Ferrite Switches in Coaxial or Strip Transmission Line*

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Summary—**An examination of the properties of longitudinally-magnetized ferrite in coaxial transmission lines reveals regions of low and high attenuation which could be used for the ON and OFF conditions, respectively, of a switch. A strip line switch designed for fast switching and L band is described. Its performance includes approximately 0.1-db insertion loss and 45-db isolation over a 13 per cent band.**

Introduction

In many microwave systems there exists a need for a fast-acting switch which has negligible insertion loss in its ON condition and high attenuation in its OFF condition. Ferrite switches can satisfy these attenuation requirements and they can in general be made fast-acting by reducing the thickness of the waveguide walls to a few "skin-depths," using low inductance coils, and applying pulse-circuitry techniques. Switches in rectangular or circular waveguide have been either of the Faraday rotation[1,2,3] or the waveguide-beyond-cutoff variety.[4] Some coaxial or strip line structures have been described which show interesting properties.[5,6,7] Early work at Bell Telephone Laboratories on ferrite-loaded coaxial lines[8] indicated that large amounts of attenuation could be obtained with axial magnetic fields. The high attenuation is the result of a cutoff condition in the ferrite loaded line, and/or ferromagnetic resonance in the ferrite. The applied field may be switched to bring the line into a propagating and low-loss condition.

The object of this paper is to describe several design considerations for the performance of the coaxial or strip line type of ferrite switch and to present data on the operation of a strip line switch at L band.

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[2] G. S. Uebele, "High speed ferrite microwave switch," 1957 IRE National Convention Record, pt. 1, pp. 227–234.

[3] J. A. Weiss, "The tetrahedral junction as a waveguide switch," IRE Trans. on Microwave Theory and Techniques (*Correspondence*), vol. MTT-8, pp. 120–121; January, 1960.

[4] R. F. Soohoo, "A ferrite cutoff switch," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 332–336; July, 1959.

[5] B. Vafiades and B. J. Duncan, "An L-band coaxial line modulator," 1957 IRE National Convention Record, pt. 1, pp. 235–241.

[6] C. M. Johnson and J. C. Wiltse, "A broad-band ferrite reflective switch," IRE Trans. on Microwave Theory and Techniques (*Correspondence*), vol. MTT-8, pp. 466–467; July, 1960.

[7] R. L. Booth, "A broad-band coaxial ferrite switch," IRE Trans. on Microwave Theory and Techniques (*Correspondence*), vol. MTT-9, pp. 452–453; September, 1961.

[8] H. Seidel, "Longitudinally Magnetized Ferrite Loaded Coaxial Components," presented at 1957 Annual PGMTT Meeting, New York, N. Y., May 10, 1957.

The Ferrite-Loaded TEM Transmission Line

The coaxial transmission line operates normally in the TEM mode and its dimensions are usually such that other modes are well beyond cutoff at its operating frequency. For purposes of analysis of the ferrite-filled coaxial line, it is convenient to "unroll" the line to parallel conducting planes with a ferrite filling between them, Fig. 1. Suhl and Walker[9] have considered this case with

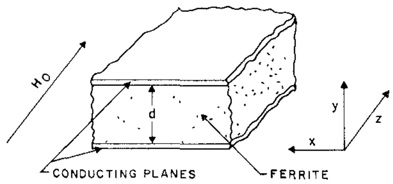

Fig. 1—Parallel plane transmission line with ferrite filling.

longitudinal magnetization of the ferrite and shown that the line behaves as though the ferrite had a relative scalar permeability μ_e given by $\mu_e = (\mu^2 - \kappa^2/\mu)$, where μ and κ are the components of the Polder permeability tensor for the infinite medium and are given by

$$\mu = 1 + \frac{4\pi M_s \gamma \omega_0}{\omega_0^2 - \omega^2} \quad \text{and} \quad \kappa = \frac{4\pi M_s \gamma \omega}{\omega_0^2 - \omega^2},$$

where:

$4\pi M_s$ = saturation magnetization of the ferrite
γ = gyromagnetic ratio of the electron (1.76×10^7 rad/oers sec)
ω = operating angular frequency
$\omega_0 = \gamma H_0$
H_0 = internal biasing field in the ferrite.

We also need to define

$\beta_0 = \omega\sqrt{\mu_0 \epsilon_0}$ = the free-space phase constant
$\beta = \beta_0 \sqrt{\mu_e \epsilon}$ = the phase constant in the ferrite line
ϵ = the relative permittivity of the ferrite.

Waves propagate in the line according to the relation $E = E_0 \exp j(\omega t - \beta z)$. As biasing field H_0 is applied, μ_e and β change as well as the characteristic impedance which is proportional to $\sqrt{\mu_e/\epsilon}$.

A plot of μ_e vs applied biasing field is shown in Fig. 2, where reduced variables are used to remove frequency as a parameter. Following the notation of Suhl

[9] H. Suhl and L. R. Walker, "Topics in guided wave propagation through gyromagnetic media," pt. 3, *Bell Sys. Tech. J.*, vol. 33, pp. 1133–1194; September, 1954.

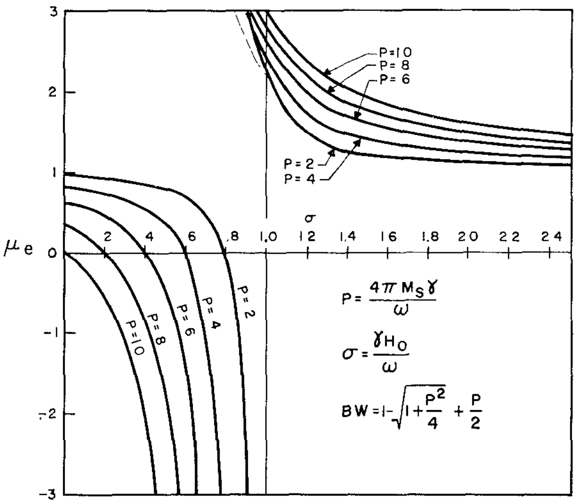

Fig. 2—Effective permeability as a function of applied field with saturation magnetization as a parameter—in reduced units.

and Walker,[9] these are

$$p = \frac{4\pi M_s \gamma}{\omega} \text{ for the saturation magnetization}$$

$$\sigma = \frac{\gamma H_0}{\omega} \text{ for the applied biasing field.}$$

In terms of these parameters,

$$\mu = \frac{\sigma^2 + p\sigma - 1}{\sigma^2 - 1} \quad \text{and} \quad \kappa = \frac{p}{\sigma^2 - 1}$$

$$\mu_e = \frac{\mu^2 - \kappa^2}{\mu} = \frac{(p + \sigma)^2 - 1}{\sigma^2 + p\sigma - 1}$$

With reference to Fig. 2, we see a region where μ_e is negative extending from $\mu_e = 0$ to $\mu_e = -\infty$ (neglecting loss in the ferrite). This represents a region where β is imaginary and the line is cutoff. The degree of cutoff depends on the value of μ_e and is a maximum at the point $\mu_e = -\infty$. This point is obviously that at which $\mu = 0$. Equating the numerator of the above expression for μ to zero, we have

$$\sigma^2 + p\sigma - 1 = 0.$$

Solving for σ and using only the positive value, since by definition[9] p and σ must have the same sign, the value of σ for the point of maximum cutoff is

$$\sigma = \sqrt{1 + \frac{p^2}{4}} - \frac{p}{2}.$$

However μ_e does not go to $-\infty$ in actual ferrite because of loss associated with the damping of the spin precession. It would have its greatest negative value at a value of σ slightly less than that given by the above expression. For higher values of σ the line again propagates with large values of β at first, gradually dropping to approach $\beta = \beta_0\sqrt{\epsilon}$ for $\sigma = \infty$. At the point $\sigma = 1$, which is ferromagnetic resonance, the ferrite loss will be high and it will also be considerable on either side of this point to an extent determined by the magnetic line width of the material. Thus the high-loss region of the switch should encompass the high cutoff point and the point of ferromagnetic resonance. A useful approximate expression for the fractional high-loss bandwidth then would be

$$BW = 1 - \sqrt{1 + \frac{p^2}{4}} + \frac{p}{2}.$$

This represents the difference in σ between $\sigma = 1$ and its value for $\mu_e = -\infty$. With a fixed bias field $\sigma = 1$ represents the low-frequency end of the high-loss band and $\mu_e = -\infty$ represents the high-frequency end.

The possibility of other propagating modes where μ_e is large and positive should not be overlooked. Suhl and Walker[9] show that both a TE and a TM mode are possible here, depending on the separation d, Fig. 1. As a practical matter, since these can propagate only near ferromagnetic resonance, their effect should be negligible in the presence of the resonance absorption.

Fig. 3 shows the relative behavior of the magnetic loss in the ferrite as a function of the applied field for ferrite shapes applicable to this type of switch. With the applied field $H_A = 0$, the so-called low-field loss predominates. This disappears when the ferrite becomes saturated, which occurs when the applied field becomes greater than the demagnetizing field, shown as point A in Fig. 3. This point also corresponds to $\sigma = 0$, since the ferrite is assumed to be saturated in the theory involving μ_e. The loss at point A corresponds to its position on the resonance absorption curve of the particular ferrite used for the switch. If a material with a sharper resonance curve (narrower line width) is used, the loss will be less. Point B represents the applied field for the high-loss condition of the switch and is usually somewhat below the field required for ferromagnetic resonance at the mid-band frequency. In ferrites of the proportions used in these switches, namely long cylinders or long rectangular slabs, resonance occurs at a value of H_A which is slightly less than $2\pi M_s$ below ω/γ according to the Kittel formula

$$\frac{\omega}{\gamma} = \sqrt{[H_A + (N_x - N_z)4\pi M_s][H_A + (N_y - N_z)4\pi M_s]}$$

where N_x, N_y, N_z are the fractional demagnetizing factors in their respective directions ($N_x + N_y + N_z = 1$). With increasing applied field above ferromagnetic resonance the loss drops rapidly and then flattens so that at some point C it is quite low and still decreasing.

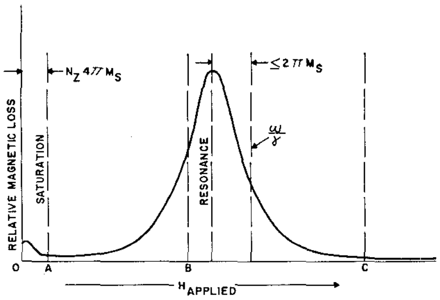

Fig. 3—Relative magnetic loss in the ferrite.

From Fig. 3 we see that there are two regions which might be suitable for the low-loss condition of the switch: the region near point A, or the region near point C. The choice between these points may depend on how the switch is to be used. If it is to remain in the transmitting condition most of the time and be switched to the high-loss condition occasionally or for short times, it would probably be advantageous to use point A for the low-loss condition. If it is desired to have the switch in the high-loss condition most of the time and to switch to the low-loss condition occasionally or for short times, it may be advantageous to bias the switch to the high-loss condition with a permanent magnet. In this case switching to the low-loss condition could be done by adding to or bucking the bias field to use either point C or point A. The use of point A in this event might require a lower switching field, but use of point C might provide lower loss and a less critical value of switching field.

The switch must be matched for the low-loss condition in order to minimize the insertion loss. If a coaxial or strip transmission line is used whose characteristic impedance is 50 ohms with air dielectric, when it is loaded with ferrite the impedance will drop to approximately 15 or 20 ohms. The impedance in the ferrite-loaded sections might be raised by making the center conductor smaller, but this would increase the ohmic losses because of the reduction in size. For reasonable bandwidth structures, quarter-wave matching sections of alumina-loaded line may be used at both ends of the ferrite-loaded section. The impedance of the ferrite-loaded line for operation at either point A or point C of Fig. 3 may be easily calculated if the dielectric constant of the ferrite is known, by obtaining the appropriate value of μ_e from Fig. 2. It will be seen that for operation at point C, the value of μ_e is changing slowly with applied field and therefore the impedance match will remain good over a range of fields in this region.

The Strip Line Switch

The construction of a switch built for L-band operation in strip line is shown in Fig. 4. It is designed to be biased to the high-loss condition by means of permanent magnets and to be switched to the high-field low-loss

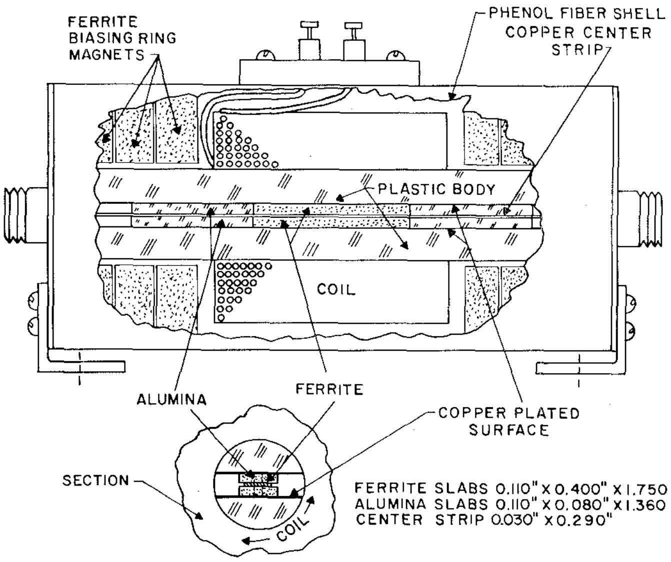

Fig. 4—Construction of the strip line switch.

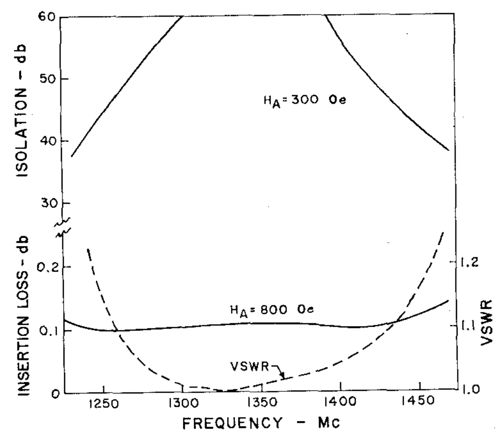

Fig. 5—Performance of the strip line switch vs frequency.

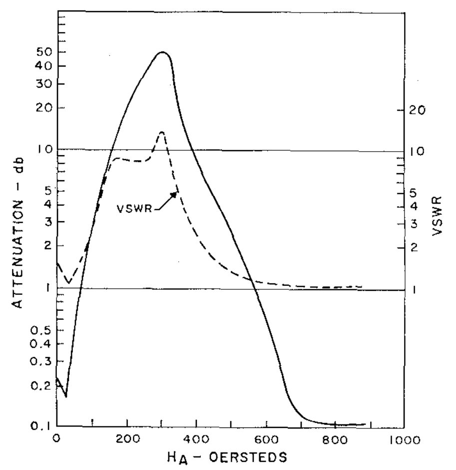

Fig. 6—Performance of the strip line switch vs applied field at a frequency of 1350 Mc.

condition by means of a solenoid. The design parameters are

$$p \simeq 0.72, \ \sigma \text{ for the low-loss condition} \simeq 2.2.$$

The ferromagnetic material used in this switch was a low saturation ($\sim$350 gauss) aluminum-substituted yttrium iron garnet. Typical performance of the switch is shown in Fig. 5. It will be noted that it operates over a 13 per cent band with insertion loss of about 0.1 db and isolation of 45 db, which provides the very attractive ratio of 450 to 1. In addition the VSWR in the transmitting condition is seen to be excellent. The impedance matching for this condition is accomplished by the use of quarter-wave sections of alumina-loaded line at both ends of the ferrite section. The alumina loading slabs are made the same height as the ferrite slabs so that the assembly forms a tight sandwich. The impedance of the matching sections is adjusted by changing the width of the alumina slabs. The design can be moved in the 1- to 2-Gc frequency range with substantially the same performance.

The high-loss characteristic is indicative of a single broad peak which, with the test equipment used, was obscured by noise. The peak value is estimated to be about 65 db. Although the strip line construction is susceptible to leakage of energy as the result of assymmetries, the leakage here was apparently negligible since no appreciable undulations are observed in the high-loss characteristic.

Fig. 6 shows the behavior of the switch at its approximate mid-band frequency as a function of the biasing field. With zero field the loss is low, being considerably dependent upon the impedance match. With application of field, the loss goes through a minimum and then increases sharply along with the VSWR as the device goes into the cutoff condition. The VSWR levels off and then shows a sharp peak in the vicinity of ferromagnetic resonance. Above ferromagnetic resonance, the attenuation and VSWR drop rapidly and then level off to very low values.

Discussion

The above behavior of the switch follows the theory quite well. At a frequency of 1350 Mc for which the data of Fig. 6 were obtained, the ferromagnetic resonance should come at an applied field of approximately 300 oersteds, and $\mu_e = -\infty$ at approximately 190 oersteds. However since loss is present μ_e would have its greatest negative value at a field somewhat lower than 190 oersteds and this field should be that at which the VSWR curve is a maximum. The VSWR curve of Fig. 6 does indeed flatten out at this point but there is a rather sharp maximum closer to resonance. The attenuation at the point of maximum negative permeability in this case is only about 12 db, so it is necessary to go much closer to resonance to get values above 30 db. It seems therefore that the expression for bandwidth of the high loss given earlier is too optimistic if really high values of attenuation are required.

The use of strip transmission line rather than coaxial line has the advantage that the ferrite and alumina parts can be rectangular slabs which are much easier and cheaper to obtain than the hollow cylinders which are required otherwise. In order to allow fast switching, anything resembling a short-circuiting turn near the ferrite slabs is avoided. The outside conductors of the strip line are copper-plated coatings on plastic bodies, and the copper is only about 0.0015 inch in thickness. The ring-biasing magnets are barium ferrite, magnetized axially. The switching speed is determined principally by the circuitry for driving the coil which has an inductance of approximately 2.7 mh. Switching speeds of the order of 10 μsec have been obtained.

Conclusion

A ferrite-loaded strip transmission line switch has been shown to provide very high ratios of isolation to insertion loss over a greater than 10 per cent bandwidth. Although a relatively high switching field is required, particularly at the higher frequencies, it is required over a relatively small volume of ferrite, so that the total energy involved is not excessive.