Magnonics

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Nanoscale spin waves get excited

Akashdeep Kamra & Lina G. Johnsen

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Disturbances in the orientation of magnetization in a magnet can propagate as spin waves or magnons. A design that makes it possible to optically excite nanoscale spin waves offers a route to developing miniaturized spin-based devices.

Waves manifest phenomena, such as condensation into a phase-coherent state, that offer exciting opportunities for science and technology. However, in order to produce devices that could be competitive with nanoscale incoherent electronics, short wavelengths are required. Nanoscale spin waves have high frequencies in the terahertz regime that are not accessible with typical voltage sources, but could be driven using millimetre-wavelength terahertz radiation. Coherent excitation of waves with nanometre wavelengths has been a challenge as it requires matching both the frequency and wavelength with those of the driving field. Now, writing in *Nature Physics*, Ruslan Salikhov and colleagues[1] have demonstrated that this wavelength matching problem can be solved with a device design that sandwiches a ferromagnet between two metals.

Electronic wavelengths are typically in the nanometre range, which has enabled the nanoscale transistors used in contemporary computers[2]. The field of magnonics focuses on spin waves, disturbances in the orientation of otherwise aligned magnetic moments that can propagate through magnets[3], instead of electrons. At the quantum level, these can be described in terms of bosonic particles known as magnons and they have many potential technological applications[3,4]. For example, spin-wave-based analogue computers[4] could overcome several limitations inherent to the Turing machine design that our electronic digital computers are based on[5]. Furthermore, phase-coherent propagation needed for quantum information applications has proven much easier to realize with waves, such as microwave light or photons in superconducting circuits, than with electrons[6].

Although significant advances in the generation and control of spin waves have been made, generating coherent short-wavelength spin waves needed for device miniaturization has remained a serious challenge due to the lack of an effective driving source. Light waves are a promising drive as they can be easily generated in the appropriate frequency range. However, coherent excitation requires matching both the frequency and wavelength between the driving light field and the magnon mode targeted for excitation. The very large speed of light means that the wavelength of terahertz light is in the millimetre regime, which is orders of magnitude larger than the nanometre wavelength of frequency-matched spin waves.

The challenge presented by the wavelength mismatch can be appreciated by considering a mechanical analogue. If a short rope is laid on an oscillating wooden block, the rope will only move uniformly with the motion of the block (Fig. 1a). This corresponds to a wave on the rope with infinitely long wavelength and the frequency of the block's motion. If instead the rope is tied to two nails in the block (Fig. 1b), the forces experienced by the rope are localized at its edges. Standing waves with short wavelengths determined by the separation of the nails may then be generated when their frequency is matched by the rate of the block's oscillations.

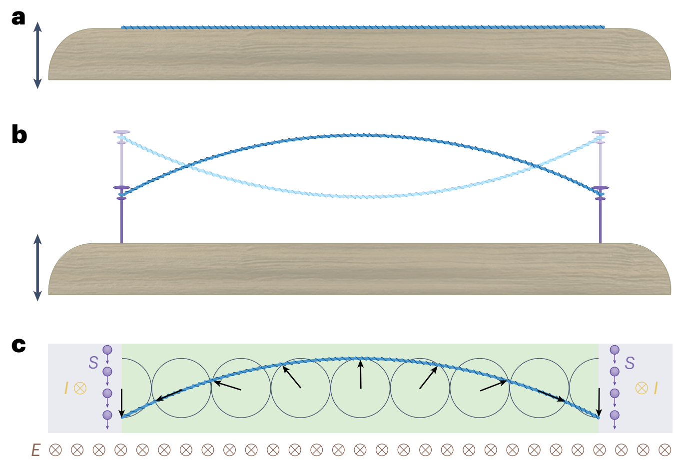

Fig. 1 | Snapshots of short-wavelength waves generated using much larger drives. a, **b**, An oscillating large wooden block (brown) attempts to move a rope. In **a**, without the purple nails, it would only be able to move the entire rope, that is, it could not excite waves. In **b**, the purple nails drive the taut rope on its edges, giving rise to a short-wavelength standing wave. **c**, Salikhov and colleagues employ a similar principle to drive spin waves in a magnet (light green). The spatially homogeneous electric field *E* (brown) associated with the incident long-wavelength light drives charge currents *I* (yellow) and the accumulation of spin *S* (purple) in the adjacent heavy metal layers (light grey). The resulting interfacial spin torques coherently generate a short-wavelength disturbance – known as a spin wave – in the magnetic moments (black arrows).

Salikhov and colleagues[1] exploited this idea with a device design in which a ferromagnetic layer with thickness of a few nanometres is sandwiched between two heavy metal layers with strong spin–orbit coupling (Fig. 1c). They drove the sample with a short terahertz light pulse. Due to the millimetre-range wavelength of the pulse, on the scale of the team's device it was effectively spatially uniform. The oscillating electric field of the pulse generated a.c. charge currents in the metal layers that themselves produced an accumulation of spin polarization at the metal–magnet interfaces due to strong spin–orbit coupling[7].

The absorption of accumulated spins by the ferromagnetic layer produced spin–orbit torque[7] at each edge. The result was standing spin waves with wavelengths comparable to the nanoscale magnetic film thickness. Thus, the spatially uniform electric field of the terahertz light could generate nanoscale spin waves, with wavelengths orders of magnitude smaller than that of the incident radiation.

The success of this approach opens tremendous opportunities. The wavelength of the generated standing wave is determined by the magnetic film thickness. Its frequency is governed by the spin-wave dispersion in the magnet. The experiment therefore provides a table-top method to measure the spin-wave dispersion in a material, which has otherwise required significantly more complex neutron scattering techniques[8].

There are, however, some drawbacks in the current demonstration. The somewhat broadband nature of the employed terahertz light limits the frequency selectivity of the generated spin waves. Furthermore, it would be desirable to launch propagating spin waves from one end of the magnetic film rather than the stationary standing waves demonstrated by Salikhov and colleagues. These two limitations appear to stem from the pump–probe detection employed and motivate frequency-selective generation of travelling spin waves using heavy metal/magnet bilayer devices in the future.

The ability to generate short-wavelength propagating waves is a key step to performing spin-wave logic and computing in nanoscale devices[3,4]. Looking beyond ferromagnetic spin waves, the principle of Salikhov and colleagues' experiment can be adapted to generate short-wavelength spin waves in antiferromagnets, or even sound waves in non-magnetic materials by replacing the heavy metal with piezoelectric layers.

The ability to generate terahertz waves could enable coherent excitation of non-reciprocal as well as topological magnonic and phononic excitations[9], which is being vigorously pursued by the scientific community. Finally, the team's device uses the electric field component of light to generate magnons using spin–orbit torques. The strength of this light–matter interaction can be increased further by improving the conversion efficiency of electric field to spin accumulation using, for example, the recently discovered stronger cousins of the spin Hall effect[7]. This could enable quantum control of magnonic excitations, unleashing their high potential for quantum information applications[10].

Over the years, we have witnessed electronic transistors getting smaller and our computers becoming more powerful in small steps. The reduction of coherent spin-wave wavelengths by Salikhov and colleagues[1] is a big advance in taking magnonic devices down the same path.

Akashdeep Kamra [1] & **Lina G. Johnsen** [2]
[1]Condensed Matter Physics Center (IFIMAC) and Departamento de Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, Madrid, Spain. [2]Center for Quantum Spintronics, Department of Physics, Norwegian University of Science and Technology, Trondheim, Norway.
e-mail: akashdeep.kamra@uam.es; lina.g.johnsen@ntnu.no

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Competing interests

The authors declare no competing interests.