Post-print of Petti, D. Building a half-adder based on spin waves. *Nat Electron* **3,** 736–737 (2020).
https://doi.org/10.1038/s41928-020-00514-4

Magnonics

Building a half-adder based on spin waves

Standfirst: A magnonic directional coupler based on yttrium iron garnet could be used to create integrated magnonic nanocircuits for logic operations.

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Spin waves and their quasiparticles, magnons, can transport energy and angular momentum in magnetically-ordered materials without the movement of electrical charges, and could thus be used to develop energy-efficient computing platforms. Magnon interference and frequency multiplexing can, in particular, be used to encode and manipulate information at the nanoscale, orders of magnitude smaller than what is possible with their electromagnetic counterpart at the same frequency. Spin waves are also naturally non-linear, have a large coherence length, a broad frequency range (from gigahertz to terahertz), and quantum-mechanical properties. They could therefore potentially be used to implement approaches such as neuromorphic[1] and quantum computing[2].

Magnonic logic gates[3], magnonic majority gates[4], and magnonic transistors[5] have already been proposed or developed for Boolean computation. Reconfigurable spin textures and nanomagnets have also been shown to efficiently guide spin waves in two-dimensional circuits[6,7]. However, building nanocircuits based on cascaded magnonic devices, which is relevant for computing systems that contain both logic and memory, has proved difficult, limiting the practical potential of the approach. Writing in *Nature Electronic*, Qi Wang, Andrii Chumak and colleagues now report a magnonic directional coupler — a universal basic unit for the construction of integrated magnonic circuits such as half-adders[8]. The researchers — who are based at the University of Vienna, the Technische Universität Kaiserslautern, the Institute of Magnetism in Kyiv, the Johannes Gutenberg University Mainz, Delft University of Technology, INNOVENT and Imec — use the spin-wave amplitude as a logic variable to demonstrate that the coupler can implement various logic operations based on the transport and processing of information exclusively via magnons.

The magnonic directional coupler (Fig. 1a) consists of two nanoconduits made of yttrium iron garnet (YIG), an insulating ferrimagnet and one of the most popular materials in magnonics research due to its extremely low spin-wave damping. The nanoconduits are separated by a nanogap in order to allow energy transfer between them via magnetic dipolar coupling. Beyond the coupling region, the gap increases to micrometre dimensions where no coupling between the two conduits exists. In this setup, a U-shaped nanoantenna is biased with radio frequency current to excite spin waves via an Oersted field.

To probe the functionality of the device, Wang, Chumak and colleagues use micro-Brillouin light scattering, which is based on the inelastic scattering of photons with magnons, to measure the spin-wave intensity in the decoupled region of the two nanowaveguides. They find that for some spin-wave frequencies, the spin-wave energy that is injected into one of the two conduits can be transferred almost completely to the other. By tuning the length of the two arms, the frequency of the travelling spin waves, and the external static magnetic field, it is possible to modulate the energy output of the conduit. Three different outputs can, in particular, be obtained:

the complete transfer of energy from one conduit to the other, the halving of the power between the two conduits (fan-out functionality), and an almost complete reflection of the energy back to the first conduit.

This energy transfer behaviour originates from the splitting of the spin-wave dispersion curve into two branches due to the dipolar interaction between the waveguides. It is also possible to shift the dispersion curve and reconfigure the device characteristics by exploiting the non-linearity of spin waves. Specifically, the energy transfer can also be modulated by varying the injected power while the geometry of the device, the frequency, and the external field remain fixed. The researchers use these properties to demonstrate, using a microwave directional coupler as first stage, a half-adder that is based on the cascade of two directional couplers operating at different regimes (Fig. 1b). In such a device, the logic inputs are two out-of-phase signals injected into the first directional coupler, which is connected directly to the antenna and acts as a power splitter. The output of the first coupler then feeds the input of the second directional coupler. Depending on the input intensity of the signals, this coupler produces different outputs, reconstructing the truth table of a half-adder.

Comparing the approach with complementary metal–oxide–semiconductor (CMOS) technology, the results are encouraging. In particular, considering a device with 30-nm-wide channels, the researchers estimate the footprint of the half-adder to be similar to that of a 7-nm-feature-size CMOS-based device. Furthermore, fewer interconnections are required, and the power consumption (for the magnonic part only) is seven times lower. The main bottleneck for the magnonic adder is the delay time, because spin waves in the GHz frequency range are slow.

The development of a magnonic coupler is an important step towards magnonic integrated circuits, but practical challenges remain. First, YIG films are grown on gadolinium gallium garnet substrates and their integration with silicon substrates is difficult. In contrast, the use of metallic ferromagnets, such as cobalt–iron–boron (CoFeB), is compatible with silicon and nanofabrication processes — at the expense, though, of energy dissipation, because the spin-wave damping in CoFeB is at least one order of magnitude higher than in YIG. Second, the conversion from the magnonic to the electric domain and vice versa, as well as the requirement for spin wave amplification to compensate for the attenuation of the spin wave amplitude, is challenging. In particular, the generation of spin waves via inductive antennas is not realistic for practical devices, because the antennas cannot be scaled down to nanometre dimensions. Alternatively, spin wave sources based on spin torque and spin hall nano-oscillators could potentially be integrated with magnonic nanocircuits[9]. However, the large electrical currents (on the order of mA) necessary for their operation can increase the power consumption up to milliwatts. To overcome these limitations, a promising approach is the use of voltage-controlled magnetic anisotropy (VCMA) to excite, amplify, and detect spin waves via electric fields[10]. But this field is still in its infancy and experimental demonstrations will be needed to demonstrate the potential of VCMA-based approaches for the development of low power magnonic devices.

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Competing interests

The author declares no competing interests.

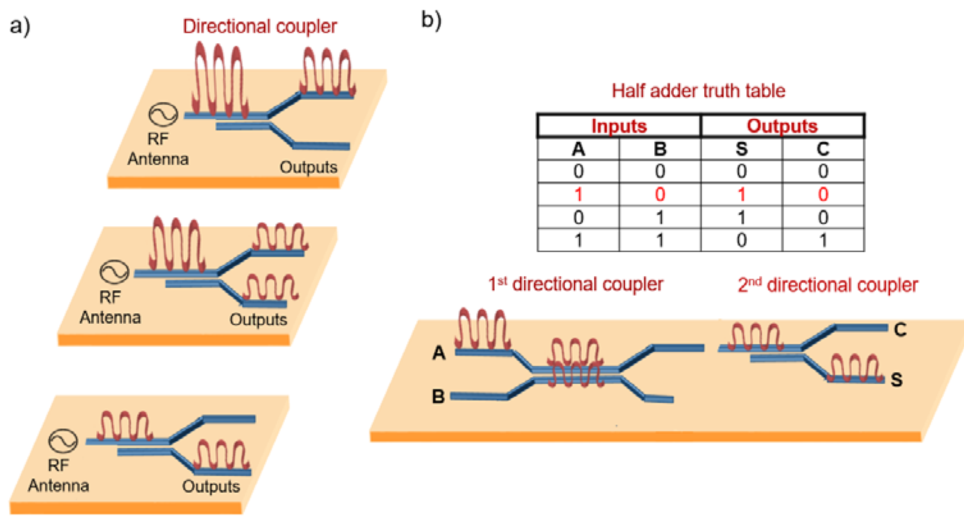

Fig. 1 **Principle of operation of the spin-wave directional coupler and half-adder. a,** The dipolar interaction between the two nanoconduits of a spin-wave directional coupler allows energy to be transferred from one to the other. This energy transfer can be modulated by the frequency of the waves, the length of the arms in the coupling region, the external magnetic field, or the input power due to the non-linearity of spin waves. Depending on the radio frequency (RF) power intensity injected in the antenna, three different energy outputs can be obtained: almost total reflection back to the first arm for high RF power (top), a split of the RF power between the two arms for medium RF power (centre), and almost complete energy transfer to the second conduit for low RF power (bottom). **b,** The proposed magnonic half-adder is made up of two cascading directional couplers. The first coupler mixes the input signals A and B, by splitting them between the two nanowaveguides. The second coupler operates in the non-linear regime to transfer energy between the arms, in order to obtain different outputs as a function of the power intensity.