Electromagnetic wave induced resonance in infinitely long and hollow square cobalt nano-prisms

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Received 21 December 2020, revised 30 March 2021
Accepted for publication 3 June 2021
Published 16 June 2021

Abstract
Confined metallic ferromagnetic nano-structures are desirable constituents in magnetic composites and devices for applications in telecommunications and electromagnetic wave absorption. Removing the core of these elements or substituting with non-magnetic fillers leads to immediate reduction in their weight and potential for tailoring their magnetic, dielectric and geometrical properties to enable the development of light-weight, high-frequency and efficient composites and devices. However the effect of this geometry change on the electromagnetic wave absorption and magnetic response in these hollow structures is not clear in comparison to their solid counterparts. In this article, electromagnetic wave propagation in long and hollow square cobalt nano-prisms with side lengths of 100 and 500 nm and with different wall thicknesses in the range 25–200 nm is simulated by solving the coupled system of Maxwell’s equations and the Landau–Lifshitz–Gilbert equation using the finite-difference time-domain method. The simulated dynamic magnetisation and power dissipation spectra indicated that the core of the long cobalt prisms can be removed up to wall thicknesses equal to the magnetic skin depth (about 50 nm estimated for cobalt) without significantly impacting electromagnetic wave absorption at the fundamental resonance frequencies. The simulations also revealed prominent higher frequency corner resonance modes in the small 100 nm prism with 25 nm wall thickness, but whose contribution becomes negligible with increasing prism size.

Keywords: electromagnetism, micromagnetics, ferromagnetic resonance, finite-difference time-domain method, magnetisation dynamics

(Some figures may appear in colour only in the online journal)

1. Introduction
Metallic ferromagnetic particles and confined nano structures, including long wires, are used in telecommunications and electromagnetic wave absorption applications due to their higher saturation magnetisation and enhanced operating bandwidths [1–7]. Moreover, they are compatible with CMOS fabrication techniques making them attractive for spintronic and magnetic devices [8–10]. The understanding and design of practicable electromagnetic composites and devices is complicated by the non-uniform electromagnetic wave absorption and propagation in these metallic constituents and resulting complex micromagnetic landscape. These lead to different transmission length scales (both magnetic and non-magnetic) that affect the resonance frequencies in these structures.

Previous theoretical work on electromagnetic wave propagation in confined metallic ferromagnetic structures
focused on long cylindrical wires for simplicity and relevance, and involved the solution of the coupled system of Maxwell’s equations and Landau–Lifshitz equation for the dynamic magnetisation [11–15]. These harmonic theories provided insight into the resonance mechanisms and their size dependence in long ferromagnetic wires, and helped explain experimental observation. However, the details of the local transient magnetisation, power absorption distribution, spin-wave exchange modes, and effects of edges and corners in practical structures and their influence on the resonance mechanisms and frequencies were difficult to model due to the complexity of the electromagnetic-micromagnetic coupling and non-uniform electric and magnetic fields. To accurately model the complex wave interaction with magnetic structures, the authors previously developed a hybrid electromagnetic-micromagnetic numerical method for solving the full coupled system of Maxwell’s curl equations and the Landau–Lifshitz–Gilbert (LLG) equation within the framework of the difference-time-domain method (FDTD) [16]. They simulated the transient (wideband) wave propagation and resonance in long solid cobalt nano-prisms with side lengths 50–1000 nm, and revealed the exchange curling mode as the main resonance mechanism in prism sizes $\leq 100$ nm. For larger prisms, the simulated local power absorption spectra showed confinement of the magnetic response to narrow regions along the prism edges, and enabled estimation of the magnetic skin depth for cobalt to be around 50 nm. These results were in agreement with the ferromagnetic theory and predictions by Kraus for solid ferromagnetic wires [12, 13].

This local confinement of the power absorption spectra to the prism edges in [16] suggest that the bulk of the prism has negligible contribution to the overall magnetic response. Removing the centre of the prism or replacing it with a non-magnetic filler leads to immediate reduction in the weight of the element, reduces eddy current effects and enable local tuning of the dielectric and magnetic properties of the element. This is particularly important for the development of light-weight, high-frequency and efficient electromagnetic absorbers using core–shell structure constituents (e.g. [17–20]). Removal of the central core changes the coupled electromagnetic absorption characteristics and micromagnetic landscape of the resulting hollow structure, which are difficult to model and the role of the wall thickness on the resonance mechanism and frequencies remain unclear. In this article, we use the hybrid electromagnetic-micromagnetic numerical model developed in [16] to study the electromagnetic absorption and resonance mechanisms in infinitely long and hollow cobalt prisms with side lengths of 100 and 500 nm as shown in figure 1 with wall thicknesses in the range 25–200 nm. The magnetisation precession in the hollow prisms is excited by a 70 GHz normally incident electromagnetic plane wave.

The next section of this article outlines the coupled mathematical system solved numerically within the FDTD method to model electromagnetic wave interaction and magnetisation dynamics in the hollow cobalt prisms. Simulation results are then presented and discussed, which include local magnetisation and power dissipation spectra to study the resonance mechanisms and frequencies in the hollow prisms as functions of prism sizes and wall thicknesses. The simulation results are also compared with an analytical theory of curling exchange resonance in hollow cylinders to analyse the resonance mechanism and identify the corresponding mode frequencies. This is followed by the main conclusions of this work.

2. Theory and numerical implementation

To model electromagnetic wave propagation and absorption in the metallic cobalt hollow prisms, the couple systems of Maxwell’s equations and the LLG equation are solved. Maxwell’s curl equations are given by:

$$\frac{\partial B}{\partial t} = -\nabla \times E, \quad (1a)$$

$$\varepsilon \frac{\partial E}{\partial t} = \nabla \times H - \sigma E, \quad (1b)$$

where $\mathbf{H}$ is the magnetic field, $\mathbf{E}$ is the electric field, $\varepsilon$ is the permittivity, $\sigma$ is the electrical conductivity and $t$ is the time. The magnetic flux density $\mathbf{B}$ is coupled to the magnetisation $\mathbf{M}$ through the constitutive relation $\mathbf{B} = \mu_0 (\mathbf{B} + \mathbf{H})$, where $\mu_0$ is the permeability of free space. The dynamic magnetisation is evaluated from solution of the LLG equation:

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{b}(\mathbf{M} \times \mathbf{H}_{\text{eff}}(\mathbf{M})) + \frac{\alpha}{|\mathbf{M}|} \left( \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right), \quad (2)$$

where $\gamma = 1.75882 \times 10^{11} \mu_0 \text{m-Hz A}^{-1}$ is the gyromagnetic ratio (with Landé $g$-factor $g = 2$ for spin motion in cobalt [21]), $\alpha$ is the phenomenological Gilbert damping coefficient, and $|\mathbf{M}| = M_s$ is the saturation magnetisation. The effective field $\mathbf{H}_{\text{eff}}$ in (2) is given by:
\[ H_{\text{eff}}(M) = H(M) + H_s(M) + H_{ex}(M), \]

where \( H \) is the Maxwell field evaluated from the solution of (1) and include contributions from electric currents, magnetisation divergence, and incident and scattered electromagnetic waves. The anisotropy field \( H_s = -gM \cdot \mathbf{z} \) describes the hexagonal close-packed uniaxial anisotropy of the cobalt prisms along the \( z \) axis where \( g = 2K_1/\mu_0M_s^2 \) and \( K_1 \) is the anisotropy constant. \( H_{ex} \) in (3) is the nearest neighbour exchange field contribution \( H_{ex} = CV^2M \), where \( C = 2A/\mu_0M_s^2 \), \( A \) is the exchange constant, and \( V^2 \) is the Laplacian operator. The unpinned magnetisation boundary condition \( \partial M/\partial n = 0 \) (in absence of surface anisotropy) is used in the solution of the LLG equation, where \( n \) is the vector normal to the surface of the magnetic material. Variations of the magnetic fields along the prism axis are assumed small and hence Maxwell’s equations were solved in the two-dimensional transverse magnetic mode with \( z \) polarisation of the electric field (TMz) to model the induced axial currents [16]. This also reduces the complexity and time of the numerical computations.

The coupled system of Maxwell’s and LLG equations is solved numerically within the FDTD method using a second-order accurate algorithm as detailed in [16]. The simulations are excited by a \( y \)-directed, \( z \)-polarised plane wave introduced and removed using a 4 cell wide total-field/scattered field (TFSF) boundary surrounding the simulation space in the FDTD grid [22]. The plane wave is introduced at the lower TFSF boundary and removed at the top of the TFSF boundary, and terminated using a second-order, one-direction wave equation analytical absorbing boundary condition, to sufficiently reduce the reflections at time steps less than the Courant limit. The simulation space, including the TFSF boundary layer, were terminated with a perfectly matched layer (PML) implemented using Berenger’s split-field formulation with a third-order polynomial grading for the magnetic conductivity and \( 10^{-8} \) reflection error [23]. The number of PML cells and the separation of the PML layer from the prism were adjusted for each simulation, with a minimum of 20 cells for the PML layer, to minimise reflection from the inner and outer PML boundaries. A 70 GHz Gaussian time profile is used to excite the plane wave with a small magnetic field of 0.1 mT to operate in the linear magnetic regime (for small perturbations of the magnetisation around the saturated \( z \)-direction), reduce resistive heating and minimise field reflections from the absorbing boundaries. The 70 GHz bandwidth of the incident wave is also large enough to excite the fundamental and higher frequency resonance modes in the cobalt prisms, while keeping the skin depth larger than the smallest prism cross-section considered here to study the magnetic skin depth.

The material parameters used for cobalt in the simulations are \( M_s = 1.422 \times 10^6 \) A m\(^{-1}\), \( A = 3.1 \times 10^{-11} \) J m\(^{-1}\) [24], and \( K_1 = 450 \times 10^3 \) J m\(^{-3}\) [25]. This yields an exchange length \( L_{ex} = \sqrt{2A/\mu_0M_s^2} = 5 \) nm, and hence a square grid with side lengths \( \Delta x = 5 \) nm was used in the simulations to sufficiently sample the spatial distribution of the magnetisation, domain structure and skin depths within the hollow prisms, while providing practical computational times.

A grid cell size \( \Delta x = 2.5 \) nm was also tested in separate simulations for the 100 nm prism with the smallest wall thickness of 25 nm and yielded negligible difference to the computed magnetisation and fields (and their spectra) using the 5 nm cell size. The 5 nm cell size yields the Courant time step \( \Delta t = \Delta x/2c = 8.3 \times 10^{-18} \) s for stable time-marching and integration of both Maxwell’s equations and the LLG equation [16]. The Gilbert damping coefficient for cobalt is approximately 0.01 [26], and is increased in the numerical computations of the LLG equation to \( \alpha = 0.02 \) to reduce the time taken for the magnetisation to converge to the minimum energy state. Thus a simulation time of 1 ns was sufficient for the magnetic energy \( |M \times H_{eff}|/M_s^2 \) to reduce to \( 10^{-6} \) or less and for fields to decay sufficiently \((E \to 0)\). A constant electrical conductivity of \( 1 \times 10^7 \) (\( \Omega \) m\(^{-1}\)) is used for cobalt [27], yielding a non-magnetic skin depth of \( 1/\sqrt{\pi \mu_0 \sigma} \approx 600 \) nm at the upper band of the incident Gaussian plane wave.

### 3. Results and discussion

The numerical simulations start with the magnetisation initially oriented towards the long axis of the prism (direction of strong shape and magnetocrystalline anisotropies). The prism sizes modelled in this work are less than the non-magnetic skin depth and hence full wave penetration is expected, to focus on the spatio-temporal magnetisation dynamics not affected by attenuated electromagnetic fields. Following excitation with the 70 GHz Gaussian source, the incident electric field couples directly to the conductive prism and induces an axial current in the prism wall. This generates a non-uniform circular magnetic field within the prism wall that is approximately given by \( H = J_z (r^2 - R_1^2)/2r \) for a circular hollow cylinder with inner radius \( R_1 \), outer radius \( R_2 \), induced current density \( J_z = \sigma E_z \) and \( R_1 \leq r \leq R_2 \) being the radial distance from the centre of the cylinder. The magnetic fields reduce to zero toward the centre of the prism cavity, and increase towards the outer prism wall. The circulating magnetic field produces a curling dynamic magnetisation with reversing chirality as shown in figures 2 and 3 for the 100 and 500 nm prisms respectively. The chirality reversal is through diverging magnetisation modes to minimise the exchange energy. The reversing chirality of the dynamic magnetisation also reciprocally reverses the direction of the circulating magnetic field and the induced currents in the prism wall as shown in figure 2 for the 100 nm prism.

In the 100 nm prisms, the fundamental curling magnetisation mode is concentrated in the central regions of the wall, with reduction in the \( x-y \) magnetisation in the outer corner regions due to the alignment of the magnetisation towards the prism long axis to reduce the demagnetising energy. The magnetic response in the 500 nm prisms with wall thicknesses \( W > 50 \) nm becomes confined to thin circumferential regions around the outer prism edges as evident in figure 3. This is consistent with the confinement of the magnetic response observed in solid cobalt prism to a magnetic skin depth of \( \sim 50 \) nm [16].

The local and integrated power dissipated in the hollow prisms (or the rate of their magnetic energy change) are now
shown that the linearised LLG equation, written in cylindrical coordinates with $e^{i\omega t}$ time dependence and without damping, is given by:

$$\left(\nabla^2 - \frac{d^2}{dr^2}\right)m_r + h_r/C + bm_\theta = 0 \quad (4a)$$

$$\left(\nabla^2 - \frac{d^2}{dr^2}\right)m_\theta + h_\theta/C - bm_r = 0, \quad (4b)$$

where $m_r$ ($h_r$) and $m_\theta$ ($h_\theta$) are the radial and circumferential components of the magnetisation (and effective field) respectively, $b = j\omega/\gamma M_s C$, and $d^2 = (g + H_z/M_s)C$ with static field $H_z$ along the prism axis. The radial component of the demagnetising field is $h_r = -N_r m_r$ with demagnetising factor $N_r \approx 1$ in the thin wall regions [15]. The circumferential field is assumed negligible ($h_\theta \approx 0$) due to the flux closure in the curling magnetisation mode and heavily damped current induced field. Solutions to (4) are assumed in the form:

$$m_r = e^{i\theta} (A_1 J_1(kr) + A_2 Y_1(kr))$$

$$m_\theta = e^{i\theta} (B_1 J_1(kr) + B_2 Y_1(kr)),$$

where $J_1$ is the Bessel function of the first kind, $Y_1$ is the Bessel function of the second kind, $k$ are the resonance eigenvalues and $A_n$ and $B_n$ are constants. Substituting these solutions in
In the curling mode theory by writing (4) and setting the determinant of the coefficients of $A_0$ and $B_0$ to zero yields the resonance frequencies $\omega$ for a non-trivial solution:

$$\omega = \gamma M_s \sqrt{(g + Ck^2)(g + 1 + Ck^2)},$$

where $H_z = 0$ as there is no static field applied in this work. The resonance eigenvalues $k$ are determined from applying the exchange boundary conditions for a hollow cylinder with inner and outer radii $R_1$ and $R_2$ respectively, $\partial m_t / \partial r = \partial m_0 / \partial r |_{r=R_1,R_2} = 0$, yielding the transcendental equation:

$$\frac{dJ_1(kR_1)}{dr} Y_1(kR_2) - \frac{dJ_1(kR_2)}{dr} Y_1(kR_1) = 0,$$

which can be solved for $k$ for a given inner and outer radii of the hollow cylinder.

In the 100 nm prism with wall thickness $W = 25$ nm, the fundamental resonance mode is at 36 GHz as indicated in figure 4(a), and increases only slightly to 37 GHz with further increase in wall thickness. Using the exchange curling theory for $W = 25$ nm in (5) and (6) (with $R_1 = 25$ nm and $R_2 = 50$ nm) yields the theoretical resonance frequencies indicated by the vertical blue dashed lines in figure 4(a), which are in close agreement with the numerical simulations. There is some discrepancy due to the difference in shape between the circular cylinder in the theory and square prism in the simulations. Thus for the 100 nm prism with $W = 40$ nm, where the integrated power spectrum is almost identical to the solid prism, the shape correction factor $2R_2 = 1.11L$ ($L$ is the prism side length) is applied to evaluate the eigenvalues in (6) [16, 31]. The corresponding theoretical resonance frequencies for $W = 40$ nm are indicated by the vertical red dashed lines in figure 4(a) and are also in close agreement with the simulated resonance peaks. This close agreement between the curling mode theory and simulations strongly indicate that magnetisation curling with radial demagnetisation is the main resonance mechanism in the hollow prisms, excited by the axially induced electric current in the prism wall.

The exchange curling mode is further confirmed by the local power dissipation spectra for the cobalt prisms shown in figure 5, calculated from the Fourier transform of the local transient magnetisation and effective field. At the fundamental resonance frequency of 37 GHz for the 100 nm prism (see figure 4(a)), the local power spectra in figure 5 (top row) indicate increased intensity of the magnetic response in the central regions of the prism wall with little activity in the corner regions. This is consistent with the curling dynamic magnetisation distribution in figure 2, and with the expected increase in current-induced circular magnetic field towards the prism edges.

In the 500 nm hollow prisms, the fundamental peak frequency is approximately 35 GHz as shown in figure 4(b). This is equal to the fundamental frequency of the solid prism of the same side length, and is independent of the wall thickness for $W > 50$ nm. This can be explained by the confinement of the magnetic response in both the hollow and solid prisms to thin circumferential regions of the prism edge, within a magnetic skin depth of $\sim 50$ nm for cobalt. This is clearly observed from the local power spectra for the 500 nm prisms in figure 5 (bottom row) for wall thicknesses $W > 50$ nm. Using the exchange curling theory in (5), the theoretical resonance frequencies for the 500 nm hollow prism with $W = 50$ nm are indicated by the vertical dashed lines in figure 4(b) and are in good agreement with the simulations. This again consolidates the applicability of the curling mode theory to larger prisms and different wall thicknesses. The theoretical frequencies for larger prisms include standing wave even modes in the radial direction of the thin prism walls, as evident in the curling mode theory by writing $R_2 = R_1 + W$ in (6) and expanding for large $R_1$ to first order to yield the eigenvalues of a thin unpinned film $k = 2n\pi / W$ (where $n = 0, 1, 2, \ldots$). With increasing wall thickness beyond 50 nm in the 500 nm prisms, the frequency shift between the curling theory modes decrease, with the higher frequency modes degenerating towards the fundamental frequency of 35 GHz. This leads to the observed broadening of the fundamental resonance peak in the total
Figure 5. Local dissipated power spectra (in W m\(^{-3}\)) for the 100 nm (top row) and 500 nm (bottom row) hollow cobalt prisms for different wall thicknesses, evaluated at the fundamental resonance frequencies of 37 GHz for the 100 nm prism, and 35 GHz for the 500 nm prism (determined from figure 4).

Figure 6. Local Fourier transforms of \(M_x\) for the 100 nm prism with \(W = 25\) nm from the numerical simulations, calculated at the centre (blue line) and corner (red line) regions of the wall (10 nm from the wall edges). Inset is the local power dissipation spectrum (in W m\(^{-3}\)) at the corner mode frequency (49 GHz).

The integrated power spectrum for the 100 nm prism with \(W = 25\) nm in figure 4(a) reveal prominent higher frequency peaks around 50 GHz. Analysis of the local magnetisation and power spectra, shown in figure 6, confirm that these are localised corner modes in the thin prism wall. The contribution of these corner modes to the total power dissipation spectrum becomes negligible in comparison to the edge (curling) modes with increasing prism wall thickness (beyond 25 nm) and...
prism size. Thus, this corner resonance mode is barely visible in the power spectra for the 100 nm prism with $W = 40$ nm and in the 500 nm hollow and solid prisms in figure 4. The corner resonance peaks also shift towards lower frequencies with increasing prism wall thickness and size. These are estimated from the local corner magnetisation spectra and are 47 GHz for $W = 40$ nm in the 100 nm prism, and 45 GHz for the 500 nm prisms for all wall thicknesses $W \geq 50$ nm (including the solid prism). Exciting the 100 nm hollow prism with $W = 25$ nm with a sinusoidal plane wave at the corner mode frequency of 49 GHz (not shown here) indicated complex domain configurations including localised vortices due to the non-uniform magnetic and electric fields in the corner regions. In the 500 nm hollow and solid prism simulations here, the corner mode frequency of 45 GHz is slightly higher than the local resonance frequency due to corner demagnetising fields $\omega_{\text{Corner}}/2\pi \approx \gamma M_s (g + 1/2) \sim 43$ GHz [16], and generally higher than the dipolar mode frequencies in thin rectangular stripes [32] (assuming that the prism wall segments can be approximated by thin rectangular stripes). This indicates an energy contribution to the corner resonance frequency that may be attributed to exchange and/or localised currents in the corners. The resonance mechanism of these higher frequency localised corner modes and their dependence on wall thickness require further investigation, particularly small prisms with thin walls (around 25 nm) that produce prominent peaks in the power dissipation spectra where both dipolar and exchange contributions are important. This is beyond the scope of this article which focuses on the high intensity fundamental resonance modes in hollow prisms and their relation to the solid prism modes. For larger prisms with wall thicknesses $>50$ nm, the contribution to the power dissipation spectrum is negligible.

4. Conclusions

The electromagnetic wave induced dynamic magnetisation in long and hollow cobalt prisms with side lengths of 100 and 500 nm were simulated by solving the coupled system of Maxwell’s equations and the LLG equation within the FDTD method. The dynamic magnetisation distribution and power dissipation spectra confirmed the exchange curling mode as the fundamental resonance mechanism by comparison to a simple analytical theory of exchange curling resonance with radial demagnetisation in infinite hollow cylinders. The simulated local power dissipation spectra indicated a circumferential magnetic skin depth of about 50 nm in the hollow prisms at the fundamental resonance frequency. Hence this explains the observed close agreement of the fundamental resonance frequencies between hollow prisms with wall thicknesses greater than 50 nm and the solid prisms of the same side length, and almost independent of the wall thickness. Comparison between the numerical calculations and theoretical eigenvalues for circular hollow cylinders indicate that the prism corners have negligible contribution to the fundamental curling resonance mode for the prism size and wave polarization considered here. However, the simulations revealed a higher frequency corner resonance mode when the prism cross-section is comparable to the wall thickness or magnetic skin depth, with decreasing contribution in larger prism sizes. The results of this work indicate that the core of long cobalt prisms can be removed up to wall thicknesses equal to the magnetic skin depth without significantly impacting electromagnetic wave absorption, at least at the fundamental resonance frequency. This is important for the design of light-weight and tuneable materials and devices operating at high frequencies.

Data availability

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors would like to acknowledge the support of Exeter’s Centre for Metamaterial Research and Innovation and the financial support of the EPSRC Centre for Doctoral Training in Metamaterials (Grant No. EP/L015331/1). This study was also partly funded by Innovate UK (Project No. 37041).

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References

[1] Shirakata Y, Hidaka N, Ishitsuka M, Teramoto A and Ohmi T 2008 High permeability and low loss Ni–Fe composite material for high-frequency applications IEEE Trans. Magn. 44 2100
[2] Feng Y-B, Qiu T, Shen C-Y and Li X-Y 2006 Electromagnetic and absorption properties of carbonyl iron/rubber radar absorbing materials IEEE Trans. Magn. 42 363
[3] Kuant B, Canmley R E and Celinski Z 2004 Effect of shape anisotropy on stop-band response of Fe and permalloy based tunable microstrip filters IEEE Trans. Magn. 40 2841
[4] Encinas A, Demand M, Vila L, Piriaux L and Huynen I 2002 Tunable remanent state resonance frequency in arrays of magnetic nanowires Appl. Phys. Lett. 81 2032
[5] Saib A, Vanhovenacker-Janvier D, Huynen I, Encinas A, Piriaux L, Ferain E and Legras R 2003 Magnetic photonic band-gap material at microwave frequencies based on ferromagnetic nanowires Appl. Phys. Lett. 83 2378
[6] Nam B, Choa Y-H, Oh S-T, Lee S K and Kim K H 2009 Broadband rf noise suppression by magnetic nanowire-filled composite films IEEE Trans. Magn. 45 2777
[7] Lagarkov A N and Rozanov K N 2009 High-frequency behavior of magnetic composites J. Magn. Magn. Mater. 321 2082
[8] Makarov A, Windbacher T, Sverdlov V and Selberherr S 2016 CMOS-compatible spintronic devices: a review凝聚态 Sci. Technol. 31 113006
[9] Nikitov S A et al 2015 Magnonics: a new research area in spintronics and spin wave electronics Phys.–Usp. 58 1002
[10] Manago T, Aziz M M, Ogrin F and Kasahara K 2019 Influence of the conductivity on spin wave propagation in a Permalloy waveguide J. Appl. Phys. 126 043904
[11] Boucher V and Ménard D 2010 Effective magnetic properties of arrays of interacting ferromagnetic wires exhibiting
gyromagnetic anisotropy and retardation effects *Phys. Rev. B* **81** 174404

[12] Kraus L 1982 Theory of ferromagnetic resonance in thin wires *Czech J. Phys. B* **32** 1264

[13] Kraus L, Infante G, Frait Z and Azquez M V 2011 Ferromagnetic resonance in microwires and nanowires *Phys. Rev. B* **83** 174438

[14] Heinrich B 1967 The theory of ferromagnetic resonance in metal whiskers *Czech J. Phys. B* **17** 1264

[15] Ménard D, Britel M, Curreru P and Yelon A 1998 Giant magnetoimpedance in a cylindrical magnetic conductor *J. Appl. Phys.* **84** 2805

[16] Aziz M M and McKeever C 2020 Wide-band electromagnetic wave propagation and resonance in long cobalt nanoprisms *Phys. Rev. Appl.* **13** 034073

[17] Chen N, Jiang J, Xu C, Yan S and Zhen L 2018 Rational construction of uniform CoNi-based core–shell microspheres with tunable electromagnetic wave absorption properties *Sci. Rep.* **8** 3196

[18] Chen Y J, Gao P, Zhu C L, Wang R X, Wang L J, Cao M S and Fang X Y 2009 Synthesis, magnetic and electromagnetic wave absorption properties of porous Fe$_3$O$_4$/FeSiO$_2$ core/shell nanorods *J. Appl. Phys.* **106** 054303

[19] Lv H, Ji G, Liu W, Zhang H and Dub Y 2015 Achieving hierarchical hollow carbon@Fe$_3$O$_4$ nanospheres with superior microwave absorption properties and lightweight features *J. Mater. Chem. C* **3** 10232

[20] Lu B, Dong X L, Huang H, Zhang X F, Zhua X G, Lei J P and Suna J P 2008 Microwave absorption properties of the core/shell-type iron and nickel nanoparticles *J. Magn. Magn. Mater.* **320** 1106

[21] Chikazumi S 1997 *Physics of Ferromagnetism* 2nd edn (Oxford: Oxford University Press) ch 3, p 69

[22] Taflove A and Hagness S C 2000 *Computational Electrodynamics: The Finite-difference Time-domain Method* 2nd edn (Boston, MA: Artech House)

[23] Berenger J 1994 A perfectly matched layer for the absorption of electromagnetic waves *J. Comput. Phys.* **114** 185

[24] Tannenwald P K and Weber R 1961 Exchange integral in cobalt from spin-wave resonance *Phys. Rev.* **121** 715

[25] Chikazumi S 1997 *Physics of Ferromagnetism* 2nd edn (Oxford: Oxford University Press) ch 12, p 249

[26] Oogane M, Wakitani T, Yakata S, Yilgin R, Ando Y, Sakuma A and Miyazaki T 2006 Magnetic damping in ferromagnetic thin films *Japan. J. Appl. Phys.* **45** 3889

[27] Avery A D, Mason S J, Basset D, Wesenberg D and Zink B L 2015 Thermal and electrical conductivity of approximately 100-nm permalloy, Ni, Co, Al, and Cu films and examination of the Wiedemann-Franz Law *Phys. Rev. B* **92** 214410

[28] Soohoo R F 1985 *Microwave Magnetics* (New York: Harper & Row Publishers)

[29] Mayergoyz I D 2009 *Nonlinear Magnetization Dynamics in Nanosystems* (Oxford: Elsevier)

[30] Aharoni A 2002 Exchange resonance modes in hollow sphere *Phys. Status Solidi* b **231** 547–53

[31] Beleggia M, De Graef M and Millev Y T 2006 The equivalent ellipsoid of a magnetized body *J. Phys. D: Appl. Phys.* **39** 891

[32] Yu K, Guslenko S O, Demokritov B H and Slavin A N 2002 Effective dipolar boundary conditions for dynamic magnetization in thin magnetic stripes *Phys. Rev. B* **66** 132402