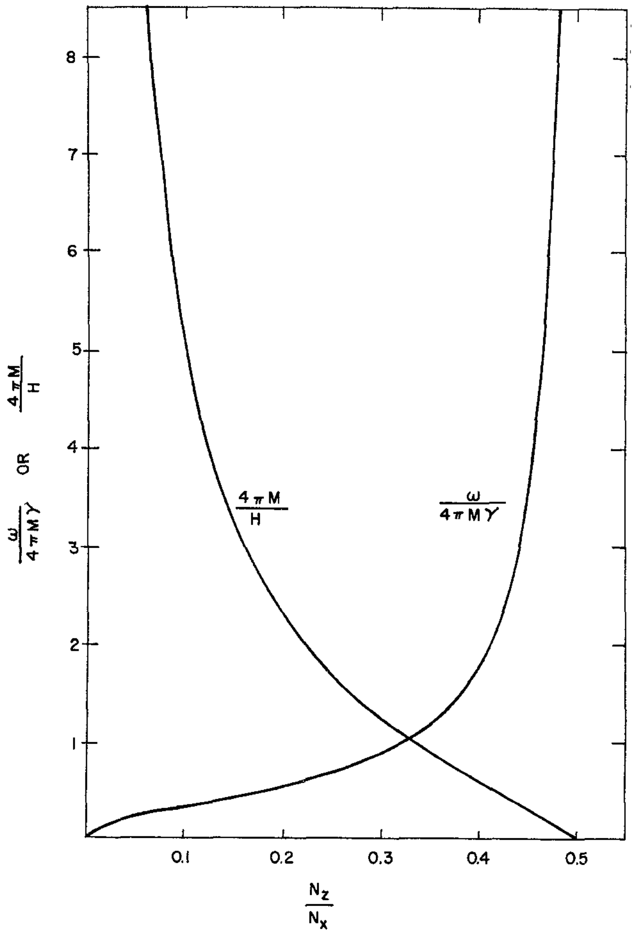

Fig. 5—Resonance frequency or magnetic field value vs N_z/N_x for $d\omega/dM=0$.

0.50, or the field to be applied is 4000 gauss. Suppose, however, we choose to use a high Curie temperature ferrite with a saturation magnetization of 3500 gauss. Then, $\omega/4\pi M\gamma$ is 0.57, N_z/N_x is 0.20 and $4\pi M/H$ is 2.25. Here the field required for resonance is 1555 gauss.

Conclusions

Ferrite shapes can be chosen to minimize change in microwave resonance frequency whenever saturation moment decreases due to ambient temperature changes. However, if the temperature rise is due to power absorption within the ferrite, several additional factors must be considered in designing a device for minimum shift of resonance frequency. First is the cooling effect of the metallic wall on the ferrite. This sets up a thermal gradient across the ferrite and consequently the optimum N_z/N_x varies, since $4\pi M$ varies throughout the material. Second, presence of the metallic wall tends to stabilize the ferrite temperature, and it will probably be found that the optimum shape for the extremely high average power device is a compromise between maximizing the area between the ferrite and waveguide wall for heat transfer reasons, and choosing an optimum shape for minimizing the thermally caused shift in resonance frequency. For applications where environmental temperature of the device is to vary over wide ranges, choice of N_z/N_x, as shown in Fig. 5, is optimum.

Discrepancies between the resonance frequency predicted by Kittel's equation and that measured for the configuration of Fig. 3(a) can be attributed to an RF image at the waveguide wall.

Characteristics of Ferrite Microwave Limiters*

G. S. UEBELE†

Summary—Microwave ferrites that exhibit a nonlinear RF absorption as a function of RF power level can be utilized in the construction of a passive microwave device which will allow small RF signals to be transmitted with very little attenuation but which will attenuate large RF signals considerably. Such a device tends to "limit" the amplitude of the microwave energy passing through the device and is therefore called a ferrite microwave limiter.

One application of the ferrite limiter is in the protection of crystal detectors in pulsed radar sets. However, when a rectangular pulse of X-band RF energy is transmitted through the limiter, the output waveform is no longer rectangular but consists of a leading edge spike of 0.1-μsec duration followed by a plateau of highly attenuated RF energy. At the present time the leading edge spike is the major obstacle in the successful use of the ferrite microwave limiter as a TR cell in the protection of crystal detectors.

Experimental techniques used to improve the performance of the limiter are presented, and the performance characteristics of an X-band ferrite microwave limiter are shown.

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Principle of Operation

The nonlinear properties of ferrites were first observed in cavity experiments conducted by Damon[1] and by Blombergen and Wang[2] in 1950 and 1951. Similar observations in ferrite-loaded waveguide

[1] R. W. Damon, "Relaxation effects in ferromagnetic resonance," *Rev. Mod. Phys.*, vol. 25, pp. 239–245; January, 1953.

[2] N. Blombergen and S. Wang, "Relaxation effects in para- and ferromagnetic resonance," *Phys. Rev.*, vol. 93, pp. 72–83; January, 1954.

experiments at other laboratories[3-5] influenced the choice of ferrite material for use in high-power ferrite devices.

In Fig. 1[6] the attenuation of a ferrite-loaded waveguide is plotted as a function of the magnitude of the magnetic bias field. An attenuation curve is plotted both for a small RF signal (about 100 mw at 9000 mc) and for a large RF signal of 60 kw. The attenuation curve for 60 kw of RF power clearly shows a subsidiary resonance at about 1250 gauss which did not occur at the lower power level. If the amplitude of the magnetic bias is fixed at 1250 gauss, a 100-mw RF signal is essentially unattenuated, but a 60-kw signal is attenuated by 1 db. The ferrite microwave limiter is based upon this effect.

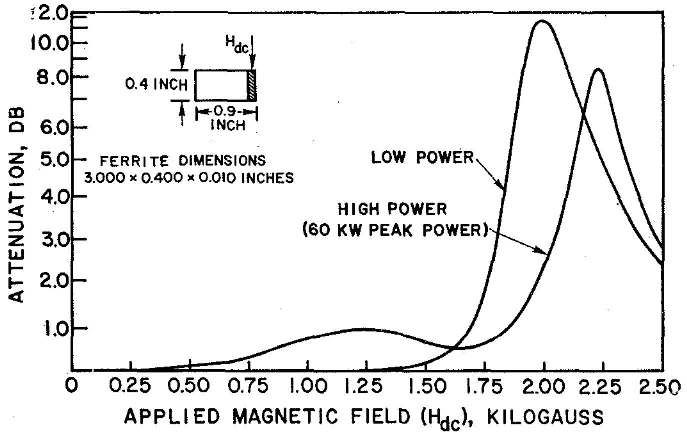


Fig. 1—Low-power and high-power attenuation curves for General Ceramics Ferramic R-1 ferrite.

A theory which qualitatively accounts for the subsidiary resonance at high RF power levels has recently been advanced by Suhl[7] of Bell Telephone Laboratories. In brief, the ferrite's nonlinear absorption and the existence of the subsidiary resonance are contributed to the generation of lossy spin modes within the ferrite's crystal lattice when the strength of the RF magnetic field reaches a critical threshold value. The threshold of RF energy is related to the saturation magnetization and ferromagnetic resonance linewidth of the ferrite for the case of single crystals of ferrite of spheroidal geometry and circularly polarized RF excitation. Suhl's theory indicates that a ferrite with a narrow ferromagnetic resonance linewidth and a high saturation magnetization is required for the greatest limiting effect.

[3] M. T. Weiss, "High Microwave Power Effects on Ferromagnetic Resonance in Ferrites; I. Main Resonance," Bell Telephone Labs., Holmdel, N. J., Tech. Memo. No. 56-123-43; October 22, 1956.

[4] N. G. Sakiotis, H. N. Chait, and M. L. Kales, "Nonlinearity of microwave ferrite media," IRE TRANS. ON ANTENNAS AND PROPAGATION, vol. AP-4, pp. 111–115; April, 1956.

[5] E. T. Wierman, unpublished data, Hughes Aircraft Co., Culver City, Calif.; September, 1956.

[6] In Fig. 1 the increased magnetic bias field required for ferromagnetic resonance at high RF power levels is due to the lowering of M_s when the ferrite temperature is raised by RF losses.

[7] H. Suhl, "The nonlinear behavior of ferrites at high microwave signal levels," PROC. IRE, vol. 44, pp. 1270–1284; October, 1956.

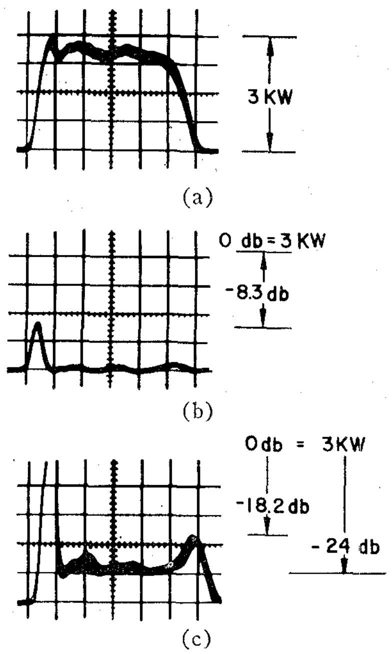


Fig. 2—Input and output RF pulse shapes for an experimental ferrite limiter (Fig. 3 configuration). (a) Input pulse, 0.1 μsec per division. (b) Output pulse. (c) Output pulse magnified 20 times.

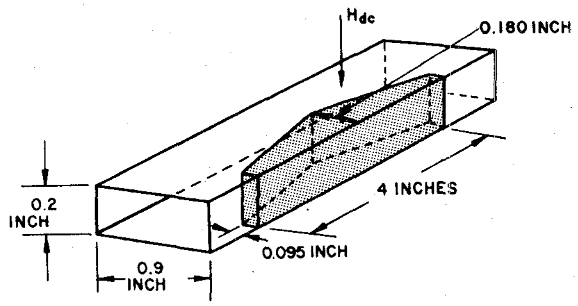


Fig. 3—An experimental ferrite microwave limiter using Ferramic R-1 ferrite.

Design Objectives

One application of the ferrite limiter is in the protection of crystal detectors in pulsed radar sets. The effect of the ferrite microwave limiter on the waveshape of pulses of high-power RF energy is therefore of considerable interest. Fig. 2 shows oscilloscope traces of an RF pulse before and after limiting for the specific ferrite waveguide configuration shown in Fig. 3, in which General Ceramic's Ferramic R-1 ferrite was used. In general, the shape of the limited RF pulse is a flat plateau with spikes of energy, approximately 0.1 μsec in duration, at the leading and trailing edges. Because of this RF waveshape distortion, it is advisable to review the theory of crystal detector "burnout" before design objectives for the limiter can be established.

It is generally accepted that crystal burnout is due primarily to excess heating in the proximity of the whisker silicon contact area.[8] The temperature in this

[8] H. C. Torrey and C. A. Whitmer, "Crystals Rectifiers," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 15, pp. 236–263; 1948.

area is a function of the energy vs time distribution of the RF input pulse and the thermal capacity of the crystal. If the RF spike energy impinging on the crystal has a time duration less than the thermal time constant (τ) of the crystal, then the energy content of the spike is the important burnout factor. However, if the width of the spike is greater than the thermal relaxation constant of the crystal, the temperature attained depends upon the rate at which energy is applied to the crystal, *i.e.*, the power amplitude of the spike.

For crystals in the 1N23 series, the burnout temperature of the whisker-silicon contact is about 500°C and the thermal time constant is of the order of 0.02 μsec. The thermal capacity of the 1N23E[9] crystal is such that, for RF pulses of about 0.02 μsec or less, the crystal burnout is 2 ergs. Since the duration of the leading edge spike of the output from a gas *TR* cell is about 0.002 μsec, gas *TR* cells are rated in ergs of energy output. By extrapolating these data (Fig. 4), one arrives at a maximum allowable peak-power level of 10 watts for spikes of long-time duration. Since the duration of the leading edge spike of a "limited" pulse of RF energy is 0.1 μsec, this spike amplitude must not exceed 10 watts if crystal burnout is to be prevented.

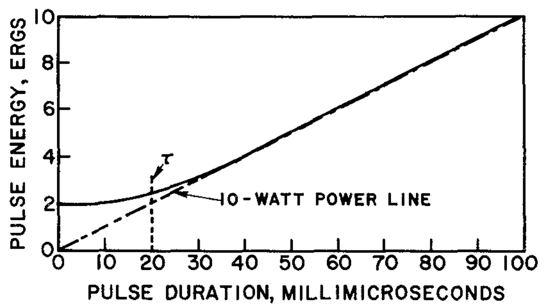


Fig. 4—Probable energy for burnout of 1N23E crystal as a function of RF pulse width.

However, crystal burnout is not the only parameter to be considered in designing a *TR* cell for crystal protection in a radar system. Equally important is the amount of service a crystal detector will give before it has to be replaced. This is determined by loss of conversion efficiency of the crystal and by the increase of noise level as a function of time. Both of these deleterious "aging" factors of a crystal are directly related to the amplitude of the input RF pulses to the crystal. Therefore, the *TR* cell requirements established by the radar designer will be a compromise between crystal life and *TR* protection required, and no rigorous specification can be made on the limiter for this purpose. However, since it appears that manufacturers design gas *TR* cells with a spike leakage value of 10 per cent of that required for crystal burnout, it seems reasonable to require that the output RF waveform from a ferrite limiter exhibit no amplitude greater than one watt.

[9] Microwave Associates, Inc., Boston, Mass., Short Form Catalog 57-BG.

Parameters Affecting Limiting

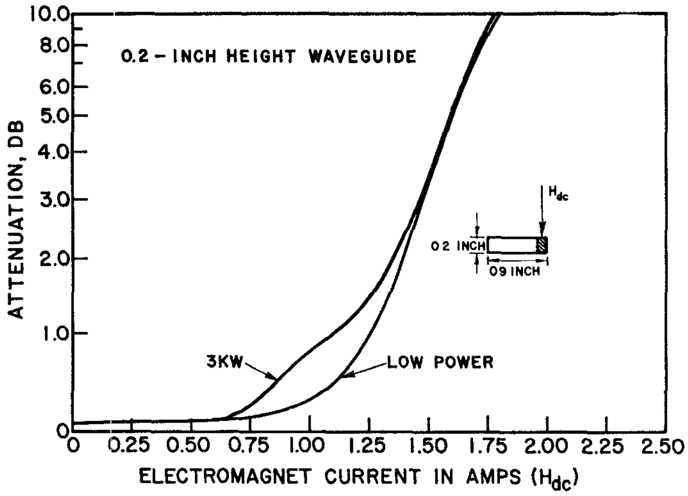
A number of commercially available ferrites as well as ferrites synthesized at Hughes Aircraft Company were tested for their nonlinear properties. Of the ferrites tested, General Ceramic's Ferramic R-1 ferrite was chosen to demonstrate limiter characteristics because it exhibits considerable nonlinearity and is readily available in quantity. Ferramic R-1 ferrite has a saturation magnetization of 2500 gauss and a ferromagnetic resonance linewidth of 320 oersteds at 9000 mc.

One of the first parameters investigated was the direction of the applied magnetic bias field in relation to the ferrite sample and the direction of RF propagation. For a slab of Ferramic R-1 ferrite, 1.5 inches by 0.195 inch by 0.120 inch, placed adjacent to the narrow wall of a 0.2-inch by 0.9-inch waveguide, there appeared to be no preferred direction of H_{dc} for greatest limiting effect. Therefore, the practical aspects of achieving the large magnetic bias fields required were considered, and the magnetic bias field transverse to the wide wall of the waveguide was chosen for further tests.

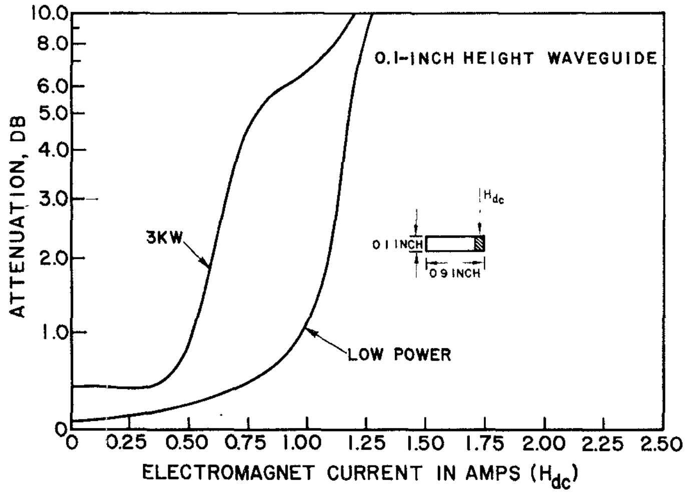
With the direction of the applied magnetic bias field established, the next parameter varied was the distance of the ferrite slab from the side wall of a 0.2-inch by 0.9-inch waveguide. For this test the ferrite was 0.030 inch thick, 0.195 inch high, and 4 inches long. Suhl's theory[7] and work done by Sakiotis, Chait, and Kales[4] would seem to indicate that optimum results will occur at that distance where a circular polarized RF magnetic field is encountered. When the ferrite is placed at this location, there is a decided difference in RF attenuation for opposite polarities of the magnetic bias field. However, there is not enough improvement in the limiting which is observed when the ferrite is in direct contact with the side wall to warrant removing the ferrite from the side wall, which acts as a good heat sink.

With the direction of the magnetic bias field and the placement of the ferrite in the waveguide established, techniques for increasing limiting action by intensification of the RF magnetic field in the ferrite can now be considered. Fig. 5 illustrates two techniques for intensifying the field: reduction of the waveguide height, and the use of dielectric loading. Since the majority of measurements on ferrite limiters were done in 0.2-inch by 0.9-inch waveguide, this size waveguide is used as a standard for comparison [Fig. 5(a)]. The ferrite used was a slab of Ferramic R-1, 0.030 inch thick and 6 inches long. The height of the ferrite was 0.195 inch for the 0.2-inch by 0.9-inch waveguide and 0.095 inch for the 0.1-inch by 0.9-inch waveguide.

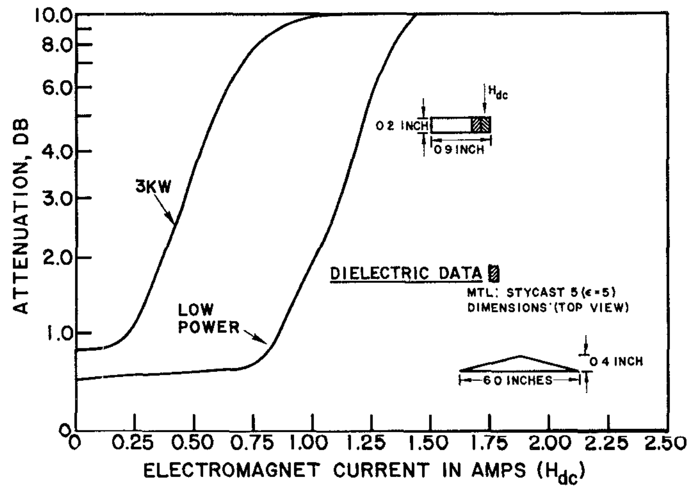
Since the RF magnetic field intensity is inversely proportional to the height of the waveguide, reduction of the waveguide height by one half to 0.1 inch [Fig. 5(b)] increased the limiting by 3 db.



(a)



(b)



(c)

Fig. 5—Effect on limiting by enhancing the RF field intensity in the ferrite. (a) "Standard" waveguide. (b) Effect of reducing height of waveguide. (c) Effect of dielectric loading.

If a dielectric material is placed adjacent to the ferrite, as shown in Fig. 5(c), the RF energy in the waveguide is "pulled over" into the ferrite. The resultant intensification of RF magnetic field increases the limiting effect considerably. In this case a 7-db increase was achieved.

Very large RF magnetic field intensities can be achieved by resonant cavity techniques.[10] The main disadvantage to this method of enhancing limiting is the narrow bandwidth of the device. However, for a narrow-bandwidth microwave system, the cavity technique should give superior results.

The effect of ferrite length on the leading edge spike and the plateau of a limited RF pulse is shown in Fig. 6.

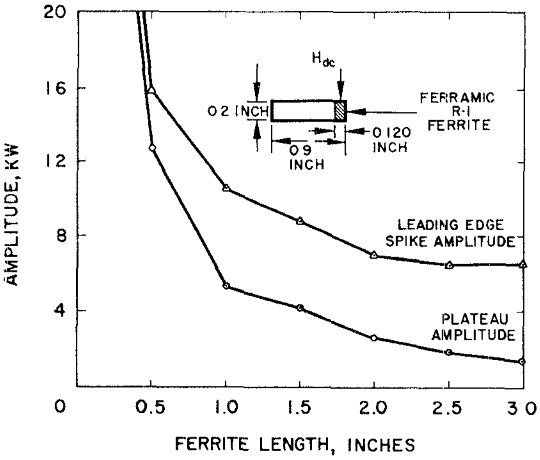


Fig. 6—Output pulse shape vs ferrite length (48-kw peak power input).

It is apparent that there must be sufficient ferrite in the waveguide to utilize the nonlinearity to its utmost, but a compromise must be made if the low power loss is to be kept at a minimum. An input power of 48 kw was chosen so that an effect could be clearly demonstrated for the shorter lengths of ferrite.

Effect on RF Waveshape

An experimental limiter using Ferramic R-1 ferrite (see configuration in Fig. 3) was constructed for the purpose of observing the operating characteristics of a limiter at high RF power levels.

The waveform of a 3-kw pulse of RF energy at 9000 mc, limited by this limiter, is shown in Fig. 2. The resultant waveform consists of a spike of energy of 650 watts amplitude and 0.1 μsec duration, then a plateau of

[10] If the RF phase shift exhibited by a ferrite, magnetically biased for optimum limiting, were different at low and high RF power levels, then a transmission cavity (containing the ferrite) adjusted for minimum loss at low power levels would be "detuned" at high RF power levels and would achieve very large *TR* attenuation ratios. A similar technique is used in most gas *TR* cells. However, phase shift measurements made on a limiter (Fig. 3) and a number of ferrite phase shifters at RF power levels up to 10 kw showed no change in phase that could not be accounted for by the change of M_s of the ferrite due to RF heating.

highly attenuated RF energy of 11.0 watts amplitude and 0.4 μsec duration, followed by a trailing edge spike of 45.5 watts amplitude and 0.1 μsec duration. The energy distribution for the leading edge spike, the plateau, and the trailing edge spike is 210 ergs, 70 ergs, and 25 ergs, respectively. At the present time it is believed that the 0.1 μsec duration of the leading edge spike is due to the conversion time from the uniform mode to the spin modes, and that the 0.1 μsec duration of the trailing edge spike is due to the relaxation time of the spin modes.

It was felt that if the build-up time of the input RF pulse was prolonged, perhaps the leading edge spike could be eliminated. Therefore, the limiter (Fig. 3 configuration) was subjected to high-power RF pulses of 0.05-μsec rise time and then to RF pulses of 0.3-μsec rise time. It was found that while the rise time of the leading edge spike was longer for the latter case, the amplitude of the spike and its decay time were unchanged.

If the limiter is to be used as a *TR* cell for a crystal detector, it is important to know how the limiter performs for various values of input power level. Therefore, an examination of the "limited" RF waveform as a function of input power level was made. A magnetron with the RF pulse shape shown in Fig. 2(a) was used as the signal source.

The results, presented in graph form in Fig. 7, show that no limiting effect takes place until the input power level reaches 110 watts. Above 110 watts a plateau is formed rapidly until, at 3 kw, the plateau reaches its lowest magnitude. During the same range of input power levels, a leading edge spike is formed. Between 3 and 9 kw input power, the plateau and leading edge spike remain unchanged. In practice it would be desirable to operate the limiter so that this stabilized region in ferrite characteristics coincides with the range of input power levels expected. Above 9 kw the plateau amplitude rises rapidly.

A possible explanation for this power level dependence is as follows. Consider the spin modes being coupled with the uniform mode through a nonlinear coupling coefficient. In this case, below 110 watts, the RF threshold of nonlinearity, the coupling coefficient is zero. Between 110 watts and 3 kw the coupling coefficient increases from zero to some finite value, energy is coupled into a lossy spin mode, and the plateau is formed. But since the coupling coefficient increases as the input power is increased, energy is coupled into the spin mode at a greater rate than if the coupling coefficient were a constant. As the result, the plateau power level is a decreasing function in this range of power levels. Because the spin modes require a certain time to build up, 0.1 μsec, the leading edge spike is formed.

Above 3 kw the coupling coefficient is constant, but as one spin mode is saturated, higher order spin modes are excited until at 9 kw all possible spin modes are excited. This would explain the stabilized region from 3 to 9 kw.

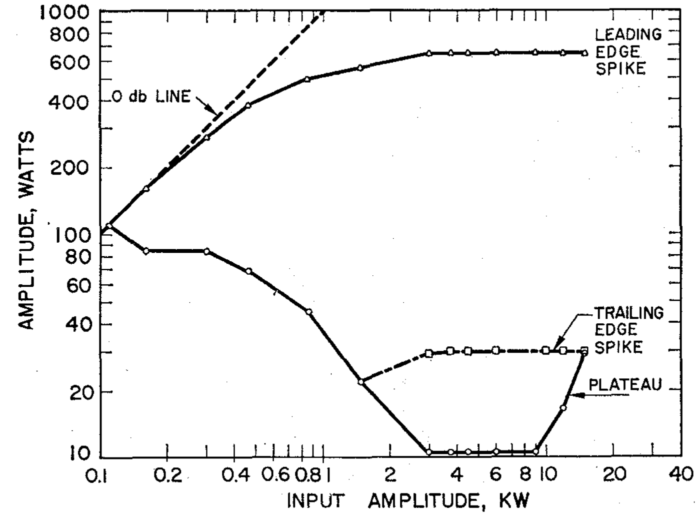


Fig. 7—Output pulse shape vs input power for a ferrite limiter (Fig. 3 configuration).

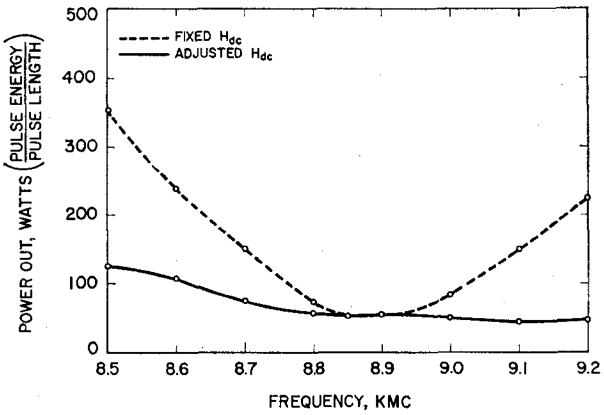


Fig. 8—Limiting vs frequency for a ferrite limiter (Fig. 3 configuration).

Above 9 kw, since all possible spin modes are saturated, the plateau power level rises.

The trailing edge spike appears to be reactive energy stored in the spin modes which is recoupled from the spin modes to the uniform mode when the input RF power level is removed; *i.e.*, similar to the ringing of an inductance or capacitance after it is de-energized. The trailing edge spike is usually hidden by the plateau until the plateau amplitude is reduced to a sufficiently small value.

In these tests, it was also observed that while the nonlinear behavior of the ferrite reached a maximum for one value of magnetic bias field, the effect existed, to a lesser degree, at all magnetic bias fields below ferromagnetic resonance but never above.

Bandwidth characteristics of the limiter (Fig. 3 configuration) are shown in Fig. 8. As can be seen, the magnetic bias field must be programmed as a function of frequency if optimum limiting is to be expected over the desired bandwidth. This programming of the magnetic bias field can be reduced or perhaps even eliminated by the use of a nonuniform magnetic bias field or a different ferrite geometry. At low RF power levels the limiter exhibits a maximum insertion loss of 0.9 db and a maximum VSWR of 1.13 over the band.

Conclusion

In this paper several techniques for increasing the insertion loss of ferrite-loaded waveguide structures at high RF power levels have been presented, and the operating characteristics of a ferrite microwave limiter have been described. The most important problem appears to be the distortion of the RF pulse waveform by the ferrite limiter. While the plateau of the limited RF pulse has been reduced to 11 watts and further improvement can reasonably be expected, the leading edge spike, because of its large amplitude and long duration, is a more severe problem. Perhaps as we learn more about the mechanism of the ferrite's nonlinear behavior, engineering techniques can be found which will solve the spike problem by an appropriate waveguide-ferrite configuration or through the use of new ferromagnetic materials.

Acknowledgment

The author wishes to thank the various laboratory personnel who contributed suggestions in a number of the experiments. The assistance of W. Asp in the laboratory measurements is especially appreciated.

Nonreciprocity in Dielectric Loaded TEM Mode Transmission Lines*

D. FLERI† AND G. HANLEY†

Summary—**An analysis is presented of partially dielectric loaded strip transmission line from the point of view of ferrite applications. It is shown that the microwave magnetic field is elliptically polarized both at the dielectric surface and within the dielectric. The degree of elliptical polarization is expressed analytically as a function of the dielectric constant, the degree of dielectric loading, and the frequency. For specific values of dielectric constant and loading, a high degree of circularity may be made to exist at the dielectric surface over extremely broad frequency bands. Experimental data are presented which are in accord with the theoretical predictions.**

Introduction

A GREAT variety of nonreciprocal propagation characteristics has been achieved at microwave frequencies through the use of ferrites. A necessary requirement for nonreciprocity is that the microwave magnetic field in the region of the ferrite be circularly polarized.[1] This requirement is easily met in rectangular waveguide propagating the dominant mode[2-4] and in circular waveguide propagating the circularly polarized TE_{11} mode.[3-4] In coaxial line and strip transmission line propagating the TEM mode, however, the microwave magnetic field is linearly polarized at all points, and therefore any ferrite effects will be completely reciprocal. It has been reported previously[5-6] that partially filling the cross section of coaxial line with a dielectric serves to distort the mode pattern and create an almost true sense of circular polarization at the air-dielectric interface. This mode distortion technique thereby renders coaxial line suitable for nonreciprocal applications. In a similar manner, polarization conversion may be effected in strip transmission line by appropriate dielectric loading.[7] Analysis of this latter transmission line structure forms the substance of this paper.

The dielectric loaded strip transmission line configuration is shown in Fig. 1. The co-ordinate axes are chosen so that Z represents the direction of propagation, and Y represents what will be referred to subsequently as the transverse direction. It will be shown that the polarization is elliptical both at the dielectric surface and within the dielectric. The degree of elliptical polarization at the dielectric surface is a function of the dielec-

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

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