FREQUENCY SELECTIVE HIGH POWER YIG LIMITERS

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Abstract

This paper describes a bulk-type YIG limiter that provides narrow-band limiting for above-threshold microwave signals and simultaneously provides low loss transmission of below-threshold signals over a broad instantaneous bandwidth. Such a device has broad application as a frequency-selective receiver protector in FM/CW radars, for overload limiting in communication receivers, or as a replacement for the fixed filter in missile firing radars, thereby increasing frequency agility. A theoretically derived expression for selectivity bandwidth is found to agree well with experimental results.

Introduction

The requirements of a frequency selective limiter (FSL) for FM/CW radar systems are (1) low insertion loss over a broad frequency band for signals below the limiting threshold, (2) low limiting threshold over a broad frequency band, (3) sharp frequency selectivity, and (4) high average power handling ability. For the wide bandwidth desired here - upwards of 1 GHz at a carrier frequency of 9 GHz - subsidiary resonance is the only choice for the power limiting mechanism in a ferrite device.

Subsidiary resonance is inherently broad-band, and any signal that can excite spin waves within the relatively broad spin-wave manifold will be limited if it exceeds the limiter threshold. Thus, a fixed bias field will provide transmitter isolation and protection from strong extraneous signals over a broad instantaneous band. The parameter compromised for this bandwidth is a somewhat higher limiting threshold than is possible with other limiting mechanisms, such as coincidence limiting.

Theory

The general theory of frequency-selective limiters is well described in the literature.[1] At low RF levels, the excitation of spin waves is essentially linear. As the RF level increases, however, the excitation of spin waves becomes nonlinear, with strong coupling arising between the applied RF field and spin waves at one-half the signal frequency. Above a certain critical RF field intensity, the half-frequency spin waves grow exponentially in time, coupling virtually all the field energy in excess of the critical level into spin waves, which couple into lattice vibrations whereby the excess field energy is dissipated as heat.

The critical RF field intensity is given by[2]

$$h_{crit} = \frac{\omega \Delta h_k \left[(\omega - \omega_r)^2 + (\gamma \Delta h)^2\right]}{\omega_m (\omega/2 + \omega_o - N_z \omega_m)} \quad (1)$$

where

ω = signal frequency (sec^{-1})
Δh_k = spin-wave linewidth (Oe)
γ = gyromagnetic ratio (≈2.8 MHz/Oe)
ω_m = $\gamma 4\pi M_s$ (sec^{-1}) where $4\pi M_s$ = saturation magnetization of the ferrite
$\omega_r = \sqrt{\left[\omega_o + (N_x - N_z)\,\omega_m\right]\left[\omega_o + (N_y - N_z)\,\omega_m\right]}$
$\omega_o = \gamma H_o$ where H_o = external bias field

and where N_x, N_y, N_z are the demagnetizing factors in Cartesian coordinates.

Through a theoretical analysis[3] of the interaction of a below-threshold RF magnetic field with the spin waves induced by an above-threshold signal, we have derived an expression for the frequency selectivity bandwidth of a ferrite limiter. The result is

$$\Delta\omega = \frac{\sqrt{2}\,\gamma \Delta h_k \phi}{\frac{p_{in}}{p_{out}} - 1} \quad (2)$$

where $\phi = (h^2/h^2_{crit} - 1)^{1/2}$ is the excess power parameter and where $p_{in}/p_{out} - 1$ is the attenuation of the weak signal. $\Delta\omega$ is therefore the selectivity bandwidth for this degree of weak signal attenuation.

It is interesting to note that, since $h_{crit} \sim \Delta h_k$, at high power levels equation 2 reduces to

$\Delta\omega \cong \sqrt{2}\,\gamma h/(p_{in}/p_{out} - 1)$. This implies that wide spinwave linewidth material may be useful in high power stages of the limiter.

For subsidiary resonance to occur, one-half the signal frequency must lie within the spin wave manifold. Also, in the experimental device, a cutoff condition is observed at the frequency $\omega = \omega_o + \omega_m$, at which the effective permeability of the ferrite becomes negative. These constraints restrict the maximum usable value of $4\pi M_s$. For $(1/3)\,\omega_m \leq \omega_o \leq \omega_m$,

$$\frac{\omega_m}{\omega_L} \leq 1 - (1/4)\left(1 + \frac{2\pi B_\ell}{\omega_L}\right)^2 \quad (3)$$

where ω_L is the low end of the limiting band and B_ℓ is the limiting bandwidth. For example, if $\omega_L/2\pi = 9$ GHz and $B_\ell = 1$ GHz, then $4\pi M_s \leq 2.22$ kilogauss.

Experimental Results

Following the lead of Carter and McGowan,[4] who have shown that the critical RF field is minimized in a transverse pumped device when $N_z = 0$ and $N_x = N_y =$

1/2, we have built a frequency selective limiter composed of an array of ferrite posts as illustrated in figure 1.

A number of separate posts are used to maintain a good demagnetizing factor and because a single post has too little volume to offer sufficient dynamic range. The volume of ferrite is considerably greater than that used in various sphere-type limiters described previously,[5] and having the ferrite mounted directly against the waveguide wall allows significantly higher power capability than does the sphere-type limiter. Dielectric spacers are placed between the ferrite posts to maintain the demagnetizing factor and to help concentrate the RF magnetic field in the vicinity of the ferrite.

When the YIG posts and dielectric spacers, made of Trans Tech D16 with $\epsilon = 16\epsilon_o$, are of equal transverse thickness, 0.11 inch, a large number of spurious reflective resonances are observed. The source of the reflections is found to be the individual posts. A single ferrite or dielectric post acts as a cavity resonator at about 11.2 GHz.

When the bias field is applied, the resonant frequency of the ferrite post shifts approximately linearly to near 12.4 GHz with H_o = 1,800 gauss. The resonance is believed to occur when the post has a dimension one-quarter wavelength long in the direction of propagation. When several posts are placed side by side, the tight coupling between individual resonators produces a number of resonant reflections down to at least 8 GHz.

The most effective means of removing these resonances has been to make the transverse dimension of the dielectric spacers several mils less than that of the ferrite posts. Changing the thickness breaks up the tight coupling between posts. Unfortunately, this reduction in dielectric thickness has the effect of raising the limiting threshold by several decibels. Figure 2 shows the below-threshold frequency response, transmission coefficient $|S_{21}|$, of an array of seven single-crystal YIG posts 0.11 x 0.11 x 0.398 inch and eight D16 posts 0.11 x 0.098 x 0.398 inch with H_o = 1,300 gauss. Figure 3 shows the CW power-limiting characteristic of the same device.

We have measured the attenuation of a weak signal in the vicinity of an above-threshold signal in this limiter. Figure 4 compares the experimental and theoretical results at three power levels. In the calculation it was taken that $\gamma\Delta h_k$ = 0.583 MHz, a value obtained from a best fit to the 1 dB points at all power levels (see below).

Agreement between theory and experiments is fair at larger frequency differences when the attenuation is low, as is to be expected from the approximations in the theory. Near the center, however, the absorption is markedly stronger for negative values of $f-f_T$ than for positive values. The possibility of such an asymmetry in the absorption was predicted, but the extent of the asymmetry could not be calculated in the second-order theory. It should be pointed out that it is quite possible for the weak signal to suffer an attenuation that exceeds the isolation of the strong signal. In particular, if the frequency of the weak signal is the same as that of the strong signal, the attenuation will be infinite, since, by definition of limiter action, the output level will not increase at all.

The calculation should give the total width of the absorption, though not its exact shape. The total width at the 1 dB level of attenuation is

$$\Delta f_{1dB} = 0.444\gamma\Delta h_k \phi \qquad (4)$$

A plot of experimentally observed 1-dB bandwidth versus ϕ is shown in figure 5. The straight line is a least-squares fit to the 9 GHz data, and it corresponds to a spin wave linewidth Δh_k = 0.42 Oe.

Since the FSL is necessarily a nonlinear device, it is to be expected that the output spectrum will contain components in addition to those at the transmit and receive frequencies, f_T and f_R. If the frequency of any component is given by $f = f_R + N(f_R - f_T)$, where N = 0, ±1, ±2, . . ., then f_o is the received signal frequency and f_{-1} is the transmitted signal frequency. It appears that, in general, the output of the limiter has components

$$P_T > P_R > P_1 > P_{-2} \approx P_2 > P_3$$

In figure 6 we have plotted the relative suppression of the weak signal, P_o/P_R, and the ratio of the total spurious output signal, $P_\Sigma = \sum_{N\neq 0,1} P_N$, to the desired output, P_o, for values of P_T = 20 W and P_R = 1 mW and 10 mW. Note that the relative spurious mixing product level decreases with increasing frequency separation or decreasing P_R.

Conclusions

The principles behind frequency-selective ferrite limiters have been presented. Also, we have given an expression relating the selectivity bandwidth to the signal levels and spin wave linewidth of the material. Several basic disign principles have been proposed, and the frequency selectivity has been demonstrated in a high power YIG limiter. Experimentally measured selectivity agrees well with theoretical predictions.

References

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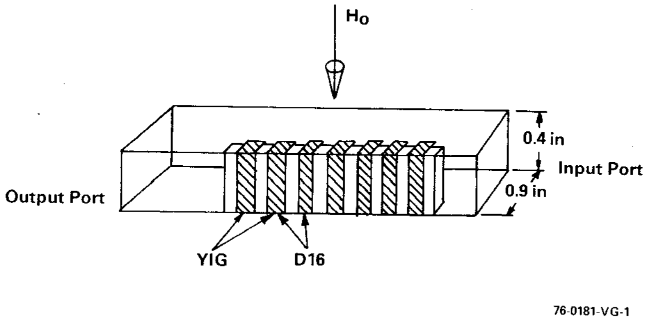

Figure 1. Bulk Ferrite Limiter

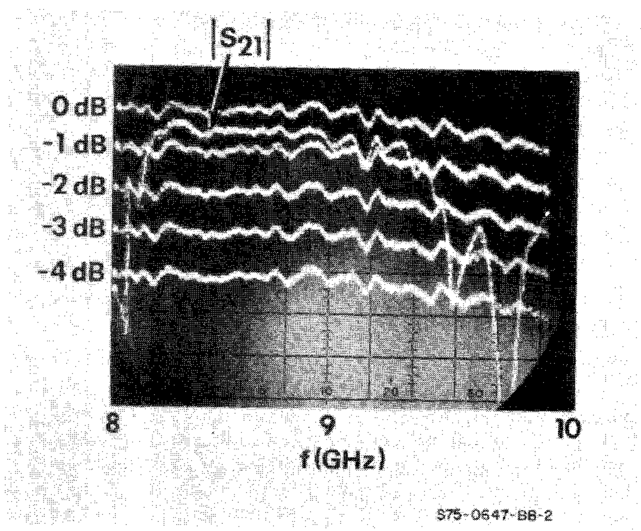

Figure 2. Below-Threshold Swept Frequency Response

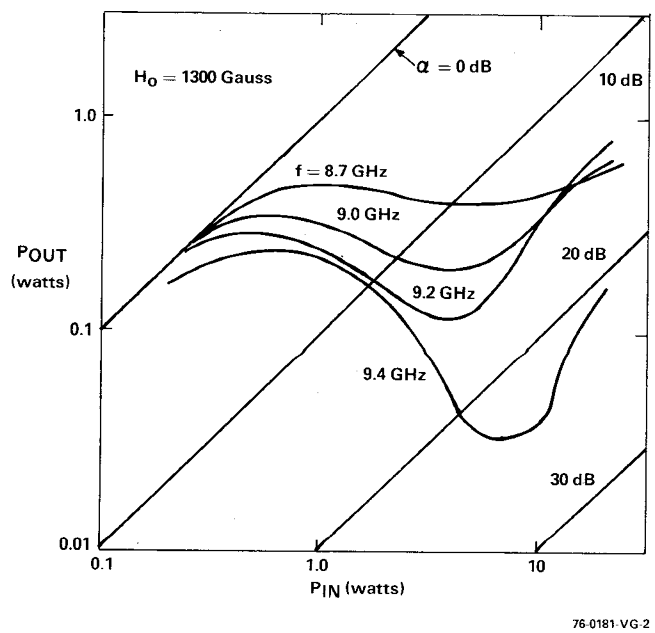

Figure 3. CW Power-Limiting Measurements with Six Single-Crystal YIG Posts

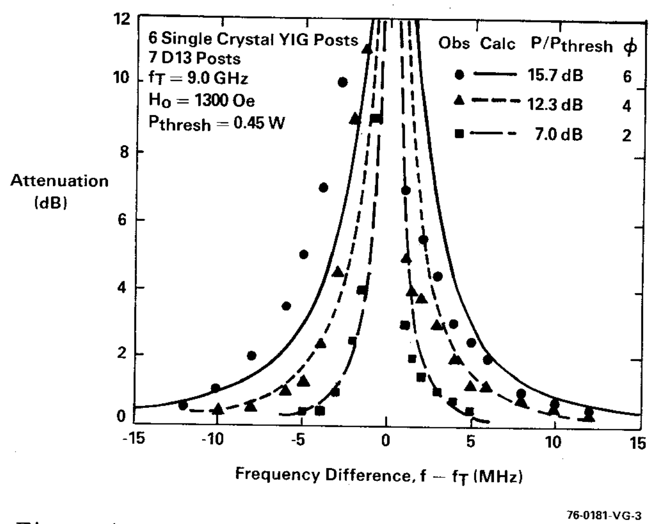

Figure 4. Dependence on Frequency of Additional Attenuation of Weak Signal for Three Power Levels of 9-GHz Saturating Signal

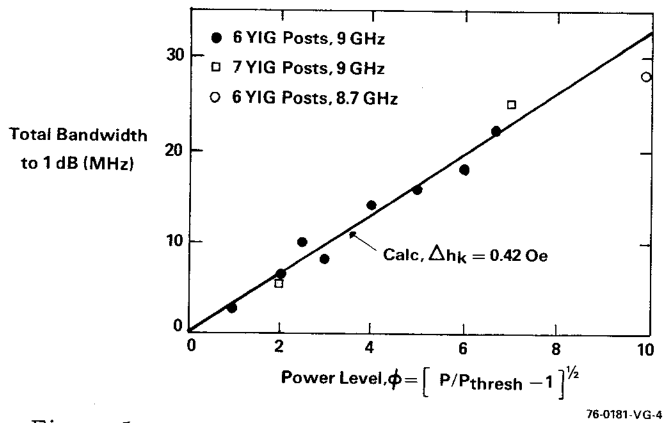

Figure 5. Total Bandwidth of Absorption (to 1-dB Level) as a Function of Input Power

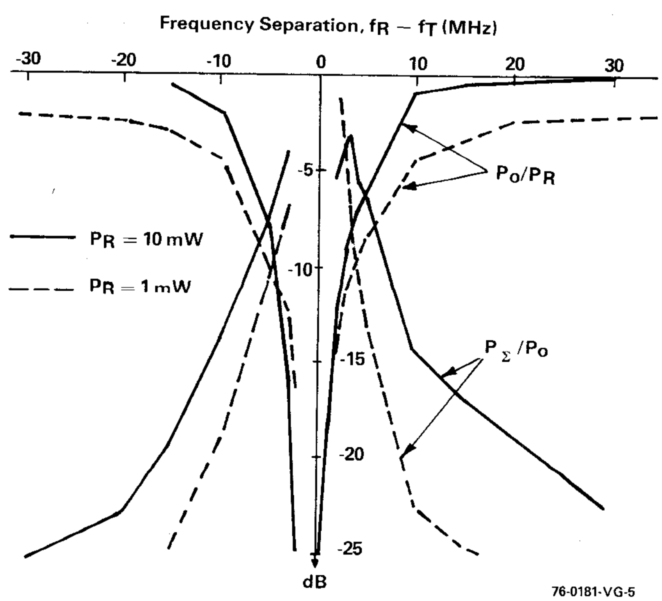

Figure 6. Weak-Signal Suppression P_o/P_R and Spurious Mixing Products P_Σ/P_o versus Frequency Separation for P_R of 10 mW and 1 mW