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Magnetically tunable micro-strip band-stop filter: Design optimization and characterization

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We investigate ultra-small band-stop filters made with continuous Fe films and with multilayered Fe/Cu films. In ferromagnetic resonance measurements, the continuous Fe(100 nm) film had a larger linewidth, on the order of 200 Oe at 10 GHz, resulting in a device linewidth, which typically was close to 2 GHz in the operational device. In contrast a $[\mathrm{Fe}(5\ \mathrm{nm})/\mathrm{Cu}(0.8\ \mathrm{nm})]_{20}$ multilayer structure showed a ferromagnetic resonance linewidth of 50 Oe at 10 GHz and had a device linewdith of about 0.5 GHz. We expect that the breaking of the Fe films by Cu reduces the typical size of crystallites in Fe, thus reducing the linewidth. The filter demonstrates wide tuning range of 10–30 GHz with bias fields up to 4 kOe. This work demonstrates a single notch-filter, which can operate from *X*- to *K*-band with a linewidth of 1.8 GHz at 0.07 kOe and 0.33 GHz at 4.0 kOe. The measured minimum insertion loss in each case is ~2.5 dB, with greater than 15 dB return loss in the entire pass-band frequency. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1853837]

INTRODUCTION

The growth of wireless communication schemes, such as Digital Communication Services (DCS), has made the rejection of spurious carriers a key design concern. Filters play critical roles in many microwave/mm-wave applications. Filters, with optimum frequency selectivity, smaller size, and high stop-band attenuation, have been used for mobile and satellite communications systems.[1–7] Where spurious carrier frequencies cause a problem, a bandstop filter can be "thrown" on a microstrip line to cut them by 20 dB or so to reject unwanted carrier frequencies in an intermediate frequency (IF) processing unit of a digital communications system. Many researchers have presented tunable magnetic filters utilizing YIG materials.[1,2] Since printed circuit board fabrication produces compact filter structures, the microstrip filter appears to be one of the appropriate choices for integrating all the rf front-end components into one module.

In this paper, we report results on planar microstrips using a dielectric/magnetic structure and operating at microwave/mm-wave frequencies. Earlier versions of such filters produced wide-band notch filters in which the device linewidth extended over 3 GHz.[6,8,9] To reduce this linewidth we introduce a multilayered Fe/Cu structure with thin Cu films separating thicker Fe films. The idea is that such a structure will produce smaller grain sizes in the Fe and as a result will lead to narrower ferromagnetic resonance (FMR) linewidths and device linewidths.[10] A microstrip band-stop filter with a multilayer Fe film is fabricated on a standard GaAs substrate to provide band-stop operation between 10–30 GHz.

FABRICATION OF NOTCH FILTER

The devices were grown using the following procedure. After cleaning the GaAs substrate in an ultrasonic bath, we annealed it to 200 °C inside the vacuum chamber. All the depositions were done at room temperature. During deposition the background pressure was maintained around $\sim 2 \times 10^{-7}$ Torr. First a 5 nm thick Ti layer was deposited for good adhesion to the substrate. This was followed by a 2 micron thick Cu layer, which was used as a ground plane for our device. The next sequence of deposition was made through a shadow mask. We deposited a 3 micron thick SiO_2 as a dielectric by a e-gun source. Then we deposited 100 nm of Fe as the magnetic layer for the continuous notch filter structure, and $[\mathrm{Fe}(5\ \mathrm{nm})/\mathrm{Cu}(0.8\ \mathrm{nm})]_{20}$ (total Fe thickness 100 nm) for the multilayered notch filter structure. At the end, we deposited a 2 micron thick Cu layer, which is used as a signal line for the device. At this point a portion of the sample was removed for FMR measurements. We patterned the films by photolithography and then dry etched to obtain the required strip widths and length for our devices.

The FMR measurements were done at 10 GHz as a function of the in-plane direction of external magnetic field to determine the resonance field (H_{res}) and linewidth (ΔH) of the films. The device characterization was done using a vector network analyzer along with a micro-probe station. Noise, delay due to uncompensated transmission lines connectors, its frequency dependence, and crosstalk which occurred in measurement data, have been taken into account by performing through-open-line (TOL) calibration using NIST Multical® software.[11] The dc bias magnetic field was applied along the length of the microstrip line, which ensures ferromagnetic resonance condition, as the rf magnetic field and the dc magnetic field are perpendicular to each other to get gyromagnetic resonance for the magnetic films. The widths of the devices are 5–24 micron and have a length of 2–6 mm. The microstrip band-stop filter was designed for a 50 Ω characteristic impedance.

RESULTS AND DISCUSSION

The 10 GHz FMR linewidth decreased from 200 Oe for continuous film to 50 Oe for the multilayer film, indicating

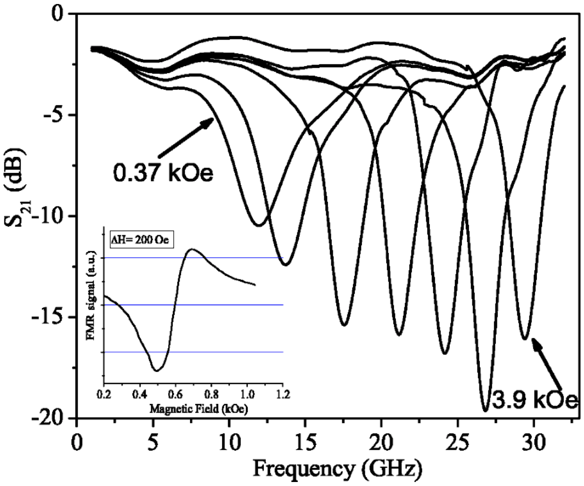

FIG. 1. Transmission response of a 3.3 mm long and 9 micron wide micro strip band-stop filter for different applied fields. The magnetic film is a 100 nm continuous Fe film. The inset shows the FMR response of this sample at 10 GHz. The FMR linewidth is 200 Oe.

better film quality in the multilayer structure. The insets of Figs. 1 and 2 show the FMR spectra for continuous and multilayered Fe films.

Figure 1 shows the transmission characteristics of a notch filter with a 100 nm continuous Fe film as the active element for frequency tuning. A stop-band bandwidth (the width of the band-stop region 3 dB below the insertion loss) of about 5 GHz was observed for this filter. The maximum attenuation was larger than 50 dB/cm, and a sharp gain slope transition was obtained. The filter was tuned from 10 to 29 GHz with a bias magnetic field up to 4 kOe.[6,8,9] The device linewidth (the width of the transmission dip 3 dB above the minimum transmission) is ~1.5 GHz.

Figure 2 shows the S_{21} response of a microstrip notch filter with a Fe/Cu multilayer structure. The pass-band insertion loss is ~2.0 dB with more than 15 dB return loss over the pass-band. In contrast to the continuous Fe film, the Fe/Cu structure produces a device linewidth which is 330 MHz around 3–4 kOe, and is increased to 900 MHz for fields of 0.37 kOe. The maximum attenuation within the stop-band exceeds 60 dB/cm. The stop-band bandwidth from the pass-band is reduced from 5 GHz for a continuous Fe film microstrip filter to 2 GHz for this Fe/Cu multilayered micro-strip filter. Therefore, this filter can be used for a rf-interference problem, and provides a narrow bandwidth with a transition to stop-band of only a few hundred of MHz.

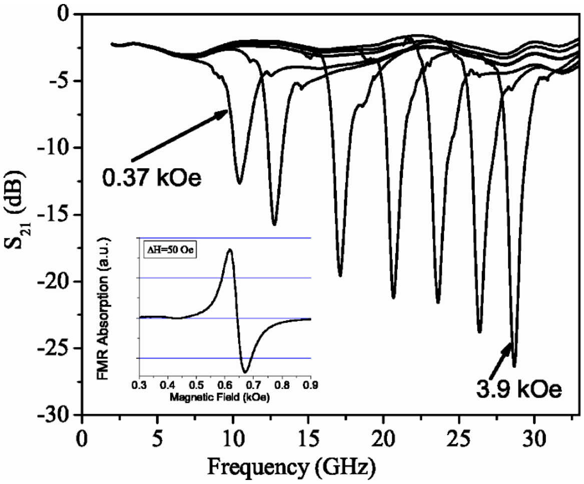

FIG. 2. Transmission response of a 3.3 mm long and 9 micron wide micro strip band-stop filter for different applied fields. The magnetic film is $[\mathrm{Fe}(5\ \mathrm{nm})/\mathrm{Cu}(0.8\ \mathrm{nm})]_{20}$ {total Fe thickness=100 nm}. The inset shows the 10 GHz FMR spectra with a linewidth of 50 Oe.

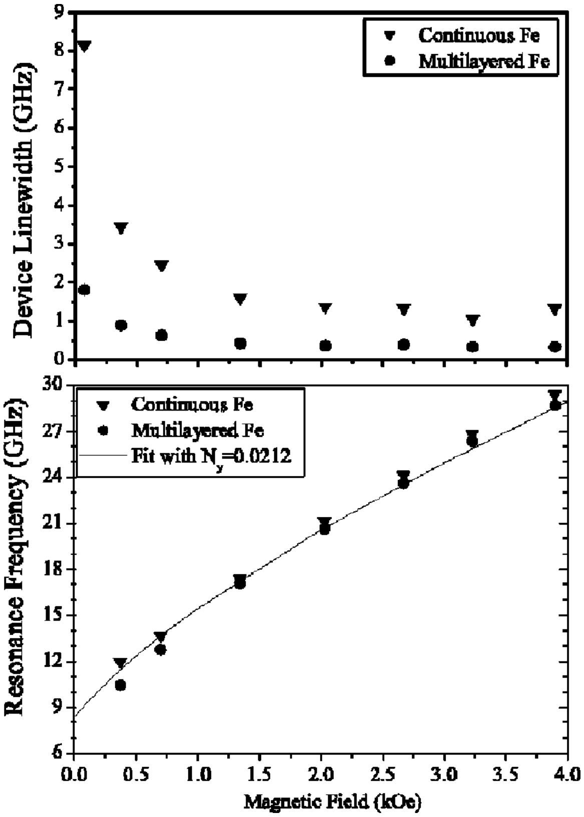

FIG. 3. The top panel shows the 3-dB linewidth from the notch in the transmission response for the continuous and multilayered Fe filters as a function of applied magnetic field. The bottom panel shows the center frequencies of these two filters as a function of applied magnetic field. The solid line on this graph is the fit made to the FMR condition taking into account the demagnetization factors for the wire-geometry.

The top panel of Fig. 3 depicts the magnetic field dependence of linewidth for both continuous and multilayered Fe film filters. In both case the linewidth decreased with fields increasing up to 1 kOe and then saturates for higher fields. As mentioned earlier, the stop-band effect is induced by gyromagnetic resonance, which occurs here even in the absence of applied dc magnetic field (very small field) due to the shape anisotropy.[8,9] The bottom panel of Fig. 3 shows the stop-band frequencies as a function of applied magnetic field. The stop-band characteristics are almost same for these two devices confirming no magnetic shielding for multilayered Fe structure. The solid line is a fit to FMR relation taking into account the demagnetizing factors ($N_x=0.9788$, $N_y=0.0212$, $N_z=0$) according to the wire-geometry of 3.3 mm long, 9 micron wide, and 100 nm thick magnetic element. The fit appeared to be almost perfect to the measured center frequencies.

We have explored above the possibility of reducing device bandwidth by improving the FMR linewidth through the

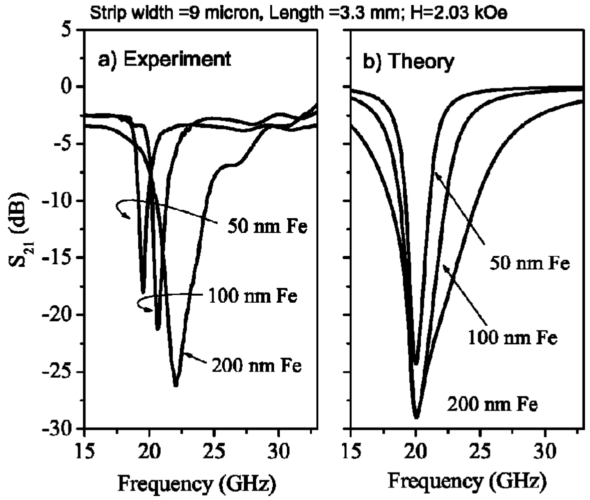

FIG. 4. Experiment (a) and theory (b) for transmission as a function of frequency for devices with different thicknesses of mutilayered Fe/Cu. The structures are $[\mathrm{Fe}(5\ \mathrm{nm})/\mathrm{Cu}(0.8\ \mathrm{nm})]_{10}$, $[\mathrm{Fe}(5\ \mathrm{nm})/\mathrm{Cu}(0.8\ \mathrm{nm})]_{20}$, and $[\mathrm{Fe}(5\ \mathrm{nm})/\mathrm{Cu}(0.8\ \mathrm{nm})]_{40}$, giving rise to total Fe thicknesses of 50 nm, 100 nm, and 200 nm. The device width was 9 microns and the length was 3.3 mm. The SiO_2 thickness is 3.5 microns and the applied field is 2.03 kOe.

use of Fe/Cu multilayers. There is an additional method to reduce device bandwidth—reducing the thickness of the metallic magnetic layer. In Fig. 4 we show experimental and theoretical results for transmission as a function of frequency for different thicknesses of the Fe/Cu multilayer. The curves show the same general behavior. The thicker films have larger linewidths and more distorted shapes. This is a result of eddy currents broadening the magnetic response. Note that the experimental data show resonances at different frequencies while theoretical calculations do not. This is a consequence of slightly different demagnetizing factors in the experiments[8,9] which are not included in the theory because this would involve a very complicated three dimensional calculation. Nonetheless, the key features in linewidth are well reproduced by the theory.

CONCLUSION

The use of a Fe/Cu multilayered film in microstrip filters demonstrates the feasibility of narrow-band magnetically tunable stop-band planar microwave device. The considerable narrowing of the stop band was due to the breaking of Fe films by Cu interlayers which is expected to reduce the typical grain size. A second method to reduce the width of the stop band is to reduce the thickness of the metallic magnetic layer, thus reducing eddy currents. The tuning frequency of the filter extends from X band to K band with a magnetic field up to 4 kOe. This way of integrating Fe films in guided wave structures opens the road to a new generation of miniature size low-cost tunable planar microwave devices with MHz linewidths.

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