Spatial chirp in Ti:sapphire multipass amplifier*

Wenkai Li(黎文开)[1,2], Jun Lu(陆俊)[1,2], Yanyan Li(李妍妍)[1], Xiaoyang Guo(郭晓杨)[1,3], Fenxiang Wu(吴分翔)[1,2], Linpeng Yu(於林鹏)[1,2], Pengfei Wang(王朋飞)[1,2], Yi Xu(许毅)[1,†], and Yuxin Leng(冷雨欣)[1,‡]

[1] *State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai* 201800, *China*
[2] *University of Chinese Academy of Sciences, Beijing* 100049, *China*
[3] *Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka* 565-0871, *Japan*

(Received 7 November 2016; revised manuscript received 9 December 2016; published online 18 January 2017)

The spatial chirp generated in the Ti:sapphire multipass amplifier is numerically investigated based on the one-dimensional (1D) and two-dimensional (2D) Frantz–Nodvik equations. The simulation indicates that the spatial chirp is induced by the spatially inhomogeneous gain, and it can be almost eliminated by utilization of proper beam profiles and spot sizes of the signal and pump pulses, for example, the pump pulse has a top-hatted beam profile and the signal pulse has a super-Gaussian beam profile with a relatively larger spot size. In this way, a clear understanding of spatial chirp mechanisms in the Ti:sapphire multipass amplifier is proposed, therefore we can effectively almost eliminate the spatial chirp and improve the beam quality of a high-power Ti:sapphire chirped pulse amplifier system.

Keywords: spatial chirp, multipass amplifier, Ti:sapphire

PACS: 42.60.Jf, 79.20.Ds, 42.55.Rz **DOI:** 10.1088/1674-1056/26/3/034206

1. Introduction

During the past several decades, immense progress has been made in the research of high-power Ti:sapphire chirped pulse amplification (CPA) laser system.[1–4] The ultrahigh peak power laser can produce a focused intensity of 10^{21}–10^{22} W/cm^2 class,[5,6] which is thought to be suitable for high-field physics, such as particle acceleration, filamentation, x-ray generation, and the study of plasma physics.[7–12] At present, the development of femtosecond high power laser systems with power levels of 10 PW or even 100 PW is being pursued.[13,14]

However, it is not sufficient to have just high power; other aspects such as spatial chirp of signal pulse also play an important role in physics experiments.[15,16] A beam with spatial chirp means that its different spectral components are separated in space transverse to the direction of propagation. In most CPA systems, the signal pulse is stretched with a positive chirp. The red portion of the pulse precedes the blue portion. When the stretched signal pulse is injected into the Ti:sapphire amplifier, the leading part of the signal pulse obtains more energy than the trailing part. As a result, the amplified signal pulse becomes redshifted (spectral components are shifted towards the longer wavelength). Furthermore, the energy flux densities of the pump and the signal determine the redshifting process; therefore, when the pump and the signal beams are spatially inhomogeneous, the signal pulse will be redshifted differently at different positions in the spot, indicating the generation of spatial chirp. Generally, the spatial and temporal frequency dependencies of the electric field of an ultrashort pulse are often assumed to be separable into independent functions. However, this assumption fails when coupling occurs between the spatial and temporal frequency dependencies of the pulse electric field, and this effect is referred to as a spatio-temporal distortion. The broadband nature of ultrashort pulses makes them particularly vulnerable to these distortions. When such pulses are utilized in amplifiers, these distortions often erode the temporal resolution, reduce the intensity, and cause various other problems.[17,18]

In this paper, we numerically investigate the spatial chirp appearing in the Ti:sapphire multipass amplifier, which is used as the main amplifier in a high-power Ti:sapphire CPA system. First, we modeled the multipass amplification process in 1D (without considering the transverse profile) by adopting Frantz–Nodvik equations[19,20] to study the influence of the pump and the signal energy flux densities on the redshifting effect. We calculated the spectrum of the amplified signal according to the different pump and signal energy flux densities, and found that the spectrum tends to move towards longer wavelengths when the pump and signal energy flux densities are increased. Next, we numerically modeled the multipass amplification in 2D (considering the transverse profile) by assuming that the pump and the signal energy flux densities have the same Gaussian spatial distribution. We found that the spatial distributions of the pump and the signal give rise to spatial chirp in the amplified signal beam, since the higher energy flux density portion in the spot makes the corresponding

*Project supported by 100 Talents Program of Chinese Academy of Sciences, the National Natural Science Foundation of China (Grant Nos. 61475169, 61521093, and 11127901), and the Youth Innovation Promotion Association of Chinese Academy of Sciences.

†Corresponding author. E-mail: xuyi@.siom.ac.cn
‡Corresponding author. E-mail: lengyuxin@mail.siom.ac.cn

© 2017 Chinese Physical Society and IOP Publishing Ltd

spectrum shift towards a longer wavelength. Since the spatial chirp of the amplified signal is influenced by the spatial distributions of the pump and signal energy flux densities, we numerically analyzed the amplification processes of four comparable cases with distinct pump and signal spatial distributions, with the aim of eliminating the spatial chirp from the output signal. The simulated results suggest that the spatial chirp in the Ti:sapphire multipass amplifier can be almost eliminated by utilization of proper beam profiles and beam sizes of signal and pump pulses, as the pump pulse has a top-hatted beam profile and the signal pulse has a super-Gaussian beam profile with a relative slightly larger spot size.

2. 1D and 2D models of Ti:sapphire amplifier

The 1D (without considering the transverse profile) and 2D (considering the radial profile in the cylindrical coordinate system) models to simulate the processes in the Ti:sapphire amplifier can be created based on the Frantz–Nodvik equations.[19,20] Within each volume element in the gain medium, three processes are accounted for: pumping the ground state atoms to an upper state, the spontaneous emission of photons (including those into the laser beam and those lost in other directions), and the amplification of the optical radiation propagating through the cell. Other de-excitation processes (e.g., collisional) are not considered, although they could be accounted for with a reduction in the effective pumping rate or through additional equations and parameters.

The 1D equations for the absorption and amplification of optical radiation have been developed by Frantz and Nodvik[19]

$$W(z,t) = W_{\rm s} \ln\left[1-\exp(\sigma\Delta N z)\left[1-\exp\left(\frac{W_0(t)}{W_{\rm s}}\right)\right]\right]. \quad (1)$$

This equation relates the input energy flux density $W_0(t)$ to the output energy flux density $W(z,t)$ obtained after passing through an amplifying or absorbing medium with the length of z. σ is the absorption or emission cross-section and ΔN is the difference between the upper and lower state population densities. Here, equation (1) has not accounted for the spontaneous emission of photons, and is thus valid only for the time step which is much smaller than the energy relaxation time of the medium.

According to the Frantz–Nodvik equations,[19] the population inversion density function can be expressed as

$$\Delta N(z) = N_{\rm T}\left(1-\left\{1-\exp(-\sigma_{\rm A}N_{\rm T}z)\left[1-\exp\left(\frac{W_0}{W_{\rm s}}\right)\right]\right\}^{-1}\right), \quad (2)$$

where $\sigma_{\rm A}$ is the absorption cross-section, W_0 is the total input energy flux density, z is the depth at which the pump light passes through the gain medium, and $N_{\rm T}$ is the total number density.

For four-level systems such as Ti:sapphire, the saturation energy flux $W_{\rm s}$ is calculated according to the following equation:

$$W_{\rm s} = \frac{hc}{2\sigma\lambda}, \quad (3)$$

where c is the speed of light in vacuum, h is the Plank's constant, and λ is the laser wavelength.

In order to analyze the spatial chirp, the pump and signal beam transverse profiles are taken into account. We model the linearly polarized beam using the energy flux densities of the laser in a cylindrical symmetry around the propagation axis z. Then the 2D amplification equations in cylindrical coordinates are deduced from Eqs. (1) and (2)

$$W(z,t,r) = W_{\rm s}\ln\left[1-\exp(\sigma\Delta N(r)z)\left[1-\exp\left(\frac{W_0(t,r)}{W_{\rm s}}\right)\right]\right], \quad (4)$$

$$\Delta N(z,r) = N_{\rm T}\left(1-\left\{1-\exp(-\sigma_{\rm A}N_{\rm T}z)\left[1-\exp\left(\frac{W_0(r)}{W_{\rm s}}\right)\right]\right\}^{-1}\right). \quad (5)$$

3. Spectral redshifting with distinct input energy flux densities

In most high-power CPA systems, gain saturation in the main amplifier is inevitable. Gain saturation will cause preferential amplification of the leading part of the pulse during the amplification process.[21] For a positively chirped pulse (red wavelengths preceding blue wavelengths), the red portion acquires higher gain than the blue portion. As a result, the signal pulse is redshifted in the spectrum. As shown in Eq. (1), the amplification process is determined by the input signal and the pump energy flux densities. In order to study the relationship between the input energy flux density and the amplified spectrum, we simulated the single-pass amplification process in two cases based on the 1D model using Eqs. (1)–(3). In the first case, the pump has a wavelength of 532 nm and the Ti:sapphire has a thickness of 3.2 cm. The duration of the signal is 400 ps and the input signal energy flux density is fixed at 0.16 J/cm^2. However, the input pump energy flux density is varied from 0.56 J/cm^2 to 1.6 J/cm^2. In the second case, we use a 3.2-cm Ti:sapphire and 532-nm pump; however, the input pump energy flux density is assumed to be fixed at 1 J/cm^2 while the input signal energy flux density is varied from 0.1067 J/cm^2 to 0.2400 J/cm^2. The simulated spectra of the amplified signals are shown in Fig. 1.

The black line in Fig. 1(a) indicates the normalized input signal spectrum. Figure 1(a) shows that when the energy flux density of the pump is increased from 0.56 J/cm^2 to 1.6 J/cm^2, the output spectrum tends towards longer wavelengths, since a higher energy flux density of the pump implies an increased gain in the leading part of the pulse. From Eq. (1), it is seen that gain increases nonlinearly with increase in pump energy

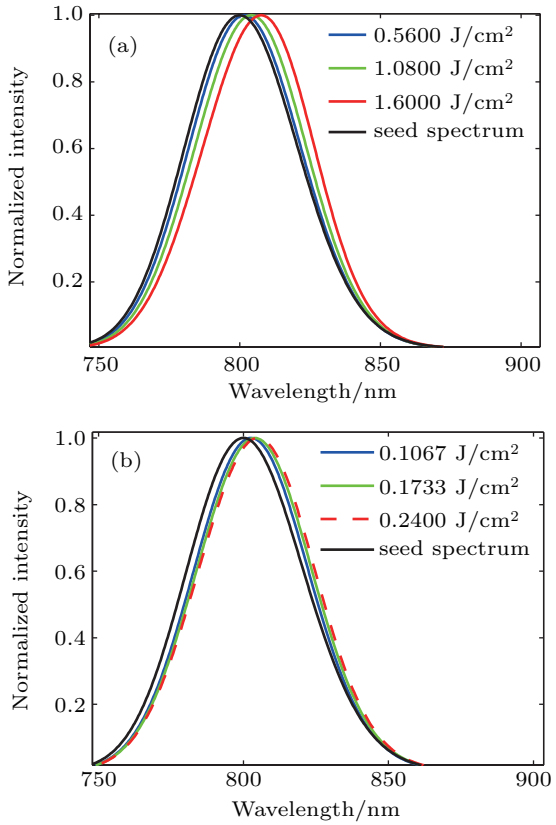


Fig. 1. (color online) Output signal spectrum corresponding to distinct input (a) pump energy flux densities and (b) signal energy flux densities.

flux density. The pulse with higher energy flux density will undergo stronger redshifting during the amplification process. In the second case, when we hypothesize that the pump energy flux density is fixed at 1 J/cm^2 (Fig. 1(b)) and the signal is varied from 0.1067 J/cm^2 to 0.24 J/cm^2, the output signal spectrum tends towards longer wavelengths along with an increase in the signal energy flux density. Therefore, the 1D simulations of the amplification process suggest that the redshifting effect becomes more pronounced with increases in the input pump and signal energy flux densities.

4. Spatial chirp generated along with spatially inhomogeneous input pulses

In the above 1D simulation, the beam profiles of signal and pump pulses have not been taken into consideration, however, the transverse energy flux density profile of the laser beam is not always ideal flat. As discussed in Section 3, this spatial energy flux density distribution causes miscellaneous redshifting at each point of the spot. In order to analyze the spectral redshifting in ordinary spatially inhomogeneous signals and pump pulses in the Ti:sapphire amplifier, we simulated the triple-pass amplification process with the 2D model by assuming that the spatial profiles of the pump and signal are Gaussian with diameters ($1/e^2$ of the maximal intensity) of 30 mm. The thickness of Ti:sapphire is assumed to be 3.2 cm. The signal input energy is hypothesized to be 1 J. The duration of the signal pulse is hypothesized to be 400 ps. We assume a two-end pump, with the energy of each pump being 7.5 J.

In the amplification process, the spectrum is redshifted towards longer wavelengths, since the central portion of the input laser beams has a larger energy flux density. In contrast, the wings of the input laser beams have lower energy flux densities, and hence there is less redshifting in the spectrum. This mechanism is shown in Fig. 2. This generates spatial chirp in the output signal pulse from Ti:sapphire amplifiers. The results shown in Fig. 3 are simulated by using the 2D model based on Eqs. (3)–(4). To explain the difference in redshifting

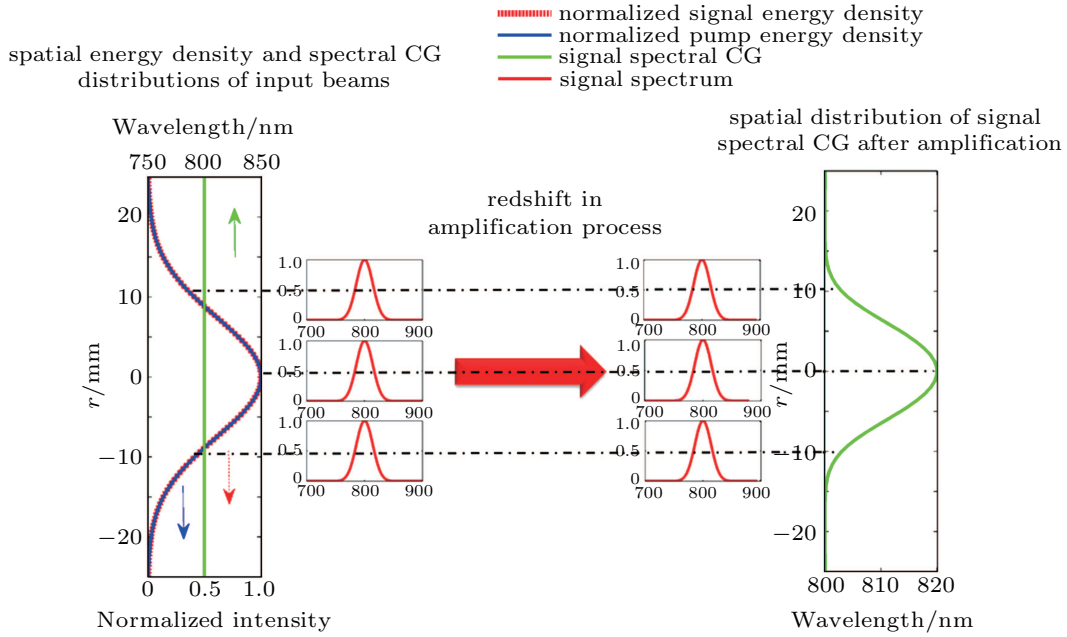


Fig. 2. (color online) Basic mechanism for the generation of spatial chirp in Ti:sapphire multipass amplifier.

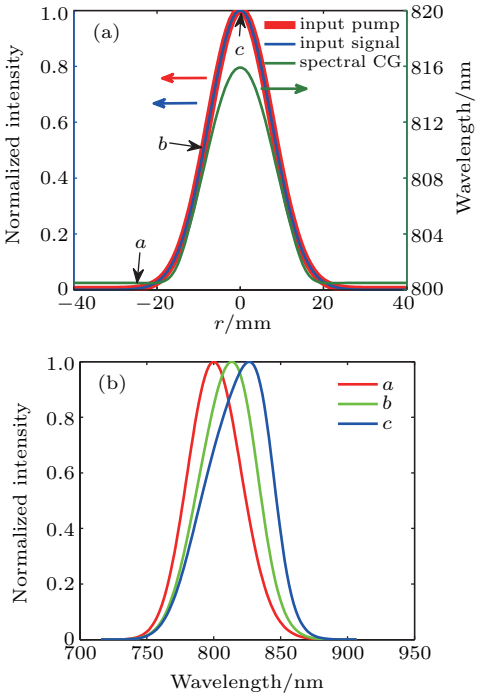


Fig. 3. (color online) Spatial chirp after triple-pass amplifier and the spectral center of gravity (CG), (a) the input pump and signal spatial energy flux density distributions; the spatial distribution of the amplified signal spectral CG; (b) the output signal spectrum corresponding to the point shown in panel (a).

at different points of the spot, we analyzed the amplified signal spectrums for three points in the spot (shown in Fig. 3(b)). In addition, the spatial distribution of the spectral CG (shown in Fig. 3(a)) of the amplified signal was used to show the amount of redshifting at every point in the spot. Based on the separation of these spectra as shown in Fig. 3(b), we can conclude that inhomogeneous energy flux density in the spot leads to the generation of spatial chirp. To eliminate the spatial chirp, the spatial energy flux density distributions of the input beams should be carefully controlled.

5. Eliminating the spatial chirp

In Section 4, it was shown that the spatial energy flux density distributions of the input signal and pump determine the generation of spatial chirp in the output signal. In order to analyze and eliminate the spatial chirp, we simulated four comparable cases with distinct input pump and signal spatial energy flux density distributions using the 2D model. In the first case, we assume a top-hat pump profile and a Gaussian signal profile with diameters of 30 mm. In the second case, we assume that both the pump and signal profiles are 5^{th} order super-Gaussian ($W(r) = W_{\text{peak}} \exp(-(r/r_0)^{2*5})$), with diameters of 30 mm. In the third case, we assume a top-hat pump profile and a 5^{th} order super-Gaussian signal profile with diameters of 30 mm. In the last case, we assume a top-hat pump profile, a 5^{th} order super-Gaussian signal profile, and the diameters of the signal and pump are 40 mm and 30 mm, respectively. Other parameters are the same as those shown in Fig. 3. Under these conditions, we simulate the triple-pass amplification process. The results are shown in Fig. 4.

The profiles of the spectral CG in Fig. 4 illustrate spatial chirp. From Figs. 4(a)–4(c), it is observed that the super-Gaussian signal and top-hat pump will lead to a flatter spectral CG profile as shown in Fig. 4(c). That is to say, the spatial chirp will be less serious in this case. Therefore, for a multipass amplifier, a super-Gaussian signal profile and a top-hat pump profile are recommended. However, residual signal spatial chirp is present in the third case as shown in Fig. 4(c). In

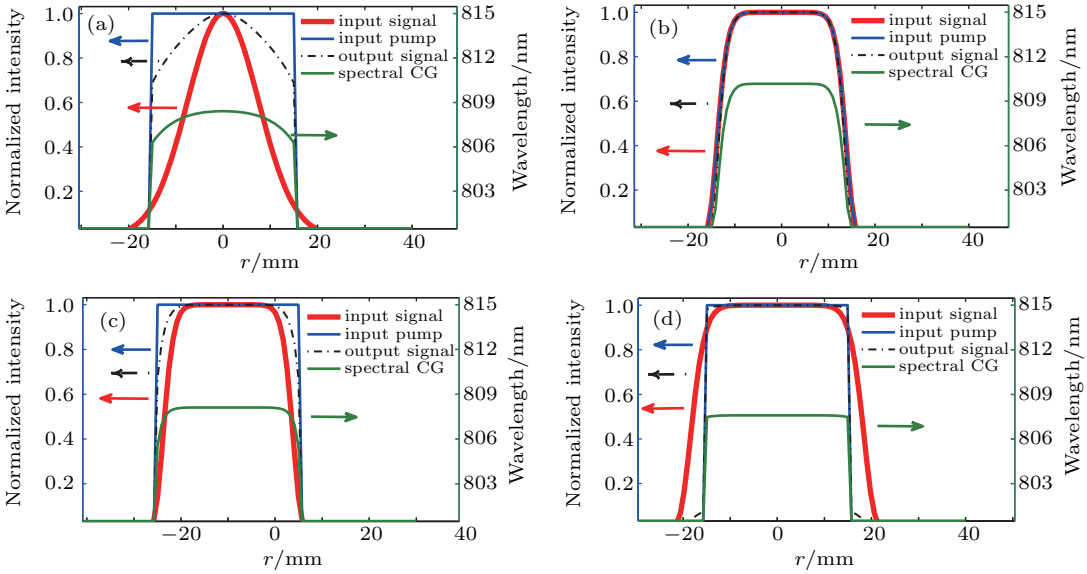


Fig. 4. (color online) Input spatial energy flux density distributions and profiles of amplified signal spectral CG in distinct cases. (a) Input signal profile is Gaussian while pump profile is top-hat. (b) Input signal and pump profiles are 5^{th} order super-Gaussian. (c) Input signal profile is 5^{th} order super-Gaussian while pump profile is top-hat with the same radius as that of the signal. (d) Input signal profile is 5^{th} order super-Gaussian, pump profile is top-hat, and the signal spot is larger than the pump.

the fourth case, the size of the signal spot was expanded relative to that of the pump spot, and we obtain an almost flat spectral CG profile, as shown in Fig. 4(d). Therefore, the best way to cancel the spatial chirp in the Ti:sapphire multipass amplifier is to adopt a super-Gaussian signal profile and a top-hat pump profile as well as keeping the signal spot slightly larger than the pump spot.

6. Conclusion

We numerically investigated the spatial chirp appearing in a Ti:sapphire multipass amplifier, which is used as the main amplifier in high-power Ti:sapphire CPA systems. First, we modeled the multipass amplification process in 1D by adopting the Frantz–Nodvik equations to study the influence of the input pump and the signal energy flux densities on the redshifting effect. The spectrum of the amplified signal corresponding to different pump and signal energy flux densities was simulated, which has a tendency to longer wavelength when either the pump or the signal energy flux density is increasing. Then, the 2D numerically modeling was also processed with the assumption that the pump and signal energy flux densities have the same Gaussian spatial distribution. In this case, the spatial chirp of the amplified signal beam get raised, since the higher energy flux density portion in the spot makes the corresponding spectrum shift towards the longer wavelength. In a word, the spatial chirp is induced by the spatially inhomogeneous gain. In addition, the amplification processes with distinct pump and signal spatial distributions were also simulated, and the simulated results suggest that the spatial chirp in the Ti:sapphire multipass amplifier can be almost eliminated by utilization of proper beam profiles and spot sizes of signal and pump pulses, as the pump pulse has a top-hatted beam profile and the signal pulse has a super-Gaussian beam profile with a little larger spot size. In this way, a clear understanding of spatial chirp mechanisms in the Ti:sapphire multipass amplifier is presented, therefore we can almost eliminate the spatial chirp and improve the beam quality of a high-power Ti:sapphire CPA system effectively.

References

[1] Yu T J, Lee S K, Sung J H, Yoon J W, Jeong T M and Lee J 2012 *Opt. Express* **20** 10807
[2] Kalashnikov M, Cao H, Osvay K and Chvykov V 2016 *Opt. Lett.* **41** 25
[3] Le Blanc C, Grillon G, Chambaret J P, Migus A and Antonetti A 1993 *Opt. Lett.* **18** 140
[4] Yu L H, Liang X Y, Ren Z J, Wang L, Xu Y, Lu X M and Yu G H 2012 *Chin. Phys. B* **21** 014201
[5] Danson C N, Brummitt P A, Clarke R J, *et al.* 2005 *Laser and Particle Beams* **23** 87
[6] Bahk S W, Rousseau P, Planchon T A, Chvykov V, Kalintchenko G, Maksimchuk A, Mourou G A and Yanovsky V 2004 *Opt. Lett.* **29** 2837
[7] Henig A, Steinke S, Schnürer M, Sokollik T, Hörlein R, Kiefer D, Jung D, Schreiber J, Hegelich B M, Yan X Q, Meyer-ter-Vehn J, Tajima T, Nickles P V, Sandner W and Habs D 2009 *Phys. Rev. Lett.* **103** 245003
[8] Kmetec J D, Gordon C L, Macklin J J, Lemoff B E, Brown G S and Harris S E 1992 *Phys. Rev. Lett.* **68** 1527
[9] Monot P, Auguste T, Gibbon P, Jakober F, Mainfray G, Dulieu A, Louis-Jacquet M, Malka G and Miquel J L 1995 *Phys. Rev. Lett.* **74** 2953
[10] Luo Q, Liu W and Chin S L 2003 *Appl. Phys. B* **76** 337
[11] Liu Y, Sun H, Ju J, Tian Y, Bai Y, Wang C, Wang T, Liu J, Chin S L and Li R 2016 *Chin. Opt. Lett.* **14** 031401
[12] Liang H, Sun H, Liu Y, Tian Y, Ju J, Wang C and Liu J 2015 *Chin. Opt. Lett.* **13** 033201
[13] Giambruno F, Radier C, Rey G and Chériaux G 2011 *Appl. Opt.* **50** 2617
[14] Khazanov E A and Sergeev A M 2007 *Laser Physics* **17** 1398
[15] Walter D, Eyring S, Lohbreier J, Spitzenpfeil R and Spielmann C 2007 *Appl. Phys. B* **88** 175
[16] Kitagawa Y, Fujita H, Kodama R, Yoshida H, Matsuo S, Jitsuno T, Kawasaki T, Kitamura H, Kanabe T, Sakabe S, Shigemori K, Miyanaga N and Izawa Y 2004 *IEEE Journal of Quantum Electronics* **40** 281
[17] Akturk S, Gu X, Zeek E and Trebino R 2004 *Opt. Express* **12** 4399
[18] Gu X, Akturk S and Trebino R 2004 *Opt. Commun.* **242** 599
[19] Frantz L M and Nodvik J S 1963 *J. Appl. Phys.* **34** 2346
[20] Planchon T A, Burgy F, Rousseau J P and Chambaret J P 2005 *Appl. Phys. B* **80** 661
[21] Cha Y H, Kang Y I and Nam C H 1999 *J. Opt. Soc. Am. B* **16** 1220