Skyrmion Based Spin-Torque Nano-Oscillator

Debasis Das, Bhaskaran Muralidharan and Ashwin Tulapurkar

Abstract—Using micromagnetic simulation, we investigate the self-sustained oscillation of magnetic skyrmion in a ferromagnetic circular nanodot, driven by spin-torque which is generated from a reference layer of a circular nanopillar device. We demonstrate, by lowering the value of uniaxial anisotropy constant ($K_u$), the velocity of the skyrmion can be increased and using this property, gyration frequency of the skyrmion oscillator can be enhanced. Annihilation of the skyrmion at higher current densities, limit the gyration frequency of the oscillator, whereas by modifying the $K_u$ value at the edge of nanodot, we are able to protect the skyrmion from being annihilated at higher current densities which in turn, increases the gyration frequency of the skyrmion based oscillator. By linear fitting the velocity value, obtained from the motion of the skyrmion in a nanostrip, we also predict the gyration frequency of the skyrmion in the nanodot which proves the validity of our idea in an intuitive way.

Index Terms—Skyrmion, spin-transfer torque, oscillator.

I. INTRODUCTION

SKYRMION is a soliton solution in the area of non-linear field theory proposed by Tony Skyrme [1], which has a stable topology. Skyrmion in a magnetic system represents a stable vortex-like spin texture which has an integer topological number [2]. This topological number or skyrmion number is given by

$$Q = \frac{1}{4\pi} \int \int m \cdot \left( \frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y} \right) dx dy \tag{1}$$

where, $m$ is normalized magnetization vector. Due to this topological protection [2], [3], it is very difficult to destroy the skyrmion which shows a possibility to use it as an information bit. Skyrmion were originally discovered in bulk ferromagnet (FM) [4] such as MnSi [5], [6], Fe$_{0.5}$Co$_{0.5}$Si [7] where inversion symmetry is broken, and later it was created in thin FM layer with a perpendicular magnetic anisotropy, grown on heavy metal [8]–[10]. In recent years, skyrmion gained a lot of attention due to various reasons such as (i) small size (diameter with few nanometer) [11], [12], which is useful for higher density storage, (ii) topological stability, which prevents the skyrmion (information) from being lost and (iii) lower depinning current density ($\sim 10^6$ A/m$^2$) [5], [13] than that of domain wall ($\sim 10^{12}$ A/m$^2$) [14]. Dzyaloshinskii-Moriya interaction (DMI) plays an important role to stabilize the skyrmion in the FM layer [11], [15]. In magnetic materials, Heisenberg exchange interaction favors the collinear alignments of spins whereas DMI favors the non-collinear alignment. Competition between these two interactions leads to the formation of skyrmion in FM [15]. Due to these above-mentioned advantages, devices such as skyrmion-based racetrack memory [16]–[18], logic gates [19], [20], synaptic devices [21], [22] were proposed using skyrmion motion. Annihilation of the skyrmion due to Magnus force [3], [23] remained as an obstacle for designing such skyrmion based devices. Due to the skyrmionic Hall effect [2], skyrmion follows a curved path during its motion which helps to design the skyrmion-based spin torque oscillators [24], [25]. In this type of oscillator, skyrmion moves in a circular path whose diameter is determined by the combined effect of the spin transfer torque and the edge repulsion force acting on it. As skyrmion oscillation frequency depends on the skyrmion velocity which is directly proportional to current density [3], so to achieve high-frequency one needs to apply higher current density. This higher velocity increases the Magnus force on the skyrmion, which pushes it further towards the boundary that finally annihilates the skyrmion. Thus, the frequency of the oscillator gets limited due to the skyrmionic Hall effect, which can only be overcome, if we are able to protect the skyrmion from being annihilated at higher current densities.

In this article, we explore the self-sustained oscillation of skyrmion results from the vortex-like spin current in a circular nanopillar geometry using micromagnetic simulation. In section II we describe the device structure, mathematical formulation and the simulation details. Following this, we explore how uniaxial anisotropy constant, affects the motion of skyrmion in a nanostrip, in section III-A. In section III-B, we discuss in details about the skyrmion-based oscillator and we also demonstrate how to protect the skyrmion in the nanodot from being annihilated so that the frequency of the oscillator can be increased further. Finally, in section III-C we explore the effect of uniaxial anisotropy constant on the oscillation frequency and the radius of the skyrmion. We also discuss a model which uses a linear fitting to predict the frequency of the oscillator using the velocity value obtained from the skyrmion motion in a nanostrip.

II. THEORETICAL FORMULATION

A. Device Structure

In this section, we describe the device structure as shown in Fig. 1 (a), where two FM layers are separated by an insulator layer. The top FM layer, called the free layer (FL) has uniaxial perpendicular magnetic anisotropy with DMI such that skyrmion can be stabilized in this layer. The bottom layer is the reference layer (RL) where the magnetization is fixed and it is assumed to have an in-plane vortex-like spin polarization as shown in Fig. 1(b). The electrons are assumed to travel from RL to FL where the spin-polarized current takes the form of the vortex and due to spin-transfer torque skyrmion gyrates in the FL. The spin polarization of the RL is assumed to be $m_p = (cos\phi, sin\phi, 0)$, where $\phi = tan^{-1}(\frac{2}{3}) + \psi$. Here, $(x,y)$ is the spatial coordinate with the origin being.
at the center of the nanodot and the $\psi$ is assumed to $\pi$ in our simulation. Although the device structure is similar to the device, shown in Ref. [25], but we modified the device (shown in Fig. 4) to enhance the gyration frequency of the skyrmion in the FL. We create an annular region of high anisotropy around the perimeter of the nanodot, to prevent the skyrmion annihilation at higher current densities.

**B. Mathematical Model**

The proposed device is simulated by solving the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation described as follows

$$\frac{d\mathbf{m}}{dt} = -\gamma |\mathbf{m} \times \mathbf{H}_{\text{eff}}| + \alpha \left( \mathbf{m} \times \frac{d\mathbf{m}}{dt} \right) + |\gamma| \beta (\mathbf{m} \times \mathbf{m}_p \times \mathbf{m})$$  \hspace{1cm} (2)

where, $\mathbf{m} = \mathbf{M}/M_S$ is the normalized magnetization vector and $M_S$ is the saturation magnetization. $|\gamma|$ is the gyromagnetic ratio and $H_{\text{eff}}$ is the effective magnetic field given by

$$H_{\text{eff}} = -\frac{1}{\mu_0 M_S} \frac{\delta E}{\delta \mathbf{m}}$$  \hspace{1cm} (3)

where, $\mu_0$ is the free space permeability and $E$ is the free energy and is given by [11], [26]

$$E = \int dV \left[ A (\nabla \mathbf{m})^2 + K_u \left( 1 - (\mathbf{m} \cdot \mathbf{z})^2 \right) - \frac{\mu_0}{2} \mathbf{m} \cdot \mathbf{H}_d + \varepsilon_{\text{DMI}} \right]$$  \hspace{1cm} (4)

Here, the first term denotes the exchange energy and $A$ is the exchange stiffness constant. The second term denotes the uniaxial anisotropy energy and $K_u$ is the uniaxial anisotropy constant. The third term is due to the demagnetization field $\mathbf{H}_d$ and the final term denotes the interfacial form of DMI, which is given by

$$\varepsilon_{\text{DMI}} = D \left( m_z \frac{\partial m_z}{\partial x} + m_z \frac{\partial m_y}{\partial y} - m_x \frac{\partial m_z}{\partial x} - m_y \frac{\partial m_z}{\partial y} \right)$$  \hspace{1cm} (5)

where, $D$ is the DMI constant. The third term of Eq. [2] represents the Slonczewski spin transfer torque, where the factor $\beta$ is given by $\beta = \hbar P J/(2 \mu_0 e M_S)$. Here $\hbar$, $P$, and $J$ are reduced Planck’s constant, spin polarization and the current density respectively, $e$ is the electronic charge and $t$ represents thickness of the FL.

The motion of the skyrmion in FL is described by Thiele [27] equation, given by [25]

$$G \times \mathbf{v} + \alpha D_0 \mathbf{v} + \Gamma_{\text{STT}} = -\frac{\partial E}{\partial \mathbf{X}}$$  \hspace{1cm} (6)

which describes different forces acting on the skyrmion. The first term of Eq. [5] represents Magnus force, where, $G$ is gyrovector and $\mathbf{v}$ is the velocity of the skyrmion. The gyrovector is defined by

$$G = \frac{M_S}{\gamma} \int dV \sin(\theta) (\nabla \theta \times \nabla \phi)$$  \hspace{1cm} (7)

where, the $\theta$ and $\phi$ are the polar and azimuthal angle. It can be shown that [28], the gyrovector can be written as $G = 4 \pi Q \hat{z}$. The second term represents the damping term, where, $D_0$ is the diagonal components of the damping tensor $D_{ij}$, given by

$$D_{ij} = \frac{M_S}{\gamma} \int dV \left( \frac{\partial \theta}{\partial x_i} \frac{\partial \theta}{\partial x_j} + \sin^2(\theta) \frac{\partial \phi}{\partial x_i} \frac{\partial \phi}{\partial x_j} \right)$$  \hspace{1cm} (8)

where, $x_i$ represents the cartesian coordinates $(x, y, z)$. The third term $\Gamma_{\text{STT}}$ of Eq. [6] represents the spin torque term which can be derived by Rayleigh dissipation function [25], [29]. The term on the right hand side of Eq. [6] represents the force acting on the skyrmion.

**C. Simulation Details**

The proposed device is simulated using Object Oriented MicroMagnetic Framework (OOMMF) public code [30] by incorporating the DMI extension module [31]. The radius of the FL is assumed to be 50 nm with a thickness of 0.4 nm which is discretized into the cell size of $1 \times 1 \times 0.4 \text{ nm}^3$. The material parameters were adopted from Ref. [3] which includes gyromagnetic ratio $\gamma=2.211 \times 10^5 \text{ m/(A.s)}$, Gilbert damping coefficient $\alpha=0.3$, exchange stiffness $A=15 \text{ pJ/m}$, saturation magnetization $M_S=580 \times 10^3 \text{ A/m}$, spin polarization $P=0.4$ and the interfacial DMI constant $D=3 \text{ mJ/m}^2$. We have chosen two different values of perpendicular magnetic anisotropy $K_u=0.6$ and $0.8 \text{ MJ/m}^3$ to investigate the effect of the anisotropy constant on the gyration frequency.

**III. RESULT & DISCUSSION**

**A. $K_u$ Dependency on Skyrmion**

In this section, we describe the effect of anisotropy constant $K_u$ on skyrmion. It was reported that the value of $K_u$ can be changed by applying a voltage in the FM layer [23], [32], so we place the skyrmion in a nanostrip with an anisotropy gradient along its length, with no spin current in FM layer to investigate the sole effect of $K_u$ on skyrmion. The gradient can be obtained by varying the thickness of the insulator as shown in Fig. 2(a). The dimension of the FM layer is taken $260 \times 80 \times 0.4 \text{ nm}^3$ and the cell size for the simulation is used $0.5 \times 0.5 \times 0.4 \text{ nm}^3$. We assume a constant gradient of $K_u$ with a value of 1.923 $\times 10^{12} \text{ Jm}^4$ such that a linear relationship between the $K_u$ and the length of the nanostrip is maintained which in turn creates the values of $K_u$ at left and the right side of the nanostrip are 0.55 MJ/m$^3$ and 1.05 MJ/m$^3$ respectively. The linear profile of $K_u$ is shown in Fig. 2(b). A skyrmion

![Diagram](image-url)
is initially created at the right side of the nanostrip with local injection of a spin current pulse of 0.5 ns with polarization along -ve z-direction followed by a 1 ns relaxation to stabilize the skyrmion in the nanostrip. After the stabilization, we apply the $K_u$ gradient along the x-axis. At time $t=0$ ns, the diameter of the skyrmion at the right side is found to be 5.02 nm, where the radius is measured from the center of the skyrmion to the region where $m_z=0$. Now due to the $K_u$ gradient, skyrmion starts to move towards the left region. From the second term in Eq. [4], it is clear that total energy of the skyrmion is directly proportional to $K_u$ and as we are applying a $K_u$ gradient, so to minimize the energy, skyrmion starts to move towards the left side where $K_u$ is decreasing. The locus of the center of the moving skyrmion due to this anisotropy gradient is shown in Fig.[2](e), where the complete path traversed by the skyrmion is shown in the x-y plane. From this figure, it can be seen that at starting, skyrmion follows a curved path due to the Magnus force, which brings the skyrmion near the edge of the nanostrip. Due to the $K_u$ gradient, the skyrmion wants to move towards the left side which indicates the initial velocity at $t=0$ ns, should be along the -ve x direction. Thus the Magnus force $G \times v$ will be along -ve y direction, which pushes the skyrmion towards the lower side of the nanostrip as shown in Fig.[2](e). It is also noticed that during its motion, skyrmion diameter also increases as the skyrmion moves to the lower $K_u$ region. As we know that there is a repulsive force act on the skyrmion near the edges of the nanostrip, so as the skyrmion is getting bigger with time during its motion, the repulsive force pushes the center of the skyrmion away from the edge, as can be seen in Fig.[2](e). Finally, at $t=14.26$ ns the skyrmion stops at the left side of the nanostrip, due to balance between the edge reflection at the boundary and force due to the $K_u$ gradient. The diameter of the skyrmion at steady state becomes 28.12 nm when it stops at the left side of the nanostrip. So, from this simulation, we can conclude that skyrmion prefers to stay in the lower $K_u$ region.

Next, we simulate the skyrmion motion in the nanostrip for various values of $K_u$ to investigate the effect of uniaxial anisotropy constant on the velocity of skyrmion. For driving the skyrmion in a nanostrip there are two ways to inject the spin current [3], [28], which are current-in-plane (CIP) and current-perpendicular-to-plane (CPP) configuration. In CIP configuration, a spin-polarized current is injected in-plane of the FM layer, whereas in CPP configuration, charge current is injected in the heavy metal (HM) layer beneath the FM layer which generates a vertical spin-polarized current in the FM layer. For this simulation we take the nanostrip with the same dimension as described earlier and varied the current density (J) in CPP configuration, taking $K_u$ as the parameter. By the method of local spin current injection (described earlier), we first generate a skyrmion at the left side of the nanostrip and then a vertical spin current, polarized along the -ve y-axis is injected in the FM layer (which can be generated by spin Hall effect) to calculate the longitudinal velocity of the skyrmion. From Ref. [3] it is seen that at the higher current density ($J \geq 6$ MA/cm$^2$) skyrmion gains enough velocity to overcome the edge repulsion of the nanostrip and annihilates. To prevent this annihilation we create a region with high $K_u$ at the edges as shown in Fig.[3](a). Here, the darker red region is having a higher value of anisotropy constant which is 1.2 MJ/m$^3$, and the inner region having lower values ($K_u=0.6-0.8$ MJ/m$^3$), which we have taken as parameter to plot skyrmion velocity as a function of J. We consider the barrier width of the high $K_u$ region is 8 nm. Although this high $K_u$ barrier enhances the edge repulsion which helps us to increase the magnitude of

![Fig. 2. Skyrmion motion under uniaxial anisotropy field gradient. (a) Schematic of the device inducing voltage controlled uniaxial anisotropy gradient along the length of the nanotrack. (b) Uniaxial anisotropy profile along the length of the nanotrack. Anisotropy constant value increasing linearly from the left to right side of the nanotrack. (c) Initial position and size of the skyrmion, (d) Final position and size of the skyrmion during its motion due to anisotropy gradient. The color bar is showing the z component of the normalized magnetization vector. (e) The path of the skyrmion motion in the x-y plane of the nanostrip.](image)

![Fig. 3. (a) Skyrmion in a nanostrip with high $K_u$ barrier at the edges (dark red region) and low $K_u$ at inner (light red region) side. (b) Skyrmion velocity profile. Variation of skyrmion velocity with current density for different anisotropy constant. Velocity decreases with the increases of the anisotropy constant at any particular current density.](image)
J to achieve higher velocity, but at much higher current density ($J>12$ MA/cm$^2$) skyrmion gets enough velocity to penetrate into the high $K_u$ region and finally annihilates at the edge. The result for velocity vs. current density is shown in Fig. 3(b), where it is observed that skyrmion velocity increases with current density and at any fixed J, lower $K_u$ leads to higher velocity.

### B. Oscillator

In this section, we describe the detail characteristics of the skyrmion based oscillator and how to improve its performance. As discussed in Section II-A, we consider the device to be a circular nanodot, where the skyrmion moves in a circular path. From the result discussed in Section II-A, it is understood that by putting a high $K_u$ barrier at the edges, we can increase the input current density that leads to increase the skyrmion velocity. As we are trying to design the skyrmion based oscillator where the skyrmion moves in a circular path in the nanodot, hence higher velocity leads to higher frequency of the skyrmion oscillator. To explore the effect of the high $K_u$ barrier on the oscillator, we consider two cases such as nanodot without high $K_u$ barrier and with high $K_u$ barrier. For the device without the high $K_u$ barrier, first we create a skyrmion in the FL of the nanodot and applied the current to study its performance. Then we put a high $K_u$ barrier at the circumference of the nanodot of width 5 nm as shown in Fig. 4 to study its effect on the frequency. For this simulation, we use the anisotropy constant value $K_{u}=0.8$ MJ/m$^3$, but for the high $K_u$ region it is taken to be 1.2 MJ/m$^3$. Other parameter values were taken the same as mentioned in Section II-C. For both structures i.e. with and without the high $K_u$ barrier, we change the current density and calculate the gyration frequency as shown in Fig. 5(a). From this plot, we observe that frequency increases with the current density for both structures. From Fig. 3(b), we have seen that for any fixed value of $K_u$, the velocity of skyrmion increases with J. Similarly, for the circular nanodot, skyrmion velocity also increases with J, which in turn increases the gyration frequency. The upper limit of the applied current density is much smaller for the device without barrier than that of with barrier. For the device, without barrier, the upper limit of J is found to be 6 MA/cm$^2$. Upon increasing the value of J beyond this limit, skyrmion gets enough velocity to overcome edge repulsion and finally annihilates at the edge. The maximum gyration frequency we obtained is 0.32 GHz at J=6 MA/cm$^2$ for this structure. On the other hand, the device with a high $K_u$ barrier is able to protect the skyrmion from being annihilated at higher J which increases the gyration frequency further. For the device with high $K_u$ barrier, we are able to increase the value of J up to 13 MA/cm$^2$, although the highest frequency we obtained for this structure at 12 MA/cm$^2$ which is 0.47 GHz. With the increase of velocity, the Magnus force acting on the skyrmion also increases. When this force becomes larger than the edge repulsion at higher J, skyrmion gets annihilated. As the energy of the skyrmion becomes high at the higher $K_u$ region, so it tries to avoid this region, but with the increase of J, the Magnus force pushes the skyrmion towards the radial direction that forces the skyrmion to enter into the high $K_u$ region and finally annihilates at the edge. Another interesting thing we notice that with the increase of J, skyrmion radius becomes smaller as shown in Fig. 5(b). For the device without barrier, this effect is not so significant as the skyrmion annihilates at a comparatively lower value of J, but due to the higher range of J for the device with the barrier, such effect is prominent. For the device without barrier, the skyrmion radius is 6.56 nm at J=1 MA/cm$^2$ and for higher J, radius decreases due to the Magnus force and it maintains a value of 5.05 nm for J=4-6 MA/cm$^2$. For the device with the barrier, there is a significant change in radius as visible in Fig. 5(b). At J=1 MA/cm$^2$, the radius is 6.06 nm, but with the increase of J, the radius decreases and the minimum radius obtained is 3.03 nm at J=12 MA/cm$^2$. As described earlier, Magnus force increases with J which pushes the skyrmion towards the barrier, whereas due to high $K_u$ region skyrmion also feels a higher repulsive force. These two opposite forces squeeze the skyrmion, hence the radius decreases with increasing J.

### C. Effect of $K_u$ on Frequency

In this section, we describe the effect of anisotropy constant on the gyration frequency. For this simulation, we take the same device structure as described in II-B but we choose two different values of $K_u$ (0.6 MJ/m$^3$ and 0.8 MJ/m$^3$) to investigate its effect. The simulation result for $K_u=0.8$ MJ/m$^3$ has already been described in the previous section. For $K_u=0.6$ MJ/m$^3$ we got similar results, but numerical values obtained for gyration frequency and radius becomes larger as shown in Fig. 6. Here, we are able to apply the current density
in the range between 3-15 MA/cm² which gives rise the
gyro frequency range (0.61-0.97 GHz). The reason behind
this higher values of f can be explained by Fig. 3(b), where
we have seen that, for any value of J, a lower value of \( K_u \)
gives a higher velocity of the skyrmion. At lower \( K_u \) as the
velocity increases so it takes much lesser time to complete
the circular path, which in turn increases the frequency. As shown
in Fig. 6(a) that lower \( K_u \) gives much higher frequency, so
from the device perspective FL having lower \( K_u \) is a better
choice.

On the other hand, from Fig 6(b), we can see that lower \( K_u \)
leads to the skyrmion with a higher radius. The similar result
we have already observed in the linear \( K_u \) gradient device
as shown in Fig 2 (c)-(d). The highest radius we obtained is
16.16 and 6.06 nm for J=3 MA/cm² at \( K_u=0.6 \text{ MJ/m}^3 \) and
J=1 MA/cm² at \( K_u=0.8 \text{ MJ/m}^3 \), respectively, and it starts
to decrease as the J increases. For the simulation at \( K_u=0.6 \text{ MJ/m}^3 \), we were not able to get a steady oscillation for J=1-2
MA/cm², where we have noticed the radius of the skyrmion
becomes 19.07 nm. Due to its larger size, it feels a higher
repulsive force from the edge of the nanodot, which could not
be overcome at this small range of current density, which leads
to the settlement of the skyrmion at the center of the nanodot
within a fraction of nanosecond after starting the simulation.
We also get the lowest radius of the skyrmion for these two
\( K_u \) values at different values of J. For \( K_u=0.8 \text{ MJ/m}^3 \), the
lowest radius we get is 3.03 nm at J=13 MA/cm², whereas
for \( K_u=0.6 \text{ MJ/m}^3 \) it is 6.06 nm at J=15 MA/cm². Due to the
larger size of the skyrmion in lower \( K_u \) device, it requires a
higher Magnus force to push the skyrmion into the high \( K_u \)
region, which is the reason we get a slightly higher value of
the upper limit of J in the case of \( K_u=0.6 \text{ MJ/m}^3 \).

For the skyrmion motion in nanostrip, described in section
III-A, we have considered the polarization of the spin current
density is along -ve y-axis, whereas for the nanodot this
direction is vortex like as shown in Fig. 1(b). Now, if we
consider a very small region of the nanodot, where spin
polarization can be assumed to be uniform as shown in Fig.
7(a), then the motion of the skyrmion in this region should
mimic the motion in nanostrip and vice versa. So at steady
state, one should be able to predict the frequency(\( f \)) of the
oscillator from the velocity (\( v \)) of the skyrmion obtained for
the nanostrip using the formula

\[ f = \frac{v}{2\pi r} \]  

(9)

where \( r \) is the radius of the circular path in which skyrmion
moves in the nanodot. We considered three cases for the
simulation to verify this idea. First, we take a circular nanodot
with a radius of 50 nm and a nanostrip with a dimension
260×80×0.4 nm³ with \( K_u=0.8 \text{ MJ/m}^3 \), but there is no such
high \( K_u \) barrier to protect the skyrmion. For the two structures,
we calculate the velocity and the frequency of the skyrmion
individually and then using Eq. 9 we calculate the frequency
from the obtained velocity. The actual frequency and the
frequency obtained from Eq. 9 are plotted in Fig. 7(b) as ‘data’
and ‘linear fit’ respectively. From this figure we can see that
the frequency obtained from linear fitting is in good agreement
with the actual frequency, proving the validity of the idea to
calculate the frequency using the linear fitting. For the second
and third case, we took the nanodot and the nanostrip of the
same geometrical size but with different \( K_u \) which are 0.6
and 0.8 MJ/m³ respectively, along with high \( K_u \) barrier as
discussed in section III-A and III-B For \( K_u=0.8 \text{ MJ/m}^3 \), we
have similar results which agree well with the actual frequency
as shown in Fig. 7(c). From this figure, we can see that the
frequency calculated from the linear fitting matches exactly
with the actual frequency up to J=6 MA/cm², but it deviated
slightly afterward. The reason behind this small deviation
can be described by the change of skyrmion size at higher
current densities. As we know that at higher J, skyrmion gets
annihilated which was prevented by keeping a high \( K_u \) barrier
at the edges, which in turn affects the motion of the skyrmion.
at the boundary between higher and lower $K_u$ region. Due to the geometrical shape difference between the nanodot and the nanostrip, the velocity of the skyrmion gets differed slightly, which leads to this deviation of the frequency obtained from the actual simulation and the linear fitting. For $K_u=0.6$ MJ/m$^3$, we have done similar calculations and plotted the result as shown in Fig. 7(d), where we notice a larger deviation between the actual frequency and the frequency obtained from the linear fitting. From the previous results, we have seen that lower $K_u$ leads to a higher radius as well as the higher velocity of the skyrmion. Due to this larger velocity and the radius, skyrmion tends to stay near the junction between the higher and the lower $K_u$, which affects the velocity of the skyrmion at this region. In the nanostrip, the skyrmion moves in an almost straight line path after reaching near the boundary, whereas the skyrmion moves along a circular path for the nanodot. Due to the straight line motion, the velocity of the skyrmion becomes slightly higher than that of the motion in nanodot, which overestimates the frequency for the linear fitting. Due to this higher velocity, at higher $J(>12$ MA/cm$^2$) skyrmion gets into the high $K_u$ region and gets annihilated in the nanostrip and this why we have omitted the actual frequency for the nanodot for $J > 12$ MA/cm$^2$ while plotting the data in Fig. 7(d).

IV. CONCLUSION

We investigated the gyrotropic motion of skyrmion in a nanodot, driven by vertically injected vortex-like spin current. It is found that in the absence of the external spin current, the skyrmion can be moved by the gradient of the uniaxial anisotropy field, and it moves towards a lower $K_u$ region. By putting a high $K_u$ barrier at the edges, we were able to protect the skyrmion from being annihilated which increase the upper limit of the injected spin current density. We have noticed that the velocity increases with the magnitude of the current density. Performing this simulation for various values of $K_u$, we have shown that the system with a lower $K_u$ leads to the higher velocity of the skyrmion. Similar to the nanostructure, by putting a high $K_u$ barrier at the edge of the circular nanodot, we were able to protect the skyrmion at higher current density, which in turn increased the upper limit of the frequency, much higher than that of obtained in the nanodot without the high $K_u$ barrier. We have shown that at a lower value of $K_u$, gyration frequency as well as the radius of the skyrmion increases. We have also shown that for the nanodot with high $K_u$ barrier, skyrmion radius reduces as the magnitude of the injected current density increases, due to balance between two opposing forces such as repulsion from the high $K_u$ region and the Magnus force. Using the velocity, obtained from the motion of the skyrmion in nanostrip, we have calculated the gyration frequency in nanodot by a linear approximation. In this method, we have noticed that this approximation works well for the skyrmion moving in nanodot with lower repulsion force from the high $K_u$ region. From this work, we can conclude that nanodot with lower $K_u$ is a better choice for the skyrmion based nano-oscillator.

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