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High attenuation tunable microwave notch filters utilizing ferromagnetic resonance

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We have constructed a series of microstrips for transmission of microwaves. These microstrips incorporate ferromagnetic and dielectric layers and therefore absorb microwave energy at the ferromagnetic resonance (FMR) frequency. The absorption notch in transmission can be tuned to various frequencies by varying an external applied magnetic field. For our devices, which incorporate Fe as the ferromagnetic material, the resultant FMR frequencies range from 10–20 GHz for applied fields up to only 1000 Oe. This frequency range is substantially higher than those found in devices utilizing a dielectric ferrimagnet such as YIG. We constructed devices using monocrystalline Fe films grown in a molecular beam epitaxy system. Our devices are of different construction than other Fe dielectric microstrips and show much improvement in terms of notch width and depth. We observed maximum attenuation on the order of 100 dB/cm, much larger than previously reported values of 4 dB/cm.
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INTRODUCTION

Tunable filters based on the ferrimagnetic dielectric YIG are a well-established technology with many practical applications.[1] Band-stop filters, for example, rely on ferromagnetic resonance (FMR) to absorb microwave power at the FMR frequency. This frequency is set by material properties, such as saturation magnetization, M_s, anisotropy fields, H_a, the gyromagnetic ratio, γ, and the magnitude of an applied field, H. If the applied field is along the easy axis, the frequency is given by

$$\omega=\gamma\sqrt{(H+H_a)(H+H_a+4\pi M_s)},$$

and therefore the resonance frequency can be varied with an electromagnet. The maximum field produced by the electromagnet determines the upper limit for the band-stop frequency. Hence, high frequencies are difficult to achieve with a device of limited physical size.

An alternative that has received attention in recent years is the use of a high M_s material such as Fe. While Fe has a much higher resonance frequency for the same applied field, its conductivity can lead to high loss at microwave frequencies. However, structures utilizing thin Fe films minimize conduction loss while still producing high attenuation at the band-stop frequency.[2,3]

Recent attempts at producing Fe-film-based structures have succeeded in making filters with high band-stop frequencies and low broadband loss.[3,4] However, the maximum attenuation has only reached about 4–5 dB/cm. We constructed microstrip band-stop filters using a slightly different geometry and growth method, resulting in much higher attenuation.

EXPERIMENT

Previous filter structures used Fe epitaxial films grown directly on semi-insulating GaAs wafers. The backside of the wafer and the Fe films were then coated with a high-conductivity metal. The Fe side was then etched into a strip to form the microstrip structure shown in Fig. 1(a). For these filters, high quality, epitaxial Fe[5,6] (linewidth of ~35 Oe) is required to get reasonable attenuation.

Our devices, in contrast, consist of layers deposited on only one side of a GaAs(001) wafer as shown in Fig. 1(b). This allows us to have a much thinner dielectric layer which ultimately results in a much higher attenuation. The first stage of film growth was performed with molecular beam epitaxy (MBE) at a pressure of $\sim 10^{-9}$ Torr during deposition. Deposition was monitored both with a quartz thickness monitor and with reflection high-energy electron diffraction (RHEED).

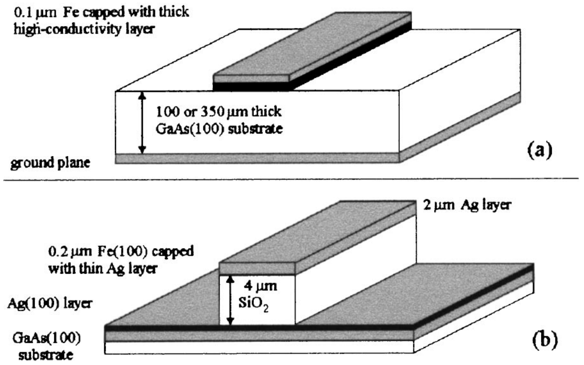

FIG. 1. Perspective cross sections for Scholemann structure using a GaAs(100) wafer as the dielectric layer (a). Our structure (b) is formed with vacuum-deposited SiO_2 as the dielectric. Note that the dielectric in (b) only exists directly below the microstrip, allowing single-sided probing.

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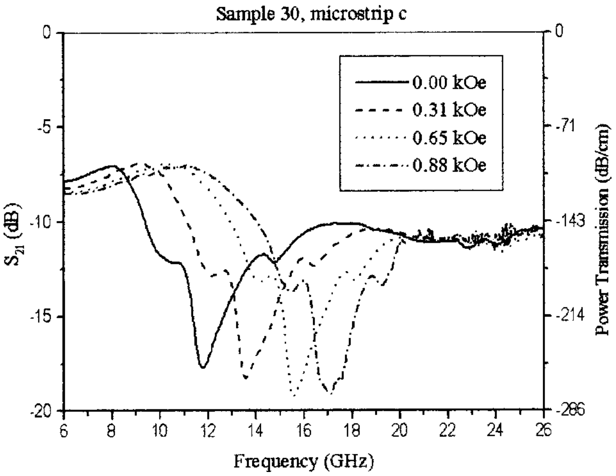

FIG. 2. Magnitude of S_{21} as a function of frequency. S_{21} represents voltage attenuation and therefore power attenuation is double in terms of dB.

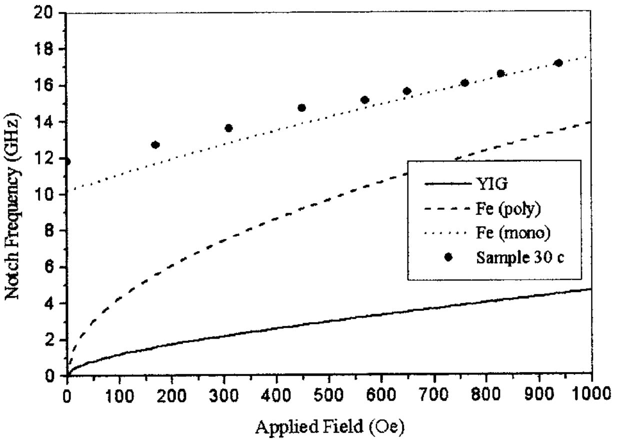

FIG. 3. Stop-band center frequency as a function of applied magnetic field for various structures. The plot for monocrystalline Fe represents our structure with the microstrip aligned with an easy axis.

First, a 1 nm thick Fe(001) ‘‘seed’’ layer was grown on a GaAs(001) substrate. A 600 nm layer of Ag(001) was then deposited and annealed at 520 K. This Ag film provides a ground plane and the template for further growth of epitaxial Fe(001). Next, 200 nm of Fe(001) was added and then covered with 5 nm of Ag to protect it from oxidation. Fe film quality was measured with FMR. This also allowed us to determine the easy axis of the film. Creating microstrips aligned with the easy axis increased the effective field in the strip and increased the operating frequency.

The sample was then transferred to a traditional e-beam evaporation system to complete the structure. A shadow mask was clipped on top of the sample before deposition to mask the ground plane and expose the microstrip shape. 4 μm of SiO_2 was deposited and capped with 2 μm Ag to form the dielectric and upper conductor, respectively. Note that because the ground plane is exposed on either side of the microstrip, the strip can be probed from the top side of the wafer.

Magnetic anisotropy, saturation magnetization, and resonance linewidth were all measured in 10 and 24 GHz FMR systems. Filter properties were measured with a Hewlett Packard 40 GHz vector network analyzer. This system allowed measurement of reflection, transmission, and characteristic impedance.

RESULTS AND DISCUSSION

Our FMR measurements showed a fourfold in-plane anisotropy field of 550 Oe. The resonance linewidth was approximately 50 Oe at 10 GHz for the monocrystalline Fe sample.

The magnitude of the ratio of transmitted voltage to input voltage, S_{21}, as a function of frequency is shown in Fig. 2 for our 0.14 cm long microstrip. The separate data sets represent applied fields ranging from 0 to 880 Oe. The stop-band depth is about 10 dB voltage attenuation or 20 dB power attenuation. For our short sample, this results in a power attenuation of over 100 dB/cm. The tremendous increase in attenuation at the stop-band center frequency compared to earlier devices is due to the use of the thinner dielectric as predicted by theory.[7]

The observed insertion loss of about 7 dB is primarily due to impedance mismatch. This could be improved either by increasing the thickness of the dielectric or by narrowing the width of the upper conducting strip. Currently, we are restricted to a maximum dielectric thickness due to our probe station and we are restricted to a minimum strip width due to use of a shadow mask.

The variation in notch frequency with applied field follows theory reasonably well as shown in Fig. 3. By placing the strip along an easy axis, we create an effective field in the strip that is the sum of applied external field and anisotropy field. Thus, the effective field is boosted by 550 Oe. Figure 3 includes a theoretical plot for monocrystalline Fe with this anisotropy and also shows plots for polycrystalline Fe and YIG for comparison. Clearly, monocrystalline Fe produces much higher frequencies for similar fields than either of the other two.

CONCLUSION

We have created a band-stop filter with center frequencies in the 10–20 GHz range which is tunable with a small external magnetic field. This device represents two major improvements over other similar devices: (1) We find substantially higher attenuation in the stop band and (2) our structure obtains high attenuation even with higher Fe linewidths.

These improvements allow a great reduction in size for a complete device including an electromagnet. Raising the frequency range reduces the applied field required to create a high center frequency and thus reduces the electromagnet size. Increasing the attenuation reduces the microstrip length required and allows the electromagnet pole pieces to be placed closer together. This allows the same field strength to be created with a smaller magnet. In addition, our structure should allow for integration with high-speed electronics on a single wafer.

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