Magnonic devices for 3D spin-wave computing

K. Szulc[a,b]
a: Institute of Molecular Physics, Polish Academy of Sciences, Poznań, Poland;
b: ISQI, Faculty of Physics and Astronomy, Adam Mickiewicz University, Poznań, Poland.

Spin waves serve as a promising information carrier for the future computing. A plenty of devices have already been proposed, but we are still waiting for the first demonstration of a full magnonic circuit. High hopes are attributed to the three-dimensional systems which enable the creation of denser networks and open up new possibilities for the steering and manipulation of the signal. In this talk, we demonstrate four systems which can be a part of three-dimensional magnonic circuit.

Firstly, we show the vertical directional coupler [1]. The dispersion relation of the vertically-coupled waveguides differs from that of the planar system. Stacked waveguides are characterized by a significantly stronger coupling for short spin waves and a mode crossing for longer waves, which is a signature of the coupling decay. These properties are used to create a nanoscale coupler which can be controlled with a low external magnetic field. We also demonstrate the multiplexing and demultiplexing (Fig. 1) of the spin-wave signal using this vertical directional coupler.

In the next part, we demonstrate the manipulation of the spin-wave propagation using the nanocoupler. The first device relies on the effect of unidirectional coupling, where the spin wave is strongly coupled between the layers in only one direction of propagation. This effect allows the design of the spin-wave diode (Fig. 1) and circulator [2]. Another device is based on the two conduits coupled through a strip resonator [3]. The modes in the resonator are rotational in nature, giving rise to multiple functionalities of the system including circulator, phase shifter, and reflector.

Finally, we aim to control the spin-wave propagation in the waveguide using the hybrid magnonic crystal based on the chain of nanodots with perpendicular magnetic anisotropy and Dzyaloshinskii-Moriya interaction [4]. Several magnetic states can be stabilized in the nanodots, among which we focus on the single-domain and skyrmion state. The dispersion relation of the hybrid system (Fig. 1) is characterized by many interesting features including the control of Bragg and non-Bragg band gaps with the magnetic state in nanodots, magnon-magnon coupling, flat bands, and bound states.

The presented systems demostrate interesting properties which can find the application in the spin-wave circuits for digital, analog, neuromorphic, or reservoir computing.

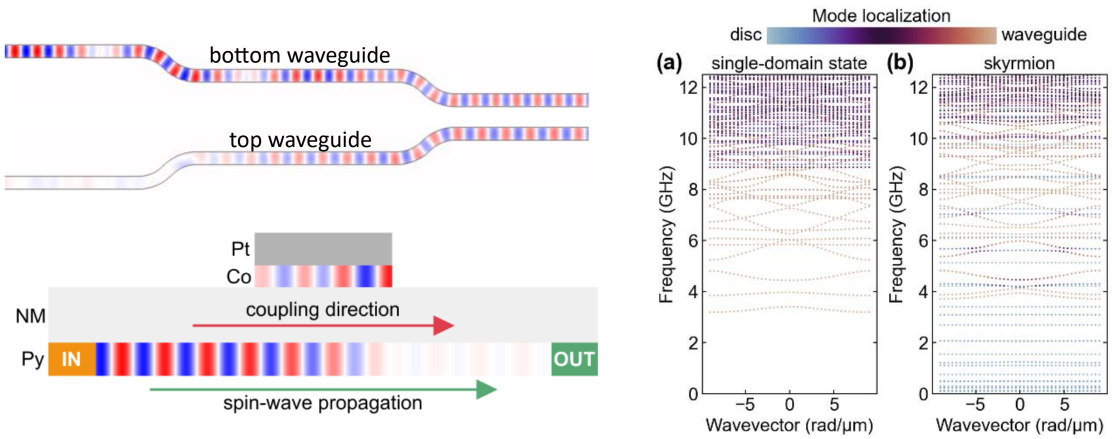

Fig. 1. (top left) The spin-wave demultiplexer. The two spin waves at 12.65 and 13.9 GHz are excited on the left side of bottom waveguide. (bottom left) The reverse direction of the spin-wave diode.
(right) The dispersion relation of the hybrid magnonic crystal with the nanodots in the single-domain state (a) and skyrmion state (b).

This work was supported by the EU Research and Innovation Programme Horizon Europe (HORIZONCL4-2021-DIGITAL-EMERGING-01) under grant agreement no. 101070347 (MANNGA) and the National Science Centre of Poland project no. UMO-2021/41/N/ST3/04478.

[1] K. Szulc, M. Krawczyk. *Magnetic field-controlled nanoscale spin-wave vertical directional coupler*. arXiv:2501.07417 (2025).
[2] K. Szulc et al. *Spin-wave diode and circulator based on unidirectional coupling.* Phys. Rev. Appl. **14**, 034063 (2020).
[3] P. Roberjot et al. *Multifunctional operation of the double-layer ferromagnetic structure coupled by a rectangular nanoresonator*. Appl. Phys. Lett. **118**, 182406 (2021).
[4] K. Szulc, M. Zelent, M. Krawczyk. *Reconfigurable spin-wave platform based on interplay between nanodots and waveguide in hybrid magnonic crystal.* arXiv:2404.10493 (2024).