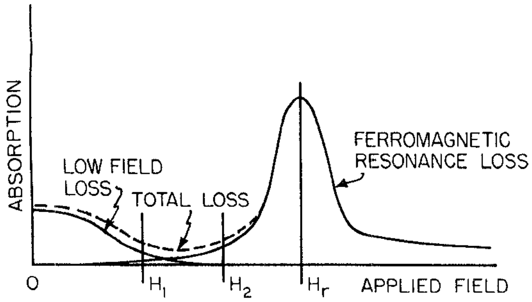

Fig. 12—The effect of low field loss on total loss in an isolator. A phase shifter would operate between H_1 and H_2.

erally the low field loss is reduced in magnitude when the saturation moment is decreased;[30] for this reason it is often desirable to have a low saturation moment even in an isolator. The moments of the garnets are relatively low.

For nonreciprocal phase shifters operating below the field required for resonance, the low frequency problem is even more difficult. Generally such phase shifters operate in the region of minimum attenuation, where the low field losses have nearly disappeared and the resonance losses have not yet become large (for example, between H_1 and H_2 of Fig. 12). For low frequencies the minimum may be very narrow or even nonexistent, as the absorption line gets closer to zero field. Then it becomes necessary to reduce the saturation moment until the low field losses do not occur. Fig. 12 also demonstrates the desirability of a narrow line width and low g factor for phase shifters.

[30] This is true for sufficiently high frequencies. For lower microwave frequencies (~1000 mc) the problem is more complicated.

Using infinite medium theory, Hogan has calculated the differential phase shift per db loss for such a phase shifter, neglecting the low field loss and including only the ferromagnetic resonance loss due to the tail of the absorption line. He finds

$$\theta / L_+ = \frac{\omega}{2.2\gamma\Delta H},$$

where θ is differential phase shift and L_+ is the attenuation of the positive circularly polarized wave. If a differential phase shift of $\pi/2$ radians with 0.5 db loss is desired, then for the yttrium garnet

$$\frac{\omega}{\gamma} \geq 380$$

or

$$f \geq 1050 \text{ mc.}$$

For a ferrite with $\Delta H = 200$, this would give $f \geq 4200$ mc. Actually both numbers are pessimistic since, for polycrystals, the absorption on the tail of the curve is usually smaller than that predicted by the Lorentzian line with the given half-width. For the numbers to be meaningful at all, the low field loss must be eliminated by making sure that the material is completely magnetized, or by reducing the saturation moment so that they do not occur.

Acknowledgment

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Reciprocal Ferrite Devices in TEM Mode Transmission Lines*

D. FLERI† and B. J. DUNCAN†

Summary—Several new reciprocal ferrite devices have been designed in TEM mode transmission lines to operate over both narrow and extremely broad bandwidths in the low-microwave frequency region. These include variable attenuators, an amplitude modulator, and a traveling-wave tube equalizer. Each component utilizes the attenuation associated with gyromagnetic resonance in low saturation magnetization ferrites. The techniques used to overcome the matching problems inherent in TEM mode transmission lines when ferrite loaded, and the design considerations pertinent to each component, are treated in detail. The parameters affecting the characteristics of each device are discussed and both final design and operating characteristics of the components are presented.

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† Sperry Gyroscope Co., Div. Sperry Rand Corp., Great Neck, N. Y.

Introduction

In recent years, considerable effort has been devoted to the design of a wide assortment of ferrite devices in various types of microwave transmission lines. Included among these are nonreciprocal ferrite components designed in circular waveguide,[1,2] rectangular waveguide,[3–5] coaxial line,[6,7] strip transmission line,[8] and a helical transmission line.[9] However, only a limited amount of information has appeared in the literature on useful reciprocal ferrite devices designed in TEM mode transmission lines.[10,11]

It is the purpose of this paper to describe a series of reciprocal ferrite devices designed for both narrow and broad-band applications. These devices are designed in coaxial line and strip transmission line structures with particular emphasis on maintaining size and weight as small as practical. Included in this series of components are variable attenuators, an amplitude modulator, and a traveling-wave tube equalizer. The design considerations leading to the development of these components are given, as are the parameters affecting their operation. Also included are the physical design of each of these component types. Finally, the pertinent features and operating characteristics of each component are presented.

General Discussion

Gyromagnetic resonance effects are the result of a coupling between a microwave magnetic field and the electrons within a ferromagnetic medium. The greater the concentration of the microwave magnetic field, the greater is the degree of coupling. In coaxial line propagating the TEM mode, the microwave magnetic field concentration is greatest in the boundary of the center conductor and decreases inversely with radial distance. Maximum interaction between the microwave energy and a ferromagnetic material will occur at the boundary of the inner conductor and, therefore, the ferrite configuration used in the coaxial structures discussed in this paper consists of thin cylindrical tubes fitting about the center conductor. Each of the coaxial components utilizes a longitudinal biasing field and since the microwave magnetic field is linearly polarized, each of these components is reciprocal.

For purposes of analysis, the thin cylindrical ferrite tubes may be considered to exhibit the same demagnetizing factors as a thin ferrite slab when longitudinally biased. The expression relating the resonant frequency, ν_{res}, and the magnetic biasing field, H_{DC}, for a thin ferrite slab, infinite in extent, biased and saturated perpendicular to its narrow dimension is:

$$\nu_{res} = \gamma[H_{DC}(H_{DC} + 4\pi M_S)]^{1/2} \qquad (1)$$

where:

γ = gyromagnetic ratio for the electron = 2.8 mc/oersted

$4\pi M_S$ = saturation magnetization of the ferrite in Gauss.

Even though the ferrites may not be completely saturated in the cases considered herein, (1) can be used as an approximate expression relating ν_{res} and H_{DC}. The approximation becomes more accurate as the wall thickness of the ferrite tube is made smaller and/or as the ferrite becomes more nearly saturated.

At a given frequency, and for a particular material, resonance attenuation is a function of ferrite length. As should be expected, the attenuation increases linearly with ferrite length and for a given length, the resonance attenuation increases with increasing frequency.

Fig. 1 demonstrates the variation of resonance attenuation with ferrite wall thickness. In the region of the curve corresponding to small wall thickness, the variation is linear. As the wall thickness becomes larger, the rate of increase of attenuation falls off. This is due in part to the decrease of the microwave field concentration with radial distance. Also, the ferrite loading gives rise to the generation of higher order modes, which causes the field pattern to be somewhat different from the pure TEM mode configuration.

The linear variation of vswr with ferrite wall thickness is also shown in Fig. 1. For a twenty-five thousandths wall, the vswr is very high, approximately 4. Even for a five thousandths wall, the vswr is appreciable, approximately 1.5. At first glance, this appears to be too high a vswr to be caused by such a thin tube. However, the incident microwave energy encounters a discontinuity greater than the actual physical discontinuity, this is, greater than the ferrite wall thickness, by a factor equal to the square root of $\mu\epsilon$, where μ is the effective permeability of the ferrite and ϵ is the dielectric constant. Since μ is about 10 or 15 at resonance, and since ϵ is of the same order of magnitude, the electrical discontinuity exceeds the physical discontinuity by a factor of 10 or greater. The discontinuity susceptance plus the change in characteristic impedance in the region of ferrite loading both contribute to the high vswr's.

The first step in reducing the vswr is to use the

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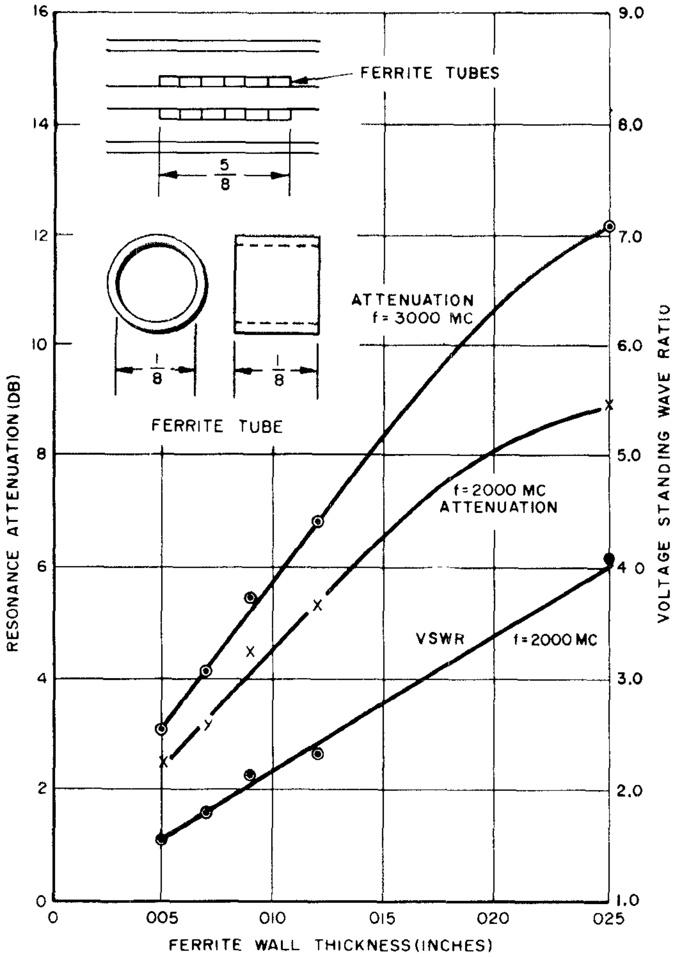

Fig. 1—Variation of gyromagnetic resonance attenuation and vswr with ferrite wall thickness.

thinnest tubes practicable. A Smith chart analysis of this structure showed that the impedance varied with frequency in an abrupt and erratic manner, both in phase and magnitude. Thus the conventional matching techniques were not effective over any appreciable bandwidth. It was found that the most effective matching technique was to space the ferrite tubes in groups of two or three along the transmission line. An optimum spacing was determined empirically such that the reflections from each of the several distributed discontinuities interfered destructively. In this way a satisfactory match was attained over very broad bandwidths.

Another TEM mode structure useful in the design of reciprocal ferrite devices is strip transmission line. The field configuration of the dominant mode is as shown in Fig. 2(a). The microwave magnetic field is most intense in plane a–b and is linearly polarized at all points in this plane. The field intensity decreases rapidly with lateral displacement and at a point, a distance w from the end of the center strip, it is 27 db below the maximum value. If a thin ferrite slab is positioned on the center strip at plane a–b, gyromagnetic resonance effects are obtained. The bias may be either longitudinal or transverse to the broad dimension of the transmission line.

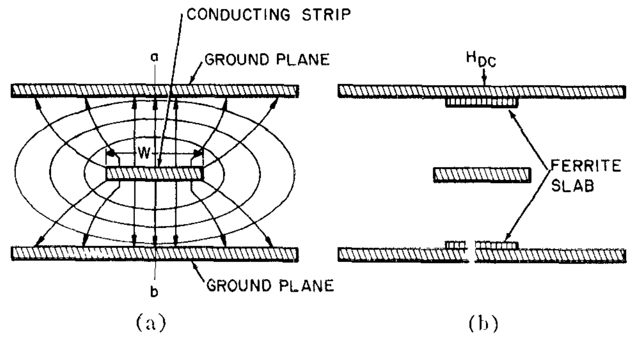

Fig. 2—(a) TEM mode field configuration of balanced strip transmission line. (b) End view of ferrite-loaded strip-transmission-line structure.

Two ferrite slabs were used: one centrally positioned on the upper ground plane, the other positioned directly below it on the lower ground plane [Fig. 2(b)]. This ferrite configuration was chosen since it preserves the symmetry of the transmission line and gives a reasonable match. The dc magnetic bias was applied transverse to the broad dimension of the transmission line.

Securing a good match is less difficult in strip transmission line than in coaxial line. In the latter case, the ferrite is situated in the region of maximum magnetic field. Also, the microwave magnetic field encounters the ferrite medium throughout its closed loop. Neither of these conditions exist in the balanced stripline configuration of Fig. 2(b). Therefore, the discontinuity created by the ferrite is less in this structure and the match is correspondingly better.

Devices

Variable Attenuator

A direct application of the ferrite-loaded TEM mode transmission line structure is the variable attenuator. For a fixed microwave frequency, there is but one value of magnetic bias corresponding to the resonant condition. If the bias field is varied from its resonant value, the attenuation will decrease from its maximum value. The value of minimum attenuation is determined by the low field characteristics of the particular ferrite employed. At a fixed frequency, the upper and lower limits of attenuation and the swing in bias required to span these limits, are solely a function of ferrite type.

The ideal ferrite for this application saturates at low bias fields, has a small imaginary component of the dielectric constant, a large imaginary component of the effective permeability at resonance, a high saturation magnetization, and a high Curie temperature. As a consequence of the first two characteristics, the insertion loss and the lower limit of attenuation will be small. The condition on the imaginary component of the effective permeability ensures a high resonance loss, and hence a large upper limit of attenuation. Eq. (1) demonstrates that at a particular frequency a ferrite of high saturation magnetization requires a low value of bias for resonance. This permits use of a small electromagnet both in terms of size and driving power. If the power

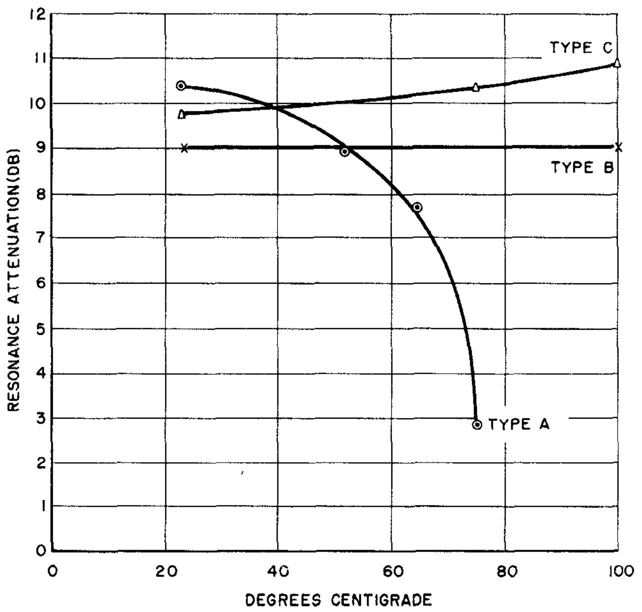

Fig. 3—Temperature dependence of resonance attenuation for several ferrite aluminates.

ferrite chosen for this application met all the criteria except that of high saturation magnetization. The material used was a ferrite aluminate having a saturation magnetization of 650 Gauss.

The variable attenuator was designed in $\frac{3}{8}$ coaxial line to operate from 2 kmc to 4 kmc. A continuous change in attenuation from 0.5 to 6 db was attained at the low end of the band and from 0.2 to 10 db at the high end. The maximum vswr was less than 1.5. Whereas this component is suitable for the particular application for which it was designed, improved results are attainable in strip transmission line.

The strip transmission line variable attenuator utilized two slabs of low loss ferrite aluminate centrally positioned on the upper and lower ground planes [Fig. 2(b)]. The attenuation was variable from a minimum of 0.3 db to a maximum of 10 db. Maximum vswr was equal to 1.22 (Fig. 4). While no attempt has been to optimize these results, they are significant in that they illustrate the feasibility of strip-transmission line in reciprocal ferrite applications.

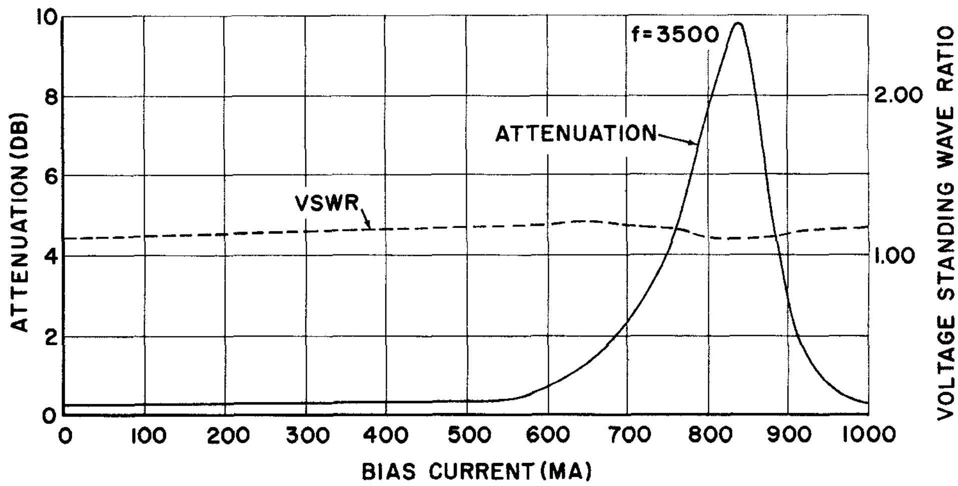

Fig. 4—Variation of attenuation and vswr with magnetic biasing at a single frequency for the strip-transmission-line variable attenuator.

dissipation of the magnet becomes too great, the temperature in the vicinity of the ferrite may approach or exceed the Curie temperature of the ferrite with a resultant deterioration or complete collapse of the attenuation characteristic.

Fig. 3 shows the temperature dependence of resonance attenuation for three ferrite aluminates at 3 kmc. Type A has a low Curie temperature and hence exhibits a rapid deterioration of ferromagnetic effects even with small increase in temperature. Types B and C have high Curie temperatures and suffer no appreciable decrease in their ferromagnetic properties over the desired temperature operating range. The resonance attenuation of type C increases with temperature because the material is not fully saturated at 3 kmc.

The criteria established with respect to ferrite characteristics were not all achievable in a single ferrite. The

Equalizer

An equalizer is used at the output of a traveling-wave tube amplifier, to correct for the variation of gain with frequency. For example, if the amplification of the traveling wave tube varies with frequency as shown in Fig. 5(a), the equalizer should possess an attenuation characteristic [Fig. 5(b)] such that the output of the tube is made independent of frequency. [Fig. 5(c)].

A stagger tuning method is employed to achieve the equalizer characteristic. Several ferrites, each of different saturation magnetization, were used. At a fixed magnetic bias, each ferrite will resonate at a different frequency. Kittel's formula for this configuration (1) indicates that a ferromagnetic material characterized by a high $4\pi M_s$ will introduce attenuation at the high end of the frequency band. Similarly, low $4\pi M_s$ ferrites will introduce attenuation at the low end of the band. By

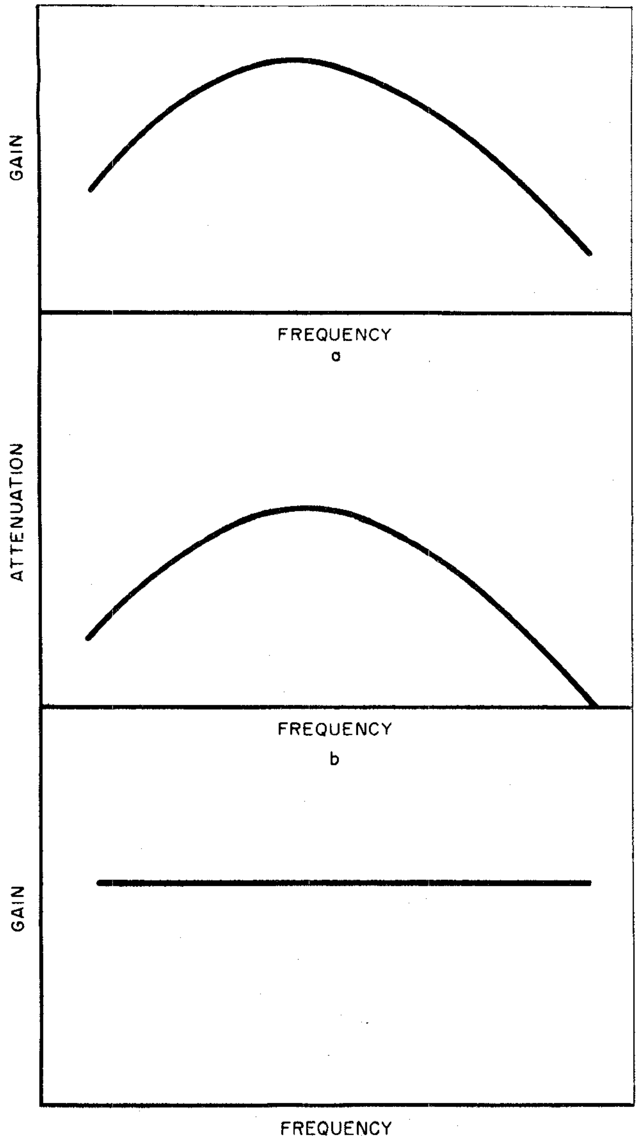

Fig. 5—(a) Typical gain-frequency characteristic of a twt amplifier. (b) Attenuation characteristic required to equalize twt output. (c) Equalized twt output.

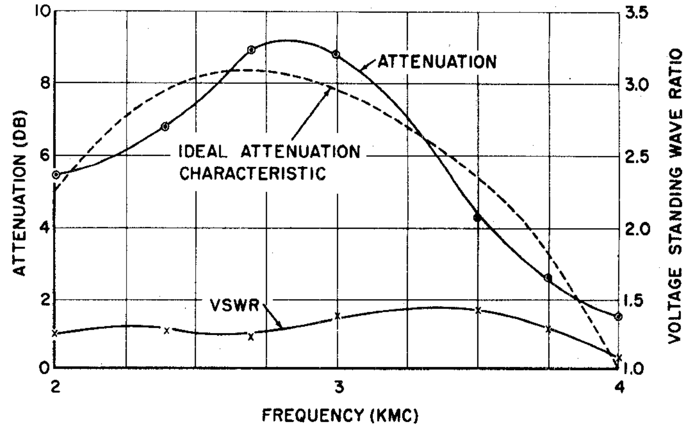

Fig. 6—Final attenuation and vswr characteristics of the coaxial traveling-wave-tube equalizer.

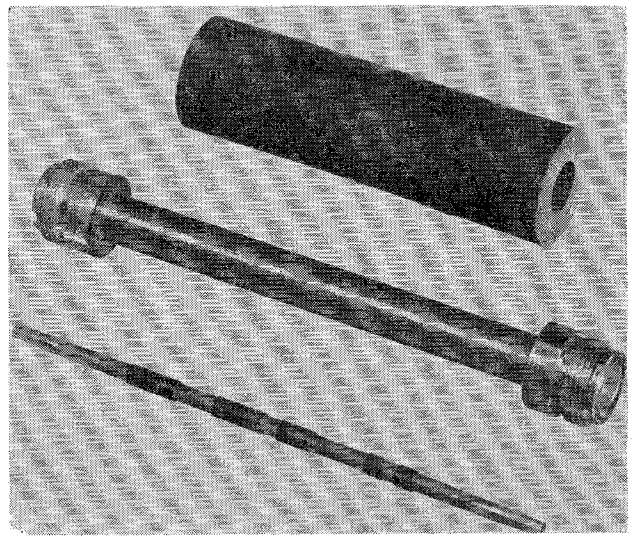

Fig. 7—Component parts of traveling-wave-tube equalizer.

suitable choice of $4\pi M_s$ values, and proper adjustment of ferrite length, the desired attenuation characteristic is achievable.

Fig. 6 shows both the ideal and actual attenuation curves. They match within approximately ± 1 db over the band. Three ferrite aluminates having saturation magnetizations of 800, 1800, and 2000 Gauss were used. Since vswr's of 1.5 could be tolerated in this application and since the over-all length of this component was to be kept at a minimum, ferrite tubes with a 12 thousandths wall were used.

The vswr varied from a maximum of 1.45 to a minimum of 1.10. A photograph of this component appears in Fig. 7. The total length is $4\frac{1}{2}$ inches.

If an electromagnet is used to provide a portion of the magnetic bias field, the attenuation characteristic may be varied. Thus the equalizer may be adapted for use with traveling-wave tubes differing in their gain-frequency dependence.

Modulator

The last component to be discussed is a $\frac{3}{8}$ coaxial line S-band amplitude modulator operating from 2 kmc to 4 kmc (Fig. 8). The ferrite-loaded transmission line structure is used in conjunction with both an electromagnet and a permanent magnet (the former fitting within the latter). The permanent magnetic field is of the proper value to bias the ferrite to resonance at the center of the frequency band. When the electromagnet is energized, the axial field produced contributes to the field of the permanent magnet, thereby, changing the bias. This in turn causes the resonant frequency to shift in accordance with (1). Thus the resonance attenuation peak may be shifted throughout the frequency range by appropriately varying the bias. The further removed a frequency is from resonance, the less is the attenuation, until at frequencies in excess of several hundred megacycles from resonance, the attenuation is negligible. If an alternating current is applied to the electro-

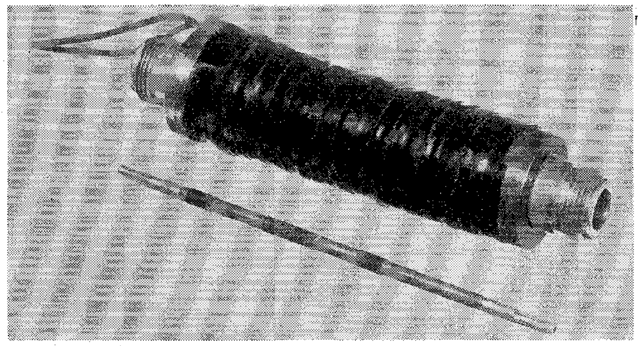

Fig. 8—Component parts of *S*-band coaxial amplitude modulator (permanent bias magnet not shown).

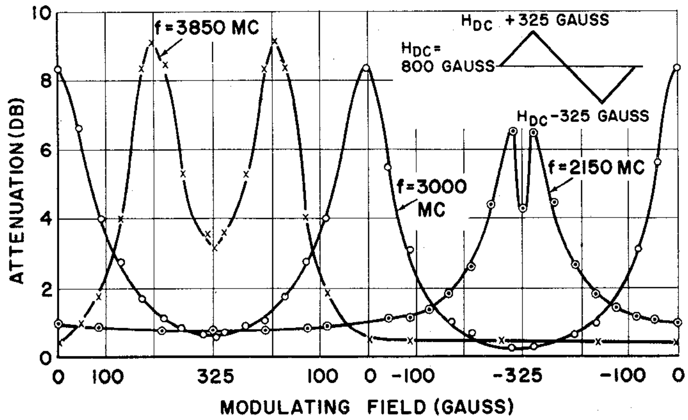

Fig. 9—Modulation characteristic at several frequencies of the *S*-band amplitude modulator.

magnet, the frequencies on either side of the center frequency will undergo cyclic variation in attenuation; maximum attenuation occurring at that frequency determined by the vector sum of H_{DC} and the instantaneous value of H_{AC} in (1). If the modulation current produces fields of sufficient strength, even the frequencies at the extremities of the band will undergo this cyclic variation; *i.e.*, amplitude modulation. Fig. 9 shows the modulation characteristic at several frequencies within the band. The modulating current waveshape was triangular and of sufficient amplitude to shift the resonance to within 150 mc of both ends of the frequency range.

A narrow linewidth ferrite aluminate was used in this application. Ten ferrite tubes, each $\frac{1}{8}$ inch long and 0.007 inch thick were spaced on the inner conductor. The average vswr was 1.35. The total length of this component is $4\frac{1}{2}$ inches.

Conclusion

A presentation has been made of the basic principles underlying the design of several reciprocal ferrite devices in TEM mode transmission line structures. Each component operated at gyromagnetic resonance and utilized either coaxial line or strip transmission line. An analysis of the mismatch ferrite loading creates in coaxial line was given and the technique used to improve the match described. A comparison was made between results in coaxial and strip transmission lines. The effect of ferrite size, shape, linewidth, saturation magnetization, temperature, and frequency on component performance was discussed and final operating data presented on each of the components.

Acknowledgment

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