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Single-crystal yttrium iron garnet phase shifter at X band

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A tunable phase shifter at X band using single-crystal yttrium iron garnet film material grown on GGG substrates is fabricated. The phase shifter is a fourth wavelength in the absence of a bias magnetic field. The phase can be tuned 120° by varying the bias magnetic field from 3440 to 3720 Oe. The resultant variation in insertion loss was 0.5 dB. Measurements compared very well with calculations. © 1999 American Institute of Physics. [S0021-8979(99)19508-2]

INTRODUCTION

Phase shifters are often constructed in terms of frequency-agile materials whose electronic properties can be changed via the application of a voltage or a magnetic field. While it is possible to fabricate a phase shifter at low frequencies by using a ferroelectric substrate,¹ say, below 5 GHz, it is not very feasible if the frequency is increased to X band or beyond, since ferroelectric materials are generally lossy at high frequencies. At X band and above, insertion losses are lower in ferrite substrates. By applying a bias magnetic field, the effective permeability of a ferrite substrate can be continuously changed, resulting in variable phase shifts for microwave signals propagating in a transmission line fabricated on a ferrite substrate.

One difficulty in using a ferrite substrate is that the bias magnetic field is required to have a magnitude at least several thousand oersteds to effectively change the permeability of the substrate at X-band frequencies. The bias field is divided into two parts: the permanent part and the variable part. The permanent part of the bias field is furnished by using a permanent magnet, or, alternatively, by using the internal (uniaxial) anisotropy field of the substrate material, providing a constant background for magnetic biasing. The variable bias field is then superimposed on the permanent part, resulting in local variation of the bias field near its permanent field value. Ideally, the variable field should be small in magnitude in comparison to the permanent field. The variable field can then be conveniently obtained by using a solenoid coil.

In order to reduce the bias current in the solenoid coil, and hence to enhance the switching speed of the phase shifter device and lower power dissipation, the range that allows the variable bias field to change shall be kept as a minimum. For this purpose, the bias condition is usually devised near ferromagnetic resonance (FMR). In the vicinity of FMR, the permeability of the ferrite material is a sensitive function of

the bias field, and a slight change in the bias field can result in a significant change in permeability. However, the price to pay is that when FMR is approached, the ferrite material becomes very lossy, and the precessional motion of spins will experience a significant magnetic damping torque. We will demonstrate in this paper that it is possible to operate a ferrite phase shifter near FMR without introducing much additional magnetic loss if the ferrite exhibits a narrow FMR linewidth.

Yttrium iron garnet (YIG) is an ideal material for the fabrication of microwave phase shifters at X band. The linewidth for single-crystal YIG is about 0.5 Oe at X band. In this article, we report the performance of an X-band stripline phase shifter which uses single-crystal YIG thick films as the substrate material. We found that at 10 GHz the phase shifter, which is a quarter wavelength in the absence of a bias magnetic field, can produce a phase change of 120° in the transmitted signal when the bias field is varied from 3440 to 3720 Oe. The accompanying change in insertion loss is from 0.4 to 0.5 dB. Thus, the phase shifter can be practically used, say, in phased-array radar systems where a constant bias field of 3580 Oe can be provided by a permanent magnet, which is superimposed with a variable field of ± 140 Oe to be supplied by a solenoid coil.

The performance of the phase shifter has also been analyzed numerically by using the transfer-matrix technique in a transmission line involving a stratified structure. The transfer-matrix technique is usually used to translate the transverse electromagnetic boundary conditions occurring at one layer boundary to another, expressing the continuity equation in the spectral domain.² Our calculations compared very well with measurements. The theoretical part of this article is currently under preparation and will be published elsewhere.

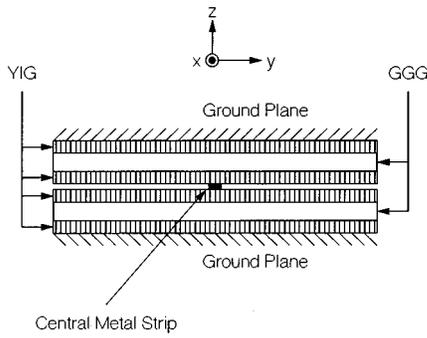


FIG. 1. Geometry of a composite stripline transmission line using single-crystal YIG thick films as the substrate material.

RESULTS

We have fabricated an X-band phase shifter using single-crystal YIG/GGG/YIG substrate assemblies in the stripline geometry, see Fig. 1. The YIG/GGG/YIG material was purchased from Airtron, Charlotte, NC. The YIG films are of a nominal thickness of 100 μm , which were epitaxially grown along the $\langle 111 \rangle$ direction on both sides of a GGG substrate (thickness 20 mil and dielectric constant 14.7). The YIG films are characterized by the following parameters: saturation magnetization $4\pi M_s = 1750$ G, dielectric constant $\epsilon_f = 14.7$, anisotropy field $H_A = 82$ Oe, and an FMR linewidth $\Delta H \approx 0.5$ Oe at 10 GHz. The dielectric loss tangent for both YIG and GGG materials is 0.0002. Using the composite YIG/GGG/YIG materials as the substrate, a stripline circuit was fabricated. The stripline is of a length 0.782 cm, which is approximately one quarter wavelength long at 10 GHz in the absence of a bias magnetic field. The width of the central conductor strip is 0.0531 cm, corresponding to a characteristic impedance of 25 Ω . The stripline circuit was connected to two air-filled quarter-wave transformers having an impedance of 35.4 Ω and was measured using a vector network analyzer, HP-8510B.

Figure 2 shows the measured insertion loss (circles) and phase shift (solid squares) of the transmitted S_{21} signal at 10 GHz. From Fig. 2 we notice that the signal phase changes rapidly near FMR accompanied by a sharp drop in insertion loss. Just above FMR the phase still varies sensitively with

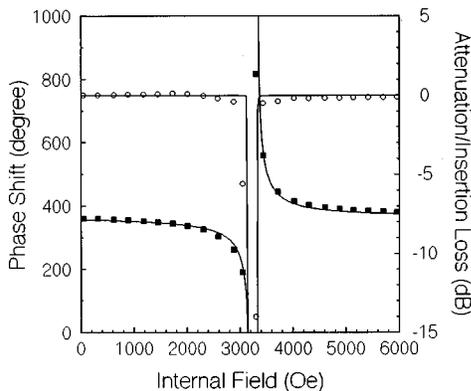


FIG. 2. Stripline device shown in Fig. 1. Calculations are shown as solid lines and measurements are shown as solid squares for phase shift and circles for insertion loss.

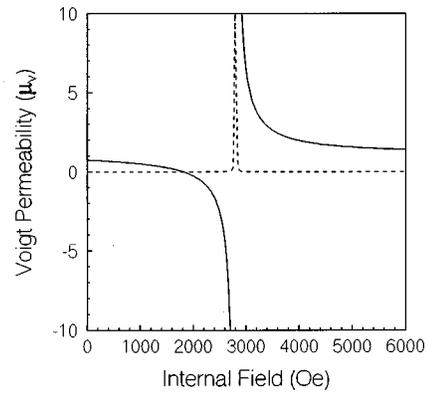


FIG. 3. Voigt permeability of the YIG material as a function of the bias field: real part (solid line) and imaginary part (dashed line).

the bias field, but with the insertion loss retained rather at a relatively constant low level. When the bias field is varied from 3720 to 4020 Oe, the phase undergoes a change from 561° to 442° with the insertion loss varying from -0.49 to -0.38 dB, indicating the usefulness of the device providing low-loss phase shift at X band. Measurements compare very well with calculations, which are shown as solid lines in Fig. 2.

The theoretical curves were obtained by solving the dispersion relation expressing the functional dependence of the wave propagation constant, k_x . While the length of the transmission line is known, the total amount of phase shift and attenuation can be calculated from the real and imaginary parts of k_x , respectively, as plotted in Fig. 2. However, we note that in Fig. 2 the experimental data are shown for the measured phase shift and insertion loss. Since the insertion loss also includes the return loss, its value is larger than the calculation showing only the attenuation part of the insertion loss. Since in Fig. 2 the measured insertion loss is not very different from the calculated attenuation when the ferrite substrate is biased beyond FMR, we conclude that the return loss, or the amount of impedance mismatch, is not very significant in the off-resonance region.

Intuitively, one may expect the functional dependence of the phase shift and attenuation shown in Fig. 2 comes directly from the Voigt permeability of the YIG material.³ The permeability is defined for the TE mode for which the rf magnetic field component, the dc bias field, and the wave propagation direction are all mutually perpendicular to each other. The permeability is given as

$$\mu_v = 1 + \frac{\omega_m(\omega_m + \omega_o)}{\omega_o(\omega_m + \omega_o) - (\omega/\gamma)^2}, \quad (1)$$

$$\omega_m = 4\pi\gamma M_s, \quad (2)$$

$$\omega_o = \gamma H'_{in}, \quad (3)$$

ω is the angular frequency, γ the gyromagnetic ratio, $4\pi M_s$ the saturation magnetization, and H'_{in} is the effective internal bias magnetic field given by

$$H'_{in} = \{[(\mathbf{H} + \mathbf{H}_A)_x]^2 + [(\mathbf{H} + \mathbf{H}_A)_y]^2 + [(\mathbf{H} + \mathbf{H}_A)_z - 4\pi M_s e_{nz}]^2\}^{1/2} - i\Delta H. \quad (4)$$

In Eq. (4) \mathbf{H} denotes the externally applied dc magnetic field, \mathbf{H}_A the anisotropy field, e_{nz} the z component of the unit vector along \mathbf{H}_A , and ΔH is the FMR linewidth. The permeability is plotted in Fig. 3 as a function of the internal field. By comparing Fig. 2 with Fig. 3 we notice that the actual FMR frequency is allocated at 3151 Oe, which is considerably higher than that predicted by the permeability occurring at 2802 Oe.

CONCLUSIONS

We conclude that practical phase shifters operating at X band can be fabricated using single-crystal YIG material characterized by a narrow FMR linewidth. While the transmission phase can be sensitively tuned by applying a bias magnetic field, the insertion loss can be retained at a rela-

tively constant low level. In addition, it is necessary to bias the YIG film material with a small variable field which can be conveniently generated using a solenoid coil. The performance of the phase shifter can be described by simply a numerical analysis in which the transfer matrix technique needs to be fully implemented.

ACKNOWLEDGMENT

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