EFFECT OF RARE-EARTH IMPURITIES ON THE PEAK POWER CAPABILITY OF GARNET TYPE LOW-FIELD MICROWAVE DEVICES

Russell G. West, Alvin C. Blankenship and Louis P. Domingues

Trans-Tech, Incorporated, Gaithersburg, Maryland 20760

Abstract

From recent work revealing that rare-earth ions of fixed concentration in a garnet ferrimagnet give rise to an additional spin-wave linewidth term that is inversely proportional to the saturation magnetization of the host garnet, it is shown that rare-earth impurities found in commercial yttrium and gadolinium oxides used for producing ferrimagnets can contribute to unwanted variations in the peak power handling capacity of low-field microwave devices.

Introduction

In low-field ferrite devices such as digital waveguide phase shifters designed to operate at high peak power, it is common practice to reduce the saturation magnetization of the ferrimagnet in order to avoid the onset of non-linear absorption above a critical r.f. magnetic field (h_{crit}). This h_{crit} must be larger than the highest r.f. magnetic field that the phaser is designed to handle. When using this approach to obtain a significant increase in h_{crit}, the ratio of ω_m/ω_p (where ω_p is the radian frequency and $\omega_m = \gamma 4\pi M_s$) is generally reduced to a value of about 0.3 by the substitution of aluminum in YIG and YGdIG. This contrasts to a ratio of about 0.8 for low power applications. In a second approach, fast relaxing rare earths are deliberately added to garnets to increase h_{crit} while keeping saturation magnetization constant. A third approach involves the controlled variation of grain size to alter h_{crit}. In this paper only the effect of rare-earth ions on h_{crit} in garnets having a given average grain size ($\sim$10 micrometers) is discussed.

Producers and users of garnets for microwave applications generally assume that rare-earth impurities in source materials of yttria and gadolinia of 99.9% nominal purity are inconsequential. However, recent work indicates that these very low levels of rare earths do contribute to unwanted variations in h_{crit} for low values of ω_m/ω_p.

Effect of Rare-Earth Ions on h_{crit}

The high-power characteristics of microwave ferrimagnets are usually described in terms of a spin-wave linewidth of low wave number ($\Delta H_{k\to o}$), which is measured using the parallel-pump technique[1,2]. This spin-wave linewidth is known to increase proportionally with the rare-earth content. To improve or modify the magnetic properties, rare-earth (*RE*) ions are substituted into the garnet material in the manner $Y_{3-x}RE_xFe_5O_{12}$. A holmium concentration of $x = 0.01$ in YIG will approximately double the power handling capacity, P_{crit}.

Recently, West et al[3], have developed an empirical equation allowing the calculation of the spin-wave linewidth contribution of each of the rare earths present in garnets. The total contribution of rare-earth impurities to the spin-wave linewidth is obtained from the equations:

$$\Delta H_{k\to o} = \sum_{RE} \Delta H^{RE}_{k\to o} + \Delta H^{i}_{k\to o} \quad (1)$$

$$\Delta H^{RE}_{k\to o} = \frac{E}{4\pi M_s} N_{RE} \quad (2)$$

where E is a constant (ergs) and N_{RE} is the number of rare-earth ions per unit volume corresponding to the amount substituted in the formula. Having obtained the total rare-earth contribution to spin-wave linewidth, the value of h_{crit} is calculated from the equation:

$$h_{crit} = \left(\sum_{RE} \Delta H^{RE}_{k\to o} + \Delta H^{i}_{k\to o}\right)\frac{\omega_p}{\omega_m} \quad (3)$$

$\Delta H^{i}_{k\to o}$ is essentially constant ($\sim$1.4oe) for $Y_3Fe_{5-y}Al_yO_{12}$, for values of y ranging from 0 to 1.3. Of major significance is the increased effect of a given N_{RE} on $\Delta H_{k\to o}$ with decrease in saturation magnetization. Values of the factor E obtained from available experimental data are given in Table 1. Values of E determined for high concentrations of Gd^{3+} are given in reference 3.

Table 1. EXPERIMENTAL VALUES OF E FOR LOW RARE-EARTH DOPING LEVELS IN YIG

Rare-Earth Ion	E (ergs) (x-band, 23°C)
Gd^{3+}	$\sim 0.17 \times 10^{-17}$
Nd^{3+}	1.8×10^{-17}
Ce^{3+}	1.9×10^{-17}
Er^{3+}	2.2×10^{-17}
Sm^{3+}	3.6×10^{-17}
Dy^{3+}	5.7×10^{-17}
Ho^{3+}	6.4×10^{-17}
Tb^{3+}	15.5×10^{-17}

Using these data and equation 3, h_{crit} can be calculated at constant ω_p for rare-earth substituted technical garnets. The threshold field, h_{crit}, as a function of ω_m/ω_p is shown in Figure 1 for theoretically pure garnets and for impure garnets prepared from source materials described in Table 2. Chemical compositions corresponding to these curves are also given in the figure. Values for the individual rare-earth substitutions in these garnets were calculated from the concentrations in weight percent given in Table 2. For example, the rare-earth impurities shown for yttria alone amounts to a total substitution of $x = 0.0026$ in $Y_{3-x}RE_xFe_5O_{12}$; RE_x is the accumulative rare-earth substitution.

Table 2. TYPICAL ANALYSIS OF GARNET SOURCE MATERIALS OF 99.9% NOMINAL PURITY

Rare-Earth Impurity	Source Material Gadolinia Gd_2O_3 (% by wt.)	 Yttria Y_2O_3 (% by wt.)
Dy_2O_3	0.029	0.046
Er_2O_3	0.005	0.048
Gd_2O_3	-	0.0076
Ho_2O_3	-	0.0205
Nd_2O_3	0.010	-
Sm_2O_3	0.010	-
Tb_4O_7	0.24	0.023

Comparing h_{crit} of the pure YAlIG system (Curve 1) with that of the impure YAlIG system (Curve 2) at a typical operating condition of $\omega_m/\omega_p = 0.3$, h_{crit} for the impure garnet is found to be 1.5 times larger. Likewise, comparing the pure and impure YAlGdIG, h_{crit} for the impure garnet is about 1.3 times larger. Thus, these impurities increase P_{crit} by a factor of 2.2 and 1.7, respectively.

Conclusions

Because the rare-earth impurities vary both in kind and amount in yttria and gadolinia, it is not surprising that h_{crit} is a random variable in garnet ferrimagnets used for high power applications. The lack of agreement among investigators is possibly explained in regard to the measured critical field for apparently similar materials of equal grain size but prepared from different lots and/or sources of raw materials. Therefore, good reproducibility of P_{crit} in garnet type microwave devices necessitates a more critical control of the rare-earth impurities in source materials.

References

[1]F.R.Morgenthaler, J. Appl. Phys., Vol. 31, p. 95S (1960).

[2]E.Schlömann, J.J.Green and U.Milano, J. Appl. Phys. Vol. 31 p. 386S (1960).

[3]R.G.West, A.C.Blankenship and R.L.Huntt, Presented at 1970 Conference on Magnetism and Magnetic Materials, Miami Beach, Nov. 1970. To be published J. Appl. Phys., Vol. 42, Mar. 1971.

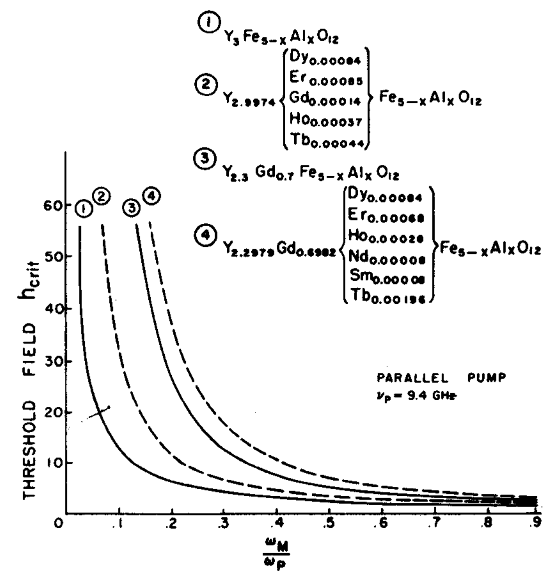

Figure 1. The calculated threshold field, h_{crit} (oe), of several ferrimagnets of varying saturation magnetization at constant ω_p. Curves (1) and (3) represent theoretically pure garnets. Curves (2) and (4) show the effect of rare-earth impurities in the starting yttrium and gadolinium oxides.

Notes

Notes