

Exchange spin-wave propagation in gallium-substituted yttrium iron garnet nanowaveguides

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Spin-wave-based computing has emerged as a promising approach to overcome the fundamental limitations of complementary metal-oxide-semiconductor technologies. However, the increasing demand for device miniaturization down to a 100 nm scale presents significant challenges for long-distance spin-wave transport. Gallium-substituted yttrium iron garnet (Ga:YIG) offers a potential solution to these challenges due to its unique magnetic properties. The reduced saturation magnetization in Ga:YIG enables efficient excitation of exchange-dominated spin waves, which exhibit enhanced transport characteristics compared with dipolar-dominated modes in conventional materials. Here, we present the first comprehensive study combining experimental, analytical, and numerical investigations of spin-wave propagation in Ga:YIG waveguides down to 145 nm width and 73 nm thickness. Using microfocused Brillouin light scattering spectroscopy, TetraX simulations, and analytical dispersion calculations, we demonstrate that Ga:YIG waveguides support spin waves with significantly higher group velocities up to 600 m/s. This value remains constant for structures with different widths, leading to longer spin-wave propagation lengths in nanowaveguides compared with nonsubstituted YIG. These results reveal that gallium substitution provides access to faster and longer-lived spin waves, opening significant possibilities for implementing this material in nanoscale magnonic devices.

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I. INTRODUCTION

Magnonics, the field that utilizes spin waves for information transport and processing, has emerged as a promising solution to overcome the fundamental limitations of complementary metal-oxide-semiconductor (CMOS) technologies [1,2]. Spin-wave-based computing offers several key advantages over conventional electronics, including scalability down to atomic dimensions, operation in the GHz-to-THz frequency range, and inherent nonlinearity for logic and beyond-Boolean operations [3–6]. Recent advances in inverse-design methods have further accelerated the development of magnonic logic devices by enabling

the systematic design of functional elements with predetermined characteristics, opening alternative pathways for complex spin-wave circuits [7–11].

The evolution of magnonic devices has progressed rapidly from initial millimeter-scale prototypes [12–14] to current nanoscale implementations [15–17]. While recent demonstrations have shown successful operation of magnonic logic elements with submicrometer dimensions [18], the demands for further miniaturization continue to grow to meet the requirements of integrated circuit applications. This scaling down necessitates the development of increasingly narrow waveguides and thin-film magnetic structures. However, reducing waveguide dimensions typically leads to decreased spin-wave group velocities and shorter propagation lengths, even in low-damping materials such as yttrium iron garnet (YIG) [19]. While switching to the Damon-Eshbach configuration can partially address these limitations, it introduces complications including challenging on-chip integration, complex multimode structures, and nonuniform field distributions

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across the waveguide cross section [20–22]. Alternative approaches using metallic ferromagnetic structures suffer from even higher magnetic damping, further limiting their practical applicability [23,24].

A promising solution to these challenges lies in the utilization of gallium-substituted yttrium iron garnet (Ga:YIG) [25], which provides access to long-wavelength exchange-dominated spin waves that remain detectable using conventional microfocused Brillouin light scattering (μ BLS) techniques [26,27]. The reduced saturation magnetization in Ga:YIG significantly increases the exchange length parameter, making exchange interactions dominant over dipolar interactions even at relatively long wavelengths. Such spin waves are easily excited and detected using conventional microwave and optical techniques, unlike more complex approaches involving exchange waves [28–30]. Crucially, the group velocity of exchange-dominated spin waves in Ga:YIG exhibits minimal dependence on waveguide width, making this material an ideal candidate for nanoscale magnonic applications [27,31].

In the present study, we experimentally investigate spin-wave propagation in Ga:YIG nanowaveguides with widths down to 145 nm. Our results demonstrate that both propagation lengths and group velocities in these nanostructures are several times greater than those achieved in conventional YIG waveguides of comparable dimensions, despite the slight increase in Gilbert damping parameter that accompanies gallium substitution [19]. Through a comprehensive approach combining μ BLS spectroscopy, numerical simulations, and analytical modeling in the backward-volume geometry, we establish the superior performance characteristics of Ga:YIG for nanoscale magnonic applications.

II. METHODS AND MATERIALS

A. Ga:YIG nanowaveguides fabrication

The nanowaveguides were fabricated from a 73-nm-thick Ga:YIG film grown on a 500 μ m-thick (001)-oriented gadolinium gallium garnet (GGG) substrate via liquid phase epitaxy [25]. This growth technique ensures excellent crystalline quality and provides magnetic films with low Gilbert damping parameters [32]. Vibrating sample magnetometry (VSM) measurements of the Ga:YIG film revealed a saturation magnetization of $M_s = 22.76 \text{ kA m}^{-1}$, which is approximately one order of magnitude smaller than that of nonsubstituted YIG [33]. This reduced magnetization yields a significantly increased exchange length $\lambda_{\text{ex}} = (2A_{\text{ex}}/(\mu_0 M_s^2))^{1/2}$, making exchange interactions dominant in governing spin-wave propagation in Ga:YIG [27]. Based on reference measurements of saturation magnetization in similar material systems [25], the Gallium concentration in the film is estimated to be approximately 1 formula unit (f.u.).

An additional characteristic of the investigated material is the presence of stress-induced out-of-plane uniaxial anisotropy arising from the crystallographic lattice mismatch between the Ga:YIG film and the GGG substrate [25,34]. Ferromagnetic resonance (FMR) measurements determined the uniaxial anisotropy field strength as $\mu_0 H_{\text{an}} = 73.6 \pm 0.6 \text{ mT}$, the gyromagnetic ratio $\gamma = 178.8 \text{ rad ns}^{-1} \text{ T}^{-1}$, and the Gilbert damping parameter $\alpha = 7.53 \times 10^{-4}$ [35–39]. This value is higher than the typical damping of nonsubstituted YIG ($\alpha \approx 2 \times 10^{-4}$), which is known for its exceptionally long magnon lifetimes [32,33]. The increased damping in Ga:YIG leads to a reduction in the intrinsic spin-wave lifetime.

Nanowaveguides of varying widths were patterned on the Ga:YIG film using electron-beam lithography (30 keV, 30 pA) followed by argon ion-beam milling [22,40]. For spin-wave excitation, coplanar waveguide (CPW) antennas [41] were fabricated on top of the waveguides through electron-beam evaporation and subsequent lift-off processes. The example waveguide and antenna configuration, along with scanning electron microscopy (SEM) image of the nanofabricated structure, are shown in Fig. 1(b).

B. Time-resolved μ BLS measurements

Spin-wave characterization was performed using μ BLS spectroscopy, a well-established technique for the investigation of spin-wave dynamics with high spatial and time resolution [42,43]. The experimental setup employs a continuous-wave single-frequency laser operating at 457 nm wavelength, focused onto the sample through a microscope objective with high numerical aperture. The laser power was maintained at $(3.0 \pm 0.2) \text{ mW}$ on the sample surface to minimize thermal effects while ensuring sufficient signal intensity for reliable measurements [19,28]. The inelastically scattered light is analyzed using a tandem Fabry-Pérot interferometer (TFPI), providing frequency resolution suitable for detecting spin-wave modes in the GHz range. The measured BLS intensity is directly proportional to the spin-wave intensity, enabling quantitative analysis of the magnonic properties.

To determine spin-wave group velocities, time-resolved μ BLS measurements were performed using the experimental setup shown in Fig. 1(a). The time-resolved technique relies on synchronized pulsed microwave excitation and photon detection to track spin-wave packet propagation. An rf source connected to a pulse generator produces microwave pulses that are applied to the CPW antenna to excite spin-wave packets in the nanowaveguide. The pulse generator simultaneously triggers the time-of-flight data acquisition system, establishing a precise temporal reference for the measurement [42,44]. During the measurement, individual photons scattered from the propagating spin-wave packets are detected by the photodetector and their arrival times are recorded.

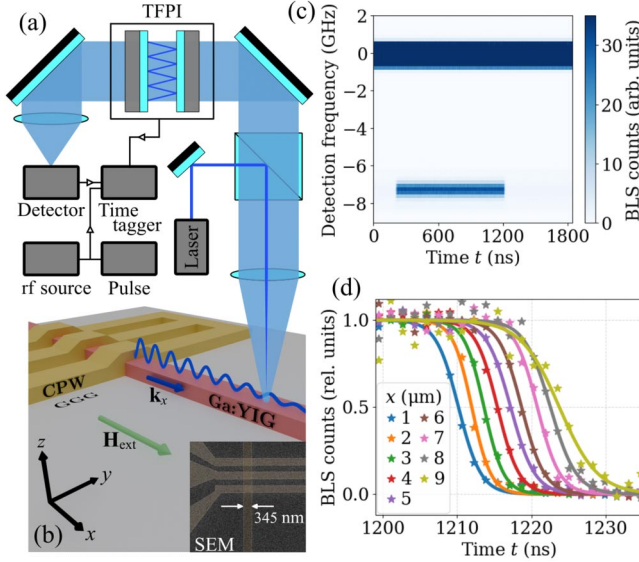


FIG. 1. (a) Schematic representation of the μ BLS measurement system showing the laser beam path from the sample through the TFPI to the photodetector. The detection system is synchronized with the rf source and pulse generator to enable time-resolved measurements of spin-wave propagation. (b) Experimental configuration showing the Ga:YIG nanowaveguide orientation with respect to the external magnetic field H_{ext} applied in the backward-volume geometry, and the CPW antenna used for spin-wave excitation. The SEM image (inset) shows the fabricated nanowaveguide with width 345 nm. (c) Time-resolved BLS spectrum showing the detection of a 1000 ns microwave pulse. The scattered magnon signal is detected at the spin-wave frequency, while the unscattered reference light appears at zero frequency. (d) Example time traces used for group velocity determination, measured over an 8 μm propagation path from the antenna. The evolution of the pulse cut-off position at different spatial positions ($x = 1$ to 9 μm) demonstrates the spin-wave packet propagation along the nanowaveguide, where x indicates the distance from the antenna edge. A sigmoid function was used to approximate the data and determine the exact position of the falling edge of each pulse.

For the group velocity determination, microwave pulses with a duration of 1000 ns were applied, and the scattered signal corresponding to the spin-wave was then detected at the frequency of the CPW antenna excitation (6.9 GHz in this particular example), as shown in Fig. 1(c). This signal was normalized to the unscattered reference signal detected simultaneously at the same time. Subsequently, this measurement was performed at different positions along the waveguide over an 8 μm path to determine the evolution of the falling edge of the pulse [Fig. 1(d)]. To precisely determine the temporal position of the falling edge t_0 , the acquired data at each spatial location was fitted with a sigmoid function:

$$f(t) = [1 + e^{a(t-t_0)}]^{-1}, \quad (1)$$

where the parameter a controls the incline of the sigmoid function and is also being fitted. The group velocity was then determined from the falling edge time position evolution over the 8 μm propagation distance by calculating the slope of the time-distance relationship.

Another significant characteristic investigated using μ BLS was the spin-wave decay length in the nanowaveguides. To determine this parameter, the spin-wave intensity was measured along a 20 μm path with a 1 μm step size. The amplitude decay rate over distance was then analyzed and fitted using the exponential decay function:

$$I(x) = I_1 \exp\left(-\frac{2x}{L_d}\right) + I_0, \quad (2)$$

where $I(x)$ is the measured BLS intensity at position x , I_1 is the initial spin-wave intensity close to the CPW antenna, L_d is the decay length, and I_0 is the background signal level. The factor of 2 in the exponent accounts for the fact that μ BLS measures the intensity of the spin waves, which is proportional to the square of the precession amplitude [19].

To ensure backward-volume geometry, an external magnetic field of 255 mT was applied parallel to the direction of spin-wave propagation. The experimental configuration on the sample is shown in Fig. 1(b). The study was performed at room temperature.

C. Numerical and analytical calculations

To interpret the experimental results, the spin-wave dispersion relation $\omega(k_x)$ was calculated analytically in the backward-volume geometry using established theoretical framework [19,45,46] while accounting for the uniaxial anisotropy present in Ga:YIG:

$$\omega^2(k_x) = [\omega_H + \omega_M(F_y(k_x) + \lambda_{\text{ex}}^2 k_x^2)] \times [\omega_H - \omega_{\text{an}} + \omega_M(F_z(k_x) + \lambda_{\text{ex}}^2 k_x^2)], \quad (3)$$

where $\omega_M = \gamma\mu_0 M_s$, $\omega_{\text{an}} = \gamma\mu_0 H_{\text{an}}$, $\omega_H = \gamma\mu_0 H_{\text{ext}}$, λ_{ex} is the exchange length, μ_0 is the vacuum permeability, and F_y , F_z denote the dynamic demagnetization tensor components accounting for the waveguide geometry and shape anisotropy that it creates:

$$F_y = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{k_y^2 \sigma_k^2}{k^2 w} f(kh) dk_y, \quad (4)$$

$$F_z = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{\sigma_k^2}{w} (1 - f(kh)) dk_y, \quad (5)$$

where $k^2 = k_x^2 + k_y^2$, $\sigma_k = w \text{sinc}(k_y w/2)$, $f(kh) = 1 - (1 - \exp(-kh))/(kh)$, w is a width of the waveguide, and h is its thickness. In the general case, dipolar interactions lead to spin pinning at the waveguide edges,

which significantly complicates the dispersion relation. However, for narrow waveguides, the system can be considered in the unpinned state, substantially simplifying the analytical treatment [45]. Therefore, Eq. (3) was implemented to analyze the fundamental spin-wave mode in the waveguide with width $w = 145$ nm.

Complementary fully numerical simulations were performed using the finite-element micromagnetic modeling package TetraX [47,48]. These simulations combine the calculation of spin-wave dispersion and lifetime with the evaluation of CPW antenna absorption, providing a theoretical framework for comparison with experimental observations. The spin-wave group velocity was obtained as the derivative of the analytically and numerically obtained dispersion relation: $v_g = \partial\omega/\partial k_x$.

The material parameters used in the calculations were those determined from VSM and FMR measurements of the Ga:YIG film, with the exception of the saturation magnetization, which was adjusted to $M_s = 17.51$ kA m⁻¹ to account for potential modifications during the nanofabrication process. The exchange stiffness $A_{\text{ex}} = 1.37$ pJ m⁻¹ was adopted from previous studies on similar Ga:YIG films [27].

The dispersion relation $\omega(k_x)$ obtained using Eq. (3) and the numerical simulations for the waveguide with width 145 nm and thickness 73 nm is presented in Fig. 2(a). Both theoretical and numerical approaches yield nearly identical results, demonstrating their reliability as robust analytical tools for investigating spin-wave behavior in nanoscale Ga:YIG waveguides.

III. RESULTS AND DISCUSSION

Comparing the dispersion relations $\omega(k_x)$ for nonsubstituted YIG and Ga:YIG obtained from numerical simulations [Fig. 2(a)], a distinct difference in behavior is observed in the backward-volume geometry. Because of the significantly reduced saturation magnetization M_s in Ga:YIG and the correspondingly increased exchange length λ_{ex} , the dispersion curve is almost proportional to $\omega_M \lambda_{\text{ex}}^2 k_x^2$ not only for the fundamental spin-wave mode but also for other high-frequency width modes [dashed lines in Fig. 2]. In contrast, the dispersion relation in nonsubstituted YIG is dominated by the dipolar interaction for low wave vectors, resulting in a characteristic negative slope.

This fundamental difference has a direct impact on the spin-wave group velocities v_g in these materials, as demonstrated in Fig. 2(b). While maximum values of v_g in the wave vector-range of interest in YIG reaches approximately 200 m s⁻¹ in waveguides with dimensions 145 × 73 nm, the group velocity in Ga:YIG scales almost linearly with k_x . The scaling rate remains constant for higher width modes due to the significantly increased exchange interaction influence on the spin-wave dispersion. This behavior enables Ga:YIG to overcome the

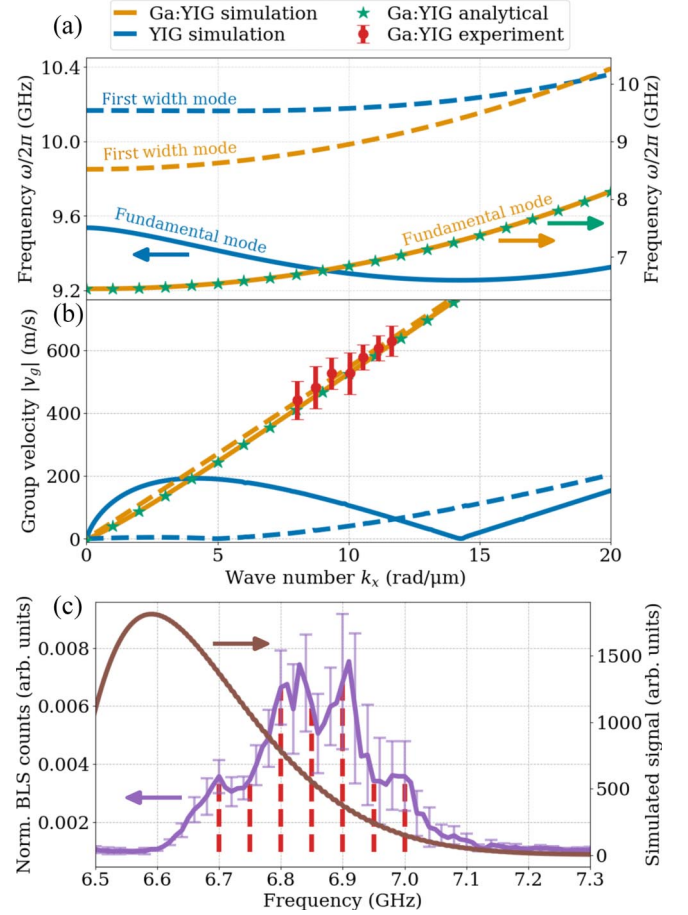


FIG. 2. (a) Calculated dispersion relations $\omega(k_x)$ for non-substituted YIG and Ga:YIG obtained using the analytical formula [Eq. (3)] and numerical simulations with TetraX. (b) Absolute values of group velocities v_g derived from the calculated dispersion relations, compared with experimentally determined values for Ga:YIG obtained from time-resolved μ BLS measurements. Solid lines in subfigures (a) and (b) indicate the fundamental spin-wave mode, while dashed lines refer to the simulations of the first width mode. (c) Experimentally measured frequency sweep (purple line) showing the spin-wave amplitude for excitation frequencies applied to the antenna, normalized to the amplitude of the elastically scattered signal. The measurement was taken at 1 μ m from the excitation antenna and the error bars in the plot indicate the experimental averaging error. Additionally, the spin-wave spectrum was estimated using microwave absorption and lifetime simulation (brown line). Red dashed lines indicate the chosen excitation frequencies, which were subsequently used for the group velocity measurements. All the theoretical calculations and experimental data correspond to waveguide dimensions of 145 × 73 nm (width × thickness).

velocity limitations of nonsubstituted YIG and achieve spin waves with significantly higher group velocities at larger wave vectors.

To validate the numerical predictions, BLS measurements were conducted to determine the group velocities of spin waves in Ga:YIG nanowaveguides. Initially, the

narrowest available waveguide with a width of 145 nm was investigated. This specific width was chosen as an optimal trade-off: it is sufficiently narrow to ensure the unpinned boundary conditions for spin-wave modes [45], yet wide enough to maintain a sufficient signal-to-noise ratio given the μ BLS focal spot size of approximately 400 nm in the current setup. A frequency sweep measurement was performed to determine the accessible frequency range for spin-wave detection using BLS, as shown in Fig. 2(c). The detection was carried out at a distance of 1 μ m from the antenna, and the excitation power was set to -10 dBm to reduce the influence of nonlinear phenomena on the spin-wave propagation.

Additionally, the spin-wave spectra were estimated using TetraX simulations. It allows for the calculation of the spin-wave mode linewidth Γ which is used to determine its wave vector-dependent lifetime τ . The decay length L_d of the mode is then obtained from the lifetime τ and the spin-wave group velocity v_g : $L_d = v_g \tau$. Combining this value with the CPW antenna absorption simulation provided by TetraX, one can estimate the spin-wave spectrum at the given distance from the antenna. The simulated in this way spin-wave spectrum demonstrates considerable overlap with the experimentally obtained frequency sweep [Fig. 2(c)], with the observed discrepancy attributed to the nanofabrication process, which typically leads to slight alterations in material parameters [19]. Specifically, ion milling releases strain at the waveguide edges, locally modifying the effective magnetization. Additionally, laser-induced heating during μ BLS measurements [19] and nonlinear frequency shift [49] can further displace the resonance frequency. To account for these combined effects, the saturation magnetization in the simulations was adjusted to yield the best agreement with the experimental data.

From the frequency sweep experiment, several frequencies were selected [indicated by red dashed lines in Fig. 2(c)] for subsequent time-resolved BLS measurements. The experimentally determined group velocities are

presented in Fig. 2(b). The specific wave vectors corresponding to the excited frequencies were calculated from the numerically obtained dispersion curve for the investigated waveguide [Fig. 2(a)]. The measured group velocities reproduce the linearly increasing behavior with wave vector predicted by the dispersion curve simulations, achieving group velocities up to 600 m s^{-1} .

Moreover, since Ga:YIG provides a platform for isotropic exchange-dominated spin waves, the internal demagnetization field distribution does not significantly affect the group velocity values when comparing nanowaveguides with different widths. Further μ BLS measurements revealed that in structures with widths of 240 and 530 nm, the group velocity values are remarkably similar: (529 ± 56) and (524 ± 41) m s^{-1} , respectively. At the same time, the numerically predicted values for YIG nanostructures with same dimensions are 106 and 97 m s^{-1} , respectively. The spin waves in these measurements were excited at the same wave vector of $k_x = 11.25 \text{ rad } \mu\text{m}^{-1}$ which roughly corresponds to the frequency of 6.95 GHz in Ga:YIG nanowaveguides. The group velocity comparison between materials constitutes an almost fivefold increase in Ga:YIG nanostructures across different widths.

This difference in group velocity values between materials increases with decreasing nanowaveguide widths. Numerical simulations predict group velocity v_g in Ga:YIG of 613 m s^{-1} and in YIG of 70 m s^{-1} for a nanowaveguide with dimensions 50×50 nm [19]. These results demonstrate the suitability of Ga:YIG for magnonic applications, enabling operation of spin waves in various nanostructures while maintaining comparable spin-wave properties across different geometries.

The group velocity of spin waves significantly influences their decay length L_d , a critical parameter that determines the propagation distance achievable within the waveguide. Its measurements were conducted in waveguides with three different widths, and the results are presented in Fig. 3. The decay length reaches a notable

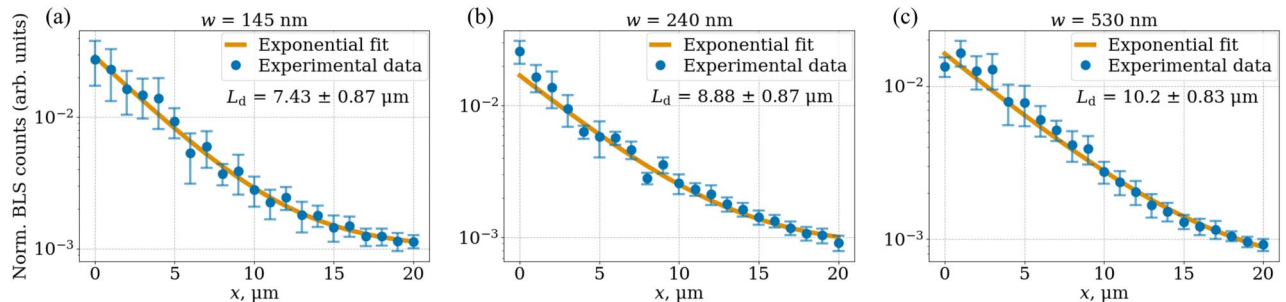


FIG. 3. Spin-wave decay length measurements in Ga:YIG nanowaveguides with different widths: (a) $w = 145$ nm, (b) $w = 240$ nm, and (c) $w = 530$ nm. Blue circles represent experimental BLS data points with error bars, where the bars indicate the experimental averaging error, while orange lines show exponential fits used to determine the decay length L_d . The BLS counts are plotted on a logarithmic scale as a function of propagation distance along the waveguide and normalized to the amplitude of the elastically scattered signal. The measurements are performed at the excitation frequency of 6.95 GHz.

value of $7.43\ \mu\text{m}$ even in the narrowest waveguide with a width of $145\ \text{nm}$ [Fig. 3(a)]. Furthermore, L_d increases in wider waveguides [Figs. 3(b) and 3(c)], demonstrating the robust propagation characteristics of Ga:YIG nanostructures. The slight deviation from the exponential fit can be explained by the presence of nonlinear effects in the spin-wave excitation. This phenomenon was previously observed by Heinz *et al.* [19] in nonsubstituted YIG nanowaveguides. Because of the enhanced group velocities and still relatively low Gilbert damping achieved in Ga:YIG [25,27], spin waves propagate here over larger distances in comparison to the experimentally investigated nonsubstituted YIG nanowaveguides [19]. This enhancement is critical for practical applications: with decay lengths significantly exceeding the typical dimensions of inverse-design logic gates [7,8], Ga:YIG waveguides offer a high potential circuit complexity (defined as the ratio of decay length to feature size [19]), satisfying key requirements for cascading and fan-out in magnonic networks [50,51], a requirement that is essential for the realization of successful hybrid spin-wave-CMOS computing systems.

Additionally, Ga:YIG provides a robust platform for a mode- and wave vector-selective spin-wave excitation. The negative slope in the dispersion relation of nonsubstituted YIG results in the simultaneous excitation of two spin waves with different wave vectors for some frequencies, one in the dipolar and one in the exchange regime [52]. Being dominated by the exchange interaction, spin waves in Ga:YIG provide a single-wave vector excitation in the entire frequency range of interest. Furthermore, the strong frequency separation between modes in Ga:YIG compared with nonsubstituted YIG allows for the easier establishment of a single-mode operation regime in a broad frequency range [from 6.45 to 8.14 GHz in the particular case shown in Fig. 2(a)] even in the wider waveguides, providing access to long distance magnon transport in complex magnonics networks.

IV. CONCLUSION

In this work, we have comprehensively investigated the spin-wave transport properties of Ga:YIG nanowaveguides through a combined experimental, numerical, and analytical approach. Our findings demonstrate that Ga:YIG represents a significant advancement in magnonic materials, offering superior performance characteristics compared with both nonsubstituted YIG and metallic ferromagnetic systems.

The key achievements of this study include the demonstration of high spin-wave group velocities reaching up to $600\ \text{m s}^{-1}$ in nanowaveguides with widths as narrow as $145\ \text{nm}$. These values represent a several-fold increase over the group velocities typically attainable in nonsubstituted YIG nanowaveguides, where performance is

significantly limited by dipolar effects. The linear scaling of group velocity with wave vector in Ga:YIG, arising from its exchange-dominated dispersion relation, enables operation with fast spin waves across a broad frequency range.

Furthermore, we have shown that Ga:YIG nanowaveguides exhibit exceptional spin-wave propagation characteristics, with decay lengths reaching $7.43\ \mu\text{m}$ (for $k_x = 11.25\ \text{rad }\mu\text{m}^{-1}$) even in the narrowest structures and extending up to $10.2\ \mu\text{m}$ in wider waveguides.

The isotropic nature of exchange-dominated spin waves in Ga:YIG provides an additional crucial advantage, as demonstrated by the width-independent group velocities observed across different waveguide geometries. This characteristic enables reliable and predictable spin-wave operation in complex magnonic circuits, overcoming the geometry-dependent limitations encountered in conventional dipolar systems.

The combination of high group velocities, long propagation distances, and isotropic behavior positions Ga:YIG as a suitable platform for advancing integrated magnonics and realizing practical magnonic logic devices at the nanoscale. These results open relevant possibilities for energy-efficient spin-wave-based computing architectures and contribute significantly to the development of next-generation magnonic technologies.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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