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COUPLING OF LAMB WAVES AND SPIN WAVES IN MULTIFERROIC HETEROSTRUCTURES

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INTRODUCTION

Circulators, isolators, phase shifters, and other devices that leverage the unique interactions of electromagnetic waves with magnetic materials are pervasive throughout telecommunication systems [1]. Despite decades of miniaturization of radio frequency electronics, these magnetic components have not seen nearly as dramatic of a size reduction and currently are the bulkiest components in radio frequency front ends [2]. Since these devices rely on the interactions of electromagnetic waves with magnetic materials, their dimensions must be on par with the electromagnetic wavelength in order to have any appreciable affect.

Magneto-acoustic devices offer a route for the miniaturization of magnetic devices used in telecommunication systems by instead leveraging the interactions of acoustic waves with magnetic materials. Due to the five orders-of-magnitude reduction in wave speed between the speed of light and the speed of acoustic waves, utilizing magneto-acoustics will lead to dramatic size reduction in device characteristic length.

To enable these magneto-acoustic devices, a new class of devices called multiferroic devices can be leveraged [3]. These devices couple magnetostrictive and piezoelectric materials through strain to enable electric field control of micro-magnetic devices. Work in micro-scale magneto-acoustics has predominantly been focused on multiferroic surface acoustic wave (SAW) devices [4, 5]. In these devices the strains are practically uniform with respect to the magnetic interaction lengths within the magnetic material, meaning uniform magnetic modes are generated. However, if magneto-acoustic devices are to reach higher frequencies, shorter wavelengths must be used and this results in nonuniform strains and coupling to nonuniform magnetic modes, called spin waves. As first steps towards high frequency magneto-acoustic devices, this work presents the first measurement of spin wave damping in a multiferroic Lamb wave device. ***The significance of this result is that it experimentally shows, for the first time, the dependence of acoustic wave/spin wave coupling in multiferroic acoustic devices on external magnetic fields***.

BACKGROUND

Work in acoustic wave interaction in magnetic thin-films has predominantly been focused on multiferroic surface acoustic wave (SAW) devices [4, 5]. In these devices, the thickness of the magnetic films is a small fraction of the acoustic wavelength and substrate thickness. In this regime, the strain throughout the magnetic film is practically uniform with respect to the thickness and magnetic interaction lengths of the magnetic thin film. The effective field from this strain thus actuates the uniform precessional mode, known as ferromagnetic resonance, in the magnetic layer.

In structures where the magnetic material is a significant portion of the device cross section and wavelengths are short, such as high frequency composite Lamb wave devices, the strains can no longer be assumed to be uniform and ferromagnetic resonance is no longer accessible. Instead nonuniform oscillations of magnetization, called spin waves, are excited. Spin wave modes have many unique properties that are not present in ferromagnetic resonance, namely that the magnetic field required for the existence of the spin wave mode, for a fixed wave number and frequency, is strongly dependent on the angle between the spin wave propagation direction and the DC magnetic field present in the sample (Fig. 1), as shown by the equation below [6].

$$\omega = \gamma\mu_0 H_{bias} + \eta k^2 + \tfrac{1}{2}\gamma\mu_0 M_s \cdot \sin^2\theta \qquad (1)$$

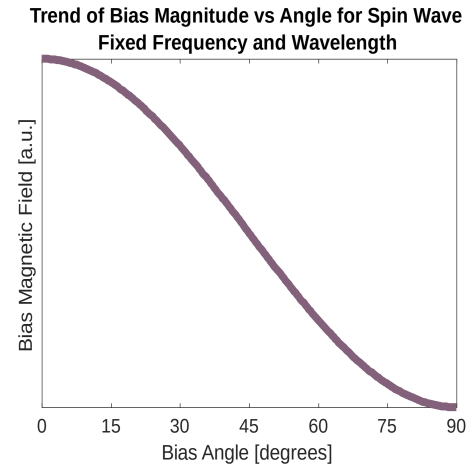

Figure 1: Analytical model for dependence of the magnetic bias needed for the existence of a spin wave mode as a function of the angle between the bias magnetic field and the spin wave propagation direction. Calculation done for fixed frequency and wavelength for the spin wave.

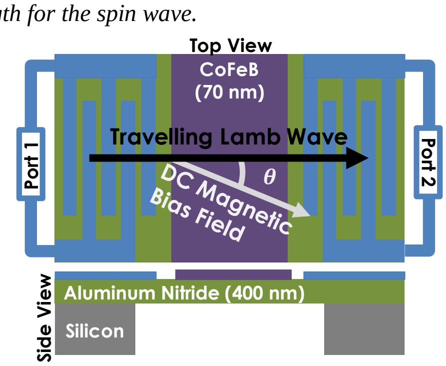

Figure 2: Schematic of Lamb wave device used for characterization. The angle between the acoustic wave propagation direction and the DC magnetic field applied by the electromagnet is shown as θ.

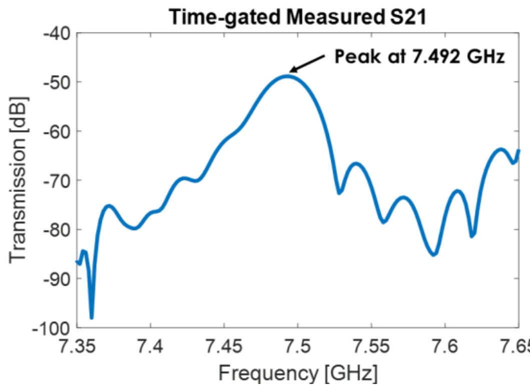

Figure 3: Frequency response of Lamb wave device in vicinity of the testing frequency. The frequency response is time-gated by the PNA-L to minimize the effect of electromagnetic feedthrough and acoustic echoes.

Here ω is the angular frequency, γ is the gyromagnetic constant, H_{bias} is the angle of the DC bias field, η is the exchange constant, k is the wave number, and M_s is the saturation magnetization.

EXPERIMENT

To investigate coupling of spin waves with acoustic waves, Lamb mode waveguides are fabricated, with 400 nm of aluminum nitride serving as our piezoelectric layer and 70 nm of CoFeB serving as our magnetostrictive layer (Fig. 2). As the magnetostrictive layer is a significant portion of the device cross section, strains can no longer be assumed uniform, and this results in nonuniform driving fields within the magnetostrictive material.

To further enhance the nonuniformity of the strain fields, the device is run at a high harmonic to shorten the wavelength. For this experiment, a mode at approximately 7.5 GHz is chosen (Fig. 3). At this frequency the Lamb wave wavelength is approximately 2 µm, which is close to what is expected for the spin waves.

The Lamb mode devices are placed in an electromagnet, which applies a DC bias field to the device at several different magnitudes and angles to tune the frequencies of the spin wave modes in the CoFeB layer. At each combination of magnetic field magnitude and angle, the device frequency response is measured using a PNA-L network analyzer.

RESULTS

Shown in Figure 4 is a representative plot from the experiment. As the magnetic field is increased, eventually the spin wave matches the acoustic wave in wavelength and frequency. This leads to increased damping of the acoustic wave as energy is dissipated by the spin wave. The DC magnetic field at which this maximal damping point is measured for each angle of the experiment is plotted in Figure 5. As the angle of the magnetic field increases, the bias field of the maximal damping point decreases, which is the same trend as predicted by theory (Fig. 1). ***This is in stark difference with previous work in surface acoustic wave excitation of uniform precessional modes, where the DC bias field to align the uniform precessional mode frequency with the acoustic mode show no dependence on the angle*** [4 ,5]. These findings are key to the realization of high frequency micro-scale magneto-acoustic devices where the short acoustic wavelengths necessitate coupling to spin wave modes instead of uniform modes.

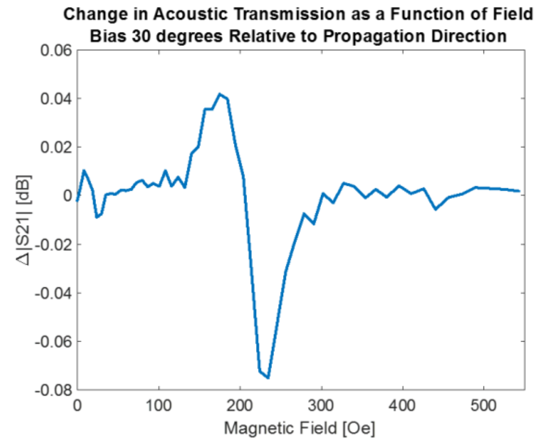

Figure 4: Change in S21 of the chosen acoustic mode, 7.492 GHz, as a function of DC magnetic bias field at an angle of 30˚. Absorption of the acoustic wave energy by the magnetic thin film maximizes near 250 Oe, indicating the presence of a spin wave mode that matches the acoustic wave wavelength and frequency.

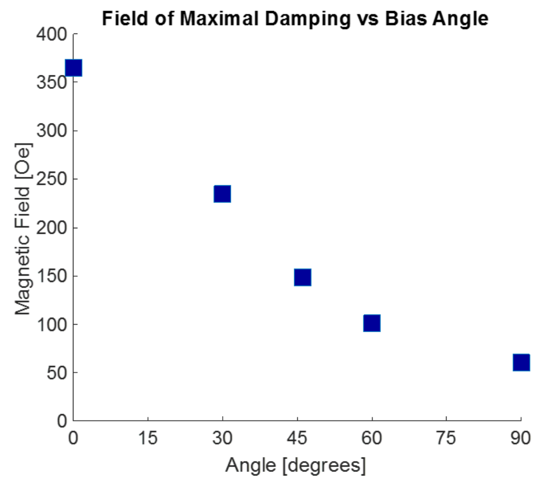

Figure 5: Measured magnetic field for maximal damping of the acoustic wave versus angle of the magnetic field relative to the Lamb wave propagation direction. As the angle increases, the bias needed decreases, which matches the trend shown in Figure 1. This is a unique aspect of coupling to spin wave modes, which can only be achievable by using highly nonuniform strain fields.

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