Reservoir Computing by Artificial Spin-vortex Ice

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1. Introduction

An artificial spin ice is a metamaterial with a lattice of, which produces collective properties like frustration, emergent magnetic monopoles, and phase transitions[1]. The single-domain nanomagnets perform their magnetic behaviors by different magnetization textures including macrospins and vortices as shown in Figure 1a and 1b[2].

An artificial spin-vortex ice (ASVI) is a four-state bi-texture system[3]. ASVIs contain submicron sized nanomagnets with different widths. Wider bars have lower coercive fields, allowing them to flip easier under external fields and turn into vortices. This new vortex state possesses nonlinear state growth, suitable to realizing reservoir computing. ASVI requires training only at system readouts and thus plays a crucial role as a physical reservoir with applications like time-series forecasting comparing with deep neural networks[4].

In this project, our ASVI has a 2D square lattice in a staircase formation. Bars with the same width are connected in the diagonal direction as illustrated in Figure 1c. **We developed an ASVI simulation tool with key functions:**

- **Animation for visual aid and validation**
- **Prediction of the macrospin/vortex population**
- **Prediction of the ferromagnetic resonance (FMR) spectrum**

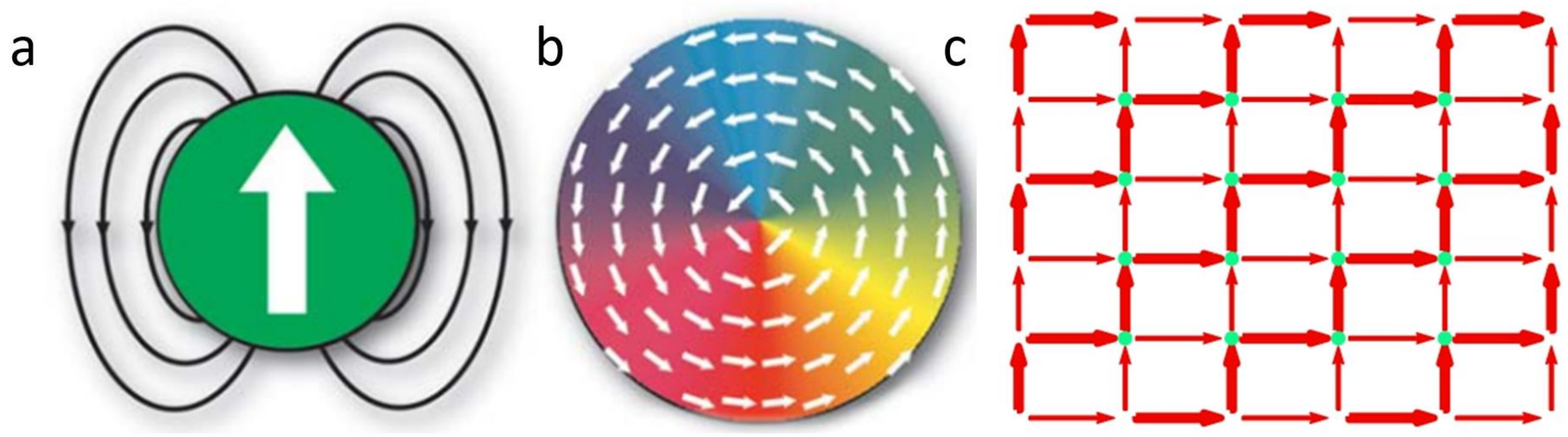

Figure 1: *Elements of an ASVI.* ***a.*** *A macrospin, the moments are aligned in the magnet.* ***b.*** *A vortex, moments in the magnet are in closed loops.* ***c.*** *5×5 square staircase ASVI with alternating rows of thin bars and wide bars.*

2. Methodology

We use python object-oriented programming to show the flipping of the bars, record the population growth of the vortices, calculate the FMR frequencies, and make an animation in two-dimensional color plots shown in Figure 2.

To validate the reconfigurability of our simulated ASVI, we teste our simulated lattice in pure macrospin state and pure vortex state under a linear external field. We track the population and found out the macro-to-vortex is exponential, and the vortex-to-macrospin evolution follows a sigmoid function.

Subsequent, we apply training onto a larger lattice, 100x100 nanobars in size. We reproduce the FMR spectrum that is directly comparable to experiments. The mode frequencies are obtained in two ways: by calculating using Kittel equation $f = \frac{\mu_0 \gamma}{2\pi}\sqrt{H(H+M)}$, or by mapping using the FMR heatmap measured in experiments[3].

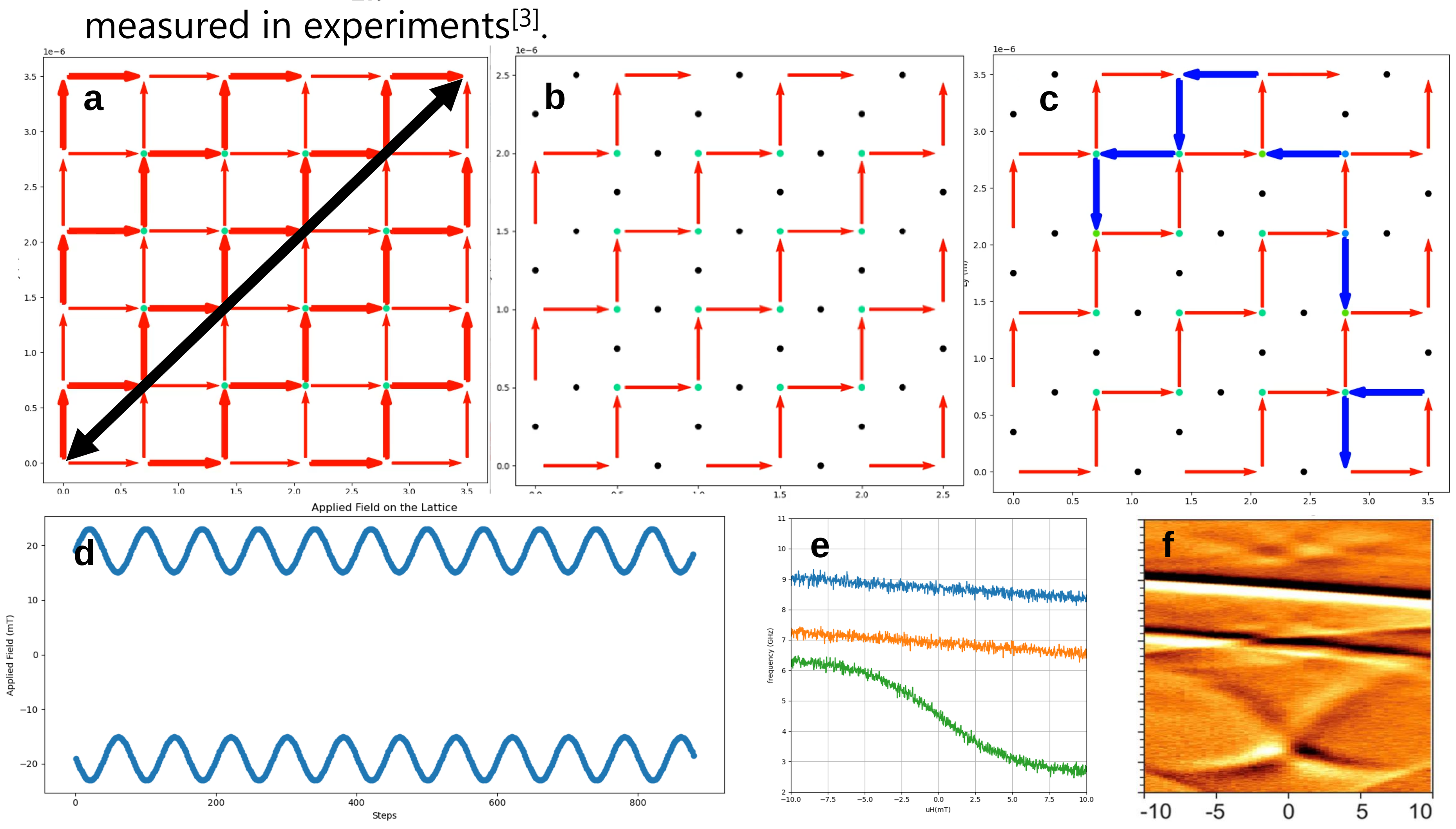

Figure 2: *ASVI lattice structure and state in out simulation.* ***a.*** *The ASVI that is prepared in the positively saturated macrospin state, and the external field is applied at a 45-degree angle shown as the black arrow.* ***b.*** *The ASVI that is set to vortex saturated state.* ***c.*** *Stabilized ASVI lattice after training with a sinusoidal field. Some wide bars are pinned to their lowest energy state (Type I vertex).* ***d.*** *Applied sin field for training.* ***e. f.*** *Simulated and experimentally measured FMR heatmaps*

3. Key Results

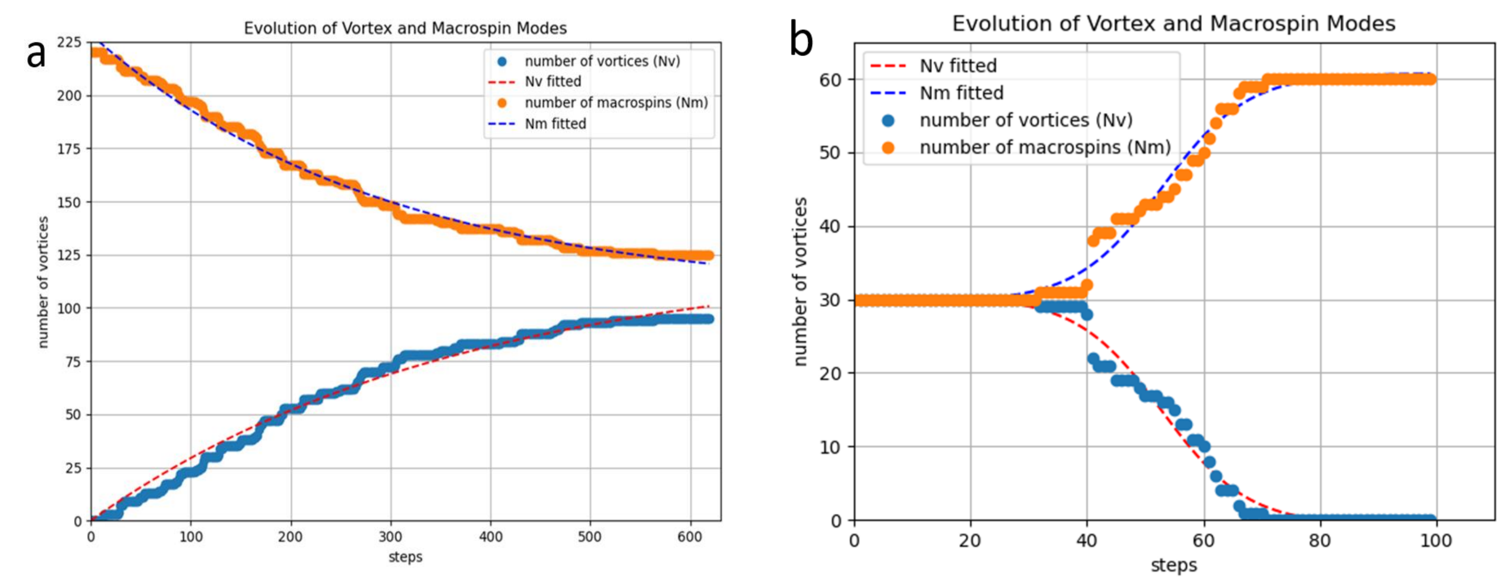

Figure 3: *Stochasticity and reconfigurability of ASVI by macrospin-vortex and vortex-macrospin conversion experiments.*
a. *The population of vortices and wide bar macrospins follow exponential change for macrospin-vortex conversion experiment.*
b. *The population of vortices and wide bar macrospins changes in sigmoid functions in the vortex-macrospin conversion experiment.*

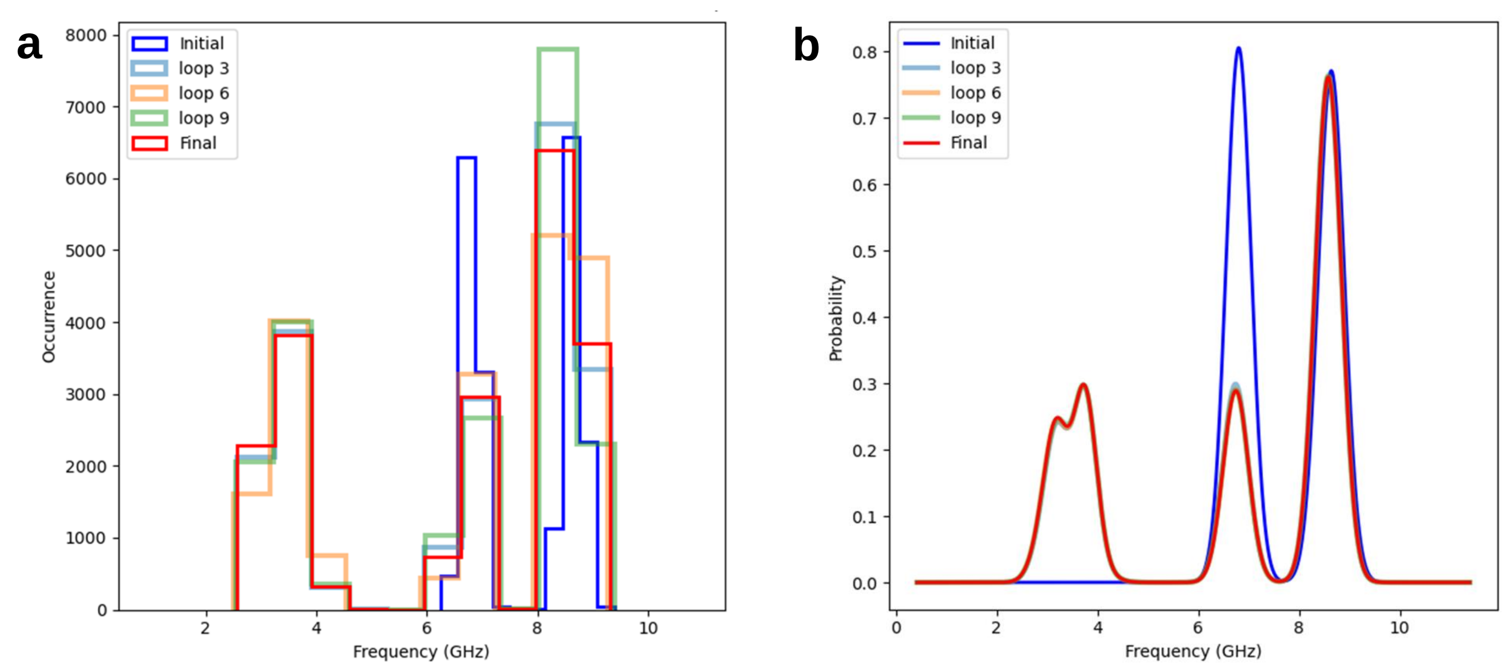

Figure 4: *Population distribution of nanobars as a function of mode frequencies to simulate the FMR spectrum for a 100×100 ASVI trained by a sinusoidal training field.*
a. *The frequency population histogram measured after loop initial, 3, 6, 9, and final.*
b. *A frequency probability distribution function determined by kernel density estimation to mimic the experimental FMR spectrum. The spectrum is stabilized after about 3 loops.*

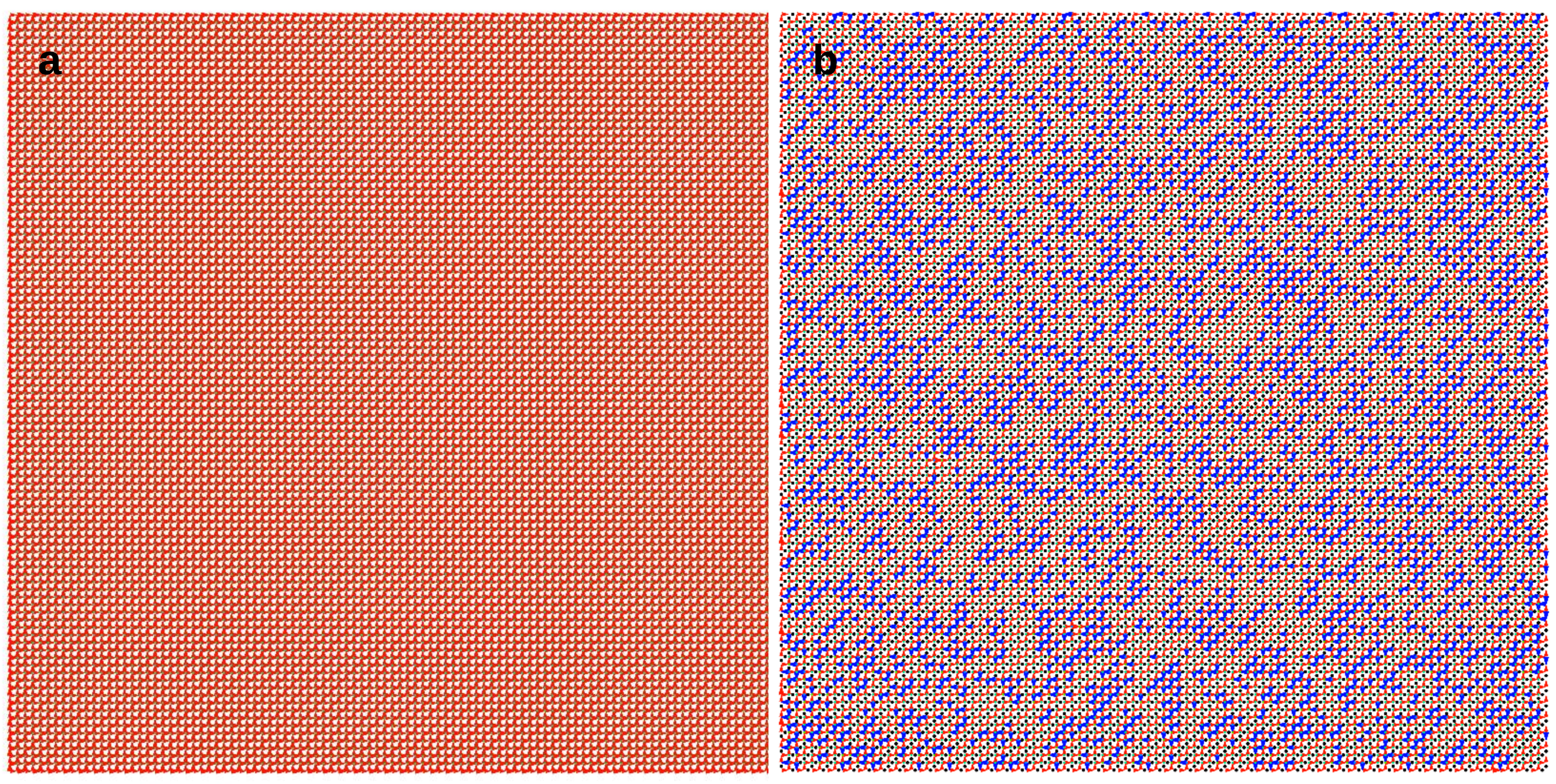

Figure 5: *Initial (**a**) and final (**b**) lattice state for the previous simulated 100x100 ASVI. The training converges as most bars are pinned in their current state.*

4. Conclusion and Discussion

Our simulation offers a fully animated ASVI simulation tool that accurately reproduce the exponential and sigmoid evolution of vortex/macrospin. It also predicts the FMR spectrum measured in experiments and can be directly applied to the training process. These properties are essential to reservoir computing as they offer randomness and the 'fading memory property'[4].

This project provides a novel method of ASVI simulation. This can be used to save the experimental time and power against real life FMR readout and larger sample sizes can also be achieved easily.

5. Bibliography

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