Appl. Phys. B (2014) 116:287–292
DOI 10.1007/s00340-013-5687-8

Applied Physics B
Lasers and Optics

Enhancement of temporal contrast of high-power femtosecond laser pulses using two saturable absorbers in the picosecond regime

Jae Hee Sung · Seong Ku Lee · Tae Moon Jeong · Chang Hee Nam

Received: 30 July 2013 / Accepted: 8 October 2013 / Published online: 26 October 2013

Abstract We characterized the transmission properties of a color-glass-filter (RG850) saturable absorber (SA) in a wide range of pulse durations (from 25 fs to 5 ps). The transmission properties were strongly related to the energy fluence, pulse duration, and chirp parameter. On the basis of these properties, the input pulse duration, chirp parameter, and energy fluence were optimized to maintain the width of the transmitted laser spectrum as much as possible with minimal energy loss. We demonstrated that, by transmitting a positively chirped 2.8-ps laser pulse to two identical SAs at an energy fluence of 15 mJ/cm^2, the temporal contrast ratio of the main pulse to the amplified spontaneous emission was enhanced by 4 orders of magnitude without any significant energy loss or strong spectral narrowing in a 10-Hz, 100-TW femtosecond laser system.

1 Introduction

The temporal contrast of a high-intensity laser pulse plays a critical role in many laser-matter interaction experiments. For example, in generating proton beams from ultrathin targets, the maximum energy and conversion efficiency of the proton beams are strongly affected by the temporal contrast of the driving laser pulses [1]. When a petawatt (PW)-class laser pulse [2–5] is focused, the laser intensity in the focal plane can easily reach 10^{21} W/cm^2 or higher [6]. In this case, the contrast ratio of a laser pulse, defined as the ratio of the intensity of the main laser pulse to that of the background, should be $>10^{10}$ to prevent the formation of pre-plasma by pre-pulses and amplified spontaneous emission (ASE) before the main pulse. A typical chirped-pulse amplification (CPA) high-peak-power laser has an ASE contrast ratio in a range of 10^6–10^7; hence, the contrast ratio must be improved by at least 4 orders of magnitude to reach temporal contrast over 10^{10} [7].

To date, several techniques, such as cross-polarized wave (XPW) generation, a self-diffraction (SD) process, and a double plasma mirror (DPM), have been proposed to improve the contrast ratio by more than 4 orders of magnitude [8–11]. The XPW and SD techniques, which are applied at the front end of a CPA high-peak-power laser, provide excellent contrast ratios with spectral broadening, although the XPW technique requires polarization-sensitive optical elements with a high extinction ratio and the SD technique does a precise alignment for spatial and temporal overlaps between two laser beams in a bulk Kerr medium. The DPM technique can be applied directly after a pulse compressor in a simple and robust way, although the energy loss is typically about 50 % and cannot be recovered afterward. Thus, an alternative contrast enhancement technique that can be implemented at the front end of a laser system is required to improve temporal contrast without precise alignment and delicate optical elements that use polarization discrimination.

Although a saturable absorber (SA) has been widely used at the front end to improve the contrast ratio without any alignment-sensitive or polarizing elements [12], in a

J. H. Sung · S. K. Lee · T. M. Jeong · C. H. Nam
Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju 500-712, Republic of Korea

J. H. Sung (✉) · S. K. Lee · T. M. Jeong
Ultraintense Laser Laboratory, Advanced Photonics Research Institute, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Republic of Korea
e-mail: sungjh@gist.ac.kr

C. H. Nam
Department of Physics and Photon Science, GIST, Gwangju 500-712, Republic of Korea

single-pass geometry, the improvement in the contrast ratio has been limited to about 2 orders of magnitude. The idea of using an additional SA after a pulse stretcher was proposed to overcome the problem of low-contrast improvement [13, 14]. However, a laser pulse is stretched to several hundred picoseconds (ps) after the pulse stretcher, and an ASE that temporally overlaps with the stretched laser pulse cannot be suppressed by a SA. Therefore, the additional SA cannot effectively improve the contrast ratio within several hundred ps before the main laser pulse. Therefore, a SA that acts within a few ps must be applied to improve the contrast ratio in a temporal range close to the main laser pulse.

An additional problem is that after passing through a SA, laser pulses suffer from energy loss and spectral narrowing [13, 14]. The large energy loss due to the SA can induce a significant reduction in the final output energy of a laser system [13]. Further, the strong spectral narrowing can induce pulse broadening in the temporal domain. Therefore, identifying the optimal conditions that minimize the energy loss and spectral narrowing due to a SA is necessary for effectively applying the SA to contrast enhancement.

In this paper, we systematically characterize the transmission properties of a color-glass-filter (RG850) used as a SA in a high-power femtosecond laser system. To identify the optimal conditions for higher throughput and minimum pulse distortion, the transmittance and laser spectrum after the SA were investigated as functions of energy fluence, pulse duration, and chirp parameter. Two identical RG850 SAs were then implemented in series at the front end of a 100-TW femtosecond laser system to improve the contrast ratio by 4 orders of magnitude. Finally, a high ASE contrast ratio over 10^{11} for the 100-TW laser system was achieved without severe energy loss or strong spectral narrowing.

2 Transmission characteristics of a color-glass-filter as a saturable absorber

We measured the transmission characteristics of a laser pulse passing through a single SA with respect to the pulse duration, chirp parameter, and energy fluence on the SA. Figure 1 shows the experimental setup for measuring the transmission characteristics of the SA. The SA (RG850, CVI laser) is 3 mm thick with antireflection coating on both surfaces. The laser pulse duration could be adjusted from 25 fs for a chirp-free pulse to 5 ps for a positively chirped (or negatively chirped) pulse by decreasing (or increasing) the distance between two parallel gratings in a grating compressor. The energy fluence was changed from 1 to 30 mJ/cm^2 by attenuating the pulse energy with a half-wave plate and a polarizing beam splitter while fixing the beam size on the SA.

The transmittance of a laser pulse is investigated as a function of the energy fluence on the SA at different pulse durations and chirp parameters. As shown in Fig. 2, the transmittance increases as the energy fluence increases up to 8 mJ/cm^2, irrespective of the pulse duration and chirp parameter. At an initial energy fluence of 1 mJ/cm^2, the transmittance remains low (within 5–15 %) at all pulse durations and chirp parameters. Interestingly, the transmission characteristics varied with the chirp parameter. A chirp-free 25-fs laser pulse has a transmittance of about 10 %. Positively chirped laser pulses (up to 5 ps) show a decrease in the transmittance to 5 %. In contrast, the transmittance for negatively chirped laser pulses increases to 14 %. At low energy fluences ranging from 1 to 6 mJ/cm^2, a negatively chirped pulse shows greater transmittance than a positively chirped pulse at the same pulse duration. However, at higher energy fluences over 8 mJ/cm^2, the transmittances for positively and negatively chirped laser pulses become similar. This trend is summarized in Fig. 3, which shows the transmittance as a function of pulse duration at energy fluences of 4, 6, 8, and 25 mJ/cm^2. Here, the reduction in transmittance with the decrease in pulse duration indicates that, contrary to the normal saturable absorption effect, the absorption of the laser pulse increases as the laser pulse intensity increases. This phenomenon may be interpreted as a nonlinear absorption effect, similar to that observed in reverse saturable absorption and two-photon absorption, due to very high intensity [15, 16]. As a result, a chirped laser pulse with a duration of a few ps has an advantage over the shortest chirp-free laser pulse in terms of transmittance when passing through a RG850 SA at a high energy fluence of over 8 mJ/cm^2.

The spectral profiles of laser pulses passing through the RG850 SA were also measured with respect to the energy

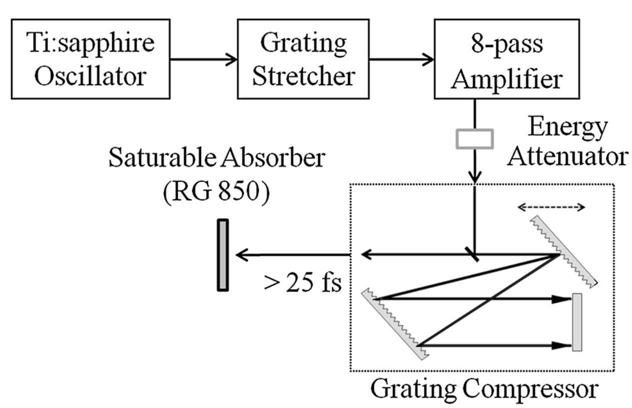

Fig. 1 Schematic of the 10-Hz CPA femtosecond Ti:sapphire laser system

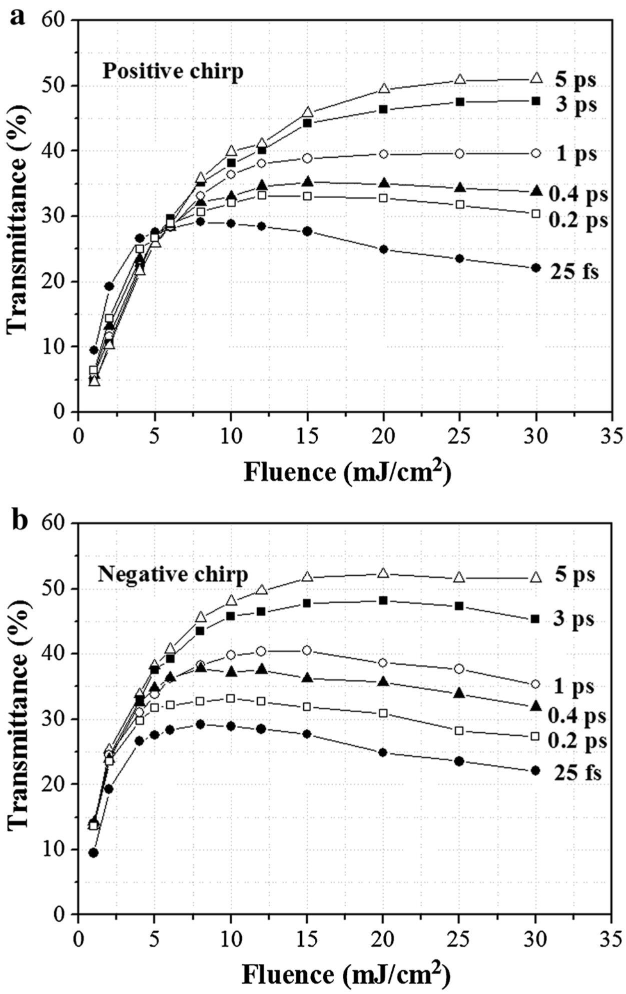

Fig. 2 Transmittance of a laser pulse passing through a saturable absorber (RG850 filter) as a function of the energy fluence on the saturable absorber at pulse durations in the range of 25 fs–5 ps with *positive chirp* (**a**) and *negative chirp* (**b**)

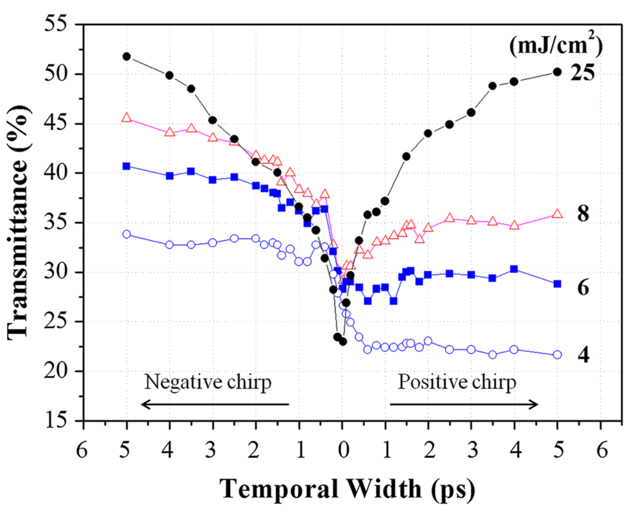

Fig. 3 Transmittance of a laser pulse passing through a saturable absorber (RG850 filter) as a function of the pulse duration at energy fluences of 4, 6, 8, and 25 mJ/cm^2 on the saturable absorber

fluence and pulse duration. Figure 4a shows that a chirp-free 25-fs laser pulse exhibits strong spectral narrowing after the SA and that a negatively chirped ps laser pulse also displays strong spectral narrowing due to the suppression of short wavelength components. In contrast, a positively chirped ps laser pulse shows minimal spectral narrowing. This is an advantage of using a positively chirped ps laser pulse. Here, the dependencies of the spectral narrowing characteristics on pulse duration and chirp parameter are not yet fully understood and should be investigated later in detail. Figure 4b shows that the spectral narrowing effect weakens as the energy fluence increases. Consequently, a positively chirped ps laser pulse with an optimized energy fluence has an advantage over the shortest and negatively chirped ps laser pulses in minimizing the spectral narrowing effect. Although it is difficult to fully understand why a positively chirped ps laser pulse shows better transmission characteristics in terms of transmittance and spectral narrowing, the transmission data shown in Figs. 2, 3, and 4 can be used to determine the optimal conditions for minimal spectral narrowing and higher transmittance.

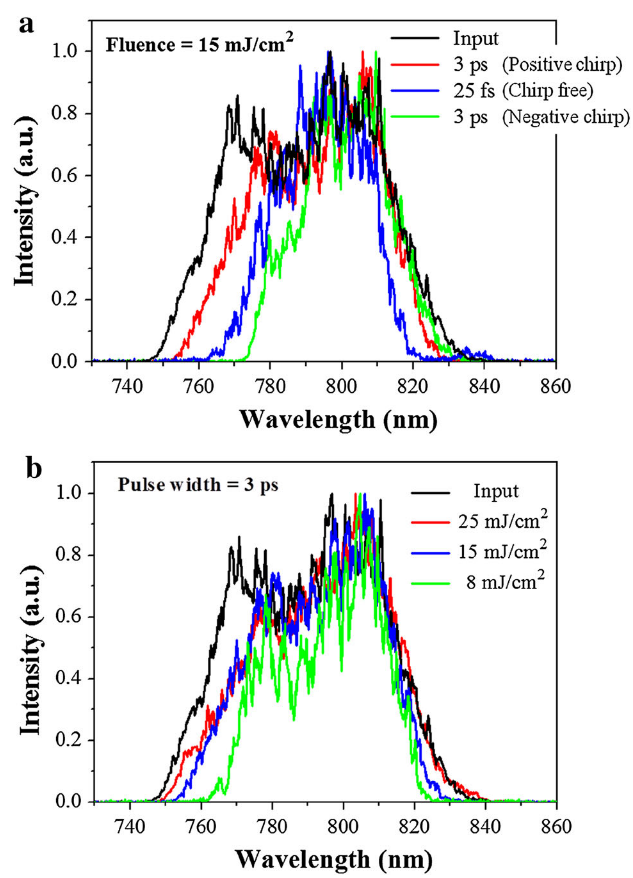

Fig. 4 Spectra of laser pulses passing through a single RG850 saturable absorber as a function of pulse duration at an energy fluence of 15 mJ/cm^2 (**a**) and as a function of energy fluence at a pulse duration of 3 ps for a positively chirped pulse (**b**)

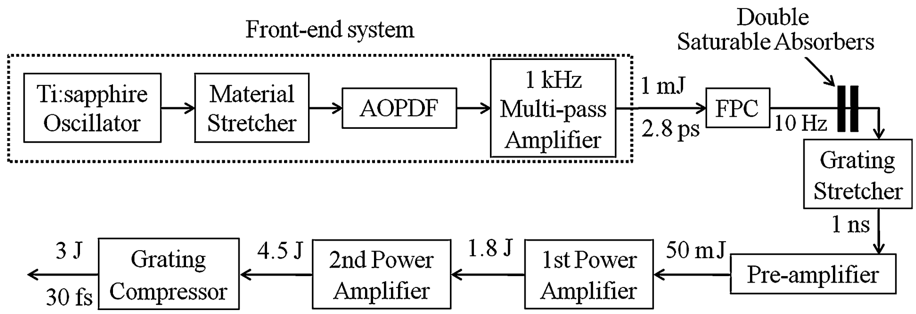

Fig. 5 Schematic of the CPA 10-Hz, 100-TW Ti:sapphire laser system. *AOPDF* acousto-optic programmable dispersive filter, *FPC* fast Pockels cell

3 Contrast enhancement using two saturable absorbers in a high-power femtosecond Ti:sapphire laser

To improve the contrast ratio of 100-TW 30-fs Ti:sapphire laser pulses, two identical RG850 SAs were implemented after a front-end amplifier. As shown in Fig. 5, the CPA 10-Hz, 100-TW Ti:sapphire laser consists of a front-end multi-pass amplifier system, a grating stretcher, a pre-amplifier, two power amplifiers, and a grating compressor. The temporal intensity profile and the spectrum of the 100-TW laser pulse are shown in Fig. 6. The front-end multi-pass amplifier system is composed of a Ti:sapphire oscillator, a material stretcher, an acousto-optic programmable dispersive filter (AOPDF; Dazzler, Fastlite), and a 1-kHz multi-pass Ti:sapphire amplifier (Femtopower Compact Pro, Femtolasers). The AOPDF was used to pre-compensate for gain narrowing in the amplifiers. Femtosecond laser pulses from the oscillator were stretched by a SF57 block and then amplified in the front-end amplifier to have positively chirped pulses of 2.8-ps duration and 1-mJ energy. Two identical SAs were placed between the front-end amplifier and the grating stretcher. Because of the high transmittance and minimal spectral narrowing, positively chirped laser pulses allowed us to use two SAs for contrast ratio enhancement.

Positively chirped 2.8-ps 1-mJ laser pulses, directly from the 1-kHz front-end amplifier, were selected at 10 Hz by a fast Pockels cell and transmitted through a pair of SAs with an energy fluence of 15 mJ/cm^2. A higher fluence close to 30 mJ/cm^2 has an advantage over the lower fluence in terms of the transmittance, as shown in Fig. 2. However, the lower energy fluence (15 mJ/cm^2) was chosen for the experiments because the higher-fluence laser pulse showed a faster decrease in transmittance due to thermally induced damage on the SA. The 4 % difference in the transmittance between the fluence levels of 15 and 30 mJ/cm^2 did not make much difference in the final output energy from the power amplifiers. After the pair of SAs, the laser pulse had an overall transmittance of 15 % with no substantial difference in the beam profiles before and after the SAs, and the energy loss was almost compensated for in the pre-amplifier. Furthermore, the laser pulse showed a slight spectral narrowing, as shown in Fig. 7. However, use of the AOPDF minimized the spectral distortion of the final laser pulse. During laser operation for several hours, the laser pulse experienced a decrease in the transmittance to 8 % and a spectral narrowing after the two SAs because of the thermally induced damage

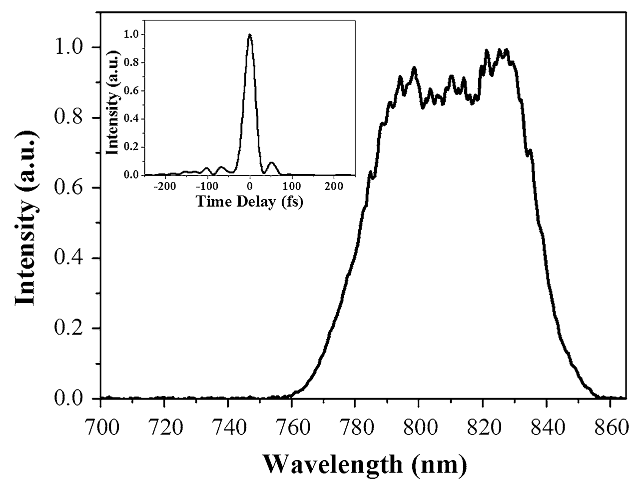

Fig. 6 Spectrum of the 100-TW laser pulse. The inset shows the temporal intensity profile of the 100-TW laser pulse

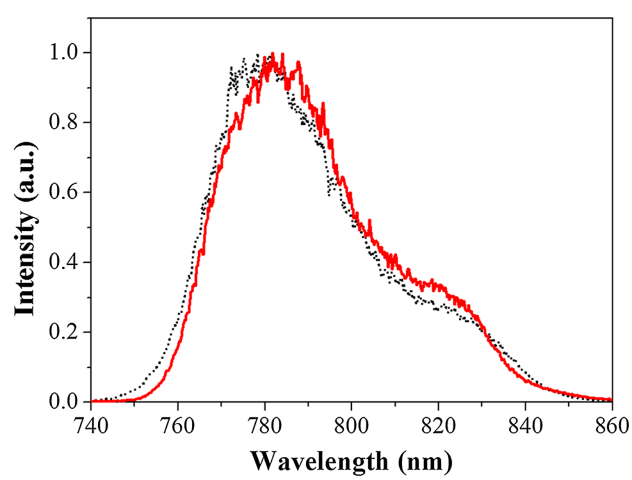

Fig. 7 Spectra of 1-mJ ps laser pulses from the front-end amplifier of a CPA 10-Hz, 100-TW Ti:sapphire laser system before (*dotted black line*) and after (*solid red line*) applying a pair of RG850 saturable absorbers

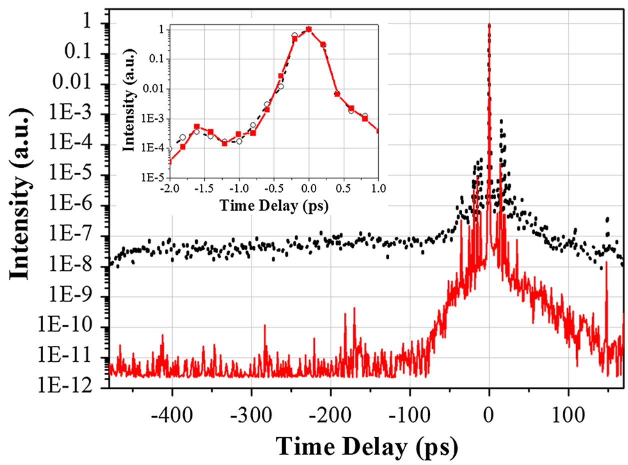

Fig. 8 Third-order cross-correlation signals of 100-TW laser pulses before (*dotted black line*) and after (*solid red line*) applying a pair of saturable absorbers

on the SAs. We slowly rotated the SAs in order to mitigate the thermally induced damage. As a result, a transmittance of 15 % was maintained and the spectral narrowing was minimized for a long-term operation.

The installation of the two SAs greatly improved laser performance. After the final compression in the 100-TW laser system, the contrast ratio for the ASE level was improved by 4 orders of magnitude up to about 80 ps before the main laser pulse (see Fig. 8). The temporal contrast was measured with a third-order cross-correlator (Sequoia, Amplitude Technologies). The laser pedestal, appearing from 80 ps before the main laser pulse in the contrast ratio plot, originated from several factors, including scattering from a diffraction grating in the stretcher [17] and uncompensated higher-order dispersions. This will be suppressed by installing a new high-quality grating in the stretcher and minimizing the spectral phase distortion with a feedback loop using the AOPDF later. Some of pre-pulses before the main pulse were ghosts of post-pulses due to the third-order cross-correlation, and others were induced by the nonlinear interference between the main pulse and the post-pulses [5, 18]. The post-pulses originated from multiple reflections at optical components installed in the laser system. Consequently, 100-TW 30-fs laser pulses with an ASE contrast >10^{11} could be obtained, without any sophisticated optical devices, by operating a pair of SAs in the picosecond regime in the front-end amplifier. Additionally, this contrast ratio enhancement technique will be valid for the 1.5-PW laser beam line demonstrated recently [5].

4 Conclusion

The transmittance and spectral profile of a laser pulse after a RG850 SA, installed for temporal contrast improvement in high-peak-power femtosecond Ti:sapphire laser systems, were investigated with respect to energy fluence, pulse duration, and chirp parameter. The results show that a laser pulse chirped to a few ps has an advantage over the shortest chirp-free laser pulse in terms of transmittance. A positively chirped ps laser pulse is particularly beneficial for minimizing the spectral narrowing effect over the shortest and negatively chirped ps laser pulses. The transmission properties of the SA in the picosecond regime enable us to simply apply multiple SAs for contrast ratio enhancement. As an example, two identical RG850 SAs were applied to 2.8-ps 1-mJ laser pulses from a front-end amplifier in a 10-Hz, 100-TW Ti:sapphire laser, and 100-TW laser pulses with contrast ratios >10^{11} were consequently obtained without significant energy loss or strong spectral narrowing. This 100-TW laser will be a powerful tool in relativistic laser-matter interaction experiments requiring high-contrast high-intensity laser pulses.

Acknowledgments This work was supported by Institute for Basic Science (IBS) in Korea and Applications of Femto-Science to Nano/Bio-Technology Utilizing Ultrashort Quantum Beam Facility through a grant provided by GIST.

References

1. D. Neely, P. Foster, A. Robinson, F. Lindau, O. Lundh, A. Persson, C.-G. Wahlström, P. McKenna, Appl. Phys. Lett. **89**, 21502 (2006)
2. M. Aoyama, K. Yamakawa, Y. Akahane, J. Ma, N. Inoue, H. Ueda, H. Kiriyama, Opt. Lett. **28**, 1594 (2003)
3. J.H. Sung, S.K. Lee, T.J. Yu, T.M. Jeong, J. Lee, Opt. Lett. **35**, 3021 (2010)
4. Z. Wang, C. Liu, Z. Shen, Q. Zhang, H. Teng, Z. Wei, Opt. Lett. **36**, 3194 (2011)
5. T.J. Yu, S.K. Lee, J.H. Sung, J.W. Yoon, T.M. Jeong, J. Lee, Opt. Express **20**, 10807 (2012)
6. V. Yanovsky, V. Chvykov, G. Kalinchenko, P. Rousseau, T. Planchon, T. Matsuoka, A. Maksimchuk, J. Nees, G. Cheriaux, G. Mourou, K. Krushelnick, Opt. Express **16**, 2109 (2008)
7. M. Aoyama, A. Sagisaka, S. Matsuoka, Y. Akahane, F. Nakano, K. Yamakawa, Appl. Phys. B **70**, S149 (2000)
8. A. Jullien, O. Albert, F. Burgy, G. Hamoniaux, J. Rousseau, J. Chambaret, F. Auge-Rochereau, G. Cheriaux, J. Etchepare, N. Minkovski, S.M. Saltiel, Opt. Lett. **30**, 920 (2005)
9. V. Chvykov, P. Rousseau, S. Reed, G. Kalinchenko, V. Yanovsky, Opt. Lett. **31**, 1456 (2006)
10. J. Liu, K. Okamura, Y. Kida, T. Kobayashi, Opt. Express **18**, 22245 (2010)
11. I.J. Kim, I.W. Choi, S.K. Lee, K.A. Janulewicz, J.H. Sung, T.J. Yu, H.T. Kim, H. Yun, T.M. Jeong, J. Lee, Appl. Phys. B **104**, 81 (2011)
12. J. Itatani, J. Faure, M. Nantel, G. Mourou, S. Watanabe, Opt. Commun. **148**, 70 (1998)
13. S. Fourmaux, S. Payeur, S. Buffechoux, P. Lassonde, C. St-Pierre, F. Martin, J.C. Kieffer, Opt. Express **19**, 8486 (2011)
14. H. Kiriyama, T. Shimomura, H. Sasao, Y. Nakai, M. Tanoue, S. Kondo, S. Kanazawa, A.S. Pirozhkov, M. Mori, Y. Fukuda, M. Nishiuchi, M. Kando, S.V. Bulanov, K. Nagashima, M.

Yamagiwa, K. Kondo, A. Sugiyama, P.R. Bolton, T. Tajima, N. Miyanaga, Opt. Lett. **37**, 3363 (2012)
15. Y. Gao, X. Zhang, Y. Li, H. Liu, Y. Wang, Q. Chang, W. Jiao, Y. Song, Opt. Commun. **251**, 429 (2005)
16. C.P. Singh, K.S. Bindra, S.M. Oak, Pramana J. Phys. **75**, 1169 (2010)
17. C. Hooker, Y. Tang, O. Chekhlov, J. Collier, E. Divall, K. Ertel, S. Hawkes, B. Parry, P.P. Rajeev, Opt. Express **19**, 2193 (2011)
18. N.V. Didenko, A.V. Konyashchenko, A.P. Lutsenko, S.Y. Tenyakov, Opt. Express **16**, 3178 (2008)