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Single crystal hexaferrite phase shifter at Ka band

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A phase shifter was fabricated from a scandium doped M-type (ScM) barium hexaferrite single crystal substrate, and tested over microwave frequencies from 20 to 40 GHz and bias magnetic fields from 0 to 2 kOe. At a microwave frequency of 40 GHz and bias magnetic field of 1.3 kOe, the differential phase-shift rate was $42^\circ/\text{kOe mm}$ and the loss rate was 0.7 dB/mm. The phase shifter utilized the large uniaxial anisotropy field inherent in ScM single crystals, where the crystallographic c axis and the magnetic bias field were parallel to each other and in the substrate plane. The performance of the phase shifter was modeled by the conjugate method for transmission electron microscopy wave and compared with experimental results. © 2002 American Institute of Physics. [DOI: 10.1063/1.1450845]

I. INTRODUCTION

In previous research,¹ a phase shifter, utilizing the large in-plane uniaxial anisotropy inherent to Y-type hexaferrite, operated up to 20 GHz at relatively low bias field (~ 1 kOe). In this research, we considered scandium doped M-type (ScM) hexaferrite, for phase shifters operating up to 40 GHz at relatively low bias field.

The so-called “M-type” hexaferrites refer to a group of ferrimagnetic oxides having a chemical composition of $\text{MeFe}_{12}\text{O}_{19}$ and a hexagonal crystal structure, where Me is a divalent cation such as Ba^{2+} , Sr^{2+} or Pb^{2+} . A basic magnetic property of M-type hexaferrites is the large uniaxial anisotropy inherent in the hexagonal crystal structure, where the crystallographic c axis is the magnetic easy axis.² Here ScM refers to scandium doped M-type barium hexaferrite, which has a chemical composition of $\text{BaFe}_{12-x}\text{Sc}_x\text{O}_{19}$. The most attractive property of ScM is that H_A can vary from 0 to 16 kOe depending on the doping concentration of Sc.³ This property enables ScM phase shifters to cover a broad frequency range from L to Q bands at relatively low bias fields. In this research, a prototype phase shifter was fabricated on a ScM single crystal substrate. The test showed that the device can operate up to 40 GHz with reasonable loss at relatively low bias field

II. EXPERIMENT

The chemical composition of the ScM single crystal used in this research was $\text{BaFe}_{11.1}\text{Sc}_{0.9}\text{O}_{19}$. The ScM single crystal was prepared at the Hewlett-Packard Company by flux-melt method.⁴ The vibrating sample magnetometer (VSM) measurements were performed to measure H_A and $4\pi M_S$ of the sample (Fig. 1). The sample was diced to 1.95 mm long (along the z axis) and 1.75 mm wide (along the y

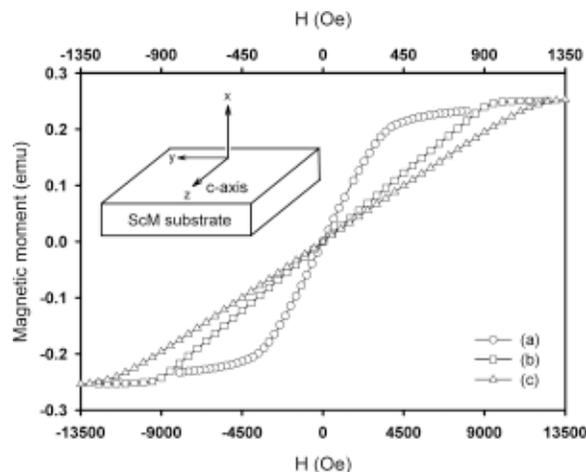


FIG. 1. VSM data of ScM single crystal sample for the external field (a) parallel to the c axis (top scale); (b) perpendicular to the c axis and in the substrate plane (bottom scale); (c) normal to the substrate plane (bottom scale).

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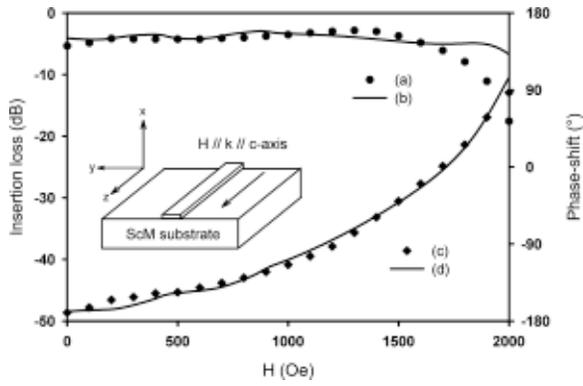


FIG. 2. The insertion loss (left scale) and phase shift (right scale) of the phase-shifter device at 40 GHz: (a) measured insertion loss; (b) calculated insertion loss corresponding to (a); (c) measured phase shift; (d) calculated phase shift corresponding to (c).

axis) and polished down to 0.24 mm thick (along the x axis). The c axis of the sample was parallel to the z axis. The saturation magnetization $M_s = 310.4$ G was deduced from $M_s = m/V$, where the measured saturated magnetic moment by VSM $m = 0.25280$ emu. When the external field was parallel to the c axis, the sample was easily saturated at $N_z M_s = 400$ Oe, since the c axis is the magnetic easy axis of M-type hexaferrites. When the external field was parallel to the x axis, the sample saturated at $H_A + N_x M_s = 11.6$ kOe. When the external field was parallel to the y axis, the sample saturated at $H_A + N_y M_s = 9.3$ kOe. The anisotropy field H_A and demagnetizing factors N_x, N_y, N_z could be solved by combining the above three measurements and $N_x + N_y + N_z = 4\pi$. The results were $H_A = 8.7$ kOe, $N_x = 9.42$, $N_y = 1.88$ and $N_z = 1.26$. When the external field was parallel to the c axis, the coercive field H_c was about 4 Oe. Ferrimagnetic resonance (FMR) measurements were performed to measure the gyromagnetic ratio factor γ and microwave linewidth ΔH . In the FMR measurement, the external magnetic field was aligned parallel to the c axis but perpendicular to the microwave magnetic field. The FMR data showed uniform, magnetostatic, surface magnetic mode excitations, and other electromagnetic excitations. Since the analysis of complex excitations is beyond the scope and purpose of this article, we only focused on the uniform mode excitation and utilized the following FMR condition:

$$\left(\frac{\omega_0}{\gamma}\right)^2 = [H + H_A + (N_y - N_z)M_s] \times [H + H_A + (N_x - N_z)M_s], \quad (1)$$

where H_A, M_s and demagnetizing factors were deduced from the above VSM measurements. From FMR data, we deduced that $\gamma/2\pi = 2.773 \pm 0.004 \times 10^6$ Hz/Oe ($g = 1.98$). The FMR linewidth ΔH was 100 Oe at 40 GHz.

The phase-shifter design consisted of fabricating a microstripline on the ScM single crystal substrate (Fig. 2). The substrate was diced to 4 mm long (along the z axis) and polished down to 0.254 mm thick (along the x axis). The microstripline was parallel to the c axis of the substrate. The relative permittivity of ScM perpendicular to the c axis (ϵ_{\perp}) was 22.⁵ To match the standard 50 Ω microwave test set, the

TABLE I. Summary of phase-shifter data.

Frequency (GHz)	21	38	40
Bias field (kOe)	0.1	0.6	1.3
Loss rate (dB/mm)	0.75	0.67	0.7
Phase-shift rate ($^{\circ}$ /kOe mm)	37	39	42

characteristic impedance of the microstripline was designed to be 50 Ω , i.e., the width of the microstripline was 0.127 mm. The bias field was applied parallel to the z axis, which is usually referred to as the “longitudinally magnetized field condition.” Before measuring the S parameters of the phase shifter, a HP 8510B network analyzer was calibrated with a through-reflection-line calibration set.⁶ After calibration the reference planes were established at both ends of the phase shifter. We measured amplitude and phase of S_{21} (or S_{12}), where S_{21} or (S_{12}) was the transmission coefficient only through the magnetic portion of the device. In the test, S parameters of the phase shifter were collected from 20 to 40 GHz at each fixed bias field varied from 0 to 2 kOe with 0.1 kOe increment.

The performance of the phase shifter was evaluated at the operating points chosen to minimize the insertion loss and maximize the phase shift (Table I). Typical data versus bias field at 40 GHz are shown in Fig. 2.

III. DISCUSSION

Since the phase shifter had a finite geometry, there were magnetostatic mode excitations besides the uniform mode.⁷ When the external field was parallel to the c axis of the single crystal sample, the resonance frequencies of these modes ω_{MS} were given by

$$\left(\frac{\omega_{MS}}{\gamma}\right)^2 = \left(\frac{\omega_0}{\gamma}\right)^2 + \frac{4\pi M_s}{k_x^2 + k_y^2 + k_z^2} \times \{ [H + H_a + (N_y - N_z)M_s]k_x^2 + [H + H_a + (N_x - N_z)M_s]k_y^2 \}, \quad (2)$$

where ω_0 is the resonance frequency of uniform mode given by Eq. (1) and \mathbf{k} is the wave vector of magnetostatic mode.⁸ According to Eq. (2), at a fixed frequency the magnetostatic mode $(0, k_y, 0)$ has the lowest resonance field and the uniform mode, which can be considered as magnetostatic mode $(0, 0, k_z)$, has the highest resonance field. Between these two modes, there are other magnetostatic modes that form a continuous loss region, in which insertion loss of the phase shifter is usually larger than 10 dB. Therefore, at a fixed frequency, the operating point of the phase shifter should be lower than the magnetostatic mode $(0, k_y, 0)$, or higher than the uniform mode, in order to minimize loss. In this phase-shifter design, where a low bias field is desired, the operating point is chosen to be lower than the magnetostatic mode $(0, k_y, 0)$. In the modeling, the magnetostatic modes $(0, k_y, 0)$, $(k_x, 0, 0)$ and the uniform mode were included with the weight ratios of 0.1, 0.1 and 0.8, respectively. The weight ratios were based upon our ability to fit the data. The relative permeability along the y axis μ_{yy} at microwave frequency ω was given by

$$\mu_{yy} = 1 + 4\pi M_s \gamma^2 \times \frac{[H + H_a + (N_x - N_z)M_s]}{\Omega^2 - \omega^2}, \quad (3)$$

where the real part of Ω is the resonance frequency ω_{MS} given by Eq. (2), the imaginary part of Ω results in the FMR linewidth ΔH .⁹ According to Eq. (3), there exists a value of bias field such that $\mu_{yy} = 0$, where the relative permeability is negative until reaching the resonance field value. In this region, the insertion loss of the phase shifter is also high. Therefore, when considering fixed frequency devices, the operating point of the phase shifter should be lower than the point where $\mu_{yy} = 0$. The effective relative permeability μ_{eff} and S parameters were calculated using conjugate method for a transmission electron microscopy wave.¹⁰ The calculated performance fitted the measured data reasonably throughout the low loss region, where the phase shifter was operating (Fig. 2). The magnetic parameters used in the fitting were assumed to be $M_s = 306$ kOe, $H_A = 8.5$ kOe, $N_x = 11.69$, $N_y = 0.38$, $N_z = 0.50$, $\Delta H = 0.1$ kOe and $\gamma/2\pi = 2.78$. The modeling also showed that reducing ΔH increases the differential phase shift and decreases the insertion loss at the operating point, as expected.

When the substrate was partially magnetized, the permeability μ was smaller than the value given by Eq. (3). Therefore, to operate the phase shifter efficiently, the phase shifter should be saturated. This means that the bias field should be larger than the demagnetizing field along its direction and the coercive field. Since the demagnetizing field along the c axis can be reduced by preparing thinner substrate and the coercive field is only 4 Oe for our sample, it is possible to operate a phase shifter with thinner substrate at high frequency but a very small bias field. Alternatively, a magnetically self-biased phase shifter will require the coercive field to be greater than the demagnetizing field.

IV. CONCLUSION

As shown in the testing and modeling, it is possible to design and fabricate a longitudinal magnetized tunable microstripline phase shifter on ScM single crystal substrate and to operate the phase shifter at much lower bias field than used for spinel and garnet materials. Both the large H_A inherent in the ScM single crystal and the alignment of c axis parallel to the microstripline and bias field reduce the requirement of biasing the phase shifter at high frequencies. In addition, the required bias field could be reduced to several oersteds for Ka band operation by reducing the demagnetizing field due to the shape.

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