EFFECTIVE-FIELD THEORY FOR FERRITE THIN-FILM JUNCTION CIRCULATOR

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ABSTRACT

We have calculated the S-parameters and losses in ferrite-film junction circulators using a new effective-field theory assuming TEM-like propagation. Conductivity losses dominate the dielectric and magnetic losses in Y-junction circulators fabricated on ferrite films with thicknesses less than 200 μm.

INTRODUCTION

Integration of ferrite-film non-reciprocal devices into microwave front-end electronic could lead to significant cost savings in T/R modules. Design of these devices must accurately model the conductivity losses, which become increasingly important as the ferrite-film thickness decreases. We have developed an improved theory for ferrite-film Y-junction circulators and applied this theory to calculate the losses in such a device as a function of ferrite-film thickness.

Previous calculations of the conductor loss in a junction assumed that the eddy-current electric fields parallel to the ground plane are independent of z, the coordinate normal to the junction's conductor plane [1]. In this paper we calculate the losses using an effective-field theory for the junction circulator which does not depend on this assumption. The derivation is based on the observation that circulation modes in the junction are TEM-like modes possessing a permeability $\mu_v = \mu - \kappa^2/\mu$. where μ and κ are Polder tensor elements [2]. The circulation modes are Voigt modes, guided between the two conductor planes of the junction, forming standing modes for clockwise and counterclockwise rotations [3]. The conductor loss can thus be found if one is able to calculate the eddy-current fields accompanying the primary fields excited in a guiding structure supporting TEM waves.

For this purpose we have solved the conductor-loss problem in a parallel-plate waveguide. We found that the eddy-current fields do show z-dependence, and the interaction between the eddy currents and the primary fields can be interpreted in a geometric way. That is, eddy-current effect can be effectively accounted for if metal boundaries are withdrawn a distance δ into the interior of the metal with the recessed volume filled with air supplied with equal amount of conductor currents and inductor currents. Here, δ denotes the skin depth of the metal. Within the air layers the permeability is therefore, $\mu_o(1 + i)$, and the overall permeability of the guiding structure can now be expressed as the arithmetic average of the constituent elements, the air layers on top and bottom and the dielectric/ferrite filling material in the middle. This establishes the foundation for the effective-field theory, and this picture resembles closely with that underlying the Wheeler's incremental impedance [4]. We note that both the effective-field model and the Wheeler's impedance are applicable only to a guiding structure supporting TEM-like propagation waves.

FORMULATION

Using the effective-field theory, the junction is viewed as composed of three layers and the overall values of permittivity, permeability, and magnetization are then

$$\epsilon_{tot} = (d\epsilon_f + 2\delta\epsilon_o)/(d + 2\delta),$$

$$\mu_{tot} = [d\mu_o + 2\delta(1 + i)]/(d + 2\delta),$$

$$M_{tot} = dM/(d + 2\delta).$$

Here d denotes the thickness of the ferrite junction. The above formulae represent first-order corrections due to finite conductivity of the junction's metal surfaces. Modification stated above are important when the junction thickness d is comparable to the skin depth δ. The other losses, magnetic and dielectric, can be included in the model by letting the dielectric constant ϵ_f and the (internal) biasing field H_i become complex numbers:

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$$\epsilon_f \Rightarrow \epsilon_f(1 + i \tan\delta),\ H_i \Rightarrow H_i - (i\Delta H/2)(f/f_r).$$

Here $\tan\delta$ is the dielectric loss tangent, and ΔH the FMR linewidth measured at frequency f_r.

The effect of the coupling transformers that match the circulator to 50 Ω lines can be considered as follow. Let $(\underline{\underline{\mathbf{S}}})_{3\times3}$ be the scattering matrix of the ferrite junction and $(\underline{\underline{\mathbf{T}}})_{2\times2}$ be that corresponding to the network transformer. The overall scattering matrix of the junction plus the network is then

$$\underline{\underline{\mathbf{W}}} = T_{11}\,\underline{\underline{\mathbf{I}}} + T_{12}\,T_{21}\,\underline{\underline{\mathbf{S}}}\,(\underline{\underline{\mathbf{I}}} - T_{22}\,\underline{\underline{\mathbf{S}}})^{-1}.$$

While $\underline{\underline{\mathbf{S}}}$ can be calculated using the theory described above and we have derived the transfer function of the network transformers using standard transmission-line theory. Lossy lines can be accounted for by using the complex propagation constant, γ .

RESULTS

Fig.1 shows the calculated S-parameters of a junction circulator, including the matching network transformer, using Wu and Rosenbaum's design [5] with 100 µm-thick single-crystal YIG substrate (dielectric constant $\epsilon_f = 14.5$, saturation magnetization $4\pi M_s = 1750$ G, dielectric loss tangent $\tan\delta = 0.0002$, FMR linewidth $\Delta H = 1$ G measured at 10 GHz). The length of each segment of the transformer is set equal to quarter wavelength at 9.3 GHz. The overall insertion loss is -0.797 dB, of which -0.208 dB is the junction loss and the remainder is the loss in matching transformers. Magnetic and dielectric losses in the junction are, respectively, -0.00991 and -0.00682 dB, which all compare negligibly small with conductor loss in the junction. For comparison, Neidert and Phillips predict a conductivity loss of -0.09 dB in the junction [1].

Fig.2 plots the calculated insertion loss as a function of the ferrite substrate thickness. The solid line represent the insertion loss due to the junction alone, whereas the dashed line refers tp the total loss of the junction plus the transformer network. We note that when the substrate thickness decreases below 100 µm, not only does the insertion loss increases drastically as seen in Fig.2, but also the bandwidth of transmission narrows rapidly as a result of the more difficult impedance matching. We have compared our calculations to a thin-film circulator fabricated by us and achieved good agreement between theory and experiment [6].

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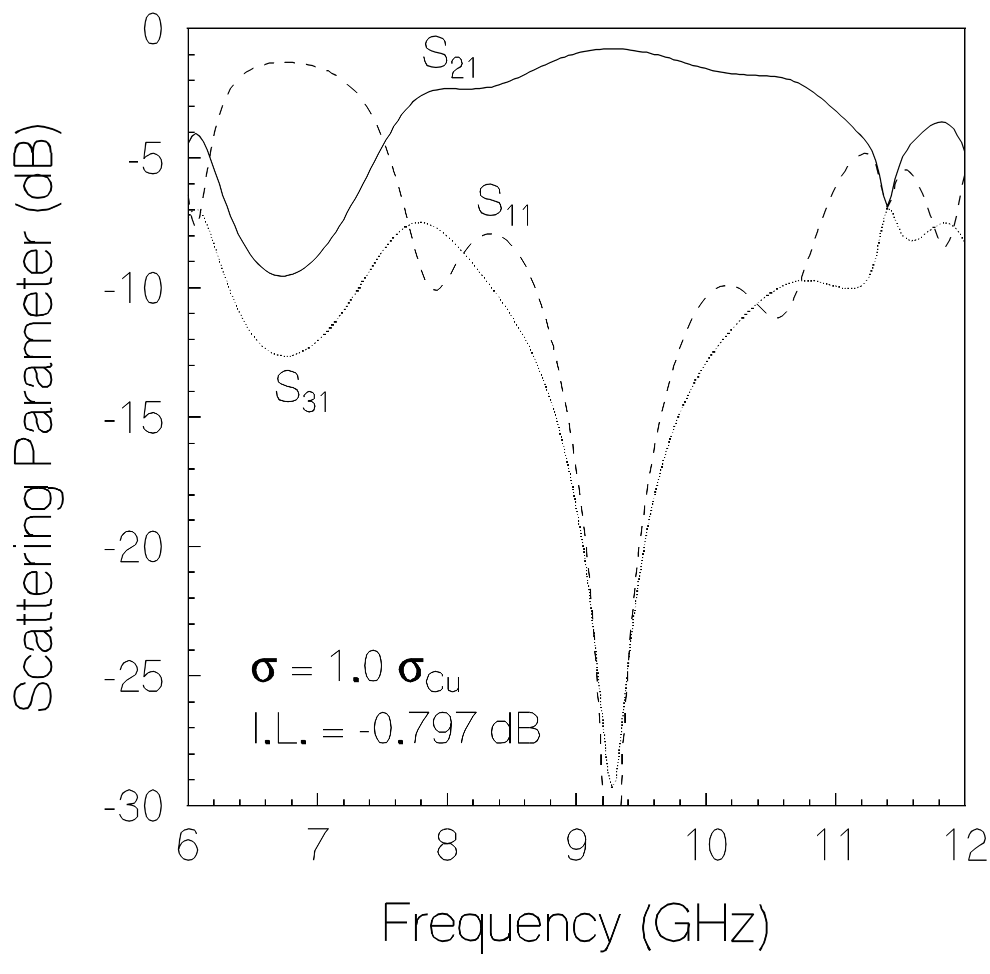

Figure 1 Calculated S-parameters of a thin-film circulator connected to a impedance transformer network. The substrate thickness is 100 µm.

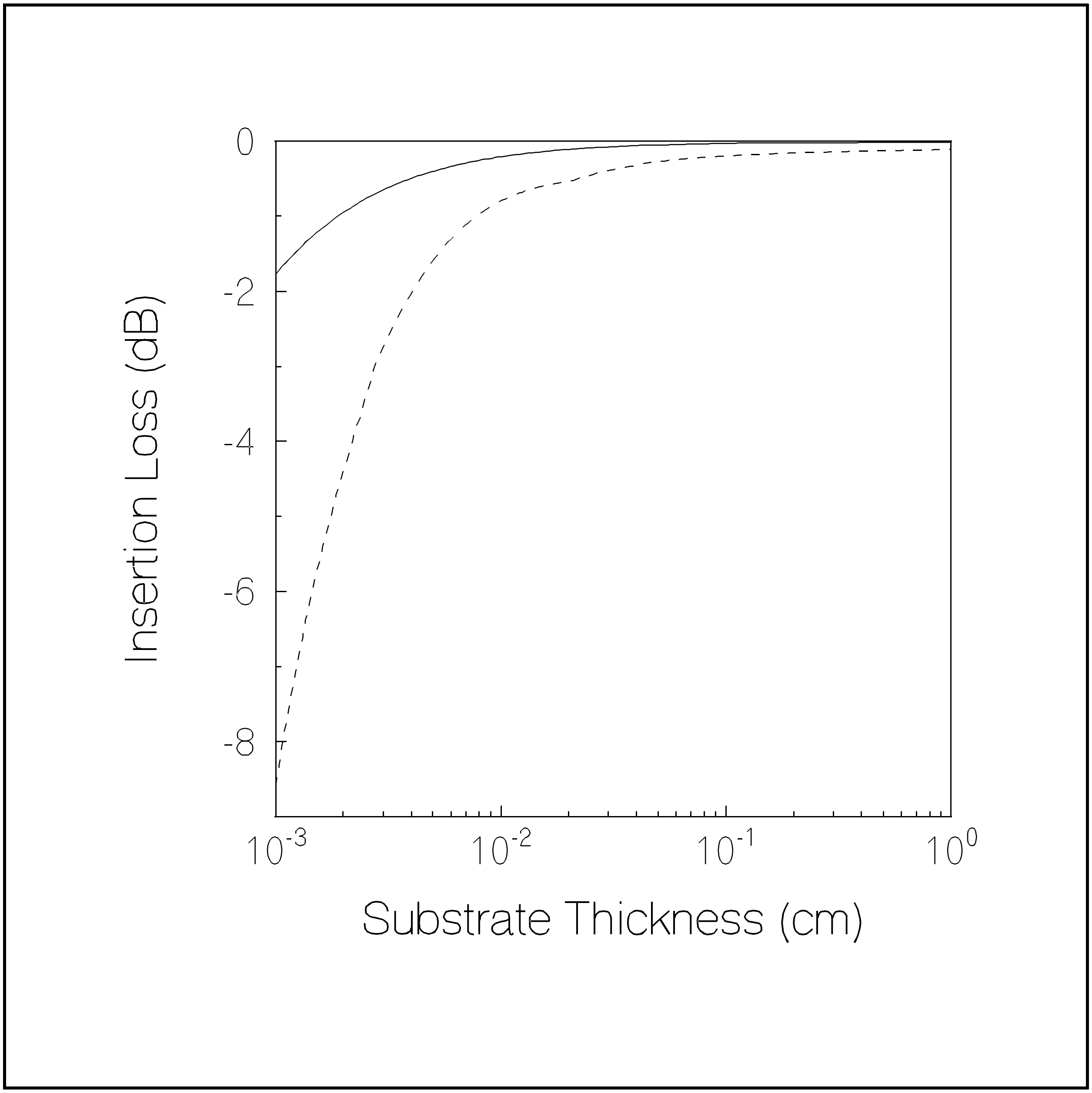

Figure 2 Calculated insertion loss as a function of the ferrite substrate thickness for a circulator junction (solid line) and for a circulator junction plus a network transformer (dashed line).