Spin current pumped by confined breathing skyrmion

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Abstract
Spin pumping is a widely recognized method to generate the spin current in the spintronics, which can be found in varieties of magnetic materials and is acknowledged as a fundamentally dynamic process equivalent to the spin-transfer torque. In this work, we theoretically verified the oscillating spin current mixed by AC and DC components can be pumped from the microwave-motivated breathing skyrmion. The spin current can be pumped within a relatively low-frequency microwave compared with the in-plane ferromagnetic resonance (FMR). Although the amplitude of spin current density for a single confined skyrmion is several times lower than the FMR spin pumping, the pumped current would be improved to be the same order as the FMR through a tight skyrmion lattice. Based on the spin pumping of breathing skyrmion, we designed a high reading-speed racetrack memory model whose reading speed is much higher than the SOT (spin–orbit torque)/STT (spin-transfer torque) skyrmion racetrack. Our work focuses on the spin pumping phenomenon inside the breathing skyrmion, and it may contribute to the applications of the skyrmion-based device.

1. Introduction
Owing to the demands of the spintronic research and application, how to generate and exploit the spin current is an important issue attracting considerable attention. In magnetism, we usually utilize a microwave signal to resonate with the magnetic material (the so-called ferromagnetic resonance (FMR)), so that the precessing magnetization induces a spin current at the FM (ferromagnet)-NM (non-magnetic metal) interface flowing into the NM [1, 2]. The time-dependent current is derived from the momentum transfer of the motivated spins (precessing magnetic moments) to the conduction electron via the exchange coupling, and then this mechanism inside magnetic metallic multi-layers is the so-called spin pumping. Due to the technological potential of spin pumping, the researchers have made numerous experiments and calculations to explore the field, even in the non-linear spin texture like domain wall [3, 4], skyrmion [5–7] and vortex [8].

The magnetic skyrmion is a kind of chiral topological protected spin texture and it attracts extensively interests since it was found in the B20-type MnSi [9] in 2009. After that, the skyrmion is widely discovered in other bulk material and multilayered ultrathin films [10]. Until now, it is still a novel topic to explore and is promising for the racetrack memory [11–13], oscillators [14, 15], artificial neuron [16], logical gates [17] and so on. Due to the researches in recent years, we have already obtained a clear realization of the skyrmion dynamics, which is generally covered by the Thiele equation [18–20]. However, according to the Onsager’s reciprocity relations [21], the momentum originating from the spin texture motion could also transfer to the conduction electrons and generate a spin current. This inspires us to explore the reciprocal effect in skyrmion resonance. The resonance of skyrmion is always generalized to two types of modes—breathing and gyration mode, where the gyration mode for skyrmion lattice has been investigated...
by Hirobe [5] who thinks that the pumped current density of gyration mode is much small. So in this work, we explored the spin pumping phenomena in the microwave-motivated breathing skyrmion amplitude through theory calculations and micromagnetic simulations. The spin pumping of the breathing skyrmion is both influenced by the DMI and the microwave. Then we made a hexagonal skyrmion lattice to investigate the spin pumping for the breathing skyrmions array. Furthermore, based on these results, we devised a high reading-speed racetrack memory whose reading speed is much higher than STT or SOT induced skyrmion racetrack memory.

2. Simulation model of the skyrmion spin pumping

Figure 1(a) shows the research model, where the Neel skyrmion in the center of the upper layer resonates with the perpendicular microwave and injects spin current into the layer of heavy metal (HM). Inside the HM layer, the direction (along the z-axis) of the microwave decides the skyrmion resonance mode—breathing mode. The micromagnetic simulations are performed by mumax3 [22] and it numerically solves the LLG equation of magnetization dynamics

\[ \frac{dm}{dt} = -\gamma m \times H_{\text{eff}} + \alpha \left( m \times \frac{dm}{dt} \right) \]  

where \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the Gilbert damping constant, and \( H_{\text{eff}} \) is the local effective magnetic field including the exchange field, anisotropy field, magnetostatic field, Zeeman field, and DMI field. The spectrum for skyrmion and uniformed perpendicular magnetized FM layer in figure 1(b) used the normal parameters of Co [23]: the microwave pulse to calculate the spectrum is applied in the formulation of \( h = h_0 \cdot \text{sinc}(2\pi f_d(t - t_{\text{eff}})) \), \( t_{\text{eff}} = 1 \) ns, \( h_0 = 0.5 \) mT, \( f_d = 100 \) GHz; the exchange constant is adopted as \( A = 15 \) pJ m\(^{-1}\); DMI constant is adopted as \( D = 3.5 \) mJ m\(^{-2}\); \( K = 800 \) kJ m\(^{-3}\) for perpendicular magnetic anisotropy; \( M_s = 580 \) kA m\(^{-1}\) as saturated magnetization and the coefficient \( \alpha = 0.02 \) for Gilbert damping (the dissipation from spin pumping is also contained in \( \alpha \)). These parameters form a skyrmion with the radius of 15.0 nm. The simulation size is 100 \( \times \) 100 \( \times \) 1 nm\(^3\) (length \( \times \) width \( \times \) thickness) and divided into 100 \( \times \) 100 \( \times \) 1 unit meshes, which is within the range of the Bloch exchange length [24]. As a result of the strong perpendicular magnetic anisotropy, the FMR of a uniformed FM layer hosts a relatively high resonant frequency (57.8 GHz, \( h \parallel y \)) while the skyrmion breathing frequency (6.9 GHz, \( h \parallel z \)) is far lower, as shown in figure 1(b).

3. Results and discussion

It is generally known that the contribution of spin pumping for LLG equation is included in the Gilbert term and the spin current density is governed by the equation [2]

\[ J_{sp} \sigma(t) = \frac{\hbar}{4\pi} A_s \left( m \times \frac{dm}{dt} \right); \]

\[ J_{dc} \sigma = \frac{1}{T} \int T J_{sp} \sigma(t) dt = J_{z} \sigma, \]

where \( m \) is the unit vector along the local magnetization, \( A_s \) of HM layer equaling to 1.147 \( \times \) 10\(^{19}\) m\(^{-2}\) (Au) is the real spin mixing conduction, \( \sigma \) denotes the direction of the spin polarization, \( J_{sp} \) is the amplitude of the spin current and the time average of \( J_{sp} \), namely \( J_{dc} \), is the DC component of the spin current. According to the symmetry structure of skyrmion, the magnetization of the skyrmion structure can be written as \( m(r) = (\cos \phi \sin \theta(r), \sin \phi \sin \theta(r), \cos \theta(r)) \), \( r = (x, y) = (r \cos \varphi, r \sin \varphi) \), and the in-plane spin current of the whole material is governed by the symmetry

\[ \int_0^l \int_0^l \left( J_{sp} \sigma \sigma(t) \right) dx dy = -\int_0^l \int_0^l \left( J_{sp} \sigma \sigma(t) \right) dx dy, \]

where \( l \) is the width of square material. According to the spin diffusion length in Au (30–90 nm), the spin current from skyrmion to the metal layer will diffuse in the HM layer, so the net in-plane spin current density of the whole skyrmion will mix to zero. To effectively evaluated in the corresponding half, we just
Figure 1. (a) Schematic of the skyrmion spin pumping model. The Neel skyrmion in FM layer can be resonant with the microwave and a current noted in yellow is pumped into HM. (b) Spectrum of skyrmion and FMR for DM interaction $D = 3.5$ mJ m$^{-2}$. For the perpendicular microwave, the skyrmion can be motivated in the frequency of 6.9 GHz, and the frequency of FMR with in-plane microwave is in 57.8 GHz. The skyrmion shows two gyration modes under the in-plane microwave. The small peak between 80–100 GHz may be explained by the non-Newtonian gyration mechanism proposed by Z-X Li [25].

calculate half part of the plane, where in-plane spin current density should reach the maximum within the half-space. So the spin current density for skyrmion spin pumping can be calculated by the following equations

$$
J_{i\sigma}(t) = \begin{cases} 
\int_{0}^{l/2} \int_{l/2}^{l} J_{sp\sigma}(t) dx dy/\ell^2, & (i = x); \\
\int_{0}^{l} \int_{0}^{l/2} J_{sp\sigma}(t) dx dy/\ell^2, & (i = y); \\
\int_{0}^{l} \int_{0}^{l} J_{sp\sigma}(t) dx dy/\ell^2, & (i = z); 
\end{cases}
$$

(4)

where the $\ell^2$ equals to the integral of the whole surface.

Based on equation (4), we calculated the in-plane spin current density $J_x$ ($0 < y < l/2$) and out-of-plane spin current density $J_z$ as shown in figure 2. As the microwave is applied perpendicularly to the skyrmion, the spins flip companies with the periodical expanding and contracting of breathing skyrmion. Correspondingly, the pumped current, which is the mixture of AC and DC components, also oscillates while the FMR spin pumping for $h \parallel y$ is just a DC spin current, as shown in figure 2(f). So it means that the small-angle precession spin-pumping equation for FMR is inapplicable for skyrmion breathing. The current crests and troughs in figures 2(c) and (f) refer to the maximum and minimum of skyrmion breathing radius. The current curves show that the spin current pumped by breathing skyrmion ($J_x = 4.6 \times 10^{-8}$ A m$^{-2}$ and $J_z = 3.6 \times 10^{-7}$ A m$^{-2}$) is lower, but approximately in the same order as the FMR ($J_x = 11.7 \times 10^{-8}$ A m$^{-2}$ and $J_z = 20.2 \times 10^{-7}$ A m$^{-2}$). It can be noticed the phenomenon that the in-plane current $J_x$ of breathing skyrmion is smaller than the $J_z$, which is already generally acknowledged in the FMR [26] and also found in our work. The figures 2(a), (b), (d) and (e) provide the spatial amplitude/phase of current density, attained by Fourier transform. The spatial maps show that the skyrmion spin pumping is independent and localized just inside the skyrmion area. The phase map also confirmed our theoretical speculation of equation (3) that there is a difference of $\pi$ between the $J_x$ in counter radial directions (figure 2(b)). It can be realized that the localized spin pumping of breathing skyrmion is restricted inner the skyrmion. Therefore, it may support a hypothesis that skyrmion lattice will help to enhance the spin pumping, and we would discuss it after we confirmed the influence of DMI and microwave amplitude $h$.

The DMI is one of the most important parameters to form skyrmions in the magnetic systems and indispensable for a nanoscale skyrmion [27]. In addition, the modulation of DMI is also one of the methods [28–30] to prevent the skyrmion Hall effect. We usually define the helicity of skyrmion by the phase $\chi$ [20] appearing in

$$
\phi(\varphi) = N_{dk} \varphi + \chi,
$$

$$
N_{dk} = \frac{1}{4\pi} \int \int d^3r m \cdot \left( \frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y} \right),
$$

(5)
Figure 2. Spatial maps of the skyrmion spin pumping current density in the polarization direction of $x$ ((a), (b)) and $z$ ((d), (e)). (c) and (f) shows the skyrmion spin pumping current density $J_x$ and $J_z$ (purple curves) at the resonant frequency of 6.9 GHz, while the FMR spin pumping in black lines is to make a contrast.

where the $N_{sk}$ is defined as the skyrmion number. In the recent year’s studies [28, 31], it is found that the skyrmion helicity can be decided by the combination of bulk and interfacial DMI. So the skyrmions with different DMI combinations, called by a joint name—the twisted (or hybrid) skyrmion, can have different helicities. The hybrid DMI of twisted skyrmion considered in C4 symmetry can be written as [28]

$$D_{\text{Hybrid}} = D_{\text{bulk}} \cos \Omega + D_{\text{inter}} \sin \Omega,$$

where the $D_{\text{bulk}}$ and $D_{\text{inter}}$ represent the common DMI of the bulk and interface. The hybrid angle $\Omega$ denotes the angle between the DMI vector and the line of the two nearest spins. The twisted skyrmion will be a Neel (Bloch) skyrmion whose helicity is $0^\circ$ ($90^\circ$), when $\Omega$ equals to $90^\circ$ ($0^\circ$). The contribution of $\Omega$ to the spin pumping of breathing skyrmion can be described in a rotation operation

$$R_{z}^{90^\circ-\Omega} J_{sp}(m(t)) = J_{sp}(R_{z}^{90^\circ-\Omega} m(t))$$

where the $R_{z}^{90^\circ-\Omega}$ denotes the rotation by $\chi$ ($90^\circ - \Omega$) around the $z$-axis. So the skyrmion’s rotational symmetry around the $z$-axis should keep $J_z$ be a constant but change $J_x$. As shown in figure 3(b), the rotated in-plane current $J_x$ matches well with the trigonometric function of $\Omega$. Therefore, we have confirmed that the rotation operation relying on hybrid DMI have no influence on the $J_z$.

In comparison with the $\Omega$ of DMI, the DMI strength also has an impact on the spin pumping of breathing skyrmion because it directly relates to the skyrmion diameter. The skyrmion breathing mode denotes that the skyrmion undertake a resonant process of periodical expand and contract. So the changing of skyrmion radius $\delta R$ is an important reference for spin pumping, and it is defined as

$$\delta R = R_{\text{max}} - R_{\text{min}}$$

where $R_{\text{max}}$ and $R_{\text{min}}$ corresponds to extremum radius of the breathing skyrmion. Due to the increase of $\delta R$ shown in figure 4(a) noted in red, the in-plane pumped current $J_x$ also increases rapidly with the strength of interfacial DMI. However, in figure 4(b), the out-of-plane current shows a different performance—the $J_z$ and $J_{dc}$ tends to be a stable value after a short raising. Comparing the magnetization components at the $x$-axis (inset of figure 4(b)) for $D = 3.3 \text{ mJ m}^{-2}$, the in-plane magnetization $m_y$ of skyrmion is confined by
the edge of the finite material, while the $m_z$ is freed from the restriction of the edge. According to the equation (2), $J_z, J_{dc} \propto f(m_x, m_y)$, so the limited in-plane magnetization ($m_z$ and $m_y$) can be explained for the stop of the increasing of $J_z, J_{dc}$. Therefore, for the skyrmion in the confined space, the DMI constant is one of the determinations of the current density at different polarization directions.

For skyrmions, even for general magnetic bubbles, the magnetic field is a regular means to adjust the skyrmion radius, so the microwave amplitude also plays a significant role in the skyrmion breathing. Moreover, changing the amplitude of the microwave field is also the most convenient method for application to control the spin current density for the ordinary FMR. So we decide to investigate the skyrmion spin pumping current density for different microwave amplitude (figure 5(a)). While the $\delta R$ is linearly increasing with the microwave amplitude (inset of figure 5(a)), the $J_x$ and $J_z$ are linearly related to the microwave amplitude $h$. This relationship is the same as the common FMR spin pumping [26]. Interestingly, the DC component of skyrmion spin pumping shows the same dependence with the microwave as FMR as well. It has been verified that the DC component of the spin current in the ferromagnetic material can be described by the relation [26, 32]

$$J_{dc} \propto h^2,$$

and the $J_{dc}$ of breathing skyrmion fits very well with the quadratic curve in figure 5(b). These results denote that the method controlling the spin current by microwave can also be applied to the spin pumping of breathing skyrmion.

We then calculated the current density of hexagonal skyrmion lattice (inset of figure 6) via the periodical boundary condition. The results in figure 6 show that the current density of skyrmion lattice can be substantially enhanced by the decline of lattice constant $a$. With the assembled skyrmions, the pumped

\[\text{Figure 3.} \quad \text{(a) The relationship between the } J_z \text{ and the hybrid angle } \Omega. \text{ (Inset) Schematic of the hybrid angle } \Omega \text{ and the DMI vectors are denoted in orange arrows. (b) The relation between } J_z \text{ and the hybrid angle, the curve is a trigonometric function by theory.} \]

\[\text{Figure 4.} \quad \text{(a) The relationship of in-plane spin current density } J_x \text{ and interfacial DMI constant. (b) The out-of-plane spin current density } J_z \text{ and } J_{dc} \text{ as a function of DMI constant. (inset) The spatial profiles of the local magnetization along the } x \text{-axis for } D = 3.3 \text{ mJ m}^{-2}. \]
current can even reach \( J_z = 23.5 \times 10^{-8} \text{ A m}^{-2} \) with \( a = 50 \text{ nm}, D = 3.5 \text{ mJ m}^{-2} \), which is in the same order with that of FMR and even higher. The lattice constant is a significant but complex determination for the skyrmion lattice spin pumping, because it has influences simultaneously on the skyrmion radius, breathing frequency and so on. Owing to that, the DC component \( J_{dc} \) of \( J_z \), especially for \( D = 3.5 \text{ mJ m}^{-2} \), shows labile curves in figure 6(b), but the decline of lattice constant primarily has a positive influence on the skyrmion spin pumping. Although the skyrmion lattice has a different resonant frequency and boundary from the single skyrmion, the breathing of skyrmion lattice could provide a higher pumped current than the single, and the amplitude of current density could be in the same order as the FMR \( (J_z = 11.7 \times 10^{-8} \text{ A m}^{-2}) \) through a small lattice constant.

One of the most important skyrmion applications is the skyrmion racetrack memory [11, 12]. Although skyrmions can be driven at an ultra low current density, the reading speed of racetrack memory is still limited—the skyrmion velocity, driving by STT or SOT, \( v \sim 100 \text{ m s}^{-1} \). However, with the assistance of skyrmion spin pumping, we designed a new multilayer skyrmion racetrack memory (figure 7(a)) with higher reading speed. For the layers from the top to the bottom, the model is respectively composed of FM layer, HM layer (where the isolator is at the center to prevent the in-plane current \( J_x \), \( 0 < y < l/2 \)) and \( (l/2 < y < l) \), from mixing) and the PZT (lead zirconate titanate, Pb\([Zr_xTi_{1-x}]O_3\)) layer. As the sectional view at the upper left corner of figure 7(a) shows, the spin current can be detected by the voltage \( V_{\text{ISHE}} \) of inverse spin Hall effect (ISHE) and the relation between \( V_{\text{ISHE}} \) and \( \sigma \) is given as [2]:

\[
V_{\text{ISHE}} = \frac{\lambda_{sd} \rho e}{\ell_{m}} \left( \theta_{SH} \frac{2e}{h} J_j \times \sigma \cdot \hat{i} \right) \tanh \left( \frac{\ell_H}{2\lambda_{sd}} \right)
\]  

(10)

where \( \ell_H \) is the thickness of the HM, \( \lambda_{sd} \) is the spin-diffusion length, \( J_j \) is denoted as the amplitude and flowing direction of the spin current, \( \ell_m \) is the material length along electric field, \( \theta_{SH} \) is the spin Hall angle and \( \rho \) is the resistivity of the metal layer. According to the equation (10), we take \( i = x \), corresponding to the polarization direction \( \sigma_x \), to generate a voltage \( V_{\text{ISHE}} \) in the \( y \)-direction. Owing to the problem that

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**Figure 5.** (a) The relationship between the out-of-plane/in-plane spin current density amplitude and the microwave amplitude. The inset displays the \( \delta R \) as a function of microwave amplitude. (b) The DC component of the current density as a function of microwave amplitude and the data symbols are fitted by a quadratic curve.

**Figure 6.** The relationship between the amplitude of pumped current density \( J_z \) (a), \( J_{dc} \) (b) and the skyrmion lattice constant \( a \) for different DMI constants.
Figure 7. (a) The model of the high reading speed structure built on the racetrack memory. The skyrmions and blanks denote data of 1 and 0, while the data gap is denoted by $u$. The brown color in the center of the HM layer shown in the three-dimensional model is the isolator. The inset map in the top left is the $y$–$z$ plane map. The $J_x$ is divided into two parts, $J_x (0 < y < l/2)$ and $J_x (l/2 < y < l)$, by the isolator, so the spin current $J_x$ will lead to the voltage $V_{y-}$ applied on the PZT layer noted in green. (b) A microwave pulse is applied to the model. As $t = t_0$ shown in figure (b), the skyrmion spin pumping voltage causes deformation peaks at the PZT track, where the 9 peaks and 3 blanks denote the data string 111 101 011 011. The color bar shows the deformation amplitude of the PZT track. After $t = 533$ ps, it is shown in the right that the deformations spread as an acoustic wave at a velocity of $v = 3018.8$ m $s^{-1}$. The gray solid line denotes the reading threshold. The black dot lines denote that the periodically read data point over the threshold and the string is still the 111 101 011 011 as $t_0$.

the net in-plane current density calculated by equation (4) shown in figure 2(a) would be mixed to zero, an insulator layer is set in the center to separate the two parts, $(0 < y < l/2)$ and $(l/2 < y < l)$.

When a skyrmion racetrack memory is motivated by a short microwave field pulse (half of a period, $f = 6.9$ GHz), the data point on the racetrack, denoted by blanks/skyrmions corresponding to 0/1, will cause a transient low/high voltage by the ISHE. In the meanwhile, the microwave of the skyrmion breathing frequency cannot motivate the resonance of the FM state material, whose pumped current should be almost zero. The high voltage in the $y$-direction at data points (where skyrmions locate) can cause a transient deformation of the PZT track. As shown in figure 7(b) at $t = t_0$, the deformation peaks and blanks in the PZT track denote data string 111 101 011 011, where the data gap $u$ is set to 100 nm to avoid the disturbance between neighbor data points. We make an approximation that the deformation is uniformly applied in the scope of 10 nm on the edge and ignore the energy dissipation, so the simulated deformations will spread along the track (x-axis) in the acoustic wave velocity of 3018.8 m $s^{-1}$. After $t = 533$ ps, the deformation peaks are mixed, but the data are still contained in the wave packet. The peaks of data 1 are mixed to four major wave peaks and the three major troughs denote the former data 0. By setting a deformation threshold denoted by the gray solid line, the wave peaks and troughs can be reciprocally translated to the original string 111 101 011 011. Because the deformation in the PZT can also be converted to a voltage, a sensitive voltage detector with an adjacent voltage threshold can realise the data reading. Through the ISHE voltage, we transfer the pumped current signal to the deformation signal of PZT layer, where the deformations can spread as acoustic waves. This design, which takes advantage of the acoustic wave and spin pumping, breaks the limitation of skyrmion velocity and provides a new thought of the racetrack memory.

4. Conclusions

The research studied the spin pumping of skyrmion breathing mode. It shows that the spin pumping of breathing skyrmion holds a lower excitation frequency and the amplitude of the pumped current density is several times lower than the FMR spin pumping. And the spin current pumped by breathing skyrmion can be dominated by the DMI and microwave. However, it should be noted that the amplitude of spin current density will be substantially improved to be the same order as the FMR after the skyrmions are
Figure B1. (a) The spectrum of skyrmion lattice with different lattice constant $a$. It should be noted that the mode 2 is the most intensive peak just only when $a = 100$ nm. (b) The $J_z$ of skyrmion lattice for different $a$ in different gyration modes.

assembled to be the hexagonal lattice. At last, we build a high reading-speed racetrack memory model. The data record by skyrmions can be transformed to the deformation signal of the PZT by the ISHE voltage, which can spread in a velocity of 3018.8 m s$^{-1}$ larger than the skyrmion velocity driven by STT or SOT. The work provides some of the new information about the researches of spin pumping and skyrmion, and it may help researchers to get some thoughts about the skyrmion-based devices.

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Appendix A. Amplitude of spin current

The spin current pumped by breathing skyrmion in the z-direction is a mixture with DC and AC component, while its waveform is apparently not a perfect trigonometric function. To assess the current efficiently, we make an operation to get the amplitude of $J_z$

$$\text{Amplitude}(J_z) = \frac{\max(J_z) - \min(J_z)}{2}.$$  \hspace{2cm} (A.1)

So, by the management, the $J_z$ can be directly valued by its amplitude. Certainly, the best method is to make a Fourier transform to separate the DC and AC component, but this operation is still intuitively understood as a valid method.

Appendix B. Spin pumping of gyration skyrmion

Our work pays attention to the spin pumping of confined breathing skyrmion, while the spin pumping of gyration skyrmion is studied by Hirobe [5] in 2015. The gyration skyrmion shows a complex phenomenon, especially for the skyrmion lattice. As shown in figure 1(b), the skyrmion with the in-plane microwave has two excitation modes. The two modes with different excitation intensity for skyrmion lattice show different pumping results in figure B1. Comparing figures B1(a) and (b), they show that the strongest peak in the spectrum is not corresponding to the strongest spin pumping. It should be noted that the most intensive peak at the spectrum of skyrmion lattice takes place by mode 2, when $a \leq 90$ nm. And the FMR ($J_z = 1.17 \times 10^{-7}$ A m$^{-2}$) is fairly higher than the skyrmion lattice with $70$ nm $\leq a \leq 95$ nm. This can also be an important proof for the formers’ work.

Appendix C. Skyrmions of different lattice constants $a$

The spin pumping in skyrmion lattice for breathing mode is influenced by many factors. Although the skyrmion density is increasing with the decline of $a$, the radius and the skyrmion frequency will change in the meanwhile. An apparent change is that the breathing frequency of an isolated skyrmion (6.9 GHz) in
Figure C1. In the skyrmion lattice for $D = 3.3 \text{ mJ m}^{-2}$, the skyrmion radius $R$ and the breathing frequency $f$ as a function of lattice constant.

$100 \times 100 \times 1 \text{ nm}^3$ square is higher than the skyrmion lattice with $a = 100 \text{ nm}$ (5.6 GHz). And figure C1 also shows a competition between skyrmion radius and breathing frequency. But if we take the results of figure 6 into consideration, we believe that the reduction of $a$ will turn to an increase of current density in general.

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