IV-3 NON-LINEAR THRESHOLD IN REMANENT FERRITE

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Introduction

The onset of non-linear loss in remanent ferrite devices is a complicated problem which has interested several workers[1-6] in the past half decade. The essential difficulty with the problem is that ferrite in the remanent state possesses localized areas (domains) wherein the effective fields[7] can be as low as the anisotropy field, H_A, and as high as $4\pi M_s + H_A$.

Recently, Betts[8] measured the threshold power in a helical phase shifter on a wide variety of substituted garnet materials. Betts observed non-linear thresholds which had escaped the notice of other workers by using measurement procedures sensitive to attenuation changes of .01 db. He was able to show that the threshold field varied roughly as m_s^{-2} even for m_s values of less than .35.

The experimental procedure of Betts is particularly well suited to the study of non-linearity in remanent ferrites: the helical phase shifter has circularly polarized rf fields disposed perpendicular to the remanent magnetization in a circular, uniformly magnetized toroid. Magnetizing current may be applied to the switching wire. It is therefore feasible to observe the behavior of the threshold with positive and negative circular polarization and with weak magnetizing fields.

The experiment was used to verify the assumptions of Hair and Rodrique: that the domains most susceptible to rf field instability have an effective field of $4\pi M_s$. According to Lax,[9] an effective field of $4\pi M_s$ is produced by the combined dipolar fields of adjacent oppositely magnetized domains at 180 degree domain walls. It follows that the threshold field should be independent to the remanence flux direction, as there should be favorably disposed domains at all times.

However, the typical experimental results show a substantially lower threshold for positive remanence direction (i.e., positive z direction in Fig. 1). Furthermore, the application of weak magnetizing fields lowered the threshold with the flux in the positive direction and raised the threshold with the flux in the negative direction (see Fig. 2).

It is this strong variation of threshold power with magnetization direction and weak fields which suggests that the susceptible domains are disposed at some variable characteristic angle ψ with respect to the remanence direction and that they are not coupled to oppositely magnetized neighbors at 180 degree domain walls. It appears that the application of a weak field rotates the domain towards the remanence direction, thereby reducing ψ (see Fig. 1).

Since the rf field is oblique to the magnetization, both normal and parallel pumping of spin waves can occur. It can be shown that the threshold field h_{th_1} of a domain oriented ψ radians with respect to the normal of the circularly polarized rf field is equal to

$$\frac{1}{h_{th_1}} = \frac{1 + \cos\psi}{h_{crit_n}} + \frac{\sin\psi}{h_{crit_p}} \qquad (1)$$

If the spin wave frequency

$$\omega_k = \omega/2 \qquad (2)$$

then

$$h_{crit_p} = \frac{\Delta H_k}{\sin^2 \theta_k} \frac{\omega}{4\pi\gamma M_s} \qquad (3)$$

$$h_{crit_n} = \frac{\Delta H_k}{\sin 2\theta_k} \cdot \frac{\omega}{4\pi\gamma M_s} \cdot \frac{\sqrt{(\omega_R - \omega)^2 + (\gamma\Delta\frac{H}{2})^2}}{\frac{\omega}{2} + \omega_i + \gamma H_{ex}(ak)^2} \qquad (4)$$

where θ_k = the spin wave direction with respect to the magnetization, $\omega_m = 4\pi\gamma M_s$, $\omega_R = \gamma H_A + N_t\omega_m$.

The microwave frequency is related to wave number (k) and the spin wave direction (θ_k) by the spin wave equation

$$\omega_k{}^2 = (\gamma H_i + \gamma H_{ex}(ak)^2) . (\gamma H_i + \gamma H_{ex}(ak)^2 + \gamma 4\pi M_s . \sin^2 \theta_k) \quad (5)$$

where a = the lattice constant, H_{ex} = the exchange field, H_i, the internal field, should be equal to at least H_A.

J. Green [10] has reported that the spin linewidth remains relatively constant in polycrystalline garnets for spin wave numbers ranging from 0 to 10^5 and then increases linearly with k greater than 10^5. Consequently, the excitation of long length spin waves is not favored particularly over the short wavelength variety.

The spin wavelength of single crystal YIG has been measured as a function of θ_k by Schloemann,[11] and as a function of k by Spencer.[12] Their results can be represented by the equation

$$\Delta H_k \sim \Delta H_{k_o} \ (1 + 10^{-5} k) \ (1 + .84 \cos^2 \theta_k) \qquad (6)$$

where ΔH_{k_o} is the linewidth for the k = 0, $\theta_k = \pi/2$, spin wave.

Although Eq. (6) is strictly applicable to single crystal YIG, it is assumed to be roughly representative of the garnet family of materials.

Equation (1) was minimized with respect to θ_k with the aid of a computer for a variety of garnet materials, and for values of N_t ranging from 0 to 1, H_i ranging from H_A to $H_A + 4\pi M_s$.

The computer predictions were compared with experimental results wherever possible. The best fit of predictions with data was obtained for domains in which $\tan \psi = 4\pi M/4\pi M_s$, $H_i = H_A$, $N_t = 0.5$; where $4\pi M$ is the net magnetization. In other words, long, thin domains lying in a direction ψ with respect to remanence are most susceptible to high power instability.

The results in Table I were arbitrarily normalized with respect to one of the materials in order to facilitate comparisons with the measured data of Betts. Note the rather good correspondence of the experimental results with $H_i = H_A$ and the much poorer correspondence where $H_i = H_A + N_t 4\pi M_s$. The latter case is consistent with the assumptions of Rodrique,(6) et. al, that the k = 0 spin wave manifold frequency can be as large as $4\pi\gamma M_s$.

Conclusion

The onset of non-linear loss in remanent ferrite occurs in pencil-shaped domains oriented at an angle $\tan^{-1}(4\pi M_r/4\pi M_s)$ with the remanence direction. The depolarizing effect of adjacent domains appears to be negligible. Consequently, the occurrence of 180 degree domain walls does not significantly contribute to the threshold characteristics. The upper bound of the spin wave spectrum in remanent ferrite appears to be, at k = 9, equal to $\gamma\sqrt{H_A(H_A + 4\pi M_s)}$. The threshold field appears to vary roughly as m_s^{-2}, and the non-linear attenuation decreases rapidly with m_s. Wherever small incremental losses of several tenths of a decibel are permissible, the threshold may be exceeded by a large factor in materials with m_s less than .4.

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COMPUTED AND MEASURED THRESHOLD FIELD RATIOS OF POLYCRYSTALLINE GARNETS

Material Parameters					Threshold Field Ratios		
						Computed	
Sample	$4\pi M_s$ (G)	$4\pi M_R$ (G)	ΔH (Oe)	ΔH_{k_0} (Oe)	Measured	$H_i = H_A$	$H_i = H_A + N_t 4\pi M$
A	300	120	40	3.4	4.47	3.44	2.47
B	400	240	45	2.0	1.54	1.37	0.88
C	550	290	75	6.5	2.76	2.99	1.5
D	680	425	70	5.5	1.74	1.80	1.06
E	680	390	45	3.4	1.12	1.13	0.66
F	800	511	65	5.5	1.20	1.38	0.94
G	1000	645	60	5.8	0.73	0.96	0.84
H	1200	700	60	5.2	0.52	0.57	0.67
I	1200	750	85	7.7	0.72	0.85	0.99
J	1000	610	120	7.8	1.46	1.33	1.15
K	850	460	160	10.0	2.65	2.37	1.70
L	1100	650	100	7.2	1.00	1.00	1.00

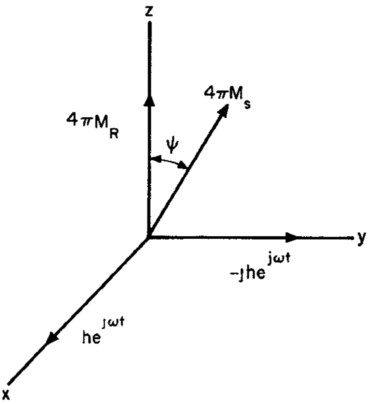

FIG. 1 - Geometrical relationships of domain magnetization ($4\pi M_s$) to the rf field (h) and remanence magnetization ($4\pi M_R$).

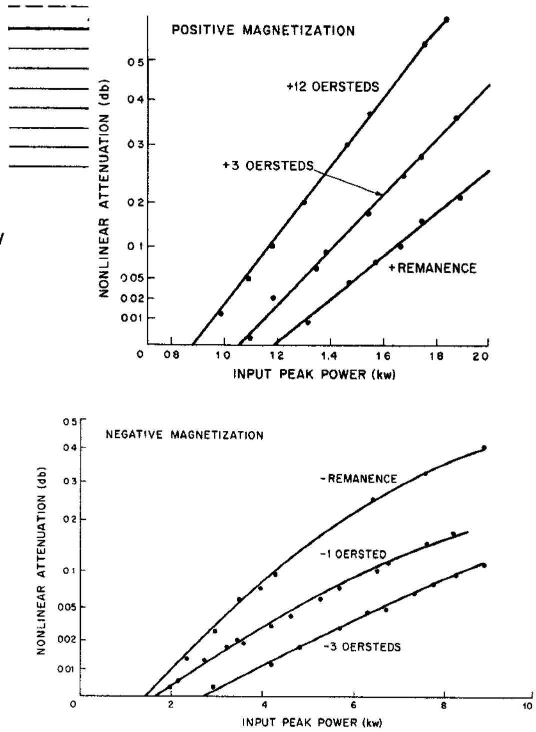

FIG. 2 - Non-linear attenuation versus power for positive (2a) and negative (2b) magnetization in a helical phase shifter at 2.8 Gc of a substituted garnet toroid with $4\pi M_R$: 495 gauss, $4\pi M_s$: 800 gauss, ΔH : 90, ΔH_{k_0} : 8 oersteds.