

Roles of quadratic and biquadratic couplings in the spin-wave modes of Co-Fe/Ru/Ni-Fe artificial spin ices

Riccardo Fornari^{1,2,*}, Mohammad Tomal Hossain³, Raffaele Silvani^{1,2}, Vinayak Shantaram Bhat,³
Rawnak Sultana,³ M. Benjamin Jungfleisch^{3,†} and Gianluca Gubbiotti^{2,‡}

¹*Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, Perugia, Italy*

²*Cnr-Istituto Officina dei Materiali, Via A. Pascoli, 06123, Perugia, Italy*

³*Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA*



(Received 10 June 2026; revised 25 July 2026; accepted 29 July 2026; published 25 September 2026)

We investigate the interplay between quadratic and biquadratic exchange coupling in an exchange-coupled Co-Fe/Ru/Ni-Fe synthetic ferrimagnetic structure and compare its behavior to that of the same trilayer, patterned into an artificial spin ice (ASI). The static and dynamic properties are investigated by vibrating-sample magnetometry and Brillouin light-scattering spectroscopy and interpreted using MuMax3 micromagnetic simulations. Following this combined experimental and computational approach, we quantify the quadratic and biquadratic interfacial coupling terms and reveal their impact on magnetization reversal and layer-resolved spin-wave dynamics in the CoFe and NiFe layers. Furthermore, simulations of the evolution of the static configurations of the ASI system as a function of the applied magnetic field reveal the significant role played by the quadratic and biquadratic coupling terms in determining the equilibrium configurations of the nanoislands, in competition with the magnetostatic interactions imposed by the shape anisotropy of the nanoelements. This competition promotes mutually orthogonal layer magnetizations and may give rise to frustrated equilibrium states in which the magnetization aligns along the hard axis of the nanoelements. Our results suggest artificial spin lattices as promising reconfigurable magnonic devices where magnetic ground-state tunability may enable field-controlled magnonic crystals, spin-wave filters, and artificial spin-ice metamaterials with switchable dynamic properties.

DOI: [10.1103/5c9l-5w7v](https://doi.org/10.1103/5c9l-5w7v)

I. INTRODUCTION

Artificial spin ices (ASIs) are engineered metamaterials composed of matrices of elongated nanomagnets that interact through dipolar coupling and that display collective properties that are not present in individual isolated elements [1]. Owing to the geometrical arrangement of the nanoelements, the magnetic moments become frustrated [2] as not all dipolar interactions between neighboring elements can be minimized simultaneously. This gives rise to a variety of emergent phenomena, making ASI systems promising magnetic metamaterials with potential applications including reconfigurable magnonic crystals [3–8].

One of the key advantages of ASIs is that their macroscopic magnetic properties can be tailored through the geometric design of the lattice, from conventional square and kagome lattices [7,9–13] to more unconventional arrangements such as artificial quasicrystals [14] and disordered ASIs [15], allowing new functionalities to be engineered [16,17]. The study of single-layer ASI systems, both in terms of their dynamical properties and the magnetic frustration of the nanoelements, has been extensively investigated [4,7,8,16,18–23]. Subsequently, these studies have been extended to three-dimensional configurations, such as layered ASI systems, in which different magnetic layers interact via dipolar coupling [16,24–26]. Compared to their single-layer counterparts, multilayer ASIs exhibit significantly richer physical behavior, including interlayer coupling of magnetic modes that can give rise to hybridized dynamical excitations. From an application perspective, ASIs offer promising opportunities for data storage and information processing and have emerged as versatile platforms for unconventional computing paradigms, including non-Boolean and neuromorphic computation [4,17].

*Contact author: riccardo.fornari@dottorandi.unipg.it

†Contact author: mbj@udel.edu

‡Contact author: gianluca.gubbiotti@cnr.it

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II. SAMPLE FABRICATION AND CHARACTERIZATION

In this work, we investigate the static and dynamic properties of both ASI structures and continuous trilayers based on exchange-coupled $\text{Co}_{90}\text{Fe}_{10}$ (15 nm)/ Ru (0.6 nm)/ $\text{Ni}_{81}\text{Fe}_{19}$ (15 nm) grown by electron-beam evaporation. The Ru thickness is chosen such that the CoFe and NiFe layers are antiferromagnetically coupled through the interlayer exchange interaction, commonly associated with the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction [27]. The trilayer heterostructure was grown on thermally oxidized Si substrates at room temperature under a base pressure of 1.8×10^{-8} Torr. The deposition rates were maintained at 0.20 nm/s for $\text{Co}_{90}\text{Fe}_{10}$ and $\text{Ni}_{81}\text{Fe}_{19}$, and 0.04 nm/s for the Ru spacer layer (for more details on the growth see Ref. [27]). Fig. 1 shows (a) the schematic representation of the ASI geometry and (b) a scanning electron microscopy (SEM) image of the investigated sample.

The magnetic parameters of the samples were extracted through a combination of magnetometry measurements and detailed micromagnetic simulations performed using MuMax3 [28]. Within a finite-difference framework, the patterned system is discretized into micromagnetic cells, enabling an accurate representation of the nanoisland geometry and magnetic interactions. This approach provides a quantitative description of the magnetization dynamics, including spatially nonuniform effects arising from the interplay between quadratic and biquadratic interlayer coupling and the shape anisotropy of the nanoislands.

To reproduce the effect of interlayer exchange coupling, by micromagnetic simulations, a custom magnetic field was introduced in the interface regions between the CoFe

and NiFe layers, derived from the following system's volume energy density:

$$\varepsilon = -\mathbf{M} \cdot \mathbf{H}_0 + J_q \mathbf{m}_1 \cdot \mathbf{m}_2 + J_{bq} (\mathbf{m}_1 \cdot \mathbf{m}_2)^2, \quad (1)$$

where $\mathbf{H}_0$ is the externally applied magnetic field, $\mathbf{M}$ denotes the magnetization vector, and $\mathbf{m}_i$ the unit vectors of the layers i , respectively. The second and third terms account for the quadratic (ε_q) and biquadratic (ε_{bq}) interlayer exchange interactions, characterized by the coupling constants J_q and J_{bq} . The coupled trilayer system does not exhibit intrinsic magnetic anisotropy; therefore, no explicit anisotropy term is included in the analytical Hamiltonian used to describe the continuous film. Shape anisotropy becomes relevant only after patterning the trilayer into ASI nanoelements, where the elongated stadium-like geometry introduces a uniaxial anisotropy through the demagnetizing field. This shape-induced anisotropy is inherently included in the micromagnetic simulations. Defining the exchange surface constant related to the quadratic term of the coupling $J_{q1,2}^{\text{Surface}} = d_{1,2} \cdot J_q$ and the surface constant related to the biquadratic term of the coupling $J_{bq1,2}^{\text{Surface}} = d_{1,2} \cdot J_{bq}$, where $d_{1,2}$ are the thicknesses of the FM layers, and the interface fields can be written as

$$\begin{aligned} \vec{B}_{J_q 1,2} &= -\frac{d\varepsilon_{J_q}}{d\mathbf{M}_{1,2}} = -\frac{J_{q1,2}^{\text{Surface}}}{d_{1,2} \cdot M_{s1,2}} \frac{d(\mathbf{m}_1 \cdot \mathbf{m}_2)}{d\mathbf{m}_{1,2}} \\ &= -\frac{J_{q1,2}^{\text{Surface}}}{d_{1,2} \cdot M_{s1,2}} \mathbf{m}_{2,1}, \end{aligned} \quad (2)$$

$$\begin{aligned} \vec{B}_{J_{bq} 1,2} &= -\frac{d\varepsilon_{J_{bq}}}{d\mathbf{M}_{1,2}} = -\frac{J_{bq1,2}^{\text{Surface}}}{d_{1,2} \cdot M_{s1,2}} \frac{d((\mathbf{m}_1 \cdot \mathbf{m}_2)^2)}{d\mathbf{m}_{1,2}} \\ &= -\frac{2J_{bq1,2}^{\text{Surface}} (\mathbf{m}_{2,1} \cdot \mathbf{m}_{1,2})}{d_{1,2} \cdot M_{s1,2}} \mathbf{m}_{2,1}. \end{aligned} \quad (3)$$

These equations describe quadratic and biquadratic exchange fields that the CoFe magnetization in the interface region generates in the adjacent NiFe interface region and vice versa. Once the geometry and the interlayer coupling were implemented, a magnetic field was applied along the x axis, varying from 400 mT to -400 mT in steps of 5 mT. A small tilt angle of 1° away from the x axis was introduced to break the symmetry and account for more realistic conditions. At each step, the system was relaxed for 1 ns, followed by applying a sinc magnetic field pulse with an amplitude of 2 mT and duration of 10 ns in the direction perpendicular to the plane's surface (z axis) to simulate the excitation of spin waves (SWs) across the volume of the simulated systems. The out-of-plane dynamic magnetization of the system was then recorded every 10 ps in order to map the SW frequencies up to a

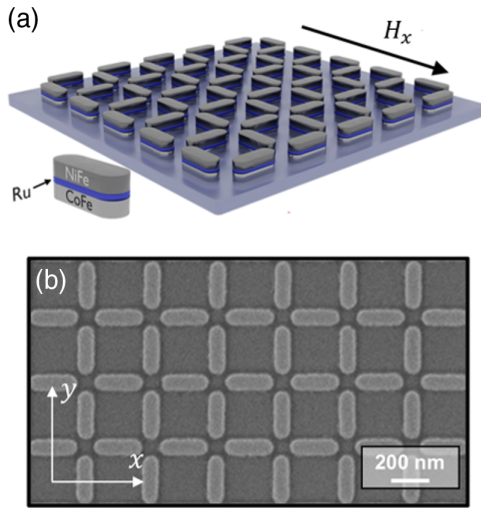


FIG. 1. (a) Schematic representation of the Co-Fe/Ru/Ni-Fe ASI array; an external magnetic field H is applied along the symmetry axis of the square ASI. (b) SEM image of a representative square ASI sample including the coordinate axes.

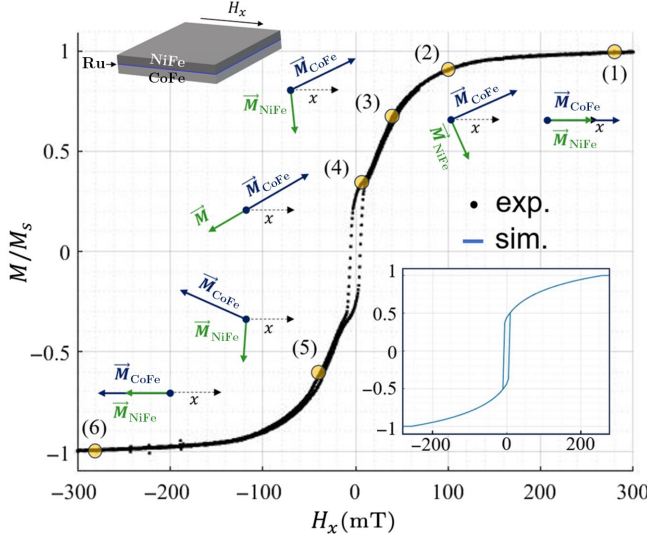


FIG. 2. Experimental VSM measurements and micromagnetic simulations, along with a schematic representation, for the continuous $\text{Co}_{50}\text{Fe}_{50}$ (15 nm)/Ru(0.6 nm)/ $\text{Ni}_{81}\text{Fe}_{19}$ (15 nm) trilayer. The orientations of the simulated in-plane magnetization directions (dark blue and green arrows) of the CoFe and NiFe layers are shown for 280 mT (1), 75 mT (2), 40 mT (3), 5 mT (4), -40 mT (5), and -280 mT (6) for the first branch of the loop.

maximum value of 30 GHz (equivalent to the cutoff frequency of the *sinc* pulse).

First, we focus on the characterization of the static magnetic properties. We performed vibrating-sample magnetometry (VSM), which provides insight into the magnetization reversal mechanism of the continuous trilayer reference film. The magnetization curve was measured at room temperature in the longitudinal configuration, over an applied in-plane field range of -3 T to 3 T in field steps of 0.5 mT. Figure 2 shows the measured and simulated VSM loops for the continuous CoFe/Ru/NiFe trilayer. The experimental data are compared to micromagnetic simulations for which we use the following magnetic parameters: exchange stiffness constants $A_{\text{ex}}^{\text{NiFe}} = 13 \frac{\text{pJ}}{\text{m}}$ and $A_{\text{ex}}^{\text{CoFe}} = 30 \frac{\text{pJ}}{\text{m}}$, saturation magnetizations $M_s^{\text{NiFe}} = 0.75 \times 10^6 \text{ A/m}$, and $M_s^{\text{CoFe}} = 1.97 \times 10^6 \text{ A/m}$, and exchange constants $J_{\text{q}1,2}^{\text{Surface}} = J_{\text{q}}^{\text{Surface}} = 0.85 \text{ kJ/m}^2$, and $J_{\text{bq}1,2}^{\text{Surface}} = J_{\text{bq}}^{\text{Surface}} = 0.5 \text{ kJ/m}^2$ (the indices 1 and 2 were omitted since the ferromagnetic layers have the same thickness). These parameters were obtained from matching the Brillouin light scattering spectroscopy (BLS) experiments to the dynamic micromagnetic simulations, as we will discuss in detail below. A comparison between experimental and simulated results suggests a significant contribution of the biquadratic exchange to the interlayer coupling; the corresponding M-H loops and field-dependent spin-wave resonances cannot be reproduced in the simulations if only J_{q} is considered. The results of

the static micromagnetic simulations are shown in the inset of Fig. 2. We can extract the saturation field, as well as the simulated mutual orientations of the average in-plane magnetizations of the layers. At a large positive field [point (1) in Fig. 2], the sample is fully saturated. Analysis of the simulated loop, shown in the inset of Fig. 2, indicates a complete parallel alignment of the CoFe and NiFe magnetizations. As the applied field is reduced [point (2) in Fig. 2], a gradual decrease in the magnetic moment is observed, suggesting a rotation of the soft NiFe layer. The presence of both quadratic and biquadratic interactions suggests a canted equilibrium state in which the magnetizations of the two layers are approximately orthogonal to each other and tilted with respect to the applied field direction, here taken as the x axis. As the field continues to decrease, the NiFe magnetization continues to reverse [point (3) in Fig. 2] and at approximately 5 mT a plateau emerges for both simulated and experimental loops. This is characteristic of an antiparallel alignment between CoFe and NiFe, which are oriented at an angle of $\theta_{\text{CoFe}} \approx 30^\circ$ and $\theta_{\text{NiFe}} \approx 150^\circ$ with respect to the x axis, according to the simulations [point (4) in Fig. 2]. Although an antiparallel alignment is observed, the remanent magnetization is not zero due to the different saturation magnetizations of the layers; hence, this structure can be considered a synthetic ferrimagnet [27]. Upon further decreasing the magnetic field, a sharp drop in the magnetization occurs near -5 mT (for both simulated and experimental loops), corresponding to the switching of the harder CoFe layer, while the NiFe magnetization undergoes a counterclockwise rotation toward the x axis [point (5) in Fig. 2]. The experimental and simulated loops are both characterized by a small coercivity of about 5.25 mT and a saturation field of $H_{\text{sat}} \approx 260 \text{ mT}$.

In the following, we turn to the modification of the SW properties in exchange-coupled ASI compared to their unpatterned counterparts. ASI arrays comprising stadium-shaped elements with lateral dimensions of $260 \times 90 \text{ nm}^2$ were patterned by electron-beam lithography using a bilayer positive resist of methyl methacrylate/polymethyl methacrylate. After exposure and development of the resist stack, electron-beam evaporation was used to deposit $\text{Co}_{90}\text{Fe}_{10}$ (15 nm)/Ru(0.6 nm)/ $\text{Ni}_{81}\text{Fe}_{19}$ (15 nm) following the same recipe as the continuous trilayer, without breaking the vacuum, followed by a lift-off process. Further details of the growth conditions can be found in Ref. [27]. SEM shown in Fig. 1(b) reveals the high quality of the patterned structures in terms of both morphological uniformity and precise control of the shape, dimensions, and periodicity. The distance between the nearest neighboring islands is 38 nm.

We investigated the thermal SW spectra in both trilayer thin film and ASI systems by BLS using a (3 + 3) Sandercock-type tandem Fabry-Pérot interferometer [29], employing a monochromatic beam from a diode-pumped

solid-state laser with a wavelength of 532 nm. The angle of incidence on the sample plane was fixed at 10° , while the external magnetic field was systematically varied from 400 to -400 mT in steps of 5 mT. The experimental results were obtained from the analysis of the BLS spectra collected for each field value, identifying the frequencies corresponding to the various observed SW modes by fitting the experimental peaks with a Lorentzian function.

III. RESULTS

Figure 3 compares the BLS spectra for the continuous trilayer and the corresponding patterned ASI.

The continuous trilayer shows two well-defined peaks, which show symmetry between Stokes and anti-Stokes signals [30]. In contrast, the ASI system exhibits a significantly richer BLS spectrum with six distinct peaks of comparable intensity. Peaks 1 and 2 are predominantly visible on the Stokes side of the spectrum, while they appear as a single sharp peak on the anti-Stokes side. Peaks 4–6 appear as a triplet in the low-frequency region of the spectrum, while peak 3 occupies an intermediate frequency position between the high-frequency doublet and the low-frequency triplet.

The corresponding field dependence of the modes detected for the trilayer film and ASI is shown in Fig. 4. For each value of the applied field, the SW frequencies were extracted by fitting each spectral peak by a Lorentzian curve and by averaging the Stokes and anti-Stokes frequency values. The reported uncertainty was determined by combining the uncertainty from the Lorentzian fitting procedure with the systematic instrumental uncertainty of the Fabry-Pérot interferometer

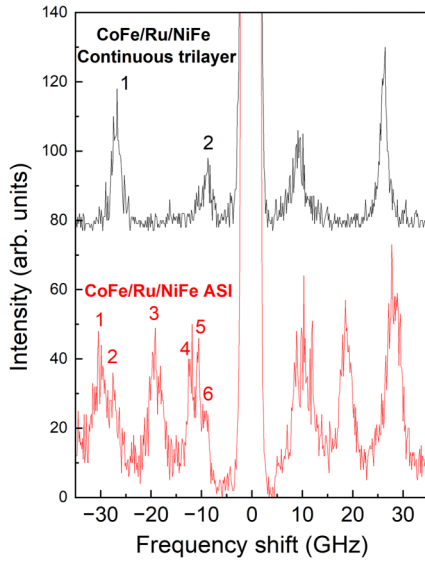


FIG. 3. Comparison of exemplary BLS spectra acquired for continuous CoFe/Ru/NiFe trilayer and ASI at $H_x = 360$ mT in which the experimental peaks have been labeled numerically.

(0.2 GHz), according to standard error propagation. Additional deviations between experiments and simulations may arise from fabrication-induced variations in the ASI geometry and material parameters, which are not included in the idealized micromagnetic model and can locally modify the spin-wave frequencies. For the continuous trilayer [Fig. 4(a)], two distinct frequency-separated modes are observed [31–36].

The high-frequency mode exhibits a monotonic increase with increasing field, while the second mode follows a similar trend for field values above $H_{\text{sat}} = 260$ mT. However, in the low-field regime close to 260 mT, a pronounced local frequency minimum is observed. This field regime corresponds to a magnetization configuration in which the two layers are no longer parallel to one

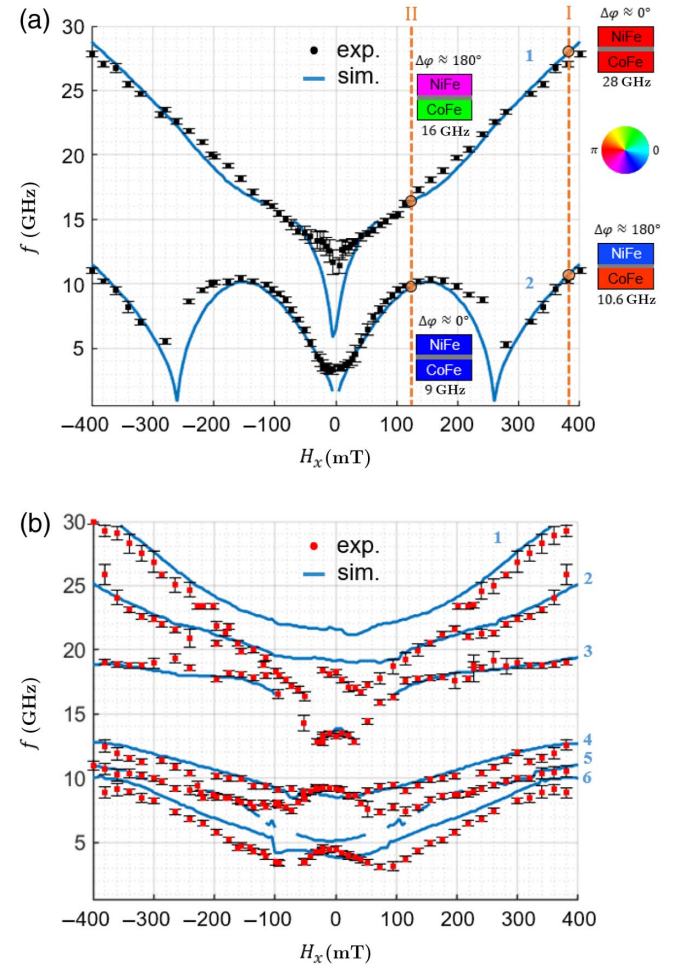


FIG. 4. Comparison between simulated and experimentally obtained field dependence of the modes for (a) the continuous CoFe/Ru/NiFe trilayer [along with the phase relation between the average magnetizations of the layers at 380 mT, (I), and 120 mT, (II)] and (b) exchange-coupled ASI. The simulated curves are labeled for direct comparison with the experimental data. The vertical dashed lines in (a) indicate the field values at which the continuous trilayer phase relations were extracted. The color wheel indicates the associated phase values.

another (see Fig. 2). As the field is further reduced, the low-frequency mode undergoes a rapid increase in frequency with a local maximum at around 150 mT, followed by a sharp decrease as the field approaches 0 mT. It is significant to note that, as the applied field approaches the values at which the low-frequency mode reaches its minimum, the mode frequency can no longer be experimentally resolved due to limitations of the BLS spectrometer.

The experimental behavior is well reproduced by the micromagnetic simulations, which successfully capture the main features of the mode evolution (blue solid lines in Fig. 4). Moreover, by extracting the phase relations of the continuous trilayer at 380 mT [vertical dashed line labeled (I) in Fig. 4(a)], we can associate the high-frequency peak as an acoustic mode (characterized by in-phase oscillations of the layer magnetizations, as can be seen by the spatially resolved simulation at 28 GHz). Conversely, the low-frequency mode can be associated with the optical mode (characterized by out-of-phase oscillations of the layer magnetizations, as can be seen by the spatially resolved simulation at 10.6 GHz). As the field is reduced below the saturation field, such that the layer magnetizations begin to cant (i.e., $H_x < H_{\text{sat}}$), the phase relations become more complex [27]. At 120 mT [vertical dashed line labeled (II) in Fig. 4(b)], the relative frequency positions of the acoustic and optical modes are inverted compared to the high-field scenario discussed above: the high-frequency mode can be associated with an optical mode characterized by out-of-phase oscillations of the layer magnetizations, as can be seen by the spatially resolved simulation at 16 GHz. On the other hand, the low-frequency mode shows acoustic character with an in-phase oscillation of the layers (vertical dashed line, spatial profile shown at 9 GHz). Consistent with previous studies [27], the main difference compared to dipolarly coupled bilayer systems is that, in the presence of exchange coupling, the two modes exhibit mode repulsion, such that no crossing is observed in their field-dependent frequencies.

Comparing the experimental results (data points) with the micromagnetic simulations (blue lines) in Fig. 4(a), we find a good agreement for the continuous trilayer using the parameters mentioned above. As previously stated, the magnetic parameters used in the simulations were optimized to obtain the best agreement with the experimental dynamical measurements.

In the following, we address the question of what happens if such an exchange-coupled trilayer system is patterned into an ASI array. Figure 4(b) compares the measured and simulated frequencies of the exchange-coupled ASI system. Because the simulated ASI system is idealized, with identical and homogeneous nanoislands, effective saturation magnetizations were used to account for structural inhomogeneities in the experimental system. Specifically, we used $M_{\text{s,eff}}^{\text{NiFe}} = 0.6 \times 10^6$ A/m and

$M_{\text{s,eff}}^{\text{CoFe}} = 1.6 \times 10^6$ A/m while keeping all other parameters compared to the continuous trilayer unchanged. These values correspond to a reduction of the layer magnetizations by approximately 20% compared to the continuous trilayer case. Experimental peaks 1 and 2 exhibit a monotonically increasing trend with increasing external field, and they remain distinct down to approximately 170 mT (field value around which the maximum in the frequency evolution of the low-frequency mode of the continuous trilayer is observed). Below that field range, modes 1 and 2 appear to merge. Peak 3 exhibits a similar frequency behavior, but with a smaller slope compared to peaks 1 and 2. Peaks 4–6 exhibit the same slope and share a common nonmonotonic behavior; moreover, peaks 4 and 5 overlap at low fields, where they are no longer distinguishable. The behavior of the low-frequency modes is markedly different from that of those observed for the continuous trilayer: their frequency dependence around zero field shows the typical frequency evolution of hard-axis systems and corresponds to the reorientation of the island magnetizations along the easy direction [16], as displayed by local minima around 100 mT in the field-frequency evolutions. The six modes identified in the experiment are in good agreement with the simulations. For relatively high fields $H_x > 170$ mT, the upper branch of the experimental data is well reproduced by simulated mode 1, whereas at lower fields, it is better described by simulated mode 2. As we will discuss below, the spatial SW profiles of the modes support this interpretation. The simulated low-frequency modes are in good agreement with the experimental trend but do not reproduce the low-field frequency upturn near 0 mT.

IV. DISCUSSION

The SW spectrum shown in Fig. 4(b) is further analyzed by evaluating the spatial profiles of the modes. For this purpose, the temporal characteristics of each micromagnetic cell are Fourier transformed at a fixed magnetic field to obtain the spatial mode profile in the frequency domain. For selected field values applied along the x axis, the two-dimensional frequency maps in Fig. 5 show the real part of the Fourier-transformed dynamic m_z component for the most intense spectral modes, normalized to the maximum amplitude (the spatial profiles omitted here are provided in the Appendix). In addition, the spatial profiles of the modes are correlated with the simulated in-plane magnetization configurations (panels (I), (II), and (III) in Fig. 5), for which the angles between the average magnetizations of the CoFe and NiFe layers are indicated. The modes can be classified based on their spatial distribution [37]; in all cases, a strong contribution of edge modes is observed in both CoFe and NiFe layers, in both vertical and horizontal islands. Figures 5(a), 5(d), and 5(g) represent the 2D profiles of modes (1), (2), and (5) shown in Fig. 4(b) in the saturated state at 380 mT, respectively.

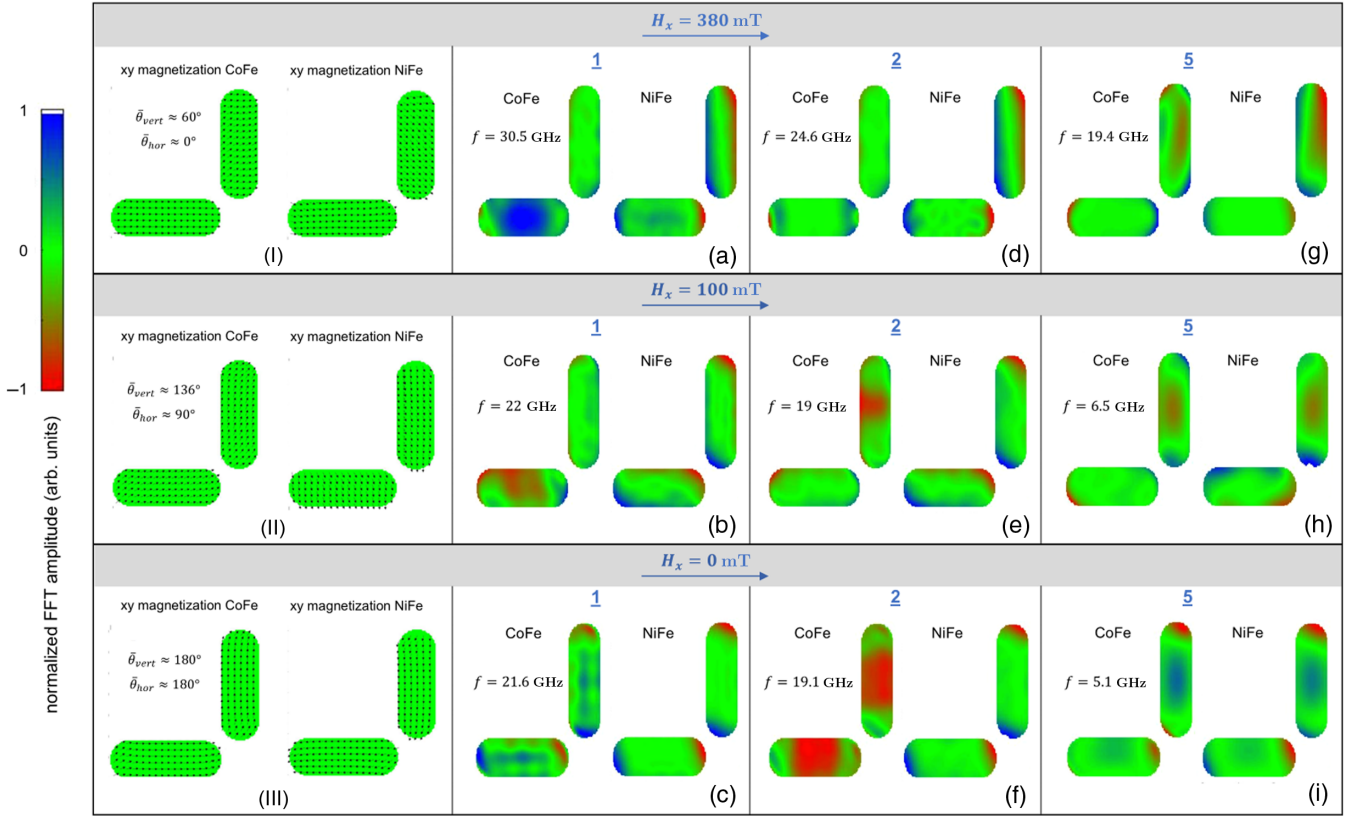


FIG. 5. Simulated 2D magnetization configuration [panels (I), (II), and (III)] as well as spatial SW profiles of exchange-coupled trilayer ASI structure at 380, 100 and 0 mT, for mode 1 [panels (a)–(c)], mode 2 [panels (d)–(f)] and mode 5 [panels (g)–(i)] (see Fig. 4). The color bar indicates the normalized amplitude of the FFT of the out-of-plane component of the dynamic magnetization, calculated for each micromagnetic cell. The results are shown for the unit cell of the ASI array; by applying periodic boundary conditions in the simulations, the entire structure can then be replicated.

Figure 5(I) shows the static configuration of the layer magnetizations in the nanoislands, where the horizontal islands are fully saturated, with the layer magnetizations aligned, whereas the magnetizations in the vertical islands form a finite angle with the field direction and are noncollinear, exhibiting an angle of approximately 60° with respect to each other. In Fig. 5(a), which shows the spatial profile of mode (1), a fundamental mode hybridized with an edge mode is observed in the CoFe layer of the horizontal islands. This mode is weakly imprinted in the NiFe layer of the horizontal islands, where a pronounced edge mode is also present. An edge mode confined to the long side of the vertical island in the NiFe layer is observed, whereas the dynamics in the vertical CoFe islands is practically negligible. The spatial profile of mode (2), shown in Fig. 5(d), is characterized by low intensity. In the vertical islands, the profile is analogous to that of mode (1). In contrast, the horizontal islands exhibit pronounced edge modes that precess out of phase in the CoFe and NiFe layers. Figure 5(g) shows the profile of mode (5), which can be identified as edge modes in the horizontal islands, with an out-of-phase correspondence between the layers. The localization of the edge modes along the short sides of the

horizontal nanoislands (i.e., at the ends of the easy axis) in the saturated state is consistent with the simulated in-plane magnetization configuration, where the static magnetization is aligned along the easy axis of each island. Furthermore, the vertical islands exhibit a mode profile extending over a large portion of the island layers.

At 100 mT, as shown in Fig. 5(II), the simulated magnetizations of the ferromagnetic layers in the horizontal islands adopt a mutually orthogonal configuration. This equilibrium state is determined by the strong influence of the biquadratic interlayer coupling favoring a perpendicular alignment between the layer magnetizations, overcoming the preferential orientation imposed by the shape anisotropy of the nanoelements. Figures 5(b), 5(e), and 5(h) show the corresponding spatial profiles of the selected modes at 100 mT. Mode (1), shown in Fig. 5(b), still appears as a fundamental mode in the CoFe layer of the horizontal islands, hybridized with an edge mode, while the contribution of the vertical CoFe islands remains negligible. However, the behavior of the NiFe edge modes is in stark contrast to the spatial mode localization observed for 380 mT. In particular, in the horizontal NiFe islands, the edge modes shift from the

short sides of the nanoislands to the long sides, consistent with the alignment of the in-plane NiFe magnetization shown in Figs. 5(I) and 5(II). Conversely, in the vertical islands, the NiFe edge modes become localized along the short sides. A similar behavior is observed for mode (2), shown in Fig. 5(e). Figure 5(e) further reveals an edge mode in the horizontal CoFe islands and a high-intensity mode emerging at the center of the vertical CoFe islands. Figure 5(h), showing the profile of mode (5), reveals a fundamental mode hybridized with an edge mode in the vertical islands, with in-phase oscillations between the ferromagnetic layers. In contrast, only edge modes are present in the horizontal islands. Again, the edge modes in the horizontal NiFe islands undergo a change in their spatial localization compared to Fig. 5(g).

Finally, the static magnetization configuration at 0 mT is shown in Fig. 5(III). The shape-induced anisotropy in the ASI system is inherently included in the micromagnetic simulations and is evident in the calculated configurations, particularly at zero applied field ($H = 0$, Fig. 5, panel III), where the magnetization preferentially aligns along the long axis of the elements. Moreover, the antiferromagnetic coupling between the two layers is observed. The spatial profile of mode (1) shown in Fig. 5(c) indicates that the fundamental mode in the horizontal CoFe layer islands is less intense compared to the previous cases, and an analogous spatial profile can also be found in the CoFe of the vertical islands. In contrast, the NiFe layers of both horizontal and vertical islands exhibit only edge modes, oscillating in phase with the edge modes present in the corresponding CoFe layers, respectively. In Fig. 5(f), corresponding to mode (2), a strong fundamental mode emerges across the CoFe layer of both the vertical and horizontal islands, whereas the NiFe layers are occupied only by edge modes. The spatial structure of mode (5), shown in Fig. 5(i), remains essentially unchanged compared to mode (2) with a fundamental mode in the vertical islands and edge modes in the horizontal islands. In this configuration, the magnetizations in the CoFe and NiFe layers oscillate in phase. The edge modes observed in these cases are localized along the short sides of the islands (at the ends of the easy axis), consistent with the magnetization orientation along the easy axis of the islands.

V. CONCLUSIONS

In conclusion, we investigated the interplay between quadratic and biquadratic exchange coupling in an exchange-coupled CoFe/Ru/NiFe synthetic ferrimagnetic structure and compared its behavior with that of

the same system patterned into an artificial spin lattice. Through the interpretation of the experimental results using micromagnetic simulations, values for the magnetic parameters of the samples were obtained to ensure consistent results between the systems. In particular, we estimated the values of $J_q^{\text{Surface}} = 0.85 \text{ kJ/m}^2$ and $J_{\text{bq}}^{\text{Surface}} = 0.5 \text{ kJ/m}^2$ for the exchange interlayer coupling, which favors an antiparallel coupling between the ferromagnetic layers at remanence. By measuring the spin-wave spectra using Brillouin light scattering, we experimentally identified the field dependence of the fundamental spin-wave modes in both the continuous trilayer and the ASI structure. Notably, micromagnetic simulations allowed us to reproduce the frequency evolution as a function of the applied magnetic field to identify the mode profiles of the eigenexcitations. We found that, unlike previous studies on monolayer ASI systems, where the static configuration of the nanoelements is governed by shape anisotropy, which favors magnetization alignment along the easy axis of the islands, the RKKY interaction present in our system induces mutually perpendicular orientations between the layer magnetizations and drives the magnetization alignment along the hard axes of the elements for particular field values. These findings demonstrate that exchange-coupled artificial spin lattices are a promising platform for reconfigurable magnonic devices where magnetic ground-state tunability could enable field-controlled magnonic crystals, spin-wave filters, and artificial spin-ice metamaterials with switchable dynamic properties.

ACKNOWLEDGMENTS

Work at the University of Delaware, including sample fabrication, static magnetization characterization, and modeling, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award No. DE-SC-0024346.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX

Figure 6 shows the spatial profiles of the simulated SW modes 3, 4, and 6 are presented.

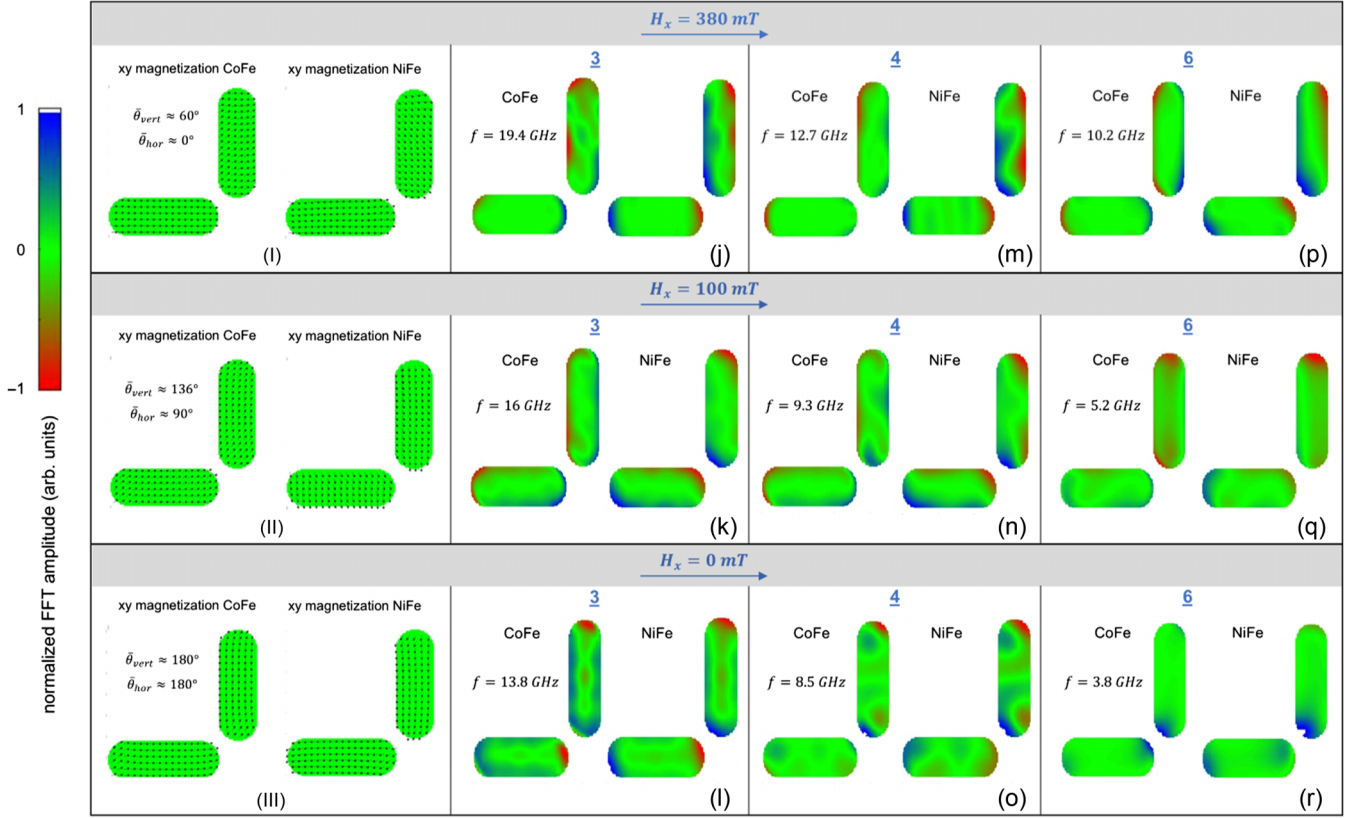


FIG. 6. Simulated 2D magnetization configuration [panels (I), (II), and (III)] as well as spatial SW profiles of exchange-coupled trilayer ASI structure at 380, 100, and 0 mT for mode 3 [panels (j)–(l)], mode 4 [panels (m)–(o)], and mode 6 [panels (p)–(r)].

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