Magnetometry enabled by micro and nanomechanical resonators has proven to be one of the most useful probes of nanomagnetism. Torsional resonators have allowed the observation of such phenomenon as real-time creation and annihilation of single magnetic vortices, Barkhausen noise from a single defect, mechanical ferromagnetic resonance spectroscopy, and collective spin modes using the technique of torque mixing resonance spectroscopy. Adding to this the sensitivity of cavity optomechanics, which allows thermomechanical torsional motion to be observed from room temperature down to millikelvin temperatures, has the potential to uncover new physics, particularly in the stochastic domain, of nanomagnetism. Here we show that by using a cavity optomechanical torque magnetometer optimized for torque mixing resonance spectroscopy, we are able to observe spin modes in magnetically-soft permalloy disks above 1.1 GHz. By comparing with micromagnetic simulations and direct-torque susceptometry measurements, we show that these modes are consistent with the gyrotropic mode of the vortex sampling the disorder potential of the polycrystalline magnetic disk. Importantly, we are able to track these spin modes at all frequencies, that is we see no drop-outs in the spin resonances, which allows us to follow the behavior of the vortex as it traverses the disk. In future studies, it should be possible to work backwards from these spin modes to recover the energy landscape of the magnetic structure. We also note that this work amounts to conversion of UHF (ultra-high frequency) signals through spin resonances to telecom wavelengths. Such wavelength conversion is a key topic in quantum technology applications and improvements to the existing device architecture may provide a promising route to high-efficiency wavelength conversion through quadruply-resonant (optical, mechanical, spin, and microwave) devices.

We present data from two devices, fabricated simultaneously on the same 500 μm thick silicon-on-insulator chip, with different permalloy disk diameters. Nanofabrication is performed using two e-beam lithography steps. The first defines the optical disks and mechanical resonators, followed by reactive ion etching to transfer this pattern to the single crystal silicon. After etching, the resist is removed and a second e-beam lithography step is used to define a disk on the “landing pad” of the torsional resonator. Up to this point fabrication is similar our previous torsional devices, but in this work we slowly deposit 50 nm of permalloy (Ni80Fe20) in ultra-high vacuum to produce low-defect density nanomagnetic disks. After permalloy deposition we perform lift-off, followed by HF vapor release of the silicon torsional resonator from the underlying sacrificial SiO2 layer. A completed de-

FIG. 1. Tilted SEM image of a 1.1 μm diameter permalloy disk fabricated onto a freestanding silicon optomechanical torsional resonator. Optomechanical detection is read out through a dimpled tapered fiber that monitors an optical resonance of the whispering gallery mode microdisk, seen at the left. AC magnetic fields can be applied to the permalloy disk in both the x and z directions, as well as a DC magnetic field in the plane of the disk. These allow monitoring of both the direct torque, encoding the disks magnetization and in-plane susceptibility, as well as the spin mode resonances through torque mixing resonance spectroscopy. a) The calibrated thermomechanical motion of the torsional mode at 12.8 MHz, and c) gyrotropic mode of the vortex detected via torque mixing resonance spectroscopy.

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we observe. To first order, the spins in the magnetically-soft
ature in this experiment to understand the spin resonance that
down-mixed signal is recorded using a 50 MHz digital lock-
bidium frequency standard. The optomechanically-detected,
their frequency difference locked to that of the torsional reso-
quencies of UHF signals applied to
TMRS data is acquired by simultaneously sweeping the fre-
sioning stage, and measured with a three axis Hall probe.
Finally, external magnetic fields are applied
above 1 GHz. Currently higher drive
powers result in heating of the printed circuit board contain-
ing the drive coils, and hence the silicon devices, causing
shifts in the optomechanical detection scheme. Future experi-
ments mitigating this heating effect could test magnetically as-
sisted vortex de-pinning and the effect on the gyrotropic mode
frequencies.
In Fig. 2, we show a sample of such a down-mixed spin res-
one for a 0.85 µm diameter permalloy disk, with a thickness
to radius ratio of 0.12. In the absence of pinning, the
in-plane gyration of the vortex, called the gyrotropic mode, is
expected to be at 480 MHz in good agreement with the aver-
age value in the current experiment. Yet there is significant
variation of the gyrotropic mode frequency with the applied
in-plane magnetic field. A variety of features can be seen,
such as a range of applied fields from 160 to 180 Oe where the
resonance changes slowly and smoothly, and regions –
near 200 Oe for example – where the resonance frequency
varies more significantly and with abrupt changes. This can
be understood as the vortex core, which is roughly 10 nm
in diameter,
moving through defect-free regions where the
resonance remains constant or regions where the vortex in-
teracts with defects. Interaction with a defect, such as a var-
iation in the film thickness, is known to confine and pin
vortices. The gyrotropic spin mode can be thought of as a
harmonic oscillation of the vortex in a potential well de-
fined by the stiffness of the in-plane magnetization. When
the vortex interacts with a defect it becomes more tightly lo-
alized and the stiffness increases, increasing the frequency of
the gyrotropic spin mode.

The UHF magnetic field applied along the x-axis serves
to drive the vortex gyrotropic precessions and, in principle,
could alter the potential landscape seen by the vortex and
hence the gyrotropic mode frequencies. To test whether or
not our drive fields affect the spin resonance frequencies we
scanned the identical vortex pathway through the permalloy
disk at multiple UHF drive powers. Fig. 2 demonstrates
that we are indeed in the regime where one can safely ig-
nore the influence of the drive amplitude. Residing in this
regime allows us the opportunity to observe the effects of
pinning, whereas at higher gyration amplitudes the vortex ef-
fectedly sees a pristine landscape. Currently higher drive
powers result in heating of the printed circuit board contain-
ing the drive coils, and hence the silicon devices, causing
shifts in the optomechanical detection scheme. Future experi-
ments mitigating this heating effect could test magnetically as-
sisted vortex de-pinning and the effect on the gyrotropic mode
frequencies.

We now turn our attention to a second device, fabricated to
house a 1.1 µm diameter permalloy disk. As seen in Fig. 3 the

permalloy can be considered to point in any direction. Yet in
mesoscale structures the magnetization is often dictated the
boundary conditions of the disk, i.e. shape anisotropy. In a
thin disk, as patterned here, the magnetization lies in the plane
and curls around the boundaries of the disk, forming a vortex
at the center of the disk in zero magnetic field. When a DC
magnetic field is applied in the plane of the disk, this vortex
is displaced orthogonal to the applied field. For example,
when a DC field is applied along the x-axis, the vortex is dis-
placed along the y-axis, increasing the magnetization in the
x direction and hence the direct torque measured. An addi-
tional AC drive field applied along the x-axis will drive the
gyration the vortex in the plane of the disk. This gyration can
then be detected by down-mixing to the mechanical resonance
frequency with an additional AC drive along the z-axis.

It is important to consider the geometry of the applied
magnetic fields and the spin texture of the magnetic struc-
ture in this experiment to understand the spin resonance that
we observe. To first order, the spins in the magnetically-soft

![Graph showing spin resonances corresponding to the gyrotropic motion of a single magnetic vortex in a 0.85 µm diameter permalloy disk at three different UHF drive powers.](image)
FIG. 3. a) Gyrotropic resonance (taken while sweeping from low to high in-plane field) and direct torque measurements of the in-plane magnetization and susceptibility of a 1.1 \( \mu \)m diameter permalloy disk. The peaks in the direct torque correspond to increases in the susceptibility, \( \partial m/\partial H \). Indicated by the dashed lines, these points of softer magnetization also correspond to dips in the gyrotropic mode frequency, indicating that the vortex experiences a lower restoring force to in-plane motion. Inset shows that at certain applied fields, particularly apparent when the vortex experiences a lower restoring force and gyrates at larger amplitude, multiple resonances can be observed. Since the vortex motion is being driven by the UHF fields, these resonances can be independently accessed as the drive frequencies are swept, and correspond to the weak interaction of the vortex with multiple defects. b) Micromagnetic simulation showing qualitatively similar behavior of the gyrotropic resonance by including 20 nm polycrystalline grains with \( \pm 10\% \) variation in the saturation magnetization. The average gyrotropic mode frequency in this disk is somewhat lower, \( \sim 400 \text{ MHz} \), consistent with expectations from geometric scaling arguments. A larger disk has lower magnetic stiffness since the vacuum boundaries are further away and hence lower gyrotropic mode frequency, predicted to be \( \sim 385 \text{ MHz} \) for a thickness to radius ratio of 0.09. Here we additionally perform measurements of the total magnetization of the nanomagnetic disk by directly driving the torsional mode on resonance with an AC magnetic field along the \( z \)-axis and measuring the direct torque, Fig. 3a. Furthermore, with a small component of the AC magnetic field applied along the \( x \)-axis, the vortex is dithered in-plane and the direct torque also encodes the in-plane magnetic susceptibility, \( \partial m/\partial H \), as recently discovered in Ref. 6. The result is a peak in the direct torque whenever there is a change in the susceptibility, as can be seen in Fig. 3. These susceptibility peaks can be compared with the behavior of the gyrotropic mode frequencies. Specifically, one can see that at the applied DC magnetic fields where there is an increased susceptibility the gyrotropic mode frequency dips. This is consistent with the picture of the vortex oscillating in a potential defined by the magnetic stiffness, as quantified by the susceptibility. When the susceptibility increases it is easier to alter the magnetization, hence the potential well is shallower and the mode frequency lower.

In light of this, one realizes that the magnetic fields in which the gyrotropic mode frequency increases correspond to the tightest confinement of the vortex, and likely correspond to defects in the permalloy disk. In order to identify a possible source of these defects we compare with micromagnetic simulations (performed using mumax). Fig. 3b shows simulations of the gyrotropic mode spectrum including a polycrystalline grain size of 20 nm with variations in the saturation magnetization of \( \pm 10\% \) (around \( M_s = 800 \text{ kA m}^{-1} \)). Good qualitative agreement is seen between the simulation and measurement, with large variations in the spin mode frequencies as the vortex moves through the pinning associated with the simulated grains. Therefore, the pinning defects observed in the measurements could originate from polycrystallinity. We also note that these simulations suggest that the vortex annihilation should occur at an applied field just above which we used in these experiments. Comparing with the radius of the disk, one can roughly calibrate the applied magnetic field in terms of vortex displacement. One can then read off of Fig. 3a that a defect occurs roughly every 50 Oe, suggesting that our permalloy film contains polycrystalline grains of \( \sim 40 \text{ nm} \).

Finally, we report on the observation of a rare event observed in the 1.1 \( \mu \)m diameter permalloy disk device. At one particular orientation of DC magnetic field in the plane of the disk, we observed a strong pinning of the vortex that drove the

FIG. 4. A rare event in which the vortex becomes strongly pinned by a defect, driving the gyrotropic mode frequency above 1.1 GHz. Pinning lasts over applied fields of 70 Oe, demonstrating the robustness of these pinning sites and the high frequency spin modes. Only one pinning site of this strength was encountered in thorough exploration of the two as-grown disks.
gyrotropic mode up to $\sim 1.1$ GHz. This event, shown in Fig. 4, pinned the vortex over a field range of approximately 70 Oe, demonstrating the stability of such a pinned state to perturbations in the applied field. Together these observations lead us to speculate that by engineering defects, as has been done with localized focused-ion-beam milling one could control the spin mode resonance frequencies for potential applications. Such as discussed above, the conversion of GHz signals to telecom wavelengths. Additionally, the ability to simultaneously study magnetization, susceptibility, and spin resonances together are of great utility in a lab-on-a-chip approach to nanomagnetism.

In conclusion, by taking advantage of the sensitivity and bandwidth of cavity optomechanical detection, we are able to observe ultra-high frequency spin modes in permalloy disks through the technique of torque mixing resonance spectroscopy. Combined with direct torque measurements of the in-plane susceptibility and micromagnetic simulations, we are able to show how the gyrotropic mode of individual magnetic vortices interacts with localized defects in the permalloy. When a vortex is pinned by such defects the spin mode frequencies can jump to as high as 1.1 GHz, a phenomenon that has previously only been observed in time-resolved Kerr microscopy. Opportunities exist for novel applications in control of these spin mode frequencies through the engineering of defects. Furthermore with the TMRS sensitivity and bandwidth presented here, it may be possible to observe non-thermal, quantum effects of vortex dynamics at low temperatures.

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