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Frequency-Selective Limiting*

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***Summary*—In the usual microwave limiter, the presence of one or more large signals above a certain threshold level produces a limiting action which can be explained as a change in insertion loss of the limiter so as to maintain a constant output power, regardless of the number of independent signals present. Experimental results of coincidence mode passive ferrite limiters in *S* band and *C* band are presented which show that they do not behave in this manner, but rather to a good approximation limit on a frequency-by-frequency or frequency-selective basis. A qualitative explanation of this phenomenon is presented, using the passive parametric limiter as a model.**

Introduction

THERE ARE MANY occasions where the performance of an electronic system can be improved by the utilization of passive low-power microwave limiters. Protection from burn-out in a sensitive receiver is one application which is well known. A limiter can also find use as a power-leveling device. For example, amplitude variations from a microwave oscillator could be suppressed by utilizing such a limiter at the oscillator output. If the limiter is free of phase distortion, it would be useful in preventing AM-to-PM conversion in systems employing frequency modulation.

An idealized limiter can be characterized as a linear device below a certain threshold value, and a constant output device above this threshold. Illustrated in Fig. 1 is such an idealized characteristic of a power limiter. Below threshold this device has constant loss; above threshold it has constant output power and hence an attenuation which increases in direct proportion to the input power level.

One type of microwave limiter which has proved to be practical for low-power limiting makes use of nonlinear effects in ferrimagnetic material. A typical limiter of this class utilizes the so-called coincidence mode of limiting which Suhl[1] has shown to result in exceedingly low threshold levels. It is the purpose of this paper to report on some recent investigations which have been made on the limiting characteristics of such coincidence mode limiters in the presence of multiple signals within the pass band of the device.

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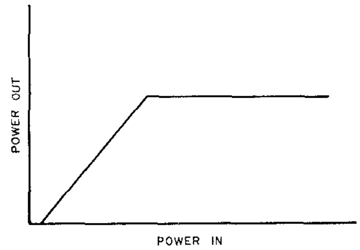

Fig. 1—Idealized characteristic of a power limiter.

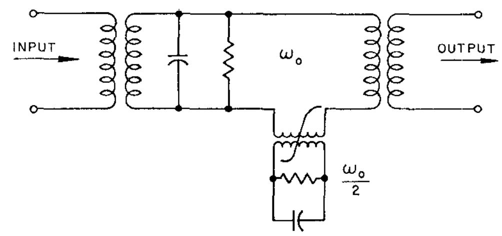

Fig. 2—Circuit model of a passive parametric limiter.

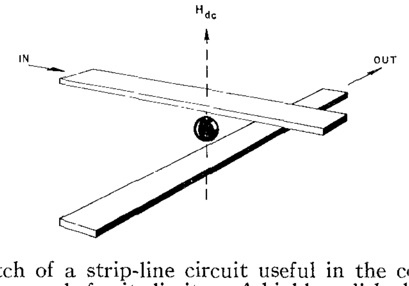

Fig. 3—Sketch of a strip-line circuit useful in the construction of coincidence mode ferrite limiters. A highly polished single-crystal ferrimagnetic sphere is placed between two orthogonal center conductors and biased to resonance by a dc magnetic field.

Coincidence Mode Ferrite Limiters

In his analysis of the nonlinear behavior of ferrites, Suhl outlined three limiting modes: saturation of the main ferrimagnetic resonance, the appearance of a second "subsidiary" absorption above a certain power level, and a coincidence condition when these two effects coincide in frequency and magnetic field. In each case Suhl describes the nonlinearity as resulting from the excitation of spin waves within the sample which above a certain threshold value can become unstable, growing in amplitude and thereby absorbing power. For both the subsidiary absorption and coincidence modes, the spin waves which first become unstable are at one half the frequency of the incident power. We can therefore use the circuit model of Fig. 2 to illustrate this mode of limiting. Here we have a circuit resonant at ω_0, analogous to the main ferrimagnetic resonance, with input and output coupling which results in a simple band-pass filter. There is also an additional nonlinear coupling to a resonant circuit at $\frac{1}{2}\omega_0$, analogous to a spin wave mode. Above a certain threshold level, this subharmonic resonator is excited into oscillation, converting power at ω_0 to power at $\frac{1}{2}\omega_0$. This is identical to the passive parametric limiter, as described by Siegman[2] and analyzed in some detail by Ho.[3]

To achieve low insertion loss below threshold and to achieve low threshold power levels, it is necessary to use narrow linewidth material such as single-crystal yttrium iron garnet (YIG) or lithium ferrite. The most usual configuration employs a highly polished sphere of ferrimagnetic material between two orthogonal center conductors of a TEM-mode transmission structure,[4–7] as illustrated in Fig. 3. A dc magnetic field is used to bias the ferrite to resonance. Off resonance, the two transmission lines are not coupled because of their orthogonality; on resonance the lines are heavily coupled through the ferrite resonator since the precessing magnetic moment induces the necessary transverse magnetic field components.

Some of the important characteristics of these limiters are

1) Low insertion loss. When operating in the linear range, a low-power ferrite limiter can have an insertion loss of less than one db since the intrinsic unloaded Q of the ferrite is usually quite high.
2) Magnetic tuning. Such limiters can have narrow instantaneous bandwidth (on the order of one per cent) and be magnetically tunable over wide ranges in frequency, or have wider bandwidths (about ten per cent) in fixed-tuned configurations.
3) Low-power limiting threshold. Between approximately 2000 Mc and 3500 Mc the limiting threshold is typically on the order of 0.1 mw or less. Over the range 4000 Mc to about 7500 Mc the limiting threshold is on the order of 1.0 mw.
4) Large dynamic range. Greater than 20 db of limiting range can be achieved.
5) Minimum phase distortion at limiting. The limiting mechanism produces very little change in phase in the limiting region. Measurements at spot frequencies have indicated phase changes of less than $\pm 5°$ over a 20-db limiting range.

Frequency-Selective Limiting

The amplitude characteristic of limiters such as diode clippers or traveling-wave tubes can be adequately explained as a variation of attenuation with input power level. Thus if two input signals are applied to such a limiter, one a small signal and one a large signal above limiting threshold, both the small signal and the large signal will be attenuated. Or alternately, if two large

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signals above limiting threshold are simultaneously applied to such a limiter, the output of such a limiter will tend to be the same as if only a single saturating signal were present. A large signal will thus tend to "block" or "capture" the limiter, thereby suppressing the presence of other signals. Also, in the presence of two large signals quite significant sum and difference frequency components will be generated by such limiters.

The behavior of coincidence mode ferrite limiters in the presence of such multiple signals has been investigated and it has been observed that quite different results are obtained. To a good approximation it has been observed that these limiters operate independently on each signal present within the pass band, as long as the signals are separated a small amount in frequency. This type of limiting will be termed *frequency-selective limiting* since the limiting occurs on a frequency-by-frequency basis. In contrast to the characteristics of the more familiar multiple-signal limiting behavior briefly discussed above, the frequency-selective limiter

1) Does not suppress a small signal when a saturating signal is present,
2) Has a saturated power output in the presence of n saturating signals equal to n times the saturated power output in the presence of a single frequency, and
3) Does not generate sum and difference frequencies of multiple saturating signals

provided that the signals are separated sufficiently in frequency.

We can obtain a qualitative explanation of this frequency-selective limiting characteristic by noting that the mode of limiting involved is closely analogous to a passive parametric limiter as previously described in which pump power supplied to a degenerate parametric oscillator is transferred to an oscillation at half pump frequency when a certain threshold has been exceeded.

Using the parametric limiter as a model, we may ask what will happen when two pump signals are simultaneously applied to this limiter. If these signals are of frequencies such that their respective half frequencies both fall within the bandwidth of the subharmonic oscillator, it would then be expected that both would contribute to a subharmonic oscillation and both would be limited in some complex manner. However, if one of the pump signals were outside of the pass band of the subharmonic oscillator, it would not be limited since it would not excite a subharmonic oscillation. If we now take a second subharmonic parametric oscillator and also couple it to the pump circuit, it would be possible to independently limit two signals which are separated in frequency by at least the bandwidth of the oscillators. By increasing the number of oscillators, we can independently limit a large number of signals, and thus approximate a device which limits on a frequency-by-frequency basis.

A ferrite resonator is a good approximation to this model, for it possesses a large number of closely spaced, high-Q spin-wave modes. On the basis of this theory, independent limiting should then be observed in such coincidence mode ferrite limiters whenever the frequency separation of the multiple signals involved is on the order of the linewidth of the spin-wave modes acting as the subharmonic oscillators.

Experimental Results

Experimental investigations of such frequency-selective limiting have been made at S band using single crystal YIG and at C band using single crystal lithium ferrite. The S-band structures used were of coaxial configuration designed for narrow instantaneous bandwidth and broad magnetic tuning ranges. The C-band structures used were of strip-line configuration designed for relatively broad instantaneous bandwidth and moderate magnetic tuning ranges.

One experiment which was performed at S band was to apply a CW signal at a power level above limiting, and a square-wave modulated signal below limiting. The amplitude of the modulated signal was then observed as the frequency of the large signal was varied. The bandwidth of the limiter was about 9 Mc and the insertion loss was about 1.5 db.

Fig. 4 shows the frequency separation required between the two signals in this experiment in order to suppress the small signal by 3 db. As the large signal power is increased, greater separation is required to avoid suppression of the small signal. Fig. 5 shows how a small signal at 2700 Mc is suppressed as the frequency and power of the large signal is varied. Quite high suppression occurs when the two signals coincide.

One disadvantage of the measurements at S band is that rather narrow bandwidths were involved. The qualitative explanation which has been given for this frequency-selective limiting effect predicts that the frequency separation needed to obtain independent limiting should depend on the linewidth of the spin-wave mode involved and hence be independent of the bandwidth of the limiter. This characteristic was investigated during the course of some measurements made on lithium ferrite limiters at C band. The small-signal suppression of such a limiter in the presence of a saturating signal is illustrated by the three oscillograph displays of Fig. 6. In the top display is shown the frequency response of the limiter as obtained with a sweeping oscillator, together with a reference display of the output of the sweeping oscillator. The small-signal characteristics of the unit displayed are 200-Mc bandwidth and 1-db insertion loss at 5.85 Gc. In the second and third displays a CW signal above limiting threshold has been added at band center. The power level of this signal in the center display is 10 db above limiting threshold, while that of the bottom display is 25 db above threshold. These drawings vividly show how the small signal is suppressed only in the immediate vicinity of the large signal, even at extremely high over-load conditions.

Another C-band limiter tested had a bandwidth of

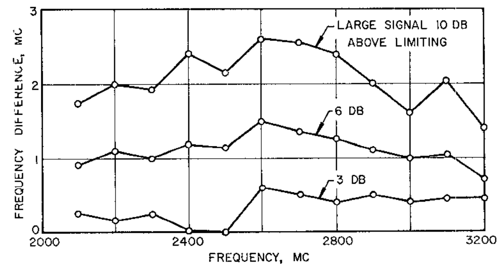

Fig. 4—Frequency difference between a large signal (above limiting) and a small signal (below limiting) required to produce 3-db suppression of the small signal.

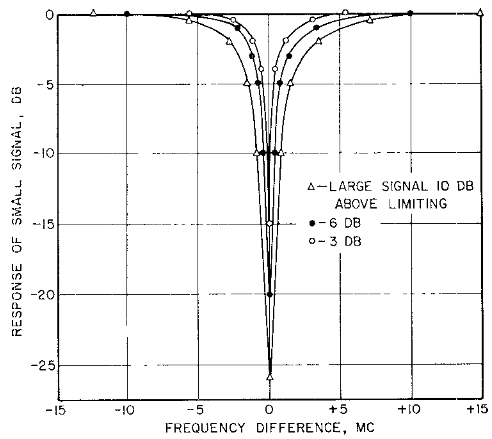

Fig. 5—Small-signal suppression at 2700 Mc as a function of frequency difference between large signal and small signal.

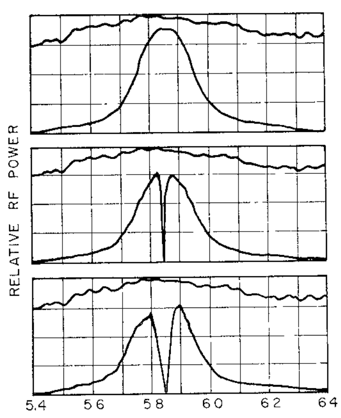

Fig. 6—Oscilloscope displays of a sweeping small signal below limiting threshold. In the top display only the small signal is present. In the middle display a large CW signal 10 db above threshold is also present, causing suppression of the sweeping signal. In the bottom display a large signal 25 db above limiting is present. The output of the sweeping oscillator used in the measurement is shown in each display for reference.

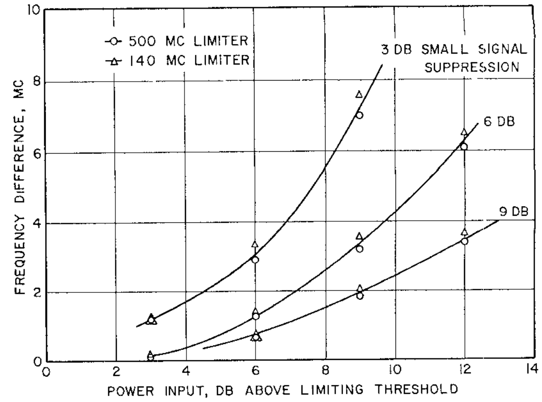

Fig. 7—Plot of the frequency difference between a large signal (above limiting) and a small signal (below limiting) for a given small-signal suppression at C band, showing invariance with bandwidth.

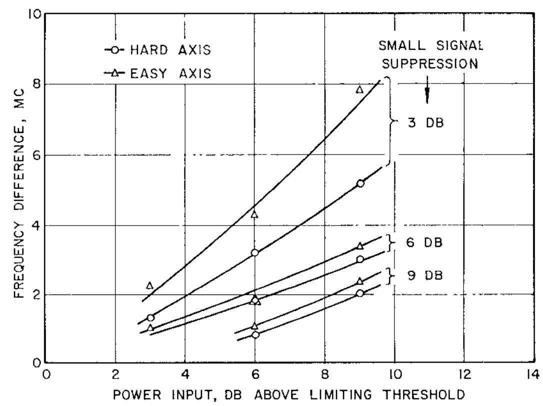

Fig. 8—Plot of the frequency difference between a large signal (above limiting) and a small signal (below limiting) required for a given small-signal suppression at C band, showing anisotropy variations.

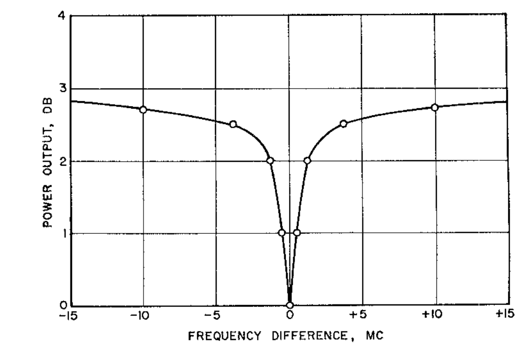

Fig. 9—Variation of the total output power of a C-band limiter with two input signals well above limiting threshold.

500 Mc centered at 5.77 Gc and a small-signal insertion loss of 0.6 db. The limiting threshold was about 3 mw. After taking data on this limiter, the bandwidth was reduced to 140 Mc by pulling the center conductors of the strip line further away from the lithium ferrite sphere. Care was taken not to disturb the orientation of the sphere so as to avoid introducing anisotropy variations. In each case one signal was introduced below the limiting threshold and one signal was introduced above limiting threshold. The required frequency separation to produce a given suppression of the small signal was recorded as a function of the power level of the large signal. The results are shown plotted in Fig. 7. The curves for the two bandwidth limiters are virtually identical, in agreement with the qualitative theory of frequency-selective limiting.

It has been reported[8] that large linewidth anisotropy sometimes exists in lithium ferrite. To investigate this effect, the foregoing limiter was modified to allow continuous rotation about an easy axis. No significant change in either limiting threshold or frequency-selective characteristics was observed. A second limiter was then investigated which used another lithium ferrite sphere. In this case about 3-db variation in limiting level was observed. Data of the small-signal suppression in the presence of a large signal was also taken as a function of sphere orientation, as shown in Fig. 8. Some anisotropy is noted, giving further evidence of the relation between linewidth and the frequency-selective characteristics.

Perhaps one of the most forceful demonstrations of the independent limiting characteristics of these limiters is the measurement of the output power when two CW signals above threshold are present. With one signal present, the output power will not exceed a certain value even when the input power is varied as much as 20 db. But when two such signals are present, the outpower doubles when the signals are separated in frequency, and the output power remains unchanged when the two signals are at the same frequency. This variation is shown plotted in Fig. 9. Two CW signals, each 6 db above limiting threshold were applied. The ordinate shows total power output relative to the output when only one of the saturating signals is present. As the frequency of one signal is changed, the output power rapidly increases and approaches a final level 3 db above that possible with only a single signal.

Conclusion

The unique behavior which these limiters exhibit in the presence of multiple signals is potentially useful in both the investigation of the properties of ferrimagnetic materials and in the development of microwave limiters. On the basis of the qualitative theory which has been presented, it should be possible to directly observe the linewidth of the spin-wave modes which participate in the limiting action. With this in mind, it is of interest to compare the results obtained with YIG in *S* band and lithium ferrite in *C* band. Comparing Figs. 4 and 7, we see that under comparable conditions the frequency difference for lithium ferrite is three times that for YIG. The measured linewidth for the uniform precession mode of the YIG was about 0.4 oersted while that of the lithium ferrite was 2.7 oersted.[9] According to Ho, the limiting bandwidth of a passive parametric limiter is a function only of the bandwidth of the subharmonic oscillator. It thus seems reasonable to postulate that the measured frequency differences in the foregoing limiters is a linear function of the spin-wave linewidths alone. If so, these limiting measurements indicate that the spin-wave linewidth of the lithium ferrite sample is about three times that of the YIG sample, while the measurements made of the uniform precessional mode indicate a factor of 6-to-7 difference in linewidths. Such linewidth differences between spin-wave modes and the uniform precession mode are not uncommon.

Some of the incidental effects which were observed during the course of these experiments may also be of significance in material investigations. The most notable of these effects was the difference in low-frequency noise level and threshold instability observed in two of the lithium ferrite samples. The instabilities were much greater in the sample which had significant linewidth anisotropy although the measured linewidth of the two samples were comparable (3.45 oersted as opposed to 2.7 oersted for the sample which showed low noise level). Both spheres were from the same material batch, but the higher linewidth sample received different heat treatment.[10]

From the device standpoint, such a frequency-selective limiter can be quite useful. One application would be the use of such a limiter before a broad-band microwave receiver. Without such a limiter a strong signal anywhere within the band of the receiver would cause the sensitivity of the receiver to be severely degraded. However, with a frequency-selective limiter ahead of the receiver, the sensitivity would be preserved over the entire frequency range except for a narrow band centered about the saturating signal. Thus it would be very difficult to jam such a broad-band receiver.

Acknowledgment

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