

Engineering Magnetic Vortex Dynamics for Next-Generation Spintronic Memory, Oscillators, Neuromorphic Computing

Saswati Barman

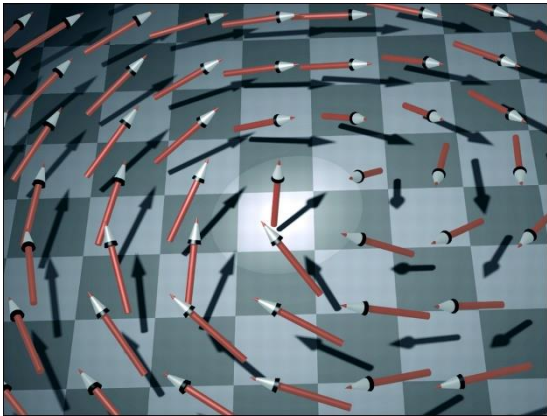
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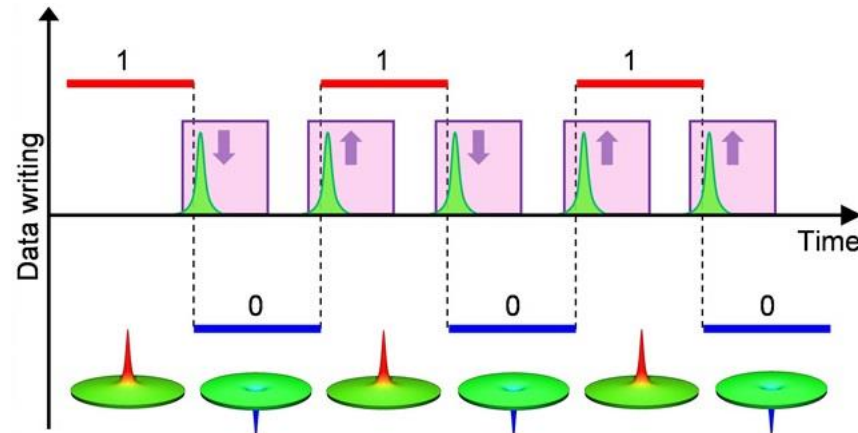
Magnetic Vortex

- A curling in-plane magnetization with a small portion of out-of-plane magnetization at the core of the vortex.
- It has **two** degrees of freedom; polarity $\mathbf{p} = \pm 1$ and chirality (CW/CCW)



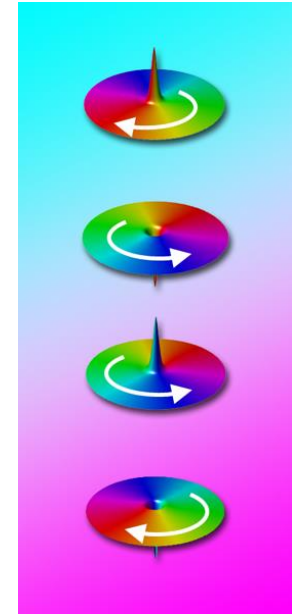
Schematic of a vortex core

A Wachowiak et al. *Science* 298, 577(2002)



Magnetic vortex-based information
recording process

Fu et al. *Sci. Adv* 4, eaat3077(2018)



Four different configurations of
magnetic vortex

- Each degree of freedom is an independent bit of information in high-density, non-volatile magnetic memory devices.
- Vortex core can be brought into gyration by the application of externally applied magnetic fields, spin-polarized currents, pure spin currents, spin waves, electric fields, etc.

Theoretical Background: LLG equation

The dynamics response of magnetization to fast changes of applied external field is governed by the Landau-Lifshitz-Gilbert (LLG) equation:

$$\frac{d\mathbf{m}}{dt} = \underbrace{-\gamma[\mathbf{m} \times \mathbf{H}_{eff}]}_{\text{precession}} + \underbrace{\alpha[\mathbf{m} \times \frac{d\mathbf{m}}{dt}]}_{\text{damping}}$$

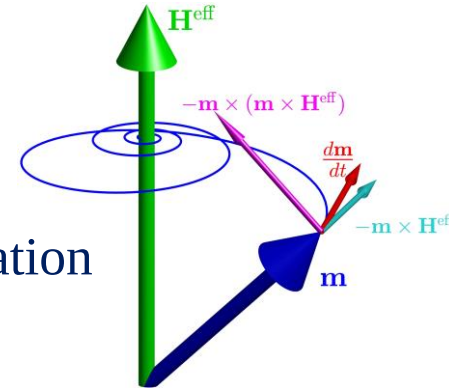
where $\mathbf{H}_{eff} = \mathbf{H}_{zeeman} + \mathbf{H}_{demag} + \mathbf{H}_{exchange} + \mathbf{H}_{anisotropy}$

γ = Gyromagnetic ratio

α = Gilbert damping constant

$\mathbf{m} = \frac{\mathbf{M}}{M_s}$, normalized magnetization

M_s = saturation magnetization



Magnetization orientation of a nanoscale ferromagnet can be manipulated by an electric current via the spin-transfer torque (STT) effect, which introduces an additional term to the RHS of the LLG equation:

$$\frac{d\mathbf{m}}{dt} = -\gamma_o[\mathbf{m} \times \mathbf{H}_{eff}] + \alpha[\mathbf{m} \times [\mathbf{m} \times \mathbf{H}_{eff}]] - \frac{\gamma_o \hbar j P}{2\mu_o e b M_s} [\mathbf{m} \times (\mathbf{m} \times \mathbf{p})] \rightarrow \text{Slonczewski}$$

$$\frac{d\mathbf{m}}{dt} = -\gamma_o[\mathbf{m} \times \mathbf{H}_{eff}] + \alpha[\mathbf{m} \times [\mathbf{m} \times \mathbf{H}_{eff}]] - (\mathbf{v}_s \cdot \nabla) \mathbf{m} + \beta \mathbf{m} \times (\mathbf{v}_s \cdot \nabla) \mathbf{m} \rightarrow \text{Zhang \& Li}$$

$\mathbf{v}_s = \frac{\mu_B P j_c}{e M_s (1 + \beta^2)}$ is the velocity vector parallel to the spin polarized current.

Landau et al. *Phys. Z. Sowjet. Un.* 8,153 (1935)

T. L. Gilbert, *IEEE Trans. Magn.* 40, 3443 (2004).

J. C. Slonczewski *J. Magn. Magn. Mater.* 159 (1996)

Zhang et al. *Phys. Rev. Lett.* 93 127204 (2004)

Numerical Methods (Micromagnetic Simulations)

Micromagnetism

In ferromagnets, neighboring magnetic moments have the tendency to align

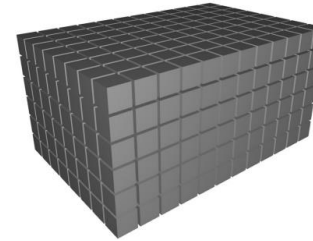


Continuum approx.

Magnetization can be described by a continuous vector field

$$\mathbf{M}(\mathbf{r}, t) = M_s(\mathbf{r}) \underbrace{\mathbf{m}(\mathbf{r}, t)}$$

Central quantity of interest



The dynamics of the magnetization direction occurs in the picosecond time scale and on the nanometre to micrometre length scale.

The magnetization dynamics is described by the Landau-Lifshitz-Gilbert (LLG) equation

Computation of the magnetization dynamics:

$$E[\mathbf{m}, t] \rightarrow H_{eff}(\mathbf{r}) \xrightarrow{LLG} \mathbf{m}(\mathbf{r}, t')$$



Micromagnetic software package in this thesis:

✓ Object Oriented MicroMagnetic Framework (OOMMF)

✓ mumax³

- Rectangular simulation box (origin in the center)
- Single regular rectangular grid
- Uniform magnetization inside cell $\mathbf{m}_{ijk} = \mathbf{m}(x_i, y_j, z_k)$
- Cell size < exchange length
- PBC values are number of virtual repetitions of the simulation box used to calculate dipolar interactions

Solves LLG equation by Finite Difference Method (FDM)

Engineering Collective Dynamics and Energy Flow in Magnetic Vortex Lattices

From Gyrotropic Modes to Reconfigurable Magnonic Transport

ADVANCED QUANTUM TECHNOLOGIES

Research Article | [Full Access](#)

Spectrum of Gyrotropic Modes and Energy Transfer between Dipolar-Coupled Magnetic Vortices in a Square Lattice via Triggered Vortex Gyration: A Promise for Spintronics Technology

[Payal Bhattacharjee](#), [Anjan Barman](#) ✉, [Saswati Barman](#) ✉

First published: 22 March 2024 | <https://doi.org/10.1002/qute.202300441> | [VIEW METRICS](#)



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Excitation Modes for Spin Waves in a Two-Dimensional Magnetic Vortex Lattice

[Payal Bhattacharjee](#), [Saswati Barman](#) ✉

First published: 15 April 2025 | <https://doi.org/10.1002/pssb.202500070> | [VIEW METRICS](#)



Journal of Physics and Chemistry of Solids

Volume 198, March 2025, 112475



Observation of higher-order gyrotropic modes and energy transfer in cylindrical ferromagnetic nanodots-based square lattices

[Payal Bhattacharjee](#) ^a, [Saswati Barman](#) ^{a b} ✉

Engineering Collective Dynamics and Energy Flow in Magnetic Vortex Lattices

Magnetic Vortex-Based 2D Square Lattice

🌀 Objective

- Investigate **collective excitation dynamics** in dipolar-coupled magnetic vortex lattices.
- Understand:
 - Gyrotropic mode spectrum
 - Spin-wave eigenmodes
 - Magnetic energy transfer dynamics and mechanisms

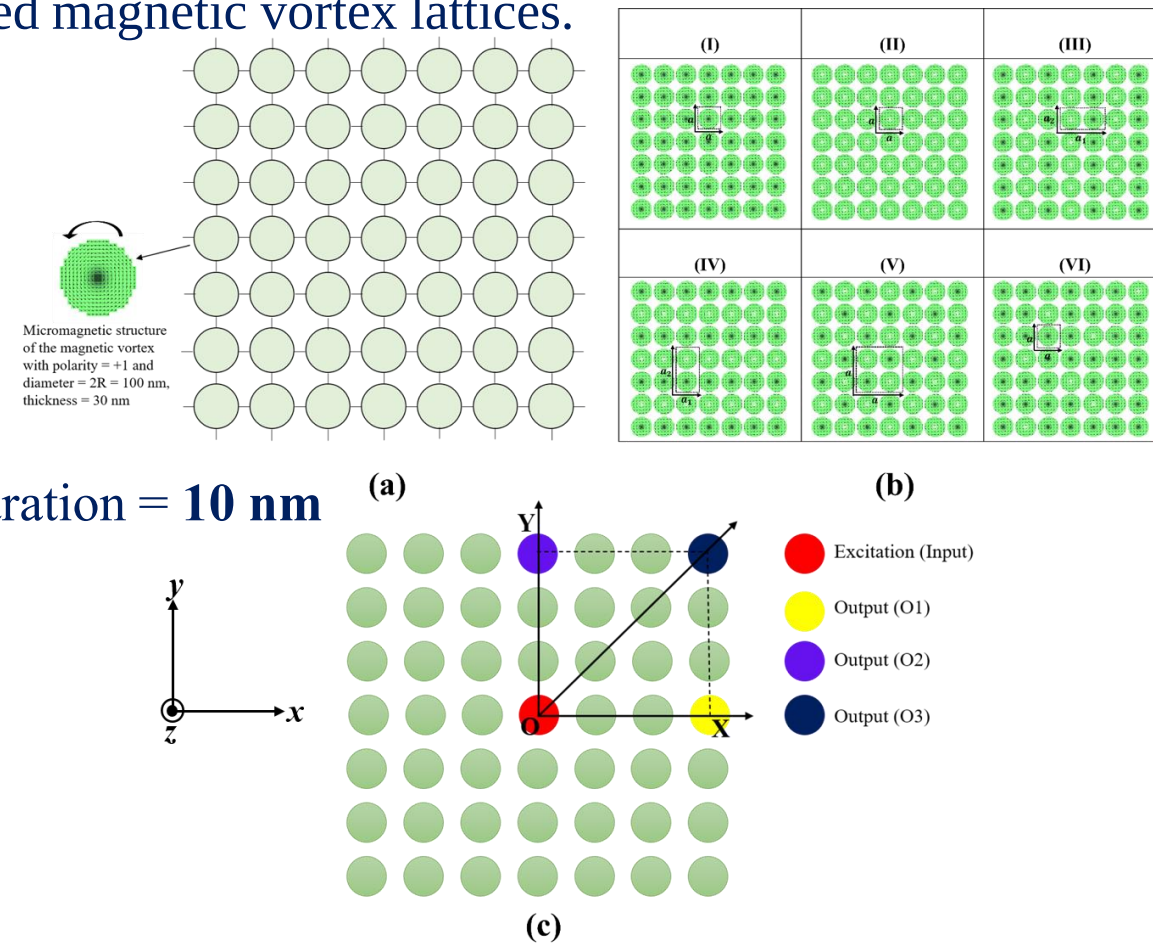
⚙️ System Configuration

- Permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) nanodisks
 - Diameter = **100 nm**, Thickness = **30 nm**, Inter-disk separation = **10 nm**
- Six tailor-made **2D square lattice configurations**

🔧 Method

- Micromagnetic simulations (LLG dynamics)
- Excitations applied using magnetic field pulses:
 - Square pulse $\rightarrow$ gyrotropic modes
 - In-plane sinc pulse $\rightarrow$ azimuthal modes
 - Out-of-plane sinc pulse $\rightarrow$ radial modes

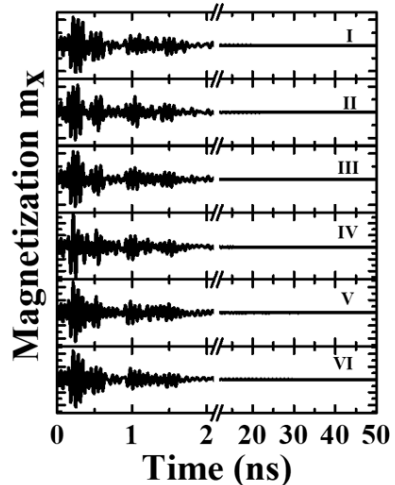
👉 **Goal:** *Reveal how vortex coupling controls collective dynamics.*



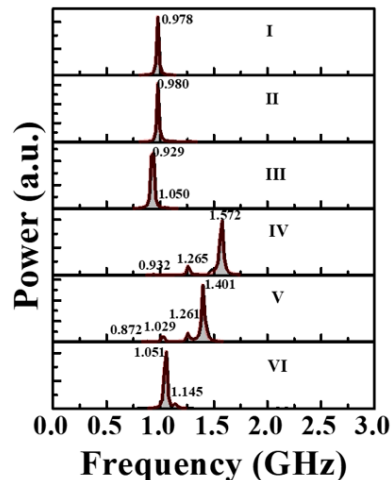
Engineering Collective Dynamics and Energy Flow in Magnetic Vortex Lattices

🌀 Gyrotropic Modes

- Collective vortex core gyration observed.
- ❑ Two main branches:
 - **Acoustic-like modes** (in-phase motion)
 - **Optical-like modes** (out-of-phase motion)
- ✓ Frequencies depend on lattice configuration and dipolar coupling.
- ✓ In nanodisks, gyrotropic modes exhibit **acoustic-like and optical-like branches**, like **phonon vibrations in mono- and diatomic crystal lattices**.



(a)



(b)

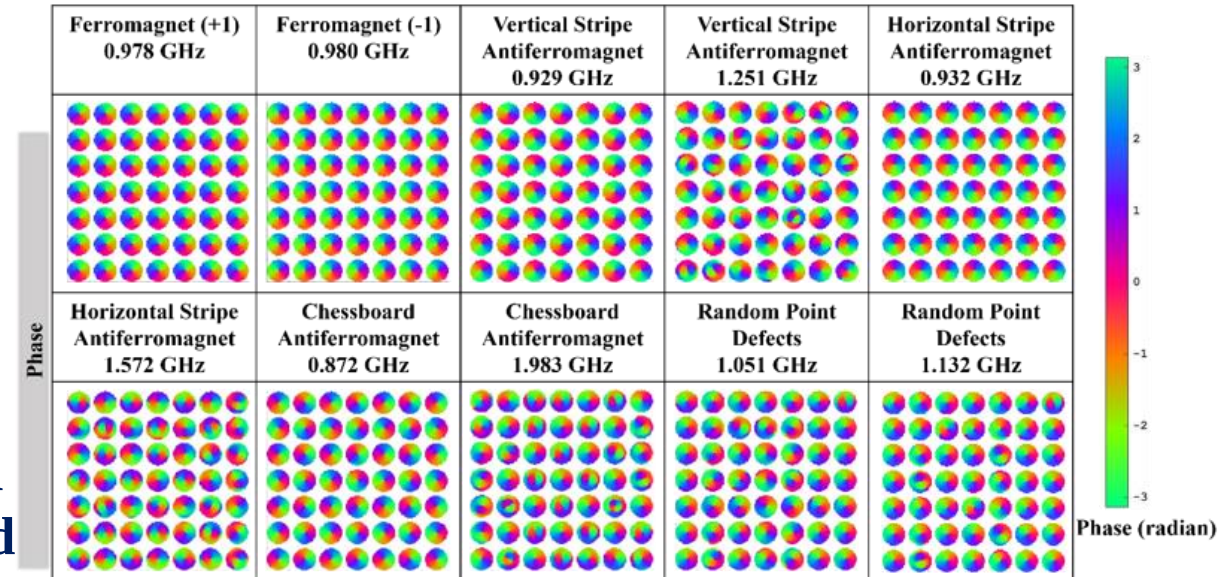


Fig. Phase profiles and (b) power profiles at the resonant gyrotropic frequencies of the magnetic vortex cores in different lattice configurations. The phase ranges from $-\pi$ to π radians.

Figure. (a) Time-varying x-component of the magnetization curve of different configurations under consideration ($d = 100 \text{ nm}$, $h = 30 \text{ nm}$) and (b) corresponding excitation spectrum in response to global excitation field displaying six configurations' collective gyrotropic eigenmodes.

Engineering Collective Dynamics and Energy Flow in Magnetic Vortex Lattices

Spin-Wave Modes

Two types identified:

1. Azimuthal modes

- Excited by in-plane magnetic pulse – Angular propagation around vortex core

2. Radial modes

- Excited by

Key Findings

Detailed analysis of **high-frequency spin-wave excitations** in vortex lattices:

- Azimuthal modes:**
 - Mode number (m) depends on vortex core polarity.
 - Mode number increases with increasing collective frequencies.
- Radial modes:**
 - Symmetric modes ($m = 0$).
 - Characterized by radial nodes ($n = 1, 2, 3$).

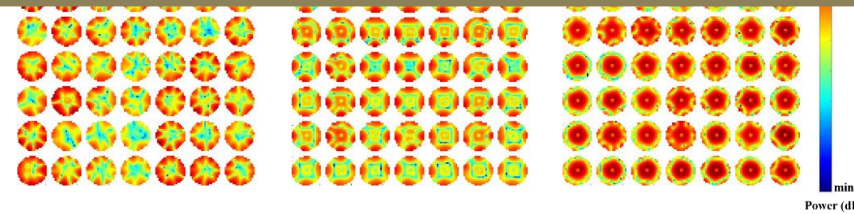
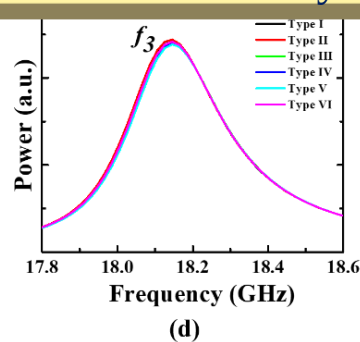
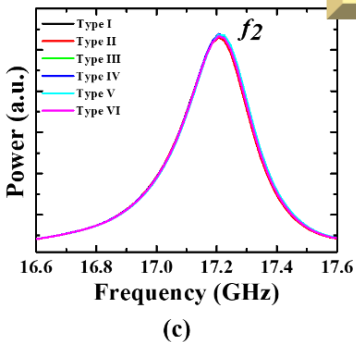
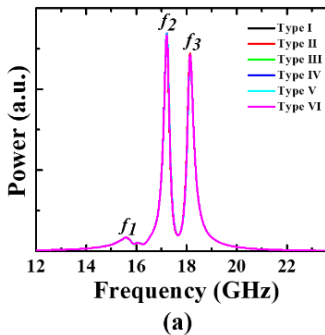
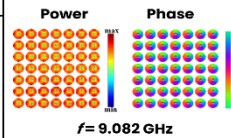
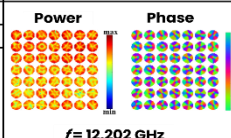
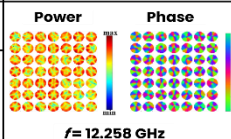
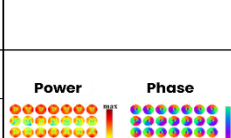
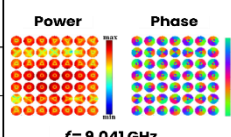
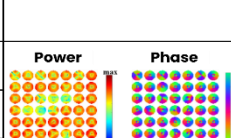


Fig. Phase profiles and power distribution of magnetic vortices in Type I configuration at radial mode frequencies.

Type of lattice configuration	Azimuthal modes (GHz)	Azimuthal mode number (m)	FFT amplitude and phase Images of azimuthal modes
Ferromagnet +1 (F+1)	9.082	+1 (CCW)	
	12.200	-3 (CW)	
Ferromagnet -1 (F-1)	9.082	-1 (CW)	
	12.202	-3 (CW)	
	13.444	+3 (CCW)	
	9.020	+1 (CCW; for $p = +1$); -1 (CW; for $p = -1$)	
	12.258	-3 (CW; for $p = +1$); +3 (CCW; for $p = -1$)	
	8.921	+1 (CCW; for $p = +1$); -1 (CW; for $p = -1$)	
	9.445	-1 (CW; for $p = +1$); -1 (CCW; for $p = -1$)	
	9.883	+2 (CCW; for $p = +1$); -2 (CW; for $p = -1$)	
	10.389	-2 (CW; for $p = +1$); +2 (CCW; for $p = -1$)	
	11.151	+3 (CCW; for $p = +1$); -3 (CW; for $p = -1$)	
Chessboard Antiferromagnet (CA)	9.041	+1 (CCW; for $p = +1$); -1 (CW; for $p = -1$)	
	9.322	-1 (CW; for $p = +1$); +1 (CCW; for $p = -1$)	
	9.540	+2 (CCW; for $p = +1$); -2 (CW; for $p = -1$)	
	10.037	-2 (CW; for $p = +1$); +2 (CCW; for $p = -1$)	
Random Point Defects (RPD)	9.217	+1 (CCW; for $p = +1$); -1 (CW; for $p = -1$)	
	11.847	+2 (CCW; for $p = +1$); -2 (CW; for $p = -1$)	
	13.532	-3 (CW; for $p = +1$); +3 (CCW; for $p = -1$)	

Engineering Collective Dynamics and Energy Flow in Magnetic Vortex Lattices

Energy Transfer in Vortex Lattice

↻ Energy Propagation

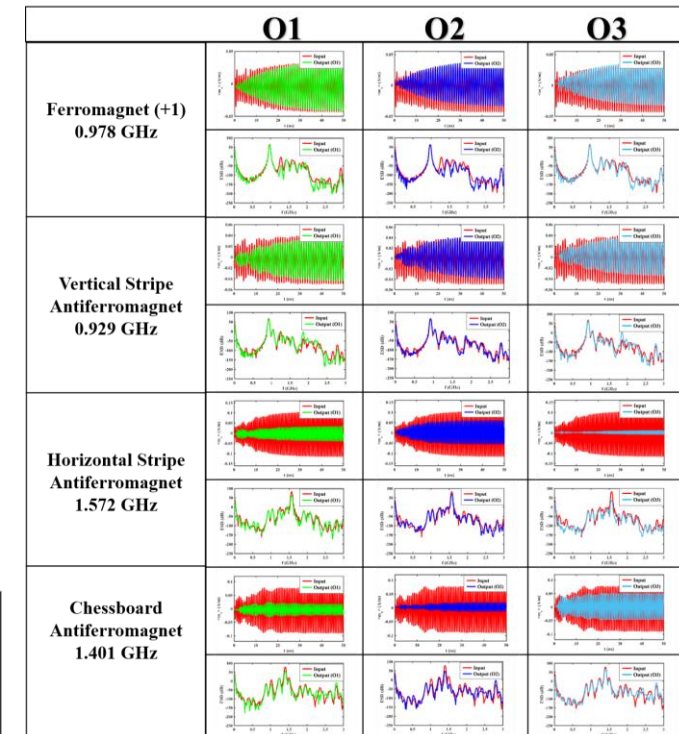
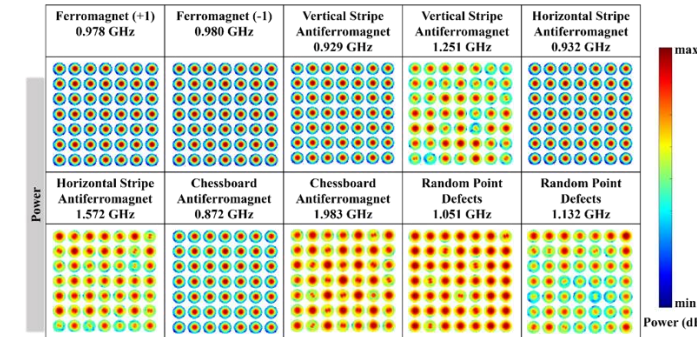
- Central vortex excited → energy transfers to neighbors via **dipolar interaction**.
- Energy analyzed along symmetry directions:
 - $O \rightarrow O_1$;
 - $O \rightarrow O_2$;
 - $O \rightarrow O_3$

✓ Energy Transfer in Vortex Lattices — Key Results

- **Nanodisks:** Energy transfer is nearly **isotropic** (>90%) along all symmetry directions under **acoustic gyrotropic excitation**.
- **Optical gyrotropic excitation** produces **anisotropic and reduced energy transmission**, similar to dominant acoustic phonon heat transport in crystals.

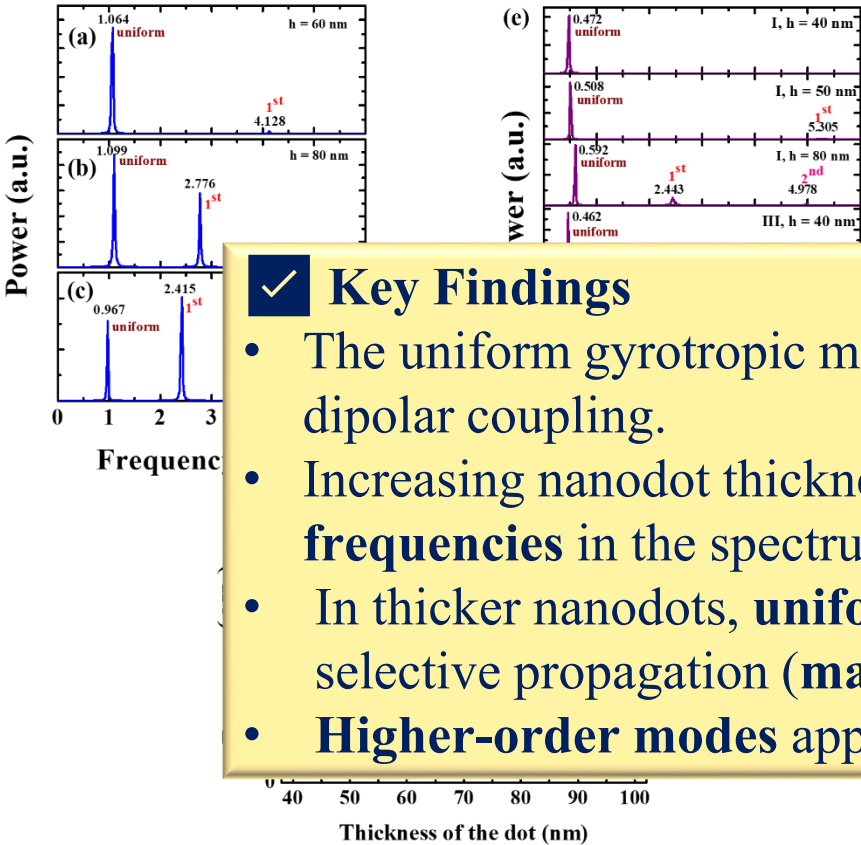
◆ Core Message ◆

Controlled collective dynamics and energy transfer in dipolar-coupled vortex lattices for functional spintronic architectures.



Engineering Collective Dynamics and Energy Flow in Magnetic Vortex Lattices

Now the question arises: what will be the influence of the third dimension on the dot excitation spectra as well as on the magnetic energy transfer, when the dots become essentially thicker?



Key Findings

- The uniform gyrotropic mode remains **unsplit** in moderately thick nanodots despite dipolar coupling.
- Increasing nanodot thickness results in the emergence of **higher-order excitation frequencies** in the spectrum.
- In thicker nanodots, **uniform gyrotropic modes** enable directional transmission, causing selective propagation (**magnonic filtering effect**).
- **Higher-order modes** appear in the spectrum but do **not contribute to energy transfer**.

Figure. (a-c) Simulated excitation spectra for the magnetic vortex gyrotropic mode with diameter $d = 300 \text{ nm}$ and thickness $h = 60 \text{ nm}$, 80 nm and 100 nm respectively; **(d)** frequency variations in the uniform mode, first order mode, and second order mode as a function of magnetic nanodot thickness **(e)** excitation spectra of Type I and Type III lattice configurations and varying dot thickness.

Sample		Excitation frequency (GHz)	Transmission along O1 (%)	Transmission along O2 (%)	Transmission along O3 (%)
Ferromagnet (F+1)	Uniform mode	0.556	25.46	23.78	12.28
			No transmission	No transmission	No transmission
			23.79	12.14	
			No transmission	No transmission	No transmission
Chessboard Antiferromagnet	Uniform mode	0.796	23.50	No transmission	97.73
	1 st order mode	3.989	No transmission	No transmission	No transmission
			No transmission	No transmission	No transmission
			No transmission	No transmission	No transmission

Engineering Collective Dynamics and Energy Flow in Magnetic Vortex Lattices

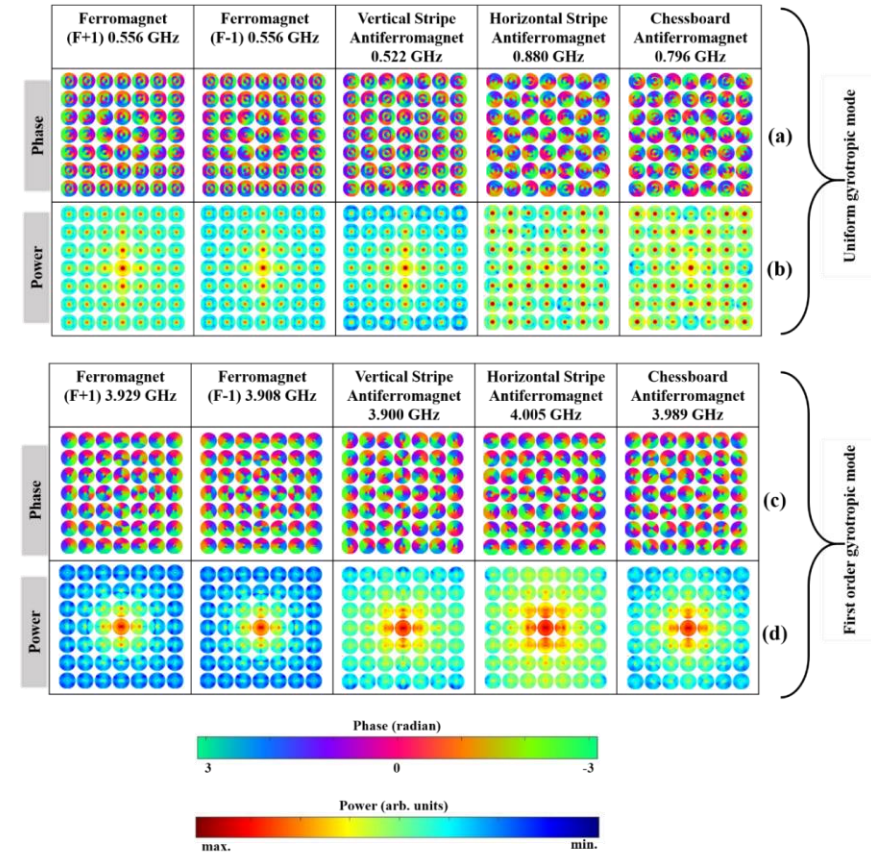


Fig. Phase and power profiles of the gyrating magnetic vortices in different lattice configurations

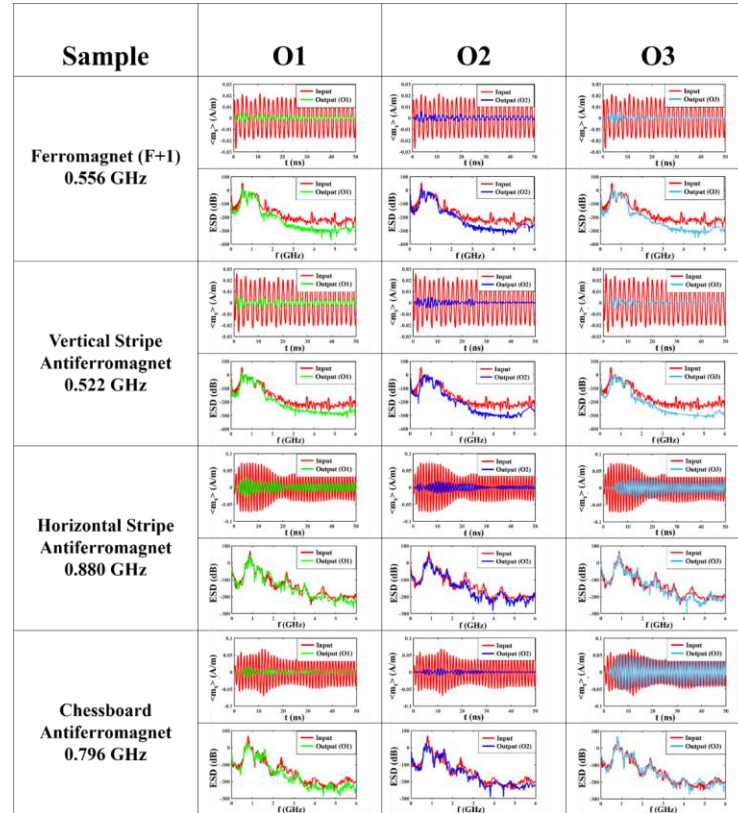


Fig. ESD spectra of various lattice configurations; excitation frequency = collective gyrotropic frequencies of the lattices.

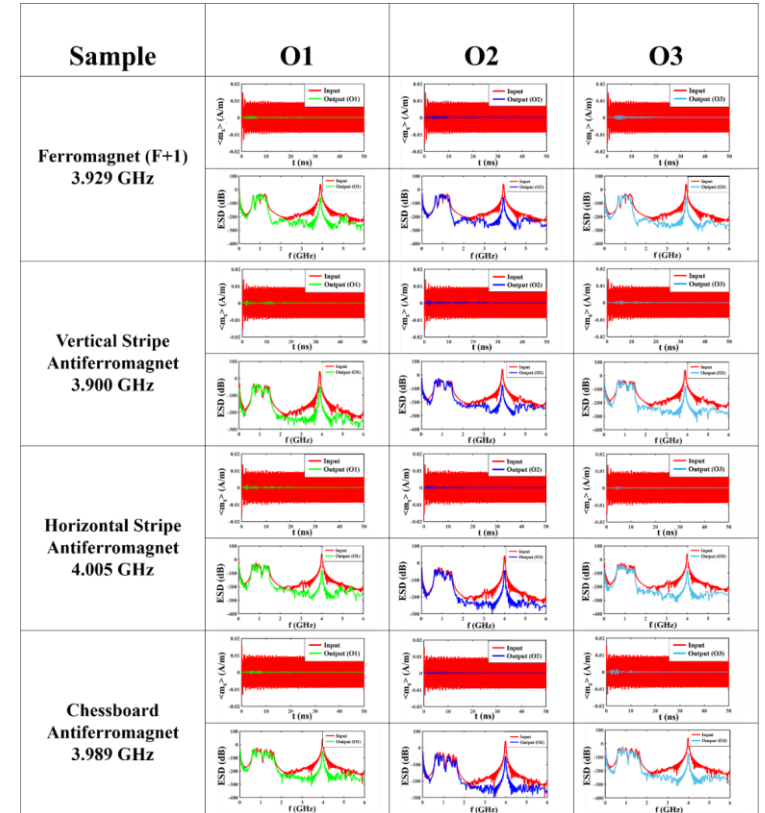


Fig. ESD spectra of various lattice configurations; excitation frequency = first higher-order frequencies of the lattices.

Engineering Collective Dynamics and Energy Flow in Magnetic Vortex Lattices

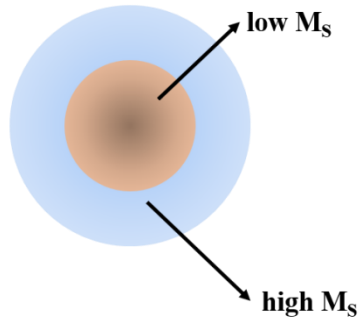
“The work demonstrates that a magnetic-vortex lattice can function as a tunable magnonic crystal in which the frequency and symmetry of collective gyrotropic modes control how efficiently magnetic energy propagates through the lattice.”

The three most important points

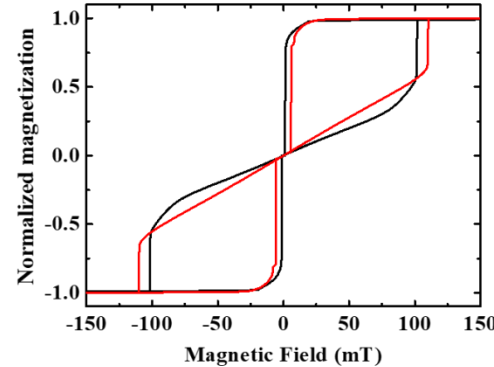
- 1. Collective modes:** Dipolar coupling between vortices creates multiple **acoustic-like and optical-like gyrotropic modes**.
- 2. Controlled energy transmission:** Acoustic-like modes enable **>90% and nearly isotropic energy transmission**, whereas optical-like modes have lower transmission.
- 3. Technological significance:** The lattice provides a route toward **magnonic waveguides, low-power information processing and customizable spintronic devices**.

Engineering Magnetic Vortex Dynamics for Tunable and Synchronized Spintronic Nano-Oscillators

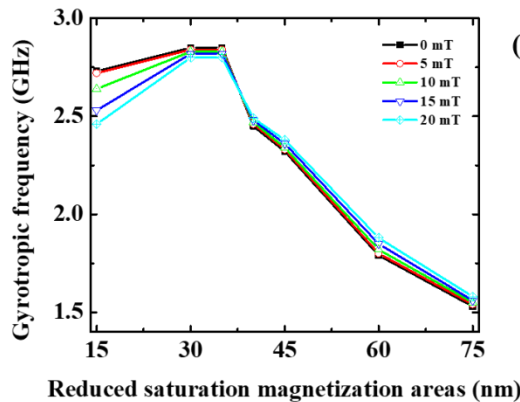
(a)



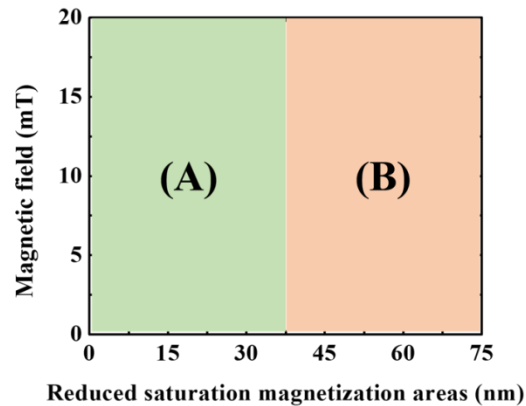
(b)



(d)



(c)



Spin-Torque Vortex Oscillators

- ✓ Scalable
- ✓ CMOS compatible
- ✓ Current/field tunable
- ✓ Capable of nonlinear oscillations
- ✓ Able to synchronize with neighbouring oscillators.

Applications

- GHz signal generation
- Signal processing
- Neuromorphic computing
- Associative memory.

A compact platform for generating and processing microwave signals,
limitation: their frequency is largely fixed by device geometry and material properties.

One nanodisk can exhibit multiple gyrotropic frequencies depending on where the vortex core is located.

Engineering Magnetic Vortex Dynamics for Tunable and Synchronized Spintronic Nano-Oscillators

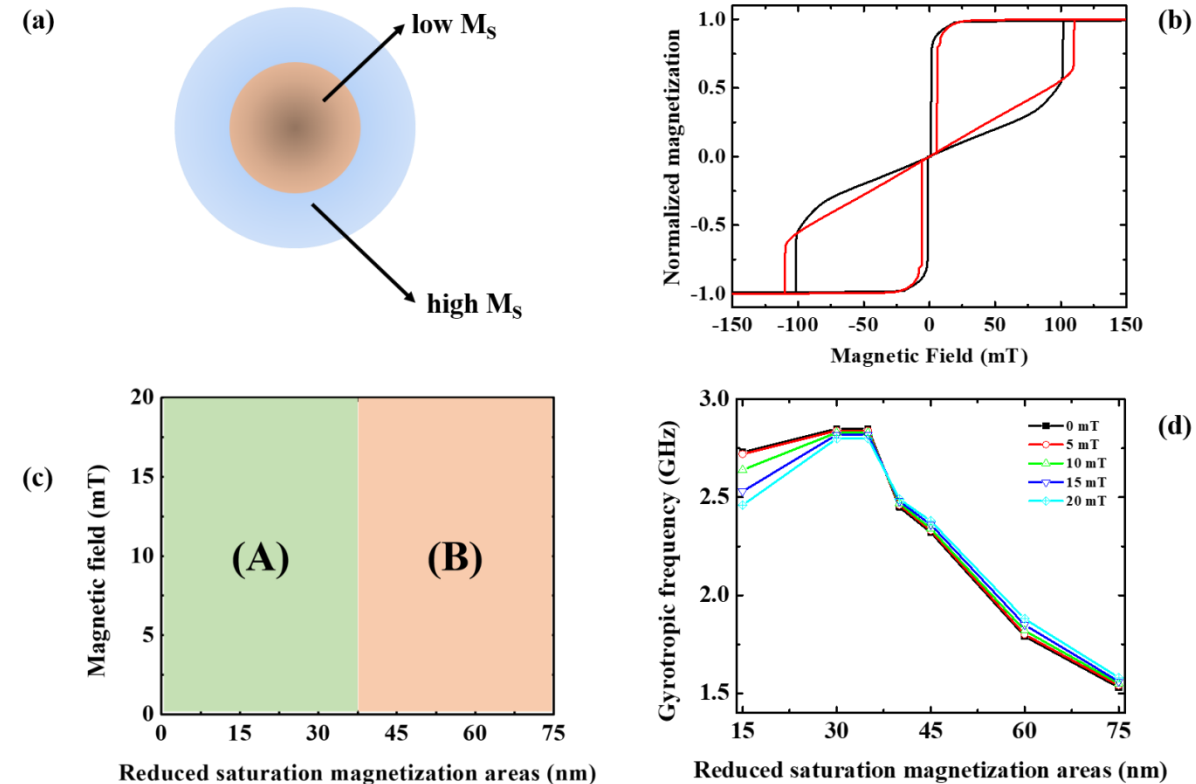
The oscillation frequency is fundamentally determined by the potential landscape experienced by the vortex core.

Local modification of M_s creates a spatially engineered magnetic potential inside a single nanodisk.

Micromagnetic simulations performed using **MuMax3**.

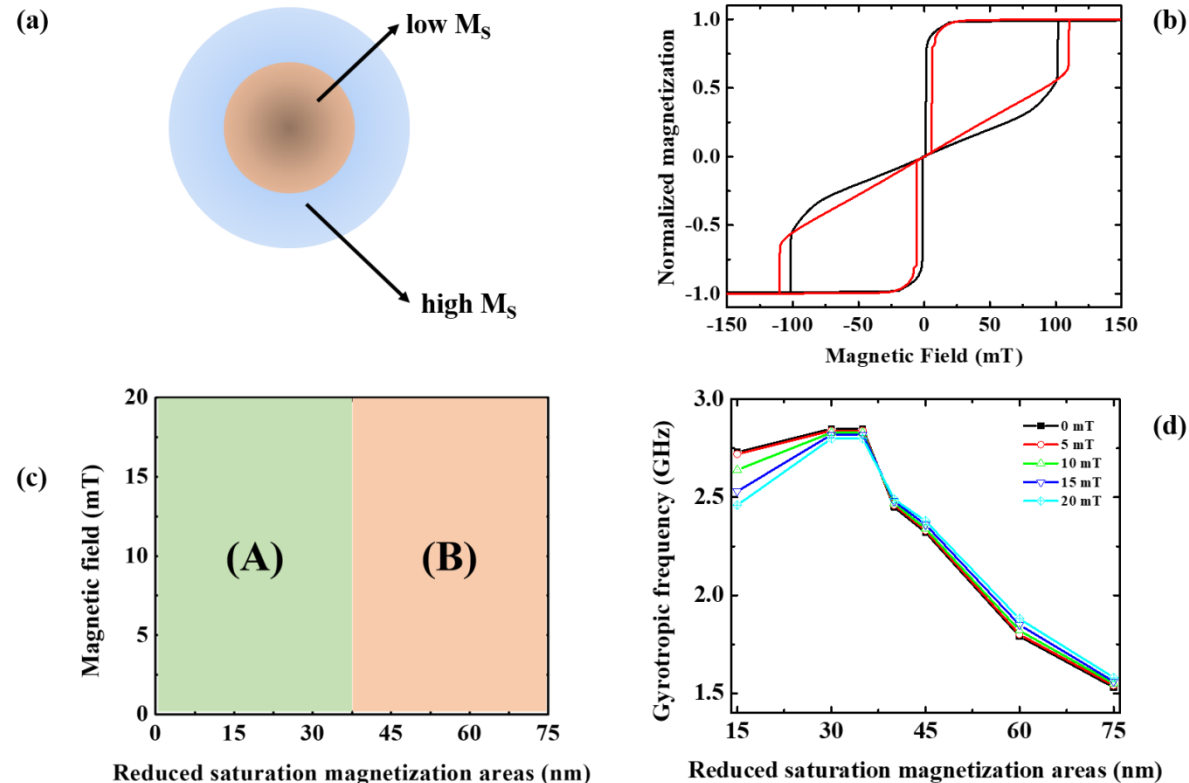
Spin-polarized DC current excites the vortex.

Changing only the size of the reduced- M_s region provides a broad frequency tuning range—from about 1.5 to 2.85 GHz in the simulated structures.



By engineering the local saturation magnetization, we can engineer the magnetic potential, tune the vortex frequency within a single nanodisk, and ultimately achieve synchronized nanoscale oscillator networks

Engineering Magnetic Vortex Dynamics for Tunable and Synchronized Spintronic Nano-Oscillators



Region A

- Reduced- M_s region below approximately **40 nm**.
- Frequency can **decrease with increasing applied field**.

Region B

- Larger modified regions.
- Frequency **increases with applied field** as the vortex moves into higher- M_s material.

Non-monotonic frequency behaviour

Differs from the simple expectation based on the standard Thiele description

Engineering Magnetic Vortex Dynamics for Tunable and Synchronized Spintronic Nano-Oscillators

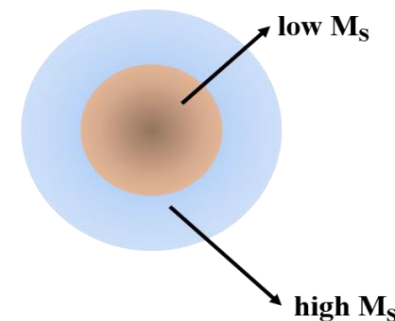
- Introducing a reduced- M_s region creates:
- A modified magnetostatic landscape.
- Effectively two parabolic contributions.
- An additional localized potential.
- This modifies the force acting on the vortex core and therefore changes its gyrotropic frequency.

This is satisfied by a **Gaussian potential** (of the form of $W_p(\mathbf{X}) = -ae^{-x^2/2c^2}$) where $\text{FWHM} = c\sqrt{2\ln 2}$ where a is the depth and c is the width of the potential.

The effect of this **additional potential is maximum when the irradiated portion covers 30 nm~40 nm of the disk** and gradually declines thereafter (in the range 40-60 nm).

Beyond about **60 nm**, the disk increasingly behaves like a nearly uniform reduced- M_s disk.

$$W(\mathbf{X}) = W(0) + \kappa|\mathbf{X} + a_o|^2/2 + \kappa|\mathbf{X} - a_o|^2/2 + W_p(\mathbf{X})$$



Frequency tunability originates from engineering the vortex-core potential—not simply from changing the applied field.

Engineering Magnetic Vortex Dynamics for Tunable and Synchronized Spintronic Nano-Oscillators

Frequency becomes a controllable degree of freedom through both material engineering and magnetic-field control.

Two independent ways to tune the frequency

Method 1 — Structural tuning

Change the size of the reduced- M_s region.

Method 2 — Field tuning

Change the strength of the static in-plane magnetic field.

A tunable GHz oscillator with tens-of-MHz linewidth is attractive for nanoscale microwave applications.

Narrow linewidth — an important device advantage

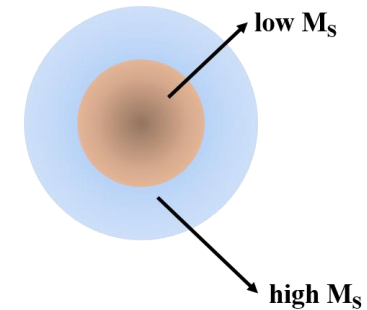
The STVOs show narrow linewidths:

- Approximately **40–50 MHz** for reduced- M_s regions extending up to 45 nm.
- The linewidth remains relatively narrow across the investigated modified regions.
- Such narrow linewidths indicate good spectral coherence.
- Spectral purity
- Sensitive to magnetic imperfection
- Better Signal processing

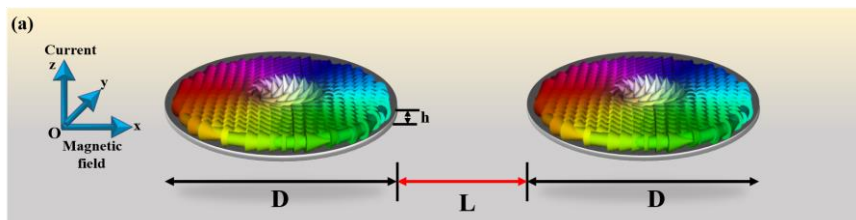
Engineering Magnetic Vortex Dynamics for Tunable and Synchronized Spintronic Nano-Oscillators

- **Spin-torque vortex nano-oscillators (STVOs):**

Local engineering of saturation magnetization provides wide frequency tunability. It also enables phase-locked synchronization of closely spaced vortex oscillators without additional lithography and altering the overall device geometry, making it suitable for next-generation spintronic RF devices. Thick Permalloy nanodots were investigated, revealing tunable vortex gyrotropic and higher-order modes, which show potential for spin-torque nano-oscillators in telecommunication applications.



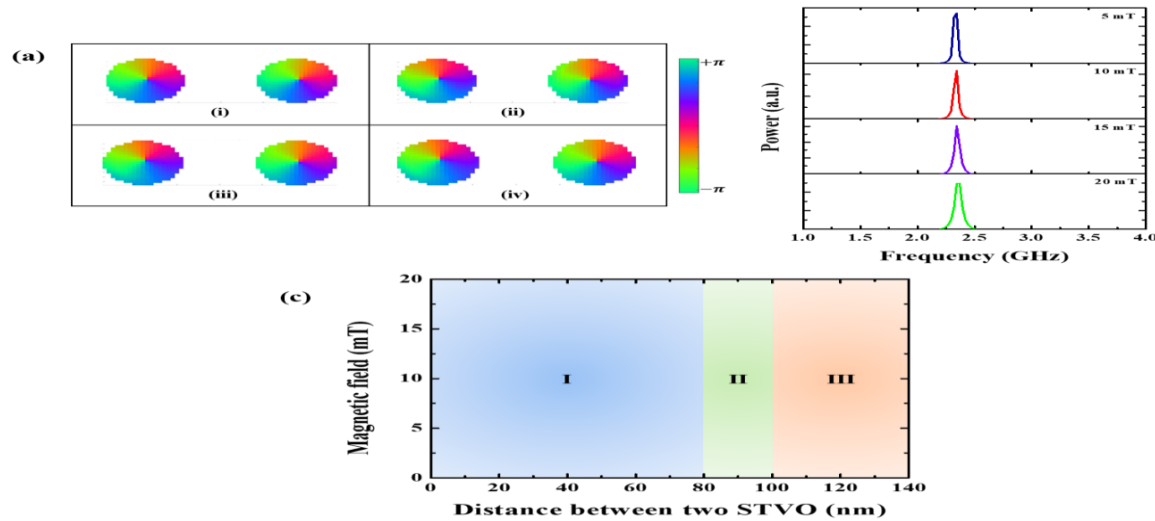
Can these tunable oscillators communicate with each other?



- Reduced- M_s region = 45 nm
- Same vortex polarity and chirality.
- The oscillators are separated by a variable distance L

We have used the in-built Mumax³ API EdgeSmooth = 8

Engineering Magnetic Vortex Dynamics for Tunable and Synchronized Spintronic Nano-Oscillators



An optimum inter-oscillator distance exists for mutual synchronization through dipolar coupling.

$L_{\text{critical}} \approx 80 \text{ nm}$

Region I: $L < 80 \text{ nm}$

- Strong dipolar coupling.
- Frequency splitting.
- Unsynchronized behaviour.

Region II: $80 - 100 \text{ nm}$

- Mutual synchronization possible.
- Single synchronized frequency.

Region III: $L > 100 \text{ nm}$

- Oscillators behave essentially as isolated disks.

(b) **Synchronization** preserves GHz operation and maintains relatively narrow spectral linewidths.

Dipolar coupling converts two independent vortex oscillators into a **coherent, phase-locked** oscillator pair.

When two vortex oscillators are close:

- Their oscillating stray fields interact.
- Dipolar coupling occurs.
- The original frequency splits into two modes.

As the distance is varied, the system transitions between:

1. Strongly coupled/unsynchronized regime.
2. Synchronization regime.
3. Essentially isolated regime.

The oscillating stray field provides a natural mechanism for communication between neighbouring STVOs.

Applications

1. Tunable microwave/GHz signal generators

- The STVO can generate coherent oscillations in the GHz range.
- By changing the position/size of the reduced- M_s region and applying an external magnetic field, the oscillation frequency can be tuned.
- This could be useful for **reconfigurable microwave sources and frequency generators**.

2. Frequency-selective signal processing

- The study reports relatively narrow linewidths of about **40–50 MHz for isolated STVOs**.
- Such narrow spectral characteristics are attractive for **high-frequency signal processing, frequency filtering and signal detection**.

3. Nanoscale frequency detectors

- Since the gyrotropic frequency depends on the magnetic environment experienced by the vortex core, changes in the local magnetic properties can modify the oscillation frequency.
- This provides a possible route toward **nanoscale magnetic-field or perturbation detection**.

Applications

4. High-density spintronic devices

- A major advantage demonstrated by this work is that **frequency tuning is achieved by modifying the local magnetic property rather than requiring a completely different device geometry.**
- This could facilitate compact and potentially high-density arrays of frequency-programmable spintronic oscillators.

5. Reconfigurable spintronic architectures

- The possibility of creating different magnetic-property regions within one nanodisk opens the prospect of **reconfigurable oscillator devices.**
- Multiple frequency states could potentially be obtained from the same physical device.

RESEARCH ARTICLE



Frequency Tunability of Spin-Torque Vortex Oscillator in Permalloy Nanodisks with Modified Material Properties

Payal Bhattacharjee and Saswati Barman*

The manipulation of the vortex state in magnetic nanostructures has received a lot of interest in recent decades, with potential applications in nonvolatile magnetic random-access memory and logic networks. For wireless communication advancements, nano-sized, and low-phase-noise, adjustable transmitter-receiver networks are critical. Herein, it is shown that by using micromagnetic simulations when the saturation magnetization is reduced in a particular region of a magnetic nanodisk, the frequency tunability in such disks can be achieved. The gyrotropic mode of the vortex core is excited with spin-polarized current and an in-plane static magnetic field and found that an isolated magnetic vortex shows different resonance frequencies at different saturation magnetization regions. The dynamics of the mutual synchronization between two such dipolarly coupled magnetic vortices are numerically investigated, and the essential distances at which synchronization occurs are also identified. These incredibly small vortex-based oscillator devices have linewidths of the order of 40–60 MHz, making them prospective candidates for signal-processing applications and a strong new tool for basic research on vortex dynamics in magnetic nanostructures.

or “STVO”) are expected to be a breakthrough in the future generation of information and communication technology, among the innovative potential of spintronic devices. These oscillators are nanoscaled, CMOS-compatible, and can be readily adjusted using dc current and/or an external magnetic field.^[6]

Because of the nonlinear oscillating behavior of the magnetization of the device and its ability to synchronize magnetically or electrically with other identical devices, spintronic oscillators are especially well suited for neuromorphic computing systems.^[7,8] The study of synchronization processes is a primary nonlinear scientific subject because of the various applications in physics, chemistry, biology, and even social systems and the numerous basic hurdles in understanding the collective dynamics of massive ensembles. Though vortex-based oscillators show the feasibility of synchronizing through dipolar interac-

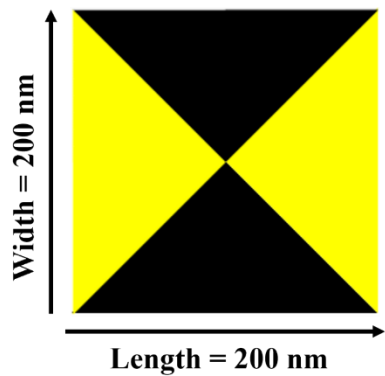
Engineering Magnetic Vortices for Multi-Bit Information Storage

Geometry, Interfaces and Field-Controlled Spin Textures in Fe–Py Bow-Tie Nanostructures

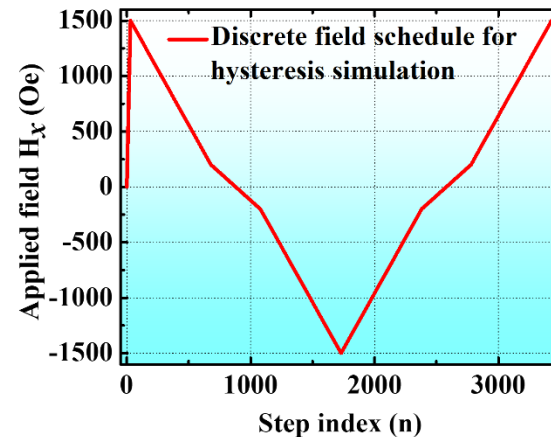
Bow-tie structure

Bi-component material structure that comprises of alternating iron (Fe) represented as yellow, and permalloy (Py) represented as black

Investigate how geometry, interfaces, magnetic field and material composition control magnetic vortex formation, stability, and magnetization reversal in a bi-component Fe–Permalloy (Fe–Py) bow-tie nanostructure.



(a)



(b)

Can we engineer the geometry and material composition of a nanostructure to control multiple magnetic vortices—and therefore store multiple bits in a single element?

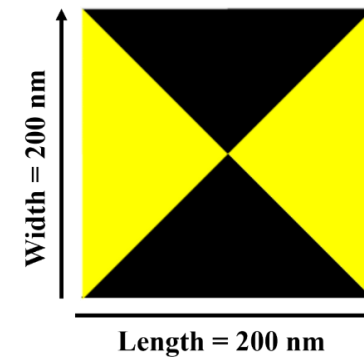
Engineering Magnetic Vortices for Multi-Bit Information Storage

*Can the **number, stability, polarity and chirality of magnetic** vortices in a single Fe–Py bow-tie nanostructure be deliberately controlled through **its geometry and applied magnetic-field direction** to increase its information-storage capability?*

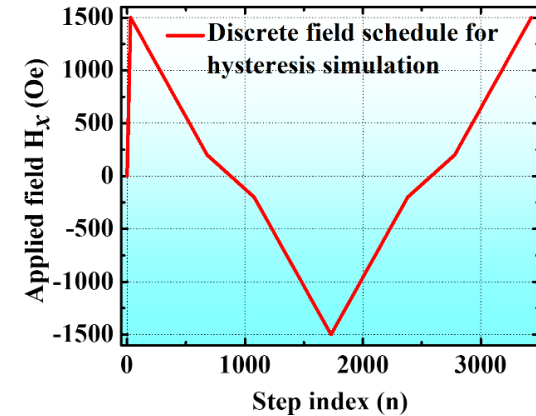
Goal: enable higher-density, multi-bit magnetic memory and spin-logic devices.

Engineering Magnetic Vortices for Multi-Bit Information Storage

1. **Examine vortex and antivortex formation** in Fe–Py bow-tie nanostructures and determine when single- or multi-vortex states become stable.
2. **Investigate the effect of lateral geometry**—particularly changing the bow-tie length from 200 to 400 nm—on the resulting magnetic spin textures and their stability.
3. **Understand magnetization reversal mechanisms** by analysing hysteresis loops and tracking vortex nucleation, motion, and annihilation under applied magnetic fields.
4. **Study the influence of magnetic-field orientation** (longitudinal versus transverse) on vortex configurations and their stability.
5. **Explore whether multiple stable vortex states can encode multiple bits of information** within a single nanostructure, thereby providing a possible route toward **multi-bit magnetic memory and vortex-based spin-logic devices**.



(a)



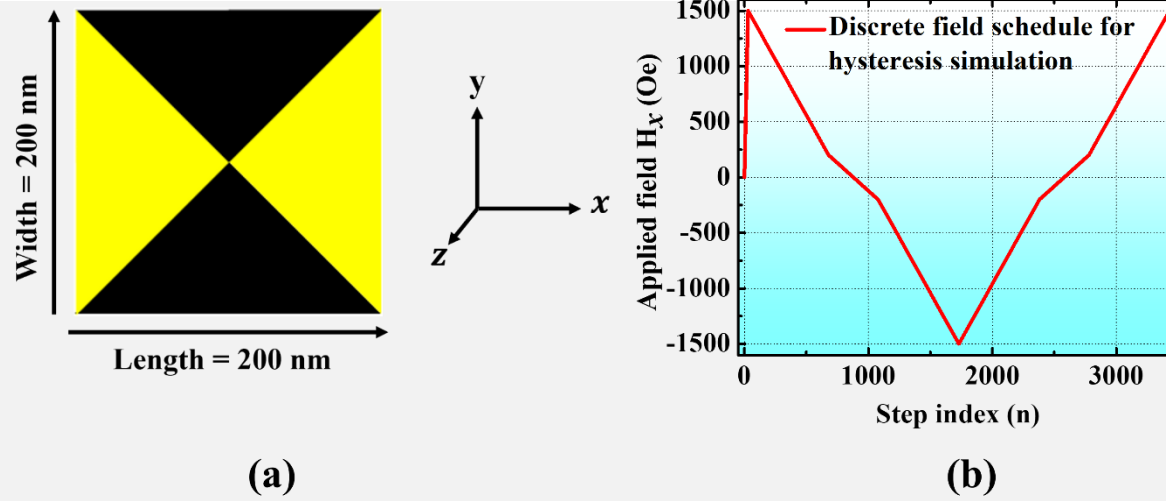
(b)

Micromagnetic simulation software Object Oriented Micromagnetic Framework (OOMMF), which solves the time-dependent Landau-Lifshitz-Gilbert equation using the finite-difference method.

Exchange length of the Fe and Py, which are 3.4 nm and 5.3 nm, respectively.

Our emphasis is on the qualitative behavior of magnetization under extreme conditions, rather than precise quantitative dynamics.

Engineering Magnetic Vortices for Multi-Bit Information Storage

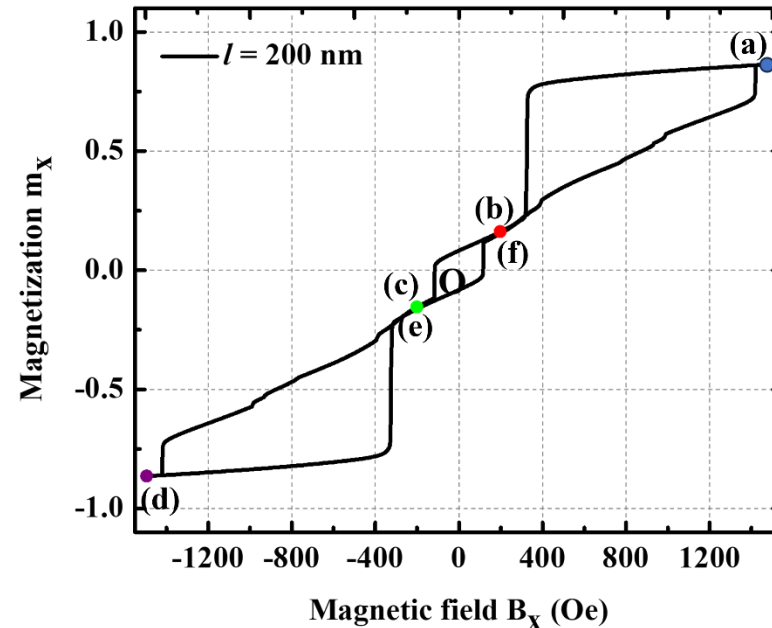


Specifically, we alter parameter l , which corresponds to the length of the considered structure, from 200 nm to 400 nm.

Material	Exchange Constant (pJ/m)	Uniaxial anisotropy (kJ/m^3)	Saturation Magnetization (kA/m)
Iron (Fe)	21	48	1700
Permalloy (Py)	13	0	800

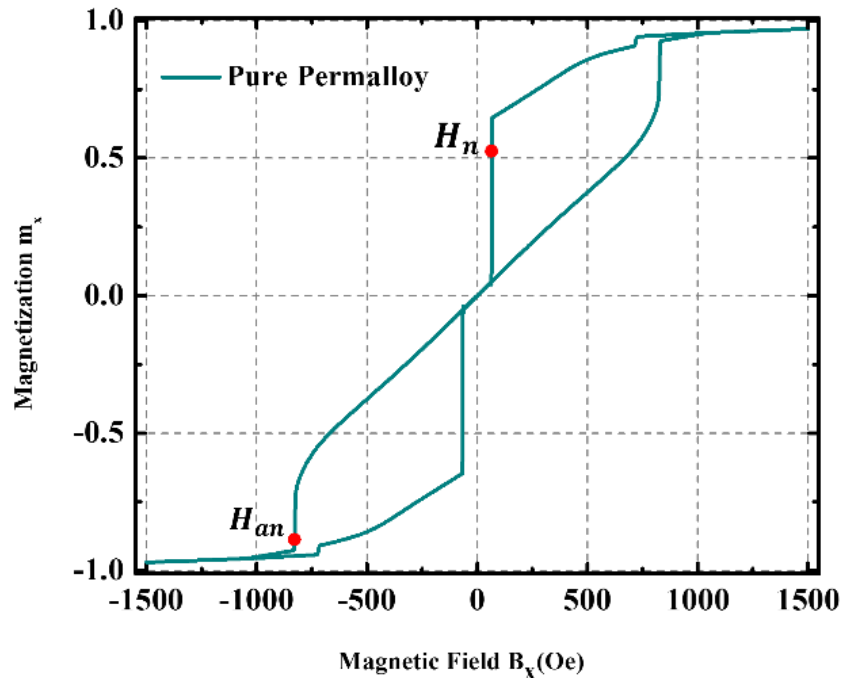
Material parameters for Py and Fe used in the simulation.

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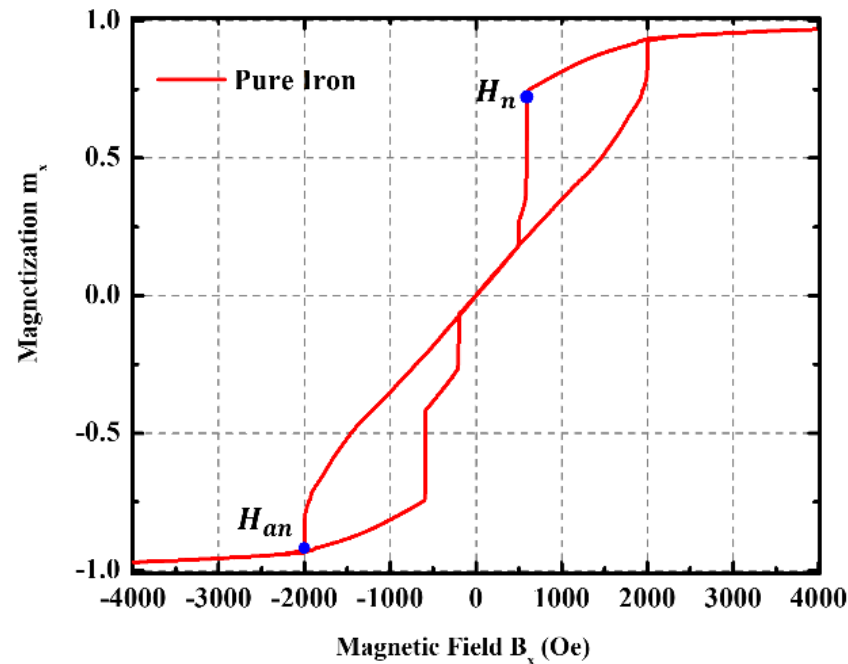


The hysteresis loop calculated using micromagnetic software for a bow-tie square structure with dimensions of 200 nm on each side and a thickness of 40 nm. The different values of the applied magnetic field in different portions across the loop are marked in the figure with dots.

Engineering Magnetic Vortices for Multi-Bit Information Storage



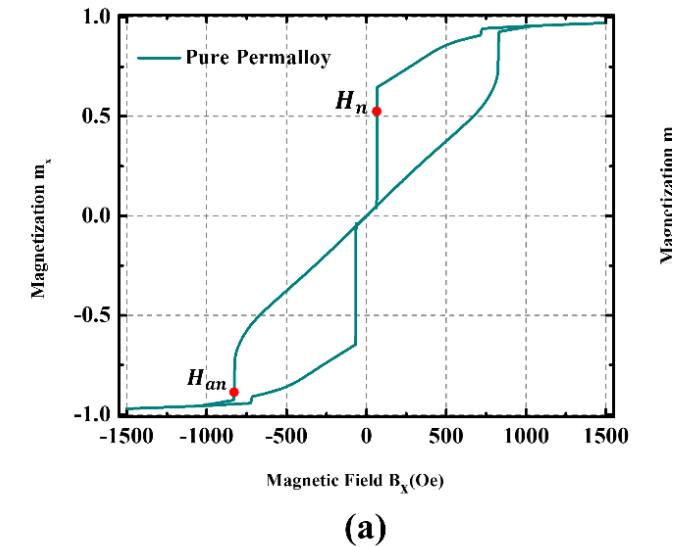
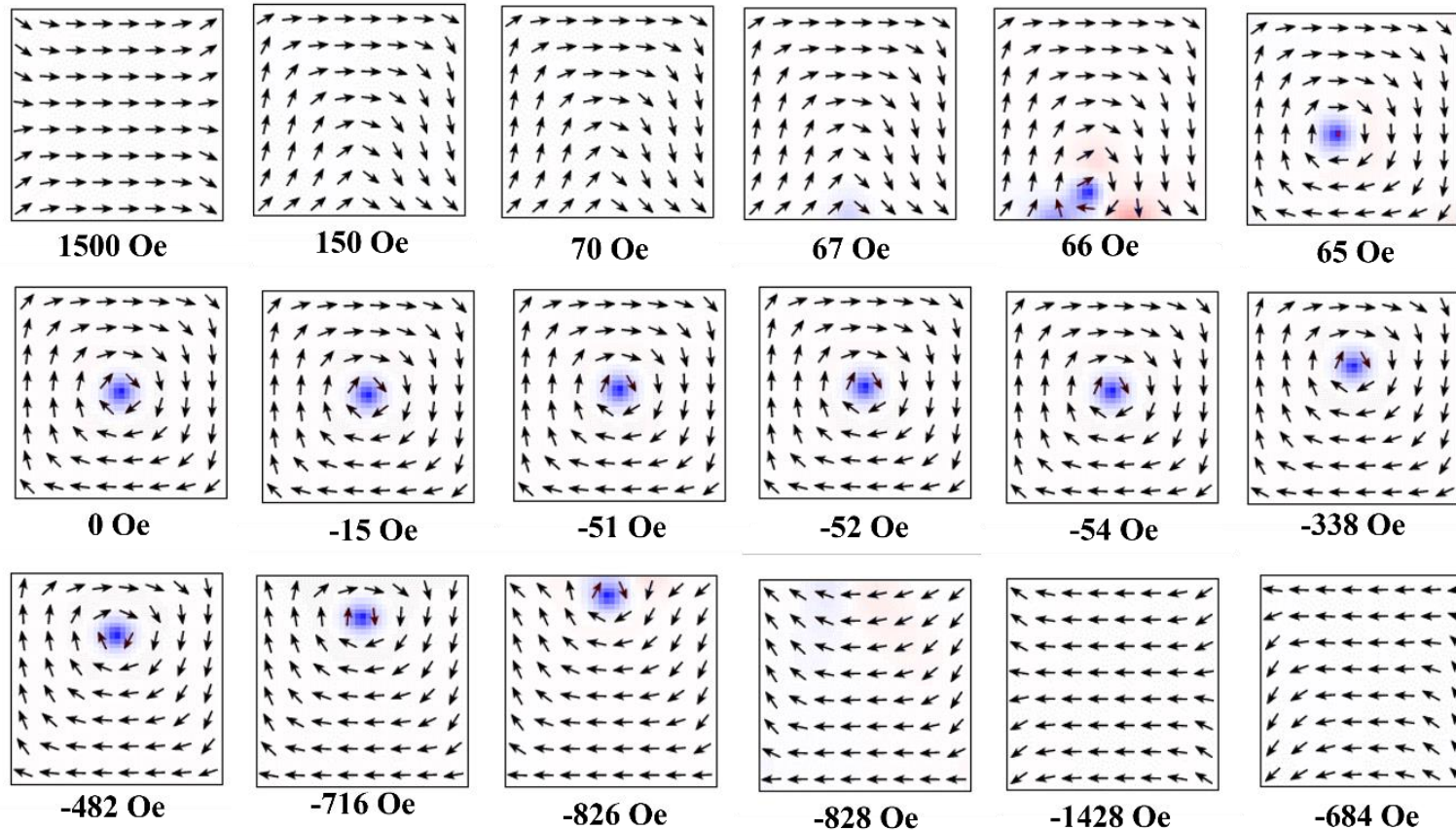
(a)



(b)

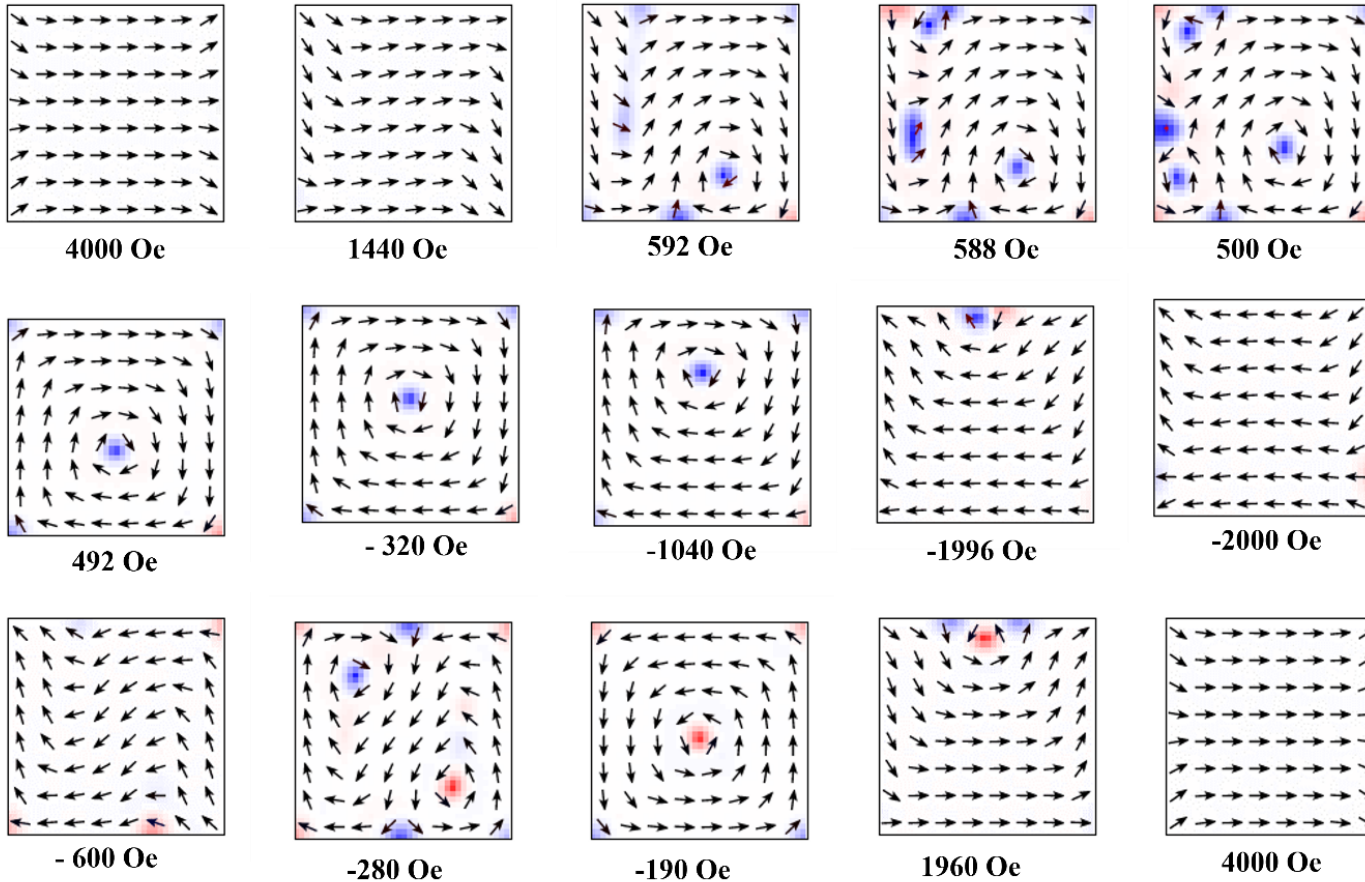
Hysteresis loop of pure square-shaped (a) Py nanodot and (b) Fe nanodot. The nucleation field (H_n) and the annihilation field (H_{an}) are denoted in the figure.

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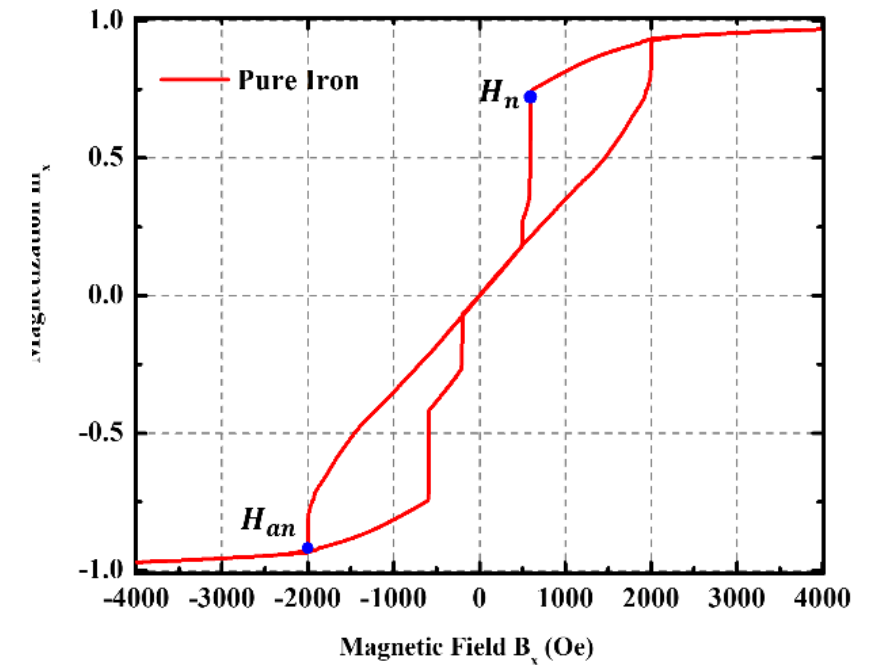


Micromagnetic spin configuration of the pure Py nanodot having dimensions of $200 \text{ nm} \times 200 \text{ nm} \times 40 \text{ nm}$ at different static applied magnetic fields along the x-direction

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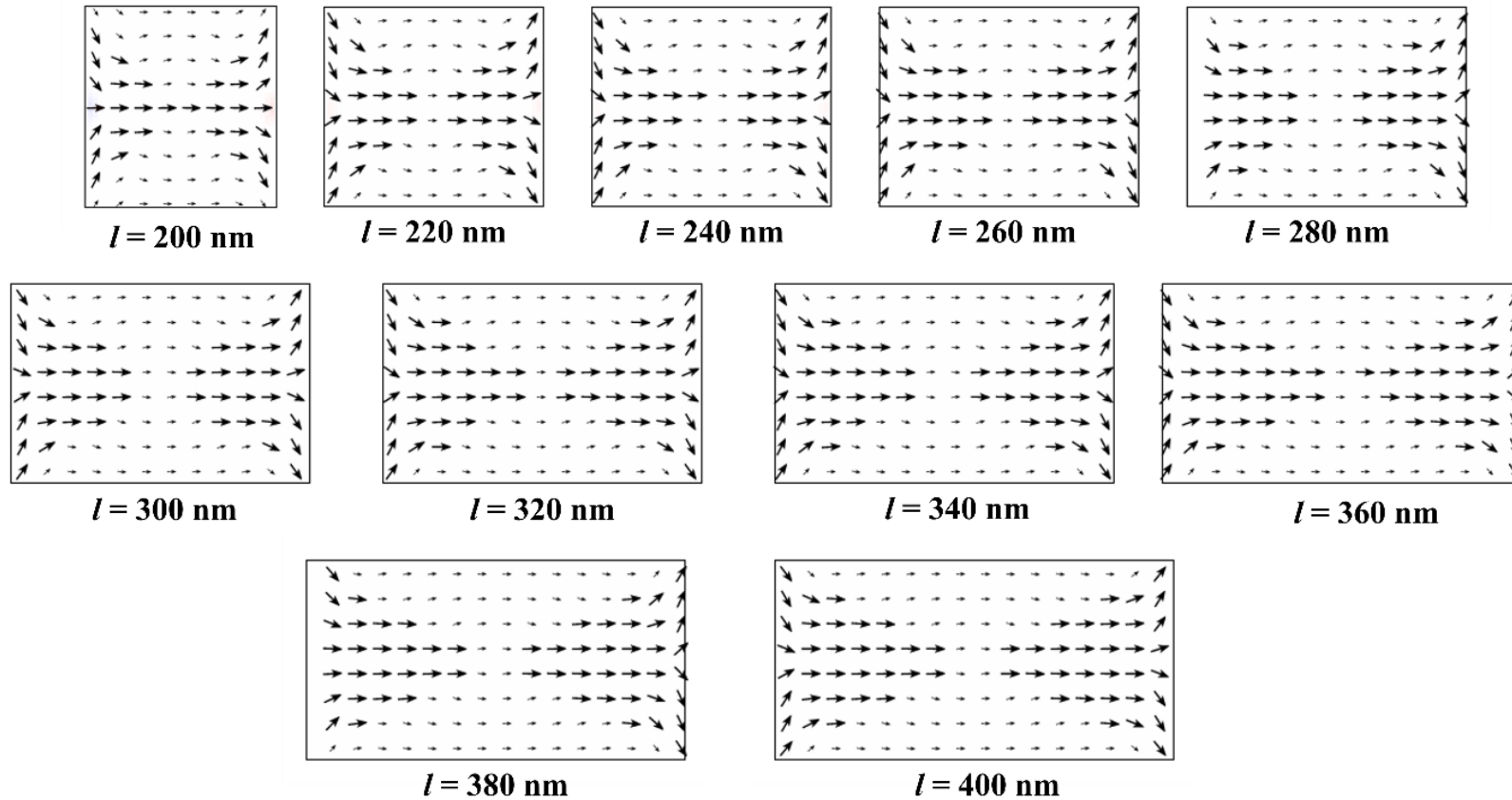


Micromagnetic spin configuration of the pure Fe nanodot having dimensions of $200 \text{ nm} \times 200 \text{ nm} \times 40 \text{ nm}$ at different static applied magnetic fields along the x -direction.



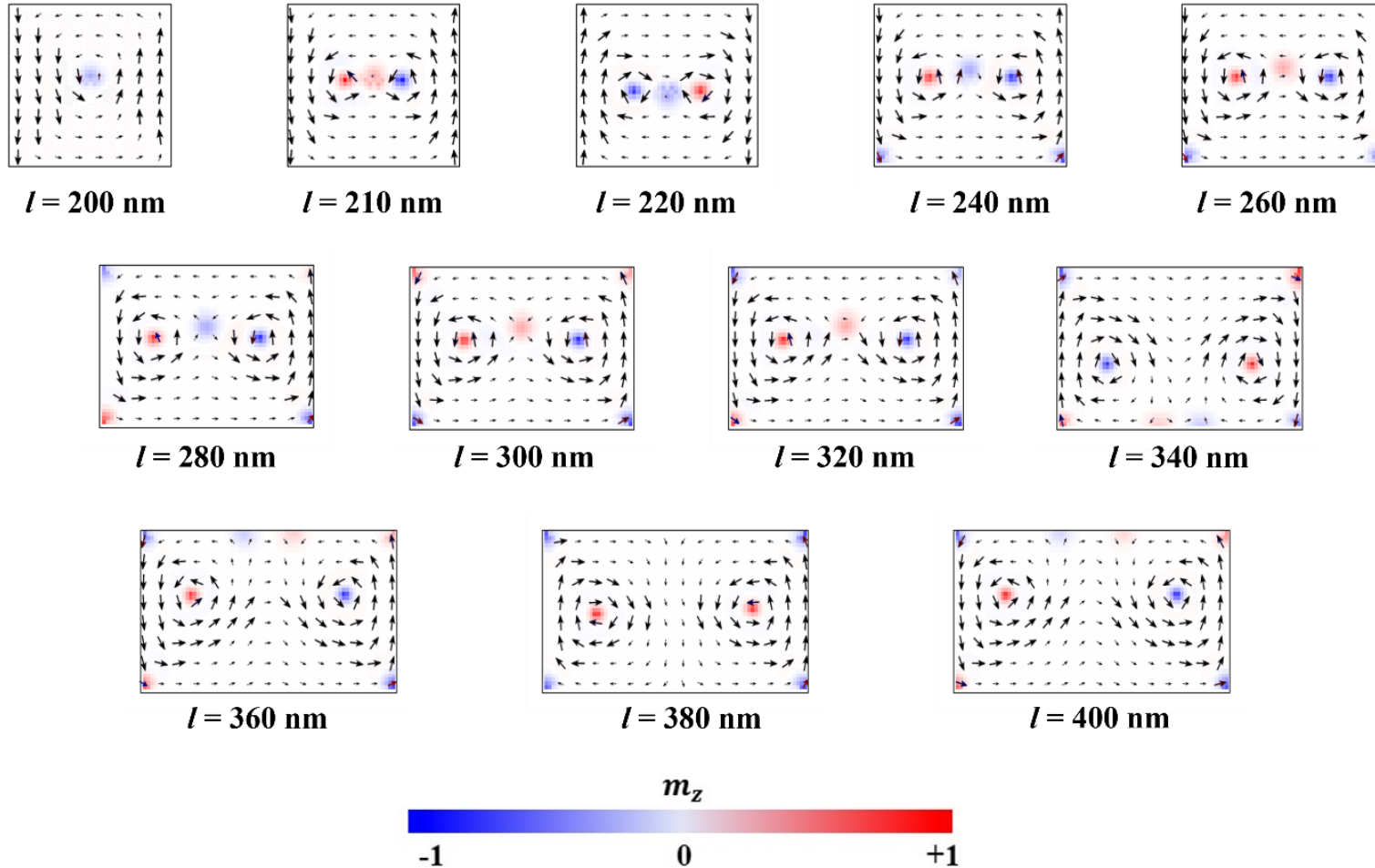
(b)

Engineering Magnetic Vortices for Multi-Bit Information Storage



Magnetic spin configuration of the considered bow-tie structure at the positive saturation state with varying lengths ($l = 200 \text{ nm} - 400 \text{ nm}$).

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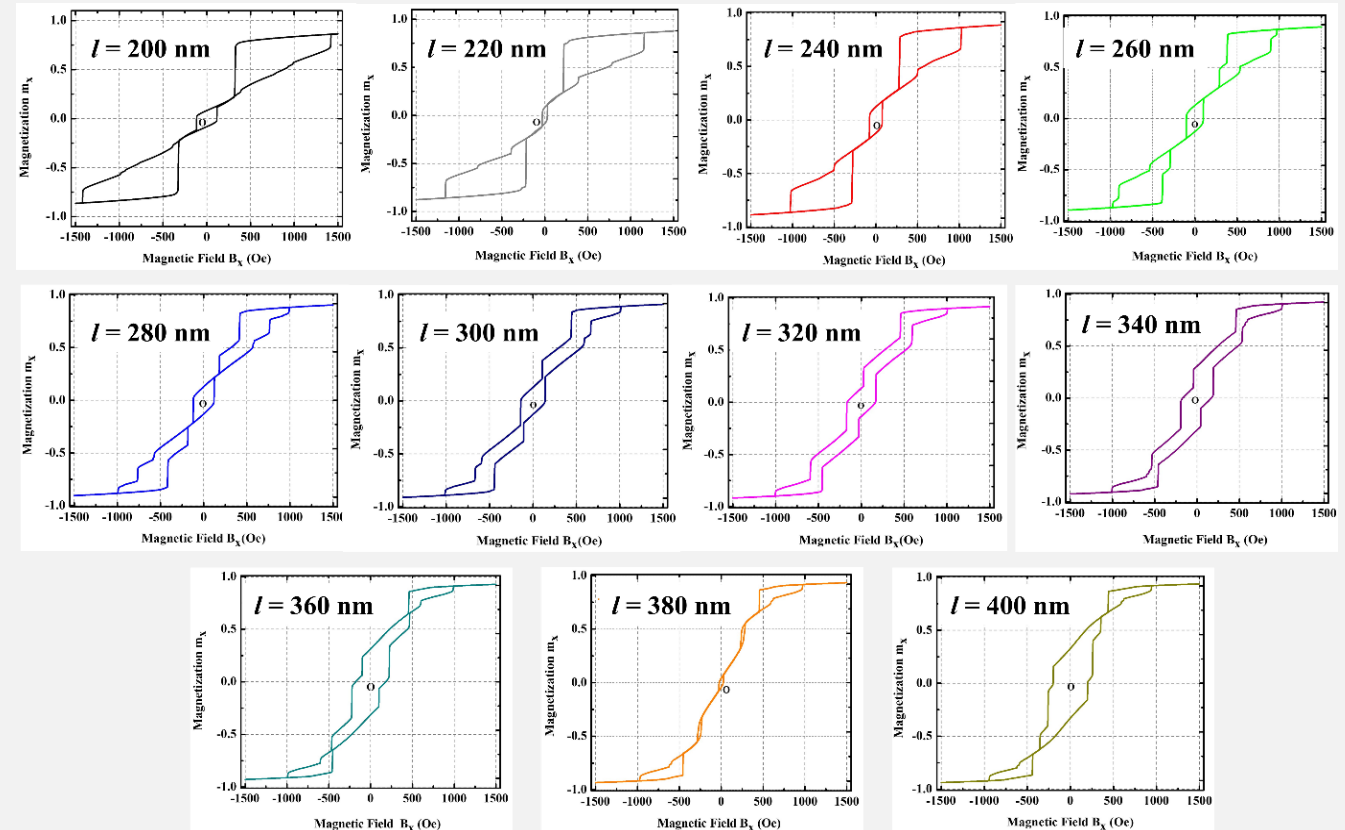


Equilibrium magnetic spin configuration (i.e., at remanence $H = 0$) along the descending branch of the hysteresis in a bi-component bow-tie structure with dimensions along the x-axis ranging from 200 nm to 400 nm.

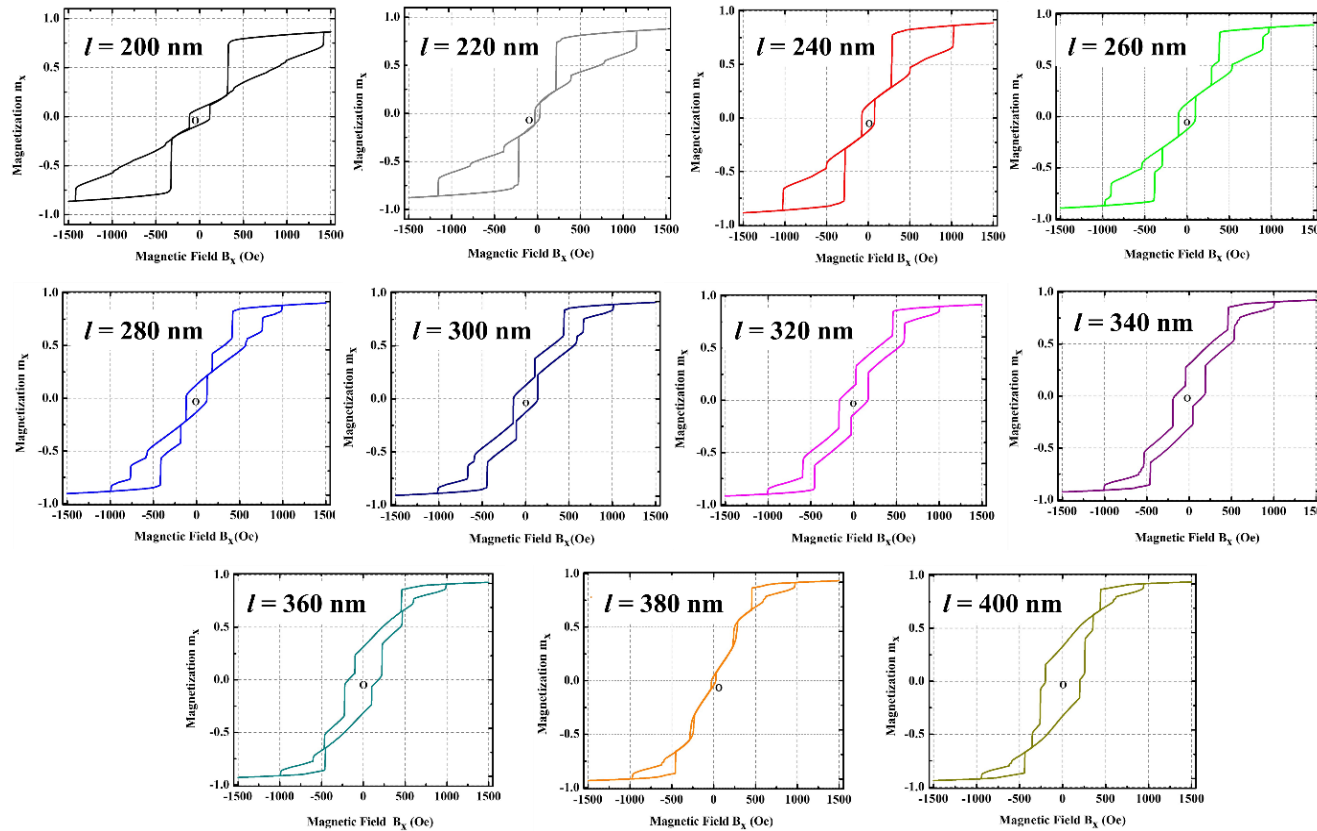
Engineering Magnetic Vortices for Multi-Bit Information Storage

- For shorter structures (200–240 nm), the hysteresis loops are nearly square, indicating coherent-like reversal with high remanence. With increasing length (260–320 nm), the loops evolve into a wasp-waisted shape with intermediate plateaus, reflecting vortex nucleation and annihilation during magnetization reversal.
- The appearance of a wasp-waisted configuration in the intermediate-length structures signifies a transition zone where magnetization reversal occurs via a combination of coherent rotation and vortex nucleation–annihilation processes.
- Showing the coexistence of ‘hard’ and ‘soft’ magnetic behaviors within the Fe–Py bow-tie structure.

Simulated x-axis magnetic hysteresis loops of the bow-tie structure with varying length

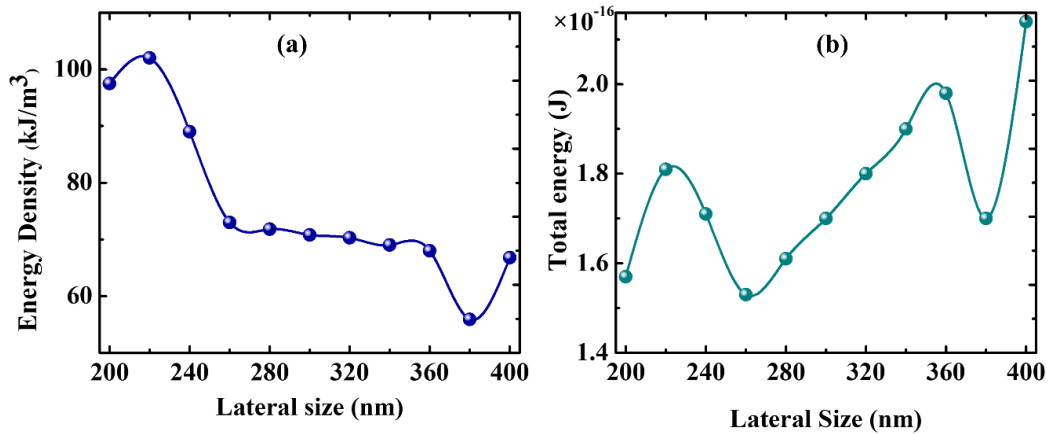


Engineering Magnetic Vortices for Multi-Bit Information Storage



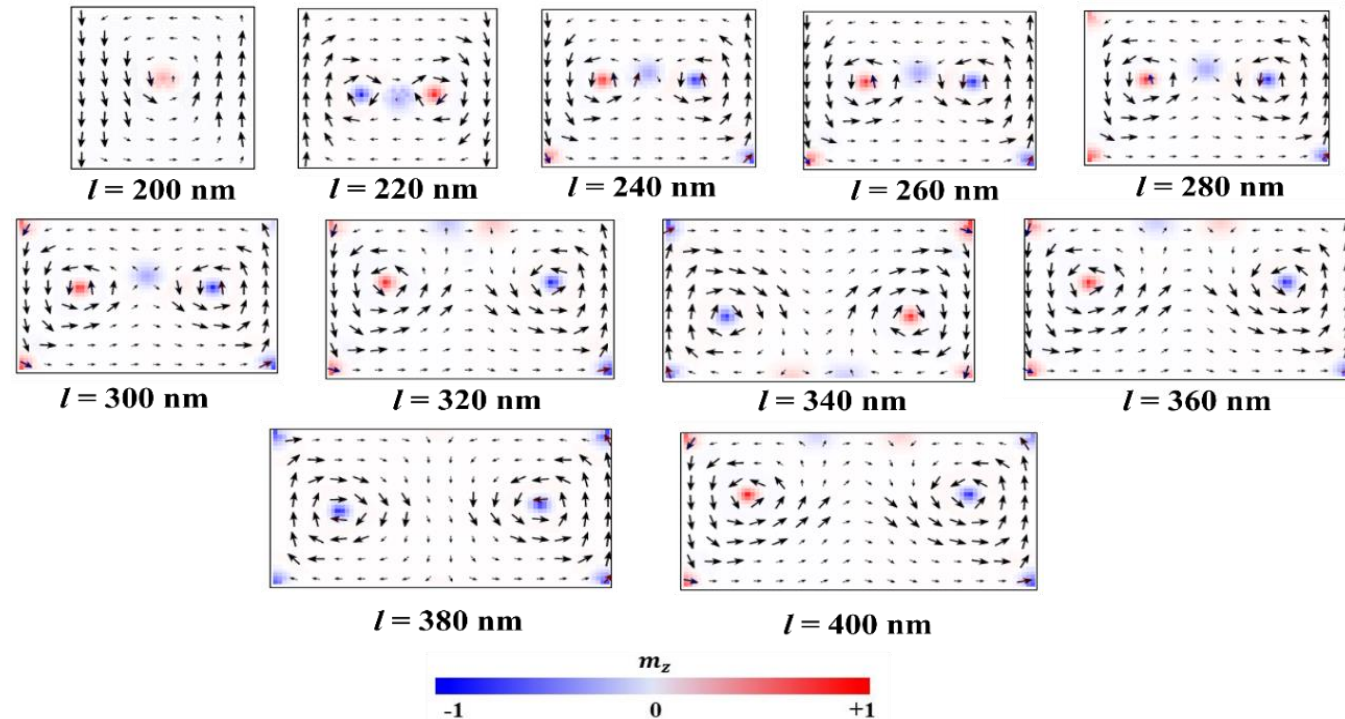
A decrease in coercivity and remanence as length increases, aligning with the shift from uniform to vortex-mediated reversal processes influenced by shape anisotropy and Fe–Py exchange coupling.

Engineering Magnetic Vortices for Multi-Bit Information Storage



Variation of (a) energy density and (b) total energy of different samples with lateral dimensions

- Show a dip when the **lateral size of the sample is 380 nm**; this is analogous to the behaviour of a Bloch domain wall, which alters the magnetization direction by orienting out of plane.
- The need to minimize the overall energy is what causes unconventional vortices to develop on the surface area.

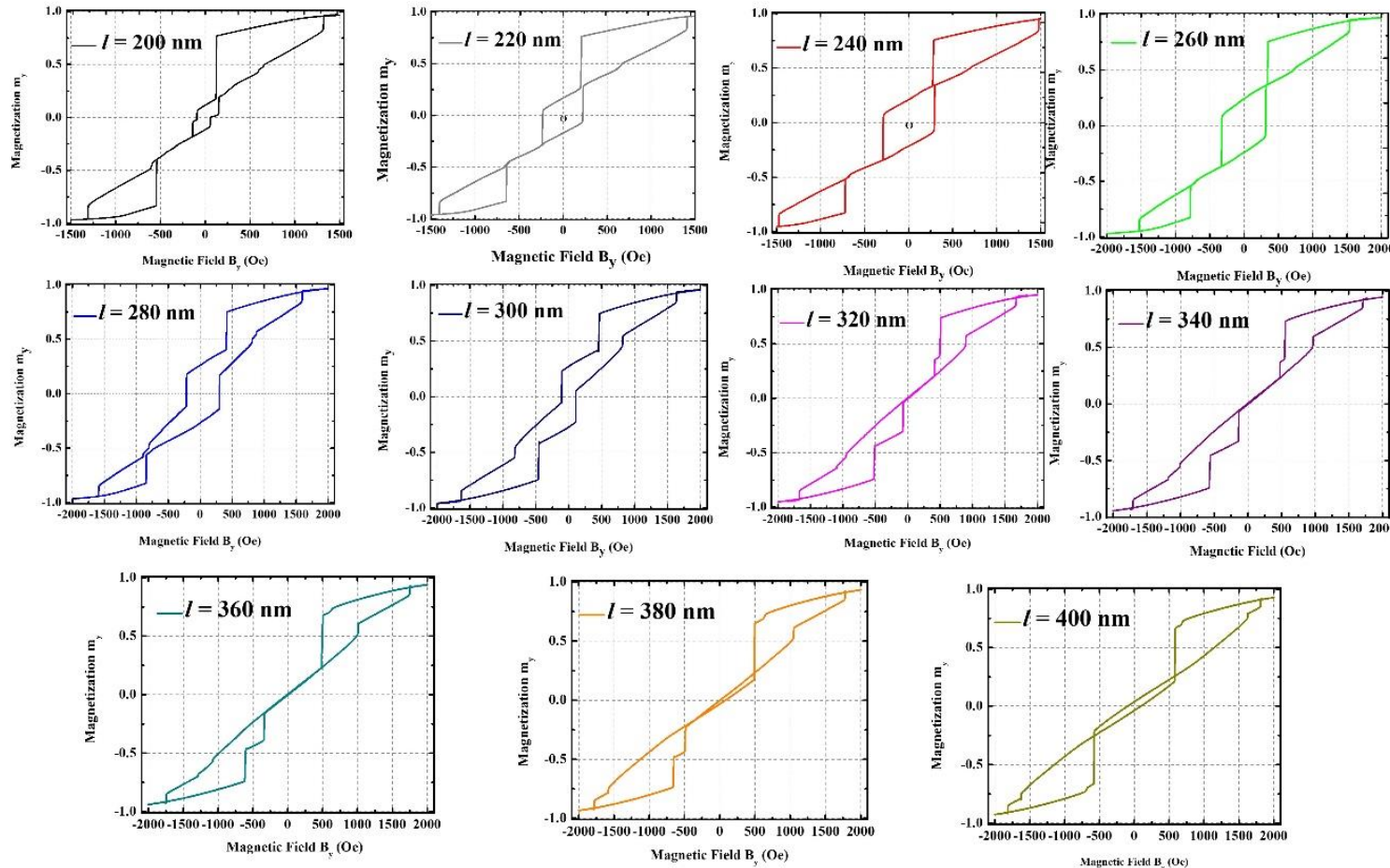


Equilibrium magnetic spin configuration at $H=0$

A **3-bit vortex-based random access memory** can be constructed with these three distinct degrees of freedom in each structure.

Madhurima Sen, Payal Bhattacharjee, and Saswati Barman. "Multi-bit magnetic recording with magnetic vortices in a bi-component bow-tie structure." *Current Applied Physics* (2026).

Engineering Magnetic Vortices for Multi-Bit Information Storage



“When the field is applied transverse to the bow-tie axis, the reversal becomes smoother and vortex-core motion dominates; increasing the lateral dimension progressively stabilizes the vortex states, eventually allowing a stable two-vortex state at remanence.”

field orientation itself is a control parameter for the number and stability of information-bearing vortex states.

Simulated y-axis magnetic hysteresis loops of the bow-tie structure with varying length.

Engineering Magnetic Vortices for Multi-Bit Information Storage

Key Messages

1. **Geometry controls the magnetic state:**
Increasing the bow-tie length drives a transition from a **single-vortex to a stable multi-vortex state**, demonstrating strong geometrical control of spin texture.
2. **Field direction controls vortex dynamics:**
 H_x and H_y produce distinctly different reversal mechanisms; the transverse H_y field gives **smoother, more reversible vortex-core motion**, with vortex stability increasing with size.
3. **Fe–Py interface governs nucleation and annihilation:**
Exchange and magnetostatic interactions at the **Fe–Py interface** determine vortex nucleation, propagation, pinning and annihilation, producing complex multi-vortex states.
4. **Multiple vortex degrees of freedom enable multi-bit storage:**
Controllable **vortex number, polarity, chirality and vortex–antivortex configurations** provide multiple distinguishable magnetic states, suggesting a route toward **multi-bit magnetic memory and spin logic**.

“By engineering geometry, material interface and field orientation, we can control multiple magnetic vortex states within a single Fe–Py nanostructure, opening a pathway toward multi-bit magnetic recording.”

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics

- The hysteresis behavior is strongly influenced by the sequence and magnitude of the applied magnetic field
- A prescribed field order enables controlled vortex nucleation and annihilation.
- This highlights the possibility that magnetization dynamics may depend not only on field strength but also on the temporal history of field application.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics

Apply exactly the same magnetic-field pulses to a magnetic nanostructure, but change only their temporal order, will the system produce the same response?

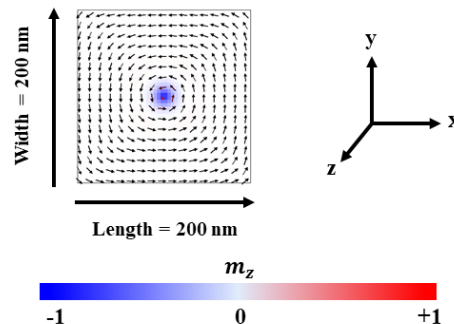
At first sight, one might expect that if the field magnitudes, pulse durations, and overall excitation are the same, the final response should be essentially similar.

But nonlinear magnetic systems do not always behave in this way.

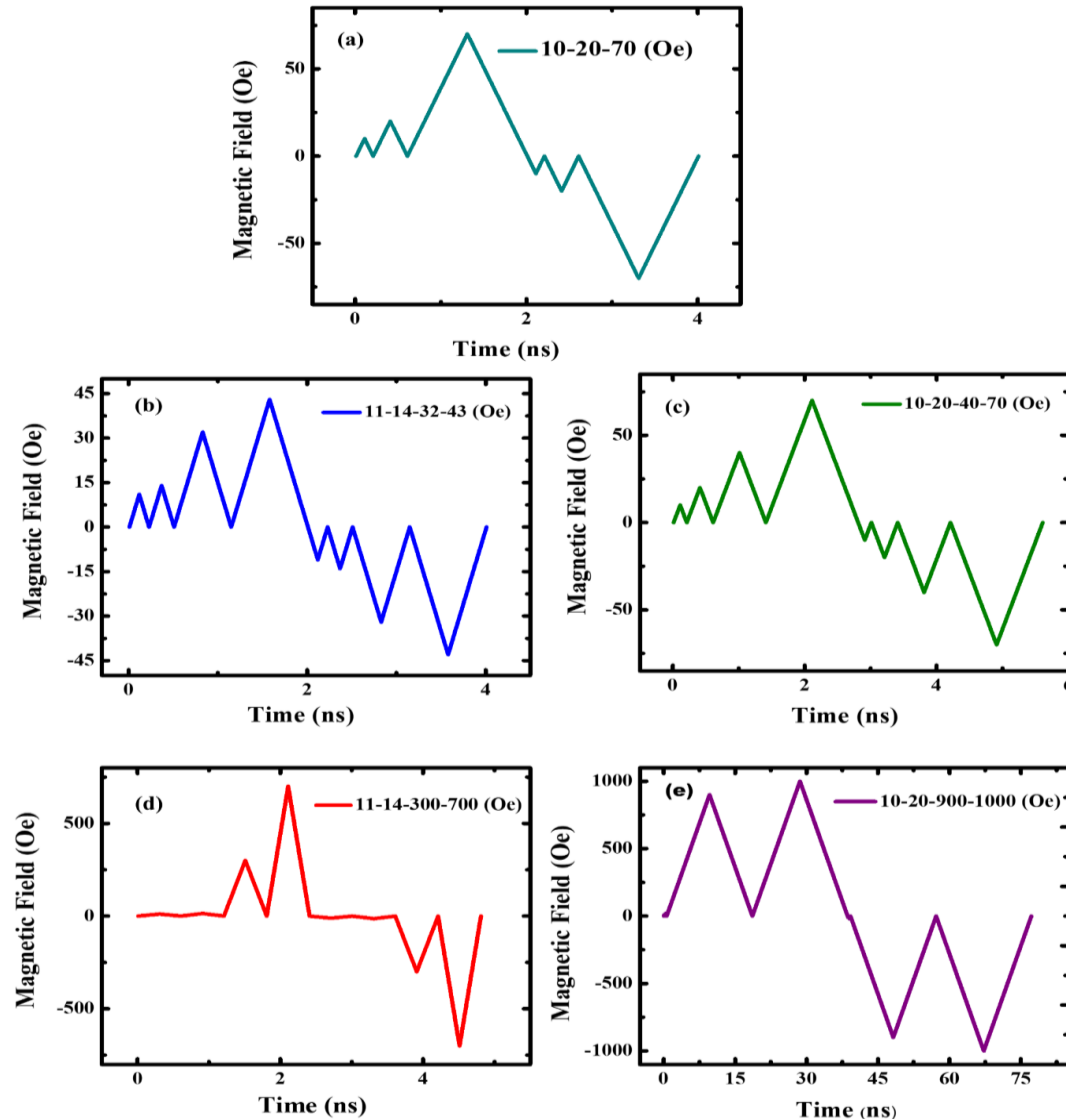
We show that the **order in which magnetic-field pulses are applied** can become an information-bearing parameter.

In other words, **the magnetic system does not respond only to *what stimulus is applied*, but also to *when and in what sequence the stimulus is applied*.**

And this gives us a very **interesting possibility: a magnetic vortex can potentially act not simply as a switching element, but as a physical system capable of recognizing and processing temporal patterns.**



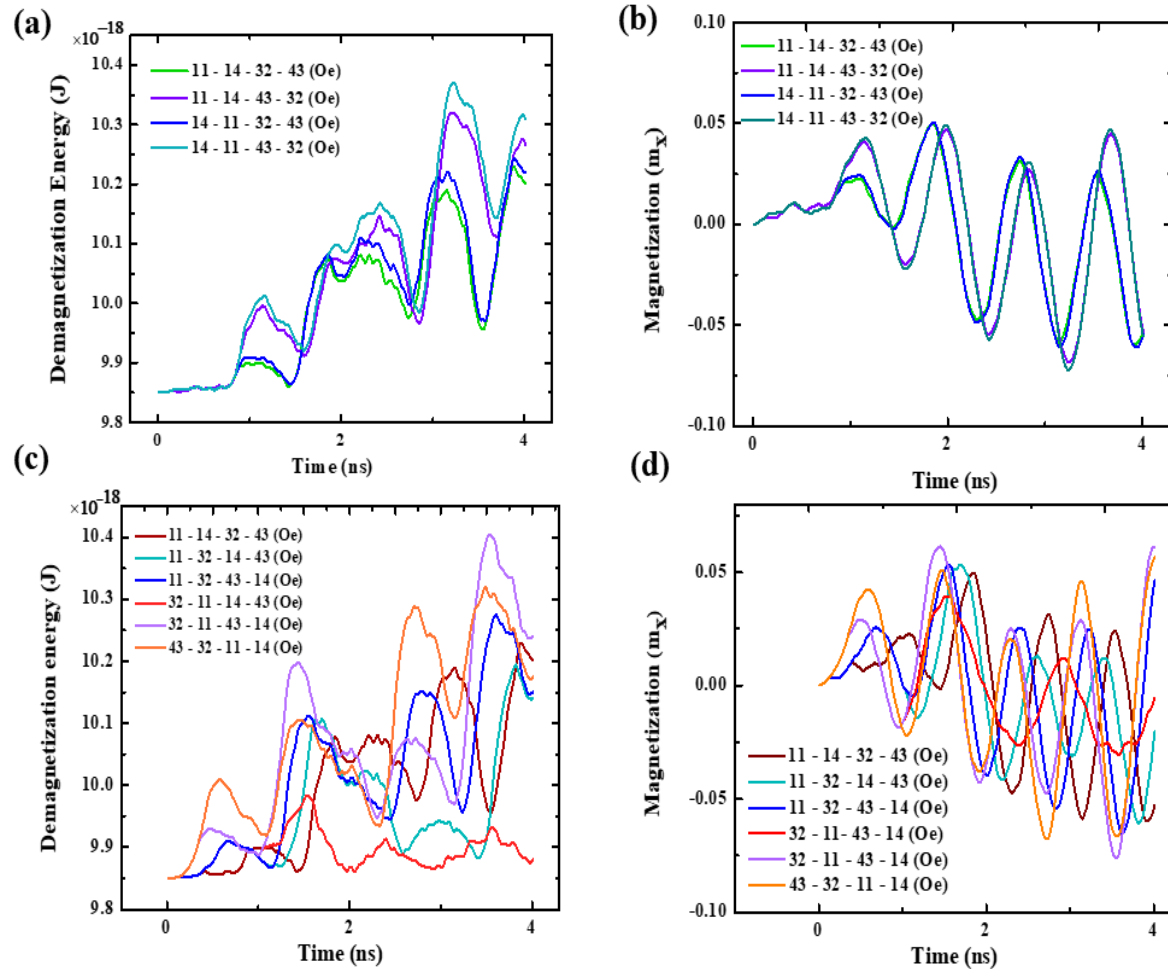
Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



The time-varying applied magnetic field to the permalloy structure (a) No-Switching three step magnetic pulse sequences 10-20-70 (Oe), (b) No-Switching four magnetic pulse sequence 11-14-32-43 (Oe), No switching four magnetic pulse sequence 10-20-40-70(Oe), (d) Polarity Switching four step magnetic pulse sequence 11-14-300-700(Oe) and (e) Chirality switching four step magnetic pulse sequence 10-20-900-1000 (Oe).

8 different permuted field pulse sequences 10-20- 70 (Oe) and **24 different permuted field pulse sequences** of 11-14-32-43 (Oe), 10-20-40-70 (Oe), 11-14-300-700 (Oe), and 10-20-900-1000(Oe) are studied

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



(a) Demagnetization energy vs. time plot for all possible sequences of pattern 0-0-1-1 for field sequence 11-14-32-43 (Oe), (b) Magnetization vs. time plot for all possible sequences of pattern 0-0-1-1, (c) Demagnetization energy vs. time plot for all patterns with one distinct sequence from each pattern, (d) Magnetization vs. time plot for all patterns with one distinct sequence from each pattern.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics

For the four-pulse sequences, **the lower field values were represented by zero and the higher field values by one.**

The different permutations to be classified into **six broad binary patterns:**

00-11,
01-01,
01-10,
10-01,
10-10,
and 11-00.

Pearson correlation coefficient, the `corr()` of the Pandas Python library is used to calculate the pairwise correlation among the time-varying magnetizations.

How can we quantify this sequence sensitivity?

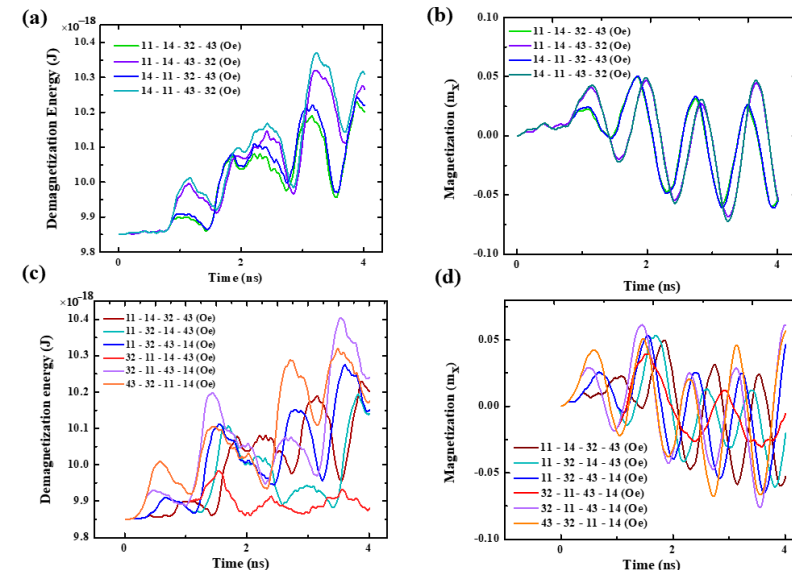
For this purpose, we used the **Pearson correlation coefficient**.

Sequences belonging to the **same pattern** could produce remarkably similar magnetization and energy profiles, even though their individual temporal ordering was different.

On the other hand, sequences belonging to **different patterns** produced distinctly different dynamical responses.

So the system was not simply responding to the average or total field.

It was responding to the **structure of the temporal stimulus**.



Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics

Pearson correlation coefficient

If two magnetic-field sequences produce very **similar time-dependent magnetization trajectories**, their correlation will be high.

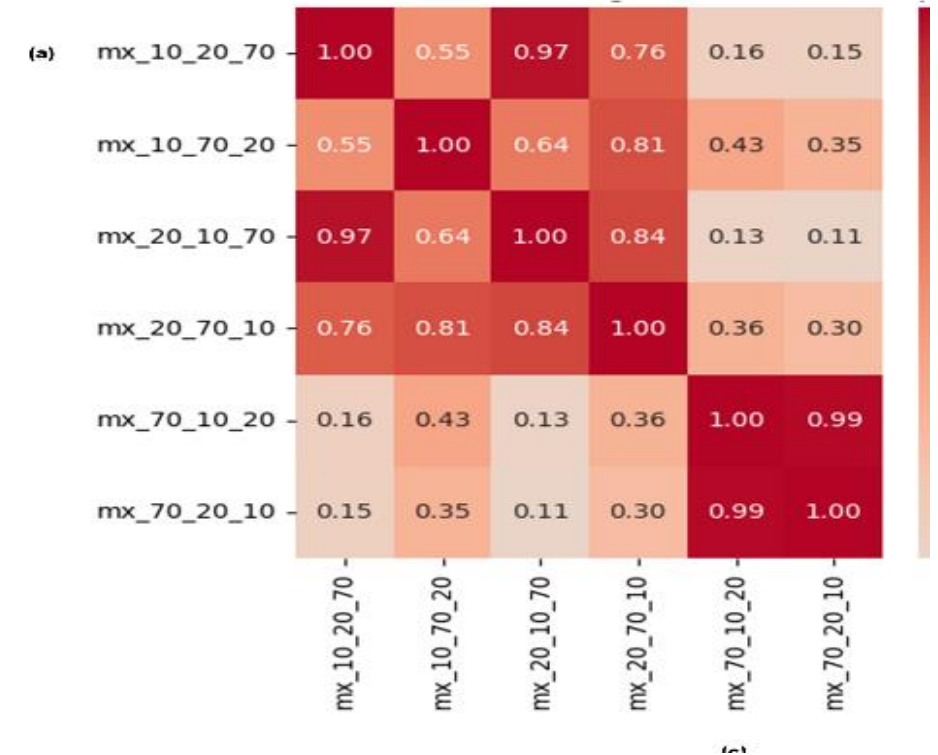
If their **trajectories are very different**, the correlation will decrease.

Responses are sufficiently different or oppositely related, negative correlations.

Pairwise correlation among the magnetization dynamics generated by the different permutations.

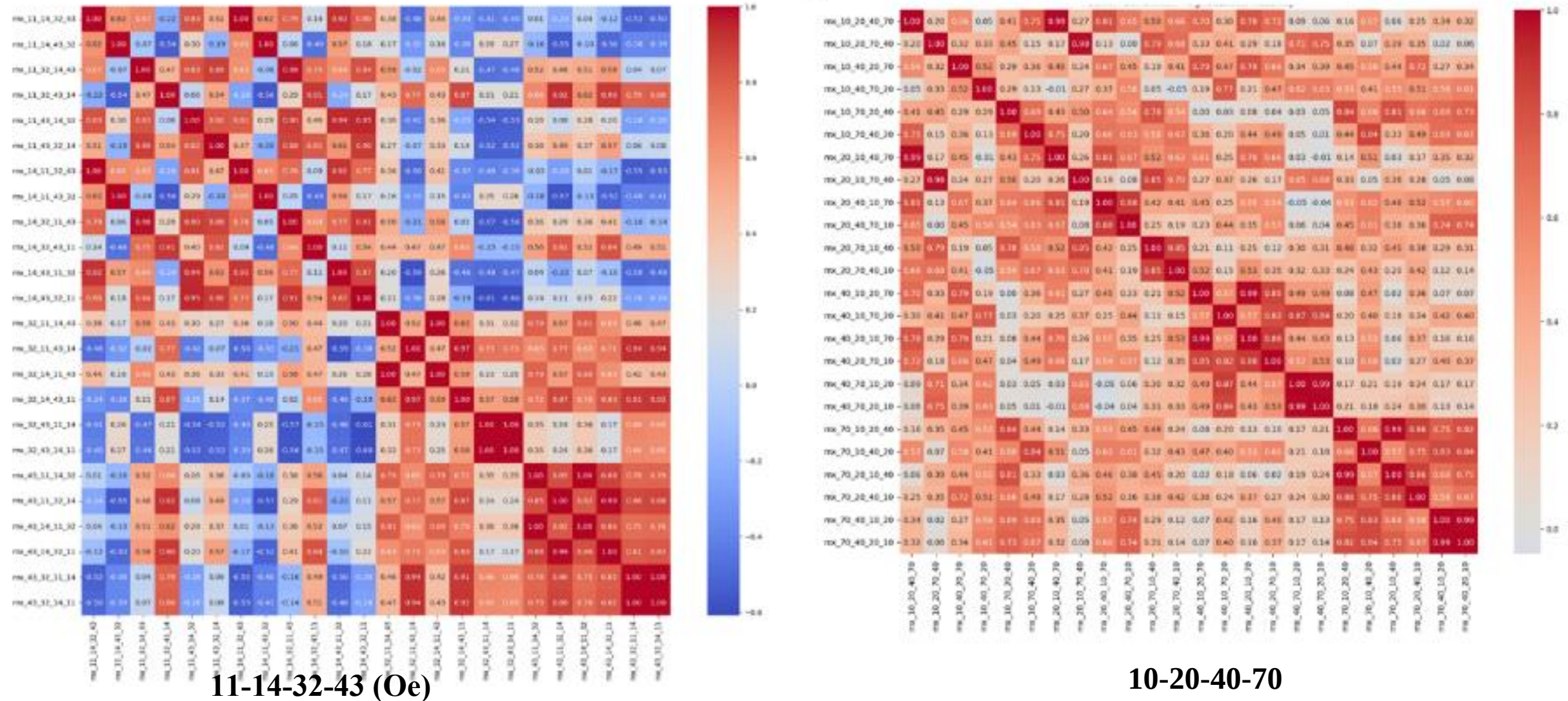
Correlation maps revealed both positive and negative correlations between sequences having exactly the same set of field magnitudes but different temporal orderings.

This is important because it tells us that the vortex is behaving as a **dynamical discriminator**.



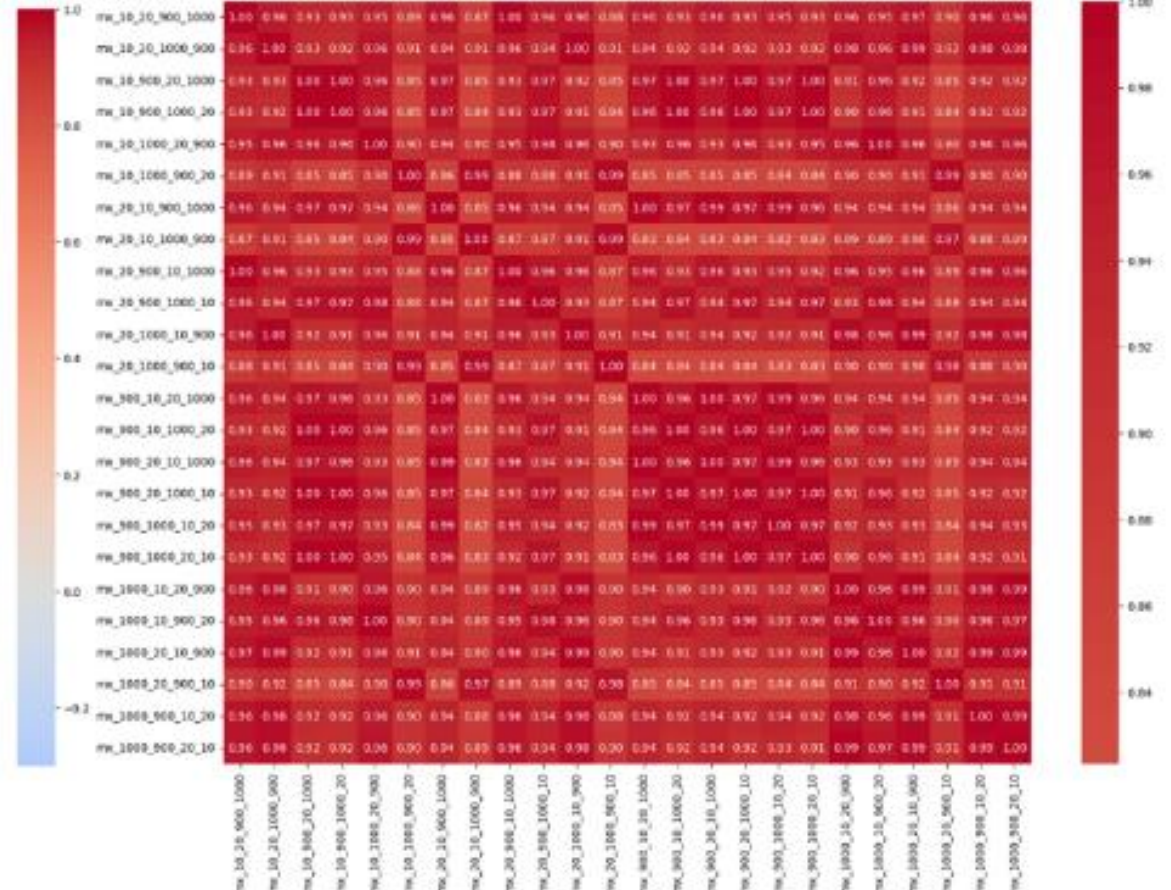
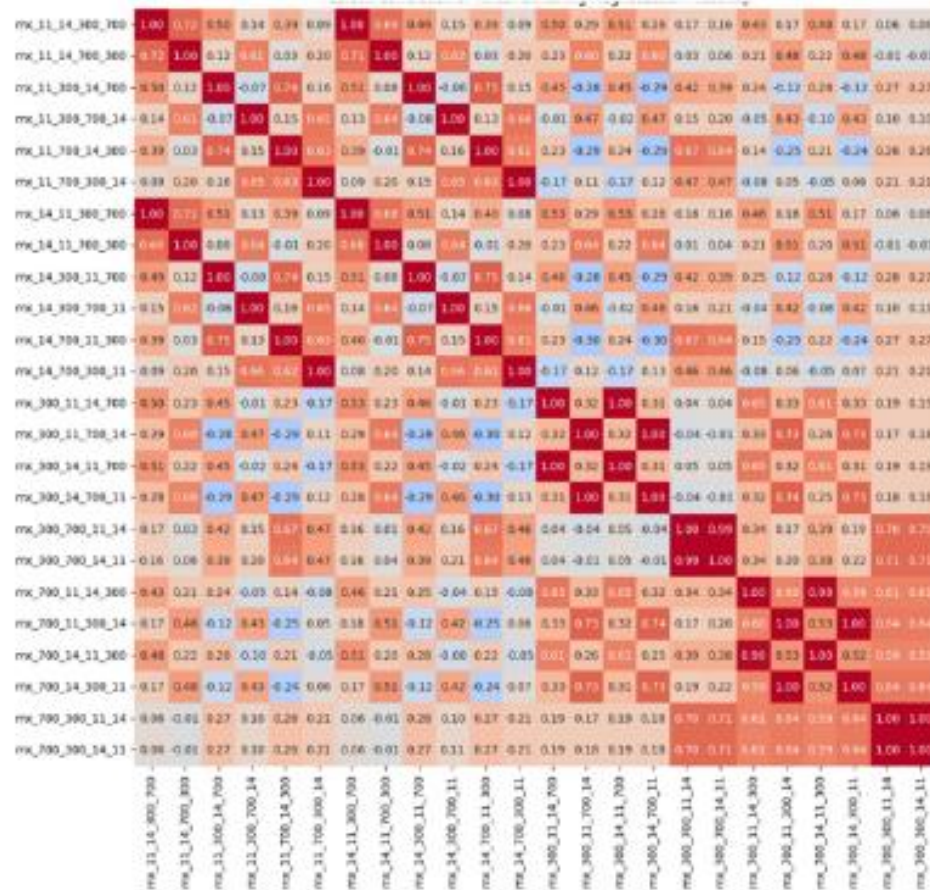
Pearson correlation coefficient, the `corr()` of the Pandas Python library is used to calculate the pairwise correlation among the time-varying magnetizations.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



Pearson Correlation of Magnetization Heatmap

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



11-14-300-700 (Oe), and 10-20-900-1000 (Oe).

Pearson Correlation of Magnetization Heatmap

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics

One step further

Treating each sequence as an isolated input

Question : The sequences could be related through a logical or mathematical structure?

The field sequences using binary encoding.

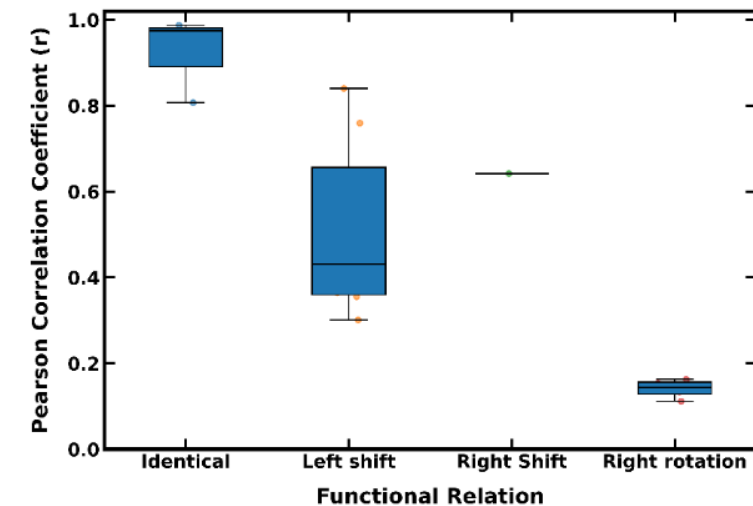
For the four-pulse sequences, **six distinct binary patterns and examined eleven functional relationships between them.**

Eleven functional (logical) relationships: **differences by one, two, four and seven, one's complement, two's complement, left and right shifts, and left and right rotations.**

Functional relations are determined by the corresponding values of the 8-4-2-1 code mapping of these patterns.

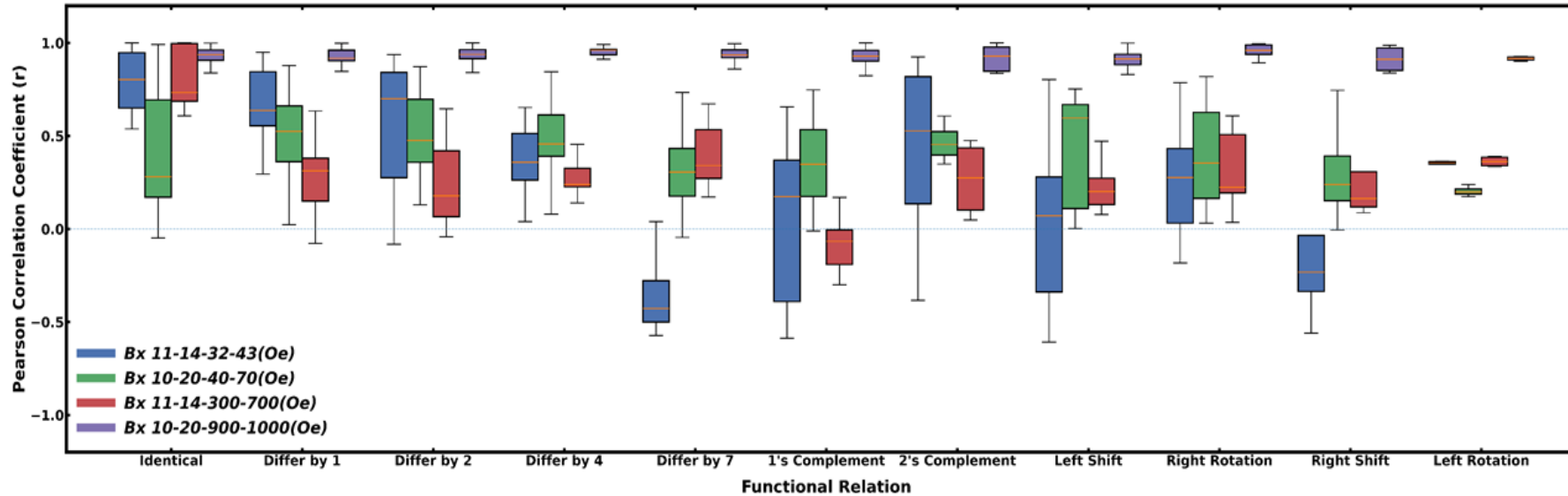
By **analyzing the correlation coefficients through these functional relationships**, a **logical framework** was established for understanding why certain sequence pairs exhibit stronger or weaker correlations in their dynamical responses.

The functional relationships established between pattern pairs are **inherently non-commutative** in nature.



Magnetic pulse sequence 10-20-70 (Oe).

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



Field Sequence B_x (Oe)	Field Sequence B_x (Oe)	Pearson Correlation
0 1 1 0 10 70 40 20	Left shift by 1 bit 1 1 0 0 40 70 20 10	0.008272639
0 0 1 1 10 20 70 40	Left shift by 1 bit 0 1 1 0 20 40 70 10	0.002496827
0 1 0 1 10 70 20 40	difference of 4 1 0 0 1 40 10 20 70	0.001322897
0 1 1 0 10 40 70 20	Right shift by 1 bit 0 0 1 1 20 10 40 70	-0.005245788
0 0 1 1 20 10 40 70	1's complement 1 1 0 0 40 70 20 10	-0.010273702
0 1 0 1 20 40 10 70	Difference 7 1 1 0 0 40 70 20 10	-0.037937747
0 1 0 1 20 40 10 70	Difference 7 1 1 0 0 40 70 10 20	-0.045273533
0 1 1 0 10 40 70 20	Identical 0 1 1 0 20 70 40 10	-0.048330431

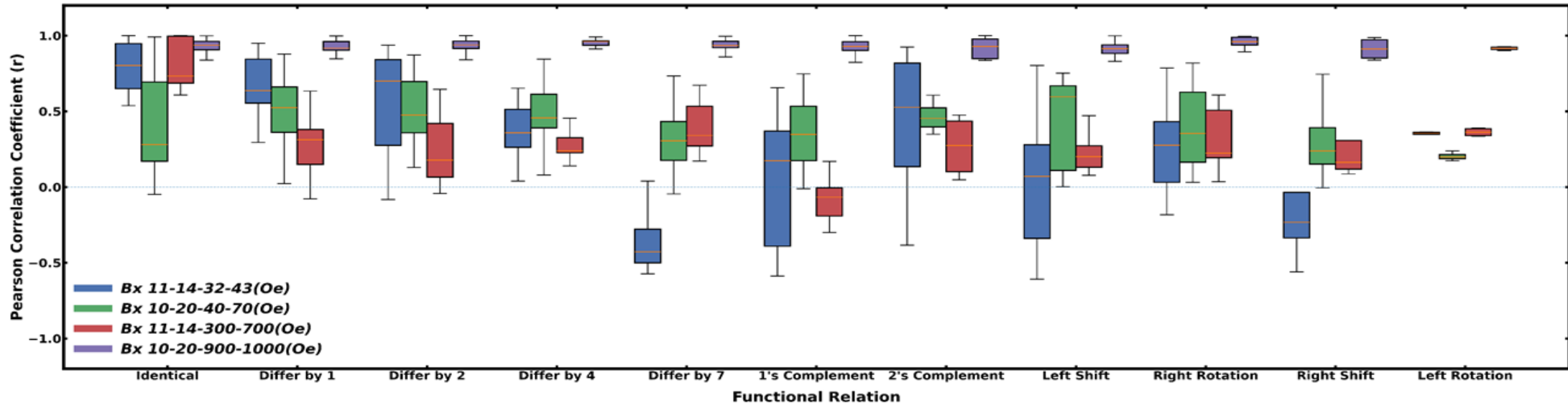
Sample Data

Boxplot of the functional relation vs. Pearson correlation coefficient among all 4-step magnetic pulse sequences

May open the pathway for

- Hardware for unconventional computing architecture
- Pattern recognition,
- Sequence classification,
- Neuromorphic computing.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



➤ Pulse sequence matters

The vortex response depends not only on the magnitude of the magnetic field but also on the **temporal ordering of the four pulses**.

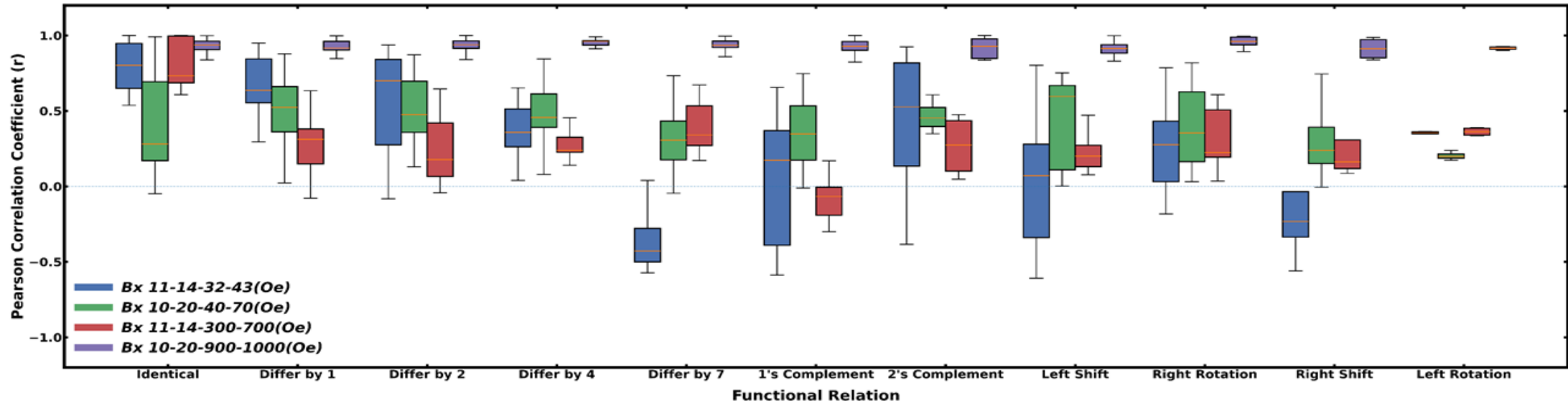
➤ Same pulses can produce different dynamics

Different permutations of the same four field magnitudes generate **different magnetization trajectories and correlation responses**.

➤ 8421 binary coding enables pattern comparison

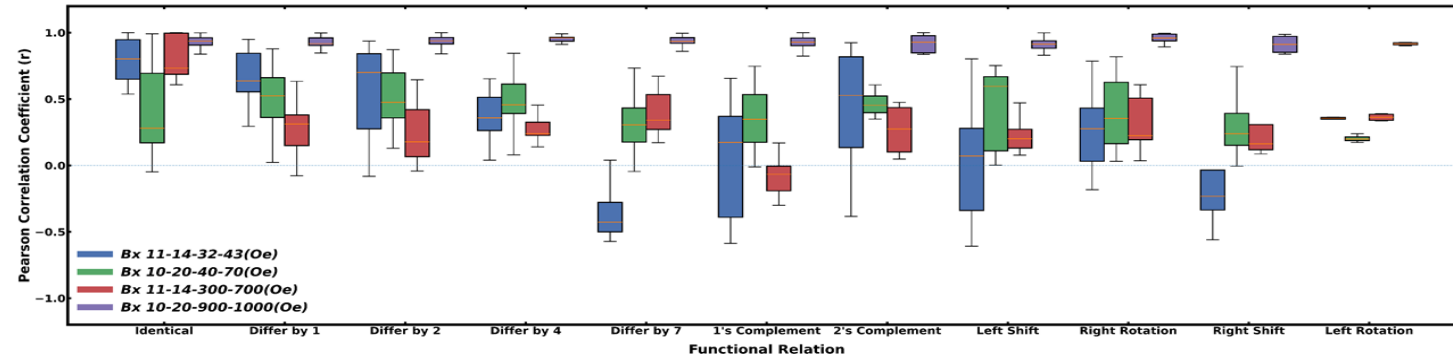
The four-pulse sequences are represented as binary patterns, allowing systematic relationships between patterns to be identified.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



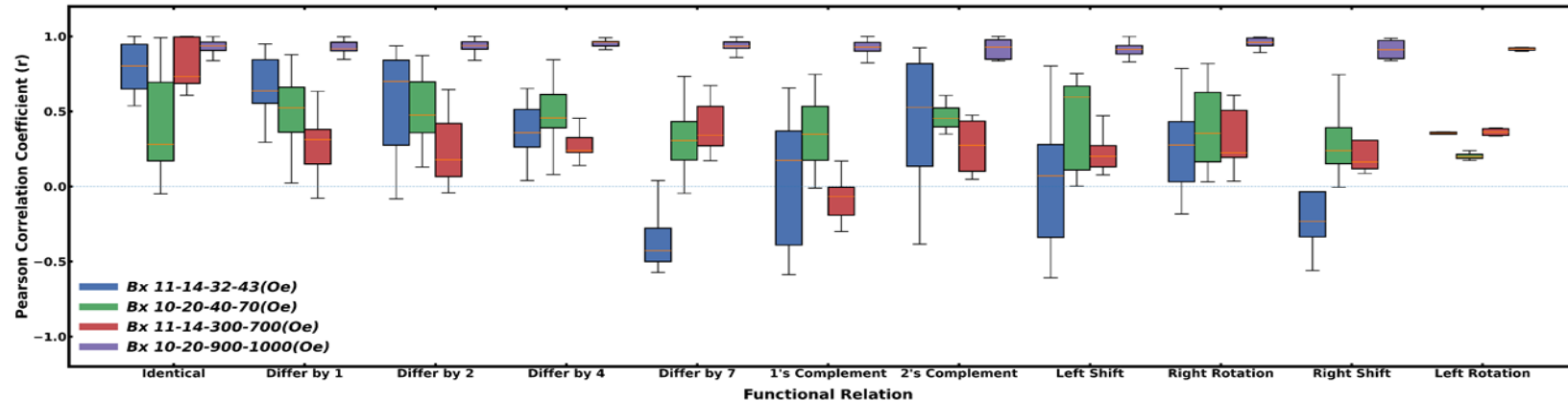
- **Different functional relationships produce different correlations**
Relationships such as **identical**, **differ by 1, 2, 4, 7**, **complement**, **shift**, and **rotation** result in different Pearson-correlation distributions.
- **Some relationships consistently produce strong similarity**
The **“differ by 4”** and **“left rotation”** relationships show the **highest positive correlations** across the investigated pulse systems.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



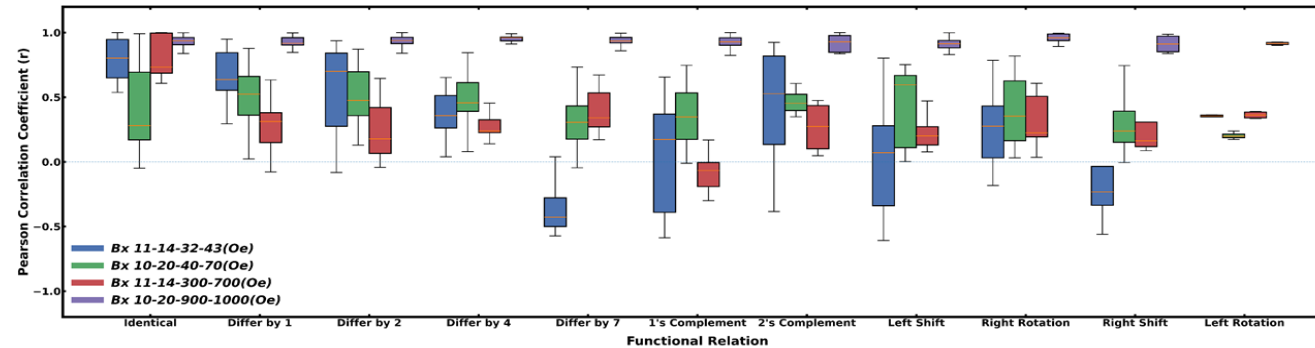
- **Some relationships strongly distinguish the patterns**
For **11–14–32–43 Oe**, the “**differ by 7**” and “**right shift**” relationships show distinct negative correlations, indicating strong pattern sensitivity.
- **Pulse magnitude influences sequence sensitivity**
For the “**differ by 1**” relationship, increasing pulse magnitude causes the correlation distribution to shift toward **lower correlation values**.
- **Switching makes the dynamics more distinct**
The transition from the **non-switching regime to polarity switching** is accompanied by increasingly dissimilar dynamical responses.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



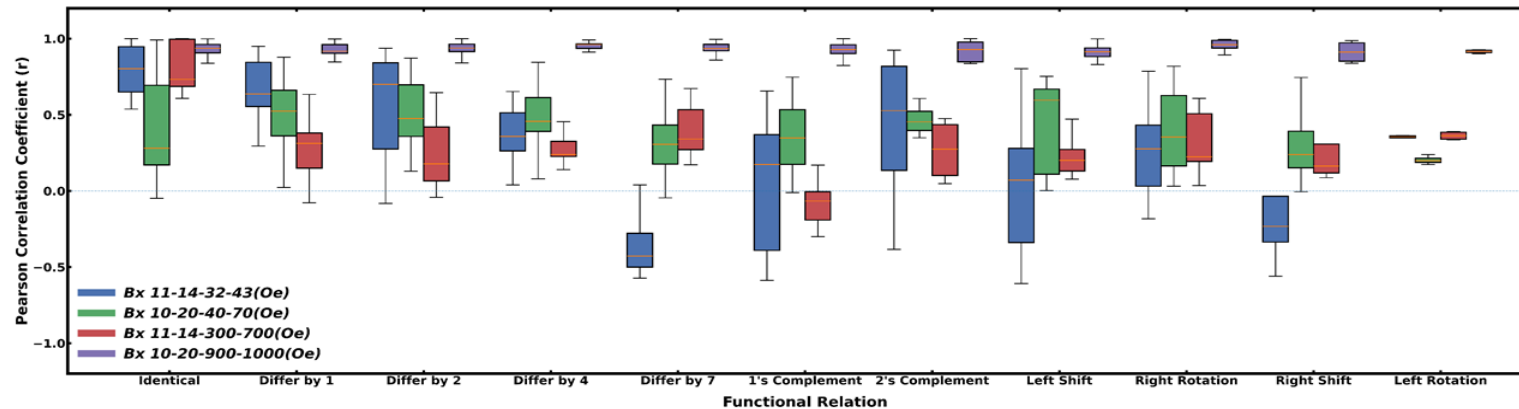
- **Different pulse systems exhibit different variability**
 - **10–20–900–1000 Oe:** narrowest distribution and lowest variability.
 - **10–20–40–70 Oe:** mostly positive and tightly clustered correlations.
 - **11–14–32–43 Oe:** wider distribution and pronounced negative correlations.
 - **11–14–300–700 Oe:** relatively tight but strongly pattern-dependent correlations.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



- **Complementary patterns can behave differently**
Patterns such as **1010** and **0101**, although containing the same number of 0s and 1s, can generate **different magnetization profiles**. Thus, the system is sensitive to **pattern ordering**, not simply pulse composition.
- **Polarity switching is sequence-dependent**
In the **11–14–300–700 Oe** system, particular pulse arrangements produce polarity switching, while other arrangements can produce different switching behavior.
- **The vortex has history dependence**
The response to a pulse depends on the **magnetic state created by the preceding pulses**. Therefore, the system possesses a form of dynamical memory.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics



- **The dynamics are non-commutative**

Reversing the order of two operations/pulses does not necessarily produce the same output:

- **Temporal order becomes an information carrier**

The results demonstrate that information can be encoded not only in **field amplitude**, but also in the **sequence in which the fields are applied**.

- **Computational significance**

The vortex can potentially act as a **physical sequence discriminator**

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics

- Magnetization dynamics of a permalloy vortex are strongly dependent on the **temporal ordering of the applied magnetic-field pulses**.
- This sequence dependence exists even when the field magnitudes, pulse durations and overall excitation conditions are kept the same.
- The vortex dynamics exhibit a clear **history-dependent response**. In particular, a **high exchange-energy peak or high vortex-core velocity** may be necessary for switching, but it is not by itself sufficient. The preceding dynamical pathway determines whether stable switching occurs.
- **By encoding the pulse sequences in binary form and analysing their Pearson correlations, we can establish relationships between the physical dynamics and logical transformations.**
- A magnetic vortex can be viewed as a **reconfigurable physical computational element**, rather than simply as a conventional magnetic switching element.

Encoding Temporal Information in Nonlinear Magnetic Vortex Dynamics

- ❑ The **temporal order** of magnetic-field pulses can act as an **information-bearing variable**.
- ❑ Even when the pulse magnitudes, durations, and net field are identical, changing their sequence produces **distinct, history-dependent vortex dynamics, switching behavior, and magnetization trajectories**.
- ❑ Thus, a magnetic vortex can function as **a nonlinear physical system capable of discriminating and processing temporal information, providing a promising foundation for reconfigurable logic and unconventional/neuromorphic computing**.

“The input is the pulse sequence, the computation is performed by the nonlinear vortex dynamics, and the output is the resulting magnetic state.”

Key message

The magnetic vortex transforms temporal ordering of input pulses into distinguishable dynamical states, demonstrating a physical mechanism for sequence-dependent information processing.

May open the pathway for

- Hardware for unconventional computing architecture
- Pattern recognition,
- Sequence classification,
- Neuromorphic computing.

ACKNOWLEDGMENT



**Dr. Michael
J. Donahue**



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Thank you!

