

Bulk-Mediated Reflection of Chirality-Protected Surface Spin Waves

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(Received 6 March 2026; revised 22 June 2026; accepted 21 September 2026; published 21 October 2026)

Surface spin waves of the Damon-Eshbach type exhibit intrinsically nonreciprocal transport properties with a chiral dynamical field structure that localizes counterpropagating waves at opposite film surfaces. Such chirality has been predicted to suppress direct backscattering in thin films within frequency ranges free of bulk modes. However, how chirality influences reflection in thicker three-dimensional magnetic media, where a dense spectrum of bulk excitations overlaps with surface waves, remains unclear. Here we demonstrate that, in micrometer-thick yttrium iron garnet films, reflection of the chiral Damon-Eshbach wave from the boundary of the magnetic medium is accompanied by excitation of spatially localized thickness-quantized bulk modes, whereas reciprocal backward-volume waves reflect nearly elastically. Brillouin light scattering spectroscopy, infrared thermography, and micromagnetic simulations reveal standing bulk excitations at the reflecting boundary and quantify the associated magnon energy accumulation and dissipation. These results identify bulk-mode excitations as the physical pathway enabling reversal of chirally localized surface waves in thick films, thereby defining the limits of chirality-based backscattering immunity and providing a general framework for wave transport in nonreciprocal magnetic media.

DOI: [10.1103/hgvh-s6h5](https://doi.org/10.1103/hgvh-s6h5)

Chirality has emerged as a unifying concept across modern magnetism and spintronics, shaping both the structure of magnetic textures and the dynamics of spin excitations [1]. In magnetic systems, the intrinsic breaking of time-reversal symmetry encoded in the Landau-Lifshitz dynamics provides a natural basis for chiral effects. Magnetodipolar interactions can lift the symmetry between counterpropagating spin-wave states, giving rise to nonreciprocal modes with asymmetric dynamical magnetization and field profiles and enabling the formation of chiral spin waves via hybridization of modes with opposite parity [2]. In two-dimensional magnonic crystals, the dipolar coupling can produce topologically protected chiral edge states residing within bulk band gaps [3]. In continuous magnetic films, a prominent realization of magnetodipolar chirality is the Damon-Eshbach magnetostatic surface wave [4,5], which exhibits intrinsically nonreciprocal propagation with asymmetric surface localization and a handed dynamical

field structure across the film thickness. Recent studies have emphasized that the nonreciprocal surface localization and propagation properties of Damon-Eshbach waves can be interpreted in terms of their chiral and topological character [6].

Indeed, micromagnetic simulations have demonstrated suppression of direct backscattering of Damon-Eshbach waves from surface topographic defects in thin films within frequency ranges where bulk modes are absent for collinear propagation [7]. However, these frequency windows do not constitute a true two-dimensional bulk band gap since bulk excitations remain available if the direction of the scattered wave vector is changed—unlike the fully gapped topological edge states in two-dimensional magnonic crystals [3]. Moreover, the considered geometry involves scattering from a shallow surface defect rather than from the termination of the magnetic medium. In thicker magnetic films, where a dense continuum of thickness-quantized bulk modes overlaps spectrally with surface waves (see the spin-wave spectrum in Fig. 1), spectral isolation of the surface mode is absent, and it remains unclear to what extent chirality can influence reflection under such fully gapless spectral conditions.

Here, we demonstrate that reflection of the chiral Damon-Eshbach wave from the edge of a magnetic waveguide involves excitation of spatially localized thickness-quantized volume modes, which provide a pathway for

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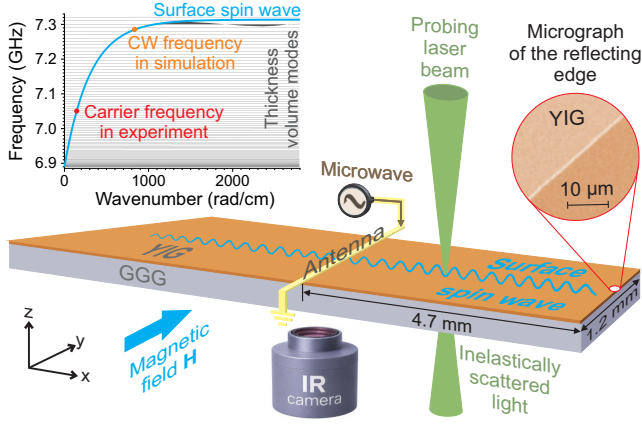


FIG. 1. Experimental geometry, spin-wave spectrum, and measurement scheme. Spin waves are excited in an in-plane magnetized, single-crystalline 16 μm -thick YIG waveguide by a microwave stripline antenna and propagate toward a reflecting edge oriented perpendicular to the waveguide axis. Right close-up: a micrograph of the cleaved reflecting edge forming the spin-wave mirror. The shown external magnetic field corresponds to the Damon-Eshbach geometry; the reference reciprocal backward-volume configuration is realized by aligning the external magnetic field along the waveguide. Upper-left inset: the calculated spin-wave spectrum for the experimental parameters, illustrating the spectral overlap between the Damon-Eshbach surface wave branch and the dense spectrum of thickness-quantized bulk modes [8]. Spin-wave intensity is measured by space- and time-resolved Brillouin light scattering (BLS) spectroscopy, and dissipated magnon energy is independently mapped by infrared thermography.

relocating the surface wave across the film thickness without direct backscattering. Using Brillouin light scattering (BLS) spectroscopy, micromagnetic simulations, and infrared thermography, we directly identify this bulk-mediated reflection pathway and quantify the accompanying magnon energy accumulation and dissipation.

Figure 1 schematically illustrates the sample geometry and the experimental techniques employed in this Letter. In our experiments, we investigated the reflection of magnetostatic spin waves from the end of a spin-wave waveguide prepared from a single-crystalline yttrium iron garnet film (YIG, $\text{Y}_3\text{Fe}_5\text{O}_{12}$) of 16 μm thickness grown on a gadolinium gallium garnet (GGG) substrate. The waveguide is 1.2 mm wide and 18 mm long. One end of the YIG stripe is mechanically cleaved perpendicular to the waveguide axis, forming a well-defined reflecting boundary with minimal edge damage and reduced defect-induced scattering. The opposite end is tapered at 45° to suppress spurious backscattering. The spin waves are excited by a microwave-driven stripline antenna of 50 μm width placed across the waveguide 4.7 mm apart from its right-angled end. The antenna is mounted on a narrow dielectric bridge, providing optical access to the sample from both sides for BLS measurements. The YIG stripe was magnetized in plane by a bias field $H = 1750$ Oe either across or along its long

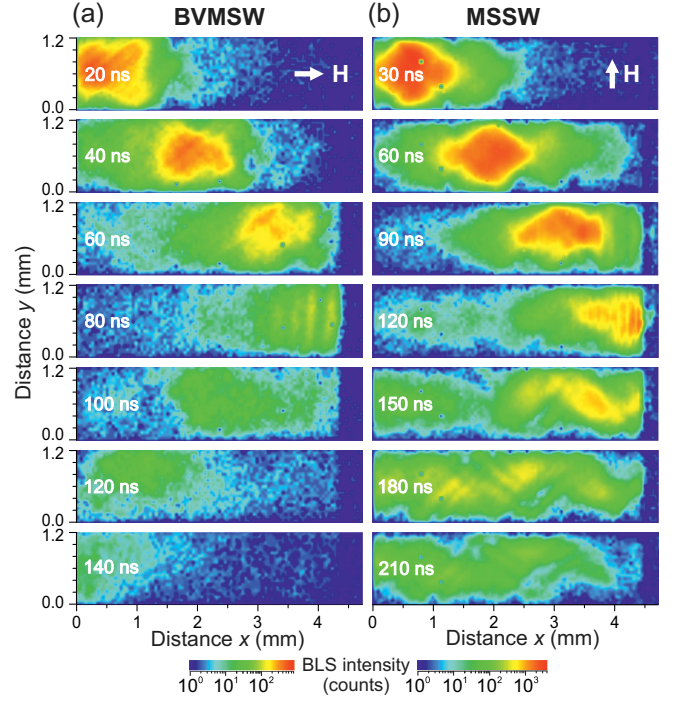


FIG. 2. Time-resolved spatial intensity maps of incident and reflected spin-wave packets in the YIG waveguide. (a) Reciprocal backward-volume waves (BVMSW) retain their shape upon reflection, consistent with elastic scattering from the edge. (b) Chiral Damon-Eshbach surface waves (MSSW) exhibit strong distortion and elongation of the reflected packet, consistent with bulk-mediated reflection. Maps show the BLS intensity of 20 ns pulses at successive delay times in false color logarithmic scale. Because of the different group velocities of BVMSWs and MSSWs (approximately 6.4 $\text{cm}\mu\text{s}^{-1}$ and 4.6 $\text{cm}\mu\text{s}^{-1}$, respectively), the selected time moments correspond to comparable stages of the wave-packet propagation and reflection dynamics within the waveguide. $x = 0$ marks the antenna position.

axis. The first case corresponds to the excitation and propagation of a nonreciprocal magnetostatic surface spin wave (MSSW, Damon-Eshbach wave), and the second one corresponds to a reference case of the reciprocal backward volume magnetostatic spin wave (BVMSW) [5,10–12]. In both cases, the spatiotemporal spin-wave dynamics was measured by means of space- and time-resolved BLS spectroscopy [13] in forward-scattering geometry, where the light inelastically scattered by spin waves is collected after transmission through the film and directed to a multipass Fabry-Pérot interferometer for frequency and intensity analysis [14].

The time-resolved BLS maps of the propagating wave packets are shown in Fig. 2. To separate incident and reflected signals, the excitation was performed using 20 ns-long microwave pulses at 6.89 GHz (BVMSW) and 7.05 GHz (MSSW), with a repetition period of 800 ns. In both cases, the carrier frequency was approximately 150 MHz away from the uniform precession frequency corresponding to the respective experimental geometry

[15], ensuring a match between the spin-wave spectrum and the Fourier spectrum of the short input pulses. With this choice of operating frequencies, the efficiency of spin wave excitation was found to be relatively low, and the transition to nonlinear regimes of spin-wave packet propagation, which could manifest itself in the formation of solitons, bullets, their nonlinear decay, or even collapse [16], was not observed even at fairly high peak input powers. Because of the different excitation efficiencies of the two modes, the applied powers were adjusted to 630 mW for BVMSW and 100 mW for MSSW to obtain comparable spin-wave amplitudes.

Both wave types propagate from the antenna to the waveguide end without qualitative differences. Their reflection behavior, however, differs markedly. The BVMSW packet retains its shape upon reflection [17,18], and the oscillatory intensity near the edge matches the carrier wavelength, consistent with interference of the incident and reflected waves and elastic scattering at the boundary [Fig. 2(a)].

For MSSWs, a clear interference pattern also develops near the reflecting edge; however, unlike in the BVMSW case, the reflected packet becomes progressively elongated and develops a pronounced snakelike spatial structure at later delay times (150–220 ns). Similar structured spin-wave intensity patterns are known to arise from coherent superposition of multiple spin-wave modes in waveguide systems [19]; see also the review by Zheng *et al.* [20] for a broader overview of spin-wave propagation phenomena in confined geometries.

The observed temporal elongation of the reflected MSSW packet cannot be attributed solely to the finite spectral width of the excitation pulse and the resulting dispersion of MSSW group velocities. For the excitation bandwidth of approximately 100 MHz, the MSSW group velocities are estimated to lie in the range of $4.3 \text{ cm } \mu\text{s}^{-1}$ to $6.4 \text{ cm } \mu\text{s}^{-1}$. According to these velocities, the entire reflected pulse would be expected to leave the observation region by approximately 210 ns. The experimentally observed persistence of the reflected signal beyond this time, therefore, cannot be explained by pulse dispersion alone. In addition, transient intensity minima and localized near-edge features appear during reflection, indicating that the scattering region develops a complex internal structure. Together, these observations show that, although coherent reflection of MSSWs is preserved, the reflected signal does not retain the spatiotemporal structure expected for purely elastic single-mode reflection.

To clarify the microscopic origin of this nonelastic reflection behavior, we performed micromagnetic simulations [21] of the experimental geometry (see Fig. 3). Because modeling the full 18 mm-long sample is computationally prohibitive, a reduced-size $16 \text{ } \mu\text{m}$ -thick YIG waveguide of $4 \text{ mm} \times 1 \text{ mm}$ was simulated. The structure was discretized into $400 \times 100 \times 8$ cells. Spin waves were excited by a microwave field generated by a $50 \text{ } \mu\text{m}$ -wide

antenna placed 1.5 mm from the reflecting edge, while damping boundary conditions suppressed spurious reflections from the opposite end.

For the BVMSW geometry, the simulations reproduce the BLS observations: the incident and reflected packets retain nearly identical shapes, and the oscillations at the edge match the carrier wavelength, consistent with elastic reflection.

In the MSSW geometry under the experimental conditions, substantial interference between the incident and reflected surface waves obscures possible bulk contributions. Because the MSSW amplitude decays across the film thickness approximately as $\exp(-2\pi z/\lambda)$, a reduction of the wavelength increases the surface localization and thereby decreases the spatial overlap of counterpropagating waves residing at opposite film surfaces. To exploit this effect, the excitation frequency was increased by 235 MHz to 7.285 GHz, shortening the wavelength from approximately $435 \text{ } \mu\text{m}$, calculated for the experimental conditions, to $75 \text{ } \mu\text{m}$ and thus suppressing trivial interference. Continuous excitation was further used to avoid spectral broadening of pulsed signals. These modified conditions were introduced solely to enhance the visibility of bulk modes in the simulations. Additional microwave transmission measurements show that the MSSW transmission at 7.285 GHz becomes strongly suppressed under the experimental conditions, preventing reliable time-resolved BLS detection at this frequency.

Under these conditions, the simulated profiles shown in Fig. 3 reveal clear standing oscillations across both the film thickness and width near the reflecting edge. Far from the boundary, the MSSW retains its characteristic surface localization, whereas close to the edge the profiles develop multiple nodes characteristic of thickness- and width-quantized bulk modes. The emergence of these localized standing modes identifies bulk excitations that mediate the reflection of the surface wave. In addition, the integrated spin-wave intensity follows the expected exponential decay far from the reflecting edge, while strong deviations from this behavior emerge near the boundary due to the excitation of localized bulk modes.

The excitation of edge-localized thickness- and width-quantized bulk modes provides a natural explanation for the anomalous reflection dynamics observed in the BLS measurements. The coexistence of these modes with the incident and reflected MSSWs introduces additional oscillatory components with different spatial profiles and propagation characteristics. Their superposition leads to a complex interference pattern, giving rise to the elongated snakelike structure of the reflected signal observed at later delay times in Fig. 2(b). At the same time, partial trapping of spin-wave energy in the edge-localized quantized modes increases the characteristic lifetime of the reflected excitation, consistent with the experimentally observed temporal elongation of the reflected packet.

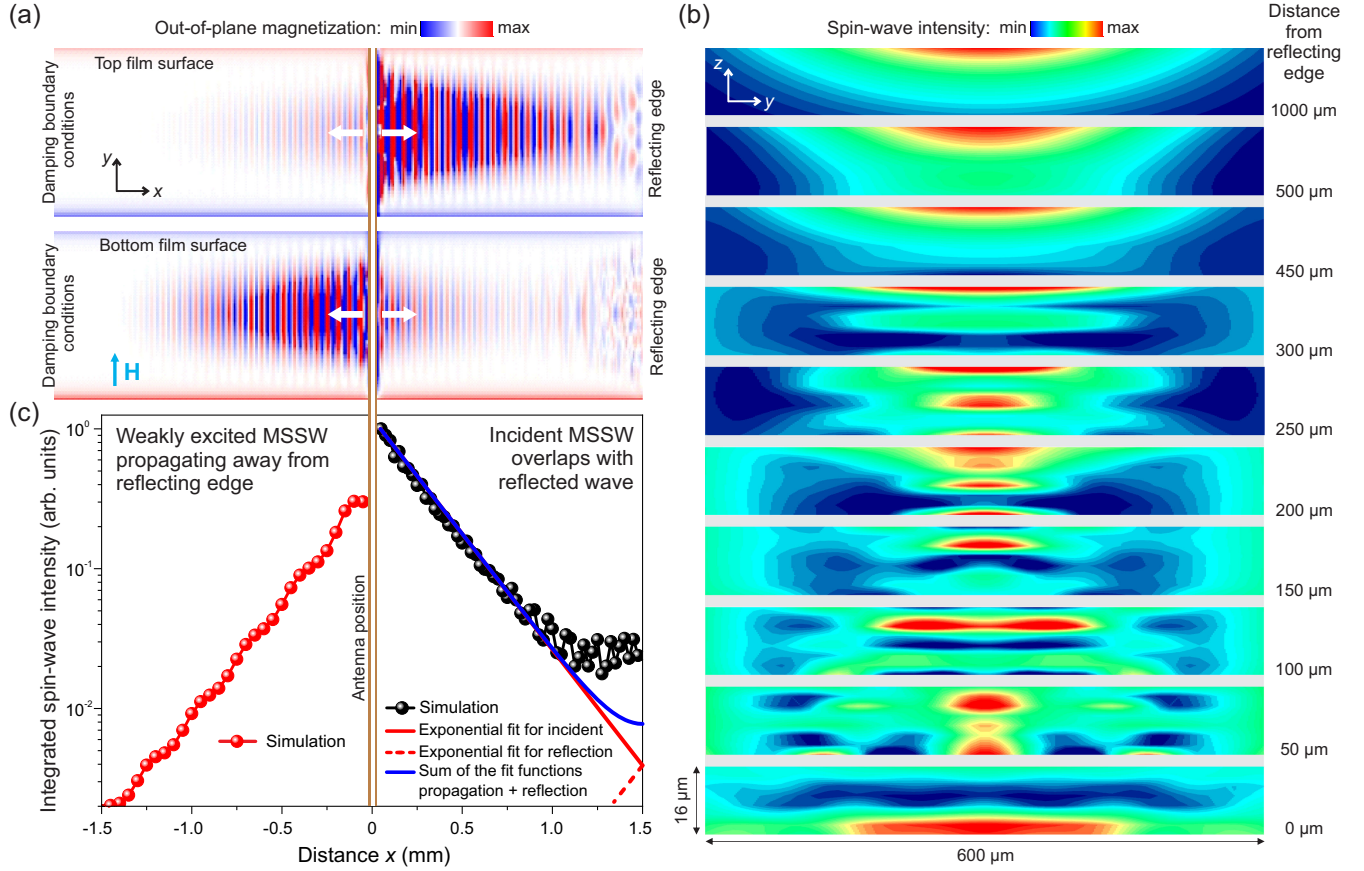


FIG. 3. Micromagnetic simulations revealing bulk-mediated reflection of the MSSW. (a) Spatial distributions of the out-of-plane dynamic magnetization at the top and bottom film surfaces, demonstrating the nonreciprocal surface localization and excitation of MSSWs propagating in opposite directions from the antenna. Near the reflecting boundary, the MSSW spatial distribution becomes strongly distorted. (b) Cross sections of the spin-wave intensity across the film thickness and width at different distances from the reflecting edge, revealing the emergence of standing thickness- and width-quantized bulk modes near the boundary. (c) Spin-wave intensity integrated over the waveguide cross section as a function of distance from the microstrip antenna. Far from the reflecting edge, the MSSW intensity follows the expected exponential decay, whereas pronounced deviations emerge near the boundary due to the excitation of localized bulk modes. Continuous excitation at 7.285 GHz is used to suppress spectral broadening and resolve the bulk-mode excitations.

Conventional BLS is insensitive to bulk modes with wave-vector components across the film thickness [14]. To obtain an independent signature of their excitation, we employed infrared thermography, which directly probes the spatial distribution of magnon energy dissipation. The film surface was imaged with spatial resolution of 135 μm using an infrared camera (FLIR SC655) with a thermal sensitivity of 0.05 K. The thermographic measurements shown in Fig. 4 were performed under the same pulsed excitation conditions as the BLS measurements presented in Fig. 2, enabling direct comparison between the measured spin-wave propagation patterns and the resulting heat accumulation. Because the thermal camera capturing time is much longer than the characteristic spin-wave propagation time, the measured thermographic images represent time-integrated temperature distributions. The thermographic images, therefore, do not represent the instantaneous

spin-wave intensity distribution. Instead, they visualize the spatial distribution of heat released by magnons during their finite lifetime, integrated over many excitation cycles. The shown temperature profiles were obtained by averaging six lines along the waveguide axis, spaced equidistantly across its width. The normalized temperature rise is defined as $\tilde{T}(x) = [T(x) - T_{\text{ref}}]/[T_{\text{max}} - T_{\text{ref}}]$, where T_{ref} is the spatially averaged temperature measured on the substrate outside the YIG waveguide. To compare the spatial heating profiles independently of the absolute heating amplitude, the temperature distributions were normalized to their respective maximum values.

The measured temperature maps are shown in Fig. 4. For the reciprocal BVMSW case, the heating profile extends on both sides of the antenna and gradually decays toward both ends of the waveguide, consistent with propagation losses of a bidirectional wave.

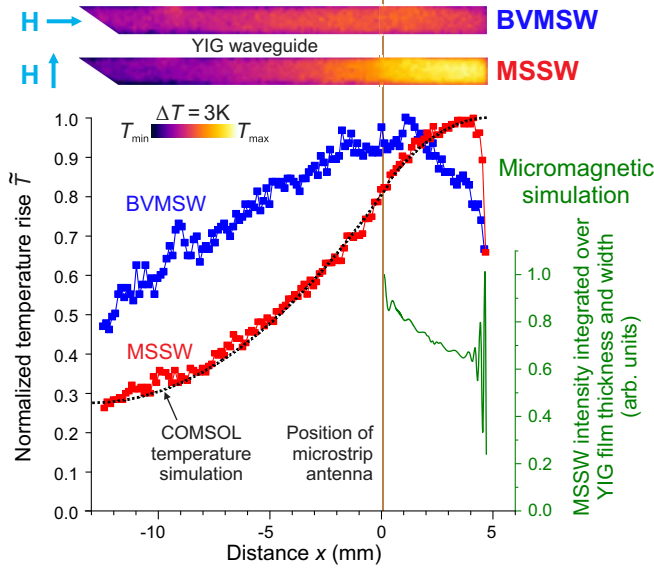


FIG. 4. Infrared thermography of magnon-induced energy dissipation for reciprocal BVMSWs and chiral MSSWs. Insets: infrared images of the YIG waveguide with identical temperature scales ($\Delta T = 3$ K). BVMSWs exhibit bidirectional heating with the temperature gradually decreasing away from the antenna region toward both ends of the waveguide. MSSWs display a strongly asymmetric heating profile, in which the temperature maximum forms near the reflecting edge instead of at the antenna, indicating localized energy accumulation associated with bulk-mediated reflection. The plotted profiles show the normalized temperature rise $\tilde{T}(x)$. The sharp temperature decrease at the waveguide termination for both wave types originates from the finite spatial resolution of the thermographic measurements and the finite extent of the magnetic medium. The vertical stripe indicates the position of the microstrip antenna. The green curve shows the spin-wave intensity profile obtained from micromagnetic simulations performed under conditions corresponding to the thermography experiment and used as the heating source in the COMSOL calculations. The black curve shows the resulting COMSOL-calculated temperature profile.

A qualitatively different behavior is found for MSSWs. Instead of a monotonic decay, the temperature increases toward the reflecting edge and exhibits a pronounced maximum at the sample boundary (red squares in Fig. 4), while decreasing in the opposite direction. Notably, the dissipation maximum is spatially separated from the excitation region, demonstrating nonlocal energy conversion during reflection.

Although nonreciprocal MSSW excitation is known to enable a unidirectional heat conveyor functionality [22], that effect leads to heating localized near the antenna, where the waves are launched. By contrast, the temperature maximum observed here appears at the reflecting boundary. The weak heating reported at the tapered tip in Ref. [22] originates from geometric concentration of spin waves and is not applicable to the present uniform geometry. Therefore, the observed edge heating cannot be explained solely by the heat-conveyor mechanism.

Instead, the temperature increases precisely in the region where the simulations predict excitation of thickness- and width-quantized bulk modes. This mechanism requires a sufficiently large spin-wave intensity at the reflecting edge. Under the experimental conditions, the relatively high group velocity ensures that a significant fraction of the spin-wave energy reaches the boundary, enabling efficient excitation of localized bulk modes and the resulting heat accumulation.

To model the experimentally observed heating profile, we performed separate micromagnetic simulations in a pulsed regime under the thermography experiment conditions. The resulting spatial distribution of spin-wave intensity, integrated over the film cross section and time, is shown by the green curve in Fig. 4. This profile was used as a spatially distributed heating source in COMSOL simulations of thermal transport within the YIG-GGG structure, assuming local energy dissipation proportional to the spin-wave intensity. Accounting for thermal diffusion within the YIG-GGG structure, we calculated the resulting temperature profile along the waveguide (black dotted line in Fig. 4). The calculated curve is shown on an arbitrary vertical scale since the thermal model aims to reproduce the spatial temperature profile rather than the absolute heating amplitude. The calculated and measured profiles exhibit the same spatial trend. This correspondence provides independent support for the interpretation that bulk-mode excitation and subsequent relaxation dominate the surface-wave reflection process.

Taken together, experiments and micromagnetic simulations show that reflection of magnetostatic surface waves is governed by excitation of thickness-quantized bulk modes near the boundary. Because electrodynamic boundary conditions enforce a chiral surface-localized mode profile, elastic reversal of an MSSW would require the mode to be effectively relocated across the film thickness, thereby constituting a strong suppression mechanism for direct elastic reflection. Excitation of bulk modes provides the additional spatial degrees of freedom required to satisfy the boundary conditions at the waveguide termination. As a result, reflection proceeds through mode conversion involving thickness-quantized bulk modes, which redistribute the dynamic magnetization across the film thickness and enhance local dissipation at the edge.

In summary, while the edge of a magnetic medium acts as an almost perfect mirror for reciprocal backward-volume waves, reflection of chiral surface waves occurs through bulk-mode mediation rather than direct backscattering. This mechanism explains the long-standing observation that surface waves are weakly reflected by thickness modulations [23] and clarifies the limits of chirality-based backscattering protection in realistic geometries. We show that chirality-protected immunity remains robust against direct backscattering even in micrometer-thick, purely dipolar films, where reversal becomes possible only

through excitation of thickness- and width-quantized bulk modes. These findings are directly relevant for studies of nonreciprocal spin-wave dynamics [24], magnon-phonon conversion [25], and energy localization in magnetic waveguides [22]. They are also important for the design of spin-wave resonators [26], magnonic crystals [27], and interference-based microwave devices, including emerging spin-wave RF platforms envisioned for 5G and 6G communication technologies [28].

Acknowledgments—This research was funded in part by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) in the framework of TRR 173 under Grant No. 268565370 “Spin+X” (Projects No. B01 and No. B13) and by the Austrian Science Fund (FWF) [Grant DOI: 10.55776/PIN1434524] through Project MagNeuro. The authors are grateful to V. S. Tyberkevych for fruitful discussions.

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.

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