Ferrite Phase Shifters Using Stress-Insensitive Garnet Materials

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***Abstract*—Stable hysteresis characteristics of ferrimagnetic mate-rials are critical to the RF performance of microwave ferrite toroidal phasers. Particularly troublesome are the magnetostrictive characteristics where the hysteresis properties are altered by stress. This paper presents the results of a study addressing Mn^{+3} substitutions in garnets to improve the resultant magnetostrictive characteristics in order to achieve stress-insensitive performance in waveguide toroidal phasers.**

I. Introduction

The RF performance of microwave waveguide ferrite toroidal phase shifters is dependent on the hysteresis characteristics of the ferrimagnetic material utilized. Since phase shift per unit length is dependent on the remanent magnetization of the toroid, a particularly troublesome feature occurs when the hysteresis characteristics are altered by stress as a result of magnetostriction in the material. The stress may be due to mechanical tolerances related to structural assembly of the phaser; even more troublesome are stresses causes by environmental performance requirements.

Virtually all ferrites have non-zero magnetostrictive constants which result in stress-induced changes of the hysteresis properties in toroidal-shaped structures. Magnetostriction describes the experimental fact that magnetic materials will become deformed (change their physical dimensions) when they are magnetized or, conversely, they will change their state of magnetization when strained.

The hysteresis properties of garnets exhibit considerably more stress sensitivity than do spinels. This is believed to be due to the dominance of magnetocrystalline anisotropy over magnetostrictive anisotropy in the spinels. In the hybrid YIG compounds, these anisotropy stresses are more comparable in magnitude, and thus garnet materials exhibit greater sensitivity to stress.

This paper presents results of a study aimed at minimizing magnetostrictive effects in toroidal phase shifters. Material investigations were focused on Mn^{+3} substitutions in yttrium–gadolinium iron garnets. The resultant compounds were evaluated in static test fixtures, as well as in dual toroid waveguide phaser structures with pressure, temperature, and RF power as variables. Changes in remanent magnetization and phase shift were simultaneously measured as induced by changes in temperature and/or RF average power. Compounds containing a manganese substitution per formula unit of 0.11 to 0.13 produced phasers exhibiting a high degree of stress insensitivity.

II. Background

Ferrite digital phase shifters utilize toroidal structures and the square loop characteristics of the ferrite for their operation.

The phase shifters are typically constructed in waveguide using either a single-toroid or a dual-toroid configuration. The ferrite toroid as mounted in the waveguide assembly may be subjected to a variety of mechanical stresses.

The insertion phase length of the structure is dependent on the state of magnetization of the toroid which is changed by a controlled pulse of current through a wire which threads the toroid. This switching operation provides a selected and controlled differential phase shift. Under high average power operation or changes in ambient temperature, the differential thermal expansion of the ferrite and metal enclosure may produce significant stress on the toroid. These stresses will, in general, result from a combination of transverse and longitudinal forces.

Such effects are illustrated in Fig. 1, which presents the differential phase shift observed as a function of temperature in an X-band dual-toroid phaser structure which was selected as a baseline test vehicle. The material used in these data was Trans-Tech G-1002 with a 0.09 Mn substitution. This phaser structure uses a thin "drum" top to capture the ferrite material. A clockwise phase versus temperature hysteresis response is observed with over 10° change between increasing temperature and decreasing temperature due to the stress-sensitive characteristics of the material.

The stress being experienced is due to the differences in the thermal expansion coefficients of the metallic housing and the garnet material.

This undesirable performance characteristic is troublesome for phasers, in general, but is very detrimental to RF networks where the phasers are utilized in a differential phase bridge configuration such as a switch or variable power divider.

The various stresses that a ferrite may experience in a waveguide phaser structure are illustrated in Fig. 2. Some of the stresses are due to physical dimensions and associated tolerances; some result from structural/assembly requirements of the phaser, and others result from environmental performance requirements. Each of these is listed and illustrated in the figure.

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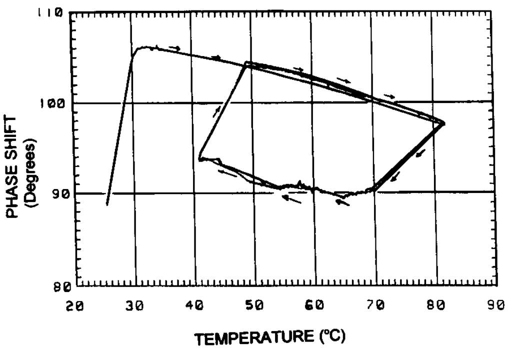

Fig. 1. Temperature hysteresis of waveguide phaser structure using TransTech G-1002 (YIG–GdIG) toroids with a 0.09 Mn substitution.

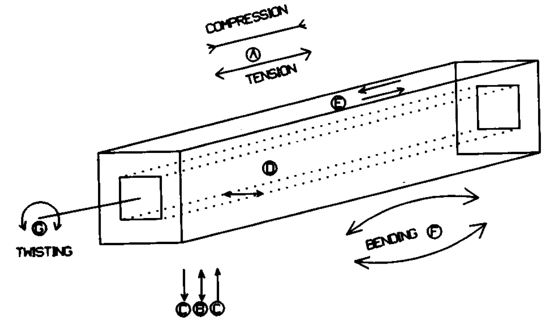

Fig. 2. Potential stresses that a ferrite may experience in a waveguide phaser structure. (A) Compression/tension along the length occurs from differential expansion of the housing and ferrite material with temperature. Extremely detrimental to phase shifters. (B) Crush compression and relief: top to bottom of phase shifter: necessary for good RF performance: can be very detrimental to phase shifter performance with temperature. (C) Differential stress from soft top RF structures (more stress on outside leg than center leg in dual toroid structures). (D) Side-to-side stress—not believed to be a major stress problem in phase shifters. (E) Differential expansion of ferrite material due to RF heating (more in center leg than in outside leg); may be detrimental to performance at high RF power. (F) Bending from tolerances in structure; ferrite hysteresis properties very sensitive to this type of stress. (G) Twisting—structure related—not believed to be a major stress problem in phasers.

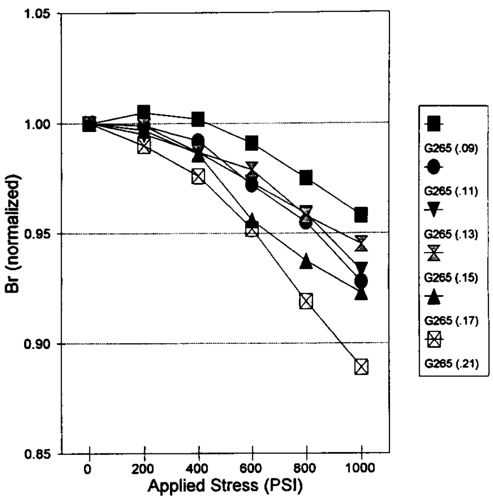

Fig. 3. Normalized remanent magnetization change as a function of applied transverse compressive stress for the manganese-substituted YIG–GdIG garnet compound (G-265(X Mn)).

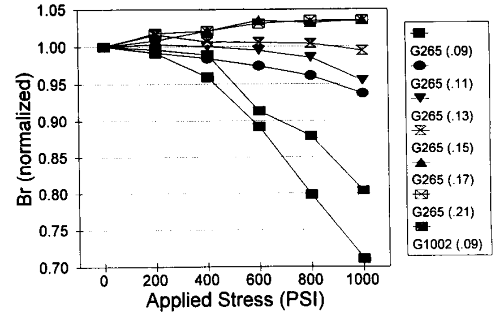

Fig. 4. Normalized remanent magnetization change as a function of applied longitudinal compressive stress for the manganese substituted G-265 garnet compound.

III. EXPERIMENTAL INVESTIGATIONS

Manganese substitution (Mn^{+3}) in garnet materials has been identified [1]–[5] as a valuable molecular engineering technique to compensate magnetostrictive constants (λ_{100} and λ_{111}). Manganese, however, will not compensate simultaneously both magnetostrictive constants. Manganese substituted in the amount of 0.09 per formula unit is utilized commercially for most garnet materials. This substitution reduces the sensitivity for stresses parallel to the direction of magnetization (B_r, the remanent magnetization) such as the top-to-bottom crush in phaser structures. (In this paper, this stress is referred to as transverse stress.) The resultant compounds are improved, but still exhibit considerable stress sensitivity as noted in Fig. 1. In most phasers, it appears that the predominant stress is longitudinal (tensile and compressive stress along the length of the toroid).

A series of manganese substituted yttrium–gadolinium iron garnets were studied with compositions given by

$$Y_{1.7}Gd_{1.3}Fe_{5\text{-}x}Mn_xO_{12}$$

with x variation from 0.09–0.21. These compositions labeled G-265(xMn) are similar to Trans-Tech G-1002(0.09 Mn) which served as a baseline material.

Fig. 3 shows changes in B_r measured on these compounds as a function of applied transverse compressive stress up to 1000 psi. (For comparison, the phaser housing provides a transverse compressive stress (top-to-bottom crush) of 100–200 psi.) Similar data are presented in Fig. 4 for longitudinal compressive stress. It is apparent from these data that no particular level of Mn provides complete immunity to stress, and different levels of Mn might be preferred for transverse and longitudinal directions. In the phaser housing, experiencing temperature variations, the toroid may be subjected to both tensile and compressive stresses.

B_r versus temperature measurements were made with the toroids mounted in the phaser structure. Fig. 5 presents data collected in the phaser simulator test fixture which show a thermal hysteresis that varies in amplitude and rotation direction with Mn content. The thermal hysteresis reverses for an Mn substitution greater than 0.13, and appears to go through zero at a value of Mn near 0.12.

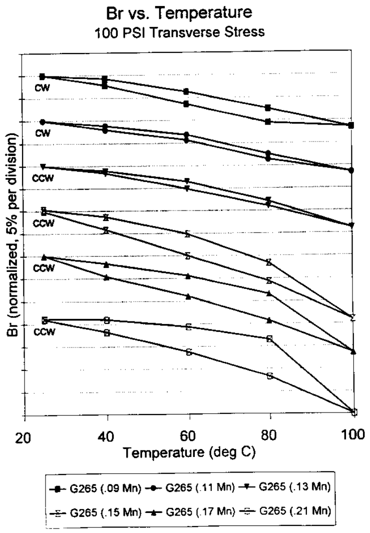

Fig. 5. Normalized B_r versus temperature for Mn substituted G-265 in the phaser simulator test fixture at 100 psi transverse compressive stress.

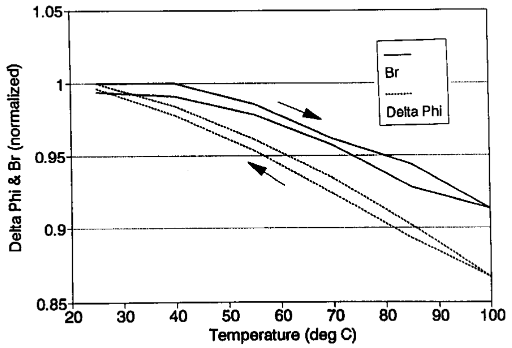

Fig. 6. Normalized remanent magnetization and phase shift changes versus temperature for 0.09 Mn substituted G-265. The temperature was cycled up and back down. The arrows indicate the clockwise (CW) direction of the hysteresis observed.

Measurements of B_r and phase shift were also made over this same temperature range. Sample data on the 0.09, 0.13, and 0.17 Mn compositions are presented in Figs. 6–8. Similar thermal hysteresis characteristics of B_r and phase are observed.

Phase shifters made from these materials were also tested at high average power levels where RF heating may cause nonuniform temperature changes in the garnet toroid. Fig. 9 shows both remanent flux (B_r) and measured phase shift as a function of housing temperature as caused by the indicated average power level in the 0.11 Mn material. A small thermal hysteresis is found, but no significant effects were observed that suggested stress arising from nonuniform differential RF heating.

The data strongly support that considerably less stress sensitivity can be achieved in Y-Gd garnets in waveguide phasers with an Mn^{+3} substitution of 0.11–0.13.

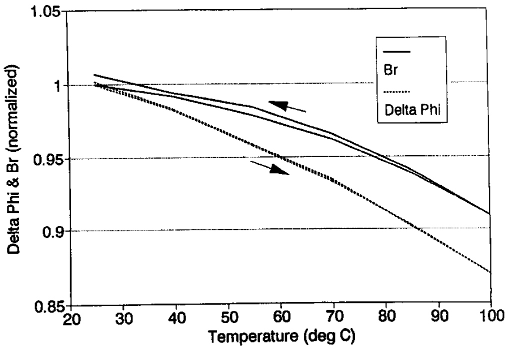

Fig. 7. Normalized remanent magnetization and phase shift changes versus temperature for G-256 (0.13 Mn). Note the slight counterclockwise (CCW) hysteresis.

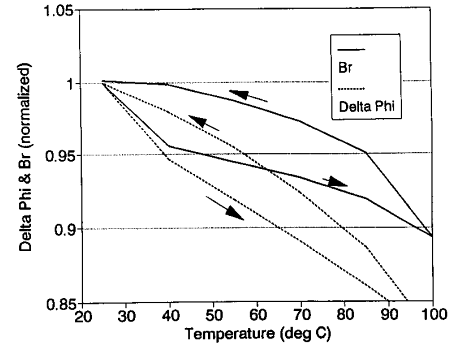

Fig. 8. Normalized remanent magnetization and phase shift changes versus temperature for G-265 (0.17 Mn). Note that severe counterclockwise hysteresis.

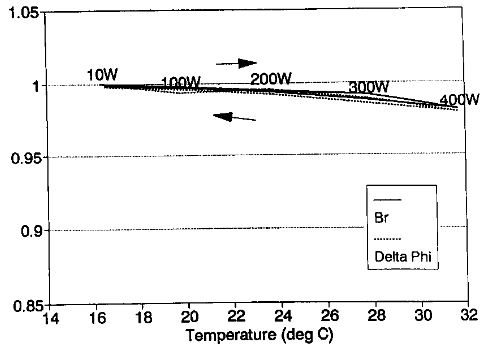

Fig. 9. Normalized remanent magnetization and phase shift for G-265 (0.11 Mn) as a function of housing temperature caused by the indicated RF average power. A very slight clockwise hysteresis is observed.

The performances of these two compounds are very similar, with a hysteresis in differential phase with temperature of not more than 0.7° over the temperature range from 25–100°C in a structure providing 111–94° total differential phase shift (<0.8% phase stress sensitivity) and suitable for acceptable RF performance up to the tested power of 400 W CW. These results can be compared to the baseline 0.09 Mn substituted compound with 10° of hysteresis in differential phase shift as presented in Fig. 1.

IV. CONCLUSION AND INTERPRETATIONS

The studies conducted have revealed that Mn^{+3} substitutions in the range of 0.11 to 0.13 produce compounds that provide stress-insensitive performance in waveguide phasers. The phase reproducibility with temperature cycling can be an order of magnitude improved in some garnet compounds. The stress characteristics achieved were observed to be very sensitive to Mn^{+3} content.

Dionne of M.I.T.(LL) has reported [1]–[4] results of his investigations of Mn^{+3} substitutions in YIG, including his data on magnetostrictive constants (λ_{100} and λ_{111}) measured on single-crystal samples. His results from measurements of magnetostrictive constants indicate that Mn^{+3} substitution has the following characteristics: His measured results [3], [4] on

	λ_{100}	λ_{111}	λ_S
Effect of one Mn^{+3} ion substitution per formula unit in YIG	$+69\times10^{-6}$	$+14\times10^{-6}$	$+36\times10^{-6}$
Magnetostrictive constants of YIG	-1.3×10^{-6}	-2.8×10^{-6}	-2.2×10^{-6}

polycrystalline garnets providing stress-insensitive remanence were as follows:

$$\frac{\partial R}{\partial\sigma} = 0 \text{ for } Mn^{+3} \text{ substitution of 0.09 and stress parallel to M;}$$

$$\frac{\partial R_{\perp}}{\partial\sigma} = 0 \text{ for 0.11 } Mn^{+3} \text{ substitution of 0.17 and stress perpendicular to M.}$$

Dionne's theory predicted 0.05 and 0.065, respectively, for Mn^{+3} substitution based on measured single-crystal magnetostrictive constants and his independent grain model for anisotropy stress energy.

Using the measured single-crystal λ_{111} values (Dionne's data) [3], [4] and adjusting λ_{100} to match the stress-insensitive polycrystalline results (Dionne's data) [3], the effects of one Mn^{+3} ion substitution per formula unit would be as follows:

$$\frac{\lambda_{100}}{+21\times10^{-6}} \quad \frac{\lambda_{111}}{+14\times10^{-6}} \quad \frac{\lambda_s}{+16.8\times10^{-6}}.$$

The above computation produces a λ_{100} considerably different from that computed from Dionne's measured single crystal data.

If $\delta R_{\perp}/\delta\sigma$ is computed using the above values for Mn^{+3}, then $\delta R_{\perp}/\delta\sigma$ vanishes for Mn^{+3} substitution of 0.122 with stress perpendicular to M. This value is also a reasonable fit to Dionne's experimental polycrystalline data [3], [4].

Dionne's model of inverse magnetostriction is based on a primitive approximation to a structure with randomly oriented grains experiencing only tensile or compressive stresses and, as a consequence, should not be expected to quantitatively describe results from a complex structure such as a waveguide toroid. Recognizing these shortcomings, the theory nonetheless provides a rationale and qualitative guide for analysis of data.

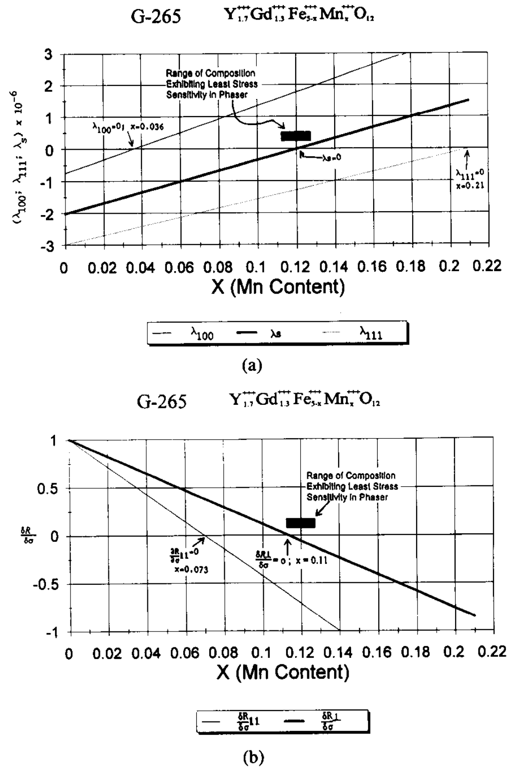

Fig. 10. (a) Predicted magnetostrictive characteristics of G-265 using $\lambda_{100} = +21\times10^{-6}$ and $\lambda_{111} = +14\times10^{-6}$ for the effects from one Mn^{+3} ion substitution per formula unit. (b) Predicted change in remanence ratio (R) with transverse ($\|$) and longitudinal ($\perp$) stress (σ) as a function of Mn^{+3} content.

Dionne's magnetostrictive constant measurements on single crystals of YIG and Mn^{+3} substituted YIG appear completely consistent. Also, similar values of magnetostrictive constants measured on samples from this same flux melt growth were reported by Gyorgy *et al.* (Bell Laboratories) [5] . The data, however, do have some uncertainty in the actual Mn^{+3} content in the single crystals measured. The Gyorgy data appear to predict the following for changes in the λ constants per Mn^{+3} ion per formula unit:

$$\frac{\lambda_{100}}{+49\times10^{-6}} \quad \frac{\lambda_{111}}{+12\times10^{-6}} \quad \frac{\lambda_S}{+27\times10^{-6}}.$$

The prime difference noted from that predicted from Dionne's data is in the value of λ_{100}.

In an effort to extract some engineering data useful to the chemical alterations of polycrystalline hybrid garnet materials for improved stress insensitivity, the above magnetostrictive effects of Mn^{+3} (λ_{100} computed value of $+21\times10^{-6}$) from Dionne's data are used and applied to the G-265 compound studied. The predicted results are shown in Fig. 10.

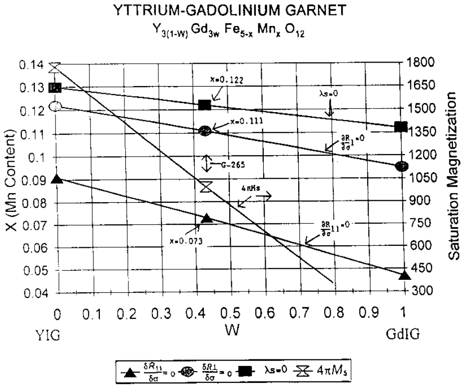

Fig. 11. Predicted Mn substitutions for stress reduction in yttrium gadolinium iron garnets.

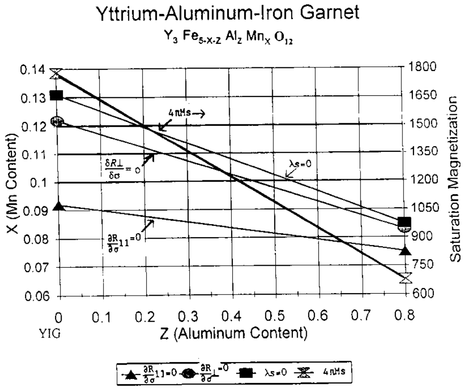

Fig. 12. Predicted Mn substitution for stress reduction in yttrium–aluminum iron garnets.

These results indicate

$$\frac{\partial R}{\partial \sigma}=0 \text{ for } Mn^{+3} \text{ substitution of 0.073 and stress parallel to M;}$$

$$\frac{\partial R_\perp}{\partial \sigma}=0 \text{ for 0.11 } Mn^{+3} \text{ substitution and stress perpendicular to M.}$$

Also, $\lambda_s = 0$ for an Mn^{+3} substitution of 0.122.

These predictions are in good agreement with the experimental data collected. The change in the direction of the observed temperature hysteresis from CW to CCW for Mn^{+3} substitutions of 0.11 and 0.13, respectively, indicate a change in the magnetostrictive characteristic within this range. This range is indicated in Fig. 10, and is consistent with the predicted conditions of $\delta R_\perp/\delta\sigma = 0$ and $\lambda_S = 0$, which could account for the observed reversal in direction of the temperature hysteresis. Other investigators [6] have also reported a significant reduction in the variation of remanent phase shift with external stress for manganese substitutions of 0.15.

During this study, other garnet compositions were prepared to further evaluate these predictions and observations. Mn^{+3} substitutions of 0.13 in YIG ($4\pi M_s = 1780$ G) as well as in a YIG–GdIG ($4\pi M_s = 1600$ G) produced compositions with equally low stress sensitivity.

The predicted optimum value of Mn^{+3} to minimize stress sensitivity will vary with composition. The predicted values are presented in Fig. 11 for the yttrium–gadolinium iron mixed garnets. The G-265 composition is noted.

Similar predictions can be generated for the yttrium–aluminum iron or yttrium gallium iron garnets by using the measured and reported data for gallium substituted YIG [7]. Aluminum and gallium substitutions in hybrid YIG compounds are very similar. Aluminum is very similar to gallium in structure, and predominantly locates on the same lattice site (24*d*) in the garnet structure, so this substitution produces almost identical effects on the magnetic and microwave properties of polycrystalline garnets [8]. These predictions, therefore, assume that aluminum and gallium would yield very similar magnetostrictive characteristics. Fig. 12 shows calculated results for these compounds.

The investigations, data collected, and results obtained from this study are expected to be very valuable in the generation of future high-power, high-precision ferrite phase shifters and the embedded impact these components have on switches and power dividers. The reduction achieved in stress sensitivity will also provide reduced costs via improved phaser structures and the reduced phase sensitivity to stress (pressure) associated with the assembly and manufacturing procedures required.

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