Nonadiabatic high-harmonic generation >100 eV enabled by few-cycle all-solid-state compression of an Yb femtosecond laser

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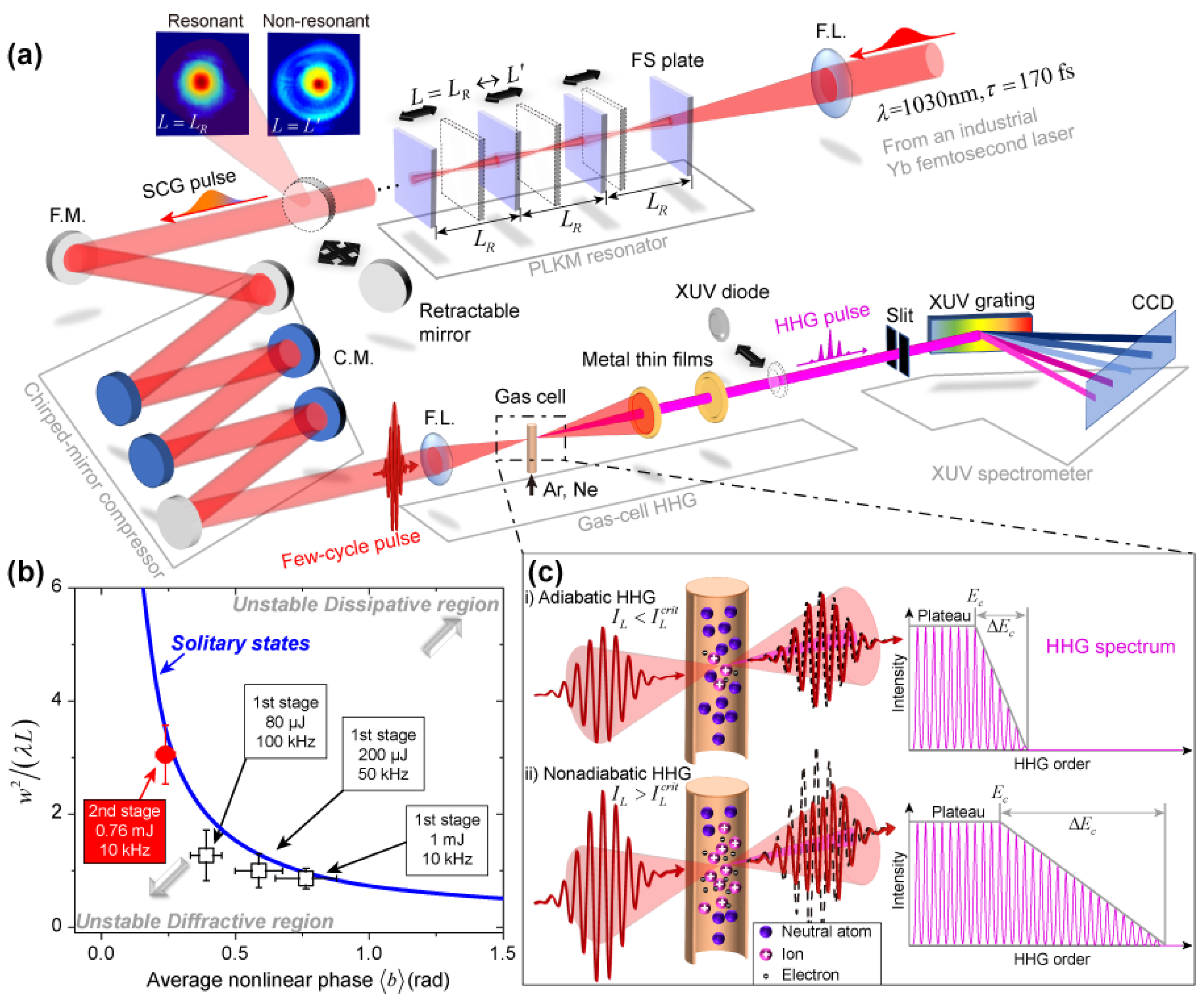
1. Introduction

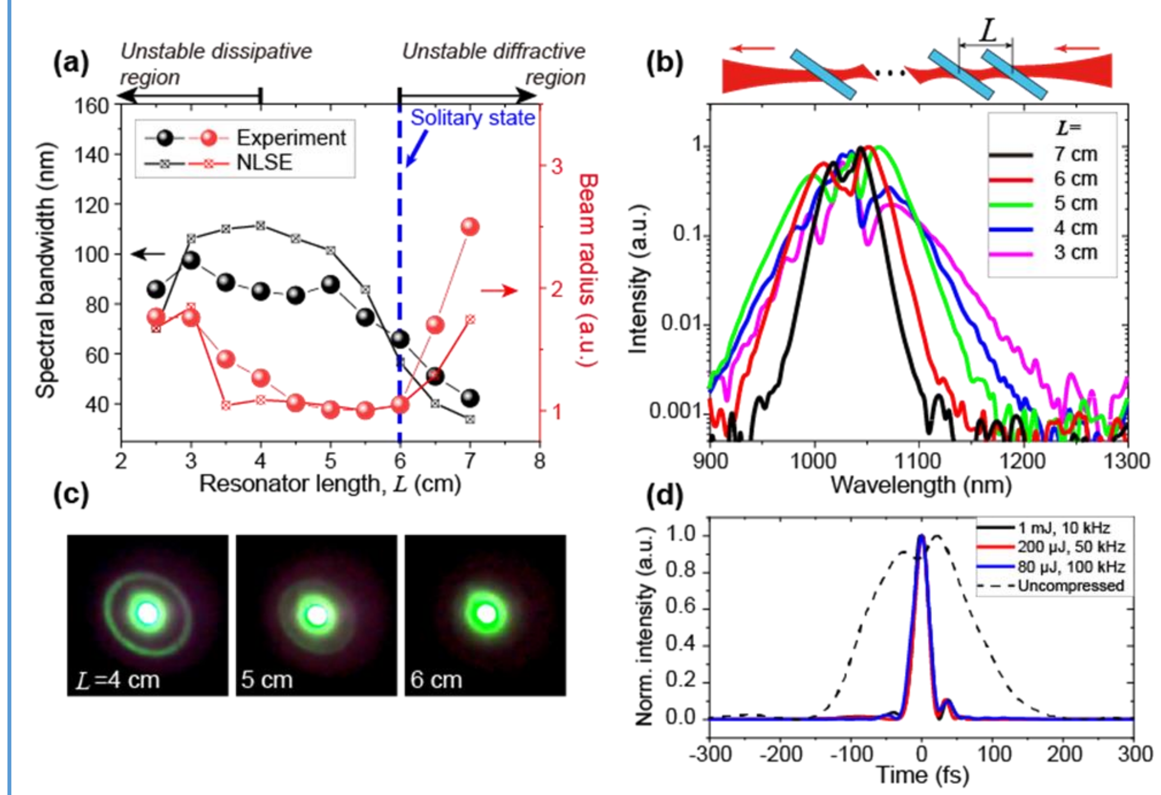
So far, the Yb-laser-based HHG sources are mostly optimized in the low-energy range (15 - 40 eV), which is fundamentally limited by their long pulse durations. In this work, we generate and optimize a >100 eV HHG source driven by a compressed Yb laser through two efforts: First, we demonstrate the flexible and efficient all-solid-state pulse compression of an Yb femtosecond laser to few cycles (~9 fs), which is enabled by the nonlinear propagation of solitary modes in periodic layers of Kerr media (PLKM). Second, we explore the generation of high-brightness >100 eV HHG in argon driven by the few-cycle pulses from the compressed Yb laser. We clearly show that the nonadiabatic effects dominate the HHG emission in argon beyond 100 eV, which is manifested as a significantly broad spectral extension beyond the cut-off energy. Remarkably, such an energy extension can be comparable to the cut-off energy. In contrast, driving HHG in argon with an Yb laser in the adiabatic region cannot reach the energy of 100 eV.



Universal relationship of the normalized beam radius squared as a function of the nonlinear phase b for the resonator solitary modes.

2. Main Results

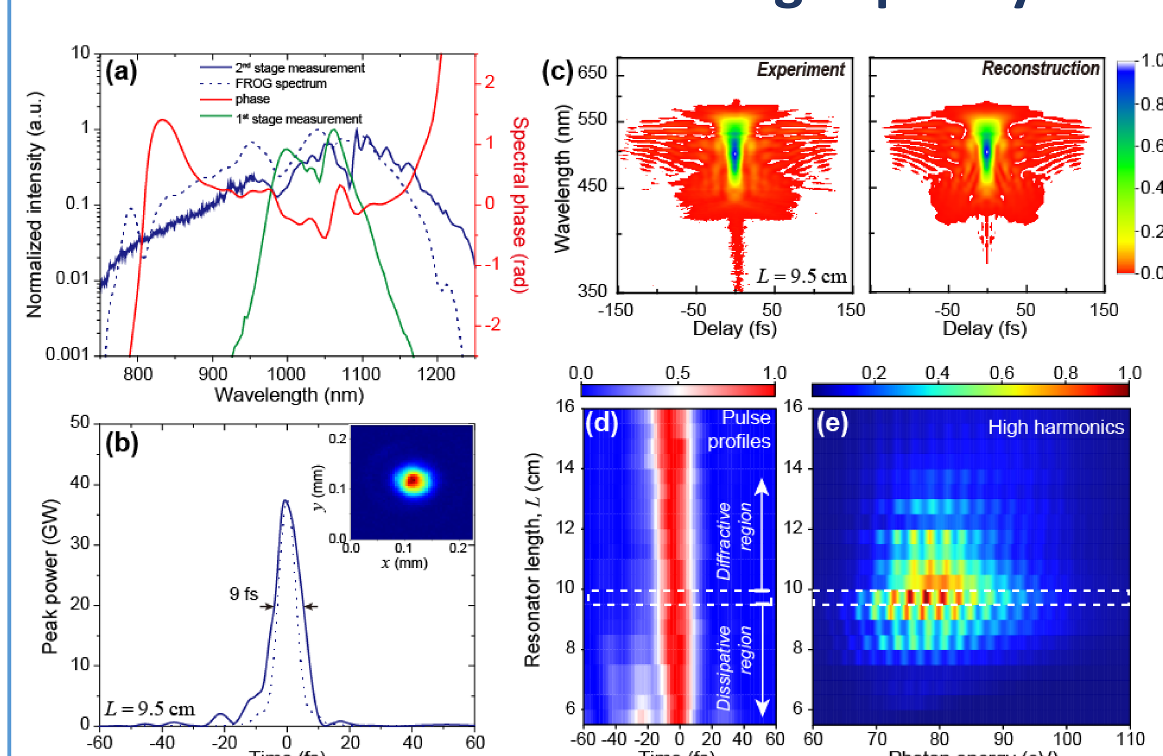
i. High-efficiency pulse compression enabled by PLKM



a) Spectral bandwidth and far-field beam radius;
b) Measured on-axial spectra;
c) Far-field spatial mode of the output beam;
d) Temporal profiles of the compressed pulses.

- Solitary state corresponds to the minimum of the far-field beam radius approaching from the long-L side.
- Shorter L condition has broader spectrum, but spatial chirp and conical emission is significant, which is manifested by the strong rings.
- Solitary state of the PLKM resulting in SCG with high efficiency and high spatiotemporal quality.
- The flexibility of our approach is demonstrated by compressing pulses under a wide range of pulse energies and repetition rates.

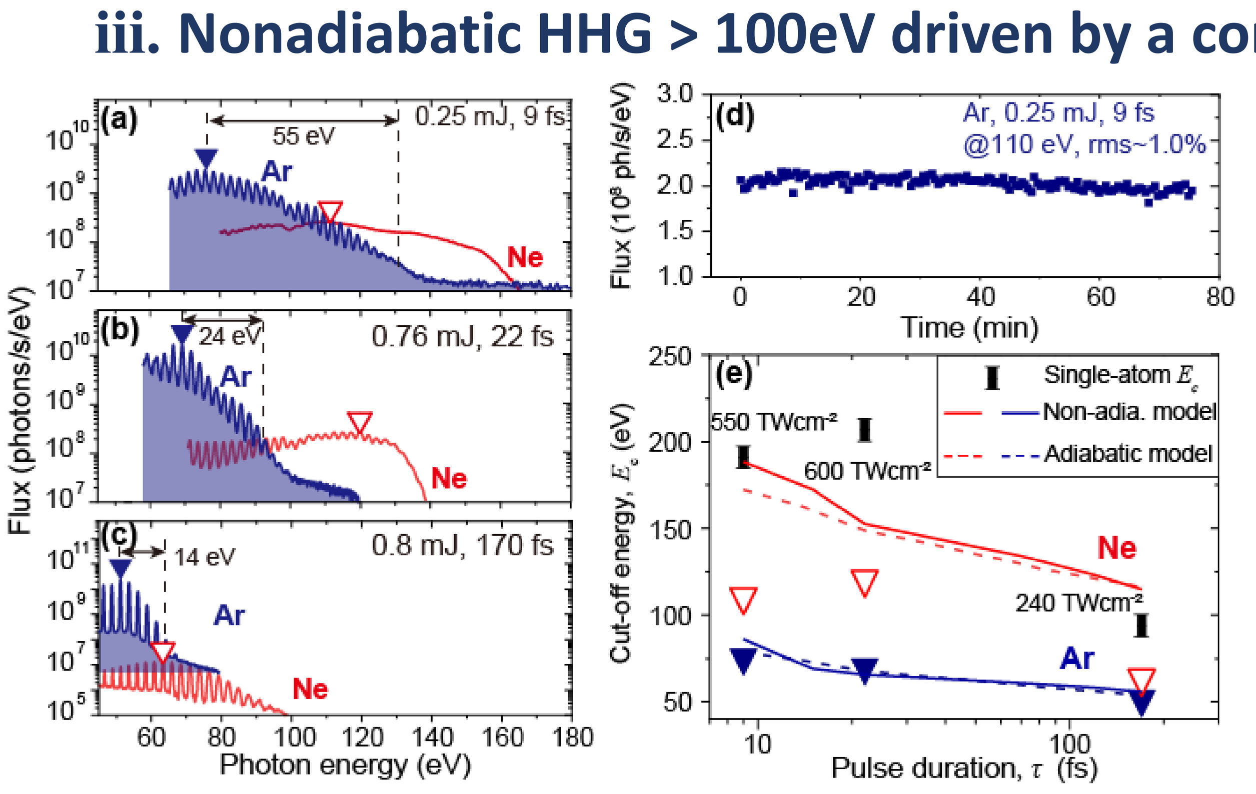
ii. Generation of high-quality few-cycle pulses



a) Measured, reconstructed spectra and the retrieved phase;
b) The temporal profile of the few-cycle pulses;
c) Measured and reconstructed FROG traces;
d) The temporal profiles under different resonator lengths L.
e) The HHG spectra excited by the pulses of (d).

- The measurement and reconstruction results have very good agreement.
- The 9fs pulse has only three cycles.
- The optimum condition is L=9.5 cm. This result demonstrates that the "resonant" condition can indeed yield optimum compression to the few-cycle pulses in both space and time.

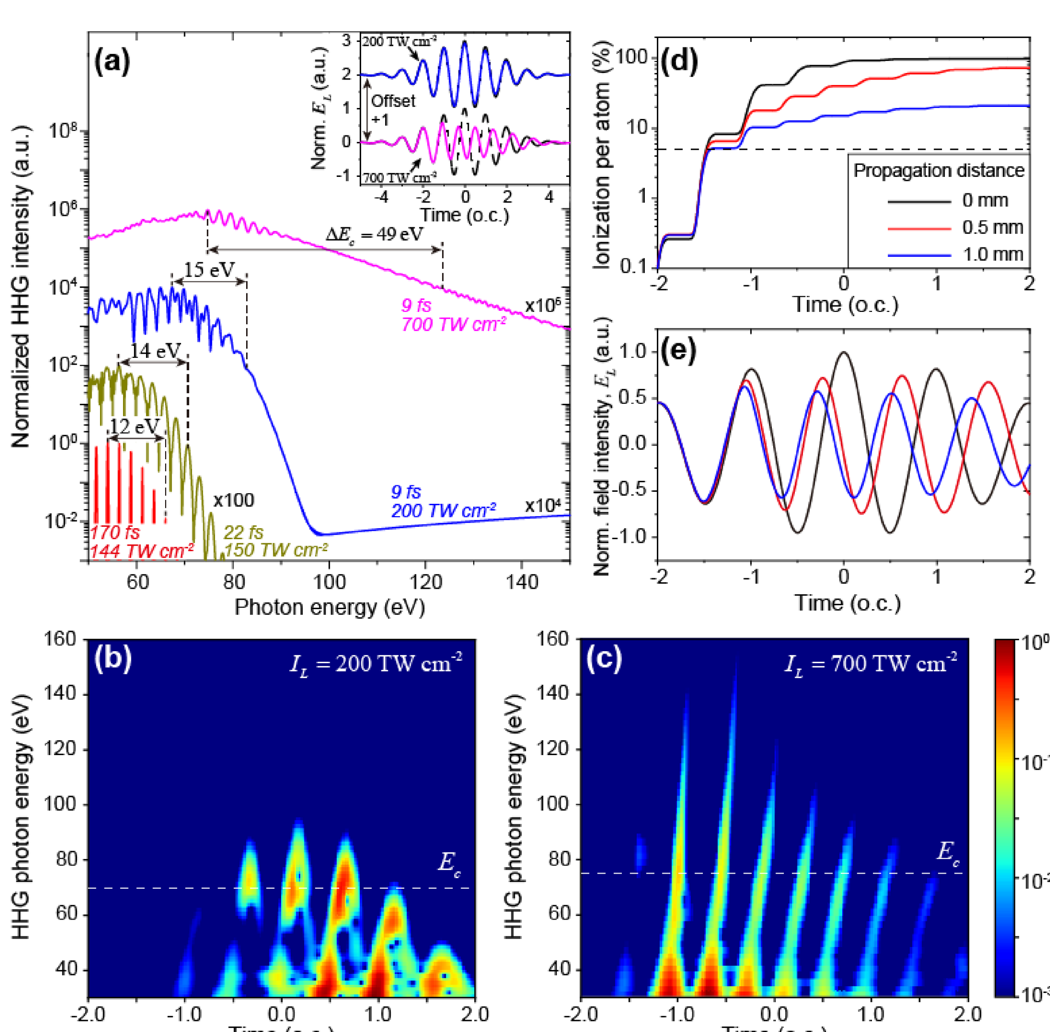
iii. Nonadiabatic HHG > 100eV driven by a compressed Pulse



a-c) HHG spectra driven by different condition. The triangle symbols label the cut-off energies (E_c);
d) Long-term stability;
e) The cut-off energies (E_c) driven under different conditions in comparison with different models.

- As the pulse length shortens, the effective harmonic energy increases significantly, and the increase is much greater than the increase in cutoff energy (the maximum spectral intensity energy).
- Phase match cutoff has a quantitative agreement with E_c under a wide range of the pulse durations, but this adiabatic model cannot explain the broad spectral extension.
- Such a good stability benefits from our stable and efficient pulse compression scheme.

3. Simulations



a) Simulation results of HHG spectra driven by different condition;
b,c) The time-frequency analysis of the HHG spectrum driven by τ = 9 fs pulse;
d) Evolution of the gas ionization driven by τ = 9 fs, I_L = 700 TW cm^{-2} for different propagation distance in argon.
e) The laser electric field at different distances corresponding to (d).

- The high-energy spectral tail ΔE_c originates from the sub-cycle generation of free electrons and the resulting variations of the laser electric field.
- HHG emission beyond E_c is mostly contributed by the pulse peak when the driving intensity is low, while it is shifted by more than 1 optical cycle to the rising edge under a strong driving field.
- Such an effect is averaged out when more optical cycles contribute to the HHG emission in longer pulses.

4. Conclusion

- We demonstrate the flexible and efficient all-solid-state pulse compression of an Yb femtosecond laser to few cycles (~9 fs), which is enabled by the nonlinear propagation of solitary modes in periodic layers of Kerr media (PLKM).
- We explore the generation of high-brightness >100 eV HHG in argon driven by the few-cycle pulses from the compressed Yb laser.
- Through the quantitative comparison between the experimental and theoretical results, we clearly show that the nonadiabatic effects dominate the HHG emission in argon beyond 100 eV, which is manifested as a significantly broad spectral extension beyond the cut-off energy.

References: S. Zhang, Z. Fu, B. Zhu, G. Fan, Y. Chen, S. Wang, Y. Liu, A. Baltuska, C. Jin, C. Tian, and Z. Tao, Light Sci. Appl. (2021).

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