Terahertz pulses enhance generation of attosecond light bursts

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High-order harmonics produced by co-propagating laser and terahertz pulses in noble gases enable shorter attosecond pulses from the extreme UV domain of the electromagnetic spectrum.

The constant drive to understand processes at the fastest timescales, in parallel with the rapid development of femtosecond lasers, has given birth to a new research field in physics called attoscience. The analysis of fundamental processes inside atoms and molecules at the attosecond timescale—such as photoionization, Auger decay, and migration of electron vacancies in atoms—calls for ever shorter and more powerful bursts of high-energy photons. The main tools of this new branch of fundamental research are represented by attosecond-length electromagnetic pulses that achieve their very short duration through a process called high harmonic (frequency) generation (HHG). This means that visible, femtosecond (a millionth of a billionth of a second) laser pulses are converted to high-order harmonics of the fundamental wavelength. These harmonics typically lie in the extreme UV spectral domain below 100nm wavelength and represent a broad spectrum supporting attosecond pulses.

Various optimization schemes for this process have been the focus of interest since the first demonstration of the technique some 10 years ago. However, when using a single-color HHG driver, the achievable photon energy and number are limited by the efficiency of the process at the single-atom level, as well as by macroscopic effects (e.g., phase matching of the harmonic radiation generated). As a new approach, we investigated a unique, robust scheme to enhance attosecond pulses by means of a co-propagating terahertz (THz) pulse (see Figure 1).

To demonstrate the versatility of this idea, we analyzed the effect of the THz field on HHG by an 800nm IR laser pulse. The IR-laser driving field and the control THz pulse propagate collinearly with maximum spatial and temporal overlap. State-of-the-art THz technology enables fields with more than 100MV/cm field strength. Under these conditions, we have performed single-atom calculations to analyze electron trajectories in the combined electric field of the laser and THz pulse.

When using few-cycle laser pulses to drive HHG, the bandwidth available for attosecond pulse production can be significantly increased (see Figure 2). This allows for pulse durations down to 85asec. With adequate chirp compensation, the

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THz-enhanced attopulse duration can be further reduced to 44 as.

To investigate the process further, we employed a complete 3D macroscopic model. In this model, the single-atom response is calculated from the Lewenstein integral, which is known to reproduce the important aspects of HHG in gases well. We solved the propagation equations for the laser, THz, and harmonic fields using a Fourier-transform method in paraxial approximation, by taking into account the effects of absorption, dispersion on atoms and electrons, as well as the optical Kerr effect. The three fields propagate in a medium with refractive indices mainly influenced by the plasma created by their total electric field.

We found that macroscopic effects play a very important role in this process (see Figure 3). The focusing of the THz field (8 μm central wavelength, 37.5 THz) to a 76 μm spot size alone is responsible for a phase shift of 0.4 rad (corresponding to ~1.7 fs) over a 1 mm propagation distance. Another important effect is that of the plasma dispersion, which—scaling with the square of the wavelength—has a very strong effect on long-wavelength fields, such as the THz. We analyzed the effects of the experimentally tunable parameters (gas pressure, delay between the two pulses, and laser pulse energy) on the process. We also tried varying the length of the gas cell. We optimized all these parameters to obtain short and powerful attopulses from high-energy photons. As a result, we predict that pulses as short as 130 as are obtainable (without chirp compensation). Another important result is that the THz field can help to eliminate some of the pulses in an attosecond pulse train, making possible the generation of single-attosecond pulses with multicycle laser pulses as long as 12 fs.

In summary, we have shown that combining femtosecond laser pulses with THz fields enables production of isolated attosecond pulses. The achievable photon energy is also increased significantly compared with a more standard scheme using an IR laser driver alone. The next goal of this research is to verify the proposed technique experimentally to deliver state-of-the-art tools for attoscience experiments.

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