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Nanomagnetic Films and Arrays for Nonlinear Devices in Highly-Integrated RF Modules

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***Abstract*— Magnetic materials have traditionally faced several limitations for RF and power applications because of their unstable permeability with frequency and electric field. However, the same attributes of these materials, when designed at nanoscale, enable interesting nonlinear properties for applications as frequency-selective limiters and signal-to-noise enhancers. Anisotropic nanostructures also enhance frequency stability. This paper explores nanomagnetic arrays for such ultra-miniaturized RF components in multimode and multiband (MMMB) RF modules. Permalloy films and nanodot arrays were modeled for their frequency-response to assess their nonlinear properties. By designing the dimensions at nanoscale, field-dependent permeability spectra were obtained using micromagnetic simulations. Permalloy thinfilm and nanodot arrays were fabricated on silicon substrates using e-beam evaporation and e-beam nanolithography. The simulation results for blanket films were validated by characterizing the permeability spectra using strip-line structures. Results indicate that nanomagnetic films and arrays can be used to create nonlinear devices as building blocks for a variety of highly-integrated RF modules.**

Keywords*— *Nonlinear properties; nanomagnetic arrays; RF; nanopackaging;

I. INTRODUCTION

Future smart systems provide not only computing (data processing) but also enable connectivity between users and machines and within themselves, while also providing several other functions such as healthcare, security, navigation etc. To enable short and long-range communications, they need to support multiband wireless communication through the integration of several standards such as LTE, Bluetooth, WLAN and WiFi, in addition to sensing. These RF modules impose a unique set of requirements in order to incorporate several frequency bands that are very closely spaced, with much higher power efficiency. These requirements are driving a variety of disruptive component and module packaging technologies.

The main challenges to system integration and miniaturization arise from the passive components that typically outnumber the active components by more than 10-to-1. This is because of the large number of lumped components such as inductors and capacitors that are used to form complex LC networks for filters, diplexers, EMI (electromagnetic interference) filters etc. New functional materials that can achieve the same microwave response with a single thinfilm component that can replace several passives can address this grand challenge. This can be achieved with nanostructured microwave magnetic materials.

Microwave materials based on hexaferrites and garnets with hexagonal crystal structure that have high uniaxial magnetic anisotropy leading to high ferromagnetic resonance (FMR), along with low FMR linewidths have been widely investigated [1, 2]. Under suitable processing conditions, these devices can be self-biased to achieve higher FMR frequency and lower linewidth without the need for external magnets. The emergence of multiferroic materials will further enhance the tunability of microwave passives, giving rise to reconfigurable bandwidths. In spite of these advances, ferrites face limitations because they are difficult to integrate onto Si and packages.

Metal-based magnetic materials can be easily integrated onto devices and packages, and also have higher FMR because of their inherently high saturation magnetization (M_s). However, in order to retain the frequency-stability, these materials need to be synthesized as nanostructures in an insulating matrix. Nanowire composites are widely investigated as next-generation microwave devices because they have high magnetic field anisotropy from the combined effects of shape and crystal anisotropies [3]. This high anisotropy makes them self-biased and still retains high FMR and low linewidth without the need for external magnetic field. Further, these materials can be fabricated using simple electrochemical plating routes without any process-compatibility issues with standard packaging substrates.

Two-dimensional and three-dimensional magnetic arrays at nanoscale present unique combination of properties that makes them attractive for several microwave and mm-wave applications. Nanomagnetic arrays enable engineering of microwave response and tunability, along with low loss, to miniaturize next-generation multiband RF modules that require higher functional density. The ferromagnetic resonance spectra from nanomagnetic arrays exhibit multiple resonant peaks due to dimensional confinement of spin waves in the nanosized dots or stripes. The absorption band can be varied with shape, aspect ratio and spacing. These materials are attractive for their potential in tunable filters, EMI isolation structures, frequency-selective limiters and signal-to-noise enhancers.

This paper focuses on modeling of nanostructured magnetic materials to demonstrate unique microwave properties. This involves two aspects 1.)Micromagnetic simulations to model and design nanoarrays for nonlinear response, 2.)Thinfilm deposition and development of a process to pattern magnetic films into nanostructured arrays with features ~50-2000 nm. The nanoarrays are schematically illustrated in Fig. 1.

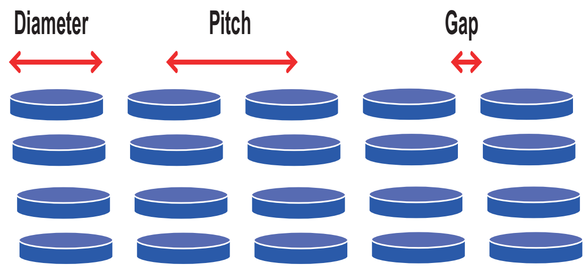


Fig. 1: Schematic of thin magnetic film patterned into nanodot array.

II. Micromagnetic Simulations

The magnetic permeability of ferromagnetic materials is nonlinear at large signal amplitudes. The nonlinearity leads to complicated dynamics where numerical simulations are essential to provide physical insight. Micromagnetic simulations aim to understand magnetic spin configuration and dynamics on nanometer to micron length scales. Micromagnetics solves the Landau-Lifshitz-Gilbert equation:

$$\frac{dM}{dt} = -\gamma M \times H_{eff} + \alpha \frac{M}{M_S} \times \frac{dM}{dt} \quad (1)$$

numerically taking into account exchange interactions, magnetocrystalline anisotropy, dipole-dipole interactions, and Zeeman interaction from external fields. M refers to the magnetization, H_{eff} is the effective field anisotropy, α is the damping factor and M_s refers to the saturation magnetization. Micromagnetic calculations result in the preferred magnetic configuration, hysteresis loops, and magnetization dynamics (magnetic permeability) when time-dependent fields are applied. Such knowledge is essential to understand the magnetic device performance.

An open-source micromagnetic simulation software package, OOMMF [4] and Mumax3 [5] was used to calculate the field dependent nonlinear RF permeability of both the blanket film and patterned nano arrays. The calculation, outlined in [6], involves applying a time dependent magnetic field pulse to the equilibrium magnetic state of the nano array. The magnetization and applied field are recorded at each time step as the system evolves. The permeability spectra are then calculated by taking the ratio of the Fourier transformed magnetization and applied field. The nonlinear behavior is, thus, naturally captured in micromagnetic simulations because the full nonlinear LLG equation is solved with no approximations in the time domain.

A representative micromagnetic calculation for a uniaxial soft thin film (M_S=8×10^5 A/m, A_{ex}=13×10^{-12}J/m, K_U=5×10^{3}J/m^3) with increasing applied field is shown in Fig. 2. As the applied field amplitude is increased, the permeability curve is distorted and nonlinear behavior is observed.

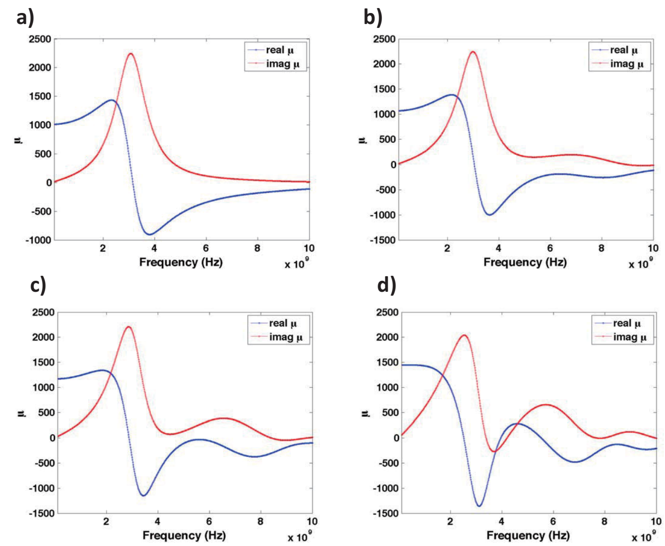
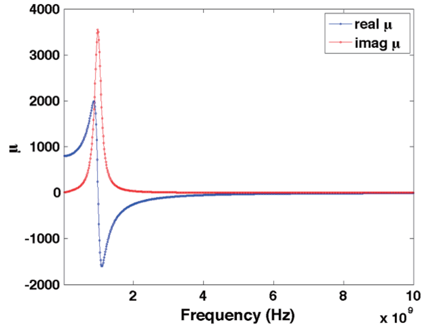


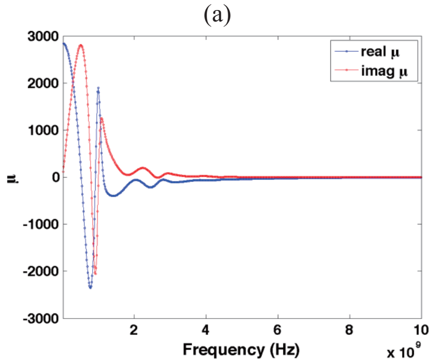
Fig. 2: The permeability spectra of soft magnetic thinfilm exhibits nonlinear behavior as the signal power is increased. Micromagnetic simulations of thin film in Figures a-d illustrate this effect. a)H_{pulse}=10^{-2} H_K b) H_{pulse}≈0.3 H_K c) H_{pulse}≈0.6 H_K d) H_{pulse}≈0.8 H_K

Samples were patterned into islands of diameter ~80nm and spaced ~100nm. Micromagnetic simulations and experimental measurements show a large drop in the low-frequency permeability. The change in permeability can be attributed to the induced shape anisotropy that alters the equilibrium spin configuration. The blanket film prefers uniform inplane magnetization while the patterned islands relax into a vortex state. The aspect ratio and distance between the islands plays a role in the magnetization state. The ferromagnetic resonance for the film is ~980MHz while the patterned islands exhibit multiple resonances. The FMR for the islands is shifted slightly higher to ~1.15GHz with the other resonances appearing at 4.3GHz and 8.7GHz.

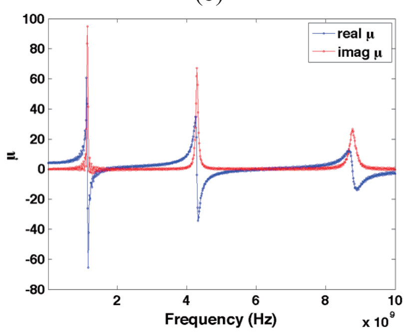
In addition to the appearance of higher-frequency resonances, the Q factor of the lowest resonance exhibits a dramatic increase compared to the blanket film. The position of the resonances can be tuned by varying the film thickness and island diameter. Also, the shape of the island can affect the resonance as well. Fig. 3 summarizes the simulation results for blanket and patterned films with different H_{rf} fields.



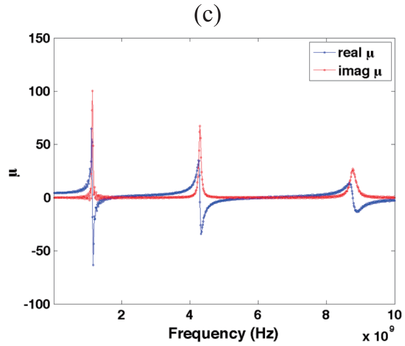
(a)



(b)



(c)



(d)

Fig. 3 Calculated permeability spectra for (a) blanket NiFe film 80nm thick 1 Oe, (b) blanket NiFe with H_{rf} 20 Oe, (c) patterned islands with 80nm diameter, H_{rf} 1Oe and (d) patterned islands with H_{rf} 20 Oe. Blanket film exhibits nonlinear behavior while the patterned islands are stable due to the vortex state.

Nonlinear behavior is seen in the blanket film at fields above ~10 Oe, whereas the patterned islands exhibit stable linear behavior until the exciting field reaches ~150 Oe. This behavior is attributed to the stability of the vortex spin configuration [7]. The configurational anisotropy can be altered by changing the aspect ratio of the nanodots. Through array optimization the threshold RF magnetic field amplitude for nonlinear behavior can be lowered.

III. Synthesis of Films and Nanoarrays

NiFe films were deposited onto SiO_2 substrates and capped with a 2nm Ti to prevent oxidation. A representative film cross-section is shown in Fig. 4.

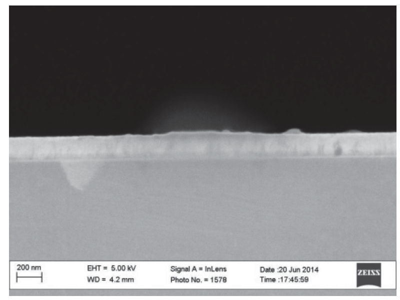


Fig. 4: NiFe film deposited on silicon substrates.

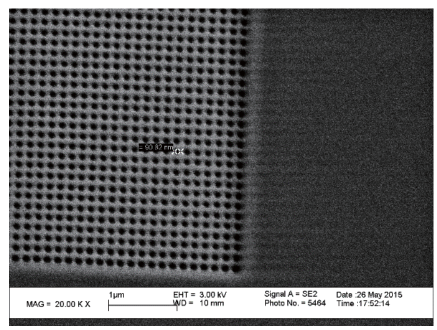


Fig. 5: SEM image of wafer after patterning the PMMA photoresist.

Nanodots are fabricated using electron beam lithography with a lift-off process. A positive photoresist, PMMA A6, was first spin coated on a 4-inch SiO_2 wafer. The wafer is spun at a speed of 5000 RPM for 60 seconds with an acceleration of 2000 RPM/second. The coated wafer is then baked on a hot plate for 90 seconds at a temperature of 180 C. After baking, the wafer is loaded into an electron beam lithography system (JEOL JBX-9300FS) and exposed under an electron beam having does value of 507 C/cm^2. The exposed wafer is then immersed into a developing solution formed by mixing 40 ml of methyl isobutyl ketone and 40 ml of isopropyl alcohol for 2 minutes, and then rinsed with isopropyl alcohol for 30 seconds. Fig. 5 shows SEM image of the wafer after developing. A NiFe layer with thickness of 100 nm is deposited on the wafer using an electron beam evaporator (Denton Infinity, Denton Vacuum, Moorestown, NJ) at room temperature. Wafer is rinsed with acetone and isopropyl alcohol to lift-off the photoresist and form the nanodots array as shown in Fig. 6.

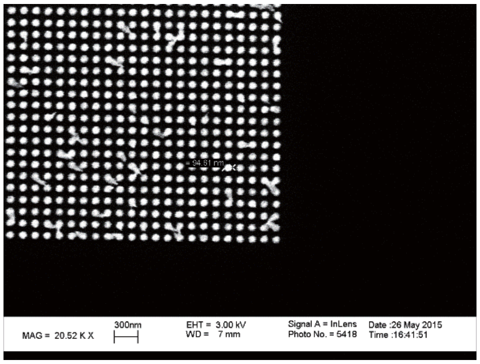


Fig. 6: SEM image of NiFe nanodot array via lift-off process.

The permeability and loss tangent as a function of frequency were extracted with a shorted strip-line structure described by Bekker et al. [7]. The reflection coefficient of the strip-line structure is related to the measured scattering parameters as (R=ln(S11)). The reflection coefficient of a transmission line is given as:

$$R = R_o e^{-2\gamma l} \quad (2)$$

where γ is the propagation constant, *l* is the length of a section and R_O is the reflection coefficient of the strip line at the termination. The propagation constant of an inhomogeneous medium (air + material) can be modeled as a quasi-TEM wave using an effective homogenous expression:

$$\gamma = \frac{i\omega\sqrt{\varepsilon_{eff}\mu_{eff}}}{c_0} \quad (3)$$

where ε_{eff} is the effective permittivity, μ_{eff} is the effective permeability of the material and c_0 is the velocity of light in vacuum. Thus, it can be seen that that the effective permeability of a material directly influences the reflection coefficient of a shorted strip transmission line. By using calibration structures such as empty strip-line, strip-line loaded with bare substrate, and strip-line loaded with a nanomagnetic structure on the substrate, the effective real and imaginary permeability of the structure was extracted. The permeability of the blanket film is shown in Fig. 7, and matches closely with the simulations in Fig. 3a, thus validating the simulations. Initial results also show substantial permeability shifts when the RF power levels are changed from 0 to 10 dBm. More experimental studies are underway to validate the nonlinear behavior models with blanket films and arrays.

IV. SUMMARY

Using micromagnetic simulations, field-dependent permeability spectra were extracted for nanomagnetic thinfilms and nanoarrays. The simulations showed nonlinear response with small fields, making these films suitable for applications such as Frequency-Selective Limiters and Signal-to-Noise enhancers. Representative films and nanoarrays were synthesized with e-beam evaporation and e-beam nanolithography. The simulated permeability spectra for blanket films were validated with experimental measurements. These simulations will be extended to other nanofilm and nanoarray designs to obtain nonlinear electromagnetic responses at low RF fields, and will also be validated with experimental results using different electrical test-structures on glass substrates.

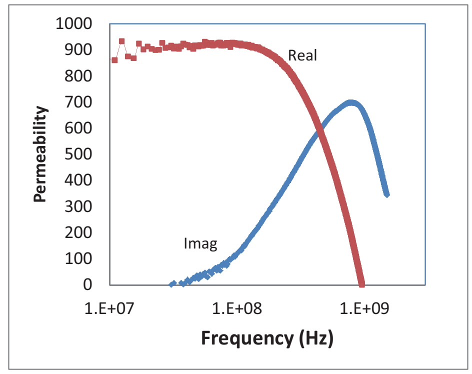


Fig. 7: Permeability spectrum of blanket NiFe films.

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