Current-induced magnetic skyrmions oscillator

Senfu Zhang, Jianbo Wang, Qi Zheng, Qiuyuan Zhu, Xianyin Liu, Shujun Chen, Chendong Jin, Qingfang Liu, Chenglong Jia and Desheng Xue

Key Laboratory for Magnetism and Magnetic Materials of Ministry of Education, Lanzhou University, Lanzhou, 730000, People’s Republic of China

E-mail: liuqf@lzu.edu.cn

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Abstract

Spin transfer nano-oscillators (STNOs) are nanoscale devices which are promising candidates for on-chip microwave signal sources. For application purposes, they are expected to be nano-sized, to have broad working frequency, narrow spectral linewidth, high output power and low power consumption. In this paper, we demonstrate by micromagnetic simulation that magnetic skyrmions, topologically stable nanoscale magnetization configurations, can be excited into oscillation by a spin-polarized current. Thus, we propose a new kind of STNO using magnetic skyrmions. It is found that the working frequency of this oscillator can range from nearly 0 Hz to gigahertz. The linewidth can be smaller than 1 MHz. Furthermore, this device can work at a current density magnitude as small as $10^8$ A m$^{-2}$, and it is also expected to improve the output power. Our studies may contribute to the development of skyrmion-based microwave generators.

1. Introduction

Skyrmions are topologically protected objects with particle-like properties that play an important role in many different contexts, such as liquid crystals [1], quantum Hall magnets [2], Bose–Einstein condensates [3], etc. Recently, with the development of observation technology, particularly in the domain of neutron scattering [4], spin-polarized scanning tunneling microscopy (STM) [5], Lorentz force microscopy [6–8], and electron holography [9], skyrmions have been observed in bulk ferromagnetic crystals, thin films and nanowires. The spin texture of magnetic skyrmions is a stable configuration that, in most systems, results from a balance between the ferromagnetic exchange coupling, the Zeeman energy from the applied field and the chiral interaction, known as the Dzyaloshinskii–Moriya interaction (DMI) [10–12]. The DMI is induced because of the lack of, or breaking of, inversion symmetry in the magnetic structure, either due to the non-centrosymmetric crystal lattice or to the interfaces between different materials [8].

Magnetic skyrmions were originally discovered in bulk ferromagnets lacking inversion symmetry, such as MnSi [13], FeGe [7, 14], Fe$_{0.5}$Co$_{0.5}$Si [15] and other B20 transition metal compounds [16]. Then they were observed in thin films and nanowires of similar materials [9, 17, 18], and recently, in the multiferroic insulator Cu$_2$OSeO$_3$ [19]. In addition, a more stable two-dimensional skyrmion crystal has been created artificially by nanopatterning [20] and a spontaneous skyrmion ground state has been created in Co/Ru/Co multilayer nanodisks without the DMI (the competition of the exchange energy, demagnetization energy and uniaxial anisotropy energy acts similar to the DMI) by a numerical approach [21]. Meanwhile, an effective method was reported to nucleate or annihilate isolated skyrmions experimentally by using STM at one monolayer of Fe grown in Ir(111) [22].

It was recently realized that the magnetic skyrmions not only have mathematical beauty but can also be used as spintronic devices. Recent research has demonstrated that magnetic skyrmions have great potential to act as the next generation of magnetic memories in nanowires [23–25] because of two evident advantages: (i) skyrmions have stable small size (10–100 nm or even as small as a few atoms in diameter), suggesting ultra-high density data encoding, (ii) skyrmions can be easily manipulated using extremely low spin current density of only about $10^6$ A m$^{-2}$ which is about $10^3$ to $10^5$ smaller than that required to drive magnetic domain walls.
These two unique properties point to an opportunity for the realization of many other novel skyrmion spintronic devices. Here, we propose another spintronic application of a skyrmion device: a spin transfer nano-oscillator (STNO). The STNO is used to generate microwaves [28]. Key features of STNO devices are: (i) small size (i.e. at the nanoscale), (ii) broad and steady working frequency. Currently, STNOs are roughly divided into two kinds: (a) precessional motion of uniform magnetization [29] and (b) magnetic vortex oscillations [30–36]. Vortex-based STNOs could present a high output power [37], and a narrow spectral linewidth [32]. However, the current density used to manipulate the oscillation of the vortex is of the magnitude of $10^{11}$ to $10^{12}$ A m$^{-2}$. Moreover, one nanodisk allows the existence of only one magnetic vortex, which limits the output power of an STNO, and also the size of the magnetic vortex is larger than a skyrmion [31, 32]. In this work, using micromagnetic simulation, we demonstrate that a magnetic skyrmion can be excited into oscillation by a spin-polarized current, and the linewidth could be smaller than 1 MHz. Arising from this effect, we propose a spintronic application of skyrmion-based STNOs. To improve its performance, an STNO with multiple skyrmions is further proposed. It is found that the range of working frequency is hugely extended. This device could work at the current density magnitude of $10^8$ A m$^{-2}$ with the start oscillation time markedly reduced. This device is also expected to improve the output power.

2. Model and simulation details

Figure 1 shows a simple schematic diagram of our STNO device (a single skyrmion here) which consists of a fixed layer, a non-magnetic spacer (either a non-magnetic-metal or a thin insulator), a free layer, and a pair of point contact electrodes at the top and bottom. The magnetization orientations of both the free layer and polarizer are perpendicular to the sample plane. The electrical current flows perpendicularly to the nanodisk through the point contact electrodes, and has a uniform distribution. The OOMMF public code [38], including the extension modules of the DMI (which was completed by S Rohart’s group), [39] and STT [40] (which works only inside the area of electrodes) are performed for the free layer at $T = 0$ K. The time dependence of the spin dynamics of each unit cell follows the extended Landau—Lifshitz—Gilbert (LLG) equation:

$$\frac{dm_i}{dt} = -\gamma m_i \times H_{\text{eff}} + \alpha \left( m_i \times \frac{dm_i}{dt} \right) + \frac{u}{l} m_i \times \left( m_p \times m_i \right) - \xi \frac{u}{l} \left( m_i \times m_p \right),$$

where the third and fourth terms describe the coupling between spins and spin-polarized current [41], and $m_i$ is the unit vector of the local magnetization, $\gamma$ is the gyromagnetic ratio, $\alpha$ is the Gilbert damping coefficient and is set to 0.01, $m_p$ (inside the area of electrodes) is the current polarization vector, $l$ is the thickness of the free layer, $\xi$ is the amplitude of the out-of-plane torque relative to the in-plane torque and is set to 0.1. The parameter $u$ has the form $u = \gamma (hJ_P/2\mu_0 c M_s)$, where $J$ is the current density, $P$ is the spin polarization and is set to 0.3, $M_s$ is the saturation magnetization. The effective magnetic field $H_{\text{eff}}$ is the sum of demagnetization field, anisotropy field, exchange field, Oersted field induced by the applied current (the skyrmion’s dynamics is less affected by the Oersted field according to our simulations, thus, in order to understand the intrinsic dynamics driven by STT, the Oersted field is neglected here), and the DMI. For bulk materials lacking inversion symmetry, the DMI in an atomic description is given by:
\[ E_{\text{DM}} = \sum_{\{i,j\}} \left( \vec{u}_{ij} \cdot \left( \vec{S}_i \times \vec{S}_j \right) \right), \]

where \( \vec{d}_{ij} = \vec{u}_{ij} \) is the DMI vector for the atomic bond \( i,j \), \( \vec{u}_{ij} \) is the unit vector between atoms \( i \) and \( j \), and \( \vec{S}_i \) is the atomic moment unit vector. As the film is very thin, magnetization direction variation along the film normal can be neglected. Supposing that the atomic spin direction evolves slowly at the atomic scale, the DMI is continuous, and the DMI energy becomes:

\[ E_{\text{DM}} = \iiint D \left( m_x \frac{\partial m_z}{\partial x} - m_z \frac{\partial m_y}{\partial x} + m_z \frac{\partial m_x}{\partial y} - m_x \frac{\partial m_z}{\partial y} \right) \, d^3r, \]

where \( D \) is the continuous effective DMI constant, \( m_x, m_y, \) and \( m_z \) are the components of the normalized magnetization \( \vec{m} = M/M_r \).

We consider a thin film of a chiral magnet with a DMI that supports vortex-like skyrmions as the free layer, which is a nanodisk with a thickness of 0.6 nm and whose radius \( R \) varies from 20 to 70 nm. The unit cell size is chosen to be \( 0.5 \times 0.5 \times 0.6 \) nm\(^3\) for \( R \leq 30 \) nm and \( 1 \times 1 \times 0.6 \) nm\(^3\) for \( R > 30 \) nm. The material parameters are chosen similar to those of [25]: exchange stiffness constant \( A = 1.5 \times 10^{-11} \) J m\(^{-1}\), uniaxial anisotropy constant \( K_u = 0.8 \times 10^6 \) J m\(^{-3}\), saturation magnetization \( M_s = 5.8 \times 10^5 \) A m\(^{-1}\) and \( D \) varies from 2 to 9 mJ m\(^{-2}\).

Considering these values, it is reasonable to assume the existence of more than one skyrmion in one nanodisk [42, 43]. Therefore, to improve the performance of the STNO, we also propose a multiple-skyrmion STNO device which we will study in detail later.

3. Skyrmion nucleation and its stability

We initially created a skyrmion at the center of the nanodisk as shown in figure 2 (this can be carried out by local injection of a spin-polarized current pulse perpendicular to the nanodisk in the experiment of [22]) as well as in [44]). The radius of the nanodisk \( R \) is set to 30 nm. For \( D < 2.5 \) mJ m\(^{-2}\), the relaxed state is a ferromagnetic (FM) state. For \( 2.5 \) mJ m\(^{-2}\) \( \leq D \leq 8.0 \) mJ m\(^{-2}\), the relaxed state is a skyrmion at the center of the nanodisk and the size (the diameter of the circle with \( M_z = 0 \)) increases with the increase of \( D \) [45]. Note that, for our system with edge effects, the skyrmion size is slightly different from that of skyrmion lattices in unbounded films, where the lattice period (proportional to \( A/D \), and strongly influenced by the external magnetic field) decreases with the increase of \( D \), and the reason has been discussed in [25]. To understand why the skyrmion stays at the center of the nanodisk, figure 3 shows the \( x, y \) and \( z \) components of the magnetization along the diameter (along the \( x \) axis) of the nanodisk where there is no skyrmion. \( m_z \) is \( -1 \) (\( m_x = m_y = 0 \), direction of the magnetic moment is down) at the center (position = 30 nm) of the nanodisk. Then \( m_z \) increases and \( m_y \) becomes larger positioned closer to the edge of the nanodisk, which reveals that the edge magnetization rotates in a plane parallel to the edge surface because of the DMI. For our case, there is a skyrmion (the magnetization direction at the boundary is down) in the disk. Thus, a skyrmion positioned away from the center will increase the total energy of the system. Due to energy minimization, it is energetically more favorable for the skyrmion to stay in the center.

To confirm that the spin structure is that of a skyrmion, we calculated the skyrmion number using the following formula:

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

where \( q \) is the topological density. \( S \) is approximately equal to 1, proving that the spin structure is just a skyrmion state [8]. For \( D \geq 9.0 \) mJ m\(^{-2}\), it becomes a multiple-domain state. Considering that we are exploring the potential application of STNOs based on skyrmions, our later simulations are performed with \( D = 3 \) mJ m\(^{-2}\).

4. Current-induced dynamic of a single skyrmion

Then spin-polarized current is applied through the nanocontact and the yellow arrow (as shown in figure 1) indicates the direction of current with the actual electron flow in the opposite direction. Note that it is regarded as an idealized current distribution between two electrodes in the simulations. First, \( R \) is set to 30 nm, the radius of electrode \( r_e \) is set to 4.24 nm (unless noted otherwise, \( R \) and \( r_e \) are set to 30 nm and 4.24 nm in the later simulations), and current density \( j = 1 \times 10^{11} \) A m\(^{-2}\) is applied. Figure 4(a) shows the related trajectory of the guiding center \( (R_x, R_y) \) of the skyrmion (the center of the topological skyrmion) which is defined by [46].
The force from the perpendicular spin-polarized current drives the skyrmion outside of the nanocontact gradually with a spiral trajectory and finally the skyrmion reaches a persistent oscillation around the injection site of the current. The final steady oscillation radius of the skyrmion core \( r_s = \sqrt{R_x^2 + R_y^2} \) is about 10.98 nm. In order to investigate the time evolution of the skyrmion motion, figure 4(b) shows \( R_x \) as a function of simulation time. \( R_x \) starts to oscillate as soon as the current is applied, but the magnitude of the amplitude is
just about \(10^{-16}\) m at the early time stage as shown in the inset of figure 4(b). Then the amplitude increases gradually with the simulation time and \(R_x\) starts to oscillate more vigorously (magnitude of nm) at about \(\tau = 25\) ns (\(\tau\) is considered as the start oscillation time) and then the amplitude increases rapidly to a steady value. The final frequency of steady oscillation \(f\) is about 0.76 GHz. To describe the dynamics of the single skyrmion oscillation, we use the approach developed by Thiele [47] for the skyrmion’s translational motion. The skyrmion is considered to be a rigid particle and thus we assume \(F = -mr \dot{r} R(t)\).

Following the treatment in [48, 49], we obtain

\[
G \times \frac{dX}{dt} + \frac{\partial U}{\partial x} + \hat{D} \frac{dX}{dt} - F_i = 0, \tag{6}
\]

where \(G = 4\pi \mu \mu \gamma /\epsilon \) is a gyrocoupling vector, \(F_i\) is the spin transfer force and \(U(R)\) is the potential acting on the skyrmion due to the boundary effect and \(U(R) = \frac{k}{2} (R_x^2 + R_y^2)\) where \(k\) denotes the spring constant for restoring force. The damping tensor \(\hat{D}\) can be computed as \(\hat{D} = \eta_j \alpha \mu \mu_0 M_r /\gamma\) where \(\eta_j = \int (\partial_m \cdot \partial_m) dx dy\), so \(\eta_j = \delta_{ij} \eta\) where \(\eta\) is a shape factor of the skyrmion. The component \(F_i\) of the force \(F_i\) is given by

\[
F_i = \frac{\mu_0 \mu_0 M_r \mu}{\gamma} \int_{P_c} \left[ (m_p - \xi m \times m_p) \cdot (m \times \partial_m) \right] dx dy, \tag{7}
\]

where the integration is over the point contact area \(P_c\). We write \(dR/dt = v_x e_x + v_y e_y\) in polar coordinates since the system is a disk. The potential \(U\) for the skyrmion is expected to be symmetric about the \(z\) axis, i.e., \(U = U(\rho)\). We can also split the force \(F_i\) into two components \(F_i = F_{ix} e_x + F_{iy} e_y\), where \(F_i\) corresponds to the first term while \(F_{ix}\) is related to the \(\xi\) term in equation (7). Therefore, equation (6) can be written as

\[
-G v_x + \frac{\partial U}{\partial \rho} + D v_{\rho} - F_{\rho} = 0, \\
G v_y + D v_{\xi} - E_{\xi} = 0, \tag{8}
\]

where \(D = \alpha h \mu \mu_0 M_r /\gamma\). For stable motion, where \(v_x = 0\) and \(v_y = \omega \rho\), we obtain

\[
\omega = \frac{k - F_{\rho}/\rho}{G}, \tag{9}
\]

or \(\omega = \frac{E_{\xi}}{D\rho}\) \(\tag{10}\)

where \(\rho\) is equal to \(r_s\). Then combining our analytical results with micromagnetic simulations, we calculate the oscillation frequency. Figure 5(a) shows the spin transfer force \(F_i\) and \(F_{ix}\) as functions of oscillation radius \(r_s\). Both \(F_i\) and \(F_{ix}\) decrease as expected with the increase of \(r_s\). The potential \(U\) is equal to the variation of total energy of the system (relative to the case where there is no applied current) as shown in figure 5(b) from where we obtained that \(k = 11.4 \times 10^{-5}\) N m\(^{-1}\), thus \(f = 0.73\) GHz and \(0.70\) GHz from equations (9) and (10) which are very close to our micromagnetic simulation result of 0.76 GHz. Note that, according to our simulation, \(k \gg F_{ix}/\rho\), so oscillation frequency is mainly determined by potential \(U\) instead of \(F_{ix}\).
5. STNO with a single skyrmion

Since the DC spin-polarized current excites gigahertz skyrmion oscillation in the free layer, which could give rise to a temporal variation of the resistance due to the magnetoresistive (MR) effect, it could be used as an STNO. Figure 6 shows a schematic diagram of an STNO device with multiple pairs of point contact electrodes. The electrode at the center of the nanodisk is used to drive the skyrmion, and the others, which have a centrosymmetric distribution, are used to detect the voltage signal. It is low resistance for the case of 1, 2, 4, 5 and 6, and high resistance for 3.

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**Figure 5.** (a) The spin transfer force (tangential and radial direction components) as a function of oscillation radius \( r_s \). (b) The variations of total energy of the system (relative to the case where there is no applied current) as a function of \( r_s \); the inset is the relationship between variation of total energy and \( r_s \).

**Figure 6.** Schematic diagram of an STNO device with multiple pairs of point contact electrodes. The electrode at the center of the nanodisk is used to drive the skyrmion; the others are used to detect the voltage signal. It is low resistance for the case of 1, 2, 4, 5 and 6, and high resistance for 3.
where $I$ is the DC current, $R$ is equal to the DC resistance, $\Delta R$ is the oscillation amplitude of the resistance induced by $I$ and $R_L$ is the impedance of the load. It is evident that maximizing $P_{out}$ requires maximizing $\Delta R$, which requires a large oscillation amplitude. When the skyrmions move into the area of the detection electrodes, and the magnetization of the free layer and the fixed layers at the area of the detection electrodes are almost in an antiparallel alignment, the resistance is relatively high, as in the case of 3 in figure 6. When the skyrmions move out of the area of the detection electrodes, the magnetizations are parallel and the resistance is relatively low, as in the case of 1, 2, 4, 5 and 6 in figure 6. Thus, the value of $\Delta R$ for our skyrmion-based STNO should be larger than that of a vortex-based STNO. What is interesting is that we could obtain six signals with different phases from six pairs of detection electrodes. Each signal is a pulse signal with a frequency in the microwave range, and the duty ratio is about 1/6.

Another method to generate microwaves arises from the electromagnetic induction principle. Putting a coil at the top and covering half of the nanodisk, the skyrmion acts as a magnet as when it goes in and out of the coil area with a frequency in the microwave range, a temporal variation voltage is generated at the coil.

Then we investigated the oscillation frequency of the skyrmion. When the spin-polarized current is $J < 1 \times 10^{10} \text{ A m}^{-2}$, it is too weak to move the skyrmion away from the center of the nanodisk. In contrast, for $J > 18 \times 10^{11} \text{ A m}^{-2}$, the skyrmion will be destroyed and the free layer becomes FM again. When $1 \times 10^{10} \text{ A m}^{-2} \leq J \leq 18 \times 10^{11} \text{ A m}^{-2}$, which is large enough to supply sufficient STT to cancel out the intrinsic damping losses, it will lead to steady oscillation of the skyrmion in the free layer. The oscillation frequency $f$ and linewidth can be obtained by conducting a fast Fourier transform (FFT) of $R_s$ as shown in the inset of figure 4(b) ($J = 10 \times 10^{11} \text{ A m}^{-2}$). It is particularly worth mentioning that the linewidth (full width at half maximum of the power spectra) is smaller than 1 MHz, which offers a huge advantage to STNO application. Figure 7 shows $f$, $r_s$, and $\tau$ as functions of current density $J$. With the increase of $J$, both $f$ and $r_s$ increase rapidly at first as expected as shown in figures 7(a)–(b). Further increasing $J$ will result in $r_s$ gradually approaching a stable value of 14.5 nm due to the effect of the nanodisk edge. In the meantime, $f$ decreases slowly. The reason why the range of $f$ is very narrow ($f$ is around 0.7 GHz) is that the oscillation frequency is mainly determined by potential $U$ instead of $E_F$ as has been discussed before in equation (9). To understand the effect of the nanodisk edge, the inset of figure 7(b) shows contour plots of $M_z$ with $J = 18 \times 10^{11} \text{ A m}^{-2}$. The yellow area indicates the area of the electrodes and the black circle is a perfect circle for comparison (the skyrmion core is deflected to the left of the center of the circle), which reveals that the skyrmion is extruded by the edge of the nanodisk, leading to a deformation of the skyrmion especially near the edge of the nanodisk. In addition, it is notable that the starting oscillation time $\tau$ is extremely long when $J$ is small (when $J = 1 \times 10^{10} \text{ A m}^{-2}$, $\tau = 774 \text{ ns}$). As $J$ increases, $\tau$ decreases rapidly and then becomes stable as shown in figure 7(c). For applications, the STNO is expected to work at smaller $J$ and smaller $\tau$. Thus $\tau$ should be reduced, which will be discussed later.

Then $J$ is set to be $4 \times 10^{11} \text{ A m}^{-2}$. We try to adjust $J$ by regulating $r_e$. Figures 8(a)–(b) shows the simulated $f$ and $r_s$ as functions of $r_e$. $r_s$ increases almost linearly with $r_e$, while $f$ first increases and then decreases with the increase of $r_e$. The range of $f$ is narrow due also to equation (9). Note that $r_e$ should not be larger than the skyrmion size, otherwise we could not obtain steady-state oscillation of the skyrmion, but it stays at the center of the nanodisk instead.

**Figure 7.** Oscillation frequency $f$ (a), $r_s$ (b) and starting oscillation time $\tau$ (c) as a function of current density with $R = 30 \text{ nm}$ and $r_e = 4.24 \text{ nm}$. The inset in (a) is the FFT power as a function of frequency with $J = 10 \times 10^{11} \text{ A m}^{-2}$. The inset in (b) is the contour plots of $M_z$ with $J = 18 \times 10^{11} \text{ A m}^{-2}$.
can also be regulated by changing the radius of the nanodisk $R$ because the potential $U$ can be adjusted hugely by the size of the nanodisk. Figure 9 shows $f$ and $r_s$ as functions of $R$ with $r_e = 2$ nm and $J = 2 \times 10^{11}$ A m$^{-2}$. $r_s$ increases almost linearly with $R$ as shown in figure 9(b). In the meantime, $f$ decreases as expected with the increase of $R$ and finally approaches about 0 Hz when $R < 70$ nm because the potential $U$ decreases with the increase of $R$. Note that when $R > 70$ nm, the skyrmion will be driven to a certain position and no longer move, which reveals that the oscillation of the skyrmion depends strongly on the force both from the spin-polarized current and the edge of nanodisk.

6. Stability of the STNO—a non-magnetic impurity in the nanodisk

In practical applications, it is inevitable that the nanodisk is impure, which may affect the STNO’s performance. To study the effect of impurities on the skyrmion dynamics, we place a non-magnetic circular impurity (a hollow area 4 nm in diameter) at 25 nm from the center of the nanodisk as shown in figure 10(a). It has been demonstrated that topological protection could drastically reduce the influence of defects on skyrmions [25]. Figure 10(b) shows the trajectory of the skyrmion core with $J = 3.5 \times 10^{11}$ A m$^{-2}$, which reveals that the skyrmion can still oscillate, though its motion trajectory is slightly distorted ($r_s$ becomes larger) at the location of the impurity. The reason why $r_s$ becomes larger is that the size of the skyrmion is changed (becomes smaller) while we estimate the guiding center of the skyrmion as its location. Actually, both the size and the shape of the...
skyrmion show slight variations. The deformation of the skyrmion is related to the magnetization of the nanodisk, thus, to have a better understanding of the skyrmion dynamics near the impurity, we give the projection of the trajectory in the \( \langle M_x \rangle - \langle M_y \rangle \) plane (where \( M_x \) and \( M_y \) are the \( x \) - and \( y \) -axis components of the total magnetization, respectively) with \( J = 1, 2, 3 \) and \( 3.5 \times 10^{11} \) A m\(^{-2} \), respectively, as shown in figure 10(c). As we have already known previously that \( r_s \) increases almost linearly with \( R \) at the same \( r_e \) and \( J \), it reveals that the skyrmion is extruded by the edge of the nanodisk, leading to the deformation of the skyrmion especially near the edge of the nanodisk. For example, when the skyrmion is at the right side of the nanodisk (the maximum of \( x \) in the real space), deformation occurs mainly at the right side of the skyrmion, leading to the variation of \( M_y \), because magnetization here is along the \( y \) axis. Figure 10(c) shows that the trajectory of the \( \langle M_x \rangle - \langle M_y \rangle \) is deformed and the deformation becomes increasingly obvious with the increase of \( J \). Continuing to increase \( J \) to \( J > 3.5 \times 10^{11} \) A m\(^{-2} \), the skyrmion will be destroyed.

Let us give a brief summary of the STNO with a single skyrmion. The linewidth is smaller than 1 MHz and \( f \) can be adjusted by changing \( J, r_e \), and \( R \). However, for regulating \( J \) and \( r_e \), the range of \( f \) is very narrow (\( f \) is just around 0.7 GHz). For regulating \( R \), \( f \) ranges from 0 Hz to about 1.4 GHz, but this is inconvenient for applications. In addition, \( \tau \) is extremely long when \( J \) is small. Finally, the output power is limited when there is only one skyrmion in the nanodisk. To solve these problems, we try to nucleate multiple skyrmions in one nanodisk (figure 11), which is expected to decrease \( \tau \), while increasing output power and also the range of \( f \).

7. STNOs with multiple skyrmions

As has been mentioned previously, it is reasonable to have more than one skyrmion in one nanodisk. Figure 11 shows the relaxed states of multiple skyrmions (two, four, five and six, respectively) in a nanodisk of \( R = 50 \) nm, forming a centrosymmetric structure. Thus, we propose a multiple-electrode STNO device as shown in figure 12 (\( R \) is set to 50 nm here and in the later simulations), where there are multiple (six) point contact electrodes in the STNO. Each skyrmion is subject to two forces at the relaxed states, namely the repulsive force \( F_{ss} \) from other skyrmions [50] and the repulsive force \( F_{se} \) away from the edge of the nanodisk. Since the skyrmions are in equilibrium, \( F_{se} \) is balanced by \( F_{re} \) as shown in figure 11(a). With an increasing number of skyrmions, the resultant force from other skyrmions becomes stronger, so the distance between the skyrmions and center of the nanodisk \( r_s \) widens, as shown in figures 11(d)–(f).

Then spin-polarized current is applied to drive the skyrmion oscillation, and it is one oscillation cycle (\( T \), and the corresponding oscillation frequency is \( f \)) when each skyrmion is rotated by \( 2\pi \), as in the case of the figure 11(a) state to the figure 11(c) state. When one skyrmion moves to the location of the next skyrmion, one
working cycle ($T_w$ and the corresponding working frequency is $f_w$) is actually completed, as in the case of the figure 11(a) state to the figure 11(b) state. Thus, for an STNO with a single skyrmion, $f_w$ is equal to $f$, while for STNOs with multiple skyrmions, $f_w = Nf$, where $N$ is the number of skyrmions. For applications, we are more concerned with $f_w$. Figure 13(a) shows $f_w$ as a function of $J$ for different $N$ with $r_e = 7$ nm. It can be seen that $f_w$ increases with the increase of $J$. For the case of $N = 1$, $f_w$ ranges from 0.07 to 0.14 GHz, while for cases of $N > 1$, the range of $f_w$ is hugely extended. Taking the case of $N = 2$ as an example, $f_w$ increases rapidly from nearly 0 GHz to 0.25 GHz and then slowly increases to 0.33 GHz. For the case of $N = 3$, the maximum $f_w$ (0.36 GHz) is relatively larger than that of two skyrmions, which is easy to understand. As we know, the point contact electrodes are at the center of the nanodisk, and the relaxed state of the skyrmion is also at the center for the case of $N = 1$, so that the function area of the spin-polarized current is totally on the skyrmion, so larger $J$ ($J > 18 \times 10^{11}$ A m$^{-2}$) will destroy the skyrmion. With the increase of $N$, the relaxed states of the skyrmions are
off-center on the nanodisk and \( r_e \) increases, so the function area of the spin-polarized current on the skyrmions becomes smaller and smaller, leading to skyrmions that could withstand a larger \( J \) and the initial growth rate of \( f_w \) for the case of \( N = 2 \) is larger than that of \( N = 3 \). It is worth noting that there is hardly any function area of the spin-polarized current on the skyrmions for \( N > 3 \) when \( r_e = 7 \) nm so that the skyrmions do not move. In order to study this issue, \( r_e \) is enlarged to \( r_e = 15.8 \) nm.

Figure 13(b) shows the results for \( r_e = 15.8 \) nm. It can be seen that the skyrmions are driven to oscillation for all simulated systems. Similar to the case of \( r_e = 7 \) nm, for \( N > 1 \), the smaller \( N \), the larger the initial growth rate of \( f_w \). Moreover, the maximum \( f_w \) is relatively large for larger \( N \), as expected, except for \( N = 6 \). It can be predicted that \( f_w \) could be larger if we continue to increase \( J \) for \( N = 6 \), but such a large current makes it pointless for applications. It is worth mentioning that the maximum \( f_w \) for \( N > 1 \) is 1.07 GHz, which is about 4.46 times higher than that of a single skyrmion (0.24 GHz) in these simulations (\( J < 300 \times 10^{11} \) A m\(^{-2}\)). The inset of figure 13(b) shows an enlarged view of smaller current density. (c) Working frequency as a function of the number of skyrmions with \( r_e = 15.8 \) nm and \( J = 1 \times 10^{12} \) A m\(^{-2}\). (d) The x-axis component of the total magnetization as a function of simulation time with \( r_e = 15.8 \) nm and \( J = 5 \times 10^8 \) A m\(^{-2}\) when there are three skyrmions in the nanodisk.

For STNOs with multiple skyrmions, the total number of detecting electrodes should be equal to that of the skyrmions to ensure that the skyrmions move into and out of the area of detecting electrodes synchronously. Thus, the six signals can be combined to enhance the output power since they are synchronous.

In practice, there is a possibility that one skyrmion moves to the center of the nanodisk, which will impede the application. In order to solve this problem, we put a hollow area at the center of the nanodisk, and this
provides an energy barrier that prevents the skyrmions from residing at the center of the disk, as shown in figure 14.

Similar to vortex-like skyrmions, hedgehog skyrmions in nanodisks can also oscillate when driven by a point contact current that is perpendicular to the nanodisk, which will be discussed in more detail in our next work.

8. Conclusion

In summary, we propose a spintronic application of skyrmion-based STNOs. For an STNO with one skyrmion, the working frequency can be adjusted by the current density, radius of point contact electrodes, and radius of the nanodisk. Additionally, the linewidth can be smaller than 1 MHz, which offers a huge advantage for STNO applications. For STNOs with multiple skyrmions, the range of working frequency is hugely extended; the minimum working frequency can be close to 0 Hz and the maximum is 1.07 GHz which is about 4.46 times higher than that of a single skyrmion for $R = 50$ nm. Moreover, this device can work at a current density magnitude of $10^8$ A$m^{-2}$ and the start of the oscillation time is markedly reduced. This device is also expected to improve the output power. Our studies may contribute to the development of skyrmion-based microwave generators.

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Figure 14. Relaxed state of one and six skyrmions in one nanodisk with a hollow area at the center of the nanodisk.
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