Wide range tuning of resonant frequency for a vortex core in a regular triangle magnet

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A magnetic vortex structure stabilized in a micron or nano-sized ferromagnetic disk has a strong potential as a unit cell for spin-based nano-electronic devices because of negligible magnetostatic interaction and superior thermal stability. Moreover, various intriguing fundamental physics such as bloch point reversal and symmetry breaking can be induced in the dynamical behaviors in the magnetic vortex. The static and dynamic properties of the magnetic vortex can be tuned by the disk dimension and/or the separation distance between the disks. However, to realize these modifications, the preparations of other devices with different sample geometries are required. Here, we experimentally demonstrate that, in a regular-triangle Permalloy dot, the dynamic properties of a magnetic vortex are greatly modified by the application of the in-plane magnetic field. The obtained wide range tunability based on the asymmetric position dependence of the core potential provides attractive performances in the microwave spintronic devices.
significant increase of the core potential is expected when the core
approaches the vertex of the triangle. Since the vortex chirality in a
triangular micro magnet is precisely controlled by the application of
the initializing in-plane magnetic field\(^2\), the core position is well
manipulated by applying the magnetic field. In fact, Vogel et al.
systematically studied the field dependence of the resonant fre-
quency in the triangular vortex for the first time and demonstrated
that the resonant frequency varies with the amplitude and the di-
rection of the external magnetic field\(^3\). However, the overall change of
the resonant frequency is 20 MHz, which is smaller than 10% of the
resonant frequency at the original position. In the present paper, we
show that, in a well-optimized device dimension and configuration,
the resonant frequency in a regular triangle micro magnet varies
greatly with the position of the vortex core. A wide range tuning of
the resonant frequency from 200 MHz to 600 MHz is experiment-
ally demonstrated.

Results
Micromagnetic simulation of vortex dynamics. First, we clarify the
relationship between the core position and the applied magnetic field
in a triangular Permalloy (Py) dot by using an originally developed
micromagnetic simulation\(^2\). Here, we focus on a regular triangle Py
dot with the 2 \(\mu\)m in diameter of the circumscribed circle and 40 nm
in thickness. In order to reflect the realistic shape of the experi-
mentally produced triangular dot with the rounded corners, the
triangle is cut by the circle with 97.5% diameter of the circum-
scribed circle of the triangle. The exchange constant and the
saturation magnetization are, respectively, 1.0 \(\times\) \(10^{-11}\) J/m and
1 T, which are typical values for Py film. The computational cell
size and the damping parameter \(x\) are \(4 \times 4 \times 40\) nm\(^2\) and 0.01,
respectively\(^2\). We confirmed that a single vortex is stabilized at the
remanent state and the chirality of the vortex can be manipulated by
the application of the in-plane magnetic field, similarly to our
previous study. Here, the vortex chirality was set to counter clock-
wise (CCW). The in-plane static magnetic field is applied along the \(x\)
direction in order to move the vortex towards the vertex of the
triangle. This means that the positive (negative) magnetic field
induces the positive (negative) shift of the vortex core along the \(y\)
direction. For a comparison, the micromagnetic configurations for a
circular dot with 2 \(\mu\)m in diameter and 40 nm in thickness is also
simulated.

Figures 1(a) and 1(b) show the relative position of the core center
as a function of the in-plane magnetic field for the circular and
triangular dots, respectively. The representative magnetic domain
structures together with the schematics for the expected magneto-
static potential under the several magnetic fields are also shown in
the figures. For the circular dot, the linear field dependence is
obtained, but it is limited only in the low magnetic field (\(|H| <\)
100 Oe). At the high magnetic field (\(|H| > 100\) Oe), the dependence
becomes nonlinear. The symmetric field dependence with respect to
the polarity of the magnetic field originates from the perfect circular
shape. On the other hand, for the triangular dot, the field dependence
of the position shift is almost linear in the wide field range from
\(-300\) Oe to 400 Oe although the slope of the position shift is slightly
different between the positive and negative magnetic fields. Since the
strong modification of the magnetic susceptibility is expected in the
triangular Py dot by changing the core position, the obtained result
implies that the core oscillation frequency is widely tuned by the
application of the in-plane magnetic field. We also find that, for
the triangular dot with 3 \(\mu\)m or larger in diameter of the circums-
scribed circle, the moving direction of the vortex core deviates from
the line perpendicular to the magnetic field because of the weak
confined potential. As a result, the core position cannot be manipu-
lated by the simple in-plane magnetic field.

We then numerically study the position dependence of the vortex-
resonance characteristic. The dynamic properties of the magnetic

Figure 1 | Numerically calculated equilibrium core positions as a
function of the in-plane magnetic field for (a) circular and (b) triangular
Permalloy dots. The schematics of the expected magneto-static potential as
a function of the core position together with the micromagnetic structure
under each magnetic field are also shown in the right-hand side.

Figure 2 | Numerically calculated oscillations amplitude of the vortex core
confined in (a) circular and (b) triangular Permalloy dots under the
constant ac magnetic field as a function of the ac frequency at the remanent
state. The numerically calculated trajectory of the vortex core at each state
are also shown in the right-hand side.
the circular and triangular dots and found that the resonant frequencies for the circular and triangular dots are 170 MHz and 220 MHz, respectively. It should be noted that the core motion makes a circular trajectory also in the triangular dot. The resonant frequency of 170 MHz for the circular dot can also be analytically reproduced by the Thiele’s equation for the vortex core motion. The resonant frequency for the triangular dot is larger than that for the circular one. This is because the vortex core is confined in stronger potential originating from the effectively larger surface magnetic charge in the triangular dot. By performing the similar calculation under various dc magnetic field along the x direction, we can also evaluate the field dependence of the resonant frequency.

Figures 3(b) and 3(d) show the field dependences of the resonant frequencies for the circular and triangular dots, respectively. For the circular disk, the resonant frequency is almost constant in the field range from −250 Oe to +250 Oe. This indicates that the potential profile for the vortex core in a circular disk is well expressed by a two dimensional harmonic oscillator. On the other hand, for the triangular dot, the resonant frequency asymmetrically changes with respect to the polarity of the magnetic field. Especially, the resonant frequency exceeds 550 MHz when the core is shifted to the corner of the triangle by applying the in-plane magnetic field of +300 Oe.

The field dependence of the oscillation amplitude of the core at the resonance is also plotted together on the same figures (Figs. 3(a) and 3(c)). The oscillation amplitude gradually varies with changing the magnitude of the in-plane magnetic field (the core position). For the circular disk, the amplitude monotonically decreases with increasing the magnitude of the magnetic field. On the other hand, for the triangular disk, the oscillation amplitude takes a maximum value when the core is located at the center of the inscribed circle of the triangle. At the corner, the amplitude of the core oscillation shows a significant reduction. These unique characteristics can be explained by the fact that the equivalent parabolic potential in the triangular dot changes with the core position. Thus, the resonant characteristic of the vortex confined in the regular triangle is greatly modified by applying the in-plane magnetic field along the side of the triangle.

**Experimental demonstration of wide-range modulation of vortex resonance.** To demonstrate the expected attractive resonant properties in the triangular dot experimentally, we have measured the 1-port transmission impedance measurements ($S_{11}$) of the micro strip line with the triangular dots. Here, the size of the triangular Py dot is the same as that in the simulation (2 μm in outer diameter and 40 nm in thickness). As shown in the inset of Figs. 4(a), a magnetic vortex confined in the triangular Py dot was clearly confirmed by the magnetic force microscope (MFM). For a comparison, the chain consisting of 1000 circular Py dots with 2-μm diameter and 40-nm thickness is also evaluated experimentally.

Figures 4(b) and 4(c) show $S_{11}$ spectra for the circular and triangular dots, respectively, in the absence of the dc magnetic field. In each spectrum, a clear single dip due to the vortex resonance was observed. The obtained resonant frequencies for the circular and triangular dots are, respectively, 180 MHz and 230 MHz, which are highly consistent with the numerical simulations described above.

We then study the field dependence of the resonant frequency by performing the similar measurements under the various in-plane magnetic field along the x axis. As shown in Fig. 5(a), for the circular dot, a weak field dependence of the resonant frequency, which is expected in the numerical simulation, is confirmed in the field range from −240 Oe to +240 Oe. Moreover, the wide range modulation of the resonant frequency is also reproduced in the $S_{11}$ measurements.

**Figure 3** | Numerically calculated resonant frequency of the magnetic vortex confined in (b) the circular and (d) triangular magnetic dots as a function of the in-plane magnetic field. The field dependences of the oscillation amplitude of the vortex core for (a) the circular and (c) triangular dots are also shown in the top.

**Figure 4** | (a) Schematic illustration of 1-port transmission impedance measurement of a chain of the triangular Py dot together with MFM images for the circular and triangular Py dots at the remanent state. Experimentally obtained $S_{11}$ spectra in the absence of the magnetic field for (b) the circular and (c) triangular magnetic dots.
for the triangular microdots, as shown in Fig. 5b. Especially, the high frequency resonance over 500 MHz is clearly observed in the spectrum at \( H = 300 \) Oe although the magnitude of the dip is one order smaller than that for Fig. 4c. The magnitude of the dip takes a maximum value at \( H \sim 100 \) Oe and its field dependence is fully in agreement with the numerical results.

**Discussion**

Although the vortex dynamics in the triangular dot has been studied in the previous experiment, the wide range modulation of the resonant frequency from 200 MHz to 600 MHz has never been reported. The present successful experiments have been achieved by optimizing the device geometry and dimension. We use a 500-nm-wide narrow and 200-nm-thick strip line, in order to sensitively detect the vortex oscillation especially at the corner of the triangle. This is because the inductive coupling between the vortex and strip line increases with increasing the ratio of the oscillation amplitude to the width of the strip line. We also emphasize that the relative direction between the triangle and strip line rotates 90 degree from the direction in Ref. 23. This is another important fact for detecting the vortex resonance at the corner of the triangle. This improved microstrip line enabled us to study the field dependence of the vortex resonance in a circular dot more sensitively. The resonant frequency of the vortex confined in the circular disk is found to show weak field dependence, meaning that the vortex potential in a circular dot can be described by a quasi-two-dimensional parabolic potential.

In summary, we have investigated the resonant properties of the magnetic vortex confined in the triangular and circular dots. A weak field dependence of the resonant frequency, which is consistent with a quasi-two-dimensional harmonic oscillator, was observed in the circular dot. On the other hand, the resonant properties for the magnetic vortex confined in the triangular dot showed a strong field dependence because the core potential is effectively modified by the core position. Especially, the resonant frequency is found to increase significantly when the core approaches to the vortex. We may realize the wider frequency tuning range by increasing the film thickness in the triangle. Thus, a variety of the field dependence of the resonant frequency can be realized by choosing the shape and dimensions for the patterned ferromagnetic dots.

**Methods**

We have prepared a one-dimensional chain consisting of 1000 triangular Py dots by using the conventional lift-off technique with electron beam lithography. Here, the outer diameter and the thickness of the Py dot are 2 \( \mu \)m and 40 nm, respectively. A single Cu strip line, 500 nm in width and 200 nm in thickness, has been fabricated also by the electron-beam lithography, and was placed on the center of the Permalloy dots for detecting the dynamic response of the magnetic vortices. The dynamic properties of the magnetic vortex have been evaluated by performing the 1-port transmission impedance measurements \( S_{11} \) using the Vector Network Analyzer, as schematically shown in Fig. 4(a). The position of the vortex core was controlled by adjusting the external magnetic field. The vortex chirality in the triangle dots was set to CCW by using an initializing in-plane magnetic field.

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**Figure 5** Experimentally obtained \( S_{11} \) parameters for (a) the circular and (b) triangular ferromagnetic dots for various magnetic fields. The inset shows image plots of \( S_{11} \) parameter as functions of the in-plane magnetic field and resonant frequency for each magnetic dots.
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Author contributions
S.Y. & K.K. carried out the experimental work, including the preparation of the sample. T.T. carried out the micromagnetic simulation including the development of simulation codes. T.K. and K.M. supervised the experimental research and micromagnetic simulation. T.K. wrote the main manuscript text and S.Y. & T.T. prepared all figures.

Additional information
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