High-harmonic generation from doped Si pumped with intense ELBE THz pulses

Fanqi Meng[1], Mark D. Thomson[1], Frederik Walla[1], Alexej Pashkin[2], Harald Schneider[2], Sergey Kovalev[2], Jan-Christoph Deinert[2], Igor Ilyakov[2], Min Chen[2], Alexey Ponomaryov[2], Sergey G. Pavlov[3], Heinz-Wilhelm Hübers[3,4], Nikolay V. Abrosimov[5], Christoph Jungemann[6], Hartmut G. Roskos[1]

[1] *Physikalisches Institut, Goethe-Universität Frankfurt, 60438 Frankfurt am Main, Germany*

[2] *Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany*

[3] *Institute of Optical Sensor Systems, German Aerospace Center (DLR), 12489 Berlin, Germany*

[4] *Institut für Physik, Humboldt-Universität zu Berlin, 12489 Berlin, Germany*

[5] *Leibniz-Institut für Kristallzüchtung (IKZ), 12489 Berlin, Germany*

[6] *Institut für Theoretische Elektrotechnik, RWTH Aachen, 52062 Aachen, Germany*

High-harmonic generation (HHG) is a phenomenon resulting from the strongly nonlinear, non-perturbative interaction between intense electromagnetic pulses and matter. It has been intensively investigated ever since its first observation with optically excited noble-gas atoms in the late 1980s [1]. The HHG effect is not only widely applied in table-top, coherent X-ray sources but is also the key for the generation of intense attosecond pulses [2]. Gases and atom clusters are the most intensively employed materials for HHG. Recently, HHG has also been observed in bulk crystals [3], which has triggered a surge of research interest in HHG from solids [4].

Here, we extend our earlier work [5], and report the observation of HHG from weakly p-doped Si up to the fifth order upon pumping by intense FELBE THz pulses, and up to seventeenth order upon pumping by intense TELBE THz pulses. The frequency of the FELBE THz pulse is 1.27 THz, and the frequency of the TELBE THz pulse is 0.3 THz. The sample is boron-doped bulk Si and the experiments were carried out at a temperature of 4 K.

At low temperature, the holes lies at their ground states instead of the valence band. Upon the irradiation of an intense THz pulse, the holes are first excited to the valence band, and then accelerated to reach a high momentum and experience changes of their effective mass and scattering time. The observed HHG are attributed to the non-parabolicity of the valence band and the energy-dependent carrier scattering time [6]. We simulated the harmonic process with FDTD calculations based on the Drude model, in which the effective mass and the scattering time depends on the strength of the radiation field at any given moment in time (values derived by Monte Carlo simulations). Quantitative agreement between simulation and experiments were derived.

References

[1] M. Ferray et al., *Multiple-harmonic conversion of 1064 nm radiation in rare gases*, J. Phys. B **21**, L31 (1988).

[2] T. Brabec and F. Krausz, *Intense few-cycle laser fields: Frontiers of nonlinear optics*, Rev. Mod. Phys., **72**, 545 (2000).

[3] S. Ghimire et al., *Observation of high-order harmonic generation in a bulk crystal*, Nat. Phys. **7**, 138 (2011).

[4] H. A. Hafez et al., *Extremely efficient terahertz high-harmonic generation in graphene by hot Dirac fermions*, Nature **561**, 507 (2018).

[5] F. Meng et al., *Intracavity third-harmonic generation in Si:B pumped by intense terahertz pulses*, Phys. Rev. B **102**, 075205 (2020).

[6] G. Vampa et al., *Strong-field optoelectronics in solids*, Nat. Photonics, **12**, 465 (2018).