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Engineering Spin-Wave Spectra through Longitudinal Compositional Interfaces

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ABSTRACT

Engineering spin-wave spectra without modifying device geometry remains a central challenge in magnonics. Here, we investigate how longitudinal compositional interfaces reshape the equilibrium magnetic configurations and spin-wave dynamics of homogeneous and multisegmented Co/CoNi/Ni nanowires using micromagnetic simulations. We demonstrate that compositional interfaces reorganize the magnetic energy landscape, stabilizing hybrid magnetic configurations that reorganize the spin-wave eigenmode spectrum through mode hybridization, localization, and spectral-weight transfer. Rather than generating additional resonances, increasing the interface density continuously shifts the dominant microwave response from the C band of Ni nanowires toward the Ku band of Co nanowires, while multisegmented architectures naturally stabilize resonances within the technologically relevant X band. These findings establish longitudinal compositional interfaces as an independent design parameter for programming spin-wave spectra and engineering reconfigurable magnonic and microwave nanodevices.

Introduction

The ability to manipulate spin-wave excitations in magnetic nanostructures lies at the heart of modern magnonics, where spin waves are envisioned as information carriers for next-generation microwave, logic, and neuromorphic devices operating with low energy consumption and high processing speeds[1–4]. Because the frequencies, spatial profiles, and propagation characteristics of spin-wave eigenmodes are governed by the internal magnetic field distribution, controlling the magnetic energy landscape has become one of the central challenges in the design of reconfigurable magnonic systems.

Among the different magnetic nanoarchitectures, cylindrical nanowires constitute an attractive platform for engineering spin-wave dynamics owing to their strong shape anisotropy, three-dimensional magnetic confinement, and rich variety of equilibrium magnetization states[5–8]. Their elongated geometry supports both localized and propagating spin-wave modes whose characteristics are highly sensitive to the internal effective field, making magnetic nanowires promising candidates for nanoscale waveguides, microwave resonators, frequency-selective devices, and spin-wave-based computing architectures[9–11]. Consequently, tailoring the magnetic configuration provides a direct route for controlling the dynamic response of these systems.

Several strategies have been proposed to engineer spin-wave spectra, including modifications of the nanowire geometry, aspect ratio, diameter modulation, and chemical composition[12–15]. Geometry primarily modifies the magnetostatic energy through changes in shape anisotropy, whereas composition alters intrinsic magnetic parameters such as the saturation magnetization (M_s), exchange stiffness (A), and magnetocrystalline anisotropy (K_1). These approaches reshape the magnetic energy landscape and consequently influence the equilibrium magnetic configurations and their associated spin-wave eigenmodes. Nevertheless, geometry and composition have generally been investigated as independent design parameters, while the role of internal compositional interfaces in determining the dynamic magnetic response has received comparatively little attention.

Binary Co_xNi_{100-x} alloys provide an ideal model system to explore this problem because their intrinsic magnetic properties can be continuously tuned through composition[13,16,17]. Moreover, template-assisted electrodeposition enables precise fabrication of multisegmented Co/CoNi/Ni nanowires with well-defined longitudinal compositional architectures[18–21]. Such structures combine materials with markedly different magnetocrystalline anisotropies within a single nanowire, creating internal magnetic interfaces capable of locally modifying the effective field and the equilibrium magnetic configuration. These interfaces therefore introduce an additional degree of freedom that can potentially be exploited to manipulate spin-wave spectra beyond conventional geometry-based approaches.

Here, we hypothesize that longitudinal compositional interfaces reshape the magnetic energy landscape, thereby reorganizing the spin-wave eigenmode spectrum. To test this hypothesis, we perform micromagnetic simulations on homogeneous Co and Ni nanowires together with multisegmented Co_xNi_{100-x} architectures containing progressively finer discretizations of an axial

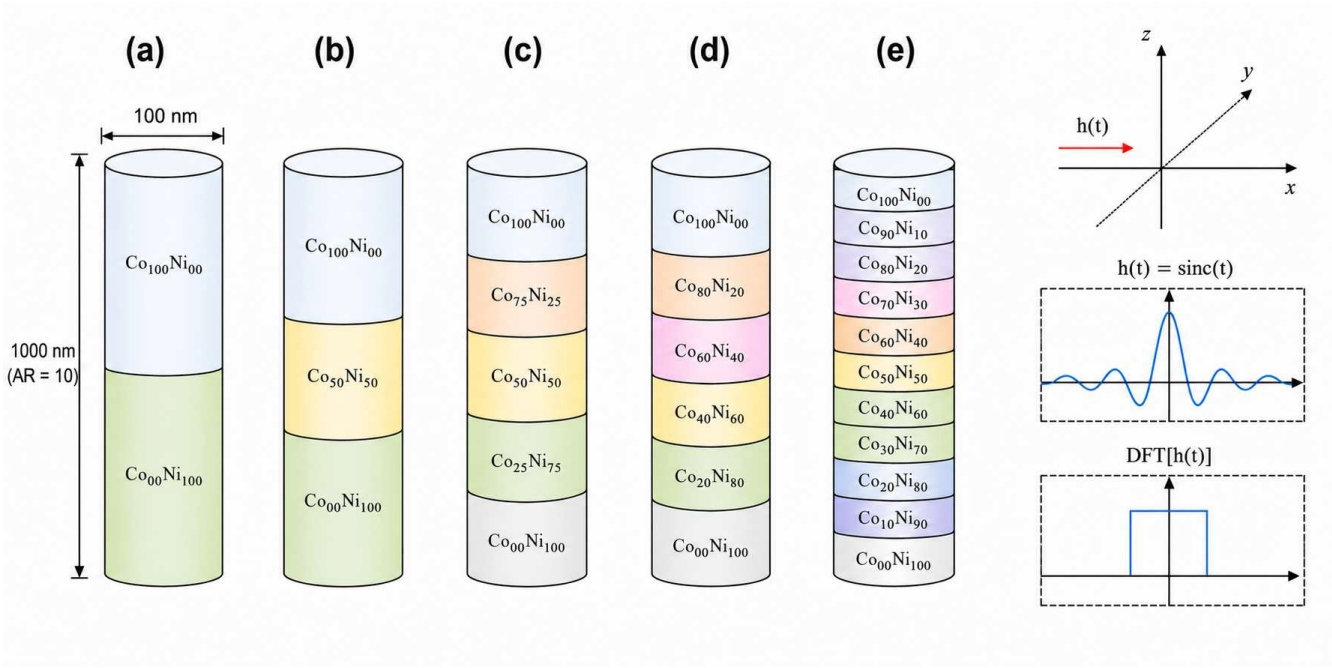


Figure 1. Schematic representation of the homogeneous and multisegmented Co/CoNi/Ni nanowires investigated in this work. Panels (a)–(e) show nanowires composed of 2, 3, 5, 6, and 11 equally thick longitudinal segments, respectively, in which the Co concentration decreases progressively from $Co_{100}Ni_{00}$ to $Co_{00}Ni_{100}$, providing successive discretizations of an axial compositional gradient. All nanowires have a diameter of 100 nm and a length of 1000 nm ($AR = 10$). The broadband sinc magnetic field pulse applied along the $+x$ direction for the dynamic susceptibility calculations is also illustrated.

compositional gradient. By systematically increasing the density of internal compositional interfaces while preserving the overall geometry, we isolate their influence on the equilibrium magnetic configurations and the dynamic susceptibility spectra.

We demonstrate that longitudinal compositional interfaces stabilize hybrid magnetic configurations and reorganize the spin-wave eigenmode spectrum through mode localization, hybridization, and spectral-weight redistribution. As a consequence, the dominant ferromagnetic resonance can be systematically displaced across technologically relevant microwave frequency bands without modifying the external dimensions of the nanowire. These findings establish longitudinal compositional interfaces as an effective design parameter for engineering spin-wave spectra and provide a general strategy for the development of programmable magnonic nanoarchitectures.

Micromagnetic Model and Simulation Procedure

Micromagnetic simulations were carried out using the open-source software MuMax3[22,23], which solves the Landau–Lifshitz–Gilbert (LLG) equation within a finite-difference framework,

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{d\mathbf{M}}{dt}, \tag{1}$$

where γ is the gyromagnetic ratio, α is the Gilbert damping constant, $\mathbf{M}$ is the magnetization vector, and $\mathbf{H}_{\text{eff}}$ denotes the effective magnetic field, including exchange, magnetostatic, and magnetocrystalline anisotropy contributions.

The model consists of homogeneous Co and Ni nanowires together with multisegmented Co_xNi_{100-x} nanowires, as illustrated in Fig. 1. All nanowires have a fixed diameter of 100 nm and a length of 1000 nm ($AR = 10$). Five multisegmented architectures containing 2, 3, 5, 6, and 11 equally thick longitudinal sections were investigated. These architectures represent successive discretizations of an ideal continuous axial compositional gradient extending from $Co_{100}Ni_{00}$ to $Co_{00}Ni_{100}$. This systematic sequence enables the isolated investigation of how the density of internal compositional interfaces influences the equilibrium magnetic configurations and the spin-wave spectra while preserving the overall geometry. Homogeneous Co and homogeneous Ni nanowires were included as limiting reference systems. Throughout this work, the nanowire axis is defined as the z direction, whereas the transverse directions correspond to the x and y axes.

The magnetic parameters of each Co_xNi_{100-x} alloy segment, namely the saturation magnetization (M_s), exchange stiffness (A), and first-order magnetocrystalline anisotropy constant (K_1), were calculated using the composition-dependent empirical relations reported by Arciniegas *et al.*[13]. Magnetocrystalline anisotropy was modeled as an effective cubic anisotropy with composition-dependent anisotropy constants assigned to each segment. All simulations employed a finite-difference discretization of $2 \times 2 \times 4$ nm^3. Consequently, the degree of longitudinal compositional segmentation constitutes the only independent variable of the present study, whereas geometry, numerical discretization, excitation conditions, and material interpolation remain identical for all simulated nanowires.

To determine the equilibrium magnetic configuration of each structure, three initial magnetization states were considered: Uniform X, Uniform Z, and Vortex. A two-step relaxation protocol was adopted. First, the magnetization was relaxed using a damping parameter of $\alpha = 0.5$ until the maximum torque fell below 10^{-4} T[24,25]. Subsequently, the relaxed state was evolved for 100 ns under the full LLG dynamics to verify its dynamical stability and suppress residual spin-wave excitations generated during the relaxation process[26]. Among the relaxed configurations, the lowest-energy stable state was selected as the equilibrium configuration for the subsequent dynamic calculations.

Spin-wave dynamics were investigated through dynamic susceptibility calculations. A broadband sinc magnetic field pulse,

$$\mathbf{h}(t) = h_0 \,\mathrm{sinc}\left[2\pi f_{\max}(t - t_0)\right]\hat{\mathbf{x}},$$

with amplitude $h_0 = 1$ mT and cutoff frequency $f_{\max} = 25$ GHz was applied along the transverse direction[14,27]. The spatially averaged magnetization was recorded every 10 ps during a total simulation time of 100 ns, providing a frequency resolution of 0.01 GHz. A reduced damping parameter of $\alpha = 0.015$ was employed during the dynamic simulations to improve spectral resolution while preserving the intrinsic resonance frequencies[28,29].

The complex dynamic susceptibility was calculated from the Fourier transforms of the excitation field and the dynamic magnetization according to

$$\chi(\omega) = \frac{M_x(\omega)}{h_x(\omega)} = \chi'(\omega) - j\chi''(\omega), \tag{2}$$

where the imaginary component $\chi''(\omega)$ was used to characterize the ferromagnetic resonance spectrum.

Finally, the spatial profiles of the spin-wave eigenmodes were obtained from the temporal Fourier transform of the dynamic magnetization in every computational cell,

$$\tilde{m}_z(r_{ijk}, \omega_n) = \mathrm{DFT}_t\left[m_z(r_{ijk}, t_n)\right], \tag{3}$$

where i, j, and k denote the spatial coordinates of the discretization cells and n labels the frequency components. This procedure provides direct access to both the resonance frequencies and the spatial distribution of the spin-wave eigenmodes, enabling a direct correlation between magnetic configuration and dynamic response.

Results and discussion

0.1 Internal Magnetic Interfaces Reshape the Magnetic Energy Landscape

Figure 2 summarizes the equilibrium magnetic configurations obtained for homogeneous and multisegmented Co/CoNi/Ni nanowires after energy minimization. The results reveal a systematic evolution of the magnetic textures as the longitudinal compositional profile becomes progressively discretized, demonstrating that compositional segmentation provides an effective mechanism for reshaping the magnetic energy landscape.

The two homogeneous nanowires define the limiting magnetic states of the investigated systems. Owing to its relatively low magnetocrystalline anisotropy, the Ni nanowire stabilizes a flower-like configuration characterized by an almost uniform axial magnetization with only slight deviations near the wire surface caused by magnetostatic effects. In contrast, the Co nanowire exhibits a vortex-like configuration in which the magnetization predominantly curls around the nanowire axis, minimizing the magnetostatic energy through flux closure[12,30].These markedly different equilibrium states arise from the competition between shape anisotropy[5], which promotes axial alignment in both materials, and the much stronger magnetocrystalline anisotropy of Co, which favors transverse magnetization components and stabilizes curling configurations.

Introducing longitudinal compositional segmentation profoundly modifies this energetic balance. Rather than simply interpolating between the magnetic configurations of the two homogeneous systems, each compositional interface locally alters the exchange, magnetostatic, and magnetocrystalline anisotropy energies[6,31,32], creating spatially nonuniform energy minima along the nanowire. Consequently, the equilibrium magnetization is no longer governed by a single magnetic state but instead results from the local competition between adjacent segments with different intrinsic magnetic properties.

This behavior is particularly evident in the two- and three-segment nanowires, where the abrupt compositional discontinuities strongly perturb the axial magnetic order. The interfaces hinder the propagation of the nearly uniform flower-like configuration

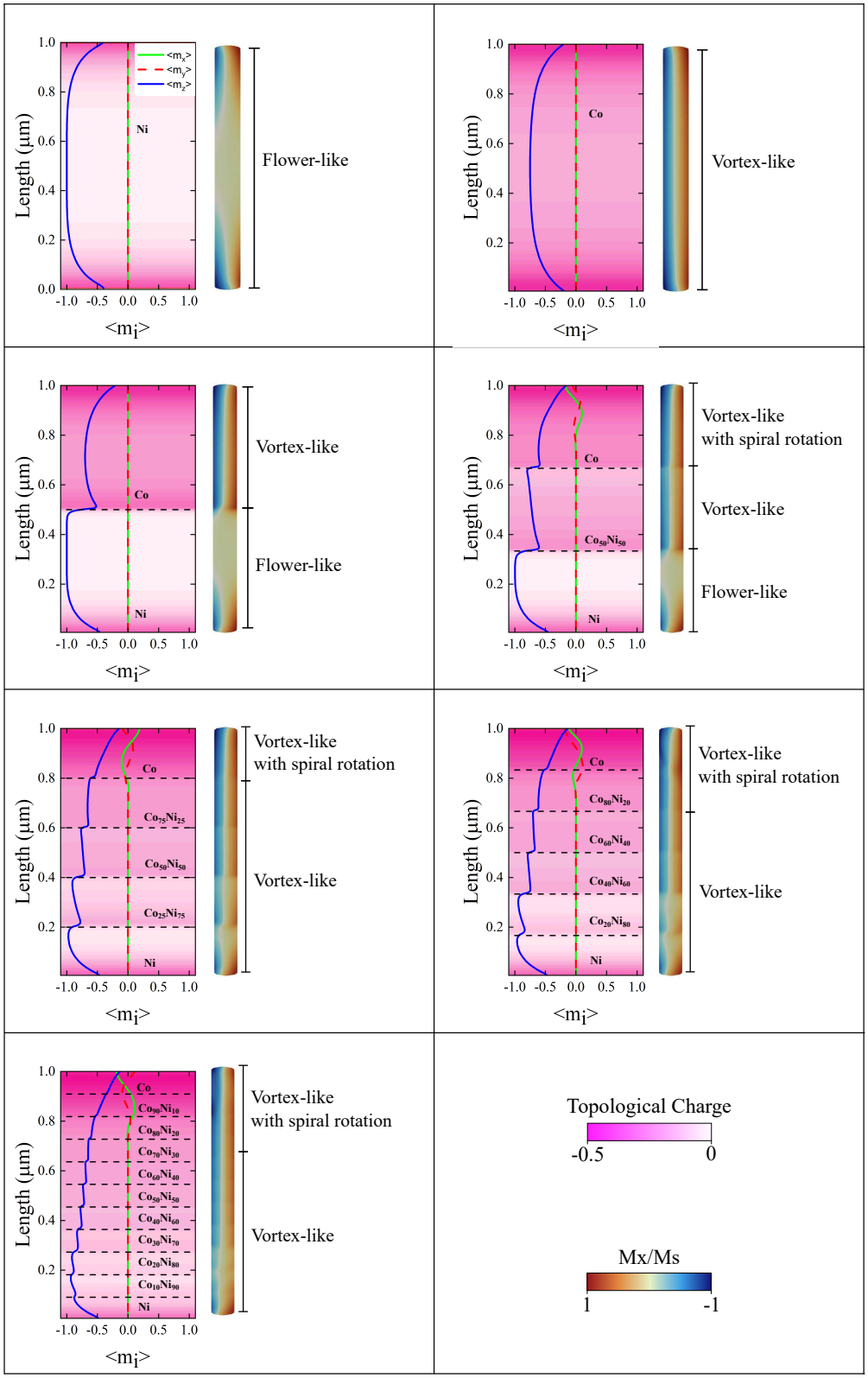


Figure 2. Equilibrium magnetic configurations of the homogeneous and multisegmented Co/CoNi/Ni nanowires obtained after energy minimization. The color scale represents the local magnetization component along the axis indicated beside each row. The spatially averaged magnetization components, $\langle m_x \rangle$, $\langle m_y \rangle$, and $\langle m_z \rangle$, are included to quantify the evolution of the magnetic state as a function of the longitudinal compositional architecture. The magenta background shows the mean topological charge calculated for each cross-sectional slice along the nanowire axis, thereby providing a quantitative measure of the transition between the different equilibrium magnetic configurations.

characteristic of Ni while simultaneously preventing the complete development of the vortex-like state favored by Co. As a result, the magnetization undergoes a continuous spatial reorientation across the interfaces, producing hybrid magnetic configurations[31,32] that combine axial and azimuthal components within the same nanowire.

As the number of longitudinal segments increases, the compositional gradient becomes progressively smoother and the magnetic textures evolve accordingly. The reduced compositional mismatch between neighboring segments weakens the local magnetic discontinuities, allowing Ni-rich regions to recover a larger axial magnetization component while Co-rich regions preserve their tendency toward curling magnetization. Instead of eliminating the hybrid character of the magnetic state, this smoother energy landscape promotes a gradual spatial transition between flower-like and vortex-like regions, giving rise to vortex-like spiral[33] configurations and increasingly complex three-dimensional magnetization textures.

The evolution of the spatially averaged magnetization components together with the mean topological charge further supports this interpretation. The progressive reduction of the axial magnetization component and the simultaneous increase in the transverse magnetization reveal that the system evolves continuously from the flower-like state characteristic of Ni toward increasingly vortex-dominated configurations as the influence of Co-rich regions becomes more pronounced. Rather than exhibiting abrupt magnetic transitions, the multisegmented nanowires display a continuous evolution driven by the local redistribution of magnetic energy across the compositional interfaces.

These results demonstrate that longitudinal compositional segmentation does not merely combine the magnetic characteristics of Co and Ni. Instead, it introduces a new degree of freedom for engineering the equilibrium magnetic state by tailoring the spatial distribution of magnetic energy within the nanowire. As shown in the following section, these hybrid magnetic configurations directly determine the organization of the spin-wave eigenmodes and ultimately govern the dynamic microwave response.

0.2 Internal Magnetic Interfaces Reorganize the Spin-Wave Eigenmode Spectrum

Figure 3 correlates the dynamic susceptibility spectra with the spatial distribution of the corresponding spin-wave eigenmodes for all investigated nanowire architectures. Rather than simply revealing shifts in the resonance frequencies, the results demonstrate that longitudinal compositional segmentation fundamentally reorganizes the spin-wave eigenmode spectrum. This reorganization is reflected not only in the spectral distribution of the resonances but also in the spatial localization and hybridization of the dynamic excitations, establishing a direct connection between the equilibrium magnetic configurations discussed above and the microwave response of the nanowires.

The two homogeneous nanowires define the limiting dynamic behaviors. The Ni nanowire exhibits a relatively simple spectrum dominated by low-frequency resonances within the L and C microwave bands. The lowest-frequency excitation corresponds to the characteristic edge mode[34,35], whose dynamic magnetization remains confined near the nanowire ends owing to the reduced internal effective field generated by magnetostatic effects[12,36]. As the resonance frequency increases, the oscillations progressively extend along the nanowire axis, giving rise to low-order standing spin-wave modes[37] with only a few longitudinal nodes. In contrast, the homogeneous Co nanowire displays a pronounced displacement of the resonance spectrum toward the X and Ku bands. The larger saturation magnetization together with the stronger magnetocrystalline anisotropy substantially increases the internal effective field, shifting the entire eigenmode spectrum toward higher frequencies. Simultaneously, the higher-order modes become increasingly localized near the nanowire surface, reflecting the stabilization of more complex dynamic magnetization textures.

The introduction of longitudinal compositional interfaces profoundly modifies this behavior. Instead of generating entirely new resonance families, compositional segmentation reorganizes the existing eigenmode spectrum. This effect manifests itself through three complementary processes: a redistribution of the spectral weight toward intermediate microwave frequencies, an increasing localization of the dynamic magnetization, and the hybridization of standing spin-wave modes extending across multiple magnetic segments. Consequently, the evolution of the spectra cannot be interpreted as the simple superposition of the responses of Co and Ni. Rather, the interfaces reshape the spatial distribution of the effective magnetic field, modifying the boundary conditions experienced by the propagating spin waves and, therefore, the eigenmodes supported by the nanowire.

This mechanism becomes progressively more evident as the degree of compositional segmentation increases. The two-segment architecture still preserves part of the high-frequency response characteristic of Co while simultaneously exhibiting the low-frequency resonances associated with Ni, producing hybrid excitations that extend across the compositional interface. Increasing the number of segments does not introduce additional resonance branches; instead, it continuously redistributes the dynamic response toward the C and X bands while suppressing the high-frequency Ku-band contribution. At the same time, the spatial mode profiles evolve from relatively extended standing waves to increasingly modulated excitations exhibiting pronounced confinement and hybridization over several neighboring segments. Particularly in the six- and eleven-segment nanowires, low-frequency edge modes become stabilized within the Ni-rich regions, whereas the intermediate-frequency resonances develop complex standing-wave patterns spanning multiple compositional interfaces.

These observations reveal that the principal effect of longitudinal compositional segmentation is not to increase the number

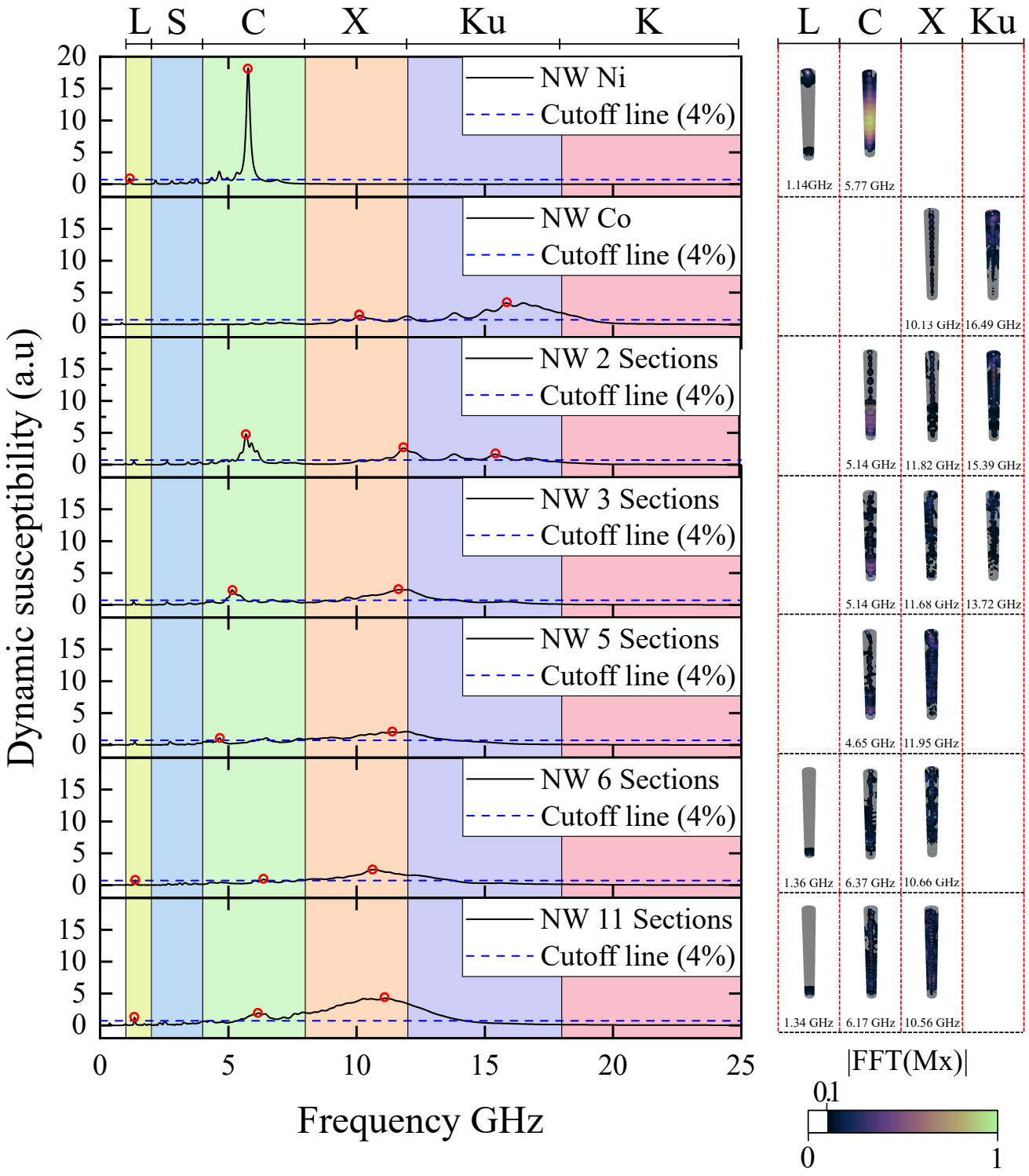


Figure 3. Dynamic susceptibility spectra together with the spatial distributions of the selected spin-wave eigenmodes for homogeneous and multisegmented Co/CoNi/Ni nanowires. The resonance frequencies selected for modal analysis are indicated by red circles and classified according to the standard microwave frequency bands (L, S, C, X, Ku, and K). The eigenmode profiles correspond to the Fourier amplitude of the dynamic magnetization component, M_x, where the color scale represents the normalized magnitude of $|\mathrm{FFT}(M_x)|$.

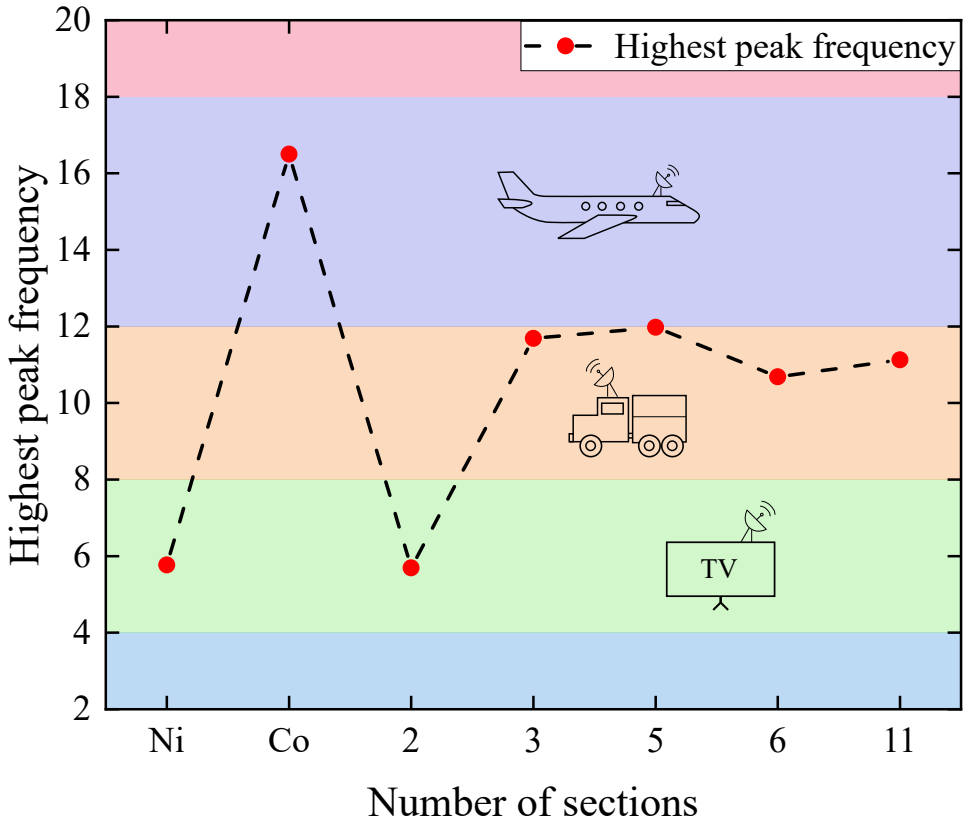


Figure 4. Evolution of the dominant ferromagnetic resonance frequency for homogeneous and multisegmented Co/CoNi/Ni nanowires. The symbols indicate the highest-intensity resonance extracted from the dynamic susceptibility spectra shown in Fig. 3. The shaded regions correspond to the standard microwave communication bands (C, X, Ku, and K), highlighting how longitudinal compositional segmentation, through the engineering of internal compositional interfaces, systematically tunes the dominant microwave response across technologically relevant frequency windows.

of accessible spin-wave modes, but to reorganize their spatial character. As the internal magnetic interfaces become more numerous, the magnetic energy landscape becomes progressively modulated along the nanowire axis, altering the local effective field experienced by the propagating magnons. This spatial modulation promotes mode confinement, modifies the coupling between neighboring oscillations, and redistributes the spectral intensity toward technologically relevant microwave bands. The interfaces therefore behave as internal scattering centers that reshape the spin-wave eigenmode spectrum without fundamentally changing its overall modal structure.

From a broader perspective, these results demonstrate that longitudinal compositional segmentation introduces an additional degree of freedom for engineering spin-wave dynamics. Unlike conventional strategies based exclusively on modifying the nanowire geometry or the average chemical composition, internal magnetic interfaces enable spatial control of the eigenmode distribution through local modulation of the magnetic energy landscape. This capability provides a versatile route for tailoring microwave responses in cylindrical nanowires while simultaneously expanding the range of accessible dynamic magnetic states.

0.3 Engineering Microwave Frequency Windows through Internal Magnetic Interfaces

Although the complete susceptibility spectra reveal the overall reorganization of the spin-wave eigenmodes, practical microwave applications are frequently governed by the dominant ferromagnetic resonance. Figure 4 therefore summarizes the evolution of the highest-intensity resonance as a function of the degree of longitudinal compositional segmentation, providing a compact representation of the principal microwave response of each nanowire architecture.

The two homogeneous nanowires define the accessible frequency limits of the investigated systems. The homogeneous Ni nanowire exhibits its strongest resonance within the C band at approximately 5.8 GHz, whereas the homogeneous Co nanowire shifts the dominant excitation toward the Ku band near 16.5 GHz. This large frequency separation reflects the markedly

different internal effective fields associated with the intrinsic magnetic properties of the two constituent materials.

Longitudinal compositional segmentation enables a continuous transition between these two limiting dynamic regimes. Introducing only a single compositional interface produces a dominant resonance that remains close to the C band, indicating that the dynamic response is still largely governed by the Ni-rich region. However, increasing the number of longitudinal segments progressively shifts the dominant excitation toward higher frequencies until it stabilizes within the X band. Beyond five segments, only minor frequency variations are observed, suggesting that the dynamic response approaches a saturation regime despite the increasing number of compositional interfaces.

This behavior demonstrates that the dominant microwave response is not determined solely by the average chemical composition but by the spatial distribution of magnetic properties along the nanowire. The progressive subdivision of the compositional gradient modifies the local magnetic energy landscape, redistributing the effective field experienced by the spin-wave modes and thereby shifting the principal resonance toward a targeted microwave frequency window. Consequently, compositional segmentation provides a simple yet powerful strategy for positioning the dominant ferromagnetic resonance within technologically relevant communication bands without altering the external dimensions of the nanowire.

From an application perspective, this capability is particularly attractive for frequency-selective microwave components, including magnonic waveguides, tunable resonators, and spin-wave-based signal-processing devices. Rather than relying on changes in geometry or external bias conditions, the operating frequency can be engineered directly through the internal compositional architecture of the nanowire, providing an additional degree of freedom for the design of multifunctional magnonic systems.

Conclusion

In this work, we demonstrated that longitudinal compositional interfaces provide an effective strategy for engineering the spin-wave spectra of cylindrical magnetic nanowires. By systematically increasing the degree of longitudinal compositional segmentation while preserving the overall geometry, we isolated the influence of internal magnetic interfaces on the equilibrium magnetic configurations and the resulting dynamic magnetic response.

Our results reveal that compositional interfaces reshape the magnetic energy landscape by locally modifying the competition between exchange, magnetostatic, and magnetocrystalline anisotropy energies. This redistribution of magnetic energy stabilizes hybrid magnetic configurations that evolve continuously from flower-like to vortex-like states as the compositional gradient becomes progressively discretized. Rather than simply combining the magnetic characteristics of Co and Ni, multisegmented architectures exhibit emergent magnetic textures arising from the interplay between neighboring regions with distinct intrinsic magnetic properties.

This evolution of the equilibrium magnetic state is directly reflected in the spin-wave dynamics through a systematic reorganization of the spin-wave eigenmode spectrum. Increasing the density of longitudinal compositional interfaces promotes mode localization, hybridization, and spectral-weight redistribution, enabling deterministic tuning of the dominant microwave response from the C band of homogeneous Ni nanowires toward the Ku band of homogeneous Co nanowires, while naturally stabilizing resonances within the technologically relevant X band.

Beyond the specific Co/CoNi/Ni system investigated here, our results establish longitudinal compositional interfaces as an effective design parameter for engineering spin-wave spectra in three-dimensional magnetic nanoarchitectures. By demonstrating that the dynamic response can be programmed through the internal magnetic architecture rather than by modifying the external geometry, this work provides a general framework for the rational design of next-generation magnonic waveguides, microwave resonators, and reconfigurable spin-wave devices.

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Author contributions statement

Felipe Sarria: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Eduardo Saavedra:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Alejandro Pereira:** Funding acquisition, Methodology, Writing – review & editing. **Juan Escrig:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

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