# A Ferrimagnetic Microwave Power Limiter

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*Abstract*—**A new method of microwave power limiting is described. In contrast to limiters previously discussed, this type limits the power reflected from a ferrite-loaded microwave cavity, the limited output power being coupled into the load by means of a hybrid or a circulator. A characteristic feature of the limiter is that the limiting level may be adjusted over a wide range by a suitable choice of the volume of the ferrite sample. Furthermore, the level may with ease be continuously varied over a wide dynamic range merely by changing the position of the ferrite sample in the cavity. Experimental results are presented.**

## I. Introduction

As is well-known [1], [2], saturation phenomena will be observed in magnetized ferrites when the applied magnetic RF field exceeds certain values. The saturation effect of interest in this connection is the saturation of the main resonance (uniform precession), resulting in a decrease in the imaginary part of the RF susceptibility when the applied RF field exceeds a threshold value. The approximate susceptibility will be inversely proportional to the applied field

$$\chi'' = \chi_0'' \frac{h_{\text{crit}}}{h} \tag{1}$$

Here $\chi_0''$ is the imaginary part of the RF susceptibility below the threshold, $h_{\text{crit}}$ is the magnetic RF field at the onset of saturation, and $h$ is the applied field.

We may distinguish between two types of main resonance saturation:

1) Saturation due to second-order coupling between the uniform procession and spin waves in the material.
2) Saturation due to first-order coupling between the uniform precession and spin waves, also called coincidence saturation of the main resonance.

The two types of saturation may be distinguished from each other by virtue of their different threshold fields, which for the two cases are given by

$$h_{\text{crit}}' \approx \Delta H \left( \frac{\Delta H_k}{4\pi M_s} \right)^{1/2} \tag{2}$$

$$h_{\text{crit}}'' \approx \frac{\Delta H \Delta H_k}{4\pi M_s} \tag{3}$$

Here $\Delta H$ is the linewidth of the main resonance, $\Delta H_k$ is the "linewidth" of the spin wave causing the saturation, and $4\pi M_s$ the saturation magnetization of the material. Typically, $h_{\text{crit}}''$ is three orders of magnitude smaller than $h_{\text{crit}}'$. Furthermore, coincidence saturation is confined to the frequency region given by

$$4\pi M_s \gamma N_T > \frac{\omega}{2} \tag{4}$$

where $N_T$ is the transverse demagnetizing factor, a quantity given by the shape of the ferrite sample, $\gamma$ is the gyromagnetic ratio, and $\omega$ the angular frequency of the RF field.

These saturation phenomena in ferrites have been utilized in a great number of microwave power limiters. However, it develops that, with limiters previously reported, the limiting level is confined to relatively narrow power ranges and is difficult to vary. The aim of this work is to show that it is possible to develop a limiter which permits the limiting level to be adjusted over wide dynamic ranges, and also to be varied continuously. This feature makes the limiter very well suited also as a power leveler.

## II. Ferrite-Loaded Cavities

The $Q$-value of a microwave cavity loaded with a ferrite sample magnetized to resonance, is by simple perturbation theory [3] found to be

$$\frac{1}{Q} = \frac{1}{Q_0} + 2k\chi'' \tag{5}$$

where $Q_0$ is the $Q$-value of the cavity without ferrite, and $k$ is a constant given by the cavity and ferrite volumes, the position of the ferrite, the cavity geometry, and the free space wavelength. Above saturation (5) will have the form

$$\frac{1}{Q} = \frac{1}{Q_0} + 2k\chi_0'' \frac{h_{\text{crit}}}{h} \tag{6}$$

The standing-wave ratio in a transmission line terminated by the cavity tuned to resonance is

$$S = \frac{Q_{\text{ex}}}{Q} \tag{7a}$$

or

$$S = \frac{Q}{Q_{\text{ex}}} \tag{7b}$$

depending on the relative values of $Q$ and $Q_{\text{ex}}$. $Q_{\text{ex}}$, the external $Q$, is a constant given by the coupling between

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transmission line and cavity. The power reflected from the cavity then will be

$$P_r = P|r|^2 = P\left[\frac{1-\dfrac{Q_{ex}}{Q}}{1+\dfrac{Q_{ex}}{Q}}\right]^2 \tag{8}$$

where $P$ is the power incident on the cavity and $r$ the reflection coefficient. From (6) and (8), we obtain after some calculation

$$P_r = P\left[\frac{1-\dfrac{Q_{ex}}{Q_0}}{1+\dfrac{Q_{ex}}{Q_0}} - \frac{4k\chi_0''Q_{ex}\sqrt{\dfrac{P_{crit}}{P}}}{\left(1+\dfrac{Q_{ex}}{Q_0}\right)\left(1+\dfrac{Q_{ex}}{Q_0}+2k\chi_0''Q_{ex}\right)}\right]^2 \tag{9}$$

Here $P_{crit}$ is the input power corresponding to a RF field equal to $h_{crit}$ at the position of the ferrite. The ferrite dimensions are assumed small compared to the wavelength. Consequently, the field may be assumed constant over the sample. If now the cavity coupling is adjusted to satisfy

$$Q_{ex} = Q_0 \tag{10}$$

(9) will be reduced to

$$P_r = P_{crit}\left[\frac{k\chi_0''Q_0}{1+k\chi_0''Q_0}\right]^2 \tag{11}$$

Thus, above saturation the reflected power is constant, independent of the input power. The reflected power may be coupled to a load by means of a hybrid or a circulator, and the cavity will work as a power limiter.

The limiting level $P_r$ and the input power at the threshold of saturation $P_{crit}$ may be calculated from

$$P[1-|r|^2] = \frac{\omega_0 W}{Q} \tag{12}$$

where $W$ is the average stored energy in the cavity. Inserting for $Q$ from (5), and using the appropriate value of the reflection coefficient $r$, we obtain

$$P_{crit} = \frac{\omega_0 W_{crit}}{4Q_{ex}}\left[1+\frac{Q_{ex}}{Q_0}+2k\chi_0''Q_{ex}\right]^2 \tag{13}$$

where $W_{crit}$ is the stored energy corresponding to a RF field at the ferrite equal to $h_{crit}$. This again, inserting $Q_{ex}=Q_0$, simplifies to

$$P_{crit} = \frac{\omega_0 W_{crit}}{Q_0}[1+k\chi_0''Q_0]^2 \tag{14}$$

and for the limiting level

$$P_r = \frac{\omega_0 W_{crit}}{Q_0}[k\chi_0''Q_0]^2 \tag{15}$$

As will be shown later, the limiting level may easily be adjusted by varying the factor $k$.

## III. A Coaxial Cavity Limiter

Now we shall apply the theory developed in Section II to a specific case, viz., a ferrite-loaded coaxial cavity. The ferrite sample is mounted as shown in Fig. 1, the static field and RF field being perpendicular to each other.

In this case, the average stored energy is given by

$$W = \frac{\pi}{2}\mu_0 l\cdot\ln\frac{R}{r}\,\frac{1}{\cos^2\dfrac{2\pi y}{\lambda}}\left(\frac{x}{r}\right)^2 h_{xy}^2 \tag{16}$$

where $h_{xy}$ is the RF field at position of the ferrite, the other quantities are given in the figure. In order to find the constant $k$, we rewrite (5) in the form

$$\frac{1}{Q} = \frac{1}{Q_0} + \frac{P_f}{\omega_0 W} \tag{17}$$

The loss $P_f$ in the ferrite is approximately

$$P_f = \tfrac{1}{2}\omega_0\mu_0\chi''\Delta v h_{xy}^2 \tag{18}$$

where $\Delta v$ is the ferrite volume. Hence,

$$k = \frac{P_f}{2\omega_0\chi''W} = \frac{\Delta v}{2\pi l\ln\dfrac{R}{r}}\left\{\frac{\cos\dfrac{2\pi y}{\lambda}}{\dfrac{x}{r}}\right\}^2 \tag{19}$$

By insertion of this expression and the value of $W_{crit}$ from (16) into (14) and (15), we obtain

$$P_{crit} = \frac{\pi}{2}\omega_0\mu_0\frac{l}{Q_0}\ln\frac{R}{r}\cdot\left[\frac{x}{r\cos\dfrac{2\pi y}{\lambda}} + \frac{\cos\dfrac{2\pi y}{\lambda}}{\dfrac{x}{r}}\,\frac{\Delta v\chi_0''Q_0}{2\pi l\ln\dfrac{R}{r}}\right]^2 h_{crit}^2 \tag{20}$$

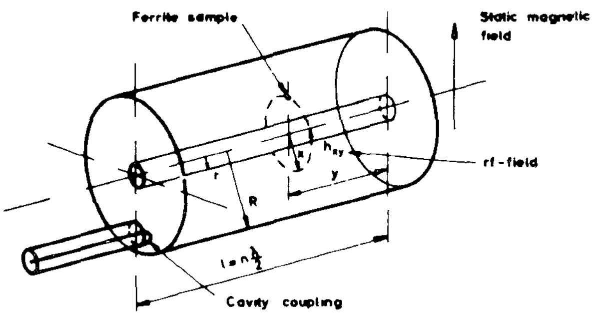


Fig. 1. A ferrite-loaded coaxial cavity.

and

$$P_r = \frac{\pi}{2}\,\omega_0\mu_0\,\frac{l}{Q_0}\ln\frac{R}{r}\left[\frac{\cos\dfrac{2\pi y}{\lambda}}{\dfrac{x}{r}} - \frac{\Delta v\chi_0''Q_0}{2\pi l\ln\dfrac{R}{r}}\right]^2 h_{\text{crit}}^2 \qquad (21)$$

From (21), it is obvious that the limiting level may be chosen almost arbitrarily, both by choosing a suitable ferrite volume and by a displacement of the ferrite in the cavity. As will be seen, the limiting level $P_r$ trends towards zero as $y$ is increased to $\pi/2$. The value of $P_{\text{crit}}$ also will be reduced at the same time. However, when (20) is differentiated, it is found that $P_{\text{crit}}$ will have a minimum for

$$\frac{x}{r\cos\dfrac{2\pi y}{\lambda}} = \left[\frac{\Delta v\chi_0''Q_0}{2\pi l\ln\dfrac{R}{r}}\right]^{1/2} \qquad (22)$$

and then increase towards infinity. It is remarkable that the value of $P_{\text{crit}}$ at minimum is independent of the cavity parameters and is given by

$$(P_{\text{crit}})_{\min} = \omega_0\mu_0\Delta v\chi_0'' h_{\text{crit}}^2 \qquad (23)$$

With $\chi_0''$ known, measuring $(P_{\text{crit}})_{\min}$ would be a well-suited method for an exact determination of $h_{\text{crit}}$.

## IV. Experimental Result

In order to test the theory, a coaxial cavity, shown in Fig. 2, was constructed.

The ferrite sample used was a YIG (yttrium iron garnet) single-crystal sphere of 0.08-inch diameter. The limiter was based upon coincidence saturation, which for YIG spheres is confined to the frequency region

$$1650 < f < 3300 \text{ Mc/s} \qquad (24)$$

In order to reduce heating effects, the crystal was mounted in a thin-walled polystyrene box containing a low-loss cooling fluid (paraffin).

An attempt was made to vary the limiting level continuously by a longitudinal displacement of the box in the cavity. However, it became apparent that this did not work very well because of the resultant detuning of the cavity. Other ways of adjusting the level then had to be investigated. It is evident that the quantity

$$\left(\frac{\cos\dfrac{2\pi y}{\lambda}}{\dfrac{x}{r}}\right)^2$$

in (19) is a measure of the coupling between the electromagnetic fields in the cavity, and RF magnetization in the ferrite, since the field applied to the ferrite is proportional to

$$\frac{\cos\dfrac{2\pi y}{\lambda}}{\dfrac{x}{r}}$$

This coupling may also be varied merely by rotating the box in the static field as indicated in Fig. 2. With the static field fixed, the effective RF field acting on the ferrite will be

$$h_{\text{eff}} = h\cos\xi \qquad (25)$$

where $\xi$ is the rotation angle. The quantity $k$ in (19) will then be modified to

$$k' = k\cos^2\xi \qquad (26)$$

and the limiting level will be proportional to $\cos^2\xi$.

The cavity was tuned by means of a variable capacitor driven by a micrometer screw as shown in the figure [4]. The effective tuning range was 2000–3200 Mc/s. In order to satisfy the condition $Q_{\text{ex}} = 0_0$, the cavity coupling was made variable by means of an antenna with variable penetrating depth.

The reflected power was monitored by connecting the detector to the transmission line through a coaxial ring hybrid. The measurements were performed at the center frequency of the hybrid $f = 2115$ Mc/s.

In Fig. 3, the reflected power is given vs. the input power at four different values of the rotation angle $\xi$. As will be seen, the behavior is linear up to a rather well-defined threshold, above which $P_r$ is fairly constant.

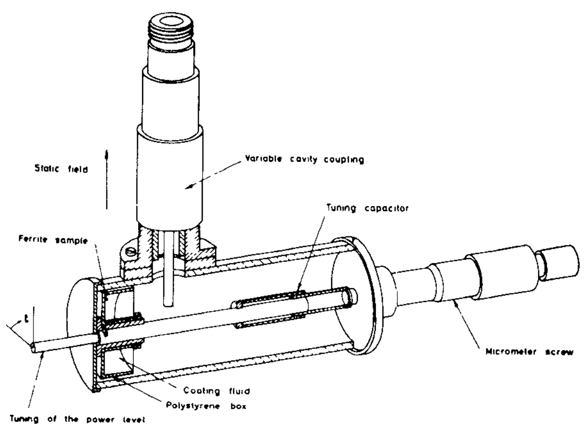


Fig. 2. Coaxial cavity limiter.

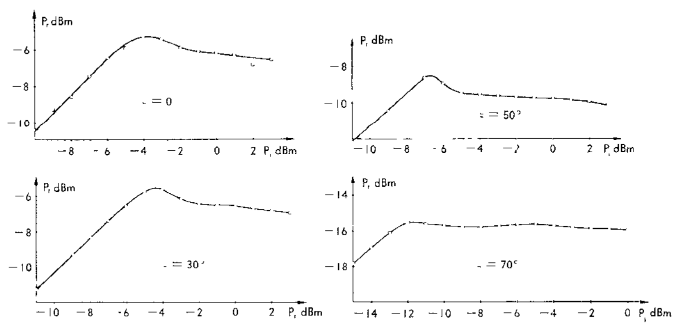


Fig. 3. Reflected power $P_r$ vs. the input power $P_i$.

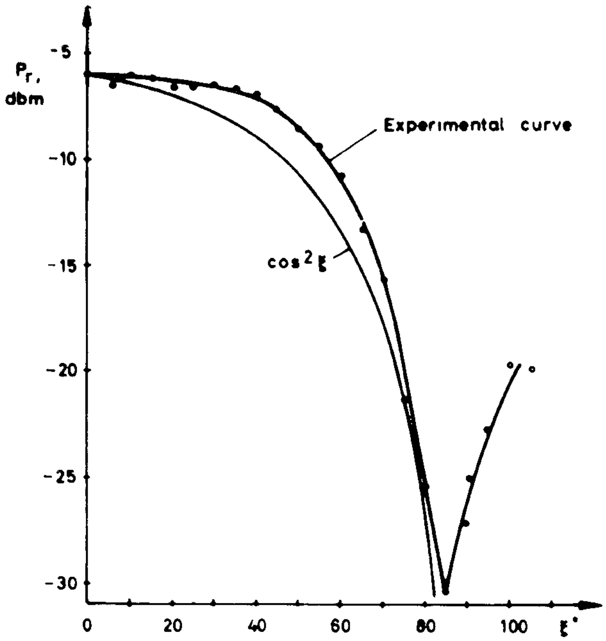


Fig. 4. Limiting level vs. the rotation angle $\xi^0$.

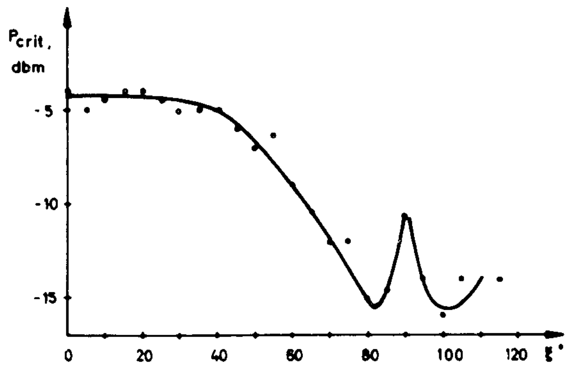


Fig. 5. Critical input power $P_{crit}$ vs. the rotation angle $\xi^0$.

The discrepancy probably is due to a slight mistuning of the coupling constant $Q_{ex}$. The dependence of $P_r$ upon $\xi$ is shown in Fig. 4 and is compared with the theoretical $\cos^{21} \xi$ behavior with reasonably good agreement. Furthermore, Fig. 4 indicates that a practically continuous tuning range of the limiting level of about 20 dB may be realized. The corresponding values of $P_{crit}$ is given in Fig. 5 with the theoretically predicted minimum at $\xi \approx 80°$.

The insertion losses below saturation (Fig. 6), excluding losses in the hybrid, are very small up to values of $\xi$ exceeding 70° where they increase rapidly. The practical tuning range, therefore, will be confined to values of $\xi$ between 0° and 70°.

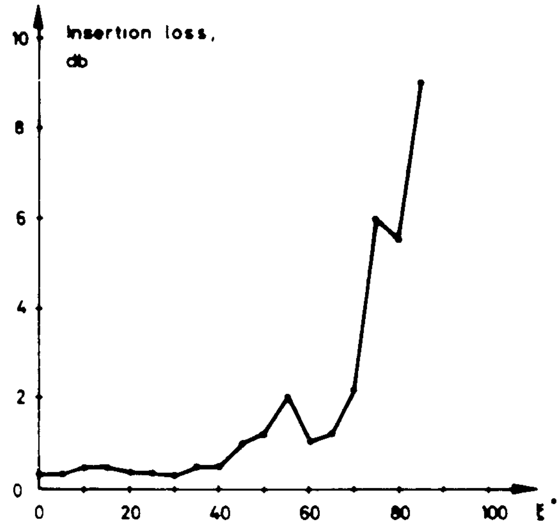


Fig. 6. Insertion loss vs. the rotation angle $\xi^0$.

The measurements are all performed at the center frequency of the hybrid. The frequency sensitivity of the device is not tested experimentally because of the lack of a broadbanded hybrid or circulator.

## V. Conclusion

It has been shown that it is possible to realize microwave power limiters for which the limiting level may easily be adjusted over a wide range. In contrast to previously reported limiters, the power utilized is the power reflected from a ferrite-loaded microwave cavity. Further investigations, not mentioned here, have shown that this type of limiter probably is best suited for power levels below 10 mW; otherwise, the heating effects would be too large. Another feature of this type of limiter is that, when the limited power is coupled to the load by means of a circulator, the generator will always look into a matched line.


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