Controlling superconductivity

The use of intense ultrafast terahertz pulses to gate superconductivity not only provides insights into charge transport in such materials but may also lead to new forms of data switching, explains Andrea Cavalleri.

What is your interest in the study of superconductors?

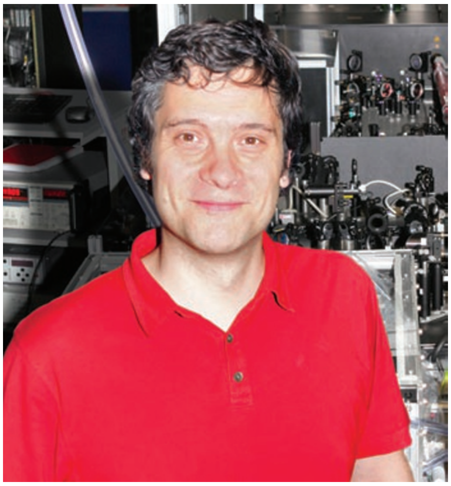
In superconductors such as $La_{1.84}Sr_{0.16}CuO_4$, clouds of charges move in each plane without resistance. Although individual superconducting layers are separated by regions of insulating material, they are coupled to each other by tunnelling. This inductor effect, together with the capacitance of the planes themselves, gives rise to a resonance in the terahertz range. The resulting collective charge oscillation in the direction perpendicular to the planes is known as a Josephson plasmon. Whereas a conventional plasmon is attributed to charge oscillations on a metal surface, a Josephson plasmon is due to oscillations of the Cooper pairs between the superconducting layers. This behaviour has been studied in detail for the past two decades and it is well-described in the literature. I wanted to investigate the nonlinear response of a Josephson plasmon to a strong oscillating electric field — an effect that requires the application of a strong field near the material's resonance frequency.

How did you get the idea of controlling charge transport using terahertz waves?

The idea comes from the classic a.c. Josephson effect, which has been studied since the 1960s in artificial junctions between low-temperature superconductors. I believed that if this effect was accessible using strong terahertz pulses then it should be possible to control the phase and amplitude of the Josephson plasmon between the layers of a high-temperature superconductor. Before the experiment, I was expecting an oscillatory transition between the Ohmic and superconducting states. Naturally, I was extremely excited when a resistive transition was experimentally observed.

What made the experiment possible?

The key was the ability to conduct a pump–probe experiment using intense and ultrashort terahertz pulses. To observe the nonlinear response of a Josephson plasmon, the electric field inside the material must be more than 100 kV cm^{-1}. At the same time, we have to remove the heat caused by the application of an external field. In fact, if the pulse is of the order of picoseconds, microjoules of energy are enough to produce the required intense electric field. Thus, the strong-field terahertz technology developed by Keith Nelson's group at the Massachusetts Institute of Technology in the USA was essential for this study. We also owe much gratitude to Hidenori Takagi's group at the University in Tokyo and RIKEN in Japan, who fabricated an optimally doped $La_{1.84}Sr_{0.16}CuO_4$ crystal for us. Without a material of such high crystalline quality, we wouldn't have discovered this exciting phenomenon.


UNIVERSITY OF HAMBURG

Andrea Cavalleri's team have found a way to modulate superconductivity using terahertz waves.

How are your findings likely to inspire others?

Our findings provide a new perspective on superconductivity. We have demonstrated that it is possible to modulate superconductivity using coherent terahertz radiation. The results are also likely to be of interest to scientists working in plasmonics, as the Josephson plasmon is non-dissipative and occurs in the terahertz range of the spectrum. Our work may also be interesting to the cold-gases community, which deals with the dynamics of coherent states such as Bose–Einstein condensation, and also to those involved in quantum communication and computing.

What applications will benefit from your results?

The most likely opportunities will be in the field of information science, such as for data storage and switching. This work may allow the realization of phase-change materials that are analogous to DVD media. Instead of switching the transition between crystalline and amorphous phases, you could switch between Ohmic (resistive) and superconducting states at ultrahigh speeds. Another potential application is the creation of a terahertz transistor with, in theory, zero energy dissipation. Note that the electric-field modulation of the conductivity is fully equivalent to transistor action, except that the change in resistance is obtained by modulating a quantum-mechanical phase and not the density of carriers in a channel. Therefore, no or very little dissipation is induced, which makes the modulation reversible at terahertz frequencies. Currently, the need for a cryogenic operating temperature is one of the factors that limits practical applications.

What are your plans and goals for future work in this area?

One important goal is to achieve control of the superconducting state at higher temperatures. The ability to manipulate the phase at ultrahigh speeds is only the first step in a process that may allow the control or even cooling of fluctuations that destroy superconductivity. Another goal is to create special non-equilibrium states in which the dimensionality can be switched from three to two, and then observe how this affects the dynamics of the system. By manipulating the pulse shape, we may be able to modulate the strength of the superconducting coupling more precisely than in our present work. Such pulses — analogues of the π pulses found in nuclear magnetic resonance (π/2 in this case) — could be used to drive a system from perfectly superconducting to perfectly Ohmic, or vice versa.

INTERVIEW BY NORIAKI HORIUCHI

Andrea Cavalleri and co-workers have a Letter on the terahertz modulation of superconductivity on page 485 of this issue.