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14. ABSTRACT

This project was on dual electric and magnetic field tunable miniature, rapid-response, frequency agile resonators, filters, phase shifters, and delay lines for use in communication devices and the next generation of phased array radars for Naval systems over the frequency range 1-67 GHz. The efforts involved layered ferrite-ferroelectric composites. Anticipated impacts of this research are new technologies for reception and processing of EM signals and a path toward dominance of the EM spectrum.

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FINAL REPORT

Electric Field Tunable Microwave and MM-wave Ferrite Devices
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Period of Performance: **May 1, 2006 – April 30, 2010**

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Summary

This project was on miniature, rapid-response, frequency agile signal processing devices for use in communication devices and the next generation of phased array radars for Naval systems over the frequency range 1-67 GHz.

The efforts involved multiferroic composites consisting of ferrites and ferroeleectrics. When such composite is subjected to an electric field *E*, the mechanical deformation due to piezoelectric effect manifests as a *frequency* shift in the spin wave spectrum or ferromagnetic resonance (FMR) for the ferrite. The traditional *magnetic field* tuning of FMR based ferrite devices is slow, noisy, and requires large power. In contrast, *E*-tuning is much faster, less noisy, and has practically zero power consumption. Such devices can easily be miniaturized and integrated with semiconductor devices.

Layered composites of yttrium iron garnet (YIG), nickel zinc ferrite, or barium ferrite for the magnetic phase and lead zirconate titanate (PZT), lead magnesium niobate-lead titanate (PMN-PT) or barium strontium titanate (BST) were studied. The magneto-electric (ME) coupling strength was measured from frequency shift in magnetic modes as a function of *E*. The coupling was strong and ranged from 1 to 30 MHz/(kV/cm). Ferrite-ferroelectric composites were used in microwave and mm-wave devices for studies on dual *E* and *H*-tuning. The following devices were designed and characterized:

Ferromagnetic resonance/magnetostatic wave based devices: Resonators, filters, phase shifter and attenuators.

Hybrid wave devies: Resonators and phase shifters.

Device characterization included E-tunability, tuning speed and insertion loss. FMR based devices, in general, were found to have low losses, high Q and high figure-of-merit.

Anticipated impacts of this research are new technologies for reception and processing of EM signals and a path toward dominance of the EM spectrum.

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1. Multiferroics for High Frequency Devices

Composites of ferromagnetic and ferroelectric materials are magnetoelectric multiferroics and have enormous potential for novel device applications. Figures 1 and 2 show schematic representations of electric-and-magnetic subsystem couplings mediated by mechanical forces in such a composite material. Thus one can control electromagnetic properties of a ferromagnet-ferrelectric composite with an electric field E across the ferroelectric and/or a bias magnetic field H.

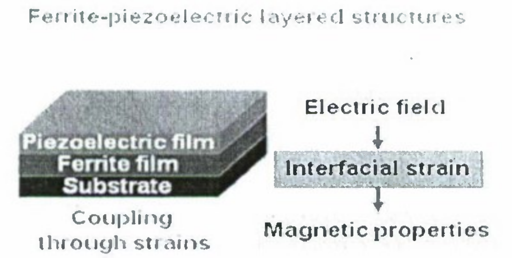

Fig.1: Electric field control of electromagnetic properties of a ferrite-piezolectric material. The control is through mechanical forces.

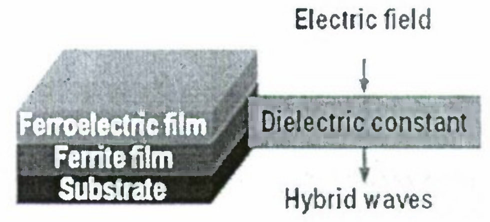

Fig. 2: Electric field control of hybrid spin-electromagnetic waves. Tuning through changes in dielectric constant.

A research program at Oakland University, funded by the ONR since 2005, focused on ME effects at microwave and millimeter wave frequencies in ferrite-ferroelectric composites. Studies were performed on basic physics and device concepts related to two important effects: (i) ME coupling between *bound* layers influencing the frequency of ferromagnetic resonance and (ii) ME coupling between *unbound* layers leading to the creation of hybrid spin-electromagnetic waves. The ME effect can be observed in the form of a shift in ferromagnetic resonance (FMR) profile for the ferrite, or frequency of hybrid spin-electromagnetic waves. Device works involved dual tunable components using bound and unbound ME structures.

During the past four years, we demonstrated several YIG-PZT, YIG/PMN-PT, YIG-BST and barium ferrite (baM)-PZT 1-67 GHz devices including [1-12] *high-Q resonators, band-pass filters, phase shifters, and delay lines. The novel feature in all of the above devices is the electric field or voltage tunability. Magnetic field tuning of ferrite devices is often slow, noisy, and requires W or kW power for operation. Such devices cannot be miniaturized or integrated with semiconductor processing technologies. But electric field tuning will be rapid, less noisy, requires minimal power and the devices can be miniaturized. Efforts focused on FMR-based devices using bonded YIG-piezoelectric bilayers and hybrid wave devices in unbounded YIG-BST.*

2. Studies on strength of high frequency magneto-electric (ME) coupling

In the microwave region of the electromagnetic spectrum, the ME effect can be observed in the form of a shift in FMR profile in an external electric field E. The response can be measured with a microstripline device similar to the one shown in Fig. 3 and a YIG/PMN-PT bilayer. Mechanical stress in the PMN-PT layer due to the electric field is coupled to the ferrite, and this leads to a shift δH_E in the FMR resonance field.

Figure 4 shows FMR profiles and the resonance frequency shift as a function of E for a bilayer of epitaxial YIG film and PMN-PT single crystal. This ME shift is determined by piezoelectric coupling, taken as d, and the magnetostriction λ. A large d and a large λ lead to a strong electric field induced shift. The ME coupling coefficient A = $\delta H_E/E$ was in the range 1-30 MHz cm/kV depending on the choice of ferrite and piezoelectric layers, volume fraction for the two phases. The data in Fig. 4 also provide the basis for a wide variety of *electric field tunable* FMR-based and spin wave based YIG signal processing devices.

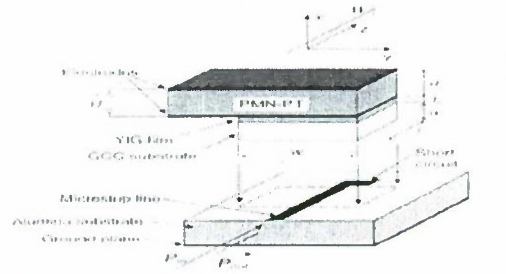

Fig.3: Stripline structure used for measurements of ME interactions in YIG/PMN-PT bilayer [13].

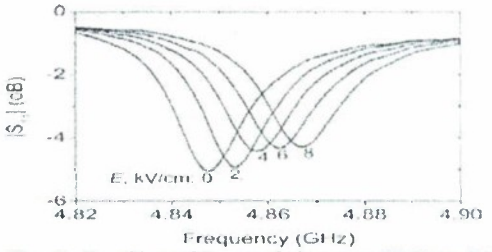

Fig.4: Profiles of S_{11} vs. f showing FMR in YIG and frequency shifts in FMR due to E applied to PMN-PT. [13]

3. Hybrid spin-electromagnetic modes

The ME effect discussed above takes place in bilayered ferrite-ferroelectric structures when the layers are tightly bound i.e. when the mechanical stress created in one layer is transferred to the neighboring layer. There are, however, other ME phenomena that do not require bonding between the layers and take place simply due to the proximity of two material having different dielectric and magnetic properties [14]. An example of such a phenomenon is the formation of hybrid spin-electromagnetic waves in the layered structures. The hybrid modes and their tunability with E were studied in a YIG-BST structure (Fig.6). We also developed a theory for hybrid waves in YIG-BST [14].

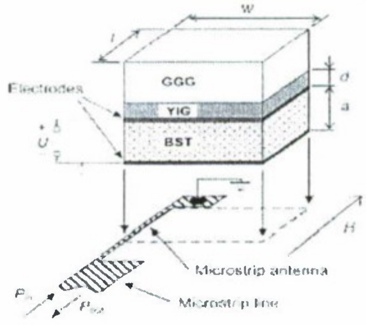

Fig.5: Stripline structure for studies on hybrid mode formed by overlap of FMR in YIG and dielectric resonance in BST [14].

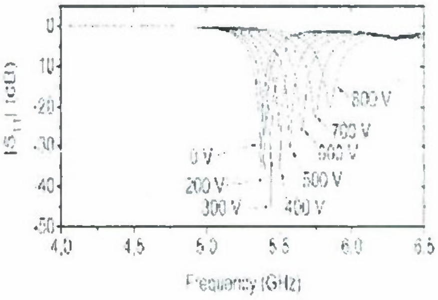

Fig.6: Hybrid-mode in YIG/BST and tuning with a voltage applied to BST [14].

4. Dual E- and H-tunable multiferroic devices

Ferrites are materials of choice in traditional tunable reciprocal and non-reciprocal microwave devices. The tunability is realized through the variation of a bias magnetic field H that could be achieved in a very wide frequency range, but it is relatively slow and is associated with large power consumption. Similar tunable microwave devices could be obtained with ferroelectrics in which tuning is realized through the variation of E. This "electric" tuning is possible in a relatively narrow frequency range, but it is usually faster and consumes less power than "magnetic" tuning. A combination of ferrite and ferroelectric materials in a layered or composite structure therefore, could potentially enable simultaneous "magnetic" and "electric" tuning with the advantages of both tuning methods.

Next we discuss FMR-based on hybrid wave multiferroic devices.

4.1: Dual tunable FMR devices

Resonators, filters and phase shifters are critical components in phased array radars and high frequency communication devices. Results of studies on such device components with the use of layered ferrite-piezoelectrics are discussed here.

***(a) Resonators*:** Figure 7 shows a YIG-PZT resonator and Fig.8 shows its response for *an electric field across PZT*: a shift δf_E is seen with the application of E. The tuning obtained here is 5-times the width of FMR in YIG and is suitable for device applications. The resonator Q is on the order of 1000-5000, depending on the frequency, and the figure-of-merit (FOM) = $\delta f_E/\Delta f$ (Δf = 3-dB width of FMR) is 100. For comparison, Q = 100 and FOM = 10 for BST resonators.

The data in Fig.8 are for an epoxy bonded bilayer. *With proper choice of the piezoelectric phase, a tuning range of 0.5-1 GHz is quite possible for heteroepitaxial YIG-PZT or YIG-PMN-PT bilayers.*

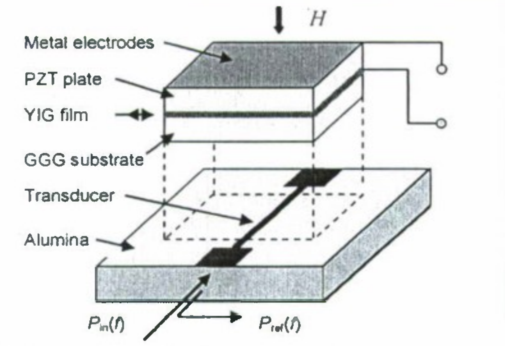

Fig. 7: A YIG-PZT resonator. [6]

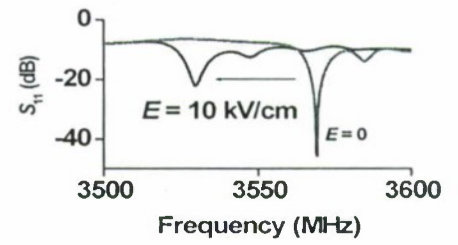

Fig. 8: Electric field tuning of resonator in Fig.7(for H = 3010 Oe perpendicular to the sample plane). The frequency shift is -50 MHz for E =10 kV/cm. [6]

(b) Filters: The single-cavity ME filter, shown in Fig. 9, consists of a 1 mm thick dielectric ground plane (permittivity of 10), input and output microstrips of nonresonance lengths, and an ME-element. Power is coupled from input to output under FMR in the ME element. The ME element consisted of epitaxial YIG film bonded to PZT. A 110 μm thick YIG film grown by liquid-phase epitaxy on a (111) gadolinium gallium garnet was used. A PZT plate with the dimensions 4×1×0.5 mm^3 was initially poled by heating up to 150 °C and cooling back to room temperature in an electric field of 10 kV/cm perpendicular to the sample plane. The layered structure was made by bonding the YIG film surface to PZT with 0.08 mm thick layer of ethyl cyanoacrylate, a fast-dry epoxy. The layered structure was placed between of the transducers as in Fig. 9 and was subjected to a field H parallel to the sample plane and perpendicular to the microstrips.

An input continuous-wave signal $P_{in}(f)$ =1 mW was applied to the filter. The frequency dependence of the insertion loss L, i.e., the transmitted power through the ME element, was measured at 4-10 GHz as a function of H and E applied across the PZT layer. Representative results are shown in Fig. 10. Consider first the profile for $E = 0$. The maximum input-output coupling is observed at f_r = 6.77 GHz that corresponds to FMR in YIG. The loss increases sharply below f_r and the off-resonance isolation is 20-25 dB. A significant modification of frequency dependent L profile is observed when E = 1 kV/cm is applied across PZT. f_r is down-shifted by 28 MHz. Further increase in E results in increase in the magnitude of the down-shift as shown in Fig. 10. *This filter can be tuned by 2% of the central frequency with a nominal electric field of 3 kV/cm. Most applications in phased arrays need tuning by 1%.*

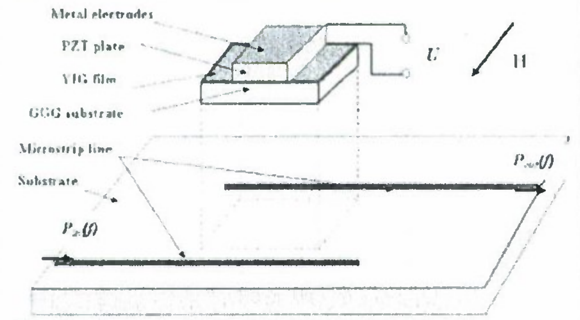

Fig. 9: A magnetoelectric (ME) band-pass filter. The resonator consisted of a 110 μm thick (111) YIG on GGG bonded to PZT.[8]

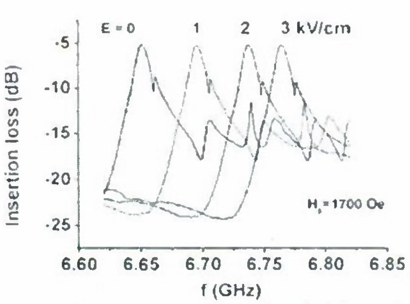

Fig. 10: Data on electric field tuning characteristics of the filter in Fig. 9.[8]

***(c) YIG-PZT FMR Phase Shifter*:** Figure 11 shows a Faraday-rotation multiferroic phase shifter that operates just above FMR in YIG. The aim is to achieve a large change in the permeability μ' and, therefore, a differential phase shift ϕ when the PZT is subjected to a voltage. For the device shown in Fig. 11 we were able to obtain a phase change of 180^0 for nominal electric fields (Fig. 12). *The insertion loss was quite small, on the order of 1.5-4 dB.*

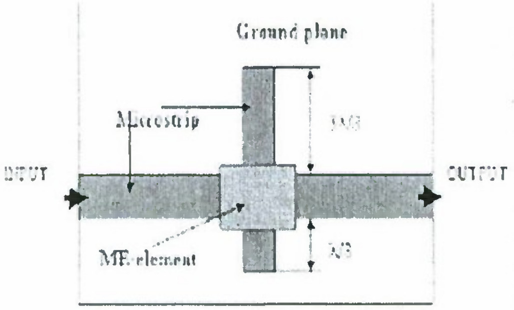

Fig. 11: Diagram showing the schematics of a YIG-PZT phase shifter.

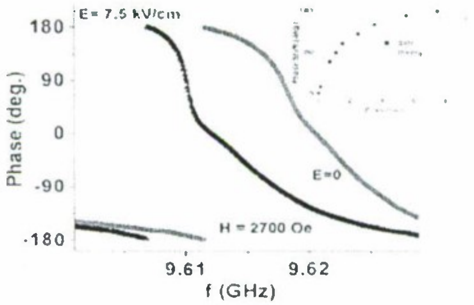

Fig. 12: The phase angle ϕ vs. frequency f at 9.6 GHz for E = 0 and 7.5 kV/cm.

It is clear from these studies that the ferrite-piezoelectric devices have insertion loss and tuning characteristics generally superior to competing technologies. Thus expensive rf amplifiers and solenoidal magnets for tuning in phased array radars could potentially be eliminated with the use of voltage tunable ferrite-ferroelectric components.

4.2: Hybrid wave devices

Another class of devices studied under this program was based on hybrid spin-electromagnetic waves in *unbounded* ferrite-ferroelectrics. Resonators and phase shifters of hybrid waves were investigated.

(a) Resonators: A novel microwave resonator of YIG and BST films in a slotline was studied (Fig.13). It consisted of a slot transmission line of width ~ 150 micron and length 20 mm. An YIG film, 6 μm thick, 0.5 mm in width and 2.5 mm long, grown on a 0.5 mm thick gadolinium gallium garnet substrate was used. The electrodes of slotline played the dual role of the waveguide structure and electrodes for voltage tuning. Films of the composition $Ba_{0.5}Sr_{0.5}TiO_3$ was deposited on a sapphire substrate by RF-sputtering. The YIG-film straight-edge resonator was placed in a tangential bias magnetic field. The resonator frequency characteristics shown in Fig.14 were measured for zero bias electric field (E) and for E = 5 V/μm. The observed frequency shift of ferromagnetic resonance in YIG was about 75 MHz under the action of the electrical field. The resonator Q-factor was about 300 and was stable with any electric field variation. The slotline construction has the advantage of integrated topology, when YIG-BST thin-film layered structure could be grown on a dielectric substrate, for incorporation in planar integrated circuits.

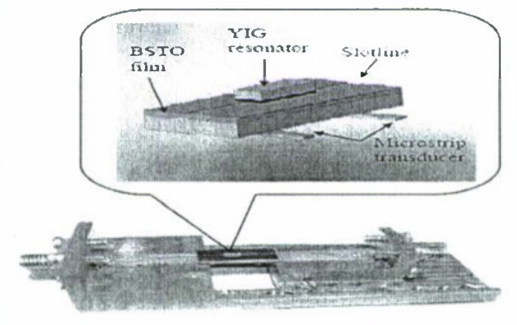

Fig.13: A schematic diagram showing the YIG film resonator on a BST film-slotline structure. [15]

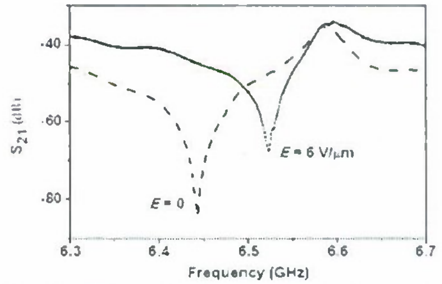

Fig.14: The scattering parameter S_{21} vs. f profiles for the hybrid wave resonator for bias electric fields of 0 and 5V/μm. [15]

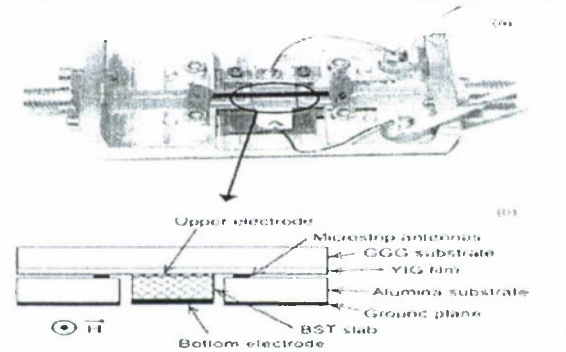

Fig.15: YIG-BST phase shifter [16].

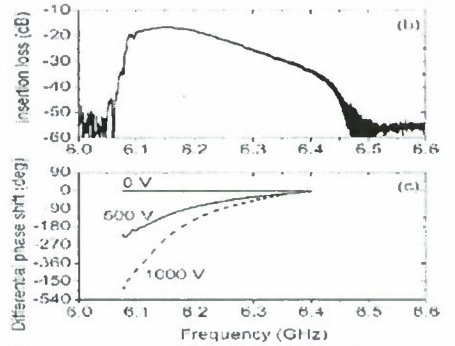

Fig.16: Insertion loss and differential phase shift for the device in Fig.14. [16]

(b) Phase shifters: A dual, electric and magnetic field tunable microwave phase shifter (Fig.15) based on the propagation of hybrid spin-electromagnetic waves in a ferrite-ferroelectric bilayer was fabricated and characterized. The bilayer consists of a single-crystal yttrium iron garnet film and a ceramic barium strontium titanate slab. The electrical tunability of the differential phase shift Δφ is achieved through the application of a voltage across BST. An insertion loss of 20 dB and a continuously variable Δφ as high as 650 degrees in the frequency range of 4.5-8 GHz were measured (Fig.16).

5. Millimeter-wave ME effects and devices

Millimeter-wave magnetoelectric (ME) interactions were studied through electric field effects on magnetic excitations in bilayers of single crystal barium ferrite and PZT. Barium hexaferrite $BaFe_{12}O_{19}$ with M-type structure (BaM) and piezoelectric bilayers are appropriate for studies on millimeter wave ME interactions. Since BaM has high uniaxial anisotropy fields H_A of 17 kOe, FMR and magnetic excitations can be observed in the frequency range 47-60 GHz for external fields H_0 = 5-9 kOe. Studies were performed on bilayers of single crystal BaM prepared by floating zone method and polycrystalline PZT. The measurement cell is shown in Fig.17 and consists of a coaxial-to- (WR-17) waveguide adapter. The bilayer was prepared from a BaM single crystal plate and was bonded to PZT. The silver electrode at the BaM-PZT interface acted as a classical short load of the waveguide. Figure 18 shows representative data on S_{11} vs.f. One observes an absorption peak for H_o = 5980 Oe and E = 0 that is identified as electromagnetic modes in BaM. With the application of E = 10 kV/cm, the mode frequency is shifted by 8 MHz. The effects were utilized to fabricate and characterize mm-wave resonators and phase shifters.

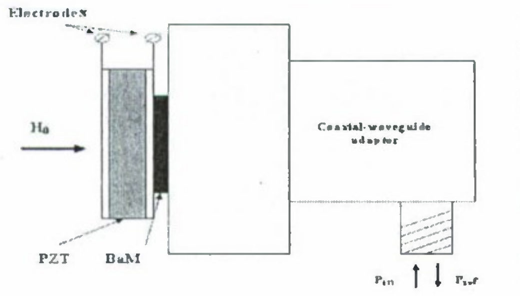

Fig.17: Diagram showing the cross section of measurement cell with a coaxial-to-waveguide adapter and a bilayer of PZT and single crystal barium ferrite (BaM).[17]

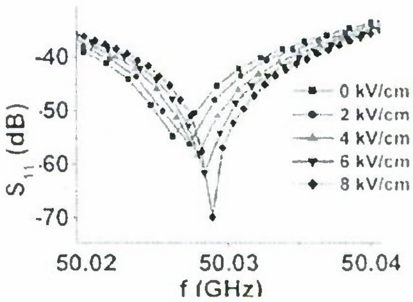

Fig.18: Electric field effects on a magnetic mode in BaM. [17]

6. Concluding Remarks and Future Directions

Investigations on microwave and mm-wave magneto-electric interactions in layered composites of ferrite and piezoelectrics show coupling strength on the order of 1-5 MHz/(kV/cm). The coupling is strong enough for realizing electric field or voltage tunable ferrite resonator, filter and phase shifter. The insertion losses for the devices are of the same order as for pure ferrite devices. But the E-tuning is fast, less noisy and the devices can be miniaturized. There is of course need for a bias magnetic field that can be provided with a permanent magnet.

Much work is needed if the multiferroic composites are to become viable components in real systems. The devices and composites described here can also serve as an ideal "test bed" for the selection of materials and device configurations for the full range of electric field tunable FMR and spin wave devices enumerated above. There are, for example, several issues:

(1) Options for different magnetic film components: Substituted YIG films can be used with higher magnetizations to cover different frequency ranges. Different substitutions also can give more or less of a ME interaction and better or worse tuning. Zinc substituted spinel ferrite can be used to achieve very high magnetizations for the low millimeter wave frequency range, and hexagonal ferrite films can be used for frequencies up to 100 GHz or so.

(2) Options for different piezoelectric and ferroelectric layer components: There are many other options for the electric layers, including single crystal PZT-PT and barium titanate.

(3) Interplay of magnetic/electric/interface properties, loss and high power capabilities: Electric field tunability of FMR and spin wave devices may come at a price. It is clear that there will be interface modes. In the case of layered devices, these effects can be controlled to some extent through the use of different bonding methods and materials.

(4) Tuning: It is well known that for basic magnetic film FMR and spin wave based microwave devices, one can also tune the frequency of operation by changing the direction of the field relative to the film plane or the direction of spin wave propagation. It is known that the magnetic loss can depend on the field orientation. The effect of field orientation on the ME coupling and the tunability remain to be determined.

(5) Speed of tuning: The obvious advantage of electric field tunability is speed. What are the limits? How can they be achieved in a useful device? What if the electric field tunability could be as fast as the microwave signal itself? This could lead to an entire class of completely new devices.

(6) Heteroepitaxial ferrite-piezoelectric structures: Finally, one needs to synthesis ferrite single crystal films on ferroelectric substrates to realize strong ME coupling for device use. Since one requires ferrites films of thickness on the order of skin depth, techniques such as MBE are not appropriate for growing 1-100 μm thick films. Techniques such as LPE, MOCVD or electro-deposition need to be considered for the growth.

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