Inverse-designed spin dynamics for neuromorphic computation

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It is well known that interference of linear waves can be used for special-purpose computing, such as calculating convolutions, Fourier transforms and vector-matrix products. This fact has long been used in optical computing. It has also been hypothesized that nonlinear waves have potential for neuromorphic and general-purpose computing [1]. So far, however, no concrete physical system has been engineered to perform such computational tasks, which is likely due to the complexities of non-linear wave propagation.

In this work, we integrate the Pytorch machine learning engine with a custom-built GPU-based micromagnetic simulator for the inverse-design of a magnetic medium where spin-wave dynamics performs computational tasks [2]. Specifically, the computational learning algorithm designs a magnetic field distribution that focuses scattered spin waves with high wave intensity at a certain output point that represents the result of the neuromorphic computation. Figure 1 shows snapshots of the designed spin-wave scatterer. The input waveforms (this case vowels) are recognized by focusing them to the desired output. We demonstrate that such a spin-wave substrate operating in the high-intensity non-linear regime is capable of functions that are not computable by a linear system.

The Pytorch engine relies on gradient-based learning. The algorithm requires a micromagnetic simulator to be fully integrated with the learning engine and the intermediate steps of the computation to be saved and passed on to the learning engine. A block diagram of the algorithm is shown in Fig 2 and details will be shown in our presentation. The system can, in principle, optimize for any computing function, without any manual intervention – albeit the numerical algorithm is demanding and this limits the size of the system that can be designed.

We believe that this work demonstrates a new methodology for the design of functional nanoelectronic/magnetic devices, and presents a specific physical system towards the longtime dream of doing computation by a material substrate.

[1] Hughes, et. al: "Wave physics as an analog recurrent neural network." Science advances 5, no. 12 (2019):

[2] Papp et. al: "Nanoscale neural network using non-linear spin-wave interference." arXiv preprint arXiv:2012.04594 (2020).

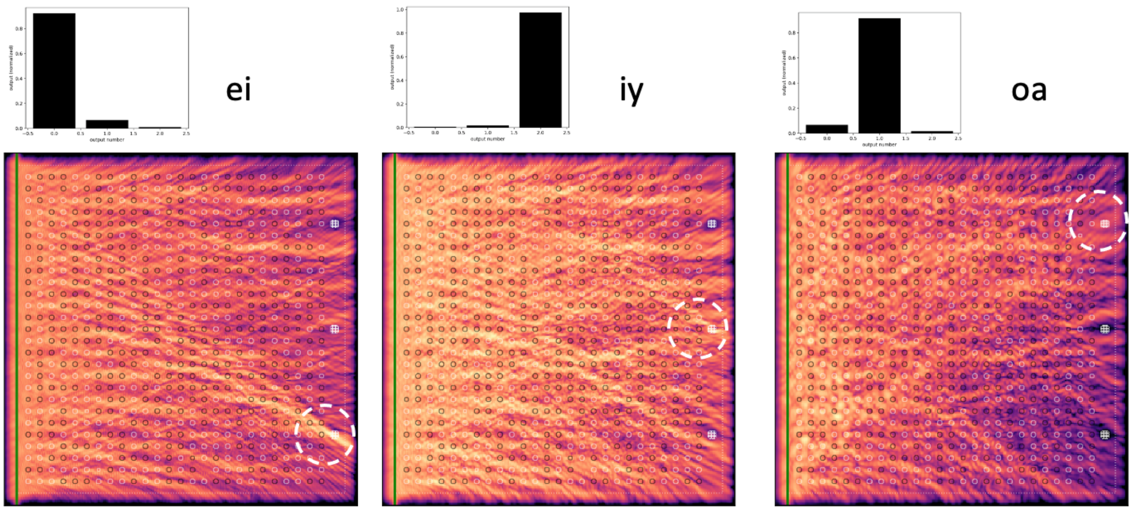

Fig 1. Spin-wave interference patterns formed as a response to various input vowel waveforms. Different vowels result in energy focused to different output points. These images resemble field-intensity distributions from linear nanophotonic designs, but they show nonlinear (rather than linear) interference patterns.

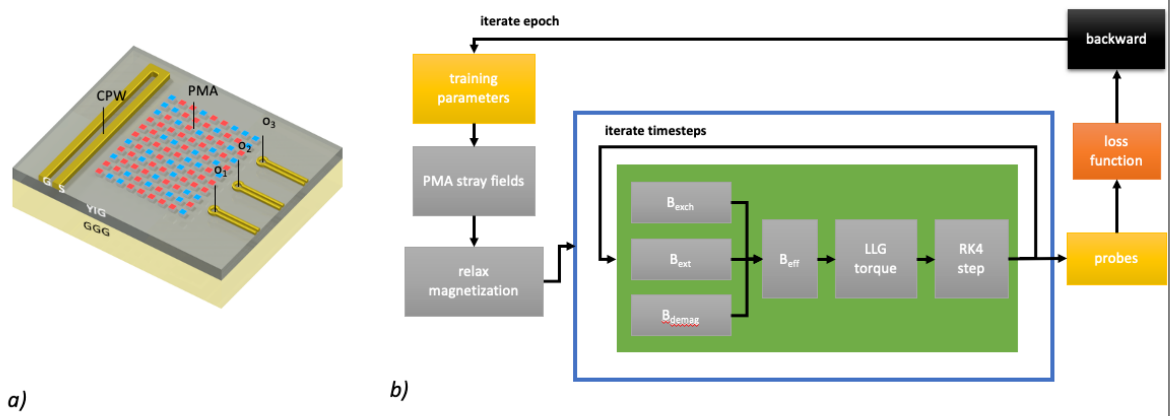

Fig. 2. a) Schematic layout of the spin-wave scatterer with waveguide inputs and field-sensor outputs. The learning algorithms adjusts the orientations of the PMA magnets on top, which function as the scattering centers. b) flowchart of the numerical engine, with the micromagnetic simulation code depicted in the framed area, and around it the controlling numerical engine.