and propagating TE-mode waves in the positive y direction, and

$\beta_- =$ the computed constant for TE-mode waves propagating in the negative y direction.

A typical plot of the computed phase constants vs slab position is shown in Fig. 2; the corresponding plot of the differential phase shift is shown in Fig. 3.

The values of the pertinent parameters were

microwave frequency,	$f = 16.0$ Gc,
inner width of K_u band waveguide,	$L = 0.622$ in,
g factor of ferrite,	$g = 2.2$,
relative dielectric constant of dielectric,	$K_d = 12.0$,
relative dielectric constant of ferrite,	$K_m = 10.0$,
saturation magnetization of ferrite,	$4\pi\ M_s = 1750$ Gauss.

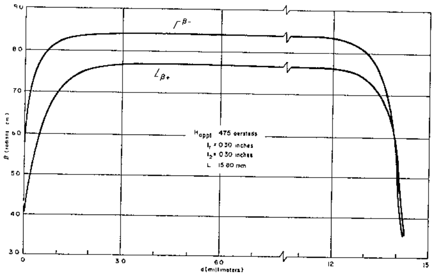

Fig. 2—Computed phase constants, β_+, vs slab position, d.

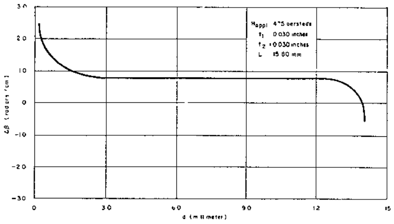

Fig. 3—Computed differential phase shift, $\Delta\beta$, vs slab position, d.

EXPERIMENTAL DATA

Direct comparison of the experimental with the theoretical values of the differential phase shifts was obtained for a series of slab positions in the waveguide. The top and bottom broad walls of a section of waveguide were cut away and replaced by sliding metal plates. The narrow walls remained stationary. The ferrite-dielectric slab configuration was affixed to the plates and was moved so that the slabs were always parallel to the narrow walls. The phase shifts and insertion losses were measured by balancing a known electrical length of transmission line against the unknown length containing the ferrite-dielectric configuration.

The values of the differential phase shifts were measured for a series of slab positions for static fields of 475, 600, and 1000 oe. A typical graph of the measured differential phase shift vs slab position is shown in Fig. 4. As was to be expected, propagation was quite lossy for slab positions near the narrow walls of the waveguide,[6] and measurements of the phase shifts proved erratic.

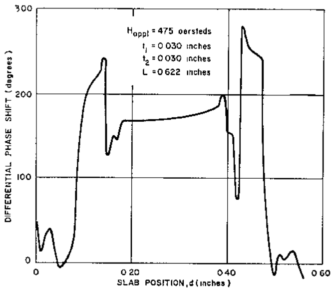

Fig. 4—Measured differential phase shift vs slab position.

The computed and measured values of the differential phase shifts are compared in Table I for the three values of the applied magnetic field. A constant, appreciable value of the differential phase shift is obtained for slab positions about the center of the waveguide. In contrast, the value of the differential phase shift for unloaded ferrite slabs tends toward zero[1] for central slab positions.

TABLE I

COMPARISON OF EXPERIMENTAL AND THEORETICAL VALUES OF THE DIFFERENTIAL PHASE SHIFT*

Applied Magnetic Field, H_z	Total Differential Phase Shift	
(oersteds)	(experimental) (degrees)	(theoretical) (degrees)
475	170	169
600	176	180
1000	184	194

* $d = 0.300$ in = distance from waveguide wall.
$l = 1.550$ in = effective length of slab.

ACKNOWLEDGMENT

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The Gyromagnetic Coupling Limiter at C-Band*

The original paper of DeGrasse[1] and subsequent publications dealing with the use of the crossed-strip gyromagnetic coupler as a limiter[2] have been concerned with the operation of this device below 3300 Mc. At these frequencies the limiter exhibits a sharp threshold at a very low power level, in the neighborhood of −20 dbm. Fig. 1 illustrates typical flat leakage characteristics at a frequency of 2600 Mc. A single crystal YIG sphere of 26 mils was used in this limiter.

When spherical single crystal YIG ($4\pi M_s = 1750$) resonators are used, the theory developed principally by Suhl[3] indicates that a pronounced change in limiting characteristics should occur at about 3300 Mc. Above this frequency the first-order nonlinear process[4] is forbidden at resonance and the limiting characteristics observed must be attributed to the second-order process.

A crossed-strip limiter constructed for operation in C-band employing a single crystal YIG sphere 23 mils in diameter with $\Delta H \approx 0.43$ oersted exhibits the flat leakage characteristics shown in Fig. 2. In contrast with the S-band limiter a relatively high threshold is apparent, and the shape of the limiting curve indicates the smooth spin wave excitation to be expected as a result of inhomogeneity broading.[4-6]

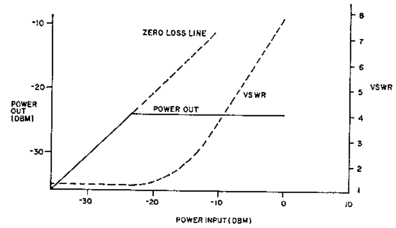

Fig. 1—Typical limiting characteristics of a gyromagnetic coupler when operating with a YIG sphere at frequencies between 1600 and 3300.

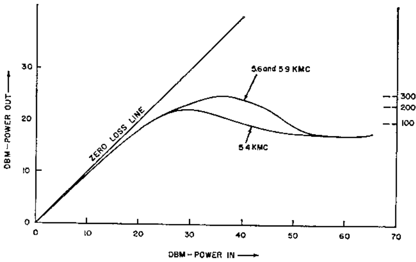

Fig. 2—Flat leakage characteristics of the C-band gyromagnetic coupling limiter.

With no field applied to the YIG sphere a strip-to-strip isolation slightly in excess of

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* Received by the PGMTT, September 8, 1961. This work was supported in part by the U. S. Army Signal Res. and Dev. Lab. under Contract No. DA-36-039-SC-85330.

[1] R. W. DeGrasse, "Low-loss gyromagnetic coupling through single crystal garnets," *J. Appl. Phys.*, suppl. to vol. 30, pp. 155s–156s; April, 1959.

[2] M. Grace, F. R. Arams and S. Okwit, "Low-level garnet limiters," PROC. IRE, vol. 49, pp. 1308–1313; August, 1961.

[3] H. Suhl, "Theory of ferromagnetic resonance at high signal powers," *J. Phys. Chem. Solids*, vol. 1, pp. 209–227; April, 1957.

[4] E. Schlomann, "Ferromagnetic Resonance at High Power Levels," Raytheon Co., Waltham, Mass., Tech. Rept No. R-48; October 1, 1959.

[5] A. M Clogston, *et al.*, "Ferromagnetic resonance line width in insulating materials," *J. Phys. Chem. Solids*, vol. 1, pp. 129–136, 1956.

[6] E. Schlomann, "Spin-wave analysis of ferromagnetic resonance in polycrystalline ferrites," *J. Phys. Solids*, vol. 6, pp. 242–256; 1958.

50 db was measured with the *C*-band limiter at 5.65 kMc. The limiter can be expected to have a dynamic range of approximately this value.

Fig. 3 illustrates the low power insertion loss characteristics over a range of frequencies in *C*-band. The biasing field was independently set for resonance at each frequency. The strip-to-strip isolation in the absence of an applied field was in excess of 40 db at each frequency.

Fig. 4 represents the output pulse of the limiter as observed on an oscilloscope. The trailing edge of the limited pulse is seen to extend beyond the trailing edge of the incident pulse. This is due to a "kickback" of energy from the garnet spin system. This effect has been observed to last from about 0.2 to 0.4 μsec, and should be regarded as the recovery time of the limiter.

The spike leakage characteristics of the limiter are favorable. Fig. 5 is a plot of incident pulse width vs average power out of the limiter ar the three *C*-band frequencies. The peak power was held at 2 kw and the PRF at 500 for each measurement. The intercepts at the vertical axis can be used to calculate the sum of spike leakage energy and kickback energy. The results as shown vary from 0.5 to 0.9 erg. Kickback energy can be estimated from measurements on the oscilloscope to be about 0.2 erg. Spike leakage from the limiter is therefore in the neighborhood of 0.5 erg.

The very low limiting thresholds of the "first-order" crossed-strip limiters reported, presently restrict their useful range to low peak power levels. In contrast with the first-order limiter, the second-order device reported here offers immediate promise for use in the capacity of crystal protection in the medium power range up to about 10-kw peak power.

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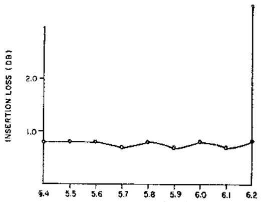

Fig. 3—Low-power (approximately 1-mw) insertion loss characteristics of the *C*-band gyromagnetic coupling limiter.

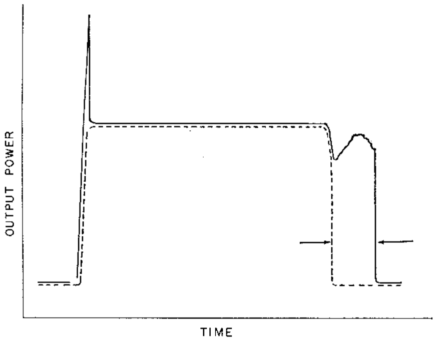

Fig. 4—Wave shape of the limited pulse as observed on the oscilloscope. Dotted line represents incident waveform attenuated for comparison with the limited pulse. The extended portion of the limited pulse is contained between the arrows.

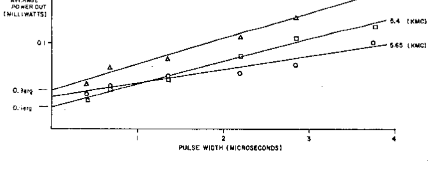

Fig. 5—Average power out of the *C*-band gyromagnetic coupling limiter at varying incident pulse widths.

Practical Microwave Power Limiters*

The near future holds considerable promise for the utilization of solid-state limiters as receiver protection elements. This correspondence describes the performance of ferrimagnetic limiters in the actual role of diode protection. The peak powers involved in the tests were up to 25 kw.

In one case a C-band coaxial line subsidiary resonance limiter was used to protect the varactor in a parametric amplifier. The safe signal power level in a varactor parametric amplifier is a difficult quantity to assess. The present test was carried out simply to provide information on short-term burnout effects in a particular parametric amplifier.

The configuration of the limiter is shown in Fig. 1. It used a high-density polycrystalline yttrium-iron garnet as the nonlinear medium. The limiter had a low power loss of 0.5 db and its output was 100-w flat power with a leading edge spike of leakage energy which was equal in amplitude to the input power and 50-nsec wide at half height. The parametric amplifier was a quasi-degenerate one-port device using a MA-4254 pill diode. The circulator used with the amplifier was a Sperry miniature coaxial circulator.[1] Similar circulators have been tested at 75-kw peak power (0.001 duty cycle) and found to maintain 30 db of isolation with 0.3-db insertion loss.

The amplifier limiter combination was subjected to 1.2-kw peak (0.0015 duty cycle) power input. The power input was increased in small increments from about 25 μw to 1.2 kw. The amplifier was allowed to run for a few minutes at each new power level and then returned to 25 μw to check for proper operation. The amplifier showed no adverse characteristics or change in performance as a result of the increases in power.

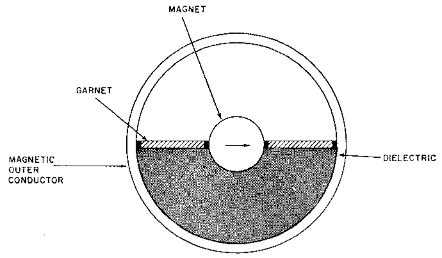

Fig. 1—Coaxial subsidiary resonance limiter.

In the second experiment, a gyromagnetic coupling limiter similar to the one described by DeGrasse[2] was used to protect a 1N23 crystal. The crystal was mounted directly on the output of the limiter in a tunable coaxial mount.

The tests were carried out at 5.7 kMc. The characteristics of the limiter used are fully described in an accompanying publication.[3] As indicated there the power output of the limiter declines after passing through a maximum of approximately 300 mw. The power output decreases as the susceptibility of the YIG sphere declines. The power output will continue to decrease until the limiting level is equal to the isolation between coupling strips in the absence of a reasonance biasing field on the sphere. For the configuration used in this test the isolation between strips was 53 db. At some input power level (probably about 10 kw for this configuration) the output power will being to rise monotonically.

For the actual test the power input to the limiter was raised in steps to 5 kw and the detected waveform of the crystal was monitored. Several crystals were selected at random and tested in this fashion. They all performed essentially the same, and showed no adverse effects. Here again only short-term effects were being tested. Fig. 2 shows a photograph of the waveform of the output of one of the crystals with 1.2 kw incident on the limiter.

In a third experiment, at 5.65 kMc, a waveguide subsidiary resonance limiter was used as a first-stage limiter ahead of the gyromagnetic coupling limiter. The characteristics of the first-stage limiter are shown in Fig. 3. A peak input power of 25 kw was

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[1] J. Clark and J. Brown, "Miniaturized, temperature stable, coaxial *Y*-junction circulators," IRE Trans. on Microwave Theory and Techniques (Correspondence), vol. MTT-9, pp. 267–269; May, 1961.

[2] R. W. DeGrasse, "Low loss gyromagnetic coupling through single crystal garnets," *J. Appl. Phys.*, suppl. to vol. 30, pp. 155s–160s; April, 1959.

[3] J. Clark and J. Brown, "Gyromagnetic coupling limiter at *C*-band," this issue, p. 84.