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# Controlling Spin-Waves by Spin-Polarized Current for Logic and Neuromorphic Computing

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**Spin-waves (magnons) are among the prime candidates for building fast yet energy-efficient platforms for information transport and computing. We here demonstrate theoretically and in state-of-the-art micromagnetic simulation the effects that strategically-injected spin-polarized current can have on controlling magnonic transport. We reveal analytically that the Zhang-Li spin-transfer-torque induced by applied current is analogous to the Dzyaloshinskii-Moriya interaction for scattering the magnons in the linear regime, to then provide a generalized Snell's law that describes the spin-wave propagation across regions with different current densities. We validate the latter in numerical simulations of realistic systems, and exemplify how these findings may help advance the design of spin-wave logic and neuromorphic computing devices.**

***Index Terms*—Magnonics, Neuromorphic Computing, Spin-Current, Spintronics.**

## I. INTRODUCTION

THE DEVELOPMENT of neuromorphic computing hardware has attracted significant attention in recent years as such platforms are capable of performing complex information processing tasks, such as classification and pattern recognition of various types of data, from e-commerce to scientific content [1]. A central challenge of this research is the requirement of highly interconnected systems, inspired by the biological concepts of the human brain. Interestingly, wave-based physical systems have been demonstrated to operate as recurrent neural networks [2], where interference patterns in the propagating substrate can realize an all-to-all interconnection between points of the substrate that mimic the action of artificial neurons by scattering and recombining input waves in order to extract their information. Especially, spin-waves (SWs) are readily demonstrated as a promising platform for performing logic operations and the recent theoretical advances in wave-based computation can pave the way for spintronic hardware in the field of artificial intelligence [3].

In this work, we detail the effect of a spin-polarized (SP) current on controlling the propagation of SWs. We show that the spin-transfer-torque (STT) induced by in-plane current has analogous effect to Dzyaloshinskii-Moriya interaction (DMI) for confining and controlling the propagation direction of SWs in the linear regime. We proceed to derive a Snell's law to describe the scattering of SWs between regions with different current densities, and validate it by advanced simulations within the micromagnetic framework. Finally we present selected tailored examples to illustrate how strategically applied current can be employed to advance logic and neuromorphic computing devices based on SWs.

## II. RESULTS AND DISCUSSION

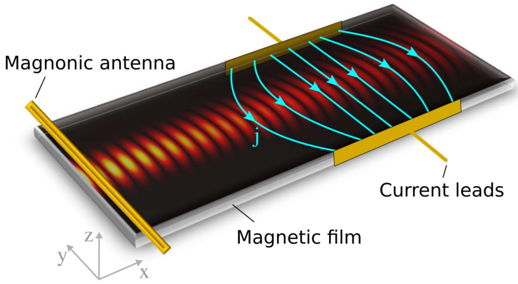

Fig. 1. **Schematic illustration of a SW facing a non-uniform distribution of the SP current**. The SW (in red) is induced by the input antenna on the left side and propagates along the magnetic film. Voltage electrodes induce the distributed spin current density ($j$) which can be tuned to control the SW propagation.

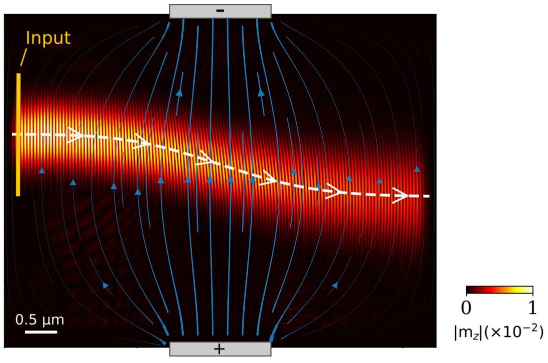

Fig. 2. **SWs under nonuniform current distribution**. Snapshot of the SW propagating across a nonuniform current distribution (blue arrows) induced between the voltage contacts (gray regions). White arrows indicate the SW trajectory calculated by iterating Eq. (2) locally along the current gradient in the propagation direction.

The dynamics of the magnetization is simulated by the Landau-Lifshitz-Gilbert (LLG) equation, from where the SW dispersion relation, i.e. the relation between its frequency $\omega$ and wavevector $\mathbf{k}$, can be obtained (see Menezes *et al.* [4])

$$\omega = \frac{\gamma H_0}{1+\alpha^2}\left(1+\xi^2 k^2\right) + \frac{1+\alpha\beta}{1+\alpha^2}\mathbf{u}\cdot\mathbf{k}. \tag{1}$$

Here, $\mathbf{u} = -\frac{\mu_B P}{e M_\mathrm{s}(1+\beta^2)}\mathbf{j}$ represents the contribution of the current density $\mathbf{j}$; $\beta$ is a dimensionless constant that represents

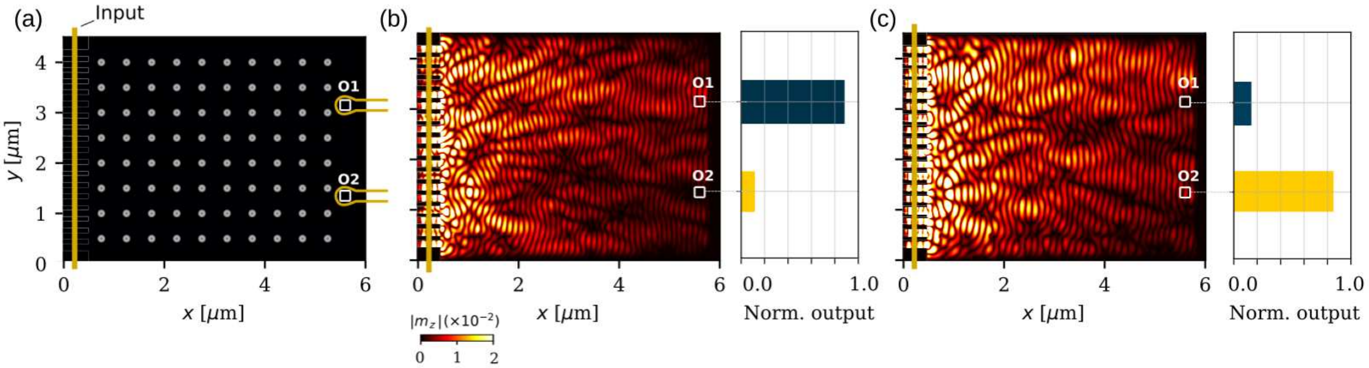

Fig. 3. (a) Scheme of the envisioned neural network hardware. The (18) input SWs are created on the left and propagate across the matrix of 80 voltage contacts (grey dots) of 100 nm in diameter each. (b-c) Snapshots of SW simulations after propagating across the neural network. The bar charts show the normalized intensities at the output locations integrated over 10 ns. Here, we consider magnetic parameters for a 20 nm tick NiFe film, with in-plane bias field $\mathbf{H} = H_0\hat{y}$ and $H_0$=100 mT.

the degree of non-adiabaticity; $e$ is the elementary charge; $\mu_B$ the Bohr magneton; $M_\mathrm{s}$ the saturation magnetization, and $P$ the spin current polarization. $\gamma$ is the gyromagnetic ratio and $\alpha$ is the dimensionless damping factor. $\xi = \sqrt{2A/H_0 M_s}$ is defined as the characteristic length scale, where $A$ is the exchange stiffness parameter and $H_0$ the applied magnetic field.

### *1) Generalized Snell's law*

In the case of nonuniform SP current, the change in current density is equivalent to an interface, and the momentum perpendicular to $\nabla j$, *i.e.*, $\mathbf{k}\cdot\hat{\tau} \equiv |\mathbf{k} - (\mathbf{k}\cdot\hat{\nabla} j)\hat{\nabla} j|$, with $\hat{\tau}$ the vector tangent to the interface, should be conserved. That results in a generalized Snell's law for the SWs facing such an interface. Since in our case the dispersion relation is asymmetric, Snell's law has to be adjusted as follows

$$k_g^{(1)}\sin(\phi_1) + \mathbf{k}_0^{(1)}\cdot\hat{\tau} = k_g^{(2)}\sin(\phi_2) + \mathbf{k}_0^{(2)}\cdot\hat{\tau}, \qquad (2)$$

where $\mathbf{k}_0 = -\frac{1+\alpha\beta}{2\gamma H_0 \xi^2}\mathbf{u}$ and $k_g = |\mathbf{k} - \mathbf{k}_0|$. The indices 1 and 2 refer to the incident and refracted waves respectively and the angles $\phi_i$ are taken with respect to $\hat{\nabla} j$ (*i.e.*, the direction normal to the interface). Similar generalized Snell's laws for the refraction of SWs at domain walls and heterochiral interfaces were derived in literature [5]. Fig. 2 shows the comparison of simulated SW under nonuniform current distribution and Eq. (2).

### *2) Logic and neuromorphic computing*

Regarding possible applications, spin currents can be used to precisely guide the SW in SW-based circuitry, for example, to selectively "write" SWs in one of multiple nanotracks or logic gates in a larger microprocessor. In this work, we demonstrate the use of SP current for the design of a multi-channel SW selector (see Menezes *et al*. [4]) and a neural-network hardware, based on SW propagation, where weights and interconnections of the network are realized by a pattern of the spin currents applied to the propagating substrate. Fig. 3 (a) illustrates the envisioned device, where we consider magnetic parameters for a 20 nm tick NiFe film. The input signal is created on the left and propagates across a region with a matrix of 80 voltage contacts [gray dots in Fig. 3 (a)] of 100 nm in diameter each. The read-out is taken from the two output antennas on the right side. An arbitrarily powered voltage matrix induces a distribution of the spin currents in the substrate that interacts with the input SWs. Training the neural network is equivalent to finding the current pattern that realizes the desired input-output mapping, for example, to classify different input signals by focusing them on different outputs. As suggested in literature [2], [3], a back-propagation machine learning algorithm can be used for training a similar SW-based network, which can perform tasks such as vowel recognition and frequency classification. Here, we demonstrate that a simple Monte Carlo algorithm can perform the same task of training the neural network for simple classification problems. In our example, we perform a frequency-recognition operation, where we consider input SWs with frequencies $f = 3.2$ and 3.4 GHz. The neural network is trained to focus the SWs with 3.2 GHz to the output O1 and SWs with 3.4 GHz to the output O2, as shown in Figs. 3 (b,c).

## III. CONCLUSION

We have demonstrated the use of non-uniform SP current for the manipulation of SWs. We showed that the STT induced by the applied current has an effect analogous to DMI for confining SWs and controlling their propagation direction in the linear regime, and derived a generalized Snell's law that describes the scattering of SWs between regions with different current densities. Finally, we demonstrate how strategically applied current can be employed in magnonic logic and neuromorphic computing devices, thereby advancing the prospects of spintronic hardware and artificial intelligence.

## REFERENCES

[1] D. V. Christensen, R. Dittmann, Linares-Barranco *et al.*, "2022 roadmap on neuromorphic computing and engineering," *Neuromorphic Computing and Engineering*, 2022.

[2] T. W. Hughes, I. A. D. Williamson, M. Minkov, and S. Fan, "Wave physics as an analog recurrent neural network," *Science advances*, vol. 5, no. 12, p. eaay6946, 2019.

[3] A. Papp, W. Porod, and G. Csaba, "Nanoscale neural network using non-linear spin-wave interference," *Nature Communications*, vol. 12, no. 1, pp. 1–8, 2021.

[4] R. M. Menezes, J. Mulkers, C. C. Silva *et al.*, "Towards magnonic logic and neuromorphic computing: Controlling spin-waves by spin-polarized current," *arXiv preprint arXiv:2301.04922*, 2023.

[5] J. Mulkers, B. Van Waeyenberge, and M. V. Milošević, "Tunable snell's law for spin waves in heterochiral magnetic films," *Physical Review B*, vol. 97, no. 10, p. 104422, 2018.