Science **322**, 386-387 (2008)

A New Spin on the Doppler Effect

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(Dated: October 17, 2008)

Electrical currents transport charge, but certain experimental setups allow them to transport spin as well. Such spin currents (excess flow of either spin-up or spin-down electrons) can by created by passing an electrical current through a ferromagnetic film; spins parallel to the film's spin orientation pass through more easily, whereas those of opposite sign are scattered more strongly. Spin currents are used in magnetic memories and are potentially useful in novel electronic switches (spintronics), because switching spin orientations may require less energy than is needed to turn a charge current on and off (1). One experimental challenge in developing such technology is that it is difficult to measure the flow of spin currents. On page 410 of this issue, Vlaminck and Bailleul (2) overcome this challenge by using a novel version of the Doppler effect to quantify the flow of spin currents in a ferromagnetic wire. They measure changes in the propagation of spin waves, which are oscillations of the spin orientation (see the figure, bottom panel).

The most prominent example of harnessing spin currents is the giant magnetoresistance (GMR) effect (3, 4), which occurs when electrical current flows through two ultrathin ferromagnetic layers separated by a nonmagnetic spacer layer. When the magnetic domains of the ferromagnetic layers have parallel orientation, current flows more readily than when they are antiparallel, because the current of only one spin type (spin down, for example) undergoes extensive scattering. GMR has found numerous technological applications, including read heads in hard-disk drives, magnetic sensors, and magnetic random-access memory (MRAM). In many of these applications, the metallic spacer layer is replaced by a tunnel barrier made of oxides such as MgO. The associated resistance changes in such tunneling magnetoresistance (TMR) devices can be much greater than those in GMR devices.

In today's MRAM devices, spin currents are used only in the reading step through the GMR or TMR effects. In the writing step, the orientation of one of the ferromagnetic layers (the "soft layer") is changed by applying an external magnetic field. In a new generation of MRAM under development, spin currents are also used to write the bits (5). When a current passes through the spacer layer, the transport of angular momentum accompanying the spin current provides a spin transfer torque (6) that drives switching of one of the magnetic layers, performing the writing step.

If such development is successful, MRAM is projected to scale down to much smaller dimensions and could compete with dynamic random access memory (DRAM), which is presently used in computer memory. MRAM has the additional advantage of being nonvolatile like hard-disk drives, but even if MRAM could be scaled as far as conceivable with advanced lithographic fabrication methods, it will not approach the storage density available in hard-disk drives.

In MRAM applications, spin transfer torques act across a spacer layer; they also act within a single material and can be used to move the pattern of magnetic domain walls (which separate regions of opposite magnetic orientation) along a wire (7, 8). A proposed "racetrack memory" (9, 10), based on moving domain walls by spin current, would compete with or exceed the memory density of mechanical hard-disk drives. These solid-state devices would stack bits on top of each other, storing information in the magnetic domains, regions of aligned spins, in vertically continuous magnetic wires. Similar to magnetic recording tape, bits of information represented by domain walls would be moved past a device that can read and write the information.

Unlike the tape, however, the magnetic racetrack wires are stationary. The magnetic information is moved by a spin current passing through the wire, so that the pattern of domains moves as the domain walls are carried "downstream" in the spin current. One difficulty in developing such devices has been characterizing the interaction between the spin-polarized current and the magnetic bits.

Direct measurements of the spin current are challenging, and the properties of the spin current are more often inferred from measurements of the magnetization or the electrical current. Some of the most interesting experiments are those that measure the current-induced motion of a domain wall. This motion is the basis for the racetrack memory mentioned above. However, one of the difficulties in interpreting these experiments is that unintentional inhomogeneities in the wires also influence the motion of domain walls (11). Thus, a basic property of the spin current, its polarization–the degree to which the current is carried by either spin-up or spin-down electrons–is not well known, and estimates generally depend on the experimental technique and the fabrication method. Because the polarization is often treated as a free parameter in the analysis of experiments, reliable polarization measurements would constrain experimental analysis and allow deeper understanding of the results.

Vlaminck and Bailleul introduce a reliable method for measuring the spin current polarization that makes use of the Doppler effect. In a common example of this effect, the pitch of a train whistle drops as the train passes the listener. In this case, there is relative motion between the source and the observer. The Doppler effect can also occur

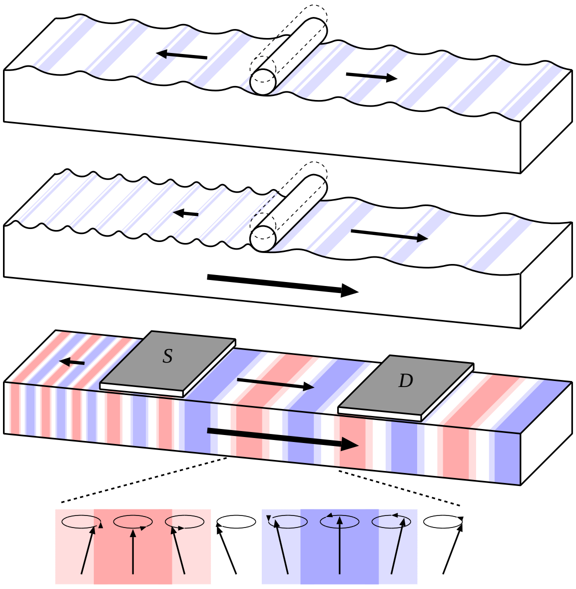

FIG. 1: Doppler effects in moving media. (Top) Water waves propagate away from a moving cylinder with a frequency set by its oscillation frequency and a wavelength determined by the properties of the water. (Middle) Water flows past the cylinder (large arrow); the waves have the same frequency as before, but the downstream-propagating waves have a longer wavelength and the upstream-propagating waves have a shorter wavelength. The speed of the water can be determined from the change in the wavelength of the waves. (Bottom) A cartoon of the spin waves excited in the experiment of Vlaminck and Bailleul; the color shading corresponds to different points in the spin's precession (lower expanded view), while the different lengths of the blocks correspond to different propagation rates. Again, the spin waves propagating to the left and right of the source S have different wavelengths because of the spin current (large arrow) present in the system. The source and detector D are efficient only for a narrow range of wavelengths, so the maximum detector output occurs at a different frequency when the current flows. This transmission frequency shift yields the velocity of the effective magnetic medium of the spin waves.

when the source and the observer are stationary, but the medium is flowing. An example is surface waves on a flowing body of water. The relation between how fast the waves go up and down (frequency) and the separation between the peaks (wavelength) as measured by the stationary observer is different than it would be if the water were not flowing (see the figure, top and middle panels). Measuring these changes can be used to determine the speed of the flowing water.

Vlaminck and Bailleul measured the change in the oscillation frequency of spin waves of a fixed wavelength in the presence of the current flow. They use the measured change to determine the effective flow rate of the magnetic medium in which the spin wave propagates. This flow rate is one of the fundamental quantities that characterize current-induced domain wall motion. We expect this experiment to be the first of a series that will enable the measurement of the spin characteristics of currents in ferromagnets. Such studies should also allow for a more quantitative analysis of experiments performed in the development of spin-based devices.

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