Reconfigurable Antennas and FSS with Magnetically-Tunable Multiferroic Components

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***Abstract*—Dielectric properties of thin-film ferroelectric materials are commonly tuned with electric field. However, thick-film tuning of RF dielectrics requires higher voltage to induce adequate electric field. Furthermore, tunability is always associated with a loss in Quality Factor (Q). We propose the use of magnetic fields to tune permittivity of RF dielectrics with current-carrying coils integrated under the ferroelectric-ferromagnetic multiferroic heterostructures. This will allow us to realize reconfigurable RF structures such as frequency-selective surfaces for smart shielding applications and tunable antennas. First, we demonstrate the feasibility of such systems by using multiphysics-based numerical modeling of ferroelectric-ferromagnetic heterostructures laminates. A representative multiferroic all-ceramic stack is synthesized and characterized to show strain-sensitive permittivity with more than 2× variation, which can be effectively created through magnetic field bias for magnetic tuning.**

Keywords-magnetostrictive, piezoelectric, reconfigurable, frequency-selective surface

I. INTRODUCTION

Multiferroic materials have recently gained major attention from the scientific and engineering communities because of the unique opportunity they provide in achieving electric tuning of magnetic properties and magnetic tuning of electric properties [1], [2]. These materials of interest exhibit multiple ferroic properties - ferroelectricity, ferromagnetism, or ferroelasticity and provides numerous potential applications in the area of wireless power, electrically-small antennas, sensors, memory devices, spintronics, frequency-selective and reconfigurable surfaces, medical devices, and so on [3]–[5]. Multiferroic materials can be classified into two categories – single-phase structures and heterostructures. Single-phase multiferroics are synthesized from one composition [6] while multiphase materials are composed of multiple layers of laminates or composite mixtures of different materials [7]. Until recently, a single-phase multiferroic material with practical applications at room temperature in terms of tuning has not been put forward [8]. Designing a system with single-phase material is challenging because of its limited flexibility in achieving an optimal combination of properties in addition to its low magnetoelectric (ME) coupling. Multiferroic heterostructures, on the other hand, provide superior ME coefficient. In most cases, ME coefficient in heterostructures is several orders of magnitude larger than that of single-phase materials [5],[9]. Since, strong ME coupling coefficient provides higher efficiency while converting the electric field to magnetic field and vice versa, we focus on multiferroic heterostructures.

The co-existence of ferroelectricity and ferromagnetism in the same system is the key to realize ME coupling. First is direct ME coupling, which provides electric polarization tunability using magnetic field, while the second effect, converse ME coupling, provides electric field control of magnetization [10]. When multiferroic heterostructures are used, coupling is mediated via strain for both cases [11]. This ME coupling allows us to realize tunable radio frequency (RF) devices with low insertion loss while having very low to negligible power usage and has practical benefits for telecommunication applications, memory devices, logic devices, satellites and radars[12].

Magnetostrictive effect that arises from a ferromagnetic material and piezoelectric effect from a ferroelectric material results in ME effect. When electric field is applied to a ferroelectric material, it deforms. The permittivity of the material also changes as the orientation of electric domains changes. Similar effect is seen in a magnetic material. When magnetic field is applied to a ferromagnetic material, the magnetic domains try to align with the field, the permeability of the material changes, and the material deforms. On the other hand, ferroelectric materials can generate electric fields when alternating stress is applied, while ferromagnetic materials can generate magnetic fields. Furthermore, ferromagnetic and ferroelectric materials, when bonded together as composites or multilayered laminates, can enable conversion of magnetic field to electric field and vice versa. This realization has paved the path for the development of a variety of multiferroic devices including tunable RF devices [13]–[20]. Tunable FSS can specifically be utilized in adaptive situations with potential implementation in areas such as beam-steering, radomes, spatial filters, dichroic reflectors, polarizer, shielding, etc. Tunable FSS has been previously presented in the literature. Those were based on liquid dielectrics, varactor and PIN diodes, spring resonators, and micro electro mechanical systems (MEMS) [21]–[26]. However, aforementioned systems have a narrow range of application and are unreliable. The biasing circuit for architecture with active devices is complicated and the

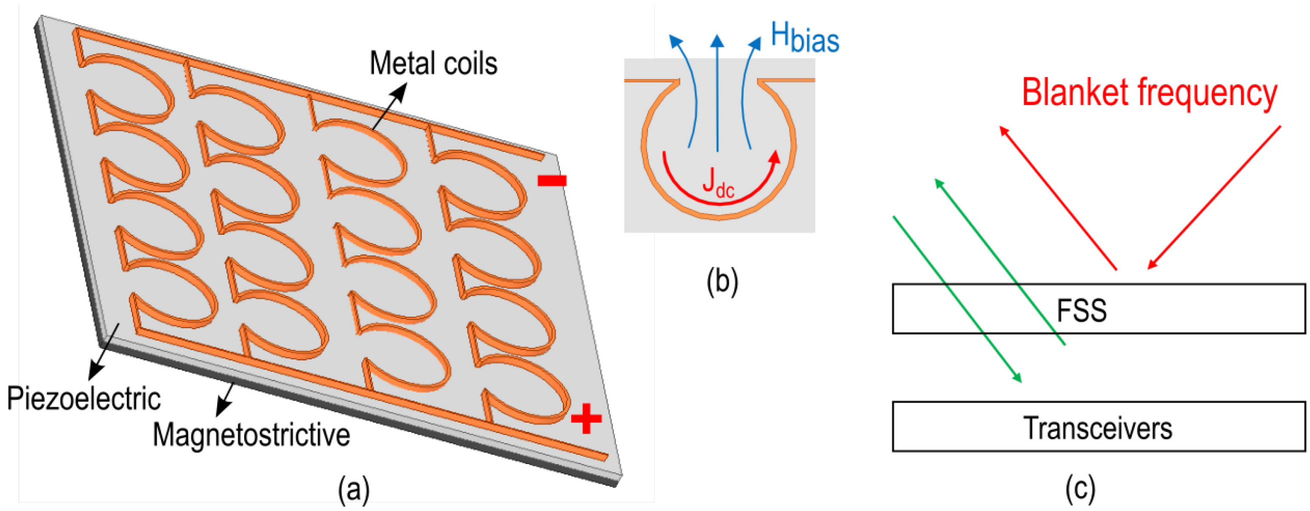

Figure 1. (a) Conceptual diagram for multiferroic heterostructure laminate implemented as a frequency-selective surface. (b) The metal provides current to tune substrate permittivity. (c) Frequency-selective surface transmitting specific frequency and blocking all blanket frequencies to and from the transceiver.

device is prone to failure. Similarly, mechanically tunable FSS has narrow tunability.

Our goal is to make use of multiferroic heterostructure laminate as a substrate for RF structures and achieve current tuning of substrate permittivity. The conceptual diagram with multiferroic heterostructure laminate composed of piezoelectric and magnetostrictive material is shown in Fig. 1a. Array of interconnected metal coils are placed on top of substrate as repetitive elements. DC current is passed through the periodic metallic element array (Fig. 1b). The resulting magnetic field produces strain in the magnetostrictive material. The stress is transferred to piezoelectric elements. Based on the amount of current applied, the permittivity of the substrate varies. The variable permittivity results in a change in resonance frequency of the FSS. The resulting structure can be used as shown in Fig. 1c where FSS allows selective frequency to and from a transceiver, and blocks all other blanket frequencies. The filter response is studied at non-ideal situations using ANSYS® HFSS™. A substrate with variable relative permittivity from 10 to 20 was assumed, a periodic tile was designed on top of such substrate, and frequency response was analyzed. As shown in Fig. 2, with the decrease in substrate permittivity, resonance frequency increases. Hence our approach of tuning substrate permittivity to design a reconfigurable FSS is viable.

In our previous work [27], we explored tunable FSS with four different substrate architectures - voltage tuning of permittivity for piezoelectric substrate, current tuning of permeability for magnetostrictive substrate, current tuning of permittivity of a stack of multiferroic laminates as well as co-sintered structures made of mixed-particles. These structures demonstrated good permittivity tunability with low current, proving feasible technology for reconfigurable RF structures such as FSS and antennas. In this work, we focus on multiferroic heterostructures laminates. We study different material systems for H-field tuning of permittivity. First, we study the material system using a multiphysics simulation tool. For numerical modeling, we first study the effect of applying varying magnetic field on magnetostrictive material, Metglas®, and its response in terms of magnetostriction strain. Then, we study the polarization response of piezoelectric materials under the application of strain. Finally, we present experimental validation for polarization tunability of a piezoelectric substrate using strain-coupling.

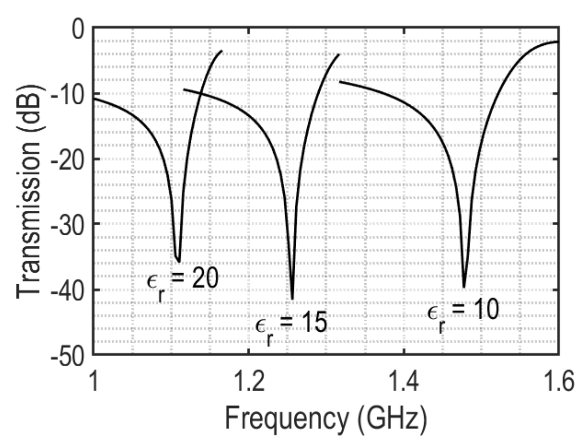

Figure 2. FSS showing variable frequency of operation with changing substrate permittivity.

II. Numerical Modeling of Multiferroic Heterostructure Laminates

A. *Magnetostrictive material and its response to applied magnetic field*

The magnetostrictive material of interest is Metglas®. A current-carrying coil, as shown in Fig. 1, is placed on the top of the substrate. While H-field is applied to the magnetic material, it undergoes strain because of magnetostriction effect. Nonlinear isotropic model is used for the simulation and Langevin function is used to model the anhysteretic shape of magnetization. Saturation magnetostriction = 27 ppm, saturation magnetization = 1.24×10^6 A/m, initial magnetic susceptibility = 100 was used. The ferromagnetic response is shown in Fig. 3. Fig. 3a shows the magnetic field generated by current in a coil placed below the substrate. Fig. 3b shows the B-H hysteresis loop of magnetostrictive material under study. Similarly, Fig. 3c shows the increasing strain in the magnetic material with increasing current. The strain increases nonlinearly with the applied magnetic field and starts to saturate at high current values. This strain is then transferred to the piezoelectric material to vary the substrate polarization property. Finally, Fig. 3d shows the varying magnetostriction with increasing applied magnetic field.

B. Piezoelectric material and its response to stress transferred from magnetostrictive material

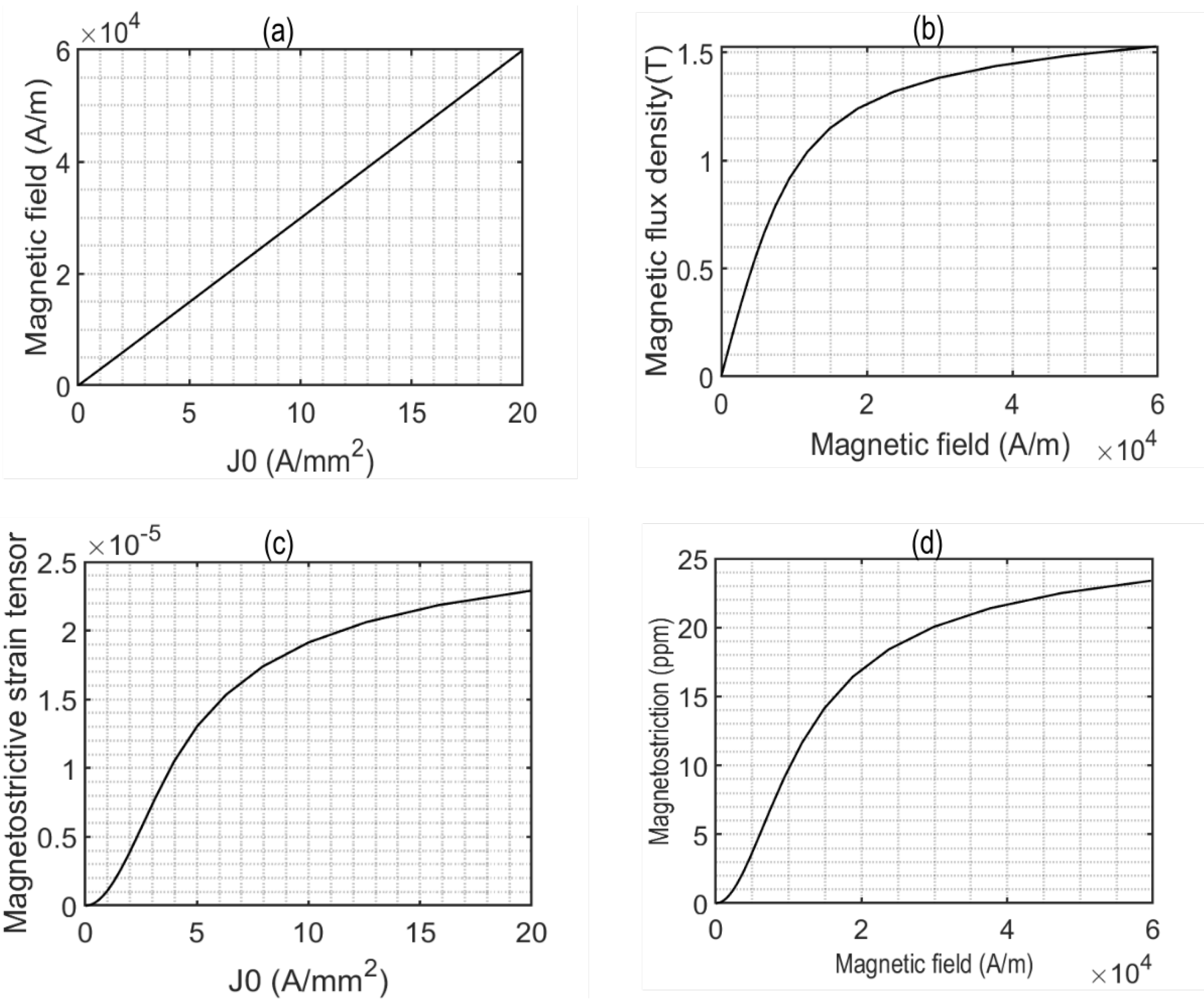

Figure 3. Response of magnetostrictive Metglas® under the application of a magnetic field. (a) Magnetic field produced by current coil, (b) B-H hysteresis curve, (c) Magnetostrictive strain tensor on Metglas® resulting from current in the coil, and (d) magnetostriction vs applied magnetic field.

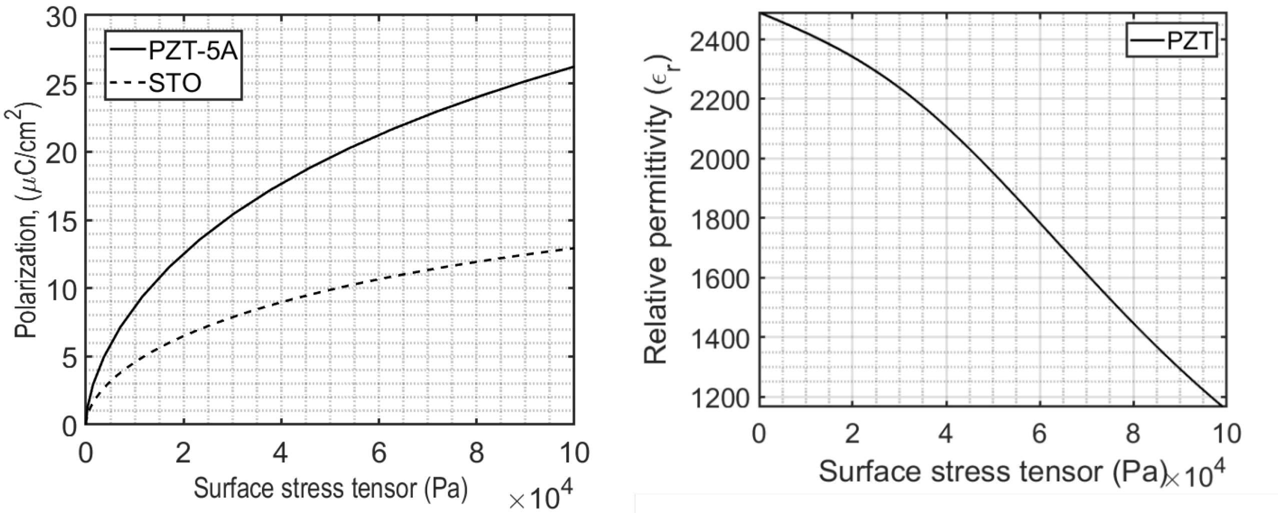

Figure 4. Variation of polarization while applying a varying stress on piezoelectric surface (lengthwise)

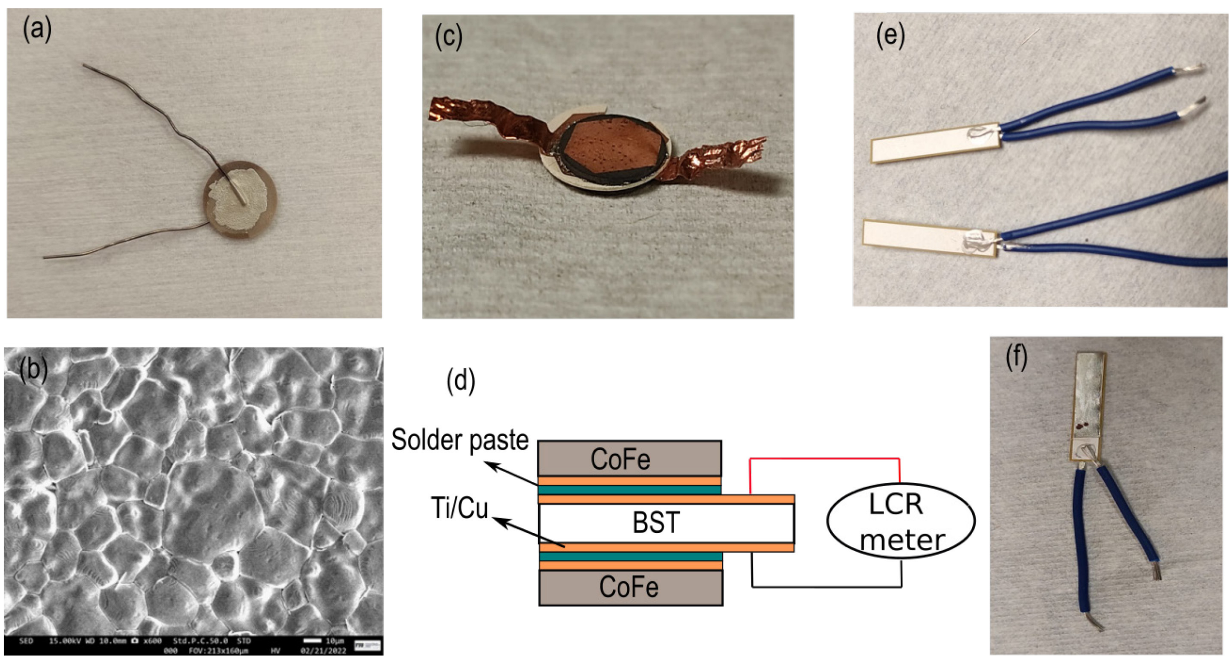

Figure 5. (a) BST pellet (sintered at 1450 ºC for 2 hours) coated with silver ink. (b)Scanning Electron Micrograph of BST. (c) ferroelectric (BST) /ferromagnetic (CFO) laminate (coated with Ti/Cu). (d) Schematic of ferroelectric (BST) /ferromagnetic (CFO) laminate. (e) PZT plate coated with silver electrode. (f) ferroelectric(PZT) /ferromagnetic (Metglas®) laminate.

For piezoelectric material, we use strontium titanate (STO) and lead zirconate titanate (PZT-5A) properties in the simulation. The piezoelectric material is used to create a heterostructured laminate as shown in Fig. 1. We assume that the strain resulting in the magnetostrictive material, due to the magnetic field from the current carrying coil, is transferred to the piezoelectric substrate. For all piezo materials, dielectric model as well as Jiles-Atherton model is used to model nonlinear ferroelectric hysteresis. Langevin function is used to model anhysteretic shape of polarization. For PZT-5A, 49 $\mu C/cm^2$ is used as the saturation polarization and 19 $\mu C/cm^2$ for STO. The resulting plot for polarization and corresponding relative permittivity of these piezoelectric materials for applied stress of up to 1×10^5 Pa is shown in Fig. 4.

For experimental verification, we fabricated piezoelectric and magnetostrictive pellets. We replicate the effect of induced strain on piezoelectric materials and multiferroic stacks using thermal stimulus. In the future work, we will present the system with piezoelectric and magnetostrictive material coupled via field-induced strain.

III. Experimental Methods

Powders of Barium Strontium Titanate (BST, Particle size (D50) < 3.0 µm) and Cobalt ferrite (CFO, Particle size = 40nm) were purchased from Alfa Chemistry, NY. These titanate and ferrite particles were used to build piezoelectric and magnetostrictive layers, respectively, in the ferroelectric/ferromagnetic laminate (Fig.5c).

BST powder was ground using a mortar & pestle and few drops of 7% polyvinyl alcohol (PVA) solution was added as a binder. The mixed powders were preheated in air till it was completely dried and those dried powders were further ground. Using hydraulic equipment (Fred S. Carver Inc. hydraulic Lab Press), 250 MPa pressure was applied to compress the BST powders into BST pellets of 10 mm diameter and 0.3 mm thickness. The samples were then sintered at 1450 ºC for 2 hours (ramp rate of 2.5 ºC/min) inside the furnace. Similarly, under the application of same pressure but without adding any binder, CFO pellets were sintered at 1100 ºC for 2 hours (ramp rate of 2.5 ºC/min). Ti/Cu was coated on these ceramic pellets to achieve 2 functionalities - to create parallel-plate electrodes and facilitate bonding of ferroelectric and ferromagnetic layers using solder. E-beam evaporation technique (CHA evaporator) was used to deposit 500 nm of Ti/Cu at deposition rate of 2 Å/s on top and bottom of BST and CFO samples. Ti acts as interposed layer to improve copper adhesion to the ceramic. Thermally stable solder paste (Chip-Quick, Inc.) was used to bond the BST ceramic (coated with Ti/Cu) to CFO discs (coated with Ti/Cu). Fig. 5d shows the schematic of ferroelectric (BST) /ferromagnetic (CFO) laminate coated with Ti/Cu. Alignment tool (Shuttle Star BGA Rework Station, Precision PCB Services, Inc.) was used to attain the reflow profile of the solder paste. To investigate thermal tuning of permittivity of the dielectric, BST pellets were coated with silver ink and cured at 120 ºC for 10 minutes (Fig. 5a). Similar ferroelectric/ferromagnetic laminates of PZT and Metglas (Fig. 5f) was fabricated using appropriate proportions of liquid epoxy resin and hardener (WEST SYSTEM® 105 Epoxy Resin)

Using Scanning electron microscopy (JEOL 6330F: Field Emission SEM w/ EDS, Japan), investigation of surface morphology and compositional analysis of BST pellets were performed. Dielectric measurements (dielectric constant and dielectric loss (tan δ)) of the samples were performed using AGILENT E4980A Precision LCR Meter at 1 KHz frequency.

IV. Results and Discussions

The dielectric properties of BST substrate were studied as a function of temperature from 25 ^{O}C to 80 ^{O}C. The BST substrate, when it is unconstrained or free-standing, showed an increased relative permittivity with increasing temperature, which peaked at ~52 ^{O}C and then decreased with further temperature increment. We have observed that the relative permittivity at the transition temperature changes by 140% with respect to room temperature (Fig. 6 Left). Dielectric loss (tan δ) at the transition temperature is 0.05 and gradually decreases to 0.01 with increasing temperature. On the other hand, BST/Cobalt ferrite (CFO) stack, where the BST is constrained by bonding to CFO with a solder film, showed different dielectric constant behavior compared to free-standing BST. Free-standing BST showed negative coefficient of permittivity while the BST/CFO stack showed positive coefficient till about 90 ºC. At a fixed temperature of 90 ºC, permittivity increased by ~2.6× when the film is constrained. The dielectric constant of BST ceramic depends on many factors such as grain size, Ba/Sr content ratio [28], sintering temperature [29] and lattice strain. Compositional analysis from SEM (Fig. 5b) shows that our sample contains high Ba: Sr ratio (80:20). High Sr content changes the crystal structure into cubic and

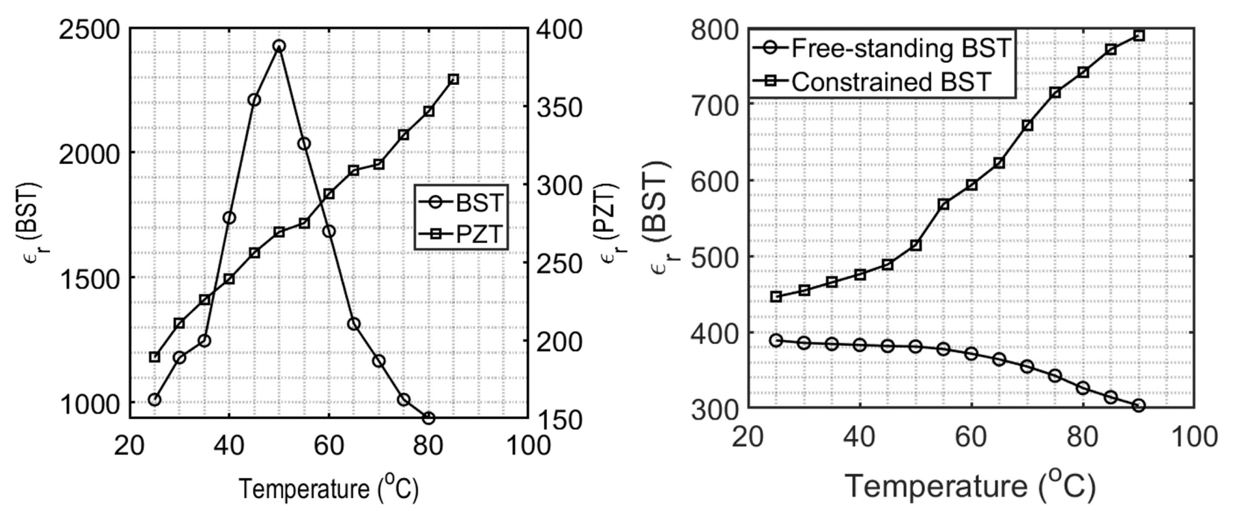

Figure 6. Variation of dielectric constant with different temperature at 1 KHz frequency for the BST (sintered at 1450 °C for 2 h) and PZT (Left); free-standing and constrained BST (sintered at 1100 ºC) (Right).

thus decreases the relative permittivity as the paraelectric cubic phase becomes more stable [28]. Since the only difference in the constrained and unconstrained films is the lattice strain, the behavior in Fig. 6 (Right) is attributed to the strain-induced changes in the multiferroic behavior.

The dielectric constant of ferroelectrics increases with temperature till the material reaches the Curie temperature (Tc) and then rapidly reduces with temperature. At the Tc, the dielectric constant is high as the phase transitions from tetragonal to cubic crystal structures. The phase transition temperature is usually modulated with the composition and results in a phase boundary between the asymmetric and the symmetric (cubic) phases, which is referred to as the morphotropic phase boundary (MPB). For example, the Tc of BST continually shifts from 390 K to 250 K with increasing strontium content. For the 20% Sr content that we utilized in this project, the Tc is ~52 ºC as seen in the thermal behavior of the dielectric constant. Easy polarization rotation and low energy barrier for switching result in the high dielectric constant and also good piezoelectric properties. Large piezoelectric response in such materials is, therefore, obtained by constructing compositions at multiphase boundaries, where nanoscale domains with local structural and polar heterogeneity are formed. Being close to the MPB, thus, gives new opportunities for tuning ferroelectric properties through lattice strains.

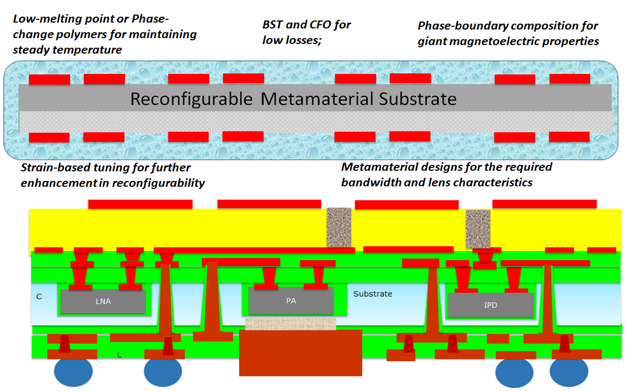

Figure 7. Giant reconfigurable metamaterial substrates based on engineered multiferroics.

Multiple reports demonstrate that the ferroelectric polarization can be further tuned by engineering the film deposition parameters for manipulating the lattice strain. For example, BST shows suppressed permittivity and tuning when subjected to tensile strains by constraining them on a low-CTE (coefficient of thermal expansion) substrate. For films that are constrained by a low-CTE glass, the annealing temperatures control the strains from the CTE mismatch, where higher annealing temperatures lead to more tensile strains. Strain-induced in-plane polarization could lead to larger variations in dielectric constant. Since strain-tuning is more tightly controlled, it can provide us ways to reconfigure the superstrate metamaterials. The same strain tuning can be created through magnetic fields. By utilizing magnetostrictive substrates to couple with ferroelectrics, it is possible to create giant magnetodielectric effects as illustrated by Wang et al. [30]. When ferroelectrics near the MPB are bonded to magnetostrictive materials, high dielectric tuning is achieved with weak DC magnetic fields of 10-20 Oe. With the strain-mediated multiferroic effects, the permittivity also changes quite dramatically at the electromechanical resonance frequency.

Structural control at nanoscale gives an additional handle and has been shown to result in 4-5× enhancement in properties compared to traditional ferroelectrics. Referred to as giant piezoelectric or magnetostrictive materials. Terfenol-D and Galfenol have high magnetostriction coefficients, making them extremely attractive to realize high magnetoelectric coefficients. Giant piezomagnetostrictive effects have also been shown in traditional magnetic materials but with nanoscale structures [31]. Introduction of rare earth dopants with the nanoheterogeneities is also known to produce giant magnetostriction [32]. All these material design parameters provide unique opportunities for reconfigurable metasubstrates using multiferroics. as described in Fig. 7. The recommended approach should, therefore, utilize: a) phase-changing low-melting point polymer environment to precisely control the temperature and maintain stable permittivity, b) a low-loss stack of multiferroics, c) compositions close to the morphotropic phase boundary for higher tunability, d) controlled thermal expansion mismatch to enhance giant tunability through strain-induced polarization, e) metamaterial designs for the bandwidth and tunability, with applied DC magnetic fields as needed. All these parameters will provide ample design space for future reconfigurable systems.

V. Conclusion

Magnetic field control of dielectric properties of multiferroic heterostructure laminates were investigated. First, we showed the strains induced inside a magnetostrictive material from magnetic fields. The strains were then transferred to the piezoelectric material and the resulting strain-induced polarization variation inside the piezoelectric material was studied. BST/CFO stacks were synthesized to study the dielectric tuning through strain modulation and temperature. A large variation in permittivity between the constrained and free-standing films is seen at a fixed temperature. The temperature dependence is also found to depend on the substrate strain. Such strains can be effectively created through small magnetic fields and can result in magnetically reconfigurable metasubstrates.

ACKNOWLEDGMENT

This project was funded by National Science Foundation (NSF), Grant number: 2029007 through its EArly-Concept Grants for Exploratory Research (EAGER) in Secure Analog-RF Electronics and Electromagnetics (SARE).

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