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Building Science and Theory of Laser-Matter Interaction toward Super-Smart Society

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The Physics Nobel Prize in 2018 was awarded for groundbreaking inventions in the field of laser physics to A. Ashkin, G. Mourou, and D. Strickland. The prize motivation for the latter two was "for their method of generating high-intensity, ultra-short optical pulses," i.e., chirped-pulse amplification (CPA). The Nobel Committee for Physics names CPA technology's major applications, among which the first is *strong-field physics and attosecond science* and the third *high-intensity lasers in industry and medicine*.

Strong-field physics and attosecond science are rapidly progressing toward a world-changing goal of direct measurement and, ultimately, control of the electron motion in matters. To exactly simulate intense laser-driven multielectron dynamics in atoms and molecules from the first principles (*ab initio strong-field physics*), we have developed various cost-effective wavefunction-based methods such as time-dependent multiconfiguration self-consistent-field (TD-MCSCF) methods [1], the time-dependent optimized coupled-cluster (TD-OCC) methods using time-varying orbitals, and the gauge-invariant time-dependent configuration-interaction-singles (TDCIS) method. In this talk, we report their formulations, numerical implementations, and comparison with experimental results.

Thanks to the advent of high-intensity mid-infrared to terahertz radiation sources, solid-state materials have recently emerged as a new stage of strong-field physics and attosecond science. In particular, the mechanism of high-harmonic generation (HHG) from solids are under intensive discussion. Here we theoretically discuss the momentum-space pictures of HHG from crystalline dielectrics and semiconductors [2]. We introduce a multiband momentum-space three-step model that incorporates intraband displacement, interband tunneling, and recombination with a valence-band hole. We also analyze how the model is modified by electron-hole interaction. Then, we present a time-dependent density-matrix method that simulates HHG from actual three-dimensional materials.

The extension of the frontier of strong-field physics and attosecond science from atomic and molecular systems to solid-state materials will further advance application of high-intensity lasers in industry and medicine, such as laser processing. Laser processing is flexible with many parameters such as wavelength, pulse duration, and pulse energy. Today, these parameters are optimized by human experience and intuition. To meet the mass customization need in the coming super smart society, it is time to replace them with approaches driven by data, artificial intelligence (AI), and science & theory that highly integrate cyberspace and physical space (CPS) [3]. To promote smart production, we develop CPS laser manufacturing capable of proposing the optimal processing parameters based on simulation in cyberspace. Understanding laser processing belongs to multiscale and multidisciplinary cutting-edge science, involving highly nonlinear, dynamical processes. One of our focuses is to understand and simulate such strong laser matter interaction by combining different techniques, even starting from the first principles of quantum mechanics.

References

[1] T. Sato, Y. Orimo, T. Teramura, O. Tugs, and Kenichi L. Ishikawa, arXiv:1804.08246 (2018)
[2] K. L. Ishikawa, Y. Shinohara, T. Sato, T. Otobe, arXiv:2003.14090 (2020)
[3] Y. Kobayashi, et al., IEEE J. Sel. Topics Quantum Electron. 27, 8900108 (2021)