10 GHz bandstop microstrip filter using excitation of magnetostatic surface wave in a patterned $Ni_{78}Fe_{22}$ ferromagnetic film

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Various microstrips with a ferromagnetic core were designed and fabricated on a silicon substrate. The core was formed by a 0.5-μm-thick $Ni_{78}Fe_{22}$ film, patterned into rectangular prisms. Measurement results for attenuation constant versus frequency show a peak value of ~50 dB/cm around 10 GHz. Electromagnetic simulations show that the attenuation observed is due to the energy exchange between the quasi-TEM mode of the microstrip and magnetostatic surface modes excited in the direction perpendicular to the signal line. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2172893]

INTRODUCTION

Microstrip transmission lines with hybrid magnetic/dielectric cores have been extensively explored for microwave applications.[1–6] In particular, it was demonstrated for a microstrip with yttrium iron garnet magnetic core, saturated perpendicular to the plane of the strip line, that transmission characteristics of the line show strong coupling phenomena between quasi-TEM and magnetostatic surface wave (MSSW) modes.[2] On the other hand, for a microstrip with a tangentially (in-plane) magnetized magnetic core, the effect of the MSSW mode has been ignored; even the possible tracks of these modes can be seen from experimental data.[1,7] In this paper, the attenuation of a quasi-TEM propagating mode due to coupling with MSSWs will be demonstrated for a fully monolithically integrated microstip with a thin-film $Ni_{78}Fe_{22}$ ferromagnetic (FM) core with an in-plane magnetization.

EXPERIMENT

Microstrips with signal lines of different lengths ($L=1$, 2, and 4 mm) and widths ($W=20$, 30, and 50 μm) were designed and fabricated on a silicon substrate (Fig. 1). The core of the microstrips was formed by a 0.5-μm-thick $Ni_{78}Fe_{22}$ layer, sputtered in the absence of an external dc magnetic field. Wet etching was then used to pattern the FM film into two groups of rectangular prisms with widths (W_{FM}) of 100 μm (sample A) and 200 μm (sample B). In each case the prisms had the same length as the signal line. SiO_2 insulation layers 1 μm thick separate the FM core from the signal and ground lines. *B-H* loop measurements showed a shape-induced easy axis orientated along the long side of the FM prism with effective shape-induced anisotropy fields H_{eff} of 60 and 40 Oe for samples A and B, respectively, and a saturation magnetization $4\pi M$ of 1.2 T for both samples. This yields the ferromagnetic resonance (FMR) frequencies of 2.4 GHz (sample A) and 1.9 GHz (sample B) according to Refs. 1 and 8:

$$f_{FMR} = \frac{\gamma}{2\pi}\sqrt{H_{eff}(H_{eff}+4\pi M)}. \tag{1}$$

The high-frequency properties of the microstrip lines were extracted from *S*-parameter measurements performed on a HP-8510 network analyzer. The microstrips were measured using ground-signal-ground (G-S-G) rf probes in a two-port configuration. Through-reflect line (TRL) calibration was performed, and open dummy structures were used to measure and deembed parasitic capacitances appearing due to the measurement patches.

RESULTS AND DISCUSSION

Figures 2(a) and 2(b) show the measured attenuation constant (real part of the propagation constant) as a function of frequency for 2-mm-long microstrips with signal lines and magnetic cores of different widths. For a narrow FM core with a high shape-induced anisotropy [sample A, Fig. 2(a)], the attenuation peak can be divided in two components: a low-frequency component with a maximum around 5 GHz (peak LF) and a high-frequency component with a maximum at 10 GHz (peak HF) [Fig. 2(a)]. The low-frequency peak of attenuation constant versus frequency can be associated with FMR of a ferromagnetic core.[1–8] The observed frequency shift with respect to the expected thin-film FMR frequency (2.4 GHz) is partly due to the combination of a high magnetic damping constant and a small width of a signal line,[9] as well as the influence of a high-frequency component (peak HF).

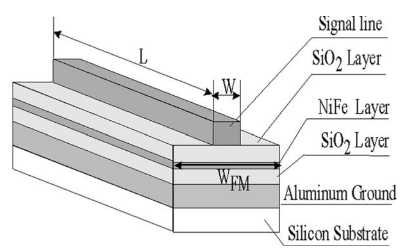

FIG. 1. Microstrip line with a FM core.

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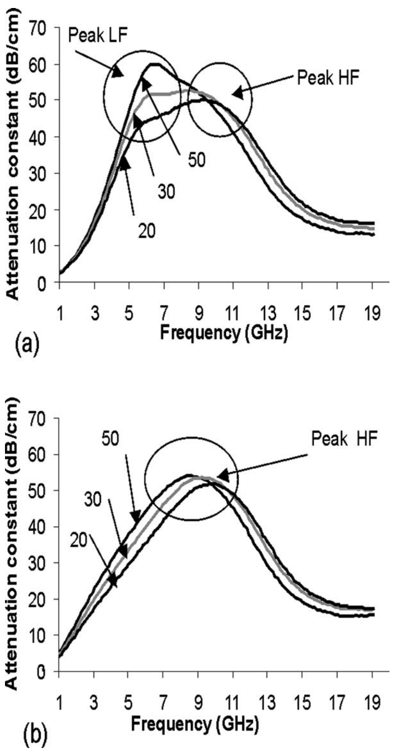

FIG. 2. (a) Measured attenuation constant vs frequency for FM core with the width of 100 μm (sample A). (b) Measured attenuation constant vs frequency for FM core with the width of 200 μm (sample B). The numbers correspond to the width of a signal line in μm. All microstrip lines are 2 mm long.

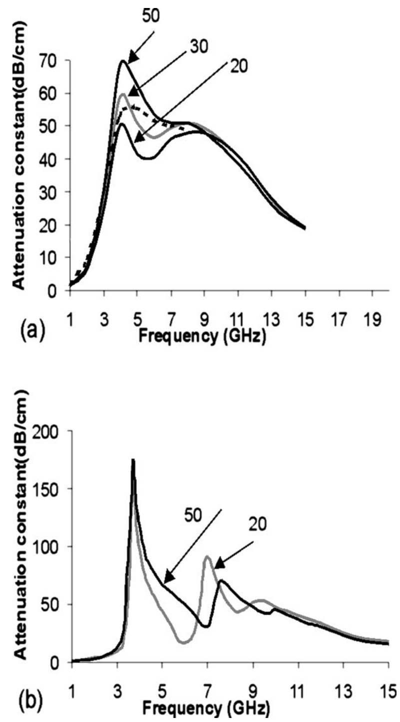

FIG. 3. (a) Calculated attenuation constant vs frequency for FM core with the width of 100 μm (sample A). $4\pi M=1.2$ T, $H_{dc}=1$ Oe, and the conductivity of the FM core $\sigma=6.4\times 10^6$ S/m. The numbers correspond to the width of a signal line in μm. For solid lines, a dissipation parameter $\alpha=0.005$ is used. For a dashed line, a dissipation parameter $\alpha=0.025$ and $W=50$ μm were used. (b) Calculated attenuation constant vs frequency for FM core with the width of 100 μm. $4\pi M=1.2$ T, $H_{dc}=1$ Oe, $\alpha=0.005$, and $\sigma=6.4\times 10^2$ S/m. The numbers correspond to the width of a signal line in μm. All microstrip lines are 2 mm long.

For sample B, the attenuation constant versus frequency demonstrates no low-frequency FMR component but only a high-frequency contribution close to 10 GHz [Fig. 2(b)]. The absence of clear tracks of the FMR in microstrips with wide FM cores (sample B) can be attributed to the low value of a shape-induced anisotropy and high nonuniformity of both dc and ac magnetic fields and magnetizations. As a result, demagnetizing fields, effective anisotropy fields, and, consequently, FMR frequency become local characteristics, depending on the position inside the FM core. The same is valid for sample A resulting in a broadening of FMR, but this effect is more pronounced for sample B due to a smaller effective anisotropy. This leads not only to a lower FMR frequency but also to a lower amplitude of the FMR attenuation peak according to our own simulations as well as those of Ref. 8.

The position of the high-frequency maximum (peak HF) in attenuation constant versus frequency depends on the width of the microstrip. For sample A [Fig. 2(a)] this dependence is partly masked by the presence of the FMR peak. For sample B, where the effect of FMR is washed out, the frequency of peak HF shifts from 8 to 10 GHz, when the width of the signal line changes from 50 to 20 μm. Measurements carried out on 1-mm- and 4-mm-long microstrip lines led to the same values for the attenuation constant and, therefore, will not be shown here.

While the nature of the low-frequency attenuation peak is clear, the source of the high-frequency peak should be explained. The microstrip devices were simulated with HFSS 9.21 (Ansoft) software package providing a three-dimensional (3D) full-wave analysis. Ferromagnetic core was modeled as a *B*-*H* nonlinear material with FM characteristics determined by the saturation magnetization $4\pi M=1.2$ T, a dc bias field $H_{dc}=1$ Oe which—in our case—models the dc demagnetizing field (should not be confused with the dc effective anisotropy field H_{eff}), and the FMR linewidth $\Delta H=4\pi\alpha f/\gamma$ which accounts for the FM losses (α is the Gilbert damping constant and γ is the gyromagnetic constant). This approach is equivalent to the description of the magnetic material based on a permeability tensor (e.g., Ref. 8). Though the nonuniformity of the dc magnetization and demagnetizing fields was neglected, the nonuniformity of the ac fields was naturally included from 3D boundary conditions.

The calculated attenuation constant versus frequency for signal lines of different width is given in Fig. 3(a). The small disparity between the measured and calculated results appears in the region of FMR frequency and, in our opinion, comes partly from additional magnetic losses, possibly associated with magnetic pinning due to the wet etching on the edges of FM core[10] and partly from the neglected nonuniformity of dc demagnetizing fields and magnetization. The disparity can be decreased by increasing the value of dissipation parameter, as it is shown for comparison in Fig. 3(a). The amplitudes and frequencies of the high-frequency attenuation peak are in a very good agreement with the measured data [Figs. 2(a) and 3(a)].

To explain the nature of the high-frequency peak, we should notice that it does not appear in the parallel plate model, when in-plane propagation perpendicular the signal line is neglected.[1,8] Hence, the high-frequency attenuation is caused by an excitation of in-plane waves perpendicular to the signal line. In the frequency range above the FMR frequency, only MSSWs can exist in the FM core.[10–14] In the magnetostatic limit, the dispersion relation for these waves can be written as[13]

$$(1+\kappa)^2 + (\kappa_\alpha + 1)\left[\kappa_\alpha - \tanh\left(\frac{t_D}{t_{\mathrm{FM}}} k t_{\mathrm{FM}}\right)\right] + (1+\kappa)^2 \times \left[1 + \tanh\left(\frac{t_D}{t_{\mathrm{FM}}} k t_{\mathrm{FM}}\right)\right] \coth(k t_{\mathrm{FM}}) = 0, \quad (2)$$

with $\kappa = \omega_H \omega_M / (\omega_H^2 - \omega^2)$, $\kappa_\alpha = \omega \omega_M / (\omega_H^2 - \omega^2)$, $\omega_M = \gamma 4\pi M$, and $\omega_H = \gamma H_{\mathrm{eff}}$. Here $\omega = 2\pi f$, and t_D and t_{FM} denote the thickness of the dielectric and ferromagnetic layers, respectively. A quasi-TEM mode propagating along the signal line couples to MSSW modes with a corresponding wave vector k which is of the order of π / W (W is the width of the signal line). This, of course, is a very coarse approximation, but gives a qualitative explanation of the effect of the strip width on the frequency of the attenuation maximum. Figure 3(b) gives the HFSS results for attenuation constant versus frequency for two signal lines of different widths (20 and 50 μm). The set of parameters used was the same as in Fig. 3(a), except for the conductivity of the FM core, which was reduced from 6.4×10^6 to 6.4×10^2 S/m in order to clearly see the nondamped magnetostatic wave effects. When conductivity of FM film decreases, the high-frequency peak splits into harmonics appearing due to the finite width of FM core.

CONCLUSION

An additional peak for attenuation constant versus frequency is observed at frequency far above FMR in microstrips with NiFe FM cores. Electromagnetic (EM) simulations are in a good agreement with experiments and lead to the conclusion that the attenuation of a signal at frequency around 10 GHz is due to the energy exchange between the quasi-TEM mode of the microstrip and magnetostatic surface modes excited in the direction perpendicular to the magnetization.

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