Astonishingly short mid-infrared pulses offer new tool for peering inside atoms and solids

October 11 2016

A newly developed laser pulse synthesizer that generates femtosecond pulses at mid-infrared (IR) wavelengths promises to provide scientists with a better view of the inner workings of atoms, molecules and solids. Understanding the behavior of electrons and other atomic elements at time scales shorter than one oscillation of a light wave could lead to a host of new developments, such as extremely sensitive sensors and electronics that are a thousand times faster than what is state-of-the-art today.

In a paper that will be presented at the OSA Laser Congress in Boston, Massachusetts, USA, researchers demonstrate a technique for generating phase-stable pulses only 13 femtoseconds long that span mid-IR wavelengths from 2.5 to 9 microns with 33 microjoules of scalable energy.

"These mid-IR pulses will allow new types of experiments that explore dynamics taking place in atoms, molecules and solids," said Kyung-Han Hong, principal research scientist at the Massachusetts Institute of Technology's Research Laboratory of Electronics, Cambridge, Massachusetts, USA, and project leader for the research team. "For example, we can use them to take a movie of how electrons behave inside of atoms and solids."

Atomic processes, such as an electron transitioning to another energy level, are some of the fastest processes known. They are measured in hundreds of attoseconds, with one attosecond equaling a quintillionth of a second or one thousandth of a femtosecond. Studying these high-speed processes requires extremely short, high power laser pulses. For the past several decades, the only technology available to accomplish this feat used near-IR wavelengths; the new device is the first to attain these extremely short pulses in the mid-IR range with favorable energy scalability.

Mid-IR benefits

Mid-IR pulses could benefit a variety of applications and scientific research areas. For example, for non-invasive surgery these wavelengths can remove diseased tissue without damaging the surrounding healthy tissue. These pulses are also useful for spectroscopy and observing fast chemical reactions since many biological molecules and atmospheric chemicals absorb in this wavelength range.

Hong's team has been interested in using the high-energy, mid-IR pulses for high-harmonic generation to produce coherent pulses in the extreme ultra-violet and soft X-ray regions. "Compared to near-IR and visible light, mid-IR pulses accelerate electrons to much higher energies and, thereby, generate higher energy photons," said Hong. "Also, isolation of soft X-ray pulses becomes easier at these wavelengths."

Soft X-ray and extreme ultra-violet pulses can be used by scientists to study various phenomena inside atoms and molecules at an attosecond time scale, for example. Near-infrared wavelengths worked well for studying gases but tended to damage solids before observation could take place.

"Scientists want to watch how electrons move around inside solids on timescales of 1000 attoseconds or less," said Hong. "At the mid-IR wavelengths it is much easier to drive high-harmonic generation in solids because the optical damage due to multiphoton processes are much less pronounced."

From two pulses to one

Much like a musical synthesizer combines notes to generate a new sound, the laser pulse synthesizer amplifies signals from any range of wavelengths and then combines those to generate stronger pulses. By combining pulses that span two octaves of mid-IR wavelengths, the researchers synthesized pulses with short durations and high peak power. This was possible because when the pulses come together, constructive interference in the middle of the pulses is additive while deconstructive interference cancels out the outer edges of the pulses. This process makes the pulses shorter and shorter until it eventually creates a sub-cycle pulse, meaning that the pulse width is less than one optical oscillation cycle.

At OSA Laser Congress, the researchers will detail how they used phase-stable 2.1-micron laser light to pump a mid-IR optical parametric amplifier (OPA) and create coherent pulses spanning either 2.5 to 4.4 microns with a pulse width of about 20 femtoseconds or 4.4 to 9 microns with a 30-femtosecond pulse width. By carefully maintaining pulse stability and making sure that the pulses precisely overlapped both temporally and spatially, they were able to combine these pulses into synthesized pulses that were only 13 femtoseconds wide and spanned 2.5 to 9 microns with 33 microjoules of energy.

Although the 13 femtosecond pulse duration is longer than what is possible with near-IR and visible wavelengths, it corresponds to less than one optical oscillation cycle of 5 micron wavelength, enabling the sub-cycle control of electron motion.

Adding more OPAs to the optical setup would allow higher energies, which would make the mid-IR pulses useful for even more experimental studies and applications. "This type of pulse synthesis has been routinely done in the microwave region, but it is much more difficult to do this in the optical region because the pulses are traveling much faster," said Hong.

Dr. Peter Krogen, a postdoc at MIT, will present "Mid-infrared sub-single-cycle pulse synthesis from a parametric amplifier covering the wavelength of 2.5-9.0 microns" during the Mid-IR Sources II session of the Advanced Solid State Lasers Conference on Wednesday, 02 November from 17:45 to 18:00 in Room 2 of The Westin Boston Waterfront.

Provided by Optical Society of America