ACOUSTICS

Now you hear me, now you don't

The first realization of an acoustic diode that passes sound in one direction but not the other signals a new approach to acoustic devices with complex functionality.

Baowen Li

Often in crime programmes on television or in films there are scenes in which a suspect is questioned while detectives watch from behind a one-way mirror. The one-way mirror reflects light from one side but lets light come through from the other. In electronics, a similar device has been in existence for decades — the electric diode, which allows an electric current to flow in only one direction. However, the analogue for acoustic waves has not been realized so far. This has now changed: in this issue, Jian-Chun Cheng and his colleagues from Nanjing University, China, experimentally demonstrate a prototype of a one-way acoustic mirror[1], theoretically proposed by the same group last year[2].

Figure 1 shows the schematic diagram of the acoustic diode. The diode consists of two segments, a phononic crystal and a nonlinear acoustic medium. The phononic crystal is a periodic structure made from alternating layers of water and glass. It acts as an effective acoustic filter, because its bandgap[3] prevents acoustic waves with frequencies within this bandgap from being transmitted through the structure. The frequency range of the bandgap can be altered by adjusting the elastic constant, mass density and layer thickness of the constituents (water and glass in the present case).

The other essential part in the acoustic diode is a material with strong acoustic nonlinearity. In their experiment, Cheng and colleagues use a layer of ultrasound contrast agent microbubble suspension. Ultrasound contrast agent is the gel that is widely used in ultrasound radiography to enhance the imaging quality of ultrasonic diagnostics. When an acoustic wave of a certain frequency travels through the microbubble suspension, it will be partially converted into a second wave of twice (or another integer multiple of) the original frequency. This is in direct analogy of the creation of overtones in musical instruments.

The acoustic diode then works as follows (Fig. 1). An acoustic wave coming in from the right-hand side goes through the nonlinear material first, which creates the overtones. Although the wave with the original frequency lies within the bandgap of the phononic crystal and will be reflected, the second harmonic, at twice that frequency, will pass freely through the phononic crystal. However, an acoustic wave arriving from the left-hand side will be totally reflected because only the original frequency is present, and this lies within the bandgap of the phononic crystal. In this case, the system works as an acoustic insulator.

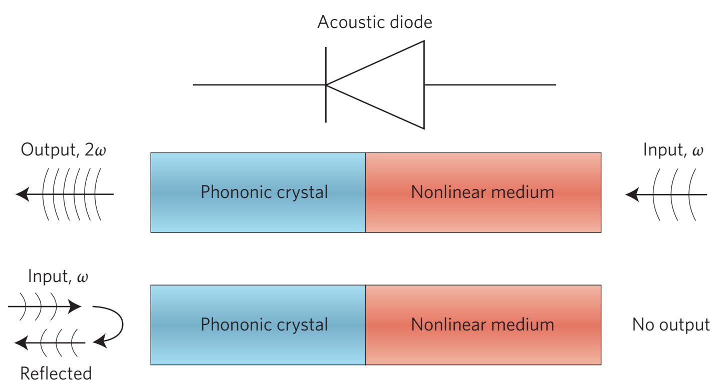

Figure 1 | The acoustic diode. The diode consists of two segments. The phononic crystal is a periodic array of water and glass layers. The nonlinear medium is a layer of ultrasound contrast agent microbubble suspension.

The invention of the electronic diode and related devices such as the transistor has revolutionized our daily lives. There are good reasons to believe that the acoustic diode might have a similarly significant effect, given that ultrasound has been used widely in biomedical imaging and non-destructive diagnostics. Even when it comes to our daily exposure to noise, an acoustic diode that acts as a noise barrier could lead to a quieter life.

However, before such applications can be developed, more work needs to be done. The difficulty of any acoustic device lies in the fact that the spectrum of acoustic waves spans 12 orders of magnitude in frequency, from a few hertz to tens of thousands of hertz (the frequency range of human hearing), to megahertz (ultrasound) and beyond, to the terahertz regime (molecular vibrations, which are in the form of heat). In contrast, the diode proposed by Cheng and colleagues works for only a single frequency or a narrow band of frequencies, which may constrain its applications. Another drawback is that when the acoustic wave goes through the diode its frequency doubles. This would distort the sounds we hear.

To overcome this limitation, we may borrow an idea from thermal diodes[4,5]. Indeed, the acoustic diode was originally inspired by the invention of the thermal diode, which rectifies heat flow due to lattice vibrations — phonons — and which works for lattice vibrations of all frequencies. Moreover, the concept of the thermal transistor[6] could also be extended to acoustic waves. It will not be a surprise if very soon researchers work out a similar device — an acoustic transistor — that manipulates and switches sound waves by using sound waves. There are good reasons to believe that one day acoustic waves and phonons will be as easy to manipulate as electrons. The new field of phononics is getting hotter and hotter[7]. ❐

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CORRELATED ELECTRON SYSTEMS

Reaching for the stars

The latest advances in our understanding of correlated electron systems have implications that range from fundamental physics such as string theory to novel applications including the manipulation and retrieval of electron spin.

Leon Balents and Zhi-Xun Shen

The interactions between electrons in condensed-matter systems are not only key to the understanding of known effects such as magnetism and superconductivity, but are also relevant to the study of phenomena such as the properties of topological insulators and their promise of low-loss spin electronics.

Bringing together these different aspects and approaches to the study of correlated electron systems was the aim of the Quantum Science of Strongly Correlated Systems (QS²C) Theory Forum, held at RIKEN's Tokyo campus from 27–30 September 2010. The forum, organized by Naoto Nagaosa (University of Tokyo and RIKEN), is part of the prestigious FIRST program on QS²C, led by Yoshinori Tokura (University of Tokyo and RIKEN).

The range of topics discussed at the meeting illustrates the breadth of this expansive field. On the first day, a spirited debate was engendered by talks by Jan Zaanen (Leiden University) and Mike Norman (Argonne National Laboratory), whose presentations discussed the anti-de Sitter/conformal field theory (AdS/CFT) correspondence, which is a mathematical approach developed by researchers working on string theory. As Zaanen highlighted in his talk, the AdS/CFT correspondence could make a successful connection between string theory and materials physics. An example where the application of the correspondence could be of benefit is with quantum critical points, which are important to the understanding of the properties of correlated materials, for example high-temperature superconductors. However, sounding a word of caution on the use of the AdS/CFT correspondence, Norman argued that such theoretical models need to arrive at independent, testable predictions.

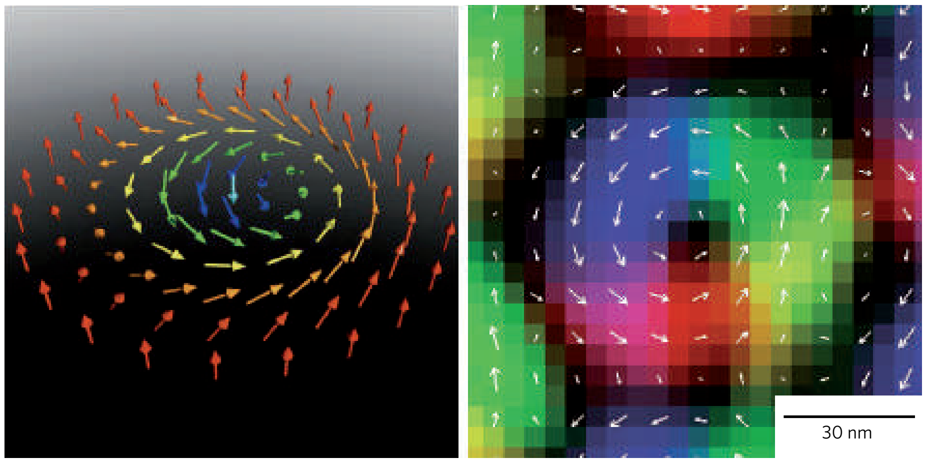

Figure 1 | Skyrmions on the surface of $Fe_{0.5}Co_{0.5}Si$. Left, schematic of spin configuration in a skyrmion. Right, the colour map and the white arrows represent the magnetization direction at each point. The formation of these magnetic structures is one of the many phenomena occurring in strongly correlated materials. (Adapted from X. Z. Yu *et al. Nature* **465,** 901–904; 2010; © NPG)

Many talks and discussions on the second day of the meeting centred on the recently discovered topological insulators. These compounds hold the promise of offering new types of one- and two-dimensional electron systems at the edges and surfaces of two- and three-dimensional materials, respectively. Shoucheng Zhang (Stanford University), Alexander Balatsky (Los Alamos National Laboratory), Masaki Oshikawa (ISSP, University of Tokyo), Yong-Baek Kim (University of Toronto) and Akira Furusaki (RIKEN) presented their latest theoretical results on the behaviour of topological insulators. The emphasis was on magneto-electrical and magneto-optical effects in topological insulators, quantization phenomena and the influence of non-magnetic and magnetic impurities on the properties of these materials. The search for new topological insulators was another topic at the meeting. So far, the materials investigated as topological insulators only show weak electron correlations. Consequently, the electronic properties of topological insulators with strong Coulomb correlations, and possible candidate materials among the oxides, were discussed by Hidenori Takagi (University of Tokyo and RIKEN).

A set of stimulating theoretical talks on transition-metal oxide nanostructures and heterostructure interfaces highlighted the potential of this rapidly growing area of materials physics. These systems open a window onto the study of strong-correlation physics and emerging phenomena where a constrained geometry provides a new ground for novel properties. This activity is stimulated by the exciting developments in materials synthesis and design, exemplified by materials such as oxide heterostructures