TUNABLE BAND-STOP FILTER BASED ON EPITAXIAL Fe FILM ON GaAs

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ABSTRACT

Theoretical and experimental work on tunable band-stop filters based on single-crystal Fe films is reported. The filters can be tuned over a broad frequency range with a relatively small magnetic field. Theoretical predictions based on a parallel plate transmission line model agree qualitatively with the observations, but the measured attenuation per unit length is about 2.5 times smaller than predicted.

INTRODUCTION

The growth of epitaxial Fe film on GaAs was first demonstrated by Prinz and Krebs [1] using molecular beam epitaxy. Deposition of such films by ion-beam sputtering was first reported by Tustison, et al. [2], and their application to microwave filters has previously been discussed by Schloemann, et al. [3]. This paper reports on the use of epitaxial Fe films on (001) GaAs in tunable band-stop filters, in which the Fe layer is part of a microstrip line and a magnetic bias field is applied parallel to the microstrip as illustrated in Figure 1.

The microstrip runs along either a [100] or a [110] direction, the "easy" and "hard" directions of magnetization of the Fe film. Theoretical analysis based on the parallel-plate approximation indicates that peak attenuation should occur at the ferromagnetic resonance (FMR) frequency and be proportional to the length of the microstrip line and inversely proportional to the substrate thickness.

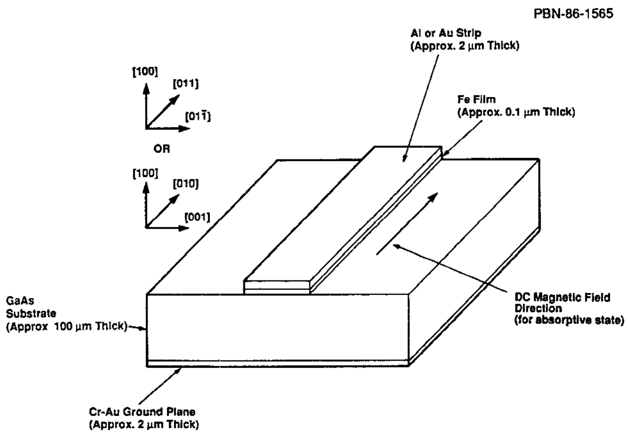

Figure 1. Tunable Band-Stop Filter Based on Epitaxial Fe Film on GaAs Substrate.

THEORY

Under the parallel-plate approximation, the microstrip structure can be modelled as in Figure 2.

Consider first the case in which the Fe film can be characterized by an effective scalar permeability μ_1. A solution of Maxwell's equations that satisfies all boundary conditions can be constructed as a superposition of plane waves. The wave vectors for these plane waves have a large

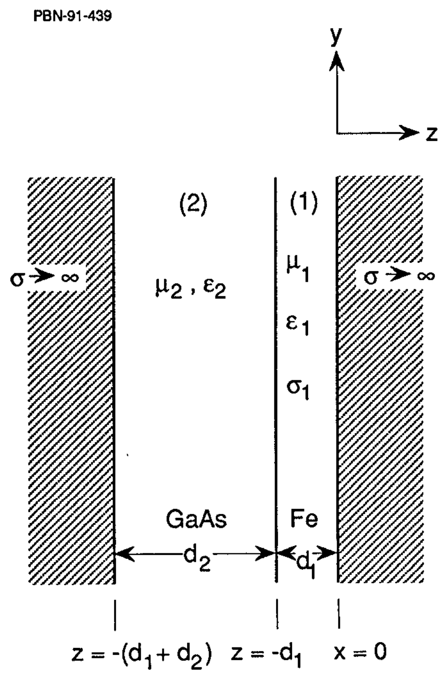

Figure 2. Parallel-Plate Model Longitudinally Magnetized.

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y component k_y and much smaller z-components (k_{1z} and k_{2z} in media 1 and 2). We assume that all fields are proportional to $e^{j(\omega t-k_y y)}$. Because of Maxwell's equations and the boundary conditions, the parameters ω, k_y, ε_1, ε_2, μ_1, μ_2, k_{1z} and k_{2z} are related by

$$k_{1z}^2 = \omega^2 \varepsilon_1 \mu_1 - k_y^2 \quad (1)$$

$$k_{2z}^2 = \omega^2 \varepsilon_2 \mu_2 - k_y^2 \quad (2)$$

$$\frac{k_{1z}}{\varepsilon_1} \tan\left(k_{1z} d_1\right) + \frac{k_{2z}}{\varepsilon_2} \tan\left(k_{2z} d_2\right) = 0 \quad (3)$$

Here

$$\varepsilon_1 = \varepsilon_1' - j\, \sigma_1/\omega \quad (4)$$

is the complex permittivity of the Fe film, and σ_1 is the conductivity. The real part of ε_1 is very small compared to its imaginary part, so that

$$\varepsilon_1 \simeq -j\, \sigma_1/\omega \quad (5)$$

In addition, k_y^2 can be neglected to a good approximation in (1), so that

$$k_{1z}^2 \simeq -j\, \omega\, \mu_1\, \sigma_1 \quad (6)$$

Furthermore, $|k_{2z} d_2| << 1$ is valid to a good approximation under typical experimental conditions. Thus, the second tangent function in Eq. (3) can be replaced by its argument and Eqs. (1-3) can be solved explicitly for k_y^2.

$$k_y^2 = \omega^2 \varepsilon_2 \mu_2 - k_{2z}^2$$

$$= \omega^2 \varepsilon_2 \mu_2 + \frac{k_{1z}\, \varepsilon_2}{\varepsilon_1\, d_2} \tan\left(k_{1z} d_1\right) \quad (7)$$

$$= \omega^2 \varepsilon_2 \mu_2 + j\, \frac{\omega\, k_{1z}}{\sigma_1\, d_2} \tan\left(k_{1z} d_1\right)$$

with k_{1z} given by Eq. (6).

The two approximations described above [neglecting k_y^2 in Eq. (1), and taking only the first term of a power series expansion of tan ($k_{2z} d_2$) in Eq. (3)] can easily be avoided. The propagation constant k_y then must be determined by an iteration (Newton's method), rather than by the explicit expression (7). The results obtained by iteration differ only very slightly from those obtained from Eq. (7).

In general, the Fe film is characterized by a tensor permeability of the form

$$\bar{\bar{\mu}}_1 = \begin{bmatrix} \mu_{xx} & 0 & -j\mu_{xz} \\ 0 & \mu_o & 0 \\ j\mu_{xz} & 0 & \mu_{zz} \end{bmatrix} \quad (8)$$

A theoretical analysis similar to that described above, but based on the tensor permeability $\bar{\bar{\mu}}_1$ rather than the scalar effective permeability μ_1 has also been carried out. The results of this analysis are substantially the same as those based on Eq. (7) provided that μ_1 is identified with the effective permeability

$$\mu_{x,eff} = \left(\mu_{xx}\mu_{zz} - \mu_{xz}^2\right)/\mu_{zz} \quad (9)$$

that applies to wave propagation perpendicular to the bias field, with the rf field in the x-direction.

The attenuation can now be determined as the real part of jk_y, either using the simple result (7) or the more realistic calculations described above, the results being very nearly identical. Dielectric loss in the GaAs substrate can be taken into account by taking ε_2 as a complex number ($\varepsilon_2 = \varepsilon_2' - j\, \varepsilon_2''$). The theory has also been generalized to take account of ohmic losses in the metal boundaries.

The FMR frequency f_{res} for microstrip lying along the easy and the hard direction of magnetization can be shown to occur respectively at

$$f_{res} = \gamma\sqrt{\left(H + H_{an}\right)\left(H + H_{an} + 4\pi M_s\right)}$$
$$f_{res} = \gamma\sqrt{\left(H - H_{an}\right)\left(H + \tfrac{1}{2} H_{an} + 4\pi M_s\right)} \quad (10)$$

where γ is the gyromagnetic ratio, H is the applied magnetic field, H_{an} is the anisotropic field and M_s is the saturation magnetization. Numerically, $\gamma \sim 2.8$ MHz/Oe, $H_{an} \sim 550$ OE, and $4\pi M_s \sim 22000$ Oe.

EXPERIMENTAL WORK

In the devices built to date, the microstrip is aligned with either an easy [100] or hard [110] direction of the Fe film and the substrate thickness is between 0.05 and 1 μm. In order to achieve large peak attenuations, a meandering line pattern is used in which the Fe film is present only in the long sections of the meander pattern as seen in the shaded regions of Figure 3.
The Fe layer was prepared at 0.05μm, 0.1 μm, 0.3 μm, and 1.0 μm thicknesses. In addition, a Ag layer is deposited on the Fe layer during the same pumpdown as pro-

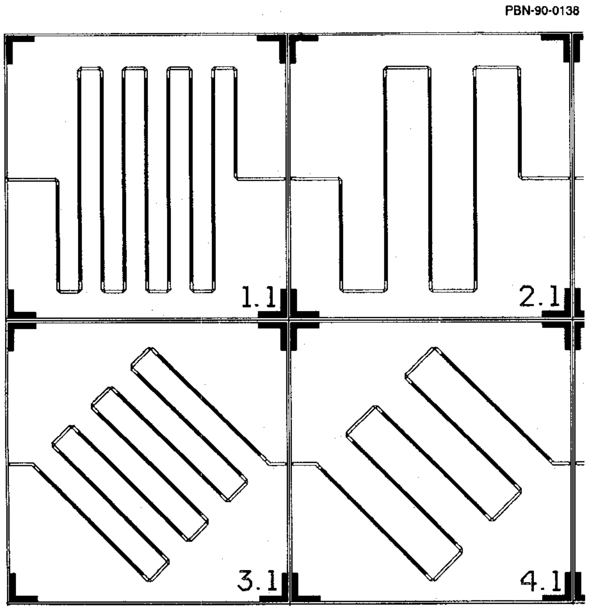

Figure 3. Meandering Line Provides Greater Attenuation Through Longer Line Length, but the Fe Layer Is Present Only in the Shaded Areas.

tection against oxidation. A Au layer, applied after the initial patterning of the Fe-Ag film, provides the continous conductive path of the microstrip. Figures 4 and 5 show the performance observed in experimental filters in which the microstrip lines are oriented parallel to the [110] direction (hard axis) and the [100] direction (easy axis), respectively. The magnetic field is applied parallel to the long sections of the meander line in both cases.

In agreement with theoretical expectations, easy-axis alignment results in filters that can be tuned only to frequencies higher than 10 GHz, hard-axis alignment in filters that can be tuned over a wide range with relatively weak fields (for instance, from 6 to 16 GHz by a magnetic field between 650 Oe and 1850 Oe). For the optimum thickness of the iron film at 0.1 μm, the observed peak attenuation is about 4.4 dB/cm with a background attenuation at 2 GHz away from resonance of 0.7 dB/cm. The bandwidth at 3 dB/cm is approximately 1.1 GHz. The measured peak attenuation is approximately 2.5 times smaller than that calculated on the basis of the parallel-plate model. The discrepancy is attributed in part to inadequacy of the model and in part to inadvertent removal of some Fe film during processing. The broken line in Figure 5 is a theoretical curve based on the parallel-plate model. The curve has been fitted to the experimental data by adjusting the vertical scale by a factor of approximately 2.5.

Figure 6 illustrates a typical device fixture used in the experimental work. This fixture allowed precise control of the direction of the bias field, which was supplied by a large electromagnet in this case. When the bias field is parallel or nearly parallel to the hard axis [110], the FMR frequency depends strongly on the bias field direction.

DISCUSSION

Since the GaAs wafer can be processed in such a way that Fe remains only in specific areas, the vacant region is free to be occupied by other microwave devices. Using known inexpensive etching techniques, a thin layer of Fe and a thicker

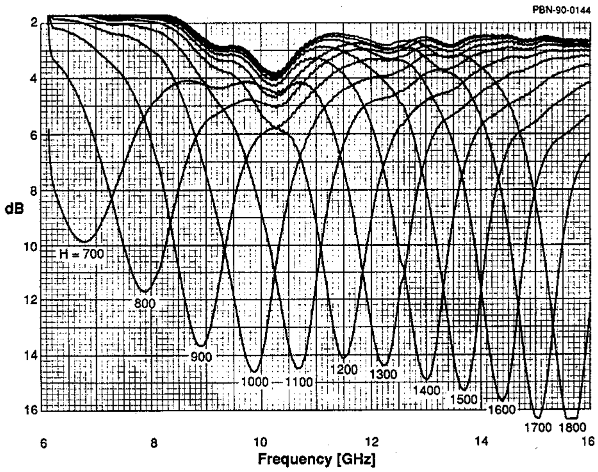

Figure 4. Representative Experimental Results Obtained for Microstrip Parallel to [110] Direction (Hard Axis).

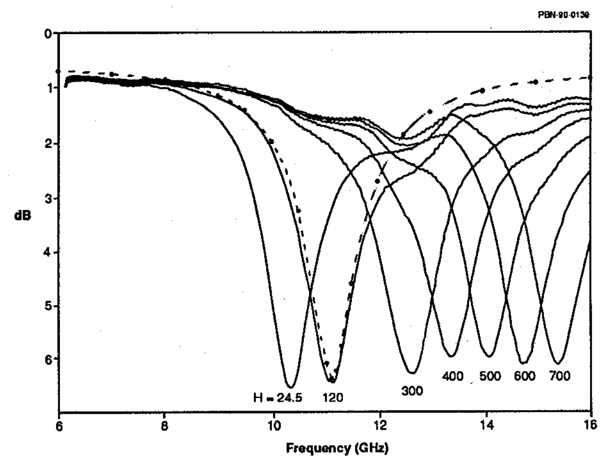

Figure 5. Representative Experimental Results Obtained for Microstrip Parallel to [100] Direction (Easy Axis).

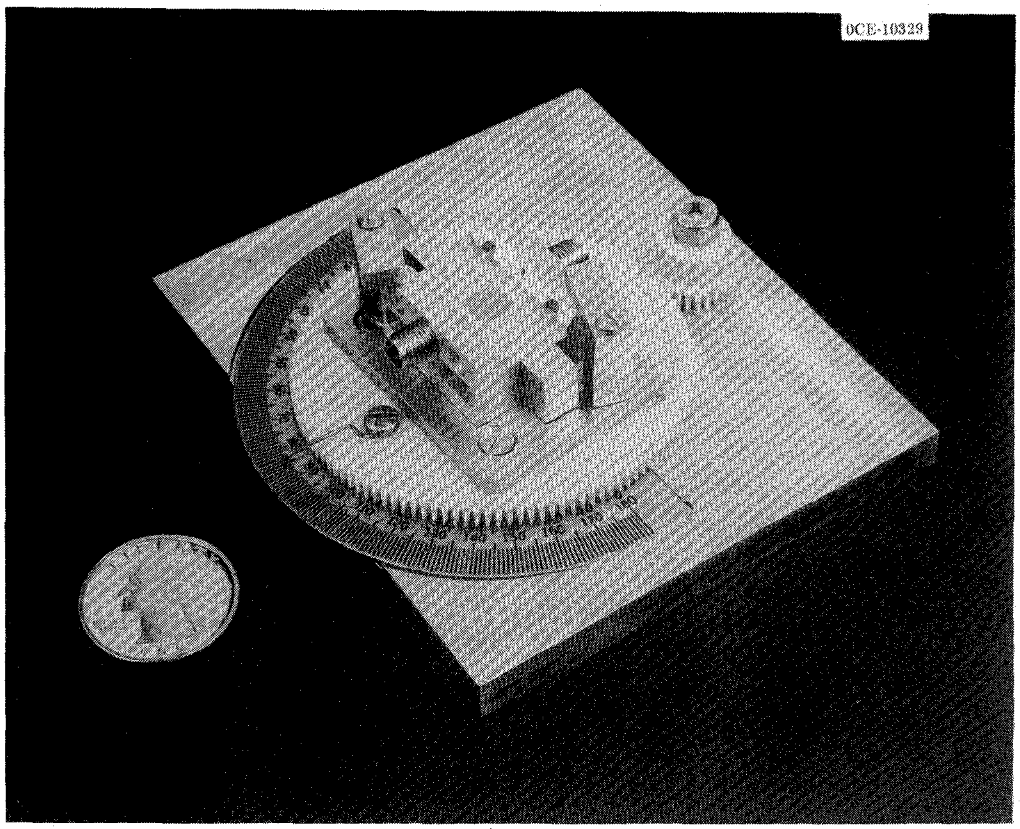

Figure 6. Device Fixture Used for Testing Filters.

layer of Au can be photolithograhically patterned and chemically removed to produce the microstrip structure. Furthermore, through the ferromagnetic properties of the Fe, high attenuation can be obtained at the resonant frequency while achieving relatively low loss at other frequencies. Also, because of the Fe's large saturation magnetization, approximately 10 times that of ferrites, only a small magnetic field is necessary to change the ferromagnetic resonance frequency from several gigahertz to over 20 gigahertz. Furthermore, with its high Curie temperature, filter devices using Fe film may exhibit greater stability over a large range of temperature. Thus, the new design of the magnetically tunable band-reject filter offers low fabrication cost and a highly integratable structure.

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