differential equation for the current i.

The solution of this equation provides a means of finding the applied field intensity H. At $t = \tau + \tau_1$ the pulse ends and the value of B is $B(H(\tau + \tau_1))$. As the current decays B follows a new contour, $B_{p+}^1\ (H(\tau + \tau_1))$ that passes through the point $[H(\tau + \tau_1),B(H(\tau + \tau_1))]$ and reaches the latched state $(0,B_p^1)$. The superscript 1 denotes the first of a series of parametric curves needed to describe the entire path of B. A second positive pulse of the same amplitude and duration will drive the induction along a path B_{p-}^2 starting from the point $(0,B_p^1)$. This piecewise analysis can be continued until the final remanent state $+B_r$ is reached. The difficulties incurred in this type of analysis are obvious, not the smallest of which is the complicated integral for ϕ which arises when (3) is substituted into (5).

Idealized Latching Analysis and Experiments

A simplified but still useful result can be obtained by assuming a square flux versus current loop such as indicated in Fig. 5 for the rectangular toroid of Table I. Fig. 6 shows the idealized flux versus current characteristic of the toroid when a reset pulse drives it to negative saturation $(-\Phi)$, followed by the minimum positive pulse needed to drive it to positive saturation, Φ (see Fig. 4). The equivalent circuit for the coil is a current generator of magnitude I when $-\Phi < \phi < \Phi$. The toroid is saturated for $i > I$. Initially, a large voltage pulse of width τ' drives the toroid to $-\Phi$ from point 0. At that time

$$v = RI - V_0. \tag{6}$$

The change in flux is

$$\Delta\phi = -\Phi - \Phi_0 = \frac{1}{N}\int_0^{\tau''} (V_0 - RI)\, dt = \frac{V_0 - RI}{N}\tau''. \tag{7a}$$

Thus

$$\tau'' = \frac{(\Phi + \Phi_0)N}{V_0 - RI}, \qquad V_0 > RI \tag{7b}$$

is the pulsewidth required to saturate the toroid with a voltage pulse of amplitude V_0. If the pulsewidth τ' is less than τ'', several pulses must be applied until the sum of the pulsewidths is at least equal to τ''.

After the reset pulse the toroid is in its remanent state at 4. If a positive pulse of height V and of width τ_1 is applied (point 5), the toroid switches to $+\Phi$. The change in flux is

$$\Delta\phi = \Phi - (-\Phi) = \frac{V - RI}{N}\tau_1. \tag{8}$$

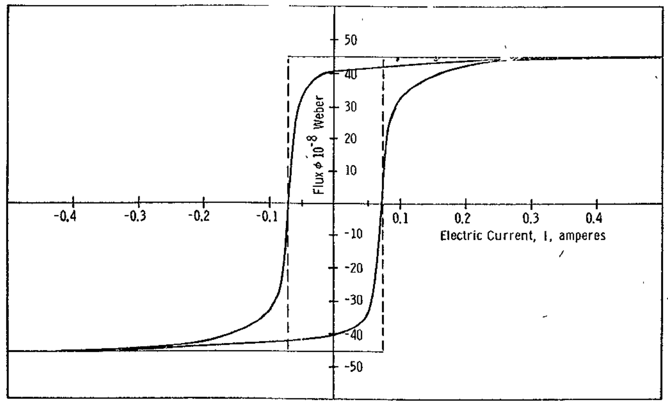

Fig. 5. Flux as a function of current for a rectangular TT1-390 toroid.

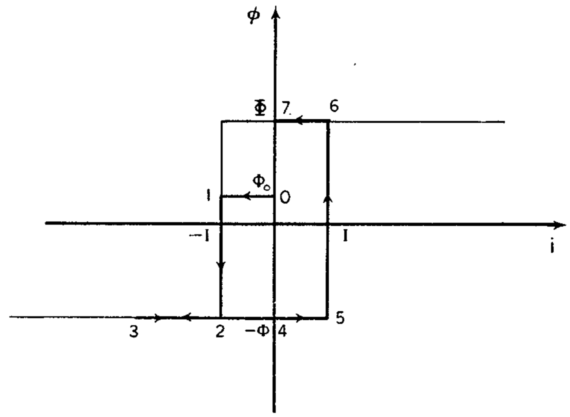

Fig. 6. Idealized rectangular current-flux loop for ferrite toroid.

At point 6 the pulse ends and the current and voltage drop to zero, latching the toroid at point 7. The required pulsewidth is found from (8)

$$\tau_1 = \frac{2N\Phi}{V - RI}, \qquad V > RI \tag{9}$$

where the flux is

$$\Phi = b\int_{r_1}^{r_2} B_r(r)\, dr.$$

If the pulsewidth is less than τ_1, then the toroid will be latched to an intermediate state. It can be driven from $-\Phi$ to $+\Phi$ with m identical pulses, provided that their width is

$$\tau_m = \frac{\tau_1}{m}. \tag{10}$$

This result is plotted in Fig. 7 for various values of m, using $N = 100$, $\Phi = 45 \times 11^{-8}$ Wb, and $I = 72.5$ mA. For example, the area marked $m = 3$ is the combination of voltages and pulsewidths for which three pulses are required. All the boundary lines asymptote the value $V = IR$, with $R = 5\ \Omega$ in our experiments.

Latching experiments were performed using CPW phase shifters [19]. A sequence of voltage pulses of adjustable amplitude and width was applied to the coil on the toroid and the phase shift measured. The number of pulses m of particular height and width needed to saturate the toroid was determined. These points are also shown in Fig. 7 and are in good agreement with the idealized model.

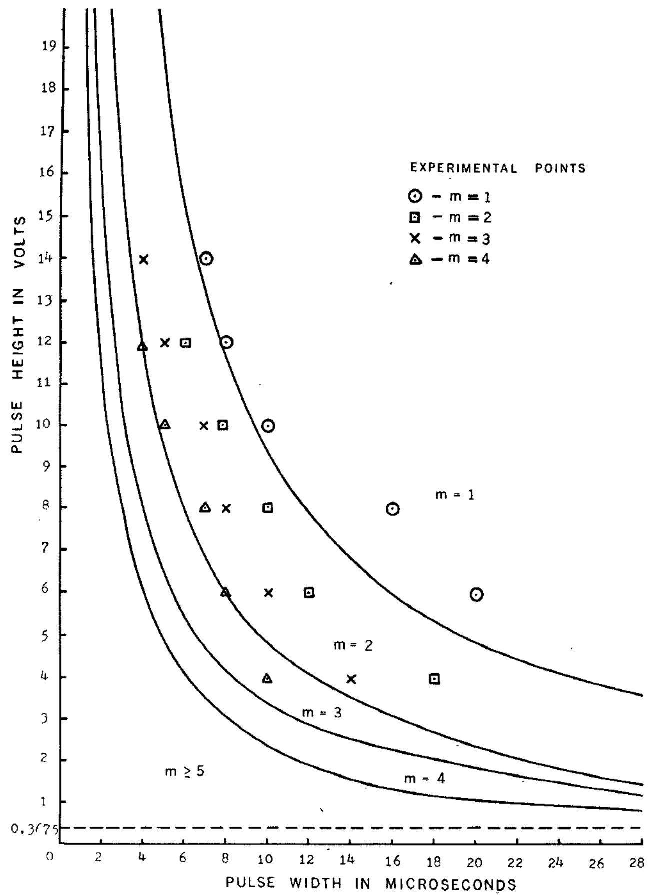

Fig. 7. Pulse height as a function of pulsewidth needed to switch a rectangular toroid of TT1-390 with m pulses.

Conclusion

Using (1) it is possible to model the major magnetostatic B–H loop of toroidal samples of some microwave ferrite materials in terms of characteristic measured parameters of the material. Approximate minor loops and switching trajectories such as those encountered in latching reciprocal phase shifters [7], [9] can be found through the use of (2). Temperature effects can also be incorporated in this model.

A relationship between the amplitude, pulsewidth, and number of pulses needed to switch a toroid was found in terms of the number of turns on the toroid, the switching current I, and the remanent flux Φ. This relation is in good agreement with the results obtained from latching experiments.

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Multiple Branch-Guide Directional Coupler Using TE_{01}-Mode Semicircular Waveguide

SHUICHI SHINDO

***Abstract*—This short paper describes experimental results derived from a newly devised branch-guide directional coupler using a TE_{01}-mode semicircular waveguide. The length of an experimental 0-dB coupler is about 150 mm, which is one-third shorter than the conventional coupled wave-type 0-dB coupler, and the loss is decreased in proportion to the reduction in length. Using this coupler, it is possible to manufacture more compact millimeter-wave diplexers with reduced insertion loss.**

Introduction

A semicircular waveguide-type diplexer for the millimeter-wave band has been developed consisting of two hybrid circuits and two cutoff filters with high-pass responses [1]. The hybrid is a coupled wave-type 3-dB directional coupler, which is composed of two parallel TE_{01}-mode semicircular waveguides, coupled to each other by a large number of small circular holes cut in the common wall of the semicircular waveguide. However, since the TE_{01}-mode semicircular waveguide is an oversized waveguide, the coupling length must be long in order to avoid spurious moding problems. For example, the length of the 3-dB directional coupler is about 270 mm for the 30-GHz band.

An alternative is the multiple branch-guide directional coupler using rectangular waveguide which is well known as being small in size. The multiple branch-guide directional coupler for rectangular waveguide has already been developed and its design method has been established [2], [3]. The multiple branch-guide

Manuscript received October 10, 1975; revised January 19, 1976.
The author is with the Yokosuka Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, Yokosuka, 238 Japan.