Low-Temperature Microwave Power Limiter*

A passive microwave power limiter, using the nonlinear properties of ferromagnetic resonance in yttrium-iron-garnet (YIG) has been evaluated at 4.2° K, 77° K, and 297° K. The limiter, of the DeGrasse type,[1] consists of two decoupled, half-wavelength coaxial cavities as shown schematically in Fig. 1. Input and output coupling is made through the use of quarter-wavelength matching transformers. An optically polished sphere of single crystal YIG is placed in the position of maximum RF magnetic fields common to both cavities.

The limiting processes involved in the YIG sphere can be explained by the use of Suhl's theory.[2] For sufficiently high RF fields and for particular dc bias fields a subsidiary ferromagnetic resonance occurs[3] caused by the generation of spin waves at one-half the applied microwave frequency. In general, the field for the subsidiary resonance is different from the field for uniform precession ferromagnetic resonance. In a particular frequency range, the dc magnetic field for uniform precession resonance is *coincident* with the dc field required for the subsidiary resonance. The coincidence frequency region is an octave wide and for a sphere is given by

$$\frac{4\pi M}{3} \leq \frac{\omega}{\gamma} \leq \frac{8\pi M}{3}, \qquad (1)$$

where M is the saturation magnetization, ω is the microwave frequency, γ is the gyromagnetic ratio and the factor $\frac{1}{3}$ is the demagnetizing factor for a sphere. The RF field, in the YIG sphere, necessary for the onset of subsidiary resonance is particularly low[4,5] in the coincidence region and is given by

$$h_{\text{crit}} \approx \frac{\Delta H \Delta H_k}{4\pi M}, \qquad (2)$$

where ΔH is the measured ferromagnetic resonance line width and ΔH_k is the line width of the spin wave generated, having a wavelength $\lambda = 2\pi/k$. The values of ΔH and ΔH_k as functions of temperature have been measured on the particular sample used in these experiments[6,7] and are given in Table I.

* Received by the PGMTT, February 2, 1961. This paper is based on work performed under a contract with the U. S. Army Ordnance Corps.

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

[2] H. Suhl, "Ferromagnetic resonance at high signal powers," *Jour. Phys. and Chem. of Solids*, vol. 1, pp. 209–227; April, 1957.

[3] The observation of the subsidiary resonance was first reported by R. W. Damon, *Rev. Mod. Phys.*, vol. 25, pp. 239–245; January, 1953, and N. Bloembergen and S. Wang, *Phys. Rev.*, vol. 93, pp. 72–85; January, 1954.

[4] E. G. Spencer, R. C. LeCraw, and C. S. Porter, "Ferromagnetic resonance in yttrium iron garnet at low frequencies," *J. Appl. Phys.*, vol. 29, pp. 429–430; March, 1958.

[5] F. C. Rossol, "Subsidiary resonance in the coincidence region in yttrium iron garnet," *J. Appl. Phys.*, vol. 31, pp. 2273–2275; December, 1960.

[6] E. G. Spencer, R. C. LeCraw, and A. M. Clogston, "Low temperature line width maximum in yttrium iron garnet," *Phys. Rev.* (*Lttrs.*), vol. 3, p. 32; July, 1959.

[7] E. G. Spencer and R. C. LeCraw, "Spin lattice relaxation of low *k*-number spin waves in yttrium iron garnet: II temperature dependence," *Bull. Am. Phys. Soc.*, vol. 4, p 297; April, 1960.

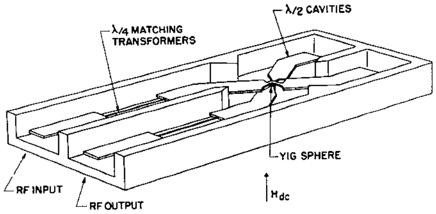

Fig. 1—Cut away view of the limiter structure made of rectangular cross-section coaxial line. The cover plate is not shown.

In the sphere, then, at sufficiently low RF power, the magnet moment M is in uniform precession. The angle of precession increases with increasing RF power until it reaches the value θ_{crit}, where it is said to *stick*. This indicates that the subsidiary resonance is now being generated. As the RF power is further increased, the excess RF energy goes into the generation of the $\omega/2$ spin waves of the subsidiary resonance. The wavelength of these spin waves is so short that they do not radiate or couple to the microwave-measuring circuit. The spin-wave energy is eventually transformed into heat energy in the sphere.

TABLE I*

T°K	$4\pi M$ (gauss)	ΔH (Millioersteds)	ΔH_k	Insertion Loss (db)	P_{crit} (μwatt)	Dynamic Range (db)
297	1750	360	150	0 5	67	28
77	2430	300	100	0.3	7	>25
4.2	2480	150	17	0.2	0 32	>38

* Intrinsic constants of YIG, and limiter characteristics for a 0.042-inch YIG sphere at 3000 Mc. ΔH and ΔH_k were measured at 9340 mc. $4\pi M$ values were obtained from the work of M. A. Gilleo and S. Geller.[9]

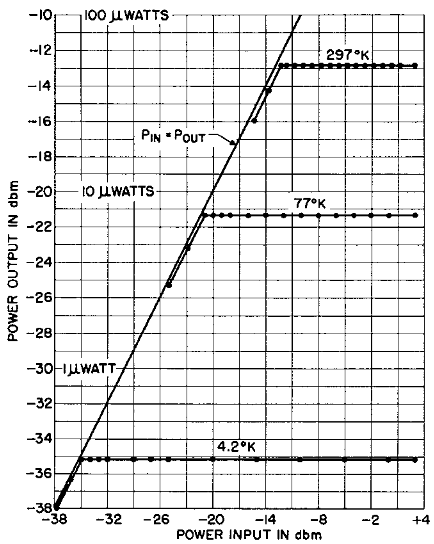

Fig. 2—Measured characteristics of the 3000-Mc limiter using 0.042-inch diameter sphere of single crystal YIG.

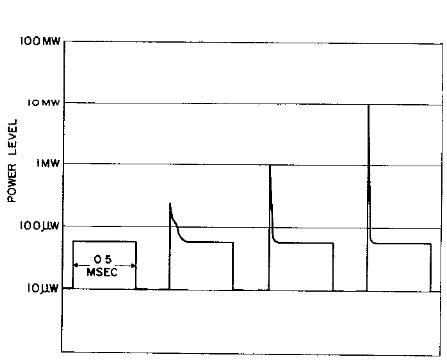

Fig. 3—Response of the limiter to pulsed RF signals. The power shown on the ordinate represents the peak spike power which is equal to the input power and also represents the plateau which is the output power.

In the limiter structure, at low RF powers, the input and output cavities are coupled by the uniform precession resonance, the maximum transfer of energy occurring when $\theta = \theta_{\text{crit}}$. As the RF power is further increased, the coupling remains constant with the excess energy going into the subsidiary resonance of the spin waves, and power limiting occurs.

The saturation magnetization of YIG is 1750 gauss at 297°K and 2480 gauss at 4.2°K giving coincidence frequency octaves of 1635–3270 and 2320–4640 respectively. The frequency of operation, 3000 Mc was chosen so as to be in the center of the coincidence octave at 4.2°K to optimize the results at that temperature. Further, the results shown in Fig. 2 and Table I were for the highest purity YIG sphere. This establishes a criterion of the best results we are able to obtain at this time. The limiting power was measured on an oscilloscope under pulsed conditions, and with a super heterodyne receiver under CW conditions. The perfect flatness as seen in the figure was obtained for both cases. The insertion loss depends on an optimum coupling of the sphere to the structure. The coupling was adjusted for the lowest value of insertion loss, 0.2 db, at 4.2°K. Other room temperature limiters have limited at as low as 10μ watts.

The use of limiters of this type at other frequencies in devices such as masers would require that either a material of a different $4\pi M$ or samples of other shapes be used to shift the coincident frequency octave. Work along these lines is in progress. As an example, for a single crystal YIG sphere[8] in which gallium ions are substituted for iron ions, there is an almost complete preference of the gallium ions for the tetrahedrally

[8] E. G. Spencer and R. C. LeCraw, "Line-width narrowing in gallium substituted yttrium iron garnet," *Bull. Am. Phys. Soc.*, vol. 4, p. 57; January, 1960.

coordinated sites,[9,10] thus reducing $4\pi M$. Using a single-crystal YIG-Ga sphere with a $4\pi M$ of 1000 gauss the measured frequency octave is from 935 to 1870 Mc at room temperature. A limiter has been constructed to operate at 1300 Mc which has an insertion loss of 0.7 db, a limiting power of 10μ watts, and a curve similar in all respects to that of Fig. 2. The 0.7-db insertion loss could be reduced by using a larger sphere.

The response of the limiter to pulses of RF energy always shows a spike on the leading edge. The reason for this is that the subsidiary resonance does not build up instantaneously. The time of build up is associated with the relaxation time of the RF magnetization. When a pulsed RF signal is applied, ferromagnetic resonance occurs and the angle of precession of magnetization increases, opening up to a value $>\theta_{crit}$. Eventually subsidiary resonance occurs and θ decays to its final value of θ_{crit}.

Fig. 3 shows the spike for a sequence of pulses of RF energy. The build-up time of subsidiary resonance becomes shorter as the power is increased [see Suhl's (24)]. For RF power levels moderately in excess of the limiting power, we were able to integrate the area under the spike and show that it remains constant. At higher power levels it was not possible, however, to show definitely that the spike energy remains constant.

We should like to thank R. C. LeCraw for helpful discussions on these experiments, J. J. Kostelnick for suggestions on the structure, S. Geller for many discussions of his work on substituted garnets, and J. W. Nielsen and R. C. Linares for the growth of all the crystals used in these experiments.

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[9] M. A. Gilleo and S. Geller, "Magnetic and crystallographic properties of substituted yttrium iron garnet, $3Y_2O_3 \cdot XM_2O_3 \cdot (5-X)Fe_2O_3$," *Phys. Res.*, vol. 110, pp. 73–78; April, 1958.

[10] S. Geller, "Magnetic interactions and distribution of ions in the garnets," *J. Appl. Phys*, vol. 31, pp. 30–37S; May, 1960.

New Coaxial-to-Stripline Transformers Using Rectangular Lines*

The most common form of coaxial-to-stripline transition consists of a simple inline butt joint, as described by Barrett.[1] A typical transition between a 50-ohm high-Q triplate and a standard N-type connector is shown in Fig. 1. This gives a VSWR<1.15 at frequencies up to 7000 Mc deteriorating to 1.25 at higher frequencies up to 11,000 Mc. While these results are acceptable for many types of stripline components and assemblies, it was felt that the design of a better transition would be necessary in order both to test and to maintain the performance of high grade components (*e.g.*, hybrids, directional couplers, and filters) and to avoid the manufacture of a special stripline standing-wave detector.

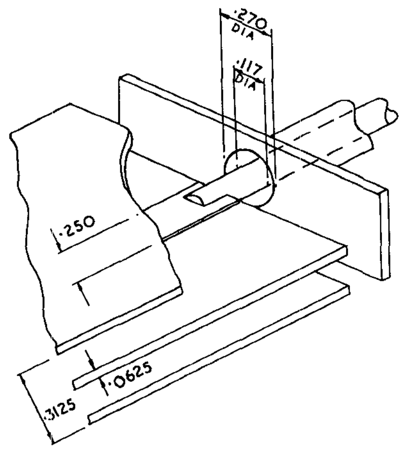

Fig. 1—Standard stripline-to-coaxial line 50-ohm transition.

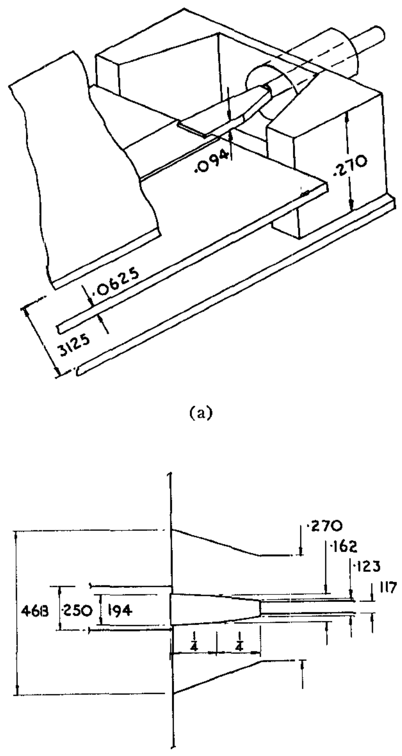

Fig. 2—Stripline-to-coaxial line tapered transitions using rectangular line.

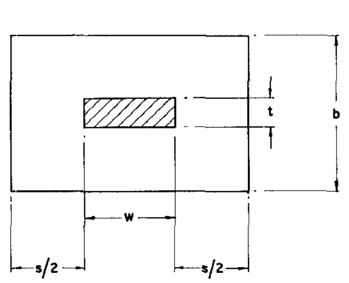

Fig. 3—The rectangular line.

The conventional transition (Fig. 1) is not perfectly matched because the fringing field of the stripline is intercepted by the outer conductor of the coaxial line, in addition to the disparity of dimensions between the inner conductors of the two lines.

A diagram of a well-matched transition is shown in Fig. 2. In this, the side walls at the start of the transition from the stripline end are positioned sufficiently far away from the stripline to avoid discontinuities, a constant 50-ohm impedance is maintained through the transition to the coaxial line, and there are no large dimensional discontinuities. The VSWR of this transition, as deduced from measurements of two such transitions back-to-back cascaded with terminating N-type connectors and a matched load, is probably better than 1.02 at all frequencies up to the highest measured frequency of 11,000 Mc; and, in fact, it is probable that the transition does not deteriorate the VSWR of the N-type connector.

A cross section through the transition in a plane perpendicular to its axis is shown in Fig. 3, and takes the form of a rectangular line. It was necessary to derive a formula for the characteristic impedance of the rectangular line, and this was obtained in the form

$$Z(w/b,\, t/b,\, s/b) = \frac{94.15}{\sqrt{\epsilon}\left[\dfrac{w/b}{1 - t/b} + C_{f0}'(t/b,\, s/b)\right]}, \quad (1)$$

where

$$C_{f0}'(t/b,\, s/b) = C_{f0}'(0,\, s/b) + \epsilon t/s. \quad (2)$$

Here ϵ is the *relative* dielectric constant of the dielectric medium of the line, and $C_{f0}'(0, s/b)$ is the fringing capacitance of the rectangular line as given by Cohn[2] in the form

$$C_{f0}'(0,\, s/b) = \frac{2\epsilon}{\pi} \log\left[1 + \coth(\pi s/2b)\right]. \quad (3)$$

A graph of $C_{f0}'(0, s/b)$ as a function of s/b is plotted in Fig. 7 of Cohn's paper.

Eq. (1) gives a good approximation to the impedance of the line, valid for $s/t \leq 5$, a condition which is always true in the case of the transition shown in Fig. 2.

More general formulas for the characteristic impedance of rectangular lines have now been derived by Chen[3] with the inde-

* Received by the PGMTT, February 3, 1961.

[1] R. M. Barrett, "Etched sheets serve as microwave components," *Electronics*, vol. 25, pp. 114–118; June, 1952.

[2] S. B. Cohn, "Shielded coupled-strip transmission line," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 29–38; October, 1955.

[3] T. S. Chen, "Determination of the capacitance, inductance and characteristic impedance of rectangular lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 510–519; September, 1960.