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## Multiferroic heterostructure fringe field tuning of meander line microstrip ferrite phase shifter

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Magnetic fringe fields emanating from a multiferroic heterostructure composite of Terfenol-D and lead magnesium niobate-lead titanate were utilized to actively tune a meander line microstrip ferrite phase shifter operating above ferrimagnetic resonance at C-band. Differential phase shifts of 65° were measured when tuned with an applied voltage to the multiferroic heterostructure. This demonstration of magnetoelectric field generation provides an alternative approach to tuning broadband planar microwave magnetic devices where neither strain nor direct electromagnetic coupling is experienced between device and multiferroic transducer. © 2010 American Institute of Physics. [doi:10.1063/1.3309592]

Ferrite phase shifters are recognized for superior insertion loss performance and microwave power handling capabilities. These devices are also highly reliable and radiation tolerant; a property of great value for space related applications. Ferrite phase shifters rely on electromagnetic wave propagation in low loss magnetic materials, such as yttrium iron garnet (YIG) and spinel ferrites typically substituted with nonferrous cations of lithium, magnesium, nickel, and zinc. Such devices require magnetic fields to bias and actively tune phase angle. These fields are conventionally generated by permanent magnets for static bias fields and current-driven coils for dynamic tuning. For operation at high frequencies (at or above x-band), permanent magnets are large, heavy, and costly. Tunable ferrite components, in addition to being comparatively large, experience high dc power consumption and slow response time due to the large inductance of current-driven coils. Improved response time and reduced dc power consumption is achieved in latching-type ferrite phase shifters where short current pulses are utilized to set the phase.

The primary application of phase shifters is in phased array radar systems that impose strict performance requirements in terms of insertion loss, power handling capability, response time, size, weight, and cost of components and assembly. In this letter, we propose an alternative approach to realizing high performance, compact, tunable, and low power consuming ferrite phase shifters based upon the following principles: (1) generation of tuning magnetic fields via low power multiferroic (MF) transducers, (2) a low bias field phase shifter design tunable with fields of (1), and (3) a planar and compact phase shifter and MF transducer design assuring penetration of the active region of the device with fields of (1).

The possibility of realizing voltage-tuned microwave devices, including phase shifters,<sup>1</sup> filters,<sup>2</sup> and resonators,<sup>3</sup> based on the converse magnetoelectric (ME) effect in stress coupled piezoelectric and magnetostrictive heterostructures has been demonstrated in recent years. Defined as the magnetic polarization induced by applied electric field, the con-

verse ME effect has received much attention<sup>4-7</sup> and yielded a number of microwave devices.<sup>1-3</sup> Thus far, the adaptation of the ME effect in microwave device design has been limited to introducing ferrite materials as the magnetostrictive component bonded to the piezoelectric substrate of the MF heterostructure. Application of an electric field across the piezoelectric acts to strain the ferrite and induce an internal magnetic field which can be expressed as<sup>8</sup>

$$\delta H_E = \frac{3\lambda Y d_{31} E_3}{M}, \quad (1)$$

where  $\lambda$ ,  $Y$ , and  $M$  are the magnetostriction constant, Young's modulus, and magnetization of the ferrite material, respectively, and  $d_{31}$  and  $E_3$  are the piezoelectric constant and electric field applied across the piezoelectric material, respectively. The induced internal magnetic field allows for variation in magnetic permeability required for tuning of a ferrite device. As evident from Eq. (1), the ferrite to be used in devices should exhibit a large magnetostriction constant. Unfortunately, most high quality microwave ferrite materials (i.e., those having low microwave loss) exhibit low magnetostriction. For example, YIG as well as M- and Y-type hexaferrites, are very weakly magnetostrictive and therefore the changes in their permeability spectra due to piezoelectrically induced strain are minimal. As such, microwave devices were previously designed to operate near ferromagnetic resonance (FMR) frequency where small magnetic fields induced, via the ME effect, resulted in sizeable variations in permeability. Taking into account the induced magnetic field in Eq. (1), the FMR frequency for a semi-infinite isotropic ferrite slab saturated in the plane is given by<sup>7</sup>

$$f_{\text{FMR}} = \gamma' \sqrt{(H + \delta H_E)(H + \delta H_E + 4\pi M_S)}, \quad (2)$$

where  $\gamma$  is the gyromagnetic ratio divided by  $2\pi$ ,  $H$  is the externally applied magnetic field, and  $M_S$  is the saturation magnetization. However, operation near FMR limits the bandwidth of devices and results in higher magnetic losses than in off-resonance operation mode. Following the aforementioned design approach, in this letter we demonstrate a voltage tunable ferrite device where the permeability is varied using *external* MF tuning elements and far from FMR in

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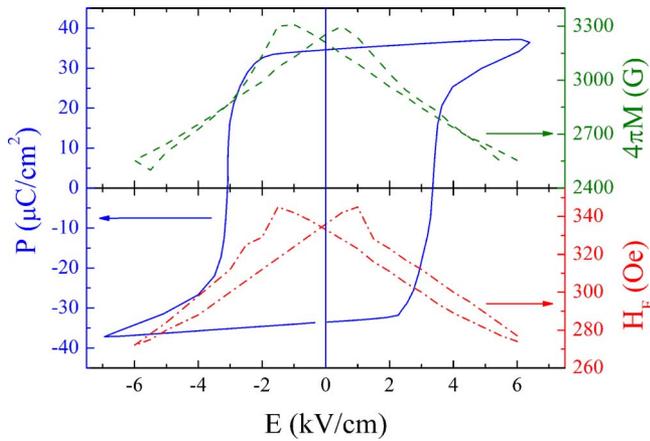


FIG. 1. (Color online) Ferroelectric hysteresis loop of the PMN-PT crystal with the electric field applied in the thickness direction (solid). Magnetization (dashed) and magnetic fringe field (dotted dashed) of the MF composite as a function of electric field at a fixed magnetic field of 200 Oe.

order to minimize propagation losses. Since the generation of the tuning field occurs outside of the ferrite, a highly magnetostrictive material can be utilized to perform this task. There is no strain being exerted on the ferrite itself, thus a low microwave loss and low magnetostriction material can be used.

The generation of static and alternating voltage tunable magnetic fringe fields using MF heterostructures, and their application in the development of an electromagnetic control device, has previously been demonstrated.<sup>9</sup> Here, we employ a similar transducer structure consisting of a terbium dysprosium iron intermetallic (Terfenol-D) slab affixed to a lead magnesium niobate-lead titanate (PMN-PT) single crystal to tune a meander line microstrip ferrite phase shifter designed to operate above FMR at C-band on a polycrystalline YIG substrate. Thus, a high frequency of operation is achieved by utilizing a transducer that generates a dc magnetic field outside the ferrite device. The transducer structure consists of a 15 mm long, 10 mm wide, and 1 mm thick Terfenol-D slab sandwiched between two PMN-PT crystals of the same dimensions. PMN-PT crystals with sputter-deposited gold electrodes on both faces were poled along the  $\langle 011 \rangle$  direction, perpendicular to the slab plane. A typical ferroelectric hysteresis loop is shown in Fig. 1. The PMN-PT crystals were bonded to both sides of the Terfenol-D slab using cyano-acrylate based adhesive with the poling directions aligned antiparallel to each other. Leads were attached to the outer PMN-PT surface electrodes and the electrically conducting Terfenol-D slab using low temperature solder.

The dependence of the magnetization of the composite on applied electric field was studied by vibrating sample magnetometer (VSM) measurements at a fixed magnetic field of 200 Oe. A butterfly shaped curve, as shown in Fig. 1, was measured. The shape of the curve is determined by the hysteretic dependence of the strain in the piezoelectric crystals on applied electric field. Electric field tunability of the magnetization was estimated from Fig. 1 to be 24.5%. The magnetic fringe fields emanating from the MF composite were investigated in the same measurement setup by disabling VSM vibration drive and attaching a Hall probe to the edge of the composite. The magnitude of the magnetic fringe field as a function of applied voltage at a fixed bias field of 200 Oe is shown in Fig. 1. The magnetic fringe field varied

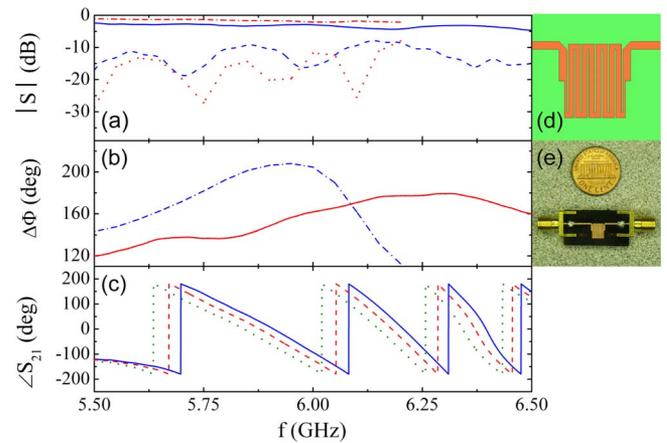


FIG. 2. (Color online) (a) Calculated (dotted dashed) and measured (solid) insertion loss. Calculated (dotted) and measured (dashed) return loss. (b) Calculated (dotted dashed) and measured (solid) differential phase shift. (c) Measured insertion phase at an applied electric field of 0 (solid), 3 (dashed), and 6 (dot) kV/cm. (d) Finite element model of the microstrip circuit. (e) Fabricated device with coaxial edge mount SMA connectors.

from 350 to 270 Oe as a function of applied electric field, corresponding to tunability of 21.2%. Therefore, when in close proximity to a magnetic device, the magnetic fringe fields emanating from the MF composite are expected to provide a static component that can be used to bias the magnetic device and a voltage tunable dynamic component that can be used to tune device performance. Based on this principle, we now turn our attention to the development of a voltage tuned ferrite phase shifter device.

Meander line ferrite phase shifters have been developed for microwave integrated circuit applications.<sup>10</sup> A meander line microstrip phase shifter on a YIG substrate was designed and simulated using finite element methods. The outline of the microstrip circuit in the finite element model is shown in Fig. 2(d). The calculated scattering parameters of the five element meander line circuit are shown in Fig. 2(a). The insertion loss and return loss were calculated to be 1.8 and 20 dB, respectively, at the C-band center frequency of 6 GHz. The center frequency was designed to occur above ferromagnetic antiresonance (AFMR) frequency given by<sup>11</sup>

$$f_{\text{AFMR}} = \gamma'(H + 4\pi M_s), \quad (3)$$

where the frequency dependent permeability varies gradually allowing broadband operation. Operation above AFMR can only be achieved with external magnetic field tuning. Differential phase shift was calculated by subtracting the insertion phase at zero internal field from the insertion phase at 100 Oe internal field. The results are shown in Fig. 2(b). A differential phase shift of  $210^\circ$  was calculated at the design frequency.

A prototype phase shifter device was fabricated on a polycrystalline YIG substrate with a thickness of 1 mm using conventional photolithographic techniques. Saturation magnetization, dielectric constant, dielectric loss tangent, and 3 dB FMR linewidth were 1785 G, 14.95,  $<1 \times 10^{-4}$ , and 25 Oe, respectively. Edge mount subminiature version A (SMA) connectors were attached to the device using low temperature solder, as shown in Fig. 2(e). Scattering parameters of the device were measured by a vector network analyzer as a function of magnetic field applied in the ferrite substrate plane and along the meander line elements direction with an

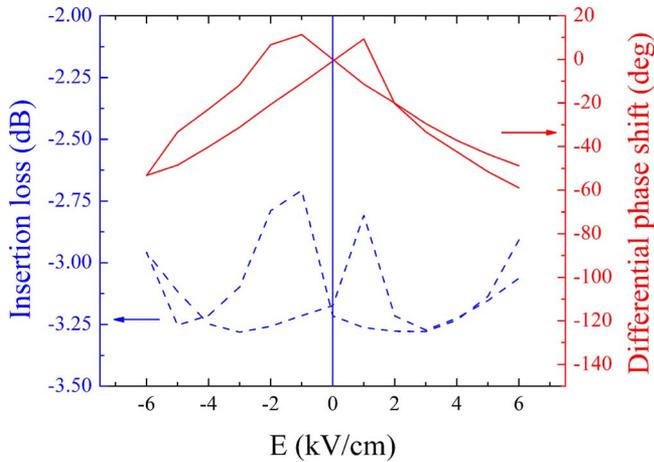


FIG. 3. (Color online) Differential phase shift (solid) and insertion loss (dashed) at 6 GHz as a function of applied electric field.

electromagnet. Measured insertion and return loss spectra are superimposed with calculated spectra in Fig. 2(a). At the frequency of 6.3 GHz, the insertion loss and the return loss were measured to be 3.2 and 13 dB, respectively. A differential phase shift of  $180^\circ$  was measured at 6.3 GHz. The phase shift was accrued over a substrate area of approximately  $5 \times 5 \text{ mm}^2$  at 6 GHz, a highly desirable performance in practical, size constrained applications. Out of the 3.2 dB of insertion loss, 0.5 dB is attributed to impedance mismatch loss. The remaining difference of approximately 1 dB between calculated and measured insertion loss at the design frequency, as well as the difference in peak value and frequency of maximum differential phase shift is attributed to connector effects, imperfections associated with the device fabrication process, and variations in the material properties from those assumed in the finite element model.

Voltage tuning of the meander line ferrite phase shifter was realized by assembling the device with two MF composites such that the Terfenol-D slabs were coplanar with the YIG substrate. This allowed the YIG substrate to be penetrated by the voltage tunable magnetic fringe fields emanating from the MF composites without experiencing any strain or microwave electromagnetic coupling. A magnetic bias field of 200 Oe was applied along the length direction of the MF structure, and along the meander line elements, by an electromagnet. The contribution of the MF composites to the insertion loss was on average less than 0.2 dB. The magnetic fringe field was non-uniform and varied from 330 Oe near the edge of the 1.3 cm YIG substrate to 210 Oe near the center. The insertion phase of the device was monitored with a vector network analyzer as a function of electric field applied to the ME composites [Fig. 2(c)]. As the electric field increased from 0 to 6 kV/cm, a linear phase shift of more than  $65^\circ$  was observed. This phase change is due to the fact that the magnetic fringe fields emanating from MF composites vary by approximately 20% with applied electric field (see Fig. 1). The variation in the insertion loss and differential phase shift of the device as a function of applied electric field at a fixed frequency of 6 GHz is shown in Fig. 3. Both sets of data exhibit a hysteretic dependence on electric field.

The asymmetric nature of these curves is attributed to the superposition of magnetic field dependent scattering parameters of the device with hysteretic dependence of the magnetic fringe field of the MF transducer on applied electric field (see Fig. 1). These results demonstrate the potential of MF composites as external tuning elements for microwave magnetic devices.

The performance of the MF fringe field tuned phase shifter device is compared with previously published results<sup>1</sup> on a strain tuned phase shifter device utilizing a MF composite consisting of a 124  $\mu\text{m}$  thick epitaxial YIG film on a 0.5 mm thick gadolinium gallium garnet substrate bonded directly to a 0.5 mm thick lead zirconate titanate. In the latter case the tuning was achieved by inducing an internal magnetic field in the YIG film via piezoelectric strain. For the device in Ref. 1, linear phase shifts up to  $90^\circ$  were achieved over a bandwidth of approximately 5 MHz centered near 9.616 GHz with the YIG film biased near FMR with an external magnetic field of 2720 Oe. In contrast, linear phase shifts up to  $65^\circ$  were demonstrated in the present work over a bandwidth of  $>500$  MHz centered at 5.95 GHz [see Fig. 2(c)] with an external magnetic field of 200 Oe. Comparable insertion loss performance was reported for both devices. It is noted that in the nonlinear operation mode phase shifts up to  $180^\circ$  were reported in Ref. 1 over a bandwidth of approximately 10 MHz. Accounting for the difference in operating frequency using Eq. (2), key advantages of the MF fringe field tuned phase shifter device include a reduction in magnetic field requirements by a factor of 7 and an increase in bandwidth by a factor of 100. The difference in the amount of peak linear phase shift ( $25^\circ$ ) can be compensated by utilizing more than five meander elements.

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