Tunable Multiferroics for Reconfigurable RF System Packages

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***Abstract*—Electric and magnetic properties of multiferroics can be conveniently tuned with applied electric and magnetic fields. Such tunability provides multiple design options for reconfigurable antennas and smart shielding applications and is thus of high interest. Dielectric tuning is commonly achieved with electric fields, which is more suitable with thin-films as they need lower voltages. For thick RF dielectrics that are used in antennas and Frequency Selective Surfaces (FSS), tuning requires 100s of Volts. To address this problem, we propose current-driven tuning of permittivity with integrated coils under the multiferroic. Tunable dielectric properties in nanostructured titanate paraelectrics are investigated through simulations by coupling them with magnetostrictive layers. In parallel, cosintered ferrite and paraelectric dielectrics are characterized for their tunability. The change in dielectric constant with magnetic fields is analyzed through multiphysics COMSOL simulations. Permittivity tuning is modeled with different coil currents. Applications in tunable FSS is demonstrated with such dielectric tuning.**

Keywords—piezoelectric, magnetostrictive, frequency selective surface, tunable, reconfigurable

I. Introduction

Multiferroics are materials with at least two ferroic characteristics, properties such as ferromagnetism, ferroelectricity, or ferroelasticity. This coexistence of magnetization and electric polarization in a material allows to realize magnetoelectric coupling (ME coupling) in two forms – direct ME coupling effect where magnetic field controls electric polarization, or converse ME coupling effect where electric field controls magnetization [1], [2]. For both cases, the coupling phenomena are mediated via strain in a heterostructure material system where ferroelectric and ferromagnetic materials are layered [3]. There are two types of ME materials - single-phase material composed of one type of structure and multi-phase ME materials composed of multiple laminates or composite of two different type of material structures [4], [5]. For optimal performance in practical applications, single-phase multiferroics face challenges because of their low ME coupling coefficient and higher temperature requirement. Whereas, composite multiferroics materials has superior ME coupling coefficients while compared to single-phase multiferroics. Strong ME coupling is required to efficiently convert magnetic field to electric field and vice versa.

The ME effect is the result of piezoelectric effect on ferroelectric material and magnetostriction effect in ferromagnetic material. Ferroelectric material deforms in the presence of electric field and at the same time, permittivity changes. When ferromagnetic material is exposed to magnetic field, it deforms, and at the same time permeability changes. Similarly, when alternating stress is applied to ferroelectric or ferromagnetic material, they generate electric and magnetic field respectively. Furthermore, when ferroelectric and ferromagnetic materials are used together as laminates or composites, they are coupled with strain and allow for conversion of electric field to strain to magnetic field and vice versa. This energy conversion capability has led to the development of various multiferroic devices such as tunable RF devices, spintronics, magnetic sensors, and so on [6]-[12]. Specifically, reconfigurable frequency selective surfaces (FSS) can be used in adaptive environments with potential applications in the areas of shielding, spatial filters, radomes, polarizer, dichroic reflector, antenna beam steering and so on. Reconfigurable FSS (RFSS) based on micro-electro-mechanical systems (MEMS), PIN diode and varactor diode, liquid dielectrics, spring resonators have been shown in the literatures [13]-[18]. However, these RFSS are unreliable as with the possibility failure of active

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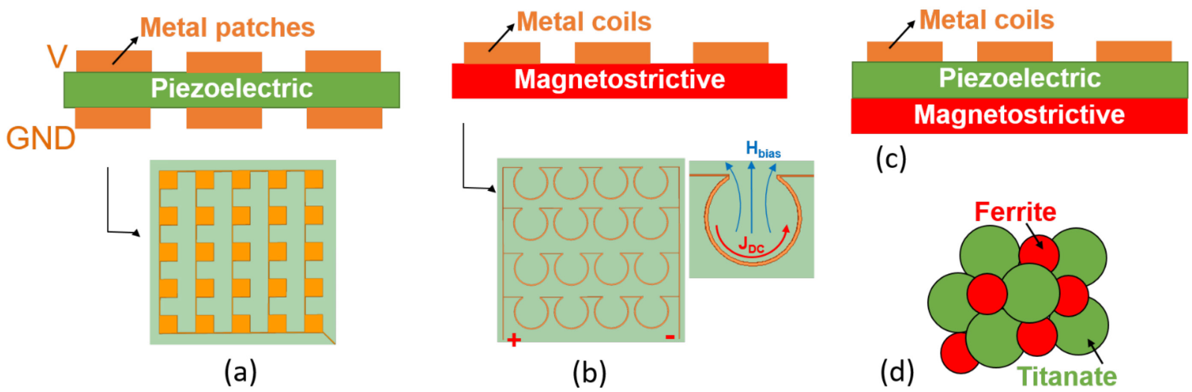

Fig. 1. Different possible architecture for reconfigurable FSS - (a) piezoelectric substrate with voltage control of permittivity (b) magnetostrictive substrate with current control of permeability (c) ferroelectric/ferromagnetic laminate with current control of permittivity (d) ferroelectric/ferromagnetic composite with current control of permittivity.

devices and MEMS devices. Also, the running capacity of mechanical RFSS is narrow.

Our goal is to use magnetostrictive and piezoelectric material to vary permeability and permittivity respectively to achieve change in frequency response. Unlike voltage-based tuning, which requires higher voltages to achieve adequate shift in dielectric constant, we propose to use current-driven tuning by integrating tiny coils under the multiferroics. In this paper, we explore four different architectures (Fig. 1) to determine suitable architecture for tunable FSS. First, ferroelectric substrate with voltage control of permittivity of substrate (Fig. 1a) is simulated. Second, we simulate ferromagnetic material with current control of permeability (Fig. 1b). Current carrying metal coil is used to provide static magnetic field bias to magnetostrictive substrate which in turn controls substrate permeability. Third is ferroelectric/ferromagnetic laminate with current control of permittivity (Fig. 1c). Here, we have piezoelectric and magnetostrictive materials separated by a dielectric along with current coil on top of piezoelectric material. The static magnetic field produces strain on magnetostrictive material, which is transferred to piezoelectric material, and in the process varying permittivity of the later. Finally, ferroelectric/ferromagnetic composite is simulated. This system also provides current control of permittivity (Fig. 1d). All the modeling is done in COMSOL multiphysics software. A potential application would be deposition of periodic metal patches to design FSS. Double sided FSS is designed to bias top and bottom end of piezo substrate and show tunable FSS.

II. Architecture 1 – Dielectric Tuning

A ferroelectric substrate with metal patches is used. Piezoelectric effect allows for voltage control of permittivity of the substrate; permittivity of piezoelectric material changes with applied electric field or stress. Strontium titanate with thickness of 0.5 mm is chosen. Jiles-Atherton model is used to simulate the structure [19]. Effective electric field including total polarization is given by (1). Anhysteretic polarization is given by (2) and anhysteretic polarization shape is given by Langevin function as shown in (3). Saturation polarization of 19 μC/cm^2 was used. The initial hysteresis curve and voltage (E-field) control of permittivity of piezoelectric substrate is shown in Fig. 2. Electric displacement field increases nonlinearly with increasing electric field while the relative permittivity of strontium titanate substrate decreases providing us with voltage control of permittivity.

$$\mathbf{E}_{eff} = \mathbf{E} + \alpha\mathbf{P} \quad (1)$$

$$\mathbf{P}_{an} = P_{sat} L(|\mathbf{E}_{eff}|)\frac{\mathbf{E}_{eff}}{|\mathbf{E}_{eff}|} \quad (2)$$

$$L^{mn} = L\,\frac{\mathrm{E}_{eff}}{a^{mn}}\delta^{mn},\ L(x) = coth(x) - \frac{1}{x} \quad (3)$$

Where, $\mathbf{E}_{eff}$ is effective electric field, α is inter-domain coupling, $\mathbf{P}_{an}$ is anhysteretic polarization, $\mathbf{P}_{sat}$ is saturation polarization, L is Langevin function, a is domain wall density.

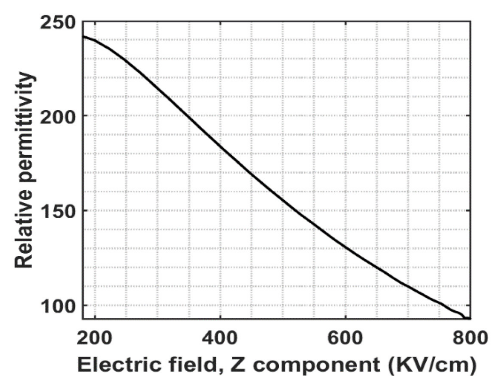

Fig. 2. Tunable permittivity range of strontium titanate.

III. Architecture 2 – Magnetic Tuning

A ferromagnetic substrate with metal coil is used. Magnetostriction effect allows for current control of permeability of the substrate; permeability of magnetostrictive material changes with applied magnetic field or stress. Magnetostrictive cobalt ferrite is chosen for simulation.

Equation (4) is used in COMSOL to model magnetostriction. Saturation magnetization of 70 emu/g was used. The initial hysteresis curve and current (H-field) control of permeability of magnetostrictive substrate is shown in Fig. 3. Magnetic flux density increases nonlinearly with increasing magnetic field while the relative permeability of cobalt ferrite decreases providing us with current control of permeability.

$$B = \mu_o[H + M(H, S_{mech})] \quad (4)$$

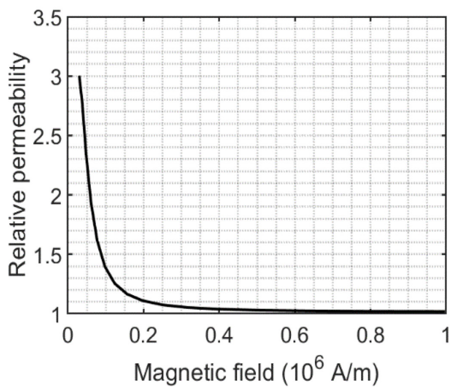

Fig. 3. Tunable permeability range of cobalt ferrite.

IV. ARCHITECTURE 3 – ME COUPLING WITH LAMINATE

A ferroelectric and ferromagnetic laminate composed of strontium titanate and cobalt ferrite respectively is modeled in COMSOL. Piezoelectric and magnetostrictive layers were coupled using solid mechanics module in COMSOL. A current-generating coil is placed below the laminate to produce static magnetic field bias through the substrate. The magnetic field induces stress in the magnetostrictive layer. The strain is transferred to piezoelectric layer that is stacked on the top, which results in a change in permittivity of the piezo layer. Hence, ME coupling in laminate is mediated by strain and provides current-based control of permittivity. The dielectric tuning with current is shown in Fig. 4 through two plots - strain vs. current and polarization vs. strain. Adequate tuning is achieving with low currents as seen in the figure.

V. ARCHITECTURE 4 – ME COUPLING WITH COMPOSITE

A ferroelectric and ferromagnetic cosintered composite composed of strontium titanate and cobalt ferrite respectively is modeled in COMSOL. The diameters of piezoelectric and ferrite particles were 150 nm and 400 nm respectively. The tunable permittivity range of ferroelectric/ferromagnetic composite obtained from simulation is shown in Fig. 5. Apart from simulation, we fabricated this architecture and report preliminary results. In order to perform experimental validation of these structure, thick-films of composites are prepared by dry-pressing and tape-casting methods. In dry- pressing, equal volume of both titanate and ferrite particles (Alfa Chemistry, NY) are crushed in mortar & pestle and mixed homogenously. Then, the pellets of desired sizes are formed by dry-pressing using appropriate die sets and sintered. Various sintering conditions from 1050 C to 1300 C were utilized to achieve strain coupling between the ferrite and titanate phases. The composite layers are metallized with silver inks and sintered at 100 °C. Initial measurements showed high relative permittivity of ~52. DC magnetic field-induced tuning of permittivity was also noted from initial measurements, although much smaller (~5% for 500 Oe of field) than estimated through models. Model-to-hardware correlations with tunability require further process optimization and will be reported in the following work.

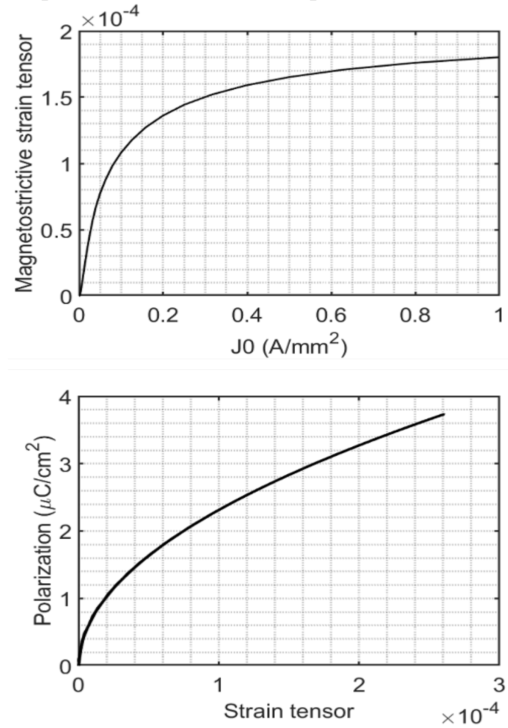

Fig. 4. (a) Current-driven magnetostriction in cobalt ferrite. (b) Resulting polarization change in the ferroelectric strontium titanate coupled as a layer with ferrite.

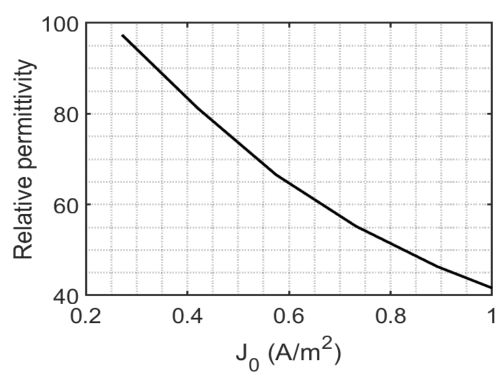

Fig. 5. Tunable permittivity range of strontium titanate/ cobalt ferrite composite.

VI. DISCUSSION

The first architecture with piezoelectric strontium titanate, provides relative permittivity tunability from 242 to 91 with applied voltage from 200 to 800 kV/cm. The thickness of piezo layer can be reduced to have control over permittivity with lower voltages. High permittivity of strontium titanate could result in a lossy device. So, nanostructured piezoelectric material with lower permittivity is required [20]. The second architecture with magnetostrictive cobalt ferrite provides permeability tunability from 2.9 to ~1 with a static magnetic field of up to 2×10^5 A/m magnetic field. A high-resistivity magnetostrictive material such as doped cobalt ferrite is ideal as opposed to other lossy ferrites so that the substrate would be fit to design antennas, and RFSS. To lower substrate permittivity even more and still have control over permittivity, a heterogeneous substrate is designed; this is shown in Architecture 4 (Fig. 1). The fourth architecture with strontium titanate and cobalt ferrite laminate and composite respectively provides tunability with high permittivity x permeability product, which directly leads to miniaturization of FSS. The permittivity of this composite system is lower compared to the monolithic strontium titanate used in Architecture 1. The strontium titanate and cobalt ferrite composite provides relative permittivity tunability from 97 to 40, as seen in Fig. 5. Finally, dielectric frequency selective surfaces (FSS) with periodic multiferroic tiles were investigated to study their notch filter response. FSS structure with variable substrate permittivities was simulated in ANSYS HFSS software. The coils that generate magnetic field are designed so that they don't interfere with the electromagnetic signature of the RFSS. Nominal relative permittivity change from 18 to 10 is assumed to achieve tuning at lower currents in non-ideal conditions. The resonance frequency increases with decreasing permittivity as shown from the simulation results in Fig. 6, hence showing the viability of this approach.

VII. Summary

Current-driven tuning of permittivity is modeled with ferroelectric-ferromagnetic composite structures using two material architectures. The first is a stack of the composites and the second is mixed-particle cosintered structures. Both structures show good tunability of permittivity with low currents, making it a viable technology for tunable FSS and antennas in reconfigurable RF electronics.

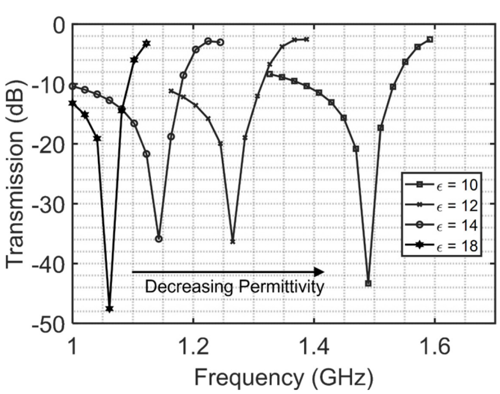

Fig. 6. Variable resonance frequency of FSS with varying permittivity.

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