Manipulating superconducting plasma waves with terahertz light

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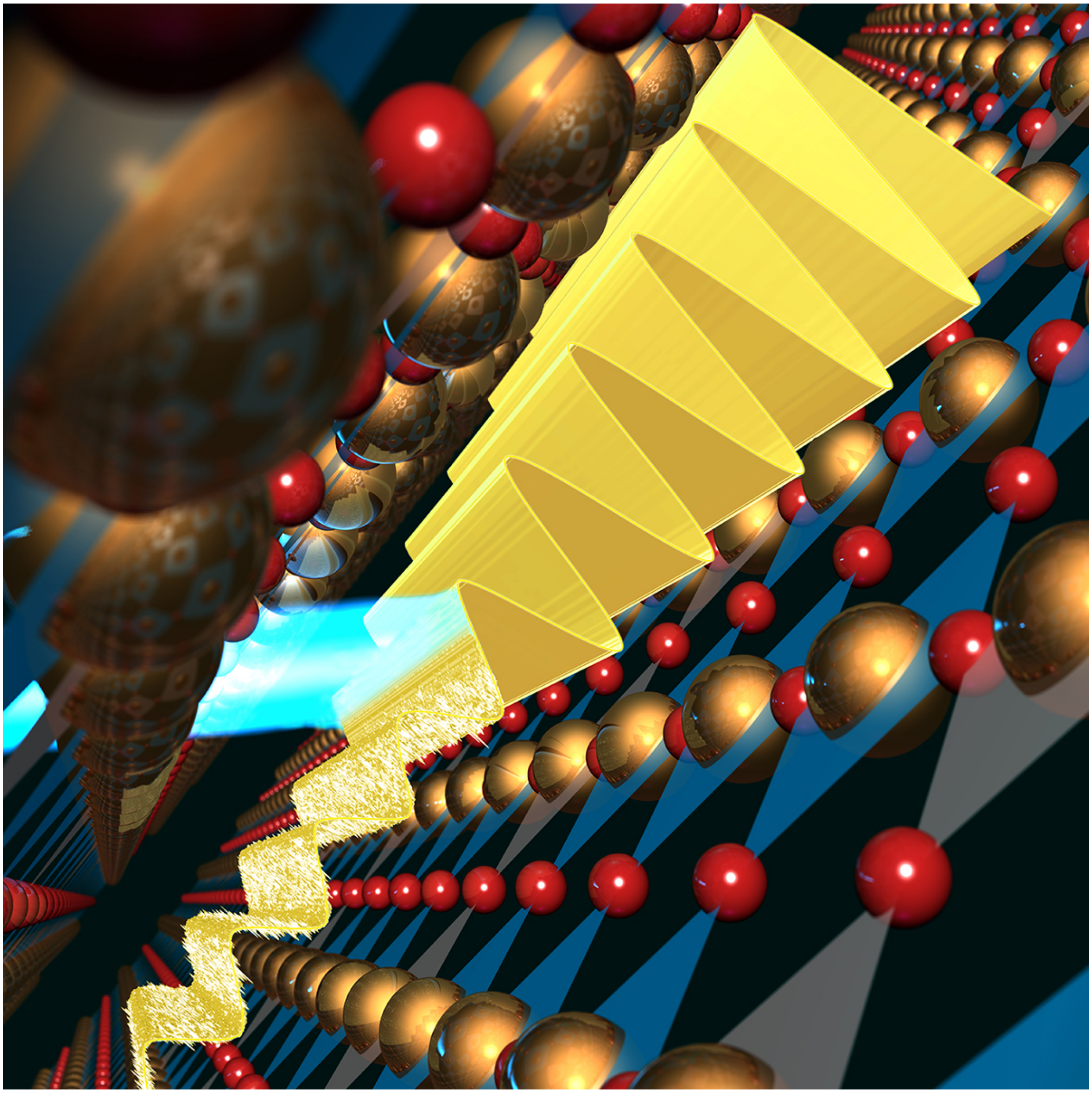

Josephson plasma wave in a layered superconductor, parametrically amplified through a strong terahertz light pulse. Credit: Max Planck Institute for the Structure and Dynamics of Matter

Most systems in nature are inherently nonlinear, meaning that their response to any external excitation is not proportional to the strength of the applied stimulus. Nonlinearities are observed, for example, in macroscopic phenomena such as the flow of fluids like water and air or of currents in electronic circuits. Manipulating the nonlinear behavior is therefore inherently interesting for achieving control over several processes. An international team of researchers led by Andrea Cavalleri from the Max Planck Institute for the Structure and Dynamics of Matter at CFEL in Hamburg utilized the nonlinear interaction between a terahertz light field and a superconducting plasma wave in a high temperature cuprate superconductor to amplify the latter. This resulted in a more coherent superconductor, which is less susceptible to thermal fluctuations. Due to the non-dissipative superconducting nature of the plasma wave, the study opens up new avenues for "plasmonics", a field of science utilizing plasma waves for transmitting information. These findings are reported in the journal *Nature Physics*.

The Josephson effect

The Josephson effect, predicted by Brian D. Josephson in 1962, consists in the tunneling of Cooper pairs across a thin, insulating junction between two superconductors. This superconductor-insulator-superconductor structure is called a Josephson junction. This theory was soon experimentally confirmed and in 1973 Josephson received the Nobel Prize in Physics, as his prediction resulted in the verification of the macroscopic quantum nature of superconductors.

The charge dynamics in Josephson junctions is governed by the Josephson equations, which state that the current associated with the tunneling Cooper pairs is proportional to the sine of the phase difference between the two superconductors. Under an applied voltage, the current oscillates at a frequency that depends on the voltage drop at the junction. The Josephson effect not only resulted in fundamental advances in physics but also in many applications including so-called SQUIDs, i.e. very sensitive magnetometers that are used to measure extremely weak magnetic fields. These are used, for instance, in medicine for mapping brain activity (magnetoencephalography). Moreover, Josephson junctions are nowadays employed as an extremely precise voltage standard, because the Josephson effect is a quantum effect that relates voltages and frequencies (or time) by a proportionality involving only fundamental constants.

Current research topics utilizing the Josephson effect include the realization of qubits for quantum computing and photonic devices in the gigahertz (GHz) and terahertz (THz) frequency regime.

Josephson plasma waves in cuprate superconductors

Layered superconductors like high-T_c cuprates – being built of alternating superconducting and insulating planes – are a nanoscale version of a stack of Josephson junctions. In these materials, superconducting transport first occurs in the copper-oxygen planes, while three-dimensional superconductivity emerges via Josephson tunneling in the direction perpendicular to the planes.

In analogy to Maxwell's equations in electrodynamics, whose temporal and spatial dependence results in electromagnetic waves, the Josephson relations result in the so-called Josephson plasma waves. The frequency of these waves falls into the THz range for cuprate materials and can therefore be observed with conventional THz spectroscopy.

The team around Andrea Cavalleri used THz radiation to probe Josephson plasma waves in barium-doped lanthanum copper oxide ($La_{1.905}Ba_{0.095}CuO_4$). From the reflection of the probe pulse they could detect oscillations at about half a THz frequency. "When we irradiated the superconductor with our weak probe pulses, we could observe oscillations of the reflected field at a specific frequency, the so-called Josephson plasma frequency," says Srivats Rajasekaran, first author of the paper and postdoc at the MPSD in Hamburg.

Nonlinearities of Josephson plasma waves and parametric amplification

Since the Josephson plasma waves are governed by the Josephson relations, they are inherently nonlinear. In the current study, these Josephson plasma waves were driven into a highly nonlinear regime using an additional intense THz pump pulse with very large field strengths of up to 100 kV/cm. This was made possible by exploiting the recent advances in THz technology. In this regime, amplification of the Josephson plasma wave was observed experimentally. "The reflectivity of the sample became larger than 100% and, on top of that, the absorption coefficient became negative. These are clear indications of amplification occurring inside the material," explains Srivats Rajasekaran.

Parametric amplification in simple oscillating systems, achieved by periodically modulating some specific parameter, is a well-understood phenomenon. For instance, a child on a swing increases its oscillation amplitude by periodically raising and lowering its center of mass. An example from electronics is an LC circuit with periodically varied capacitance or inductance. Parametric amplifiers of this type have applications in the enhancement of weak signals without increasing its noise (used e.g. in radio astronomy). "When it comes to parametric amplification, a layered superconductor acts very much like an LC circuit," says Srivats Rajasekaran. "The Josephson supercurrent is like a wire connecting the plates of a capacitor – the copper oxide layers." The inductance of the supercurrent depends on the phase difference between the layers, and this phase difference varies with time and position on the plane.

"When we applied our intense pump pulse, the pump-probe response oscillated at twice the Josephson plasma frequency. This is equivalent to modulating the inductance periodically, which is required for parametric amplification," adds Srivats Rajasekaran. "This is the first time that the effect of parametric amplification by light irradiation has been demonstrated for Josephson plasma waves," declares Andrea Cavalleri, director at the MPSD in Hamburg.

Potential Applications

Amplification of Josephson plasma waves, exploiting the nonlinear Josephson relations with THz pulses, falls in the category of the previous works led by Andrea Cavalleri on layered superconductors, wherein THz light was utilized to switch off and on superconductivity between the planes and to generate superconducting solitons. In addition, this work has implications in the control of fluctuations of the superfluid. "The possibility to parametrically control the superfluid in layered superconductors might eventually provide a tool to stabilize fluctuating superconductivity, perhaps even for temperatures above the critical temperature," concludes Andrea Cavalleri.

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