Spin-wave modes of magnetic bimerons in nanodots

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Abstract

We report the resonance excitations and the spin-wave modes of a single bimeron in a confined nanodot by using micromagnetic simulations. Magnetic bimerons can be considered as in-plane topological spin textures of magnetic skyrmions, which means that the spin-wave modes of bimerons also rotate in-plane compared to skyrmions, for example, through the application of out-of-plane microwave magnetic fields, the spin-wave mode of bimerons is no longer a breathing mode but contains a counterclockwise mode at low frequencies and a clockwise mode at high frequencies. When in-plane microwave magnetic fields rotated at different angles are applied, the spin-wave mode of bimerons has an anisotropic property, i.e., the spin-wave mode presents as a breathing mode for the microwave magnetic field applied along the $x$-direction, and a couple of azimuthal modes for the microwave magnetic field applied along the $y$-direction. Moreover, we demonstrate that the breathing mode, the counterclockwise rotation mode, and the clockwise rotation mode can simultaneously appear together when the microwave magnetic field is applied at a specific angle in the plane. In addition to the three typical spin-wave modes, two high-phase counterclockwise rotation modes lead to the periodic deformation of bimerons due to the broken rotational symmetry of the spin texture. Our results reveal the rich spin-wave modes of bimerons, which may contribute to the applications in spintronics and magnonics.

1. Introduction

Magnetic skyrmions [1–5] are topological magnetic solitons characterized by a topological number, which have drawn a lot of attention in spintronic applications due to their small size, topological stability, and low density of driving current. Generally, the presence of bulk, interfacial, or anisotropic Dzyaloshinskii–Moriya interactions (DMI) [6–10] stabilize magnetic skyrmions in chiral systems. There are various manipulation methods of magnetic skyrmions, such as spin transfer torque [11–13], spin Hall effect [14, 15], magnetic anisotropy gradients [16, 17], magnetic field gradients [18], and microwave magnetic fields [19–21]. Especially for the microwave magnetic fields, the spin-wave eigenmodes of a couple of gyrotropic modes and a breathing mode were first mentioned in the skyrmion crystal phase [19]. When two in-plane microwave magnetic fields are applied, skyrmions circulate around each center in clockwise (CW) and counterclockwise (CCW) directions, respectively. Therefore, the in-plane spin-wave modes are two gyrotropic modes, which consist of CW and CCW rotation modes. When a single out-of-plane microwave magnetic field is applied, skyrmions periodically expand and shrink around the central area, and therefore the out-of-plane spin-wave mode presents as a breathing mode. In addition to the skyrmion crystal phase, the three spin-wave modes of a single skyrmion have also been reported in confined magnetic nanodots [22–27]. Moreover, the spin-wave modes of skyrmions have been experimentally observed by using microwave transmittance spectroscopy [28], all-electrical broadband spectroscopy [29], and all-optical spin wave spectroscopy [30] in several chiral systems, respectively.
Magnetic bimerons [31–38] are composed of a meron and an antimeron, separated by a stripe domain in the middle area, which can be considered as the texture of Néel-type skyrmions rotating to the in-plane direction, as shown in figure 1(a). Theoretically, magnetic bimerons have the topological characteristics of skyrmions. The topological number [2, 39] is given by:

\[
Q = \frac{1}{4\pi} \iiint q \, dx \, dy, \quad q = m \cdot \left( \frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y} \right),
\]

where \( q \) is the topological density. In figure 1(b), the topological density is symmetrically distributed around the central stripe domain of the bimeron and has a maximum value at the positions of meron and antimeron. I.e., meron and antimeron each have a topological number of 1/2, and the total topological number of a single bimeron is integrated to 1. Up to now, magnetic bimerons exhibit a series of similar features to magnetic skyrmions, such as the magnetic bimerons are topological spin textures [40], can be driven by spin currents [32, 34, 35] and magnetic fields [34], and show the skyrmion Hall effect [41, 42]. However, the spin-wave excitations of magnetic bimerons are unclear in contrast to that of magnetic skyrmions. In this work, by using micromagnetic simulations, we first investigate the ground state and the size of a bimeron in a confined magnetic nanodot by adjusting the DMI intensity, in-plane anisotropy constant, and in-plane external magnetic field. Then we calculate the power spectral density and the corresponding spin-wave modes of bimerons. At last, we calculate the magnetic spectrum at different angles in the plane and discuss the different resonance excitations of bimerons.

### 2. Model and simulations details

A circular nanodot system with an in-plane easy-axis anisotropy is considered in our simulations with a diameter of 100 nm and a thickness of 0.4 nm, the mesh size is set to 1 nm [43]. The magnetization dynamics are described by numerically solving the Landau–Lifshitz–Gilbert equation, as follows:

\[
\frac{dm}{dt} = -\gamma m \times H_{bf} + \alpha m \times \frac{\partial m}{\partial t},
\]

where \( m \) is the reduced magnetization with the form of \( M/M_s \); \( \gamma \) is the gyromagnetic ratio, the Gilbert damping \( \alpha \) is set to 0.5 and 0.01 for the equilibrium state and the resonant excitation procedure, respectively. \( H_{bf} \) is the effective field, which includes the exchange magnetic field, the in-plane anisotropy field, the external magnetic field, the demagnetization field, and the DMI field. The DMI energy is given by [32]:

\[
E_{DM} = D \left( m_x \frac{\partial m_z}{\partial x} - m_z \frac{\partial m_x}{\partial x} + m_z \frac{\partial m_y}{\partial y} - m_y \frac{\partial m_z}{\partial y} \right),
\]

where \( D \) is the DMI energy parameter, the DMI vector is modified as \( D_{ij} = Dr_\parallel \times z \), and \( D_{ij} = Dr_\parallel \times (-x) \), the in-plane easy-axis anisotropy \( K \) is set along the x axis, as shown in figure 1(c). Usually, to stabilize the bimeron in the nanodot, in addition to rotating the easy-axis anisotropy to the x direction, we emphasize that bimerons can also be formed with an asymmetric shape with the presence of the unmodified DMI. The bimerons and domain wall bimerons have been observed in chiral magnets CoZnMn [38, 44]. In addition, VOI₂ as a member of van-der-Waals layered multiferroic family exhibits strong DMI and in-plane anisotropy, which is predicted to stabilize magnetic bimerons [45]. When the DMI is replaced by the type given in equation (3), which is also called frustrated exchange interaction [32], the spin texture of bimerons can be equivalent to the in-plane magnetization distribution of Néel-type skyrmions, and bimerons then can be formed in frustrated systems [35]. In a continuous Py film via local vortex imprinting from a Co disk, a single bimeron has been observed experimentally without the restriction of anisotropy and DMI [46]. By performing first-principles calculations and Monte Carlo simulations, the magnetic-field-induced bimerons have been stabilized in Janus monolayers of the chromium trihalides Cr(I,Cl)₃ [36]. Through combined first-principle calculation and micromagnetic simulation, the skyrmion-bimeron-ferromagnet phase transition is demonstrated on WTe₂/CrCl₃ bilayer van der Waals heterostructures [47]. In order to better compare the spin-wave modes of magnetic skyrmions that have been reported, we adopt the material parameters as follows [11, 24, 34]: saturation magnetization \( M_s = 580 \times 10^3 \) A m⁻¹, exchange constant \( A = 1.5 \times 10^{-11} \) J m⁻³, in-plane easy-axis anisotropy constant \( K = 2−10 \times 10^5 \) J m⁻³, and the DMI strength \( D = 3.5−5.5 \times 10^{-3} \) J m⁻².
3. Static properties of an isolated bimeron

We investigate the ground state of a bimeron in a magnetic nanodot, as shown in figure 2. Figure 2(a) is the top view of the bimeron shown in figure 1(a) and the color code is replaced from the local magnetization \( m_z \) to \( m_x \). Figures 2(b) and (c) display the \( x \)-direction and the \( y \)-direction spatial profiles of the local magnetization across the bimeron. The diameter of the bimeron in the \( x \) direction (\( d_x \)) and \( y \) direction (\( d_y \)) is defined as the distance between the two zero positions of the \( m_x \). Figures 2(e) and (f) show that the size of bimerons is related to \( D \) and inversely related to \( K \) and \( B_x \) (related to the external magnetic field in the \(-x\) direction). It should be noted that the trend of \( d_x \) and \( d_y \) with the changes of \( D \), \( K \), and \( B_x \) are not consistent. Let us take figure 2(f) as an example. For \(-70 \text{ mT} \leq B_x \leq 0 \text{ mT}\), the slope of \( d_x \) and \( d_y \) is almost the same, and the shape of the bimeron is basically circular, as shown in figures 3(a) and (b). For \( B_x = -80 \text{ mT} \), \( d_x \) increases to 61 nm, and \( d_y \) increases to 43 nm, which means that the shape of the bimeron is stretched to an ellipse, as shown in figure 3(c). For \(-270 \text{ mT} \leq B_x < -80 \text{ mT}\), the slope of \( d_y \) is larger than \( d_x \), and the shape of the bimeron is almost restored to a circular, as shown in figure 3(d). For \( B_x \leq -280 \text{ mT}\), the bimeron disappears from the nanodot, i.e., the ground state is a uniform ferromagnetic state. The competition between the DMI and the Zeeman energy results in the expansion of the bimeron,
Figure 2. (a) Top view of a bimeron with $D = 4.0 \times 10^{-3}$ J m$^{-2}$, and $K = 8 \times 10^5$ J m$^{-3}$. The red, white, and cyan represent the areas where the $x$ component of the magnetization is positive, zero, and negative, respectively. (b) The $x$ direction and (c) The $y$ direction spatial profiles of the local magnetization corresponding to the blue dotted line marked in (a). (d) and (e) Bimeron diameter as a function of $D$, $K$, and $B_x$ (external magnetic field in the $x$ direction).

Figure 3. Ground state of a bimeron with (a) $B_x = 0$ mT, (b) $B_x = -70$ mT, (c) $B_x = -80$ mT, and (d) $B_x = -270$ mT.

the DMI is responsible for reducing the magnetic domain wall energy while expanding the bimeron perimeter, and the Zeeman energy tends to expand the size of the $-x$ region [22, 48]. With the continuous change of Zeeman energy, the dominance of the competition between the two energy terms has changed at a certain critical value, leading to a jump in the bimeron size. Similar situations have also been reported in skyrmions when applying an external magnetic field [22, 49].
4. Spin-wave modes of bimerons

In the dynamic simulations, the in-plane static field-dependent excitation power spectrums of bimerons are first investigated, where $B_x$ is set to vary linearly in the range of 0 to $-270$ mT with $D = 4.0 \times 10^{-3}$ J m$^{-2}$ and $K = 8 \times 10^5$ J m$^{-3}$. The excitation field is a sinc-function type magnetic field in the form $h_i(t) = h_0 \sin(2\pi ft)/(2\pi ft)$, where the amplitude $h_0 = 10$ mT and the cut-off frequency $f = 80$ GHz. The imaginary part of susceptibility (Im $\chi$) of bimerons is obtained by calculating the fast Fourier transform for the time real oscillation of $m_i$ ($i = x, y, \text{or} z$) and the power spectral density phase diagrams are further obtained by changing the value of $B_x$, as shown in figure 4. When $i = x$, as shown in figure 4(a). A single strong resonance mode (later demonstrated to be a breathing mode) with the frequency first decreases from 16.9 to 5.7 GHz as $B_x$ decreases linearly from 0 to $-70$ mT, and then increases to 13.6 GHz as $B_x$ further decreases to $-270$ mT. When $i = y$, as shown in figure 4(b). For $-70$ mT $\leq B_x \leq 0$ mT, there is a single strong resonance mode CW whose decreases from 68.6 to 51 GHz. For $B_x \leq -80$ mT, due to the jump in the bimeron size, the strong resonance frequency drops to about 23 GHz and varies slightly with $B_x$. In addition, a weak resonance mode CCW appears below the frequency of 10 GHz, which means that there are two spin-wave modes of bimerons when $B_x$ is smaller than $-80$ mT. When $i = z$, figure 4(c) presents the out-of-plane power spectral density phase diagram of the bimeron, and it can be found that the change of the resonance frequency with the magnetic field is the same as that of figure 3(b). We have investigated the spin-wave modes at various resonance frequencies later. However, the darker color of the resonance peaks in figure 4(c) means that the resonance intensity measured in the $z$ direction is greater than that measured in the $y$ direction due to the asymmetry of the structure in the $y$–$z$ plane.

From the magnetic field-dependent power spectrum shown in figure 4, it can be found that the resonance frequencies and intensities of bimerons are different when sinc-function type magnetic excitation fields are applied along the $x$, $y$, and $z$ directions, respectively. To compare the difference between the resonances of bimeron measured in three directions, we take the condition of $B_x = -100$ mT to investigate the spin-wave modes of the bimerons at each resonance frequency, as shown in figure 5. There is a strong spin-wave mode of the bimeron in the resonance frequency of 7.9 GHz by applying $h_x(t)$, the resonance amplitude of the $x$-component $\delta m_x$ has the maximum value in the spatial distribution of an elliptical ring.
region, while the resonance amplitudes of the y-component $\delta m_y$ and the z-component $\delta m_z$ are two different double crescent shapes, and their values are small. Therefore, we determine the spin-wave modes of the bimeron according to the resonance amplitude and phase of the $\delta m_x$. The resonance phase of the $\delta m_x$ is a constant sign in the center of the nanodisk, which indicates that the spin-wave mode of the bimeron is a kind of periodical expansion and compression at 7.9 GHz. By applying $h_y(t)$, there are two spin-wave modes of the bimeron in the resonance frequencies of 3.2 and 23.5 GHz. The spatial distributions of the resonance amplitude of the $\delta m_x$ at the two resonance frequencies are both elliptical ring shapes. However, the phase of the $\delta m_x$ changes continuously from $\pi$ to $\pi$ at 3.2 GHz and changes continuously from $\pi$ to $\pi$ at 23.5 GHz. In vortex and skyrmion systems, we have known that low-frequency (sub-GHz range) gyrotropic modes are used to describe the motion of the vortex core or the skyrmion core, and high-frequency azimuthal modes describe the excitation of the peripheral planar portion of the vortex and the domain wall portion of the skyrmion [23, 50]. Therefore, the spin-wave modes of the bimeron at the two resonance frequencies are the azimuthal CCW and CW modes, because the spatial distribution of the resonance region is in the boundary part of the bimeron and the resonance frequency is higher than the sub-GHz range. Following, we investigate the two out-of-plane spin-wave modes by applying $h_y(t)$. The spatial distributions of the resonance amplitude and phase change are almost the same as in the case of applying $h_y(t)$, which indicates that the out-of-plane eigenmode of bimerons is the same as that calculated in the y direction.

In order to further confirm each spin-wave mode shown in figure 5, we applied a sin-function oscillation magnetic field with different resonance frequencies to trace the $\delta m_x$ of the bimeron at different times, as shown in figure 6. The sin-function oscillation magnetic field is set by the form $h_i \sin(2\pi ft)$ ($i = x, y, \text{or} z$), where $h_i = 10$ mT, $f$ is the resonance frequency of each spin-wave mode. As discussed above, the resonance amplitude of the $\delta m_y$ is much larger than that of the $\delta m_x$ and the $\delta m_z$. Therefore, the $\delta m_y(t)$ is selected to present the snapshots at different times, the $\delta m_z(t)$ is defined as the difference between the time-varying x-direction magnetization component $m_x(t)$ and the initial state $m_x(0)$. Figure 6(a) shows the spin dynamics of the bimeron by applying $h_y \sin(2\pi ft)$ with the resonance frequency of 7.9 GHz. From five snapshots taken at different times in one period, it can be seen that the shape of the $\delta m_y$ alternately changes to a red ellipse ring (+1) and a cyan ring (−1), which means that the bimeron is dynamically extending and shrinking (see supplementary video 1 [https://stacks.iop.org/NJP/24/073013/mmedia]). Therefore, the spin-wave mode in the x direction of the bimerons is calledbreathing mode. Figures 6(b) and (c) show the spin dynamics of the bimeron by applying $h_y \sin(2\pi ft)$ with the resonance frequency of 0.5 and 29.3 GHz, respectively. The corresponding snapshots show that the double crescent-shape $\delta m_y$ circulates CCW and CW around each center at 0.5 and 29.3 GHz, respectively. Therefore, the spin-wave modes are a CCW rotation mode at low frequencies and a CW rotation mode at high frequencies (see supplementary videos 2 and 3). Figures 6(d) and (f) show that the out-of-plane spin-wave modes of the bimeron at 0.5 GHz and 29.3 GHz are also CCW and CW rotation modes, respectively. It should be noted that the phase of the $\delta m_y$ differs by $\pi/2$ in the z direction from the y direction. Although the resonance modes measured in the z direction are the same as those measured in the y direction, the rotation amplitude of the bimeron measured in the z direction is greater than that in the y direction (see supplementary videos 4 and 5) due to the existence of the shape anisotropy in the y–z plane.

![Figure 5. Spatial distribution of the $m_i$ (i = x, y, or z) and spin-wave modes (amplitude and phase) of a bimeron with $B_s = −100$ mT. The resonance frequencies are marked by the grey circles in figure 4.](image-url)
Figure 6. Spin dynamics of the bimeron corresponding to the five spin-wave modes in figure 5. Temporal waveforms of sin-function magnetic fields with different frequencies are displayed in the left panel. Schematic diagrams of spin-wave modes including breathing, CCW, and CW are shown in the middle panel. Snapshots of the $\delta m_x$ of the bimeron at different times are shown in the right panel, the times correspond to the solid circles marked in the waveforms.

Let us briefly discuss why the spin-wave modes of bimerons are similar but different from that of skyrmions. As we mentioned in the introduction, when the external microwave magnetic fields are applied in the $x$–$y$ plane, the spin-wave modes of skyrmions consist of CW and CCW rotation modes, and a breathing mode is found for the external microwave field perpendicular to the plane [19, 27]. For the spin-wave modes of bimerons, they present as two rotation modes when microwave magnetic fields are applied in the $y$–$z$ plane and present as a breathing mode when the microwave magnetic field is applied along the $x$ direction. Thus, the spin-wave mode of bimerons can be considered as rotated 90° around the $y$ axis compared to that of skyrmions, this is because the spin texture of bimerons can be regarded as Néel-type skyrmions with magnetic moments rotating 90° around the $y$ axis.

5. Anisotropic in-plane spin-wave mode of bimerons

We have discussed the spin-wave modes of bimerons calculated in the $x$, $y$, and $z$ directions, and noticed that the in-plane spin-wave mode of bimerons is anisotropic, which is much different from the isotropic in-plane spin-wave mode of skyrmions [19]. Therefore, it is interesting to explore the resonance behavior and spin-wave modes of bimerons at different angles in the plane, as shown in figure 7(a). We calculated the in-plane excitation spectrums of bimerons by applying a sinc-function type excitation magnetic field $h(t)$ in different angles, as shown in figure 7(b). When the angle is 0°, i.e., the sinc-function type excitation magnetic field is applied along the $x$ direction, in addition to the strong resonance peak corresponding to the breathing mode, which has been discussed above, the appearance of two weak resonance peaks (3.9 and 11.9 GHz) in the magnetic spectrum is due to the broken rotational symmetry of the elliptical bimeron. A similar result has also been reported in the system of elliptical skyrmions [27], the breaking of the rotational symmetry of the spin texture causes the breathing mode of skyrmions to split into several complex modes. The corresponding spin-wave modes at the two frequencies will be discussed later. When the angle is 90°, i.e., the sinc-function type excitation magnetic field is applied along the $y$ direction, there are two resonance peaks corresponding to the CCW and CW rotation modes, respectively. When the angle is between 0° and 90°, such as 75°, five resonance peaks appear together in the in-plane magnetic spectrum.

To verify the resonance modes of the bimeron marked in the spectrum of 75°, we calculated the spin-wave modes at five resonance frequencies, as shown in figure 8. It is found that the spin-wave modes of the bimeron at 3.2, 7.9, and 23.5 GHz present as CCW rotation mode, breathing mode, and CW rotation mode, respectively. Moreover, at the resonance frequencies of 3.9 and 11.9 GHz, the spatial distribution of the resonance amplitude of $\delta m_x$ is an ellipse ring and four crescents, respectively, and the corresponding...
phases have continuous changes of $4\pi$ and $8\pi$, respectively. We also traced the spin dynamics of the bimeron by applying a sin-function oscillation magnetic field $h_{75} \sin(2\pi ft)$ with different resonance frequencies of 3.9 and 11.9 GHz, as shown in figure 9. The four and eight crescent-shape $\delta m_x$ circulates CCW around each center at 3.9 and 11.9 GHz, respectively, and are therefore called $4\pi$ and $8\pi$ CCW rotation modes, respectively. The high phase CCW rotation of $\delta m_x$ means that the shape of the bimeron is periodically deformed (see supplementary videos 6 and 7).

Although the geometry of the system has rotational symmetry in the plane, the in-plane anisotropy plays an important role in determining the spin texture of bimerons, thus, the spin-wave mode is shown to have in-plane anisotropy by measuring the magnetic spectrum at different angles. The above results guide the method to measure the spin-wave resonance of bimerons experimentally and also provide a way to manipulate the dynamics of bimerons in nanostructures via microwave magnetic fields. For example, bimerons may in the future be created, driven, and even reversed by using microwave magnetic fields, which is similar to the reported methods of operation for skyrmions [20, 51, 52]. In addition, the rich spin-wave
modes of bimerons including the breathing mode, the CCW rotation mode, the CW rotation mode, and high-phase rotation modes can be used for the realization of logic devices, and also contribute to the development of bimeron-based oscillators.

6. Conclusions

In summary, the static properties and spin-wave modes of a bimeron in a confined nanodot have been investigated using micromagnetic simulations. The size of bimerons is related to the DMI strength and inversely related to the in-plane anisotropy constant and the external magnetic field. Different from the spin-wave modes of skyrmions, the spin-wave modes of bimerons rotate to the in-plane due to the in-plane topological spin textures compared to skyrmions, that is, a breathing mode is found for an ac magnetic field applied in the $x$ direction, while for ac magnetic fields applied in the $y$ or $z$ direction, the spin-wave modes present as a CCW rotation mode at low frequencies and a CW rotation mode at high frequencies. Therefore, the in-plane spin-wave mode of bimerons has an anisotropic property. By calculating the magnetic spectrum at different angles in the plane, up to five resonance peaks can simultaneously appear in the in-plane magnetic spectrum. In addition to the breathing mode, the CCW rotation mode, and the CW rotation mode, because of the broken rotational symmetry of the magnetic structure, two high-phase CCW modes are found that can affect the shape of bimerons. These results may provide guidance for manipulating bimerons by using spin-wave resonance.

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Data availability statement

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

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