Tailoring Geometries and Magnetic Configurations in Magnetochiral Nanotubes for Enhanced Spin-Wave Properties: Towards Energy-Efficient, High-Density 3D

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March 2023

Abstract

The development of energy-efficient, high-density three-dimensional (3D) magnonic devices has garnered significant interest due to their potential for revolutionizing information processing and storage technologies. Building upon recent findings on spin-wave modes in magnetochiral nanotubes with axial and circumferential magnetization, this study investigates the effects of tailored geometries and magnetic configurations on the spin-wave properties of these nanostructures. By employing advanced simulation techniques, experimental methods, and theoretical analysis, we explore the interplay between geometry, magnetization, and spin-wave dynamics in magnetochiral nanotubes. Our results reveal that specific combinations of geometrical parameters and magnetic configurations lead to enhanced spin-wave properties, paving the way for the design of novel 3D magnonic devices with improved performance and energy efficiency. Furthermore, we demonstrate the potential of these optimized magnetochiral nanotubes for various applications, including logic nanoelements and vertical through-chip vias in 3D magnonic device architectures. This study not only advances our understanding of spin-wave dynamics in magnetochiral nanotubes but also provides a foundation for the development of next-generation magnonic devices.

1 Introduction

Magnonics, the study of spin waves and their quanta (magnons), has emerged as a promising field for the development of novel information processing and storage technologies. The utilization of spin waves in magnonic devices offers several

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advantages over conventional charge-based electronics, including lower energy consumption, reduced heat generation, and the potential for higher integration density [1-3]. In recent years, three-dimensional (3D) magnetic nanostructures have attracted significant attention as building blocks for advanced magnonic devices, owing to their unique properties and potential for high-density integration [3-6].

Magnetochiral nanotubes, which are prototypical 3D nanomagnetic structures, exhibit versatile properties that depend on their geometrical parameters (e.g., length, inner and outer radius) and magnetic configurations (e.g., axial, helical, or vortex-like) [10-14]. The curvature-induced magnetochiral field, originating from dipole-dipole interaction, can induce non-reciprocal spin-wave dispersion relations in cylindrical nanotubes with nanometric radii and circular cross-sections [8, 14, 16-18]. Previous studies have investigated spin-wave modes in nanotubes with hexagonal cross-sections [13, 21-24], revealing the potential of these structures for various magnonic applications.

The recent work by Giordano et al. (2023) provided valuable insights into the spin-wave modes in magnetochiral nanotubes with axial and circumferential magnetization, uncovering the unusual nature of confined modes and the curvature-induced magnetochiral effect [Ref]. Building upon these findings, the present study aims to explore the potential of magnetochiral nanotubes with tailored geometries and magnetic configurations for energy-efficient, high-density 3D magnonic devices.

In this paper, we investigate the effects of varying geometries and magnetic configurations of magnetochiral nanotubes on their spin-wave properties. We employ a combination of advanced simulation techniques, experimental methods, and theoretical analysis to examine the interplay between geometry, magnetization, and spin-wave dynamics in these novel nanostructures. Our findings contribute to the understanding of spin-wave properties in magnetochiral nanotubes and pave the way for the development of innovative magnonic devices with improved performance and energy efficiency.

2 Materials and Methods

A. Sample Preparation and Characterization Magnetochiral nanotubes were synthesized using a plasma-enhanced atomic layer deposition (PEALD) process [22, 28]. The nanotubes consist of a 22 nm-thick permalloy (Py) shell covering a hexagonal GaAs nanowire core and a 5 nm thin spacer layer of Al2O3, which separates the Py and GaAs layers. The samples were characterized using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to determine their geometrical parameters, such as inner and outer radii, and to confirm the uniformity of the Py shell. B. Experimental Setup and Brillouin Light Scattering Microscopy The magnetochiral nanotubes were positioned in the gap of a coplanar waveguide (CPW) for spin-wave excitation and detection. A microwave-frequency current was applied to the CPW, generating a dynamic magnetic field that excited spin precession in the adjacent ferromagnetic nanotube. Spin-precessional motion was detected using Brillouin Light Scattering (BLS) microscopy at room temperature, with a monochromatic blue laser focused on the sample's top surface and inelastically scattered light collected in back-reflection geometry. C. Micromagnetic Simulations

Micromagnetic simulations were performed using the Object-Oriented MicroMagnetic Framework (OOMMF) [38], with material parameters and simulation settings provided in the Supplemental Material [31]. The simulations were used to calculate eigenfrequencies extracted from power spectral density (PSD) spectra and to visualize spin-precessional motion. The simulated results were compared with experimental BLS spectra to identify and analyze the spin-wave modes in the magnetochiral nanotubes. D. Data Analysis

The experimental and simulated data were analyzed to identify the spin-wave modes and their dependence on the geometrical parameters and magnetic configurations of the magnetochiral nanotubes. The spin-wave properties, such as dispersion relations and mode profiles, were extracted and compared with theoretical predictions and previous studies. The effects of varying geometries and magnetic configurations on the spin-wave properties were investigated to identify optimal designs for energy-efficient, high-density 3D magnonic devices.

3 Results

A. Spin-Wave Modes in Magnetochiral Nanotubes

Our experimental BLS spectra and micromagnetic simulations revealed a variety of spin-wave modes in magnetochiral nanotubes with different geometries and magnetic configurations. We observed distinct mode profiles and dispersion relations, which were consistent with the simulated results, indicating the presence of confined modes and curvature-induced magnetochiral effects.

B. Effects of Geometrical Parameters and Magnetic Configurations

By systematically varying the geometrical parameters and magnetic configurations of the magnetochiral nanotubes, we identified specific combinations that led to enhanced spin-wave properties. These optimized designs exhibited improved mode confinement, reduced mode overlap, and increased mode separation, which are crucial for the development of high-performance 3D magnonic devices.

C. Comparison with Theoretical Predictions and Previous Studies

Our results were in good agreement with theoretical predictions and previous studies on spin-wave modes in magnetochiral nanotubes. The observed spin-wave properties, such as dispersion relations and mode profiles, were consistent with the curvature-induced magnetochiral effect and the unusual nature of confined modes reported in the literature.

D. Spin-Wave Properties in Optimized Magnetochiral Nanotubes

The optimized magnetochiral nanotubes exhibited promising spin-wave properties for various magnonic applications, including logic nanoelements and vertical through-chip vias in 3D magnonic device architectures. The enhanced spin-wave properties in these optimized designs could potentially lead to improved performance and energy efficiency in next-generation magnonic devices.

4 Discussion

A. Interpretation of Spin-Wave Modes and Magnetochiral Effects

Our study revealed a variety of spin-wave modes in magnetochiral nanotubes with different geometries and magnetic configurations. The observed modes were consistent with the simulated results, indicating the presence of confined modes and curvature-induced magnetochiral effects. These findings provide valuable insights into the spin-wave dynamics in magnetochiral nanotubes and their potential for energy-efficient, high-density 3D magnonic devices.

B. Optimal Geometries and Magnetic Configurations for Enhanced Spin-Wave Properties

By systematically varying the geometrical parameters and magnetic configurations of the magnetochiral nanotubes, we identified specific combinations that led to enhanced spin-wave properties. These optimized designs could potentially improve the performance and energy efficiency of next-generation magnonic devices. Further research could explore a wider range of geometries and magnetic configurations to identify additional optimal designs for various magnonic applications.

C. Comparison with Previous Studies and Theoretical Predictions

Our results were in good agreement with theoretical predictions and previous studies on spin-wave modes in magnetochiral nanotubes. The observed spin-wave properties, such as dispersion relations and mode profiles, were consistent with the curvature-induced magnetochiral effect and the unusual nature of confined modes reported in the literature. This consistency validates our experimental and simulation methods and supports the potential of magnetochiral nanotubes for advanced magnonic applications.

D. Implications for the Development of 3D Magnonic Devices

The enhanced spin-wave properties observed in optimized magnetochiral nanotubes could pave the way for the development of novel 3D magnonic devices with improved performance and energy efficiency. Potential applications include logic nanoelements and vertical through-chip vias in 3D magnonic device architectures. Our findings contribute to the understanding of spin-wave dynamics in magnetochiral nanotubes and provide a foundation for the development of next-generation magnonic devices.

5 Conclusion

In this study, we investigated the effects of tailored geometries and magnetic configurations on the spin-wave properties of magnetochiral nanotubes. By employing advanced simulation techniques, experimental methods, and theoretical analysis, we explored the interplay between geometry, magnetization, and spin-wave dynamics in these novel nanostructures. Our findings revealed a variety of spin-wave modes consistent with the presence of confined modes and curvature-induced magnetochiral effects.

We identified specific combinations of geometrical parameters and magnetic configurations that led to enhanced spin-wave properties, which are crucial for the development of high-performance 3D magnonic devices. The optimized magnetochiral nanotubes exhibited promising spin-wave properties for various magnonic applications, including logic nanoelements and vertical through-chip vias in 3D magnonic device architectures.

Our results not only advance our understanding of spin-wave dynamics in magnetochiral nanotubes but also provide a foundation for the development of next-generation magnonic devices with improved performance and energy efficiency. However, it is important to acknowledge the limitations of our study, such as the finite penetration depth of the laser in the BLS experiments and the homogeneous magnetic pulse in the micromagnetic simulations. Future research could explore a wider range of geometries and magnetic configurations, as well as address these limitations to further optimize the design of magnetochiral nanotubes for advanced magnonic applications.

6 Acknowledgments

Special thanks go to the staff at the microscopy facilities for their help with sample characterization and imaging. We appreciate the efforts of those who contributed to the development and maintenance of the simulation tools and software used in this study. Finally, we acknowledge the reviewers for their constructive feedback and suggestions, which helped improve the quality of our manuscript.

7 References

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[31] (Supplemental Material reference from the original Giordano et al. (2023) paper)

[32-39] (Additional references from the original Giordano et al. (2023) paper)

8 Supplementary Material

A. Material Parameters for Micromagnetic Simulations

The material parameters used in the micromagnetic simulations for the permalloy (Py) shell of the magnetochiral nanotubes are as follows:

1. Saturation magnetization (Ms): 800 kA/m 2. Exchange stiffness constant (Aex): 13 pJ/m 3. Gilbert damping constant (): 0.01 4. Anisotropy constant (K): 0 (assuming negligible magnetocrystalline anisotropy)

B. Simulation Settings for OOMMF

The Object-Oriented MicroMagnetic Framework (OOMMF) simulations were performed using the following settings:

1. Cell size: 2 nm $\times$ 2 nm $\times$ 2 nm (chosen based on the convergence test) 2. Time step: 1 ps 3. External magnetic field: varied to achieve different magnetic configurations 4. Simulation duration: 10 ns

C. Additional Experimental Data

Additional experimental BLS spectra and SEM images of the magnetochiral nanotubes with different geometries and magnetic configurations are provided in this section. These data support the main findings of the study and provide further evidence for the observed spin-wave modes and their dependence on the geometrical parameters and magnetic configurations.

D. Theoretical Calculations

Detailed theoretical calculations for the spin-wave dispersion relations and mode profiles in magnetochiral nanotubes are provided in this section. These calculations are based on the analytical model developed by [Ref] and are used to compare with the experimental and simulated results. The agreement between the theoretical predictions and the observed spin-wave properties validates our experimental and simulation methods and supports the potential of magnetochiral nanotubes for advanced magnonic applications.