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High-Efficiency Generation of 0.12 mJ, 8.6 Fs Pulses at 400 nm Based on Spectral Broadening in Solid Thin Plates *

Yang-Yang Liu(刘阳阳)[1,2], Kun Zhao(赵昆)[1**], Peng He(何鹏)[3], Hang-Dong Huang(黄杭东)[3], Hao Teng(滕浩)[1], Zhi-Yi Wei(魏志义)[1,2**]

[1] *Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190*

[2] *University of Chinese Academy of Sciences, Beijing 100049*

[3] *School of Physics and Optoelectronics Engineering, Xidian University, Xi'an 710071*

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We demonstrate efficient generation of continuous spectrum centered at 400 nm from solid thin plates. By frequency doubling of 0.8 mJ, 30 fs Ti:sapphire laser pulses with a BBO crystal, 0.2 mJ, 33 fs laser pulses at 400 nm are generated. Focusing the 400-nm pulses into 7 thin fused silica plates, we obtain 0.15 mJ continuous spectrum covering 350–450 nm. After compressing by 3 pairs of chirped mirrors, 0.12 mJ, 8.6 fs pulses are achieved. To the best of our knowledge, this is the first time that sub-10-fs pulses centered at 400 nm are generated by solid thin plates, which shows that spectral broadening in solid-state materials works not only at 800 nm but also at different wavelengths.

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Intense ultrashort pulses have significant applications in high-order harmonic generation (HHG), coherent light synthesis, optical frequency combs, studies of ultrafast phenomena, and especially in isolated attosecond pulse generation.[1−5] As an important offspring of atomic, molecular and optical physics, attosecond optics has always been a hot spot. To generate isolated attosecond pulses, a number of methods such as amplitude gating, polarization gating, attosecond lighthouse, double optical gating, and generalized double optical gating have been demonstrated.[6−10] Though isolated pulses as short as 67 as have been generated, the pulse energy is too low to perform nonlinear atto-optics experiments.[11] One of the key issues is how to generate high-flux isolated attosecond pulses. Since HHG efficiency is higher for shorter wavelength driving pulses, a short-wavelength pulse is suitable for high-flux isolated attosecond pulse generation.[12] It is therefore interesting to develop few-cycle short-wavelength pulses to drive attosecond pulse generation.

Currently, there are two main ways to generate ultrashort 400-nm pulses. One is called broadband frequency doubling, which can generate high energy sub-10-fs 400-nm pulses,[13,14] but the beam in such a configuration carries angular dispersion. The other is to compress long 400-nm pulses to a few-cycle regime with a hollow-core fiber setup.[15] In this way, the spectrum was broadened by self-phase modulation. Then the broadened spectrum was compressed to short pulses by chirped mirrors.[16,17] Unfortunately, the pulse generated in this way suffers energy and beam-pointing instabilities.

In this Letter, we demonstrate the efficient generation of intense ultrashort 400 nm pulses by solid thin plates. The driving laser emits 0.8 mJ, 30 fs pulses centered at 800 nm. After a BBO crystal, 0.2 mJ, 33 fs pulses at 400 nm are generated. Continuous spectrum of 0.15 mJ is obtained when the 400 nm pulses propagated through 7 thin fused silica plates. Compressed by chirped mirrors, 0.12 mJ, 8.6 fs pulses at 400 nm are obtained. Compared with the conventional methods, spectral broadening in solid-state materials is more robust, efficient, and has the potential of energy scaling. This is the first time that 400 nm few-cycle pulses are generated by solid-state spectral broadening. Our results show that spectral broadening in solid-state materials produces few-cycle pulses not only at 800 nm but also at different wavelengths.[18,19]

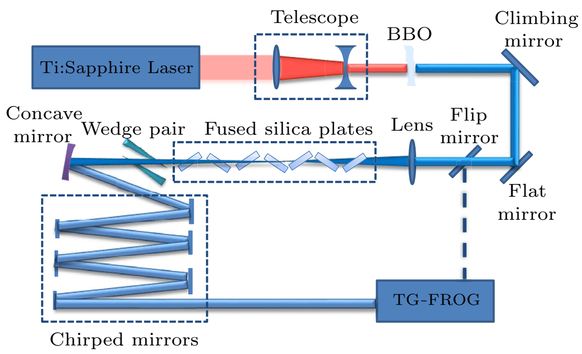

Fig. 1. The experimental setup for 400 nm continuum generation and compression.

The experimental setup is illustrated in Fig. 1. In the experiment, the Ti:sapphire laser emitted 0.8 mJ, 30 fs pulses at 1 kHz. The diameter of the beam was about 12 mm. A telescope was employed to shrink the

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**Corresponding author. Email: zhaokun@iphy.ac.cn; zywei@iphy.ac.cn

beam diameter to 4 mm. The telescope was composed of two lenses, one was plano-convex with $f = 300$ mm and the other was plano-concave with $f = -100$ mm. The distance between them was 200 mm. After the telescope, a BBO crystal (29.2°) with the thickness of 140 μm was used to generate second harmonic. Pulses of 0.2 mJ at 400 nm were obtained when 0.8 mJ, 30 fs driving pulses at 800 nm were employed. A set of climbing mirrors were placed after the BBO crystal. It not only selected the 400 nm laser since the mirrors were designed for high reflectance at 400 nm and high transmission at 800 nm, but also changed the polarization of the 400-nm pulse from s to p. After a flat mirror and a flip mirror, the pulse duration of 33 fs was characterized by a homemade transient-grating frequency-resolved optical gating setup (TG-FROG).[20] Focused by an $f = 500$ mm lens, the beam was 300 μm (at $1/e^2$ of the intensity profile) in diameter at the focal point, corresponding to an intensity of 8.5×10^{12} W/cm^2. Around the focal point, 7 thin fused silica plates with the thickness of 0.1 mm were strategically placed. The distance between the first and last plates was about 9 cm. The plates were placed with nearly equal spacing, and the focal point of the beam was between the third and fourth plates. The effective thickness of the plates was 0.12 mm since they were placed at Brewster's angle (55.8°). After the plates, a 0.15 mJ continuum, covering from 350 to 450 nm at −20 dB intensity level, was achieved. Then the beam was collimated by a concave mirror with a radius of curvature of 500 mm. With a wedge pair and three pairs of chirped mirrors, the pulse was compressed to 0.12 mJ, 8.6 fs, which was measured by TG-FROG.

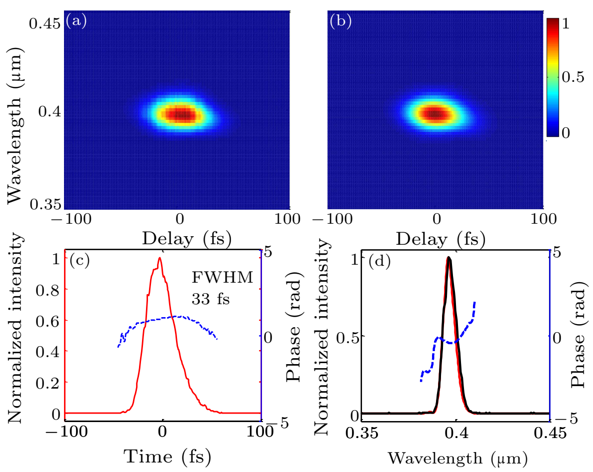

Fig. 2. Characterization of 33 fs pulse before thin solid plates. (a) The experimental FROG trace, (b) the retrieved FROG trace, (c) the retrieved pulse shape (red solid line) and the retrieved phase (blue dashed line), and (d) the measured spectrum (black solid line), the retrieved spectrum (red solid line) and the retrieved phase (blue dashed line).

As illustrated in Fig. 1, the pulse duration before the lens is characterized by TG-FROG, and the result is shown in Fig. 2. The experimental and retrieved FROG traces match well, and the retrieved spectrum is the same as the measured one, which indicate that the measurement is reliable. The transform-limited pulse duration of the measured spectrum is 30 fs, while the measured pulse duration is 33 fs.

The input spectrum (zeroth) and spectra after the first, fourth and seventh plates are shown in Fig. 3. The full width half maximum (FWHM) of the input spectrum before the first plate is 7 nm, corresponding to the transform-limited pulse duration of 30 fs. After 7 solid thin plates, the spectrum is broadened to 37 nm (FWHM), which supports the transform-limited pulse duration of 7 fs. As shown in Fig. 3, the broadened spectra are more or less symmetric to the input spectrum, which indicates that the primary process responsible for spectral broadening is self-phase modulation (SPM). After all 7 thin plates, the energy of the continuum is 0.15 mJ, corresponding to an efficiency of 75%.

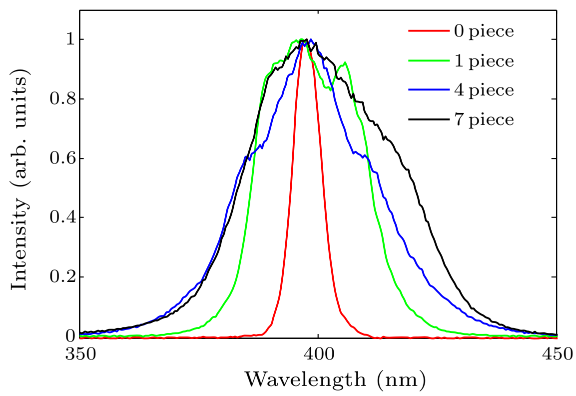

Fig. 3. The input spectrum (zeroth, red) and spectra taken after the first (green), fourth (blue) and seventh plates (black).

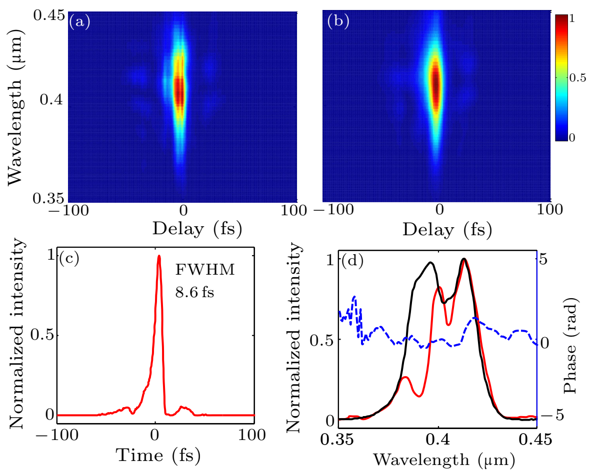

Fig. 4. The compressed 8.6 fs pulse characterized by TG-FROG, (a) the experimental FROG trace, (b) the retrieved FROG trace, (c) the retrieved pulse shape (red solid line), and (d) the measured spectrum (black solid line), the retrieved spectrum (red solid line) and the retrieved phase (blue dashed line).

To compensate for the dispersion, a wedge pair and three pairs of chirped mirrors (UltraFast Innovations) are used. The compressed pulse is characterized by TG-FROG, and the result is shown in Fig. 4. After compression, 0.12 mJ, 8.6 fs pulses centered at 400 nm are achieved. It is the first time that sub-10-fs pulses at 400 nm are generated by solid thin plates.

In conclusion, we have demonstrated the first generation of sub-10 fs pulses centered at 400 nm based on solid thin plates. By focusing 0.2 mJ, 33 fs, 400 nm pulses into 7 thin fused silica plates, a continuum with the energy of 0.15 mJ, covering from 350 to 450 nm, is obtained, corresponding to an efficiency of 75%. Compressed by a pair of wedges and three pairs of chirped mirrors, 0.12 mJ, 8.6 fs pulses at 400 nm are achieved. The main process responsible for spectral broadening is self-phase modulation. Continuum centered at 400 nm generated by solid thin plates is robust, stable, reproducible and has the potential for higher energy and shorter pulse duration, which made it an ideal driving laser for high-flux, high-order harmonic generation and isolated attosecond pulse generation.

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