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Propagation properties of spin wave in Co_2FeAl Heusler alloy ultrathin films

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Suraj Singh^{1,*} , Nanhe Kumar Gupta², Soumyarup Hait², Sujeet Chaudhary², Thomas Tybell³  and Erik Wahlström¹

¹ Center for Quantum Spintronics, Department of Physics, NTNU—Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

² Thin Film Laboratory, Department of Physics, Indian Institute of Technology Delhi, New Delhi 110016, India

³ Department of Electronic Systems, NTNU—Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

* Author to whom any correspondence should be addressed.

E-mail: rsinghsuraj1992@gmail.com

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Supplementary material for this article is available [online](#)

Abstract

We report an investigation of spin wave propagation in ion beam sputtered Co₂FeAl Heusler alloy thin film on Si(100) substrate. The spin wave transmission spectra measured at fixed frequencies by sweeping the external applied magnetic field were used to estimate technologically relevant spin wave propagation parameters. The spin wave group velocity was found at 6.1 km s⁻¹ with an attenuation length larger than 7 μm. The Gilbert damping parameter was estimated to be 0.019. The frequency dependency of the group velocity decreased with increasing frequency and the attenuation length increased at low frequencies while started to decrease at larger frequencies. The amplitude of non-reciprocity also decreased with increasing frequency. The propagation parameters presented were also independently verified by time-resolved propagating spin wave spectroscopy.

Introduction

Magnon spintronics, an emerging field of spintronics also known as magnonics, aims at utilizing a magnon current instead of a charge current for information and data processing [1, 2]. Magnons are quanta of spin waves and offer a promising way to realize miniaturized, fast and energy efficient spintronics devices. Recent realization of several concepts such as bidirectional conversion of spin to charge current [3], spin wave logic gates [4], a spin wave multiplexer [5] and spin torque nano-oscillators [6] (STNO) have boosted the interest of the science community in this field. For such applications, materials with low Gilbert damping are important, particularly for the realization of low power spin-transfer torque and spin-orbit torque based devices where the switching current is proportional to the Gilbert damping parameter (α) [7, 8]. Yttrium iron garnet (YIG), an insulating ferrimagnet known for its low Gilbert damping, $\alpha \approx 10^{-5}$, is often the material of choice for magnonics devices [9]. However, the incompatibility of Gd₃Ga₅O₁₂ (GGG) substrates, widely used for YIG growth, with CMOS technology put a constraint on the technological applications of YIG based devices [2]. This asks for the exploration of new magnetic materials with low Gilbert damping coefficients that are at the same time CMOS compatible.

Heusler alloys are a promising alternative among various possible magnetic material due to the often low Gilbert damping, high Curie temperature, half metallicity and compatibility with CMOS technology [10–12]. Among the numerous Heusler alloys, Co₂FeAl (CFA) is known for its high Curie temperature ($T_C = 1000$ K), high spin polarization and low Gilbert damping ($\alpha = 0.001$) which makes it an interesting candidate for both spintronics and magnonics applications [13, 14]. CFA has been widely studied for its interesting static and magnetodynamic properties. A large tunneling magneto resistance reported by Wang *et al* makes it a candidate as electrode in magnetic tunnel junctions (MTJs) [15, 16]. Moreover, it has been studied extensively in CFA/NM

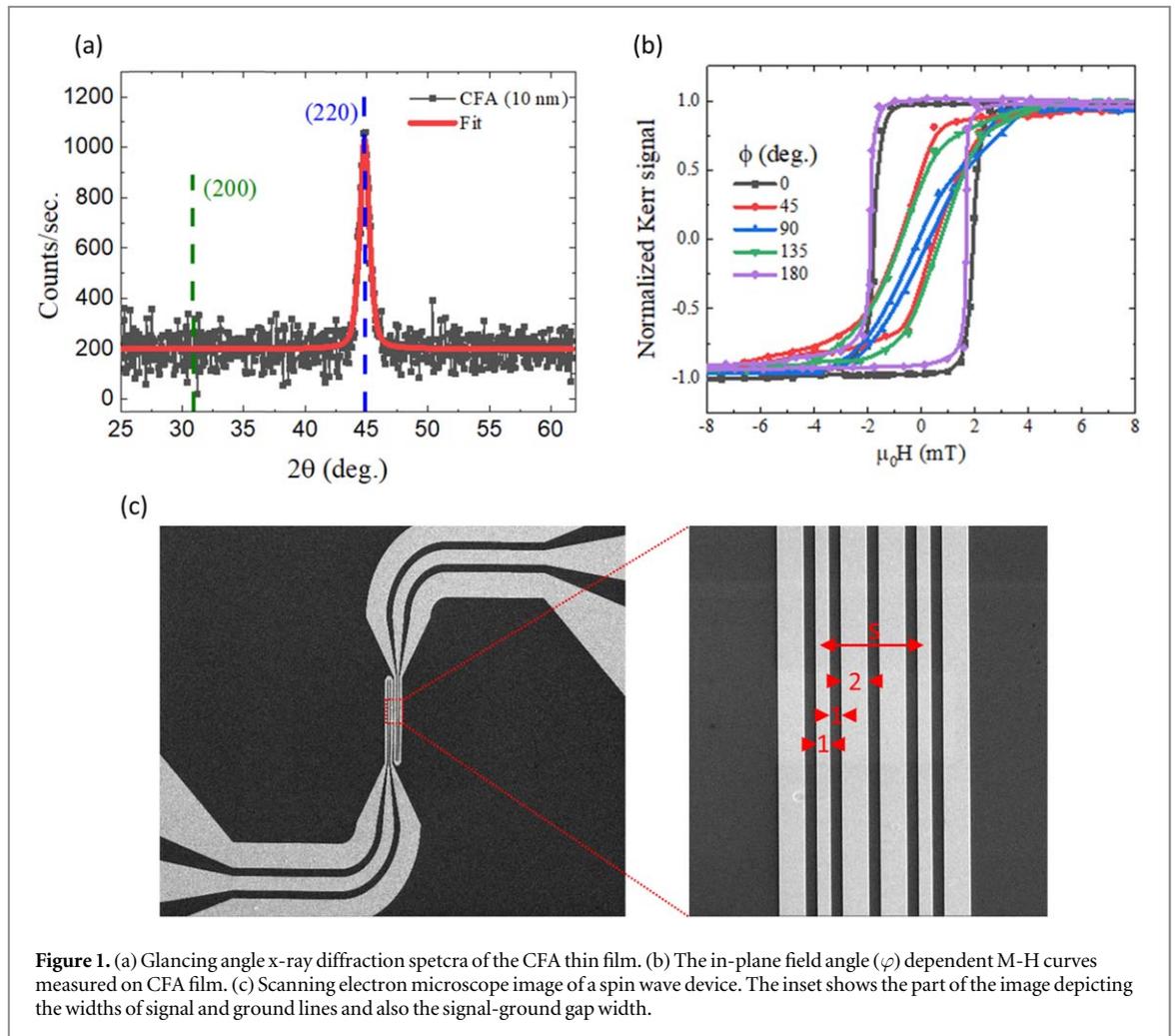


Figure 1. (a) Glancing angle x-ray diffraction spectra of the CFA thin film. (b) The in-plane field angle (φ) dependent M-H curves measured on CFA film. (c) Scanning electron microscope image of a spin wave device. The inset shows the part of the image depicting the widths of signal and ground lines and also the signal-ground gap width.

bilayers, here NM stand for non-magnetic metal, because of its low Gilbert damping and for the potential application in magnetic random-access memory (MRAM) devices [17, 18]. However, data on spin wave propagation properties and its dependence on spin wave frequency is still missing. Determining spin wave propagation properties in CFA is thus essential for its application in magnonics devices.

Here we report a study of magnetostatic surface spin waves excited in CFA thin films utilizing an all electrical propagating spin wave spectroscopy technique. The spin wave transmission measurements were performed sweeping an external magnetic field at different constant microwave frequencies, and the spin wave propagation parameters were thus estimated as a function of frequency. The so obtained propagation parameters were also independently verified by time resolved spin wave measurements.

Experimental

The CFA thin film was deposited by ion beam sputtering at base pressure and working pressure of 2×10^{-7} Torr and 8×10^{-5} Torr at the room temperature respectively. The crystalline structure of the film was investigated using x-ray diffraction (XRD) technique. Figure 1(a) shows the glancing incidence XRD measurement performed at the glancing angle 1° . Presence of diffraction peak (220) at 45° and absence of peak (200) at 32° suggest A2 type crystalline ordering in the deposited film [19]. The stoichiometry of the film was investigated by energy dispersive x-ray analysis (EDX), see figure S in the supplementary information (available online at stacks.iop.org/MRX/8/086101/mmedia). The M-H loops were measured by magneto optic Kerr effect (MOKE) magnetometer in longitudinal geometry at room temperature. The in-plane field angle (φ)-dependent MOKE measurements found to display in-plane uniaxial anisotropy of the film, see figure 1(b).

A series of spin wave devices were fabricated on the CFA thin film depositing an insulating layer of SiO_2 followed by deposition of a pair of microwave antennas by a combination of electron beam lithography and lift-off techniques. Both, the SiO_2 layer and the microwave antennas were deposited by electron beam evaporation. A typical device fabricated for the excitation of spin wave along the hard axis is shown in figure 1(c). The

microwave antennas were chosen in the ground-signal-ground (GSG) geometry. The widths of ground and signal lines were 2, 1 μm respectively with ground-signal gap of 1 μm , see figure 1(c). The patterned devices were placed between the pole piece of an electromagnet, allowing an in-plane magnetic field parallel to the coplanar waveguides (CPWs) to be applied to excite magnetostatic surface spin wave (MSSW). Microwave current/voltage pulses from an Agilent analog signal generator/picosecond pulse generator were sent to one antenna in order to excite spin waves. The excited spin waves travelling towards the second antenna induce a voltage which is detected by a spectrum analyzer and sampling oscilloscope in continuous and time resolved spin wave measurements, respectively. The spin wave measurements were performed at various antenna gap distances, s , ranging from 8–20 μm (see figure 1(c)) along the positive and negative directions of the applied magnetic field.

To quantitatively evaluate the spin wave propagation parameters, the signal recorded as a function of magnetic field was fitted to the product of a Gaussian and oscillatory function given by [20]:

$$y = \frac{A}{\Delta H \sqrt{\frac{\pi}{2}}} \exp\left(-\frac{2(H - H_r)^2}{(\Delta H)^2}\right) \exp\left(i2\pi\left(\frac{H - H_{ref}}{H_{per}}\right)\right) \quad (1)$$

where, A is the amplitude of the spin wave, ΔH the linewidth, H_r the resonance field, H_{per} the period of oscillation, and H_{ref} the reference field for which there is no spin wave signal.

The spin wave amplitude, resonance field, and oscillation period are extracted from the fittings. The spin wave amplitude, which follows an exponential decay, $A = \exp(-s/\Lambda)$, where Λ is the attenuation length, was estimated as a function of gap distance, and was used to determine the spin wave attenuation length. The oscillation period observed in field space was converted to frequency space in order to estimate the spin wave delay time (t_d). More information of this method can be found somewhere else [21]. Plotting t_d versus s allows to estimate the group velocity (as $s = v_g t_d$). Finally, the spin wave relaxation time was inferred from the slope of $\ln(A)$ versus t_d plots.

Results and discussion

The induced voltage measured at various gap distances, $s = 10, 15,$ and $20 \mu\text{m}$ is shown in figure 2(a). A clear oscillatory signal was observed, and the amplitude and oscillation period decreased with increasing gap distance. Figure 2(b) depicts a FFT transform of the current density calculated numerically from the spatial distribution of microwave current in the antenna. A main peak at wave vector, $k = 1.34 \mu\text{m}^{-1}$ and two secondary peaks were observed. The calculated wavevector relates to the actual wave vector of the spin wave to be excited. To verify this, the spin wave resonance field was extracted as function of frequency and fitted to MSSW dispersion curve given by equation (2), see figure 2(c).

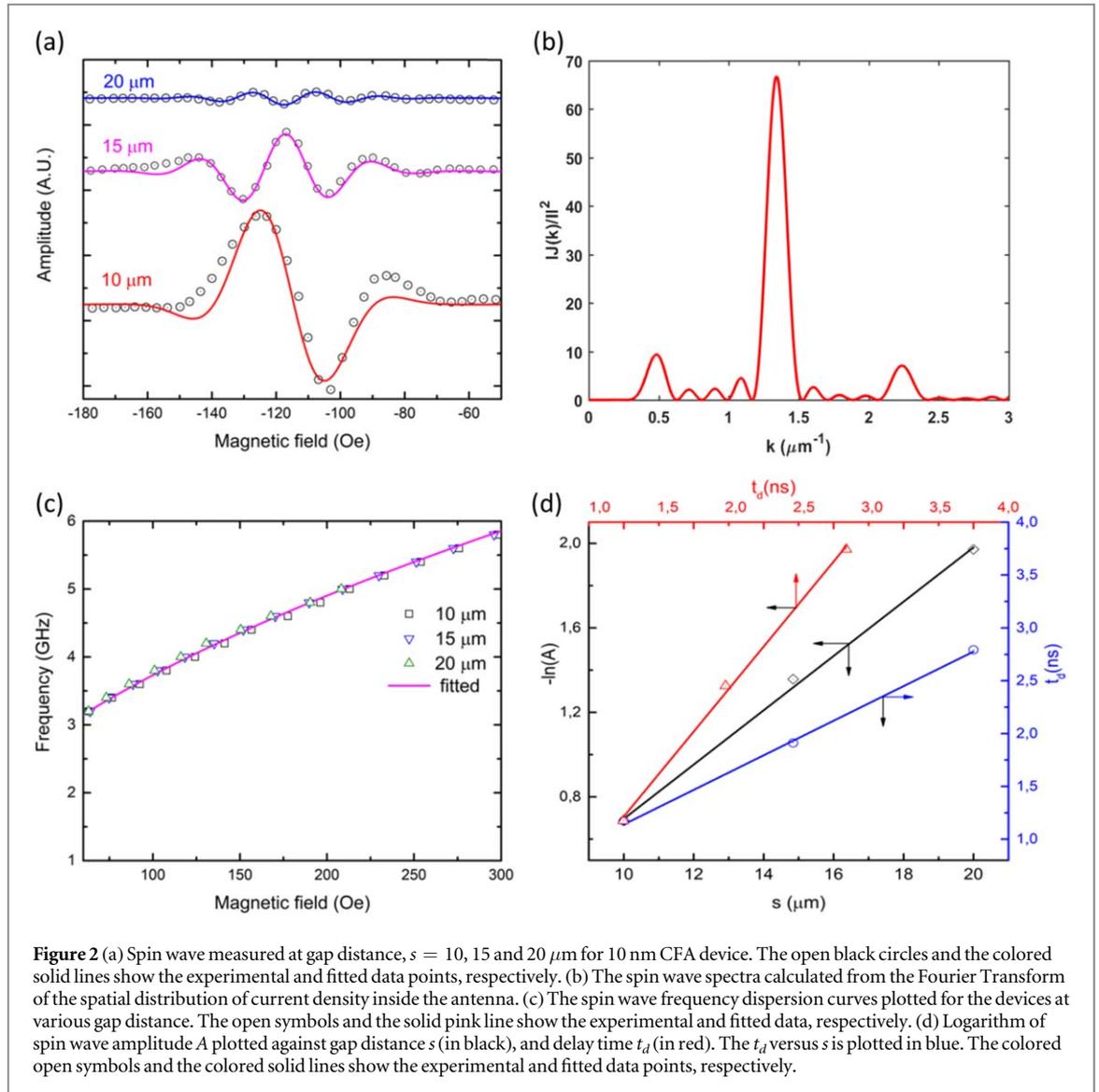
$$f_{MSSW} = \frac{\gamma}{2\pi} \sqrt{H(H + M_{eff}) + (M_{eff})^2 \left(\frac{1 - e^{-2kd}}{4}\right)} \quad (2)$$

where, f_{MSSW} is magnetostatic surface wave frequency, γ is the gyromagnetic ratio = $g\mu_B/h$, g is the Landé g -factor, μ_B is the Bohr magneton, and h is the Planck's constant.

The best fit between experimental and theoretical data is found for an effective field, $M_{eff} = 12500 \pm 100$ Oe, and $k = 1.24 \pm 0.2 \mu\text{m}^{-1}$ [22]. The experimentally observed wave vector matches well with the theoretical value. The effective field extracted is further used for estimating the spin wave delay time.

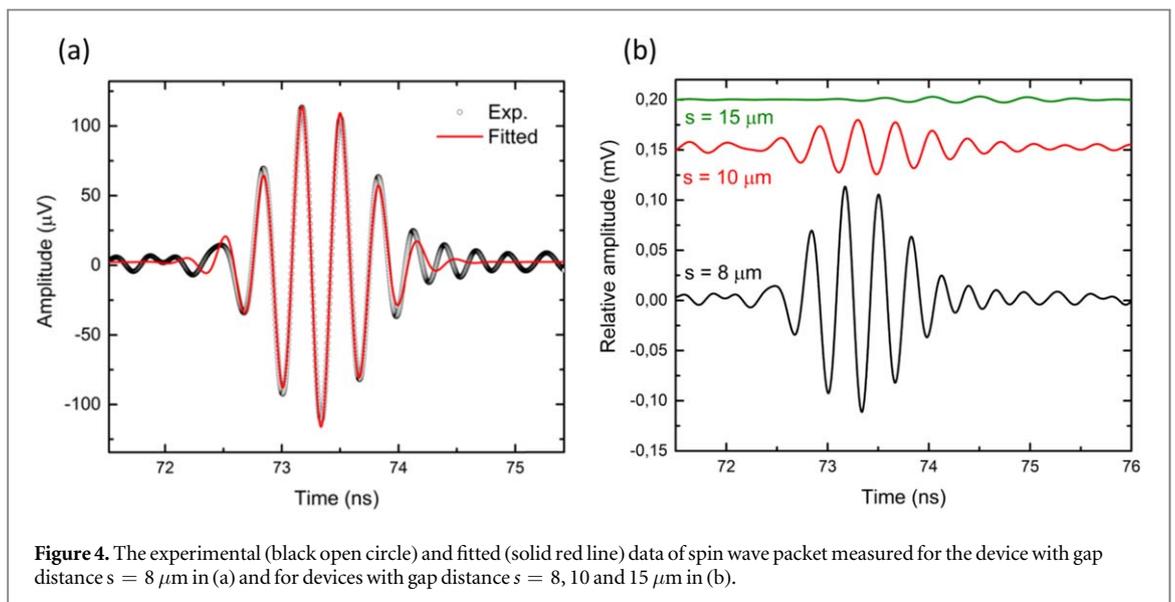
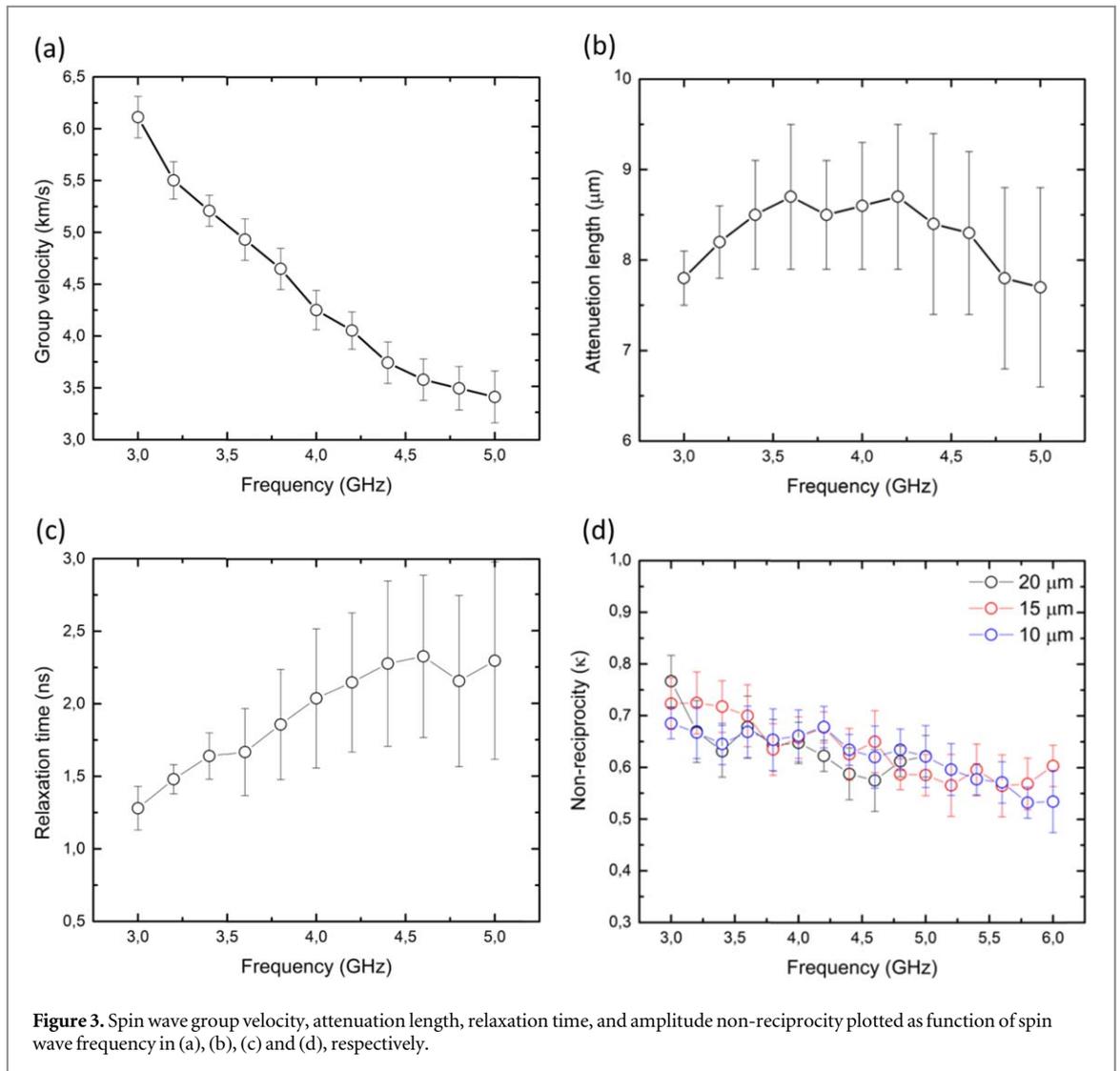
The signal amplitude measured corresponds to the amplitude of the spin wave and the oscillations attributed to the phase delay acquired by the spin wave during propagation between the two antennas [23]. The spin wave excited by the antenna is not perfectly monochromatic. This non-monochromaticity is attributed to the finite width (Δk) of the excited wave vector due to the antenna geometry. Therefore, the excited spin wave signal consists of multiple wave vector components. These components acquire different phase delays, $\varphi = ks$, after propagating the distance s between the two antennas. Spin waves arriving with different phases satisfy the resonance condition at different fields and results in an oscillatory behavior in the measured signal. The spin wave amplitude and the oscillation period are two important parameters containing the details of spin wave. Investigating these two parameters as a function of gap distance thus allows to estimate the spin wave propagation properties. Figure 2(d) (data in black open square) shows a plot of logarithm of spin wave amplitude against gap distance. A straight line fitted to $-\ln(A)$ versus s gives an attenuation length at $7.7 \mu\text{m}$ at 3 GHz. Similarly, the spin wave relaxation time and group velocity were estimated fitting $-\ln(A)$ versus t_d and t_d versus s data, see figure 2(d) (data in red and blue open circles). The relaxation time and group velocity were found to be 1.2 ns and 6.1 km s^{-1} at 3GHz, respectively. The Gilbert damping parameter, $\alpha = v_g/\Lambda\omega$, is estimated at 0.019.

To investigate the dependence of propagation parameters on spin wave frequency, measurements were performed at various microwave frequencies. Figure 3 summarizes the variation of group velocity, attenuation



length, relaxation time and amplitude non-reciprocity with the spin wave frequency in (a), (b), (c), and (d), respectively. The group velocity was found to decrease with increasing frequency. While the attenuation length is found to increase at low frequencies and to decrease at larger frequencies. Such behavior is unexpected, normally the behavior follows the same trend as the group velocity. To investigate this behavior, we examined the spin wave amplitude, which used to extract the spin wave attenuation length, in more detail. The spin wave amplitude was found to follow the same trend as the attenuation length. One possible explanation is that the sample is not fully in a saturation state at low magnetic fields. As the external magnetic field increases, the magnetization increases and hence the spin wave amplitude increases at first until the film is fully saturated. The observation is matching well with the trend observed in the $M-H$ curve along the hard axis. The spin wave amplitude reaches its maximum value at the saturation, and for even larger applied field the amplitude starts to decrease because of damping which has a linear dependency on spin wave frequency. The spin wave relaxation time was found to increase with increasing magnetic field. The observed frequency dependence is in accordance with the observed attenuation length behavior. The spin wave amplitude non-reciprocity was estimated taking the ratios of spin wave amplitude propagating along positive and negative magnetic fields. The non-reciprocity parameter (κ) was found at 0.72 ± 0.15 at 3 GHz and decreasing in a linear fashion with increasing frequency.

Furthermore, to verify the spin wave parameters estimated using this approach, time resolved propagating spin wave measurements were performed. The spin wave packet measured was fitted to a Gaussian function, see figure 4(a). Wave packet measured at various gap distances is reported in figure 4(b). The spin wave amplitude and delay time was used to estimate the group velocity and the attenuation length using the same method as discussed above. The spin wave group velocity and attenuation length were estimated at 6.9 km s^{-1} and $9.2 \mu\text{m}$ at 3 GHz , matching well with the continuous spin wave measurements.



Finally, we discuss the promise of sputtered Co_2FeAl for future high-performance magnonic device technology. A large group velocity and low Gilbert damping are the basic requirements for any material to be useful for magnonics applications. Our measurements reveal a low Gilbert damping, $\alpha \approx 0.019$, for ultrathin,

10 nm CFA film on a CMOS compatible silicon substrate. Thick (53 nm) Co₂FeAl films have also been reported to have low Gilbert damping, $\alpha \approx 0.0015$ [21] which is one order of magnitude smaller than other sputtered Heusler alloys [24]. We note that the enhanced Gilbert damping we measure in ultrathin films can tentatively be attributed to the impurity induced scattering which typically dominates at low thicknesses [25]. Moreover, the film degradation due to lithography processes may have also caused the enhancement in the damping parameter. The spin wave group velocity measured for the CFA films is 5 times larger than typically reported for YIG [26], and competes well with those reported for other Heusler alloy thin films [24]. Therefore, our findings support that CFA holds a great promise for application in magnonics devices including fast propagating spin waves over long distances.

Conclusion

In conclusion, we have investigated spin wave propagation properties of ion beam sputtered Co₂FeAl, Heusler alloy ultrathin films using all electrical propagating spin wave spectroscopy. We established a spin wave group velocity of 6.1 km s⁻¹, substantially larger than for YIG. Moreover, we found a Gilbert damping parameter of $\alpha \approx 0.019$ for ultrathin films on Si, comparable to that in the thicker films of other Heusler alloy films. The spin wave propagation parameters namely the group velocity is found to decrease with increasing frequency while the relaxation length found to increase with increasing frequency. The spin wave attenuation length is found to increase at low frequencies and started to decrease at larger frequencies. The amplitude non-reciprocity was also found to decrease with increasing frequency. The obtained data for the spin wave group velocity and attenuation length were independently verified by time resolved propagating spin wave spectroscopy. The results, presented here for ion beam sputtered Co₂FeAl ultrathin films on silicon, i.e., a large spin wave group velocity and low Gilbert damping are promising for applications in magnonics applications.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Suraj Singh  <https://orcid.org/0000-0001-9113-0000>

Thomas Tybell  <https://orcid.org/0000-0003-0787-8476>

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