Modeling of novel concept design for extremely small, UHF band transmit/receive element based on multiferroics.

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ABSTRACT

An array design of ferromagnetic nanoelements and electrode network, patterned on a piezoelectric substate, that maximizes the effective magnetic dipole and minimizes fabrication complexity is theretically investigated as a novel concept design for ultra small antenna applications. Conditions for creating strain-mediated, voltage-driven radiating magnetic dipole are considered. Controllable and scalable uniform oscillations of magnetic spins on the proposed patterned array are found spanning several octaves of frequency bands up to the GHz regime. Frequency dependent system material losses and theoretical prediction of the total power radiated are presented.

Keywords: multiferroics, magnetic dipole radiation, ultra small antenna

1 INTRODUCTION

Multiferroic heterostructures consisting of a piezoelectric and a ferromagnetic material with magnetostrictive properties allow for cross control of the electric and magnetic degrees of freedom via strain mediation of the magnetoelectric coupling. Voltage driven reorientation of magnetic spin has been studied both experimentally and computationally in the long wavelength approximation of the electrostatic/magnetostatic limit by the UCLA group for continuous thin films [1], rings [2, 3] and single domain ferromagnetic structures [4, 5]. In the dynamic regime, where electromagnetic fields are coupled, the magnetoelectric effect of multiferroic materials or nanostructures has been usually considered only under the concept electrically shifting the ferromagnetic resonance for phase shifters [6, 7] and as a bulk acoustic wave (BAW)-mediated multiferroic antenna structure [8].

This fundamentally new approach based on multiferroics as antenna element in the UHF band, promises a reduction of the antenna size up to $<\lambda/100$. One mechanism responsible for this reduction in antenna size is the acoustic coupling in these materials and the transduction of electromagnetic to acoustic waves through the intrinsic property of the strain-mediated magnetoelectric coupling in the multiferroic materials. Coupling of the electromagnetic wave to acoustic resonant modes slows down the wave speed dictating reduced antenna dimensions. Another mechanism resulting in reduced size antenna is the high strength of the magnetic dipole magnitude that can be created by arrays of ferromagnetic single domain nanoelements.

In this work we investigate the feasibility of a new concept design of multiferroics to be used directly as an antenna "surface" material or transmitting/receiving element. The surface element is conceptualized as an array of nanoengineered ferromagnetic single domain elements and patterned electrode network on a piezoelectric substrate. The design is optimized to maximize the volume fraction of ferromagnetic elements, resulting in higher densities of the equivalent magnetic dipole. The electrode network is chosen such that minimizes both fabrication and voltage feed circuitry complexity and can ensure coherent rotation of the magnetic dipoles.

The remaining of this paper is organized as follows. The computational template used for the numerical solution of the strain-mediated magnetoelectric effect is introduced next, along with the design concept of an array of patterned electrode network and ferromagnetic nanodisks and conditions met for voltage controlled radiating magnetic dipole. Then, the results of the calculations are presented and discussed in terms of system material losses and total power radiated.

2 THEORY FORMULATION

A computational template is developed following [9], for the numerical solution of the strain-mediated magetoelectric effect, coupling electrokinetics and elastodynamics, describing the behavior on the piezoelectric substrate and the acoustic response of the ferromagnetic element as well as micromagnetic dynamics to describe the dissipative dynamic precession of the magnetic spins of the ferromagnetic nanoparticles.

2.1 Theory Formulation

The Landau-Lifshitz-Gilbert equation along with electromechanical balance laws considered, are formulated on the long wavelength approximantion considering small deformations and rotations. For a body of volume V, the momentum balance of the mechanical fields implies:

$$\sigma_{ij,j} + b_i = \rho \ddot{u}_i \text{ in V.} \tag{1}$$

Here σ_{ij} are the components of the Cauchy stress tensor, b_i are the components of body force per unit volume and u_i the components of the displacement respectively. The quasi-electrostatic Maxwell's equations governing the electrical quantities on the piezoelectric substrate are:

$$D_{i,i} = q \text{ in } V. \tag{2}$$

Here D_i are the components of the electric displacement and q is the volume charge density. The Landau-Lifshitz-Gilbert equation is used to describe the dissipative dynamic precession of the magnetic spins on the ferromagnetic nanoparticle and reads as:

$$\frac{\partial \mathbf{M}}{\partial t} = -\mu_0 \gamma \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \tag{3}$$

Here **M** is the magnetization vector, M_s the saturation magnetization, μ_0 the permeability of free space, γ the gyromagnetic ratio and α the Gilbert dumping constant. The effective magnetic field $\mathbf{H_{eff}}$ is derived by a free energy potential E that includes exchange energy, magnetoelastic, and demagnetizing energy giving rise to the respective magnetic fields that act as a driving torque for the spin rotation as :

$$\mathbf{H}_{eff} = -\frac{1}{\mu_0} \frac{\partial E}{\partial \mathbf{M}} \tag{4}$$

The strain mediated magnetoelectric coupling is modeled as a body force transferred from the piezoelectric substrate to ferromagnetic-ferroelastic response through magnetostriction [9]. A weak formulation for the above equations is introduced in the Mathematics Module of COMSOL Multiphysics finite element package. The material parameters that describe the linear constitutive response of the piezoelectric substrate are chosen to describe commercial PZT-5H. The material parameters that describe the nonlinear magnetic constitutive behavior of the ferromagnetic elements are chosen to match Nickel properties [9]. The magnetocrystalline anisotropy is neglected assuming a polycrystalline nickel element; typical of most material processes like electron-beam or nanosphere lithography. The Gilbert damping constant is set equal to 0.038 to realistically represent the spin dynamics of the nickel elements which is a necessary step to establish a continuous spin rotation as the spin dynamics depend on the damping constant, the exchange interaction between the spins and the magnetoelastic strain transfer from the piezoelectric substrate which is spatially nonuniform.

2.2 Periodic Array Design Parameters

A periodic three voltage input, hexagonal electrode network patterned on a piezoelectric substrate is considered in order to induce strains capable of individually controlling magnetic moment rotation on ferromagnetic nanoelements. Invoking periodicity, the geometric characteristics of a unit cell are optimized. The shape of the ferromagnetic element is chosen to be a circular disk in order to take advantage of the in-plane isotropy of the effective magnetic moment which in this case act as static magnetic dipoles. Creating a radiating magnetic dipole by continuously rotating the in plane magnetic spin in ferromagnetic single domain nanoelements can be conceptualized as the linear superposition of two perpendicular magnetic dipoles oscillating 90-deegree out of phase, reducing the multiferroic system and the magnetic dipole radiation to a turnstile antenna Hertzian dipole problem.

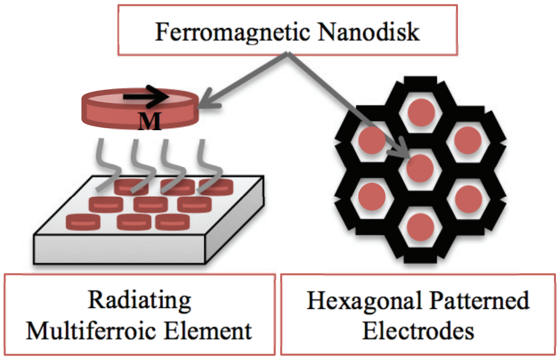

Figure 1 : Hexagonal periodic electrode patterned array for individual controlled magnetic dipole rotation on nanodisks.

The optimal diameter in order to avoid the formation of s-shaped magnetization distribution is taken as 100nm and the optimal thickness for this diameter in order to maintain in plane magnetization distribution and suppress the out of plane component during rotation is takes equal to 10nm. Next we optimize the width and spacing of the electrode network for high close packing as this aspect is proportional to the power radiated. However, the width of the electrodes must be appropriately chosen to create a strain response strong enough to induce rotation. Simulations show that an electrode thickness of one diameter spaced at a distance corresponding to two diameters apart is efficient in inducing magnetization switching in the nanoelements in the unit cell. Finally the piezoelectric substrate thickness is set equal 500nm, simulating a bulk PZT substrate.

2.3 Voltage Pulse Optimization

Next, we proceed in the investigation of the applied voltage input function for continuous rotation of the magnetization vector. A multi start optimization technique to surpass the unknown convexity of the problem is employed. The optimization problem is a minimization of the sum of the three voltage inputs at a given angle under the constraint that the principal strain aligns with the given angle. The averaged principal strain at the interface between the piezoelectric substrate and the ferromagnetic nanoelements are computed as a weighted linear combination of the surface strains resulting from the deformation created in the substrate by the activation of the electrode inputs under 1V loading. For the hexagonal cell the three opposite pairs of electrodes serve as control inputs.

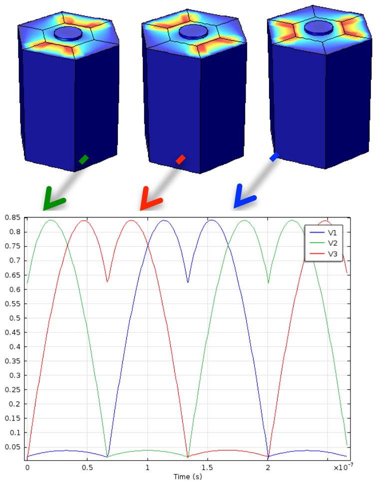

Figure 2 : Optimized voltage input pulse as a function of time for three input voltage/strain combination corresponding to rotation of the principal strain direction at 125 MHz. The unit cell schematics show the electrode area that is being activated.

The value of the principal strain was set to 1000με which was determined to be appropriate to overcome inertial effects and align the magnetization vector with the principal strain direction. The minimization scheme, which can be reduced to an angle-tracking problem, can be scaled to any value of compressive/tensile maximum principal strain required for the specific combination of materials as well as for any given angular speed of rotation, hence frequency, at which the magnetic dipole moment oscillates. Figure 2 shows the resulting voltage pulse function obtained from the optimization routine on the three inputs and the corresponding three opposite electrode pairs activated for the hexagonal pattern at 125 MHz. Once the optimized voltage pulse combination has been found for a given frequency, the function is readily scaled to accommodate different radiating frequencies.

3 RESULTS

A periodic unit cell with the geometric parameters discussed above is considered and the voltage function obtained from the optimization scheme is scaled to accommodate principal strain rotation on the piezoelectric/ferromagnetic interface at 16, 125, 500 and 1000MHz respectively. Figure 3 shows the plot of the volume averaged magnetic moment components as a function of time for the hexagonal unit cell at the given frequencies, successfully demonstrating highly stable, controllable and scalable voltage driven in-plane oscillations of magnetic moment on the ferromagnetic nanodisks, spanning a six octave bandwidth.

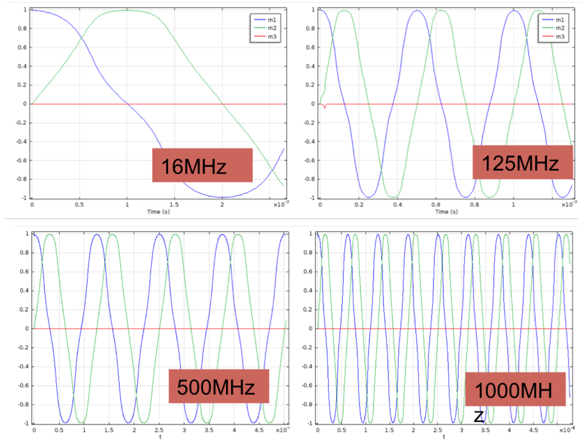

Figure 3 Volume averaged magnetic dipole moment components as function of time for corresponding frequencies of 16, 125, 500 and 1000MHz, spanning 6 octaves of frequency bands.

Next, we model a cluster of hexagonal magnetic elements to ensure scalability and superposition of the magnetic moment dipoles as well as robust individual control of the magnetic elements in the array configuration (i.e. no negative dipole-dipole interaction effects). Figure 4 shows the magnetic moment as function of time oscillating at a nominal frequency of 500MHz for a cluster of hexagonal cells. This step is very important in the proposed design as the strength of the magnetic dipole moment lies in the fundamental assumption that the rotation of each element is coherent with the rotation of the nearby elements in order to superpose the magnetic moment dipoles to achieve the highest dipole moment strength.

Note that the given frequencies hold for the voltage driven rotation of the principal strains and are only nominal frequencies for the magnetic moment rotation due to a noted lag time between induced strain and magnetic spin rotation. For example, the time required for a full rotation of the magnetization vector at the lowest analyzed frequency is 3.93×10^{-7}s and at the highest frequency is

$6.28\text{x}10^{-9}$s respectively. Furthermore, the time step required for stability of the dynamic equations is on the order of 1e-11s. This fact makes lower frequency calculations time consuming and for this reason we report the response only down to 16MHz, however voltage driven oscillations of the magnetic dipole moment in the kHz regime, spanning perhaps up to a 10 octave bandwidth should readily follow.

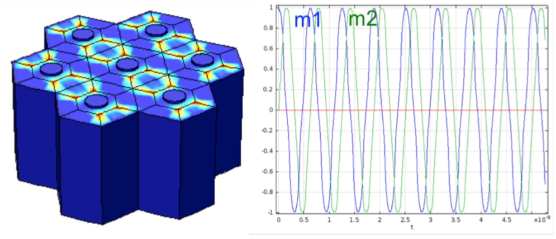

Figure 4 : Magnetic dipole moment components as function of time for a cluster of hexagonal unit cells corresponding to a nominal angular frequency of 500 MHz.

The radiated power is theoretically approximated with the radiated power of two orthogonal magnetic dipoles of equal strength and out of phase by π/2. According to [10] the total magnetic vector potential for the dipole system can be computed as:

$$\mathbf{F}_{total} = \frac{\varepsilon I_m l}{4\pi R}\left(j\hat{\mathbf{x}} + \hat{\mathbf{z}}\right) \tag{5}$$

where R is the distance between the source and the observation point, and according to [11] we have:

$$I_m l = j\omega\mu_0 m = j\omega\mu_0 \int_V M_s \, dV \tag{6}$$

Then, the far field electric and magnetic fields and the Poynting vector can be computed from the above vector potential [10] as:

$$P_{rad} = \iint_{\partial\Omega} S \bullet \hat{a}\, ds = \frac{\left(\omega^2 \mu_0 m\right)^2}{6\pi\eta c^2} \tag{7}$$

Here m is the magnitude of the total magnetic dipole moment and depends on the packing density of the ferromagnetic nanoelements on a surface area. The established surface area of a single cell is $7.8\text{x}10^{-14}\text{m}^2$, giving rise to $1.28\text{x}10^{13}M_sV$ total dipole moment per m^2 of covered area considering a 50nm diameter Nickel nanodisk of thickness of 10nm and M_s = 500kA/m. Using these values the total radiating power for the hexagonal network is found equal to 0.98 W/m^2 at an operational frequency of 1GHz.

Finally, we calculate the electrical power on the electrodes per unit cell area which is the power required to maintain continuous rotation of the magnetic dipole moments in the ferromagnetic elements, i.e. to overcome the Gilbert dumping associated with the magnetization precession and hence is considered to be a measure of the material system losses. We find that for the hexagonal unit cell the average material losses are frequency dependent and range from 0.06W/m^2 at 16MHz to 0.053W/m^2 at 1GHz.

4 DISCUSSION

We successfully simulated stable, controllable and scalable radiating multiferroic element, spanning a six octave bandwidth. The level of radiating power reported is very promising considering the source is thin magnetic nanoparticles and can be multiplied by design of stuck configurations giving rise to very high efficiency small antenna system.

5 ACKNOWLEDGMENTS

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REFERENCES

[1] J. Cui et al., J. Appl. Phys. 115, 17C711 http://dx.doi.org/10.1063/1.4863258, 2014.
[2] C. Y. Liang et al., J. Appl. Phys. 118, 174101; http://dx.doi.org/10.1063/1.4934196, 2015.

[3] H. Sohn et al., ACS Nano, 9 (5), pp 4814–4826, DOI: 10.1021/nn5056332, 2015.
[4] S. M. Keller et al., Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS), 2015 Transducers - 2015 18th International Conference on, Anchorage, AK, pp. 796-798, 2015.
[5] X. Li et al., J. Appl. Phys., 118 014101 http://dx.doi.org/10.1063/1.4923350, 2015.
[6] X. Yang et al., IEEE Microwave and Wireless Components Letters, Vol. 24, No. 3, 2014.
[7] A. B. Ustinov, B. A. Kalinikos,and G. Srinivasan, Appl. Phys. Lett. 104, 052911; 10.1063/1.4864315, 2014.
[8] Z. Yao, Y. E. Wang, S. Keller and G. P. Carman, IEEE Transactions on Antennas and Propagation, vol. 63, no. 8, pp. 3335-3344, 10.1109/TAP.2015.2431723, 2015.
[9] C. Y. Liang et al., Nanotechnology, Vol. 25, No. 43, 2014.
[10] C. A. Balanis, Vol. 1. John Wiley & Sons, 2005.
[11] Haus, A. Hermann , and J. R. Melcher, Prentice Hall, 1989.