Toward clearer, cheaper imaging of ultrafast phenomena

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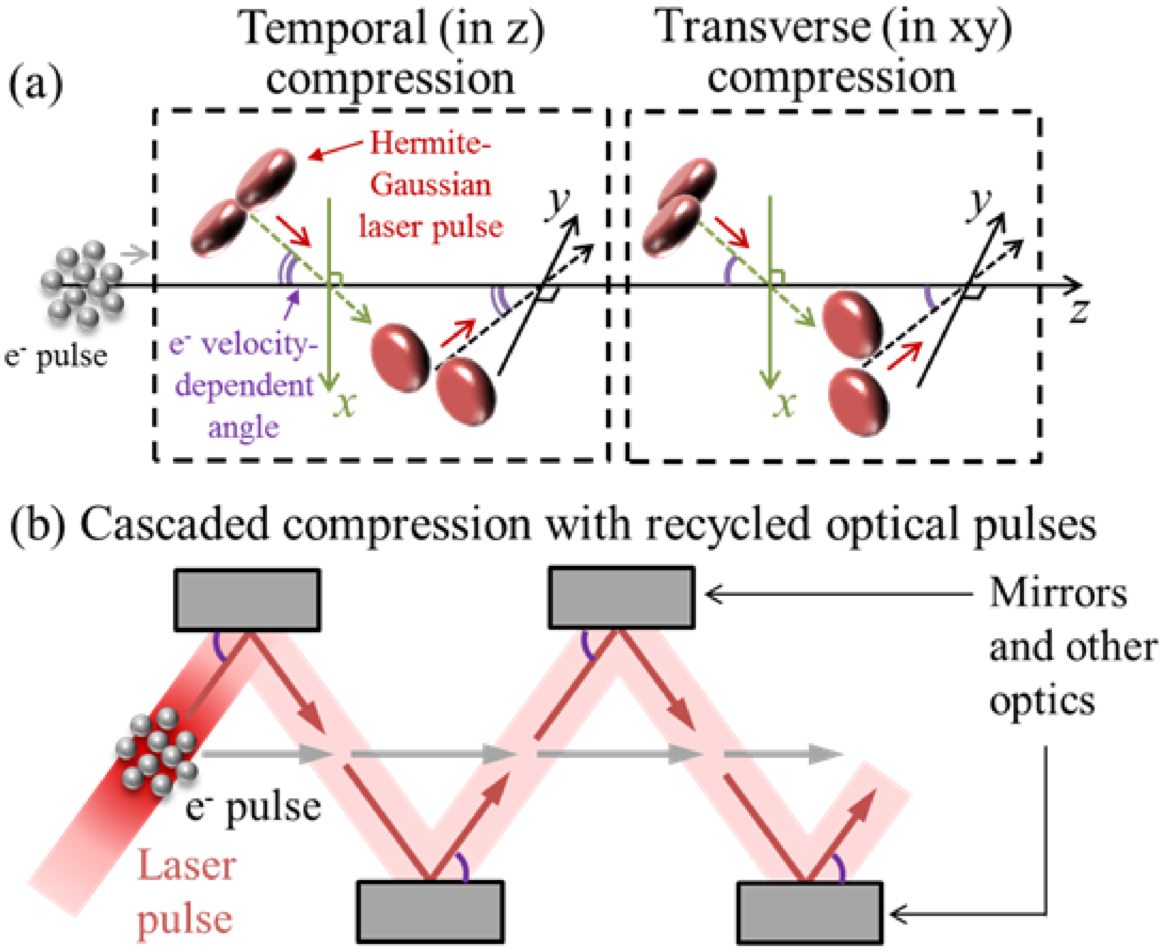

An all-optical, 3-D method of electron pulse compression for applications like ultrafast electron imaging is shown schematically in (a), with a cost-effective implementation depicted in (b). Credit: Liang Jie Wong/ Singapore Institute of Manufacturing Technology and Massachusetts Institute of Technology

Many mysteries of nature are locked up in the world of the very small and the very fast. Chemical reactions and material phase transitions, for example, happen on the scale of atoms—which are about one tenth of one billionth of a meter across—and attoseconds—which are one quintillionth (10^-18) of a second long. A research team from Massachusetts Institute of Technology (MIT), Massachusetts, in collaboration with the Singapore Institute of Manufacturing Technology (SIMTech), Singapore, have proposed a new technique that may help record better images of such ultrafast phenomena. The team will present their work at the Frontiers in Optics, The Optical Society's annual meeting and conference in San Jose, California, USA, held from 18-22 October 2015.

Ultrafast electron pulses are one tool scientists use to probe the atomic world. When the pulses hit the atoms in a material, the electrons scatter like a wave. By setting up a detector and analyzing the wave interference pattern, scientists can determine information like the distance between atoms. Conventional electron pulse technology uses a static magnetic field to compress the electrons transversely. However, the static field can interfere with the electron source and the sample and lead to temporal distortion of the electron pulses—both of which can lead to lower quality images.

To avoid the problems associated with static field compression the MIT and SIMTech team proposed the first all-optical scheme for compressing electron pulses in three dimensions and demonstrated the viability of the scheme via first-principle numerical simulations. In the scheme, laser pulses, functioning as three-dimensional lenses in both time and space, can compress electron pulses to attosecond durations and sub-micrometer dimensions, providing a new way to generate ultrashort electron pulses for ultrafast imaging of attosecond phenomena.

"Using this scheme, one can compress electron pulses by as much as two to three orders of magnitude in any dimension or dimensions with experimentally achievable laser pulses. This translates, for instance, to reducing the duration of an electron pulse from hundreds of femtoseconds to sub-femtosecond scales," said Liang Jie Wong, the lead researcher on the team, who is now at the Singapore Institute of Manufacturing Technology and was formerly a postdoctoral fellow at the Massachusetts Institute of Technology.

"Notably, the scheme involves no static fields and features independent control of the compression in each dimension," Wong noted.

Compressing Electron Pulses in Time and Space

Short pulse durations are critical for high temporal resolution in ultrafast electron imaging techniques. These techniques can create movies that allow scientists to observe, in real-time, how molecules interact in a chemical reaction, or how the structure of a material or microorganism is affected by the introduction of external stimuli.

To ensure that the electron pulse arrives at the sample or detector with the desired properties in spite of inter-electron repulsion, ultrafast electron imaging setups usually require means to compress the electron pulse both transversely and longitudinally. Conventional methods typically employ static-field elements such as solenoids, which are coils of wire that create uniform magnetic fields, to focus the electron beams. The use of static field elements can lead to the undesirable presence of static magnetic fields on the electron source (cathode) and the sample and can also cause temporal distortions when transporting ultrashort electron pulses.

To solve these problems, Wong's team conceived an all-optical scheme that focuses electron pulses in three dimensions by using a special type of laser mode with an intensity "valley" (or minimum) in its transverse profile, which is technically known as a "Hermite-Gaussian optical mode." The pulsed laser modes successively strike the moving electrons at a slanting angle, fashioning a three-dimensional trap for the electrons.

"To compress the electron pulse along its direction of travel, for instance, the laser-electron interaction accelerates the back electrons and decelerates the front electrons. As the electrons propagate, the back electrons catch up with the front electrons, leading to temporal compression of the electron pulse," Wong explained. The force that the optical field exerts on the electrons is called the optical ponderomotive force, a time-averaged force that pushes charged particles in a time-varying field towards regions of lower intensity.

"Just as conventional lenses can be used to focus a light beam, our configuration can be used to focus an electron beam. In our case, however, we can perform the focusing not only in the dimensions perpendicular to the direction of travel, but also in the dimension parallel to the direction of travel. Hence, the entire setup can be seen as a spatiotemporal lens for electrons," Wong said.

By modeling the fields with exact solutions of Maxwell equations and solving the Newton-Lorentz equation, which together describe classical optical and electromagnetic behavior, Wong and his collaborators have analytically and numerically demonstrated the viability of their scheme. Among their findings is the fact that the longitudinal compression is sensitive to the laser pulse incidence angle, which is a function of the electron pulse velocity for optimal performance.

A major cost-saving feature in the proposed scheme is the fact that a single optical pulse can be used to implement a succession of compression stages. Since the scheme allows laser pulses to be recycled for further compression of the same electron pulse (not restricted to the same dimension), one is able to maximize the use of a single laser pulse and to achieve 3D compression with that single pulse.

Besides being of great interest in ultrafast electron imaging for compressing both single- and multi-electron pulses, the proposed scheme is potentially useful for focusing other particles such as accelerated protons and neutral atoms. Broader applications include the creation of flat electron beams and the creation of ultrashort electron bunches for coherent terahertz emission in free-electron based terahertz generation schemes, which in turn has a wide range of applications from biomedical imaging to airport security.

The next step for the research team is to present a proof-of-concept experimental realization of this scheme.

More information: The presentation, "Temporal Lenses for Three-Dimensional Electron Pulse Compression," by Liang Jie Wong, will begin at 17:00, Thursday, 22 October 2015, in The Fairmont Hotel, San Jose, California, USA.

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