High Energy Picosecond Optical Parametric Amplifier Pumped by the Second Harmonic of a Two-Stage Ti:sapphire Laser

Jiangfeng Zhu, Weijun Ling, Xin Zhong, Zhaohua Wang, and Zhiyi Wei

***Abstract*— We demonstrate a high energy picosecond optical parametric generation and amplification (OPA) system in the visible range based on two type-I phase matched β-barium borate crystals, in a walk-off compensating geometry. The second harmonic of a two-stage 60 ps Ti:sapphire laser amplifier at 10 Hz repetition rate serves as the pump. The signal is continuously tunable from 460 to 750 nm, which covers most of the visible range. The corresponding tuning range in the idler branch is from 0.86 to 3.07 μm. At a pumping energy of 110 mJ per pulse, the signal pulse energy is at 20 mJ class for most of the tuning wavelength in the OPA stage, and reaches a maximum of 33 mJ at 710 nm, corresponding to a conversion efficiency of ~30%.**

***Index Terms*— Optical frequency conversion, optical parametric amplifiers, ultrafast optics.**

I. Introduction

Wavelength-tunable lasers with high peak power and narrow linewidth are essential laser sources for a lot of applications in science and technology. Ti:sapphire laser amplifiers based on chirped pulse amplification (CPA) technique are widely used sources with tunable, energetic ultrashort pulses. However, the wavelength tuning range is limited within a narrow band around 800 nm for the fundamental or 400 nm for the second-harmonic (SH). As a result, it leaves a rather large gap in the visible between the fundamental and the SH. The wavelength tuning range can be widely extended by the optical parametric generation (OPG) and amplification (OPA), and subsequently by sum frequency generation (SFG) or difference frequency generation (DFG). Early in the 1990s, with the development of excellent nonlinear crystals, such as β-barium borate (BBO) and lithium triborate (LBO), a great number of OPA experiments have been investigated employing the SH or the third harmonic (TH) output of the mode-locked Nd: YAG laser as the pump, resulting in picosecond pulses tunable from visible to mid-infrared (MIR) [1]–[7]. Shortly after that, femtosecond OPAs pumped either by the fundamental or the SH of the Ti:sapphire amplifiers reach unparalleled performance with UV to MIR tunibility [8]–[11] and down to few-cycle pulse compression [12]–[14]. Most of them, either picosecond OPAs based on Nd:YAG laser or femtosecond ones based on Ti:sapphire amplifier, however, pay little attention to higher energy scaling. In fact, the output pulse energy is usually on the 1 mJ class or less. Higher output energy requires a much powerful pumping source and also a careful design of the OPA setup. Energy scaling of the OPAs is evidently significant not only for the development of novel laser sources but also for applications in the frontier of science. Recently, energy scaling of an infrared OPA pumped by a Terawatt femtosecond Ti:sapphire laser system has resulted in 10 mJ, 40 fs pulses for high-order harmonic generation (HHG) [15].

In this paper, we investigate the energy scaling of a picosecond visible optical parametric generation and amplification apparatus based on the type-I phase matched BBO crystals. Pumped by the second harmonic of a two-stage 60 ps Ti:sapphire amplifier at 400 nm at 10 Hz repetition rate, the output signal is tunable from 460 to 750 nm. By the pumping energy of 110 mJ in the OPA stage, the signal energy is above 20 mJ for most of the signal wavelength, and the maximum of 33 mJ is obtained at 710 nm with a conversion efficiency of about 30%. This is, to the best of our knowledge, the highest energy from a picosecond OPA pumped by the SH of a Ti:sapphire amplifier.

II. Experimental Arrangement

The schematic layout of the high energy picosecond OPG-OPA is shown in Fig. 1. The OPG-OPA system is pumped by the SH output of a 60 ps two-stage Ti:sapphire laser amplifier, operating at 10 Hz repetition rate. The Ti:sapphire amplifier is seeded with an actively mode-locked Ti:sapphire oscillator (Tsunami, Spectra-Physics Inc.) which delivers near Fourier transform-limited 60 ps pulses with a central wavelength tuning range of 715-855 nm. Since the seed pulse is tens picosecond in duration, it was directly amplified by a regenerative pre-amplifier and subsequently a multi-pass power amplifier without stretching and compressing processes. Compared to the standard CPA system where the pulse is stretched to hundreds pisosecond, the 60 ps pulse duration in this system is not sufficiently broad for amplification, so

Manuscript received May 29, 2012; revised July 9, 2012; accepted July 14, 2012. Date of publication July 18, 2012; date of current version August 6, 2012. This work was supported in part by the National Natural Science Foundation of China under Grant 10874237 and the Knowledge Innovation Program of Chinese Academy of Sciences under Grant KJCX2-YW-N48.

J. Zhu is with the School of Technical Physics, Xidian University, Xi'an 710071, China (e-mail: jfzhu@xidian.edu.cn).

W. Ling is with the College of Physics and Information Science, Tianshui Normal University, Tianshui 741001, China (e-mail: wjling@mail.tsnc.edu.cn).

X. Zhong, Z. Wang, and Z. Wei are with the Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China (e-mail: zhongxin@iphy.ac.cn; zhwang@iphy.ac.cn; zywei@iphy.ac.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JQE.2012.2209408

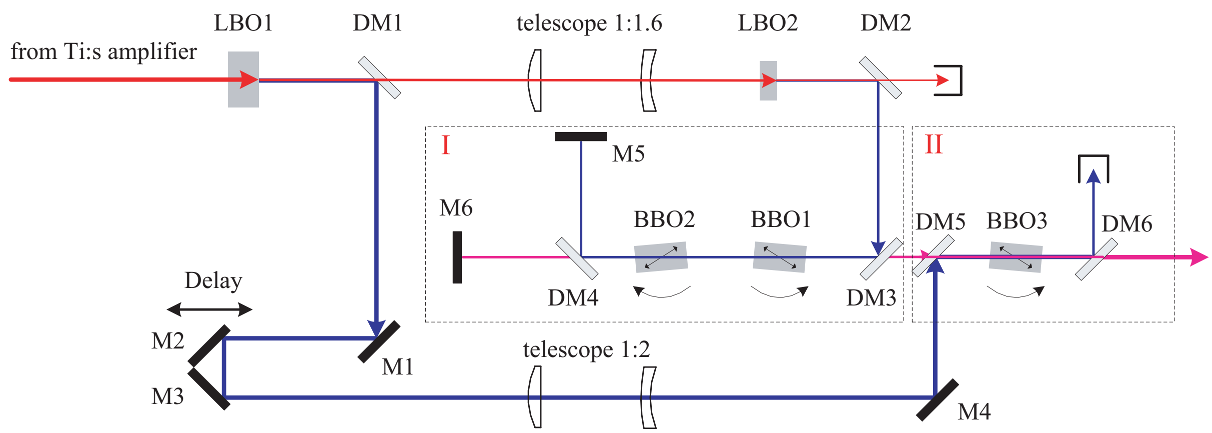

Fig. 1. Schematic of the experimental arrangement of the OPG-OPA system, pumped by the SH output of a 60 ps two-stage Ti:sapphire amplifier running at 10 Hz repetition rate. Ti:s, Ti:sapphire. DM1 and DM2, dichroic mirrors with high reflectance at 400 nm and high transmittance at 800 nm. DM3–DM6, dichroic mirrors with high reflectance at 400 nm and high transmittance at 450–900 nm. M1–M4, 45° high reflectance mirrors at 400 nm. M5 and M6, 0° high reflectance mirrors at 400 nm and 450–900 nm, respectively. I and II, OPG and OPA stages, respectively.

there is risk to damage the optics in the amplifier, including the Ti:sapphire crystal and the crystal in the Pockels cell, or degradation of the output beam by self focusing and wavefront aberration due to very high peak power in the power amplifier. Much attention was paid to prevent damage and to improve the beam quality in the amplification [16]. Finally the seed pulse was boosted to 360 mJ, pumped by two 0.8 J, 532 nm Nd:YAG lasers at 10 Hz repetition rate. A top-hat beam profile with 9 mm diameter was produced due to gain saturation and the B-integral was estimated to be less than 0.5.

Second harmonic generation (SHG) is obtained in a 7 mm long LBO crystal cut for type-I critical phase matching in the $X-Y$ plane ($\theta = 90°$, $\phi = 31.7°$) at room temperature. Both sides of the crystal are antireflection coated for the central wavelengths of 800 nm and 400 nm. At a pumping intensity of $\sim$9 GW/cm^2, as high as 135 mJ frequency-doubled pulses were obtained, corresponding to a conversion efficiency of 37.5%. The SH efficiency versus the fundamental intensity is shown in Fig. 2. The 400 nm frequency-doubled pulses were separated from the fundamental by a dichroic mirror (DM1) and used to pump the OPA stage after a suitable time delay. The beam quality of the fundamental after the SHG is still good since the amplifier produces a top-hat profile due to gain saturation. We'd like to utilize this part to pump the OPG stage after frequency-doubling in order to obtain as high OPA energy as possible. The diameter of the residual fundamental pulses after the dichroic mirror is decreased by a 1:1.6 telescope (focal length with 400 mm and -250 mm, respectively, uncoated) and frequency-doubled again by a second 8 mm LBO crystal. The fundamental after the telescope is about 160 mJ, corresponding to an intensity of $\sim$9 GW/cm^2, and about 50 mJ 400 nm pulses were generated by the second SHG.

The OPG stage is made up of two BBO crystals separated by $\sim$15 cm in a double-pass configuration. After passing through these two crystals, the parametric signal and the pumping beam are separated by a dichroic beam splitter (DM4) and then reflected back to the crystals with the same delay for parametric amplification again. Both the BBO crystals are cut at $\theta = 25.7°$ and $\phi = 0°$ for type-I phase matching in the $X-Z$ plane ($e \rightarrow o + o$) at room temperature with a length of 14 mm. These two crystals are arranged in walk-off compensation geometry [1], [4] so that the beam walk-off between the pump and signal in the two crystals is canceled by tilting the two crystals in opposite directions. Only the central portion of the parametric output is overlapped with the pump and is amplified. Thus the double-crystal scheme also serves as a spatial and spectral filter that improves the beam divergence and bandwidth [4]. Moreover, the parametric interaction length is doubled, so that the parametric conversion efficiency is effectively increased. The parametric signal after the OPG stage was combined with the 400 nm main pumping pulses by DM5 for OPA in a third 14 mm long BBO crystal.

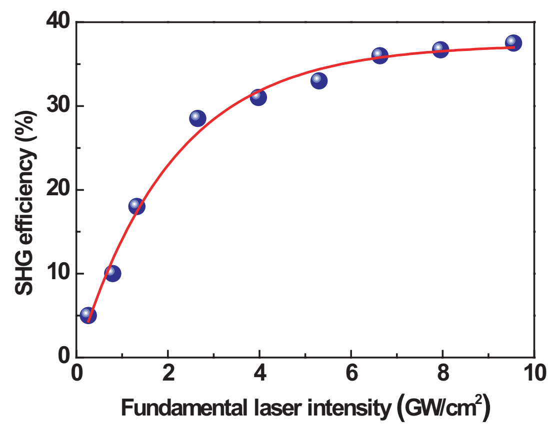

Fig. 2. Conversion efficiency from the fundamental to the SH versus incident laser intensity.

III. Experimental Results and Discussion

The OPG-OPA system employing BBO crystals has a very broad wavelength tuning range. The BBO crystals are mounted on precise rotation stages. Wavelength tuning is achieved by slightly counter-rotating the two BBO crystals in the OPG stage and accordingly the BBO crystal in the OPA stage. The measured tuning curve in the signal branch is drawn in Fig. 3 with the pumping wavelength fixed at 400 nm. The signal pulse is continuously tuned from 460 to 750 nm.

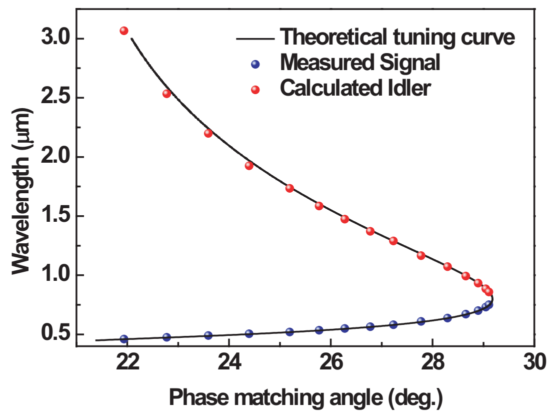

Fig. 3. Wavelength tuning curve for type-I BBO crystal as a function of the internal phase matching angle. Blue circles show the measured signal wavelength and red circles show the calculated idler wavelength. The pumping wavelength is fixed at 400 nm.

Signal pulse energy drops rapidly for the wavelength below 460 nm and approaching the degeneracy point. The measured tuning wavelength with the internal phase matching angle is in good agreement with calculation based on the Sellmeier equation by Kato [17]. The corresponding idler wavelength has a tuning range of 0.86 to 3.07 μm. The Ti:sapphire amplifier in our experiment has a tuning range of 760-840 nm, and the corresponding SH wavelength is between 380-420 nm. As a result, the parametric tuning range has the potential to be extended in the short wavelength to ~440 nm using 380 nm pumping wavelength and in the long wavelength to ~3.3 μm using 420 nm pumping wavelength, without replacing any optics in the OPG-OPA system.

At present, we did not use any other optics to reduce the parametric bandwidth. The spectra of the signal generated by the highest pumping energy are depicted in Fig. 4. We see the bandwidth is variable with signal frequency. At short wavelength, the bandwidth is estimated to be less than 1 nm. While near the degeneracy point of the tuning curve, the bandwidth increases rapidly to several nanometers. The bandwidth can be significantly narrowed either by seed-injection or by spectral filtering by grating in the OPG stage [1], [4], [7], [18].

The threshold of OPG is measured to be 9 mJ at 400 nm, corresponding to a pulse intensity of 0.8 GW/cm^2. When increase the pumping energy to 30 mJ (intensity: 2.7 GW/cm^2), the output of the signal from the OPG is about 2 mJ. Further increasing the pumping energy will cause colorful super-fluorescence that will deteriorate the signal beam quality. So we keep the pumping intensity at 2.7 GW/cm^2 for the OPG stage. The frequency-doubled pulses used for pumping the OPA are firstly passing through a 1:2 telescope (focal length with 400 mm and −200 mm, respectively, uncoated) and then pump the OPA for single-pass. The pulse energy arriving at the BBO crystal is about 110 mJ with intensity of about 2.9 GW/cm^2. The amplified signal at most of the wavelengths has energy over 20 mJ, as seen in Fig. 5, corresponding to a parametric gain of about 10, with a rms energy instability less than 10%. The fluctuation originates mainly from the pumping energy instability and the spatial pointing instability of the pump pulse (The Ti:sapphire amplifier has an energy instability of 3%). The highest pulse energy is obtained to be 33 mJ at 710 nm, corresponding to a conversion efficiency of ~30%. Further increasing the pumping energy will not increase the output energy notably but has the risk to damage the surface of the BBO crystal. Strong off-axis parametric emission with rainbow color was observed at very high pumping intensity which is due to non-collinear phase matching in the BBO crystal [19]. The off-axis parametric super-fluorescence consumes a large part of the pump energy and thus limits the growth of on-axis parametric gain. The spatial profile of the OPA output inherited the top-hat shape of the pump beam due to gain saturation and the beam divergence was measured to be ~1.5 times the diffraction limit.

We have also carried out the preliminary SHG experiment of the visible signal into UV using a type-I BBO crystal ($\theta = 43.3°$, $\phi = 0°$). By loosely focusing the 20 mJ 570 nm signal pulses into the 14 mm long BBO crystal, about 2 mJ 285 nm pulses were generated, corresponding to a conversion efficiency of 10%. So we are confident that by a set of BBO crystals cutting at appropriate phase matching angles for SHG of 460-750 nm wavelengths, milli-Joule class picosecond UV pulses tunable in the 230-375 nm wavelength range can be obtained. Together with the signal/idler and the fundamental,

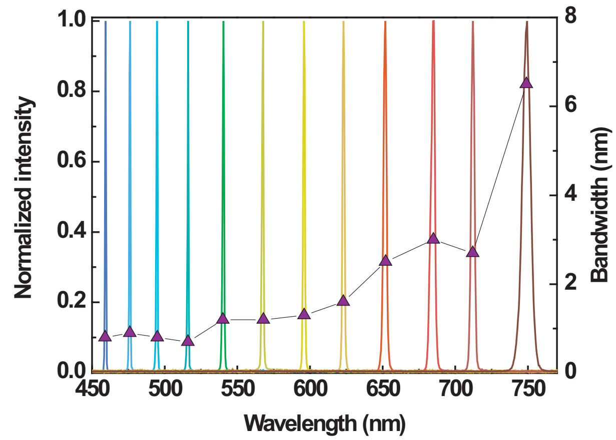

Fig. 4. Normalized spectra of the signal tunable from 460 to 750 nm in the OPA stage. Solid triangles show the bandwidth at each wavelength.

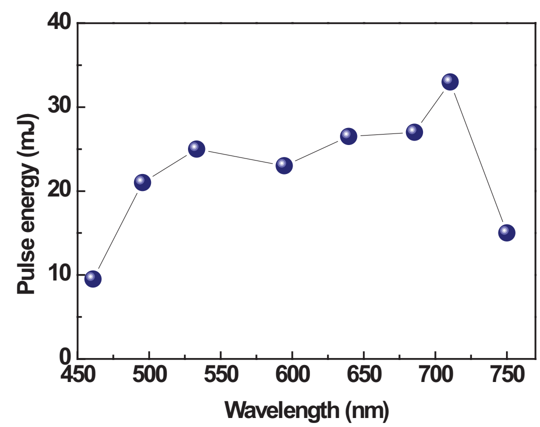

Fig. 5. Signal pulse energy measured for different wavelengths at the pumping energy of 110 mJ.

we can expect to get gap-free high energy picosecond pulses from deep UV to MIR.

IV. Conclusion

In conclusion, we have developed a high energy picosecond optical parametric generation and amplification system, pumped by the second harmonic output of a picosecond two-stage Ti:sapphire amplifier operating at 10 Hz repetition rate. By angular tuning of the BBO crystals in the OPG stage, signal wavelength tunable from 460 to 750 nm was realized with average pulse energy of 2 mJ. The signal pulses were further amplified to the 20 mJ class in the OPA stage and reached a maximum of 33 mJ at 710 nm with a conversion efficiency of $\sim$30%. We believed this is the highest pulse energy ever achieved up to the present from a picosecond OPA in the visible pumped by the Ti:sapphire amplifier.

Acknowledgment

The authors would like to thank J. Sun for his instructive suggestions and advice.

References

[1] J. Y. Huang, J. Y. Zhang, Y. R. Shen, C. Chen, and B. Wu, "High-power, widely tunable, picosecond coherent source from optical parametric amplification in barium borate," *Appl. Phys. Lett.*, vol. 57, no. 19, pp. 1961–1963, 1990.

[2] J. Y. Huang, Y. R. Shen, C. Chen, and B. Wu, "Noncritically phase-matched second-harmonic generation and optical parametric amplification in a lithium triborate crystal," *Appl. Phys. Lett.*, vol. 58, no. 15, pp. 1579–1581, Apr. 1991.

[3] J. Y. Zhang, J. Y. Huang, Y. R. Shen, C. Chen, and B. Wu, "Picosecond optical parametric amplification in lithium triborate," *Appl. Phys. Lett.*, vol. 58, no. 3, pp. 213–215, 1991.

[4] J. Y. Zhang, J. Y. Huang, Y. R. Shen, and C. Chen, "Optical parametric generation and amplification in barium borate and lithium triborate crystals," *J. Opt. Soc. Amer. B*, vol. 10, no. 9, pp. 1758–1764, 1993.

[5] X. D. Zhu and L. Deng, "Broadly tunable picosecond pulses generated in a β-BaB2O4 optical parametric amplifier pumped by 0.532 μm pulses," *Appl. Phys. Lett.*, vol. 61, no. 13, pp. 1490–1492, 1992.

[6] F. Huang and L. Huang, "Picosecond optical parametric generation and amplification in LiB3O5 and β-BaB2O4," *Appl. Phys. Lett.*, vol. 61, no. 15, pp. 1769–1771, 1992.

[7] F. Huang and L. Huang, "Picosecond optical parametric amplification in β-BaB2O4," *IEEE J. Quantum Electron.*, vol. 30, no. 11, pp. 2601–2607, Nov. 1994.

[8] V. Petrov, F. Seifert, and F. Noack, "Visible optical parametric generator producing nearly bandwidth-limited femtosecond light pulses at 1-kHz repetition rate," *Appl. Opt.*, vol. 33, no. 30, pp. 6988–6991, 1994.

[9] S. R. Greenfield and M. R. Wasielewski, "Optical parametric amplification of femtosecond pulses tunable from the blue to the infrared with microjoule energies," *Appl. Opt.*, vol. 34, no. 15, pp. 2688–2691, 1995.

[10] J. Zhang, Z. Xu, Y. Kong, C. Yu, and Y. Wu, "Highly efficient, widely tunable, 10-Hz parametric amplifier pumped by frequency-doubled femtosecond Ti:sapphire laser pulses," *Appl. Opt.*, vol. 37, no. 15, pp. 3299–3305, 1998.

[11] V. Petrov, F. Noack, P. Tzankov, M. Ghotbi, M. Ebrahim-Zadeh, I. Nikolov, and I. Buchvarov, "High-power femtosecond optical parametric amplification at 1 kHz in BiB_3O_6 pumped at 800 nm," *Opt. Express*, vol. 15, no. 2, pp. 556–563, 2007.

[12] A. Baltuška, T. Fuji, and T. Kobayashi, "Visible pulse compression to 4 fs by optical parametric amplification and programmable dispersion control," *Opt. Lett.*, vol. 27, no. 5, pp. 306–308, 2002.

[13] K. Yamane, T. Tanigawa, T. Sekikawa, and M. Yamashita, "Angularly-dispersed optical parametric amplification of optical pulses with one-octave bandwidth toward monocycle regime," *Opt. Express*, vol. 16, no. 22, pp. 18345–18353, 2008.

[14] D. Brida, G. Cirmi, C. Manzoni, S. Bonora, P. Villoresi, S. Silvestri, and G. Cerullo, "Sub-two-cycle light pulses at 1.6 μm from an optical parametric amplifier," *Opt. Lett.*, vol. 33, no. 7, pp. 741–743, 2008.

[15] E. Takahashi, T. Kanai, Y. Nabekawa, and K. Midorikawa, "10 mJ class femtosecond optical parametric amplifier for generating soft X-ray harmonics," *Appl. Phys. Lett.*, vol. 93, no. 4, pp. 041111-1–041111-3, 2008.

[16] J. Zhu, W. Ling, Z. Wang, P. Wang, J. Sun, Z. Wei, D. Zhang, X. Ma, and W. Zhan, "High-energy picosecond near-vacuum ultraviolet pulses generated by sum-frequency mixing of an amplified Ti:sapphire laser," *Appl. Opt.*, vol. 46, no. 25, pp. 6228–6231, 2007.

[17] K. Kato, "Second-harmonic generation to 2048 Å in β-BaB2O4," *IEEE J. Quantum Electron.*, vol. 22, no. 7, pp. 1013–1014, Jul. 1986.

[18] D. E. Gragson, D. S. Alavi, and G. L. Richmond, "Tunable picosecond infrared laser system based on parametric amplification in KTP with a Ti:sapphire amplifier," *Opt. Lett.*, vol. 20, no. 19, pp. 1991–1993, 1995.

[19] H. Wang, K. S. Wong, D. Deng, Z. Xu, G. K. L. Wong, and J. Zhang, "Kilohertz femtosecond UV-pumped visible β-barium borate and lithium triborate optical parametric generator and amplifier," *Appl. Opt.*, vol. 36, no. 9, pp. 1889–1893, 1997.

Jiangfeng Zhu received the Ph.D. degree in ultrafast optics from the Institute of Physics, Chinese Academy of Sciences, Beijing, China, in 2008.

He was with the Department of Applied Physics, Hokkaido University, Sapporo, Japan, from 2008 to 2011, as a Post-Doctoral Fellow. Since 2011, he has been with the School of Technical Physics, Xidian University, Xi'an, China, as an Associate Professor. His current research interests include novel ultrashort pulse generation, nonlinear frequency conversion, and their applications.

Weijun Ling received the Ph.D. degree in ultrafast optics from the Institute of Physics, Chinese Academy of Sciences, Beijing, China, in 2006.

He has been with the College of Physics and Information Science, Tianshui Normal University, Tianshui, China, since 2006, as an Associate Professor. His current research interests include amplification of ultrashort pulses by optical parametric amplification or chirped pulse amplification methods, nonlinear frequency conversion, and their applications.

Xin Zhong was born in Sichuan, China, on October 30, 1982. He received the B.S. degree in electronics engineering from Tsinghua University, Beijing, China, in 2005, and the Ph.D. degree in ultrafast optics from the Institute of Physics, Chinese Academy of Sciences, Beijing, China, in 2010.

His current research interests include ultrafast laser technology, especially on optical parametric progress.

Zhaohua Wang received the Ph.D. degree in ultrafast optics from the Institute of Physics, Chinese Academy of Sciences, Beijing, China, in 2004.

He was as a Post-Doctoral Fellow with the National Astronomical Observatories, Chinese Academy of Sciences, from 2004 to 2007. Since 2007, he has been an Associate Professor with the Institute of Physics, Chinese Academy of Sciences. His current research interests include novel ultrashort pulse generation, amplification, and their applications.

Zhiyi Wei was born in Gansu, China, in May 1963. He received the Ph.D. degree from the Xi'an Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Xi'an, China, in 1991.

He was a Visiting Scholar with the Rutherford Appleton Laboratory, Didcot, U.K., the Chinese University of Hong Kong, Hong Kong, the Hong Kong University of Science and Technology, Hong Kong, and the University of Groningen, Groningen, The Netherlands, from 1993 to 1997, after two years as a Post-Doctoral Fellow with the Ultrafast Laser Spectroscopy Laboratory, Sun Yat-Sen University, Guangzhou, China. He joined the Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, in 1997. From 2000 to 2002, he was also with the National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan, as a NEDO Fellowship Researcher. He is currently the Group Leader with the Ultrafast Laser Group and the Director with the Joint Laboratory of Advanced Technology in Measurements, Institute of Physics, Chinese Academy of Sciences. His current research interests include generation, phase control, amplification, and compression of femtosecond laser pulses.

Prof. Wei is an International Advisory Member of the *IOP Journal for Measurement Science and Technology*, and a member of the C2 (Symbol and Constants) Sub-Committee, International Union of Pure and Applied Physics, London, U.K.