300 μ J, 3 W, few-cycle, 3 μ m OPCPA based on periodically poled stoichiometric lithium tantalate crystals

Zou, Xiao; Li, Wenkai; Liang, Houkun; Liu, Kun; Qu, Shizhen; Wang, Qi Jie; Zhang, Ying

2019

Zou, X., Li, W., Liang, H., Liu, K., Qu, S., Wang, Q. J. & Zhang, Y. (2019). 300 μ J, 3 W, few-cycle, 3 μ m OPCPA based on periodically poled stoichiometric lithium tantalate crystals. *Optics Letters*, 44(11), 2791-2794. <https://dx.doi.org/10.1364/OL.44.002791>

<https://hdl.handle.net/10356/149180>

<https://doi.org/10.1364/OL.44.002791>

© 2019 Optical Society of America (OSA). All rights reserved. This paper was published in *Optics Letters* and is made available with permission of Optical Society of America (OSA).

Downloaded on 26 Apr 2023 23:23:24 SGT

300 μ J, 3 W, sub-two-cycle, 3- μ m OPCPA based on periodically poled stoichiometric Lithium Tantalite crystals

XIAO ZOU,^{1,2} WENKAI LI,^{1,2} HOUKUN LIANG,^{1,*} KUN LIU,^{1,2} SHIZHEN QU,^{1,2} QI JIE WANG,^{2,*} YING ZHANG¹

¹ Singapore Institute of Manufacturing Technology, 2 Fusionopolis Way, 138634, Singapore

² Centre for OptoElectronics and Biophotonics, School of Electrical & Electronic Engineering & The Photonics Institute, Nanyang Technological University 639798, Singapore

*Corresponding author: hkliang@simtech.a-star.edu.sg

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We report a carrier-envelop phase (CEP)-stable 3- μ m optical parametric chirped-pulse amplifier (OPCPA), based on periodically poled stoichiometric Lithium Tantalite nonlinear crystals, with a 306 μ J pulse energy and a 64 fs pulse width at 10 kHz repetition-rate. A 2-mm-thick YAG crystal is employed to further compress the pulses to 19 fs, which corresponds to a sub-two-cycle pulse duration, with no ionization loss observed. Driven by this OPCPA, high-order harmonics up to the 15th order are generated in a ZnO crystal, and 1-order enhancement of the harmonics intensity is demonstrated with nonlinear compression.

<http://dx.doi.org/10.1364/OL.99.099999>

High-energy, high-repetition-rate, few-cycle, carrier-envelop phase (CEP) stable mid-infrared (mid-IR) lasers are intensively desired by a wide range of strong-field physics applications and among others. Examples are high-order harmonic generation (HHG) in atoms [1-3] and solids [4-7], electron dynamics control in femtosecond and attosecond timescale [8], ultrafast electron diffraction imaging [9, 10], incoherent femtosecond hard x-ray generation [11], and isolated attosecond pulse generation [12, 13]. The studies of strong-field physics demand both high peak power that is deep into the tunneling ionization region, and high repetition rate which generates high ionization flux for practical usage. Combining with high peak power and high repetition rate, ~ 3 μ m driving lasers are very promising for strong-field physics applications. With such ~ 3 μ m high-energy, high-repetition-rate driving sources, coherent soft x-ray with keV photon energy and decent photon flux could be generated via HHG, and the atomic unit of time (i.e. 24 as) can be possibly accessed.

Among the various methods of producing mid-IR pulses, optical parametric chirped-pulse amplifier (OPCPA) is a promising one for

generating high-energy, high-power, and ultrafast mid-IR pulses. High-energy ~ 3 μ m OPCPAs at Hz-level repetition rate were demonstrated firstly in bulk KTA and LiNbO₃ crystals with the large aperture sizes [14-16]. Mid-IR pulses at 3.9 μ m with an up to 35 mJ pulse energy at 20 Hz repetition rate and ~ 100 fs pulse width have been delivered [15]. At higher repetition rate, the mid-IR OPCPA based on KNbO₃ delivers 3.25 μ m pulses with 131 μ J pulse energy at 160 kHz repetition rate, and 97 fs pulse duration before the nonlinear compression [17]. The non-collinear OPCPA combined with the post angular dispersion compensation in KTA was also used to achieve broader PM bandwidth. Mid-IR pulses at 3.1 μ m were generated with 73 fs pulse width and 125 μ J pulse energy at 100 kHz repetition rate [18]. To achieve a broader amplification bandwidth supporting a shorter pulse width, the periodically poled lithium niobate (PPLN) or apodized PPLN, with quasi phase match was adopted in the mid-IR OPCPA [19-21]. Up to 40 μ J, 3.1 μ m pulses at 100 kHz repetition rate, with 38 fs pulse width were generated [21]. However, scaling up the pulse energy in PPLN is hindered by the low damage threshold of the PPLN crystal (~ 10 GW/cm² at 6 ps for MgO-doped PPLN [22]). The periodically poled lithium tantalite crystals, especially the periodically poled stoichiometric lithium tantalite (PPSLT), have a large damage threshold of 80–180 GW/cm² [22-24] which is 1-order higher than that of MgO-doped PPLN. The degenerated OPCPAs with decent pulse energy and few-cycle pulse duration at ~ 2 μ m have been demonstrated in PPSLT [23, 24]. Despite that the PM bandwidth of PPSLT is slightly smaller than that of PPLN at ~ 3 μ m (233 nm v.s. 195 nm in 2-mm-thick PPLN and PPSLT, respectively [22]), it is possible to enhance the gain bandwidth by using thinner PPSLT in the OPCPA while applying higher pump intensity. It is also worth mentioning that compared to the large-aperture mid-IR nonlinear crystals, such as KTA, LiNbO₃, and KNbO₃, PPSLT is superior by its larger effective nonlinear coefficient (7.7 pm/V). PPSLT thus becomes a good candidate to generate ~ 3 μ m pulses with high pulse energy and few-cycle pulse width. Furthermore, sub-two-

cycle or even single-cycle pulses are required by some strong-field physics applications, such as the isolated attosecond pulse generation. Post nonlinear compression with good energy efficiency has been demonstrated by using thin dielectrics [25-28], which paves the way towards the high-energy, high-power, sub-two-cycle or even single-cycle 3- μm pulse generation.

In this work, we present a 3- μm OPCPA based on PPSLT, which delivers 306 μJ pulse energy, 3 W average power, and 64 fs pulse width. A 2-mm-thick YAG crystal is employed to further compress the 3- μm pulses to 19 fs corresponding to sub-two-cycle pulse width. 83% compression efficiency is demonstrated with only the Fresnel reflection loss at the two surfaces of xxx. Driven by the high-energy, high-power, 3- μm OPCPA, HHG with up to the 15th order is generated in a 0.5-mm-thick ZnO crystal. With the help of nonlinear compression, the 1-order enhancement of the harmonic intensity is demonstrated, which reveals the significance of the intensity enhancement of the driving source for HHG in solid.

The schematic of the 3- μm OPCPA is shown in Fig. 1. A 1030 nm Yb:YAG laser (AMPOHS 100) with 12 mJ pulse energy at 10 kHz repetition rate, and 1 ps pulse width serves as the pump source of the OPCPA. 80 μJ , 1030 nm pump is split to generate the stable super continuum (SC) spanning up to 2 μm wavelength in a 16-mm-thick YAG crystal. Clipped by an iris, ~ 10 μJ 1030 nm pulses are focused to the YAG crystal by a lens with 100-mm focus length. Passing through a 1300-nm long pass filter (LPF), signal pulses centered at 1550 nm with 2 nJ pulse energy are obtained as the OPCPA seed. They are subsequently stretched by a 4-mm-thick Silicon (Si) block to ~ 300 fs pulse width, then combined with the pump pulses at a dichroic mirror. 4-stages amplifiers with collinear geometry are adopted in the OPCPA. The first stage amplifier is based on an uncoated, 3-mm-thick 5%-MgO-doped PPLN crystal (HC Photonics), in which the seed pulse energy is amplified to 14 μJ , with 350 μJ pump energy. The signal pulses are then further stretched to 850 fs by an acousto-optic programmable dispersive filter (AOPDF) (Fastlite, Dazzler), by adding -22500 fs^2 2nd-order dispersion. The same 3-mm-thick uncoated MgO:PPLN crystal is used in the 2nd-stage amplifier which delivers 40 μJ , 3 μm idler pulses, when pumped with an energy of 800 μJ . The generated 3 μm idler pulses are stretched again to ~ 700 fs by a 7-mm-thick AR-coated Si block, and fed into the 3rd-stage amplifier. In this stage, an uncoated PPSLT crystal (Deltronic Crystal) with the 1.2-mm thickness and 3 mm $\times$ 10 mm aperture is employed. The working temperature of the PPSLT is set at 170 $^\circ\text{C}$, for mitigating the photorefractive effect. 5 mJ pump pulses with ~ 140 GW/cm^2 intensity are incident on the PPSLT crystal, without beam distortion observed. 160 μJ , 3 μm pulses are obtained in this stage. Another PPSLT crystal with a 0.9-mm-thickness is used in the final stage amplifier, for further boosting the pulse energy to 306 μJ .

Fig. 1. The schematic of the high-energy, high-power, sub-two-cycle, 3 μm OPCPA based on PPSLT, and the HHG demonstration in thin ZnO plate.

Fig. 2 (a) shows the measured 1-hour long-term energy stability of the 3 μm idler pulses. It reveals an average output energy of 306 μJ , and 0.5% root-mean-square (RMS) instability. The total efficiency of the OPCPA system is 2.6%. The losses from the Fresnel reflection on the uncoated PPLN and PPSLT crystals constrain the OPCPA efficiency, which could be further enhanced by the AR coating. The left inset of Fig. 2(a) shows a good Gaussian profile of the idler beam measured by a pyroelectric camera (Ophir, PyroCam III).

Fig. 2. (a) The long-term stability of the 3 μm OPCPA measured at the output of the sapphire bulk compressor. The left and right insets are the measured beam profiles before and after the nonlinear compressor (NC), respectively. (b) The SG spectrum (black dash), the amplified signal and idler spectra from the 1st (green), 2nd (black), 3rd (purple) and 4th stage (blue) OPCPA, and the broadened idler spectrum (red) from the nonlinear compressor.

The spectra of the signal and idler pulses in different stages of the OPCPA are characterized and shown in Fig. 2 (b). Thanks to the good PM bandwidth in PPLN crystals, and the small ratio of the signal-to-pump pulse duration, the broad signal (green) spectrum from the 1st stage and the idler (black) spectrum from the 2nd stage amplifier are obtained, spanning from 1400 nm to 1700 nm and 2600 nm to 3250 nm, respectively. In the 3rd and 4th stages based on PPSLT crystals, the 3 μm idler pulses lose the amplified bandwidth on the shorter wavelength of the spectrum (purple and blue) as shown in Fig. 2(b), attributed to the slightly narrower PM bandwidth in PPSLT compared to that in PPLN.

The generated high-energy, high-power, 3 μm pulses are compressed in Brewster-angle-cut sapphire blocks with the thickness of 20 mm. The high-order dispersions are compensated by adding -100000 fs^3 3rd-order and -650000 fs^4 4th-order dispersions in the AOPDF. The temporal profiles of the 3 μm idler pulses are characterized by using the method of second-harmonic generation frequency-resolved optical gating (SHG-FROG). A 30- μm -thick GaSe is used as the SHG crystal for its broad SHG PM

bandwidth. Fig. 3 shows the measured and reconstructed FROG traces together with the retrieved temporal and spectral profiles. 64 fs pulse width is measured, which corresponds to 1.05 times the transform-limited (TL) pulse width of the measured idler spectrum.

Fig. 3. The frequency-resolved optical gating (FROG) measurement at the output of the sapphire bulk compressor. (a) The measured, and (b) the retrieved FROG traces. (c) The measured, and retrieved spectra. (d) The measured and retrieved temporal profiles of the 3 μm pulses after the sapphire bulk compressor.

To pursue the few-cycle 3 μm pulse width, the nonlinear compression of the idler pulse from the PPSLT-based OPCPA is investigated. A 2-mm-thick uncoated YAG plate is chosen for its high 3rd-order nonlinearity and good mechanical properties. An AR-coated CaF_2 lens with 75-mm focus length is used to focus the high-energy, high-power, 3 μm beam to the YAG plate which is located slightly after the linear focal spot, to avoid the damage and obvious ionization. The > 80% transmission is observed with the losses mainly from the Fresnel reflection on the uncoated surfaces. The broadened spectrum spanning from 2160 nm to 3840 nm which supports 18 fs pulse width, is obtained and plotted as the red curve in Fig. 2 (b). The temporal profile of the 3 μm idler pulses from the nonlinear compressor is measured, as shown in Fig. 4. 19 fs pulse width is obtained, corresponding to sub-two cycles of the 3 μm wave. The beam profile of the 3 μm pulses after the nonlinear compressor is shown in the right inset of Fig. 2(a), which manifests a good Gaussian profile, without ring structures observed.

Fig. 4. The Frog measurement at the output of the nonlinear compressor. (a) The measured, and (b) the retrieved FROG traces. (c) The measured, and retrieved spectra. (d) The measured and retrieved temporal profiles of the 3 μm pulses after the nonlinear compressor.

For few-cycle mid-IR pulses in the strong-field physics applications, the stable CEP are desired. The CEP stability of the 3 μm idler output is measured by an f-3f spectral interferometer. The 3 μm idler beam is split to two arms by a 1-mm-thick silicon wafer serving as a beam splitter. The pulses in one arm is focused to a 3-mm-thick uncoated YAG plate to generate SC with the extended spectrum in the third-harmonic frequency, through single filamentation in the YAG plate. The 3 μm pulses in the other arm is focused into a 2-mm-thick, GaSe crystal with type-I PM, which generates the third harmonics at ~ 1000 nm. The SC and the third-harmonic pulses with the orthogonal polarizations are combined at a polarizing beam splitter (PBS), and they interfere with each other at the ~ 1000 nm wavelength. The interference spectrum is measured with a near-infrared spectrometer equipped with a fast detector (AVANTES, AvaSpec-ULS2048-EVO-RS) for the 10 kHz operation. The visibility of the spectral fringes is optimized with another PBS, and a typical interference spectrum is shown in Fig. 5 (b). An interferogram as plotted in Fig. 5(a) is acquired over 100 s. The extracted CEP fluctuations as a function of time are shown in Fig. 5 (c), and its RMS value is measured to be 391 mrad over a 100 s time period.

Fig. 5. (a) The interferogram over 100 s based on the f-3f measurement, (b) a typical interference spectrum, and (c) the measured CEP fluctuation indicating an RMS value of 391 mrad over 100 s period.

To test the high-energy, high-power, few-cycle, 3 μm OPCPA, HHG in a thin ZnO crystal (1120 cut) is demonstrated. The ZnO crystal is chosen for its large band gap energy of 3.3 eV which corresponds to 376 nm in wavelength, and the larger nonlinearity ($\chi_{1111} = 1.32 \times 10^{-13} \text{ cm}^3 \text{ erg}$) compared to the other common dielectrics such as YAG, sapphire and CaF_2 . A 0.5-mm thickness is used to avoid beam collapse by forming multi-filamentation. The reflected HHG signals are characterized to avoid disturbance of the strong fundamental 3 μm pulses, as depicted in Fig. 1. 120 μJ , 3 μm pulses clipped by an aperture are focused to the ZnO plate, by using an AR-coated CaF_2 lens with a 150-mm focus length. The estimated vacuum intensities are 4.4 TW/ cm^2 and 1.3 TW/ cm^2 , for the 3 μm pulses with and without the nonlinear compression, corresponding to the field intensity of 0.42 V/ $\text{\AA}$, and 0.23 V/ $\text{\AA}$, respectively. Stable concentric circles with visible colors are obtained, and sent into two different Ocean Optics spectrometers

(HR 2000+ and Maya 2000 Pro). The HHG spectra driven by the 3 μm OPCPA before and after the nonlinear pulse compression are compared. The stitched HHG spectra driven by the 3 μm OPCPA with and without the nonlinear compression are plotted in Fig. 6. The odd harmonics up to the 15th order which is well beyond the bandgap energy are clearly seen in both HHG spectra. It is observed that the nonlinear compression boosts the HHG intensity by 1 order, which is attributed to the enhancement of the pump intensity. We also characterized the harmonics energy by using a 1300-nm short-pass filter. Driven by the 19-fs 3 μm OPCPA, 1.6 μJ pulse energy is obtained, which corresponds to 1.3% conversion efficiency for the 3rd-order and above harmonics.

Fig. 6. The measured HHG spectra driven by the 3 μm OPCPA with (black) and without (red) the nonlinear compressor (NC). The HHG spectra measured by different spectrometers are calibrated, and stitched. The discontinuity at ~ 4 eV is due to the lack of measured spectra at the edge of the spectrometer.

In conclusion, a CEP-stable, high performance, 3 μm OPCPA system based on PPSLT crystals is reported. To the best of our knowledge, this is the first demonstration of ~ 3 μm OPCPA in PPSLT in which good pulse energy and PM bandwidth are obtained simultaneously. The demonstrated OPCPA delivers 306 μJ pulse energy at 10 kHz repetition rate, and 64 fs pulse width. A 2-mm-thick YAG crystal is employed to further compress the pulses to 19 fs with 83% energy efficiency. The nonlinear compressor cut in the Brewster angle would be used to further enhance the efficiency. It is worth mentioning that with longer pump pulse width, for example ~ 10 ps duration, the few-cycle 3 μm OPCPA based on PPSLT could be further scaled with mJ output energy, which would serve as an idea driving source for the strong-field physics applications.

Funding. SERC (Grant No. 1426500050, and 1426500051)

Acknowledgment. We thank the Agency for Science, Technology and Research (A*STAR), Singapore to support this work.

References

1. B. Shan and Z. Chang, *Phys. Rev. A* **65**, 011804 (2001).
2. P. Colosimo, G. Doumy, C. I. Blaga, J. Wheeler, C. Hauri, F. Catoire, J. Tate, R. Chirla, A. M. March, G. G. Paulus, H. G. Muller, P. Agostini and L. F. Dimauro, *Nat. Phys.* **4**, 386-389 (2008).
3. T. Popmintchev, M. Chen, D. Popmintchev, P. Arpin, S. Brown, S. Ališauskas, G. Andriukaitis, T. Balčiūnas, O. D. Mücke, A. Pugžlys, A. Baltuška, B. Shim,

- S. E. Schrauth, A. Gaeta, C. H. García, L. Plaja, A. Becker, A. J. Becker, M. M. Murnane, and H. C. Kapteyn, *Science* **336**, 1287-1291 (2012).
4. S. Ghimire, A. D. DiChiara, E. Sistrunk, P. Agostini, L. F. DiMauro, and D. A. Reis, *Nat. Phys.* **7**, pages 138-141 (2011)
5. O. Schubert, M. Hohenleutner, F. Langer, B. Urbanek, C. Lange, U. Huttner, D. Golde, T. Meier, M. Kira, S. W. Koch and R. Huber, *Nat. Photonics* **8**, 119-123 (2014).
6. M. Hohenleutner, F. Langer, O. Schubert, M. Knorr, U. Huttner, S. W. Koch, M. Kira and R. Huber, *Nature* **523**, 572 (2015).
7. H. Liu, Y. Li, Y. S. You, S. Ghimire, T. F. Heinz and D. A. Reis, *Nat. Phys.* **13**, 262-265 (2017).
8. G. Herink, D. R. Solli, M. Gulde, and C. Ropers, *Nature* **483**, 190-193 (2012)
9. M. G. Pullen, B. Wolter, A. T. Le, M. Baudisch, M. Hemmer, A. Senftleben, C. D. Schroter, J. Ullrich, R. Moshhammer, C.D. Lin and J. Biegert, *Nat. Commun.* **6**, 7262 (2015)
10. B. Wolter, M. G. Pullen, A.T. Le, M. Baudisch, K. Doblhoff-Dier, A. Senftleben, M. Hemmer, C. D. Schröter, J. Ullrich, T. Pfeifer, R. Moshhammer, S. Gräfe, O. Vendrell, C. D. Lin, and J. Biegert, *Science* **354**, 308-312 (2016).
11. J. Weisshaupt, V. Juvé, M. Holtz, S. Ku, M. Woerner, T. Elsaesser, S. Ališauskas, A. Pugžlys, and A. Baltuška, *Nat. Photonics* **8**, 927-930 (2014)
12. T. Gaumnitz, A. Jain, Y. Pertot, M. Huppert, I. Jordan, F. Ardana-Lamas, and H. J. Wörner, *Opt. Express* **25**, 27506-27518 (2017)
13. J. Li, X. Ren, Y. Yin, K. Zhao, A. Chew, Y. Cheng, E. Cunningham, Y. Wang, S. Hu, Y. Wu, M. Chini, and Z. Chang, *Nat. Commun.* **8**, 186 (2017)
14. G. Andriukaitis, T. Balčiūnas, S. Ališauskas, A. Pugžlys, A. Baltuška, T. Popmintchev, M. Chen, M. M. Murnane, and H. C. Kapteyn, *Opt. Lett.* **36**, 2755-2757 (2011).
15. A. V. Mitrofanov, A. A. Voronin, D. A. Sidorov-Biryukov, S. I. Mityukovsky, A. B. Fedotov, E. E. Serebryannikov, D. V. Meshchankin, V. Shumakova, S. Ališauskas, A. Pugžlys, V. Ya. Panchenko, A. Baltuška, and A. M. Zheltikov, *Optica* **3**, 299-302 (2016).
16. Y. Fu, B. Xue, K. Midorikawa, and E. Takahashi, *Appl. Phys. Lett.* **112**, 241105 (2018)
17. U. Elu, M. Baudisch, H. Pires, F. Tani, M. H. Frosz, F. Köttig, A. Ermolov, P. S. Russell, and J. Biegert, *Optica* **4**, 1024-1029 (2017)
18. M. Mero, Z. Heiner, V. Petrov, H. Rottke, F. Branchi, G. M. Thomas, and M. J. J. Vrakking, *Opt. Lett.* **43**, 5246-5249 (2018)
19. O. Chalus, A. Thai, P. K. Bates, and J. Biegert, *Opt. Lett.* **35**, 3204-3206 (2010).
20. B. W. Mayer, C. R. Phillips, L. Gallmann, M. M. Fejer, and U. Keller, *Opt. Lett.* **38**, 4265-4268 (2013).
21. N. Thiré, R. Maksimenka, B. Kiss, C. Ferchaud, P. Bizouard, E. Cormier, K. Osvay, and N. Forget, *Opt. Express* **25**, 1505-1514 (2017)
22. M. Baudisch, M. Hemmer, H. Pires, and J. Biegert, *Opt. Lett.* **39**, 5802-5805 (2014).
23. T. Fuji, N. Ishii, C. Y. Teisset, X. Gu, Th. Metzger, A. Baltuška, N. Forget, D. Kaplan, A. Galvanauskas, and F. Krausz, *Opt. Lett.* **31**, 1103-1105 (2006).
24. J. Moses, S.-W. Huang, K.-H. Hong, O. D. Mücke, E. L. Falcão-Filho, A. Benedick, F. Ö. Ilday, A. Dergachev, J. A. Bolger, B. J. Eggleton, and F. X. Kärtner, *Opt. Lett.* **34**, 1639-1641 (2009)
25. M. Hemmer, M. Baudisch, A. Thai, A. Couairon, and J. Biegert, *Opt. Express* **21**, 28095-28102 (2013).
26. H. Liang, P. Kroger, R. Grynko, O. Novak, C. Chang, G. J. Stein, D. Weerawarne, B. Shim, F. X. Kärtner, and K. H. Hong, *Opt. Lett.* **40**, 1069-1072 (2015).
27. V. Shumakova, P. Malevich, S. Alisauskas, A. Voronin, A.M. Zheltikov, D. Faccio, D. Kartashov, A. Baltuška, and A. Pugžlys, *Nat. Commun.* **7**, 12877 (2016)
28. F. Lu, P. Xia, Y. Matsumoto, T. Kanai, N. Ishii, and J. Itatani, *Opt. Lett.* **43**, 2720-2723 (2018)

References

1. B. Shan and Z. Chang, "Dramatic extension of the high-order harmonic cutoff by using a long-wavelength driving field", *Phys. Rev. A* **65**, 011804 (2001).
2. P. Colosimo, G. Doumy, C. I. Blaga, J. Wheeler, C. Hauri, F. Catoire, J. Tate, R. Chirla, A. M. March, G. G. Paulus, H. G. Muller, P. Agostini and L. F. Dimauero, "Scaling strong-field interactions towards the classical limit", *Nat. Phys.* **4**, 386-389 (2008).
3. T. Popmintchev, M. Chen, D. Popmintchev, P. Arpin, S. Brown, S. Ališauskas, G. Andriukaitis, T. Balčiūnas, O. D. Mücke, A. Pugzlys, A. Baltuška, B. Shim, S. E. Schrauth, A. Gaeta, C. H. García, L. Plaja, A. Becker, A. J. Becker, M. M. Murnane, and H. C. Kapteyn, "Bright coherent ultrahigh harmonics in the keV x-ray regime from mid-infrared femtosecond lasers", *Science* **336**, 1287–1291 (2012).
4. S. Ghimire, A. D. DiChiara, E. Sistrunk, P. Agostini, L. F. DiMauro, and D. A. Reis, "Observation of high-order harmonic generation in a bulk crystal", *Nat. Phys.* **7**, pages 138–141 (2011)
5. O. Schubert, M. Hohenleutner, F. Langer, B. Urbanek, C. Lange, U. Huttner, D. Golde, T. Meier, M. Kira, S. W. Koch and R. Huber, "Sub-cycle control of terahertz high-harmonic generation by dynamical bloch oscillations", *Nat. Photonics* **8**, 119–123 (2014).
6. M. Hohenleutner, F. Langer, O. Schubert, M. Knorr, U. Huttner, S. W. Koch, M. Kira and R. Huber, "Real-time observation of interfering crystal electrons in high-harmonic generation", *Nature* **523**, 572 (2015).
7. H. Liu, Y. Li, Y. S. You, S. Ghimire, T. F. Heinz and D. A. Reis, "High-harmonic generation from an atomically thin semiconductor", *Nat. Phys.* **13**, 262–265 (2017).
8. G. Herink, D. R. Solli, M. Gulde, and C. Ropers, "Field-driven photoemission from nanostructures quenches the quiver motion", *Nature* **483**, 190-193 (2012)
9. M. G. Pullen, B. Wolter, A. T. Le, M. Baudisch, M. Hemmer, A. Senftleben, C. D. Schroter, J. Ullrich, R. Moshhammer, C.D. Lin and J. Biegert, "Imaging an aligned polyatomic molecule with laser-induced electron diffraction", *Nat. Commun.* **6**, 7262 (2015)
10. B. Wolter, M. G. Pullen, A.T. Le, M. Baudisch, K. Doblhoff-Dier, A. Senftleben, M. Hemmer, C. D. Schröter, J. Ullrich, T. Pfeifer, R. Moshhammer, S. Gräfe, O. Vendrell, C. D. Lin, and J. Biegert, "Ultrafast electron diffraction imaging of bond breaking in di-ionized acetylene", *Science* **354**, 308-312 (2016).
11. J. Weisshaupt, V. Juvé, M. Holtz, S. Ku, M. Woerner, T. Elsaesser, S. Ališauskas, A. Pugžlys, and A. Baltuška, "High-brightness table-top hard X-ray source driven by sub-100-femtosecond mid-infrared pulses", *Nat. Photonics* **8**, 927–930 (2014)
12. T. Gaumnitz, A. Jain, Y. Pertot, M. Huppert, I. Jordan, F. Ardana-Lamas, and H. J. Wörner, "Streaking of 43-attosecond soft-X-ray pulses generated by a passively CEP-stable mid-infrared driver", *Opt. Express* **25**, 27506-27518 (2017)
13. J. Li, X. Ren, Y. Yin, K. Zhao, A. Chew, Y. Cheng, E. Cunningham, Y. Wang, S. Hu, Y. Wu, M. Chini, and Z. Chang, "53-attosecond X-ray pulses reach the carbon K-edge", *Nat. Commun.* **8**, 186 (2017)
14. G. Andriukaitis, T. Balčiūnas, S. Ališauskas, A. Pugžlys, A. Baltuška, T. Popmintchev, M. Chen, M. M. Murnane, and H. C. Kapteyn, "90 GW peak power few-cycle mid-infrared pulses from an optical parametric amplifier", *Opt. Lett.* **36**, 2755-2757 (2011).
15. A. V. Mitrofanov, A. A. Voronin, D. A. Sidorov-Biryukov, S. I. Mitryukovsky, A. B. Fedotov, E. E. Serebryannikov, D. V. Meshchankin, V. Shumakova, S. Ališauskas, A. Pugžlys, V. Ya. Panchenko, A. Baltuška, and A. M. Zheltikov, "Subterawatt few-cycle mid-infrared pulses from a single filament", *Optica* **3**, 299-302 (2016).
16. Y. Fu, B. Xue, K. Midorikawa, and E. Takahashi, "TW-scale mid-infrared pulses near 3.3 μm directly generated by dual-chirped optical parametric amplification" *Appl. Phys. Lett.* **112**, 241105 (2018)
17. M. Mero, Z. Heiner, V. Petrov, H. Rottke, F. Branchi, G. M. Thomas, and M. J. J. Vrakking, "43 W, 1.55 μm and 12.5 W, 3.1 μm dual-beam, sub-10 cycle, 100 kHz optical parametric chirped pulse amplifier", *Opt. Lett.* **43**, 5246-5249 (2018)
18. U. Elu, M. Baudisch, H. Pires, F. Tani, M. H. Frosz, F. Köttig, A. Ermolov, P. S. Russell, and J. Biegert, "High average power and single-cycle pulses from a mid-IR optical parametric chirped pulse amplifier", *Optica* **4**, 1024-1029 (2017)
19. O. Chalus, A. Thai, P. K. Bates, and J. Biegert, "Six-cycle mid-infrared source with 3.8 μJ at 100 kHz", *Opt. Lett.* **35**, 3204-3206 (2010).
20. B. W. Mayer, C. R. Phillips, L. Gallmann, M. M. Fejer, and U. Keller, "Sub-four-cycle laser pulses directly from a high-repetition-rate optical parametric chirped-pulse amplifier at 3.4 μm ", *Opt. Lett.* **38**, 4265-4268 (2013).
21. N. Thiré, R. Maksimenka, B. Kiss, C. Ferchaud, P. Bizouard, E. Cormier, K. Osvey, and N. Forget, "4-W, 100-kHz, few-cycle mid-infrared source with sub-100-mrad carrier-envelope phase noise", *Opt. Express* **25**, 1505-1514 (2017)
22. M. Baudisch, M. Hemmer, H. Pires, and J. Biegert, "Performance of MgO:PPLN, KTA, and KNbO₃ for mid-wave infrared broadband parametric amplification at high average power", *Opt. Lett.* **39**, 5802-5805 (2014).
23. T. Fuji, N. Ishii, C. Y. Teisset, X. Gu, Th. Metzger, A. Baltuška, N. Forget, D. Kaplan, A. Galvanauskas, and F. Krausz, "Parametric amplification of few-cycle carrier-envelope phase-stable pulses at 2.1 μm ", *Opt. Lett.* **31**, 1103-1105 (2006).
24. J. Moses, S.-W. Huang, K.-H. Hong, O. D. Mücke, E. L. Falcão-Filho, A. Benedick, F. Ö. Ilday, A. Dergachev, J. A. Bolger, B. J. Eggleton, and F. X. Kärtner, "Highly stable ultrabroadband mid-IR optical parametric chirped-pulse amplifier optimized for superfluorescence suppression", *Opt. Lett.* **34**, 1639-1641 (2009)
25. M. Hemmer, M. Baudisch, A. Thai, A. Couairon, and J. Biegert, "Self-compression to sub-3-cycle duration of mid-infrared optical pulses in dielectrics", *Opt. Express* **21**, 28095–28102 (2013).
26. H. Liang, P. Krogen, R. Grynko, O. Novak, C. Chang, G. J. Stein, D. Weerawarne, B. Shim, F. X. Kärtner, and K. H. Hong, "Three-octave-spanning supercontinuum generation and sub-two-cycle self-compression of mid-infrared filaments in dielectrics", *Opt. Lett.* **40**, 1069-1072 (2015).
27. V. Shumakova, P. Malevich, S. Alisauskas, A. Voronin, A.M. Zheltikov, D. Faccio, D. Kartashov, A. Baltuška, and A. Pugžlys, "Multi-millijoule few-cycle mid-infrared pulses through nonlinear self-compression in bulk", *Nat. Commun.* **7**, 12877 (2016)
28. F. Lu, P. Xia, Y. Matsumoto, T. Kanai, N. Ishii, and J. Itatani, "Generation of sub-two-cycle CEP-stable optical pulses at 3.5 μm from a KTA-based optical parametric amplifier with multiple-plate compression", *Opt. Lett.* **43**, 2720-2723 (2018)