A Ferrite Cutoff Switch*

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Summary—The theory and operating characteristics of a new type of high performance reflective switch is given. It utilizes the cutoff phenomenon in transversely-magnetized ferrites. The insertion loss of the device is 0.4 db and over 60 db within the 8.8 to 9.5 kmc band when the ferrite is demagnetized and magnetized respectively. The reflection coefficient of the switch in the "off" state is more than 90 per cent over this same band. In contrast to most other ferrite devices, it is of the reflective rather than the absorptive type. Furthermore, it has the unique property that its operating bandwidth is determined mainly by the magnitude of the applied field. Possible applications of the device in antenna switching and as a tunable cutoff filter will be discussed.

INTRODUCTION

An extensive study of the cutoff phenomena in a longitudinally-magnetized ferrite-filled circular waveguide has been made by Suhl and Walker,[1] and the results have been summarized by Kales.[2] They have shown that there are three kinds of cutoffs. The first is similar to the cutoff which occurs if the circular waveguide is filled with a homogeneous, isotropic medium of the appropriate equivalent permeability. The second and third types were shown to occur when $\mu \pm K = 0$ and $\mu = 0$, respectively. Calculated values of the propagation constant for several special cases are given by Gamo.[3] The author[4] had also made some cutoff studies for circular waveguides partially filled with ferrite.

In a previous publication,[5] the author theoretically treated the cutoff phenomenon in transversely-magnetized ferrites. In this paper the theory will be extended and utilized in the design of a reflective switch. This switch will be shown subsequently to have an "off" to "on" attenuation ratio of over 150/1 in db over an 8 per cent band. The attenuation as a function of frequency at constant applied dc fields will be studied. The electromagnetic field configuration in the waveguide in the "on" and "off" states will also be determined to achieve a better understanding of the cutoff phenomena involved. Because of its reflective nature, the switch has many interesting applications some of which will be discussed.

The cutoff frequency ω_c of a waveguide of width L loaded by a ferrite slab of thickness δ placed against the guide wall and extended from top to bottom of the waveguide (see Fig. 1) was shown to be determined by the transcendental equation[5]

$$-\sqrt{\frac{\epsilon_0}{\rho\epsilon}} = \frac{\cot\left[\omega_c\sqrt{\mu_0\epsilon}\sqrt{\frac{1}{\rho}}\,\delta\right]}{\cot\left[\omega_c\sqrt{\mu_0\epsilon}(L-\delta)\right]} \tag{1}$$

where ϵ is the dielectric constant of the ferrite, and $1/\rho$, the equivalent permeability, is given by

$$\frac{1}{\rho} = \frac{\mu^2 - K^2}{\mu_0\mu} = \frac{(1+\chi_{xx})^2 + \chi_{xy}^2}{1+\chi_{xx}} \tag{2}$$

and

$$\chi_{xx} = \frac{4\pi M_s\gamma(\gamma H_i)}{(\gamma H_i)^2 - \omega^2}$$

$$\chi_{xy} = \frac{-j\omega\gamma 4\pi M_s}{(\gamma H_i)^2 - \omega^2} \tag{3}$$

where

$4\pi M_s$ = saturation magnetization of the ferrite
γ = gyromagnetic ratio of the electron, and
H_i = internal magnetic field in the ferrite.

Eq. (1) was derived by setting $\gamma = 0$ in the transcendental equation involving γ which in turn was obtained by solving the boundary value problem[6]

$$\frac{k_a}{\rho}\cot k_a(L-\delta) + k_m\cot(k_m\delta) = \frac{-\gamma}{\theta} \tag{4}$$

where

$$k_a^2 = \omega^2\mu_0\epsilon_0 + \gamma^2$$

$$k_m^2 = \omega^2\mu_0\epsilon\frac{1}{\rho} + \gamma^2, \text{ and}$$

$$\theta = \frac{\mu}{-jK} = \frac{1+\chi_{xx}}{\chi_{xy}}\,. \tag{5}$$

The cutoff frequency ω_{ca} of the dominant mode has been obtained from (1) for $L = 0.700''$, $\delta = 0.090''$, and plotted in Fig. 1. As was shown by Soohoo,[5] there are two cutoff frequencies involved in the solution of (1), one, ω_{ca}, being above and the other, ω_{cb}, being below the resonance frequency of the ferrite. Only the cutoff frequency ω_{ca} will be of concern here.

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[1] H. Suhl and L. R. Walker, "Topics in guided-wave propagation through gyro-magnetic media, part I, the completely filled cylindrical guide," *Bell Sys. Tech. J.* vol. 33, pp. 579–659; May, 1954.

[2] M. L. Kales, "Topics in guided-wave propagation in magnetized ferrites," PROC. IRE, vol. 44, pp. 1404–1405; October, 1956.

[3] H. Gamo, "The Faraday rotation of waves in a circular waveguide," *J. Phys. Soc. (Japan)*, vol. 8, pp. 176–182; March/April, 1953.

[4] R. F. Soohoo, "Higher-Order Mode Propagation in Ferrite Devices and Wide-Band Tunable Ferrite Microwave Filters," presented at the Conf. on Microwave Ferrites and Related Devices and Their Applications, 1957 Annual PGMTT meeting of the IRE, New York, N. Y.; May, 1957.

[5] R. F. Soohoo, "Cutoff phenomena in transversely magnetized ferrites," PROC. IRE, vol. 46, pp. 788–789; April, 1958.

[6] B. Lax, K. J. Button, and L. M. Roth, "Ferrite phaseshifters in rectangular waveguide," *J. Appl. Phys.*, vol. 25, pp. 1413–1421; November, 1954.

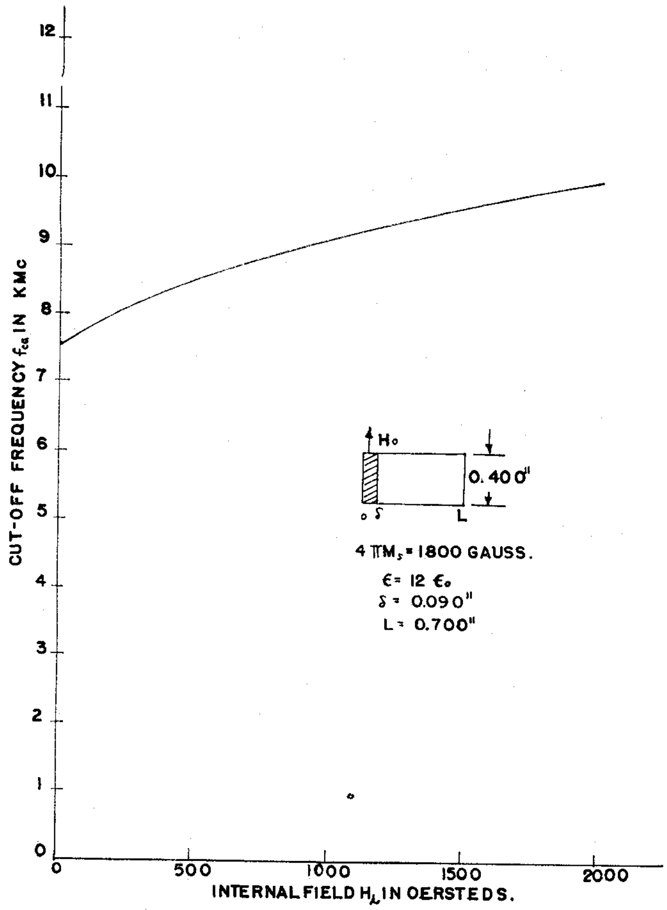

Fig. 1—Cutoff frequency of ferrite-loaded waveguide vs internal magnetic field.

From Fig. 1, it is immediately seen that if the ferrite is demagnetized, the loaded waveguide will transmit any frequency above 7.5 kmc. If an internal magnetic field of 1500 gauss, for example, is applied to the ferrite, the cutoff frequency f_{ca} of the structure will be moved up to 9.8 kmc. Thus, within the 7.5 to 9.8 kmc band, the device can be made to reject rather than transmit the incident energy by applying merely a magnetic field of the appropriate magnitude to the ferrite.

ATTENUATION AND REFLECTION

The reactive attenuation below cutoff for any empty lossless waveguide could be obtained from (5). In general,

$$\gamma = \alpha + j\beta = \frac{2\pi f_c}{c}\sqrt{1 - \left(\frac{f}{f_c}\right)^2}. \tag{6}$$

For frequencies below cutoff, $f/f_c < 1$, γ is real and we have for the reactive attenuation per unit length in db

$$\alpha = \frac{54.5 f_c}{c}\sqrt{1 - \left(\frac{f}{f_c}\right)^2}. \tag{7}$$

Eq. (7) could be plotted as a function of frequency f with f_c as a constant parameter; when $f/f_c < 1$, α decreases continuously with increasing frequency and reaches zero when $f/f_c = 1$. When $f/f_c > 1$, α is zero for all values of f.[7]

When the waveguide is loaded by a demagnetized ferrite slab against the guide wall, α must be determined from the transcendental (4) with $\rho = 1$ and $\theta = 0$. Solving (4) and (5) simultaneously, we obtained an α vs f curve for a particular lossless ferrite-waveguide configuration ($L = 0.700''$, $\delta = 0.090''$). It can be shown that the appearance of this curve is similar to that of the empty waveguide case; the introduction of a lossless dielectric would not change the shape of the $\alpha - f$ curve.

In actual cases, the waveguide and ferrite are not lossless and the α's will always remain finite with the general occurrence of a "tail" beyond the projected cutoff frequency.[7]

When the ferrite is magnetized, $1/\rho$ deviates from unity and θ takes on finite values. The exact solution of (4) becomes rather complicated. However, experimental results (Fig. 2) have shown that the attenuation behavior of the loaded waveguide when the ferrite is magnetized is similar to that of the demagnetized state. The projected intersections (dotted) of the attenuation curves for constant dc fields with the horizontal frequency axis give approximately the cutoff frequency at the respective value of H_0 where H_0 is the applied dc magnetic field. The reflection coefficient of the device at the various dc fields are plotted in Fig. 3. It is seen that over a certain frequency band the device transmits almost all of the incident energy when the ferrite is demagnetized but rejects a large portion of it when magnetized. Thus, Figs. 2 and 3 indicate clearly that the cutoff frequency of the device is moved upward with increasing dc fields as predicted by Fig. 1.

The cutoff frequency at zero applied field is seen to be higher than the 7.5 kmc value predicted by Fig. 1. However, it must be remembered that the internal field of Fig. 1 in general is composed of the applied, demagnetizing, and anisotropy fields. Furthermore, the effective permeability of the ferrite at zero field could be appreciably different from 1;[8] the value of unity for the effective permeability has been assumed above. When comparisons are made between the experimental cutoff frequencies of Figs. 2 and 3 and the theoretical ones of Fig. 1, one must bear in mind the difference between internal and applied fields mentioned above.[5] Moreover, the ferrite is not lossless as assumed in the theoretical treatment so the idealized theory should be considered to some measure qualitative. (See "Discussion" Section.)

FIELD CONFIGURATION

From the expressions given for the electric field by Lax, *et al.*,[6] the electric field distribution in the guide

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[7] S. Ramo and J. R. Whinnery, "Fields and Waves in Modern Radio" (1st ed.). John Wiley and Sons Inc., New York, N. Y.; p. 373; 1944.

[8] R. C. LeCraw and E. G. Spencer, "Measurement of the components of the permeability of ferrites," 1956 IRE CONVENTION RECORD, pt. 5; pp. 66–74.

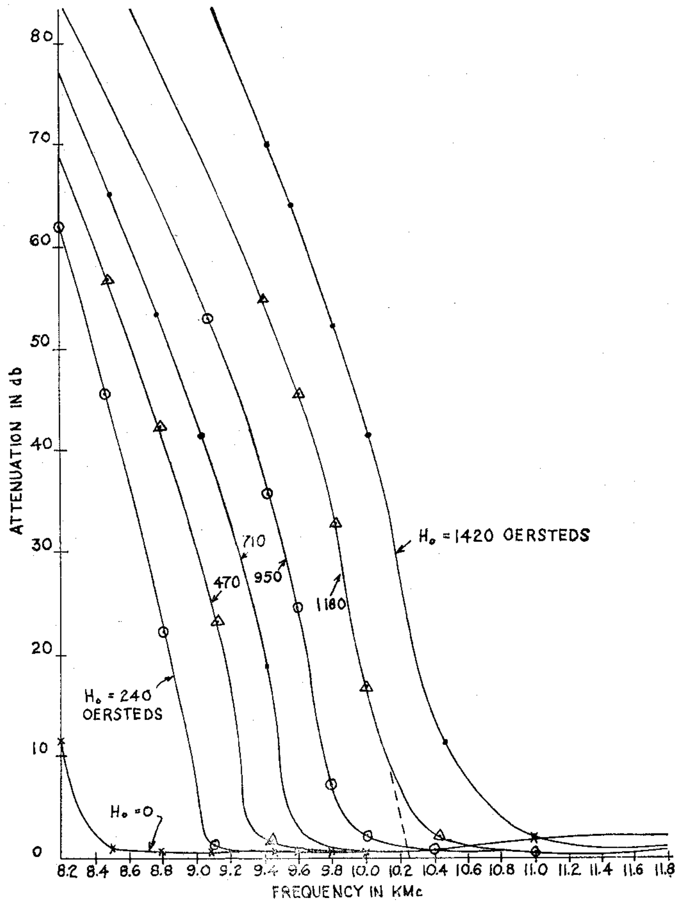

Fig. 2—Attenuation of ferrite loaded waveguide at constant applied fields vs frequency.

$4\pi M_s = 1800$ gauss
$\epsilon = 12\epsilon_0$
$\delta = 0.090$ inch
$L = 0.700$ inch
Length of ferrite = 2.75 inches.

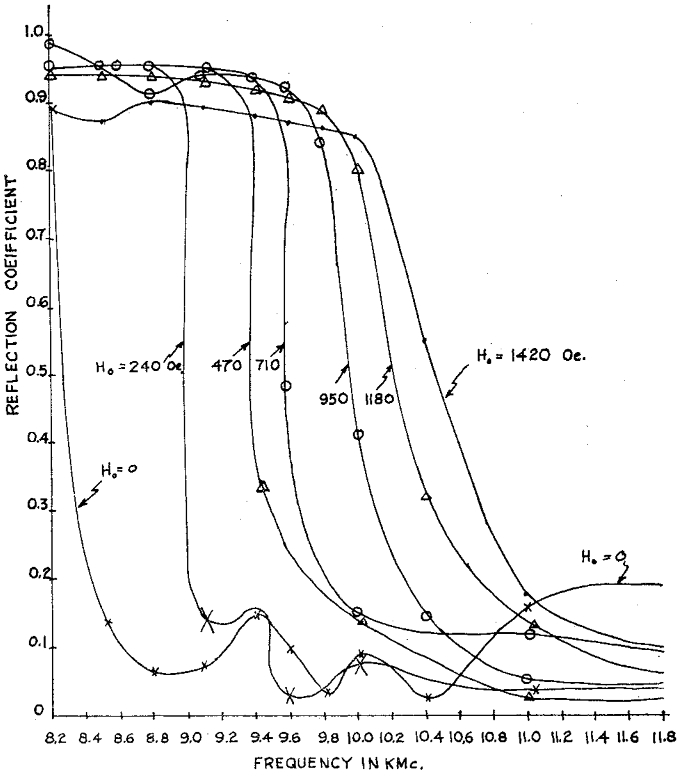

Fig. 3—Reflection coefficient of ferrite loaded waveguide at constant applied fields vs frequency.

$4\pi M_s = 1800$ gauss
$\epsilon = 12\epsilon_0$
$\delta = 0.090$ inch
$L = 0.700$ inch
Length of ferrite = 2.75 inches.

cross section can be obtained. This has been done for the empty waveguide case and the ferrite loaded case with both zero field and at an internal field corresponding to cutoff at 9.1 kmc (Fig. 4); the latter is reciprocal as the device is now exactly at cutoff ($\gamma = 0$). The cutoff frequency of the empty waveguide is 8.45 kmc while that of the ferrite loaded waveguide at zero field is lowered to 7.5 kmc. It is interesting to note that the electric field is pulled over to the ferrite when it is demagnetized due to dielectric loading effects while at an internal field corresponding to cutoff, the electric field is pushed out of the ferrite making the guide width effectively smaller.

The electric field intensity at the center of the waveguide, in the direction of propagation when the ferrite was demagnetized and when it was magnetized by an applied field of 1300 oersteds after a short was placed at the output end, has been monitored and plotted in Fig. 5. When the ferrite is demagnetized and the device terminated in a matched load, the VSWR is equal to 1.05; this low VSWR was achieved by tapering the ferrite at both ends. It is seen that for the zero field case, the standing wave pattern has maxima and minima of about equal spacing and respective amplitudes along the guide signifying propagation. For the $H_0 = 1300$ oersted case, the electric field decays rapidly and exponentially with distance with no maxima or minima observed, and this pattern remained essentially unchanged even when the short was replaced by a matched load. This supports the contention that the phenomena is predominately a cutoff one. The fact that the higher order TE_{20} mode is beyond cutoff for the experiment just described can be shown by obtaining the second root of (1).

OPERATING CHARACTERISTICS

The attenuation and VSWR at zero field and at 1300 oersted field of an actual switch built using the principle enumerated above is plotted in Fig. 6. It is seen that from 8.8 to 9.5 kmc the attenuation at zero field is 0.4 db, while that at 1300-oersted field is over 60 db. Thus the "off" to "on" attenuation ratio is over 150 to 1 (in db) over an 8 per cent band. Similarly, a ratio of over 60 to 1 (in db) could be obtained for a 16 per cent band (8.5 to 10 kmc). The VSWR is seen to be quite high and reasonably low when the switch is in the "off" and "on" states, respectively. We observed from Figs. 2 and 3 that the bandwidth or attenuation ratio of the switch can be increased further by applying a magnetic field of higher than 1300 oersteds. Conversely, for a smaller bandwidth, a lower applied field value is re-

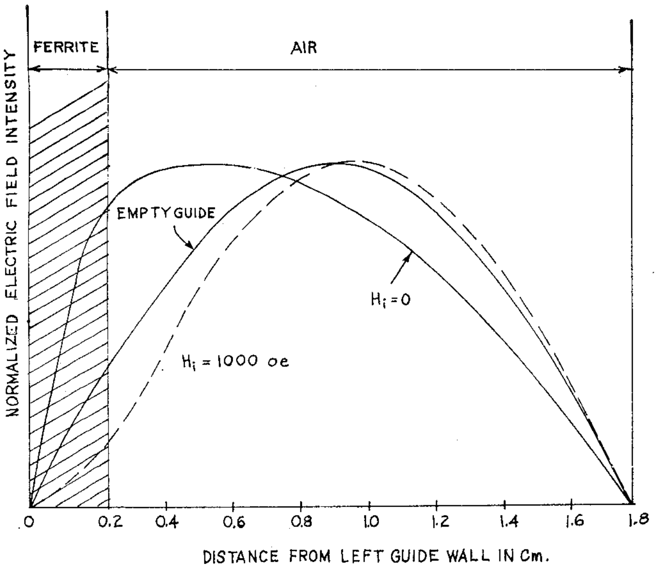

Fig. 4—Normalized electric field intensity vs distance from guide wall of ferrite loaded waveguide.

$4\pi M_s = 1800$ gauss
$\epsilon = 12\epsilon_0$
$\delta = 0.090$ inch
$L = 0.700$ inch.

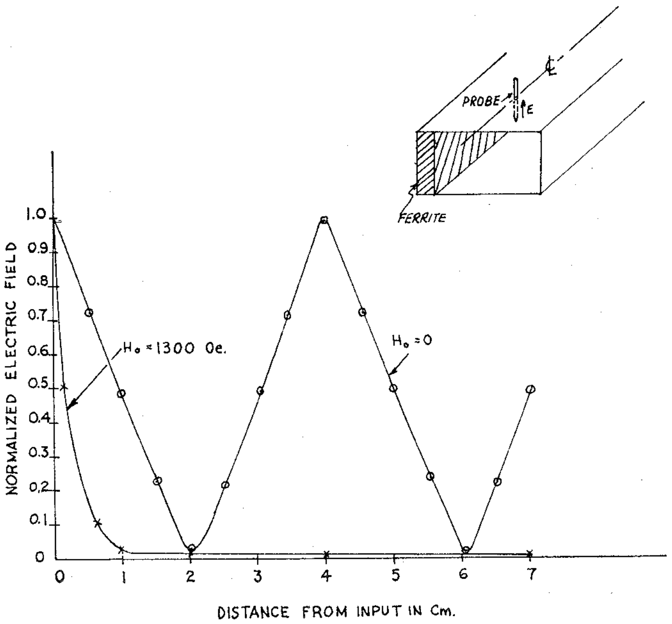

Fig. 5—Normalized electric field intensity at center of waveguide vs distance in the direction of propagation of ferrite loaded waveguide.

$4\pi M_s = 1800$ gauss
$\epsilon = 12\epsilon_0$
$\delta = 0.090$ inch
$L = 0.700$ inch.

quired. This dependence of bandwidth and attenuation ratio upon applied field magnitude is one of the novel features of this type of device.

The switching coil has a resistance of 20 ohms and an inductance of 9 mh. Thus the driving power required to give 1 ampere is rather large and switching time would be limited to the millisecond range. To reduce this power requirement, one might reduce the height of the waveguide. To minimize eddy current effects produced when a transverse magnetic field is applied from top to bottom of the waveguide, a ferrite rectangular ring magnetized by a single turn of wire arranged as shown in Fig. 7 may be used.[9,10] The legs of the ferrite ring that is against the top and bottom guide wall are used to close the magnetic circuit to reduce the required field for switching. Cutoff phenomena can be shown to occur with a slab against each side wall as well as with a slab against only one side wall. The waveguide may be made of nonmetallic material such as phenolic and coated on the inside with about 0.0005 inch of silver to lower eddy current losses still further. Preliminary results show that this is a very promising approach; it has been found that whereas a high current is required because of the single turn of wire used, the required switching voltage is very small, and the result is a considerable reduction in switching power. Using this method it is expected that switching times of the order of μs could be obtained.

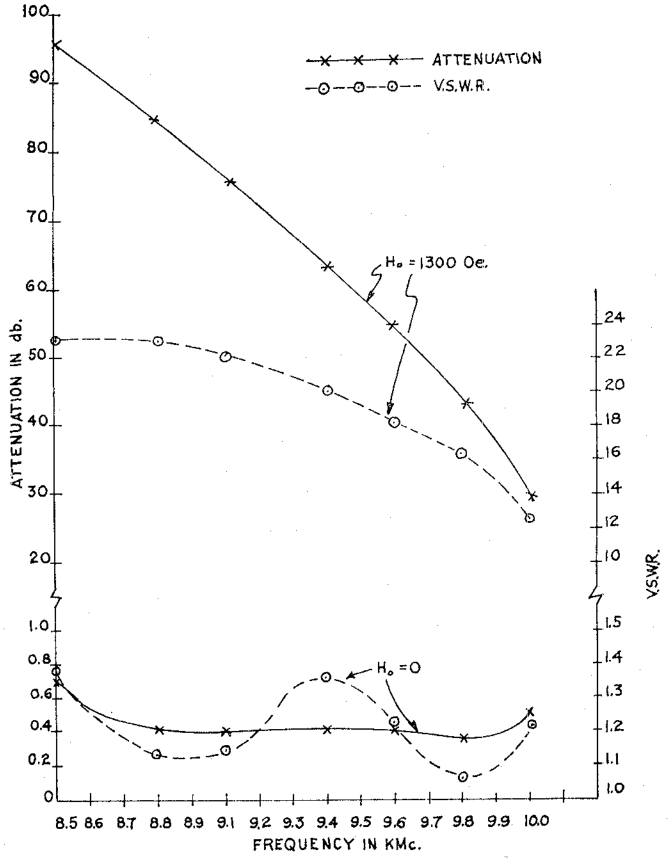

Fig. 6—Attenuation and VSWR of cutoff switch vs frequency

$4\pi M_s = 1800$ gauss
$\epsilon = 12\epsilon_0$
$\delta = 0.090$ inch
$L = 0.700$ inch
Length of ferrite = 2.75 inches.

It should be noted again here that if the switch were to operate over a very narrow bandwidth the magnetic

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[9] B. N. Enander, "A new ferrite isolator," Proc. IRE, vol. 44, pp. 1421–1430; October, 1956.

[10] L. M. Silber and M. A. Treuhaft, "Low-Energy Ferrite Switch," presented at the Annual PGMTT Meeting at Stanford, Calif.; May, 1958.

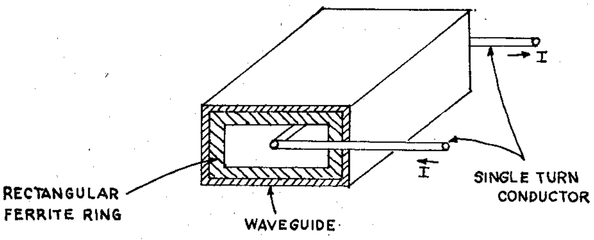

Fig. 7—A scheme for rapid switching of cutoff attenuator.

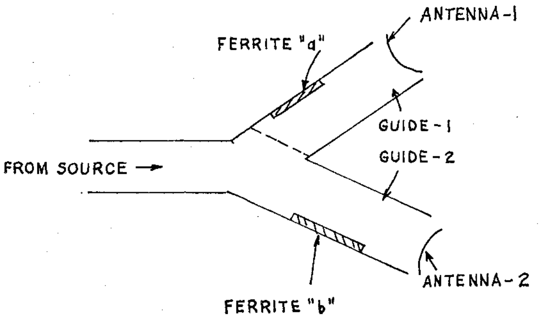

Fig. 8—Application of cutoff attenuator in antenna switching.

field requirement would be small and switching power required would be much reduced. If the location of the frequency band is to be changed, the guide width may be adjusted so that the loaded guide at zero field just cuts off at the low end of the operating band to reduce switching field requirement.

Applications

This switch can obviously be used as a tunable cutoff filter. It is seen from Fig. 2 that the attenuation varies almost linearly with frequency over a substantial bandwidth.

The switch could be used to switch from one antenna to the other as shown in Fig. 8.[11] When ferrite "a" is magnetized, waveguide 1 is cut off presenting an apparent short at the dotted plane while waveguide 2 whose ferrite "b" is demagnetized transmits and therefore energy is radiated out of antenna 2. If now ferrite "b" is magnetized while ferrite "a" is demagnetized, energy will go out antenna 1. Experiments have shown that a transmission loss of about 1 db for the "on" antenna and an attenuation of over 60 db for the "off" antenna over about 8 per cent band is possible.

Since the attenuation of the switch goes from a constant low value up to the high value rather linearly, it can be used in an AGC system for high stability (see Fig. 9).

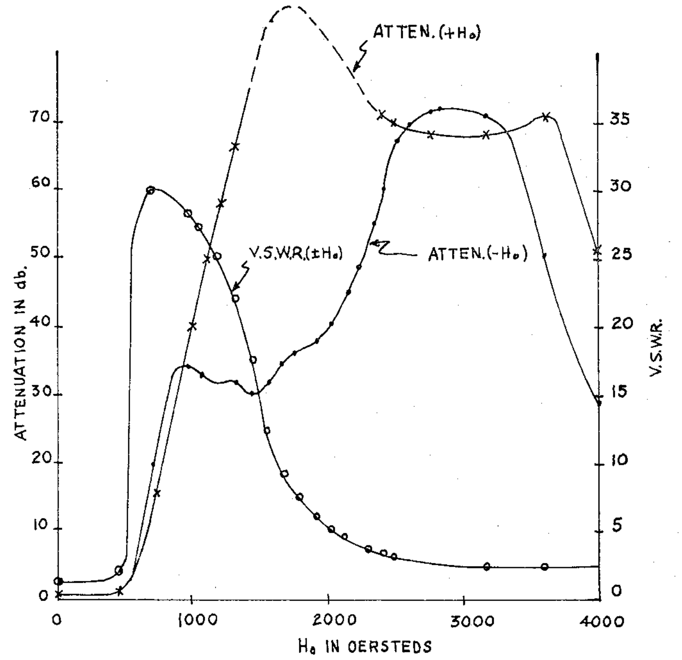

Fig. 9—Attenuation and VSWR of cutoff switch vs applied field.

$4\pi M_s$ = 1800 gauss
$\epsilon = 12\epsilon_0$
δ = 0.090 inch
L = 0.700 inch
Length of ferrite = 2.75 inches
= 9.1 kmc.

Discussion

The attenuation and reflection coefficients of the switch at 9.1 kmc are plotted for the two different directions of applied field in Fig. 9. There are several interesting features shown. First of all, the reflection coefficient and therefore the reflected power is almost the same for the two directions of magnetic field. However, the attenuation may be quite different for the opposite field orientations. This may be due in part to the fact that the RF magnetic field is in general elliptically polarized at the ferrite and that one sense of polarization should exhibit resonance while the other sense should not. It is noted also that the VSWR remains high in the region of H_0 between 500 and 2000 oersteds signifying cutoff but decreases to a relatively low value for a value of H_0 above 2000 signifying absorption. This band rejection characteristic and its relationship to ferromagnetic resonance has been previously discussed by the author.[5]

The reflection coefficient data of Fig. 3 could account for only part of the high attenuation depicted by Fig. 2. The total attenuation is due to a combination of cutoff and its resultant reactive attenuation as well as a resistive type of attenuation in the ferrite.

Acknowledgement

The author wishes to thank D. Chang and M. Gan who aided with the calculations and measurements for this paper.

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[11] Whereas there is a physical resemblance of this switch to the Tee and Y circulator, the power in this device does not "circulate." For example, if energy is fed in at the source arm when ferrite "a" is appropriately magnetized, it will go out of antenna 2. On the other hand, energy cannot pass freely from antenna 1 to the source due to the cutoff phenomena in the waveguide containing ferrite "a." For reference on Tee and Y circulators, see W. E. Swanson and G. J. Wheeler, "Tee circulator," WESCON Convention Record, vol. 2, pt. 1, pp. 151–156, 1958; and H. Chait and T. Curry, "The Y Circulator," Fourth Conf. on Magnetism and Magnetic Materials, Philadelphia, Pa.; November 17–20, 1958.