Vol 14 No 2, February 2005
1009-1963/2005/14(02)/0359-07

Chinese Physics

© 2005 Chin. Phys. Soc.
and IOP Publishing Ltd

Pulse-front matched ultra-broadband optical parametric chirped pulse amplifier for sub-12 fs pulse generation*

Zhao Wei(赵 卫)†, Liu Hong-Jun(刘红军), Wang Yi-Shan(王屹山), Wang Hong-Ying(王红英), Cheng Zhao(程 昭), and Chen Guo-Fu(陈国夫)

State key Laboratory of Transient Optics and Technology, Xi'an Institute of Optics and Precision Mechanics, Chinese Academic of Sciences, Xi'an 710068, China

(Received 21 April 2004; revised manuscript received 30 June 2004)

We propose a LBO-based ultra-broadband chirped pulse optical parametric amplifier employing pulse-front-matching to yield transform-limited sub-12-fs pulses. Measurement of the maximum possible gain bandwidth for the LBO-based OPCPA demonstrates more than 60nm gain bandwidth FWHM. For the generation of TL pulses by the use of this OPCPA, a suitable combination of OPCPA and PFM is first presented. The PFM pump geometry realizes tilt-free signal amplification, and permits this OPCPA to generate TL sub-12-fs pulses.

Keywords: optical parametric amplification, chirped pulse amplification, pulse front matching
PACC: 4265K, 4280W

1. Introduction

Recently, there has arisen much interest in the generation of extremes in power, pulse duration and intensity for high intensity interaction, and the advent of chirped pulse amplification (CPA) has revolutionized the generation of ultra-short pulse and ultrahigh intensity laser. However, CPA has already reached its practical limit in pulse duration, as determined by the gain narrowing effect and thermal problems at high average powers within the amplification process, but this limit is largely removed using a new technique called optical parametric chirped pulse amplification (OPCPA),[1−14] where an optical parametric amplifier (OPA) pumped by a laser beam with relatively narrow spectral bandwidth and long pulse duration (typically about 1ns) is used to amplify a large bandwidth and chirped pulse of equal pulse duration prior to recompression. OPCPA has many advantages such as high gain without spectral narrowing, high contrast ratio, negligible thermal load, potentially large bandwidth, and scalability in terms of peak and average power. Another feature of OPCPA is the possibility to produce ultrahigh peak-power laser pulses of tabletop size and low cost.[12] This technique makes use of the uniquely large gain bandwidth of OPA with increased gain bandwidth at high energy. The large gain bandwidths of OPCPAs potentially allow the direct amplification of sub-10 fs pulses with a suitable nonlinear crystal length.[2,15] The OPCPA has reached 3.67 terawatt power levels for 1.064μm pulses in the 155fs regime.[8] The non-collinear phase-matched OPCPA technique has also been applied in the wavelength range around 800nm by us,[12] and it has already been proven useful for ultra-broadband amplification of pulses in the near-IR. The future development of OPCPA systems to higher powers would require the generation of shorter pulses. On the other hand, the shortening of the output pulse from OPA faces the problem of the spectral acceptance of the phase-matched condition, which is mainly limited by the group-velocity mismatching (GVM) between the signal and idler pulses in the nonlinear optical crystal. The broadening of the bandwidth is the most important factor for obtaining ultrahigh intensity and ultra-short pulse duration. A non-collinear phase-matched geometry is quite attractive

*Project supported by the National High Technology Development Programme of China and the NSFC (Grant No 10390160).
†E-mail:weiz@opt.ac.cn

to modify the phase-matched condition as well as the amount of the GVM in a straightforward and simple way for the spectral broadening in an OPA. It can realize the group-velocity matching between the signal and idler, which is equivalent to an achromatic phase matching with the spectral angular dispersion of the idler, and the broadest bandwidth is attained.[7,16−18] Therefore, noncollinear phase-matched optical parametric amplification (NOPA) operated away from degeneracy ($\omega_s > \omega_i$), to date, offers exciting prospects for generating new extremes in power, intensity, and pulse duration.

However, the noncollinear phase-matched geometry has difficulty in generating transform-limited (TL) pulses, and only a large time-bandwidth product ($\Delta t \Delta \nu \sim 1$) could be obtained. Even though sub-10-fs durations are expected from the ultrabroad bandwidth, this is due mainly to pulse-front tilting, which is equivalent to angularly dispersing the beam and is inevitable in noncollinear interaction.[19−21] The pulse-front tilting of a signal can cause signal-pulse broadening, accompanied by spatial chirp. But this limit can be removed by a pulse-front-matched geometry, which gives maximum lateral spatial overlap between the pump and signal and dramatically eliminates the spatial chirp of the signal pulse, indicating nontilted signal amplification, resulting in the generation of non-tilted signal pulses that are compressible to the TL pulses. This pulse-front-matching (PFM) has been used to generate successfully sub-5-fs pulse in a noncollinear OPA (NOPA).[21] To our knowledge, however, to date the PFM has not been employed in OPCPA to generate a TL pulse.

In this paper, a suitable combination of OPCPA and PFM is presented for the first time for the generation of TL pulses by the use of OPCPA. We propose a LBO-based ultra-broadband chirped pulse optical parametric amplifier employing PFM to yield TL sub-12-fs pulses. The key techniques for utilizing the full capability of NOPAs such as group-velocity matching and PFM are detailed. An experimental measurement of the maximum possible gain bandwidth for the LBO-based OPCPA demonstrates that more than 60nm gain bandwidth in FWHM can be obtained. Since the PFM pump geometry realizes tilt-free signal amplification, this PFM-OPCPA is expected to generate TL sub-12-fs pulses.

2. Broadening of the bandwidth by noncollinear geometry

2.1. Theoretical calculations of the bandwidth for a LBO-based NOPA

In a collinear geometry, the temporal output of OPAs is restricted by group-velocity mismatch between the pump and the generated signal and idler fields. In a noncollinear arrangement, this effect can be overcome since only the projection of the idler group velocity onto the seed is important. By arranging the pump and seed incidence angles with respect to the phase-matching angle correctly, this group-velocity mismatch can be zeroed in some nonlinear crystals. In the case of NOPA the collimated signal is amplified and the beam direction has a noncollinear angle of α with respect to the pump beam.

The bandwidth is dependent on parameters such as crystal length, GV, GVD and parametric gain. The parametric bandwidth (namely, phase-matched bandwidth) is the intrinsic bandwidth of an OPA, it is independent of the parametric gain. The output signal spectrum bandwidth of an OPA is primarily limited by the parametric bandwidth, which determines the maximum achievable gain bandwidth. The parametric bandwidth $\Delta\lambda_{\text{parametric}}$ and gain bandwidth $\Delta\lambda_{\text{gain}}$ in FWHM for an OPA are then given by the following Eqs.(1) and (2), respectively:[12,15]

$$\Delta\lambda_{\text{parametric}} = \begin{cases} \dfrac{\lambda^2}{c} \cdot \dfrac{|u_{si}|}{l_c} & \dfrac{1}{u_{si}} \neq 0, \\ \dfrac{0.8\lambda^2}{c} \cdot \sqrt{\dfrac{1}{l_c \cdot |g_{si}|}} & \dfrac{1}{u_{si}} = 0, \end{cases} \tag{1}$$

$$\Delta\lambda_{\text{gain}} = \begin{cases} \dfrac{0.53\lambda^2}{c} \sqrt{\dfrac{\Gamma_0}{l_c}}\, |u_{si}| & \dfrac{1}{u_{si}} \neq 0, \\ \dfrac{0.58\lambda^2}{c} \left(\dfrac{\Gamma_0}{l_c}\right)^{1/4} \sqrt{\dfrac{1}{|g_{si}|}} & \dfrac{1}{u_{si}} = 0, \end{cases} \tag{2}$$

with

$$\begin{cases} \dfrac{1}{u_{si}} = \dfrac{1}{v_i \cos(\alpha+\beta)} - \dfrac{1}{v_s}, \\ g_{si} = \left[\dfrac{1}{2\pi v_s^2} \tan(\alpha+\beta) \right. \\ \qquad \left. \times \tan\beta \left(\dfrac{\lambda_s}{n_s} + \dfrac{\lambda_i \cos(\alpha+\beta)}{n_i}\right) - (g_s + g_i)\right], \\ g_m = \left(\dfrac{\partial^2 k_m}{\partial \omega_m^2}\right)|_{\omega=\omega_m} \quad (m = s, i), \\ \beta = \arcsin\left(\dfrac{n_s}{n_i}\dfrac{\lambda_i}{\lambda_s}\sin\alpha\right). \end{cases}$$

Here v_s and v_i are the signal group-velocity (GV) and the idler group-velocity, respectively. The g_m is the GV dispersion, l_c is the effective length of the nonlinear crystal. From Eqs.(1) and (2), the bandwidth strongly depends on noncollinear angle α, and there exists an α where the maximum bandwidth was obtained. Here a broadband amplification is expected, which is attributed to the GV matching between the signal and idler, when the signal GV is equal to the component of the idler GV projected to the signal direction. The maximum possible gain bandwidth is limited by the parametric bandwidth; the gain bandwidth increases with the increase of pump intensity within the range of the maximum parametric bandwidth, until the gain bandwidth is eventually saturated into the parametric bandwidth. Therefore, for a designed OPA, the parameters such as noncollinear angle, crystal length and pump intensity have been chosen, so the output spectrum bandwidth can be evaluated by the lesser one of the parametric bandwidth $\Delta\lambda_{\text{parametric}}$ and gain bandwidth $\Delta\lambda_{\text{gain}}$.

LBO is a biaxial optical crystal, we define the three optical axes of LBO as X, Y and Z, and $n_X < n_Y < n_Z$, and assume that the beams propagate in the X–Y plane and perpendicular to Z axis. The pump beam is polarized perpendicular to Z axis, and the signal and the idler beams are polarized parallel to Z axis. Figure 1 illustrates geometry of the noncollinear phase matching in an LBO-based OPA, where the signal beam is injected into the crystal with a fixed noncollinear angle α with respect to the pump direction while the idler is generated with the variable angle β to satisfy the phase-matching condition,[7]

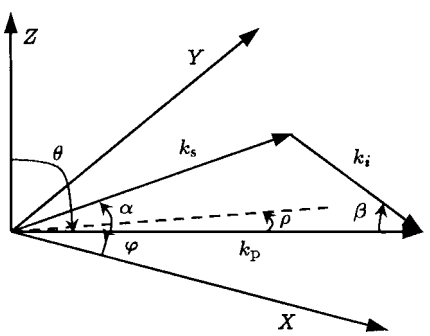


Fig.1. Geometry of the noncollinear phase matching in LBO crystal.

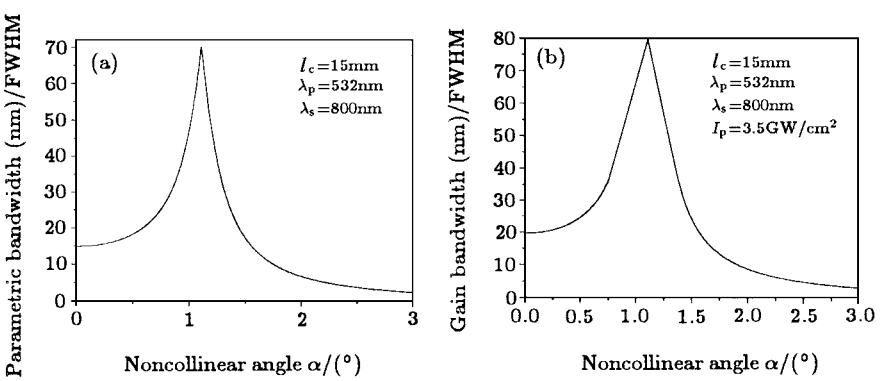


Fig.2. In type-I (in X-Y plane) phase-matched LBO (l=15mm) OPA pumped by 532nm light, and seeded by 800nm light, (a) Parametric bandwidth (FWHM) versus noncollinear angle α; (b) Dependence of gain bandwidth on noncollinear angle α at I_p=3.5GW/cm^2.

For a type-I (in the X–Y plane) phase-matched LBO (l=15mm) OPA pumped by 532nm light, and seeded by 800nm light, we can estimate its bandwidth according to Eqs.(1) and (2). Figure 2(a) demonstrates the variation of the parametric bandwidth of the LBO (l_c=15mm) OPA versus noncollinear angle α with λ_p=532nm and λ_s=800nm. From Fig.2(a), we can see that the parametric bandwidth of the OPA is only 15nm-FWHM at $\alpha = 0°$, but increases to 70nm-FWHM at $\alpha = 1.12°$. Figure 2(b) illustrates the dependence of the gain bandwidth of the LBO (l_c=15mm) OPA on the noncollinear angle α with λ_p=532nm and λ_s=800nm at I_p=3.5GW/cm^2, and Fig.2(b) shows that the gain bandwidth increases rapidly from 19nm-FWHM at $\alpha = 0^0$to 79nm-FWHM at $\alpha = 1.12°$. The gain spectra of the signal for the LBO-based OPA pumped by 532nm light, and seeded by the broadband signal light with center wavelength at 800nm is depicted in Fig.3. Figure 3(a) shows the gain spectra of the signal at I_p=5GW/cm^2 and noncollinear angle 0°, 0.8°,1.12°; Fig.3(b) illustrates the logarithm of gain of the signal spectra at different

pump intensity. Obviously, from Fig.2 and Fig.3, we can see that the noncollinear geometry results in large broadening of the bandwidth for the OPA.

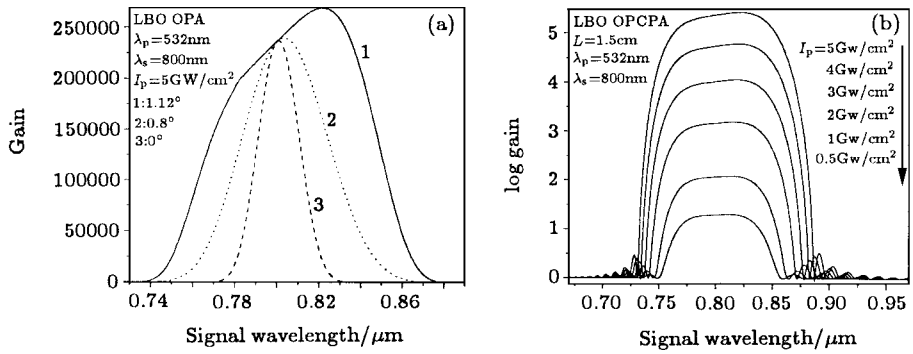


Fig.3. Gain spectra of the signal for the 15mm-length LBO OPA pumped by 532nm light, seeded by 800nm light (a) with I_p=5GW/cm^2 at noncollinear angle 0°, 0.8°, 1.12°; (b) The logarithm of gain of the signal spectra at different pump intensities.

Since the maximum possible gain bandwidth is determined by the maximum possible parametric bandwidth for an OPA, according to Eqs.(1) and (2), we can obtain the dependence of gain bandwidth on pump intensity for the type-I (in X-Y plane) phase-matched LBO (l=15mm) OPA pumped by 532nm light, and seeded by 800nm light with optimum noncollinear angle $\alpha = 1.12°$, the result is shown in Fig.4. From the Fig.4, it is seen that the gain bandwidth is saturated into the parametric bandwidth at pump intensity I_p=1.3GW/cm^2, and the maximum possible gain bandwidth for this LBO-based OPA under these conditions is 70nm (FWHM).

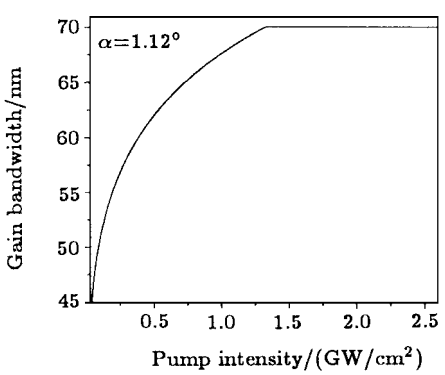


Fig.4. Dependence of gain bandwidth on pump intensity with 15mm crystal length at α=1.12° for the LBO-based OPA pumped by 532nm light and seeded by 800nm light.

2.2. Experimental measurement of the maximum possible gain bandwidth

Experimental investigations of nondegenerate ultrabroadband OPCPA using the above LBO-based OPA have been carried out by us,[12] the broadest 53nm (FWHM) parametric gain spectrum bandwidth at 800nm wavelength has been obtained. The parametric gain reached 3.6×10^3, and the 53nm-FWHM gain spectrum of output amplified signal was mainly limited by the maximum input 57nm spectrum bandwidth (FWHM) from our self-made Kerr lens mode-locked Ti:sapphire oscillator in our experiment. But this gain bandwidth does not fully utilize the capability of NOPA theoretically predicted.

The principal aim of the following experiment is to confirm the predicted maximum possible gain bandwidth for the above LBO-based OPA in noncollinear geometry. A schematic of the experimental setup is shown in Fig.5, in which the NOPA is pumped by the 5ns second-harmonic generation output of a Q-switched Nd:YAG laser at 1064nm, operating at 10Hz. The seed laser source was a cw and wavelength-tunable Ti:sapphire laser system.

For the OPA we used a 4×4×15-mm^3 LBO type-I (in X-Y plane) crystal cut at $\theta = 90°$, $\varphi = 12.6°$. The 532nm pump beam polarized vertically was reduced to 1.5mm diameter by a 3× telescope. The seed signal beam polarized horizontally was reduced to 500μm diameter by a 5× telescope and then directed into the LBO crystal at an external angle 1.8° respect to the pump beam, and the internal noncollinear angle is 1.12°. The phase matching angle of the LBO crystal was aligned to central signal wavelength at 800nm.

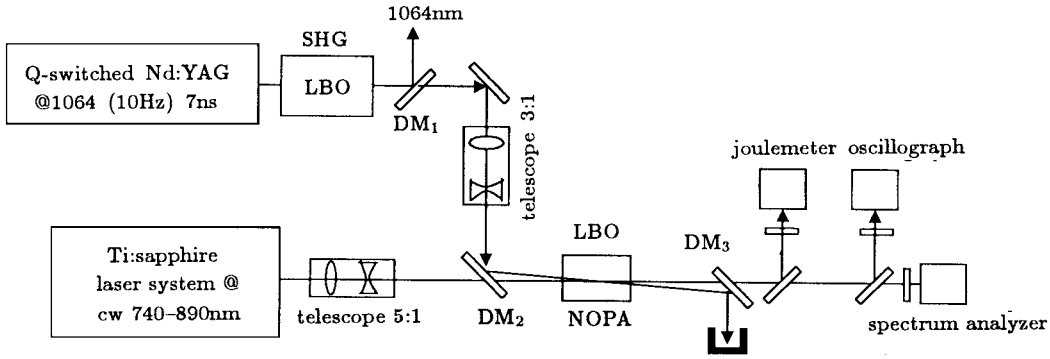


Fig.5. Experimental setup: DM, dichroic mirrors; NOPA, noncollinear optical parametric amplifier.

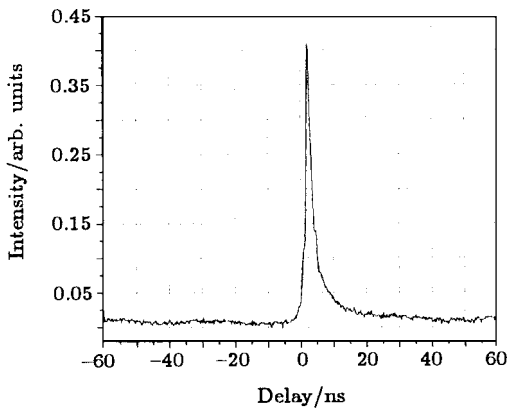


Fig.6. Measured time profile of the output signal pulses in the LBO NOPA.

The nanosecond pulses from the Nd:YAG pump laser were mixed with the cw seed signal light from the Ti:sapphire.[17] The pump intensity of 532nm light is fixed at I_p=2GW/cm^2, then changing the wavelength of the seed signal, the amplified output signals with different wavelength all have a temporal width of ~2ns in FWHM as shown in Fig.6, and the spectral amplification was measured as shown in Fig.7.

Figure 7(a) shows the amplified signal spectrum at $\alpha = 0°$, Fig.7(b) shows the amplified signal spectrum at $\alpha = 1.12°$. Comparing Fig.7 with Fig.4, there exists a discrepancy between experimental measurements and theoretical prediction, but this discrepancy is acceptable under these experimental conditions.

In the experimental measurement, the maximum gain bandwidth is determined by the parametric bandwidth, which is mainly limited by the crystal length. Undoubtedly, a larger gain bandwidth could be achieved by minimizing the crystal length, but this would lead to decreasing of the conversion efficiency. In particular, we can achieve both high gain and large gain bandwidth by maximizing the pump intensity and minimizing the crystal length. However, for longer pulses, especially nanosecond pulses, the damage threshold requires a reduction in the pump intensity and an increase in the crystal length, leading to reduced gain bandwidth.

Since experimental measurements demonstrated that more than 60nm in FWHM gain bandwidth exhibited by the amplified spectrum as shown in Fig.7(b) can be obtained, this gain bandwidth corresponds to TL signal pulse as short as 11.2fs, so this LBO-based OPCPA can support TL 11.2fs pulses amplification.

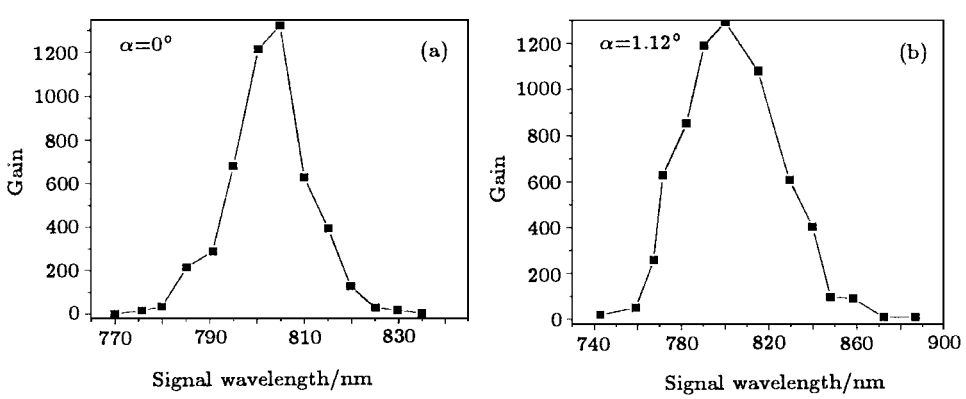


Fig.7. Measured gain-bandwidth of (a) collinear and (b) noncollinear LBO OPCPA pumped by 532nm light at I_p=2GW/cm^2.

However, even after the group-velocity matching condition between signal and idler pulses is satisfied by taking the noncollinear geometry, one more important matching condition must be taken into account.[19] In the case of the NOPA the noncollinear interaction causes a slanted gain volume in the signal beam, resulting in a tilted surface of the generated signal with a tilting angle equal to the noncollinear angle between the pump beam and signal beam. The time and space coupling across the cross section by some distortion induced by the different velocity of propagation among the components across the pulse front may give a pulse front surface tilted from the wave front surface.[20,21] This phenomenon is called pulse-front tilting, which is inevitable in noncollinear geometry. It results in undesired pulse-width broadening and spectral lateral walk-off equivalent to the angular dispersion. In this case even though at each point of the pulse front the component can have a nearly Fourier-transform-limited pulse width, the whole pulse width can be much greater.[21] As a result, using the noncollinear geometry, which is employed in the above LBO-based OPCPA, it is difficult to generate TL sub-12-fs pulses. To remove this limitation, we present a suitable combination of the OPCPA and PFM geometry in the following section.

3. Pulse-front matched geometry for the LBO-based OPCPA

The PFM is a tilted pumping geometry in fact, which is the geometry required essentially for pulse compression to a TL pulses. Referring to Refs.[12] and [21], we present a suitable combination of OPCPA and PFM, the PFM-OPCPA, the configuration of which is depicted schematically in Fig.8.

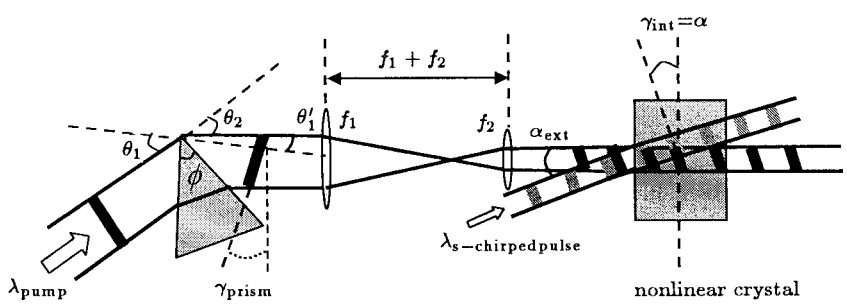


Fig.8. Schematic design of PFM-OPCPA geometry. α_{ext} is the external noncollinear angle between the pump and signal. α is the noncollinear angle between the pump and signal inside the crystal for group-velocity matching. The tilt angles generated by the prism and imaged in the crystal are γ_{prism} and γ_{int}, respectively.

As shown in Fig.8, the pump beam passes through a prism with incident and exit angles ϕ_1 and ϕ_2, respectively. The PFM condition $\gamma_{int} = \alpha$ is given by:[21,22]

$$\tan\alpha = \frac{1}{n_p} M \tan\gamma_{prism}, \tag{3}$$

and

$$\tan\gamma_{prism} = -\lambda_p \frac{d\theta_2}{d\lambda_p} = -\frac{\sin\phi}{\cos\theta_1' \cos\theta_2} \lambda_p \frac{dn}{d\lambda_p}. \tag{4}$$

Here γ_{prism} and γ_{int} are the tilt angles generated by the prism and imaged in the crystal, respectively. n is the refractive index of the prism material, ϕ is the prism apex angle and θ_1' is the angle of refraction. $M = f_1/f_2$ is the longitudinal magnification factor of the telescope composed of two lenses with different focal lengths f_1 and f_2. Since the spot size is reduced by the lateral demagnification factor given by the ratio between the two focal lengths, $1/M$, the parameters of the telescope are practically determined for the efficient amplification. Thus the prism apex angle and incident angle are the most essential parameters for the optimization of amplification without undesirable extra pulse broadening to satisfy the condition given by Eq.(3). In order to decrease the reflection loss at the surface of prism, the incident angle θ_1 is generally chosen at the Brewster angle.

From Eqs.(3) and (4), we can obtain the dependence of the prism apex angle ϕ on the noncollinear angle α with Brewster's angle incidence for a LBO-based OPCPA pumped by 532nm light. Accordingly, for the above LBO-based OPCPA, the 800nm chirped pulses are then noncollinearly amplified with the external noncollinear angle α_{ext} of 1.8° and the noncollinear angle α of 1.12° inside the LBO crystal and in the configuration of the crystal angle of $\theta = 90°$, $\varphi = 12.6°$ for the signal and idler group-velocity matching. The tilted-pump geometry with an apex angle $\phi = 19°$ fused-silica prism for pulse-front tilt-

ing with $\theta_1 = 55.6^\circ$ that is equal to Brewster's angle and the telescope magnification factor $M = 3$ satisfies the PFM condition of Eq.(4) in the LBO crystal. Then the non-tilted chirped pulse signal amplification is attained accompanying the elimination of the spatial chirp. This PFM geometry ensures a maximum lateral spatial overlap between the pump and signal and dramatically suppresses the spatial chirp, permitting the generation of non-tilted signal pulses that are compressible to the TL sub-12-fs by the use of this LBO-based OPCPA.

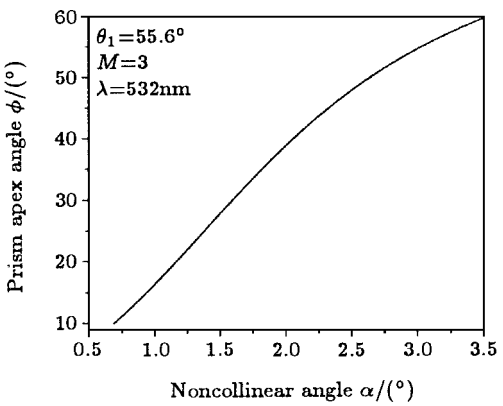


Fig.9. Dependence of the prism apex angle ϕ on the noncollinear angle α with Brewster's angle incidence for a LBO-based OPCPA pumped by 532nm light.

4. Conclusions

In conclusion, an ultra-broadband optical parametric chirped pulse amplifier with pulse-front matching scheme for sub-12-fs pulse generation is proposed. Experimental measurement of the maximum possible gain bandwidth for the LBO-based OPCPA demonstrates that a wider than 60nm (FWHM) parametric gain bandwidth can be obtained, this gain bandwidth corresponds to TL 11.2fs pulses. For the generation of TL pulses by using the OPCPA technique, a suitable combination of the OPCPA and PFM is provided. This PFM interaction gives maximum lateral spatial overlap between the pump and signal and dramatically suppresses the spatial chirp, resulting in realizing tilt-free signal amplification for TL pulse generation. Therefore, this LBO-based PFM-OPCPA is expected to generate TL sub-12fs pulses. This idea of OPCPA with PFM can be realized to construct low-cost, compact high-peak power ultrashort pulse laser systems that only require commercially available lower energy Q-switched Nd:YAG lasers. Since OPCPAs pumped by nanosecond lasers operating at high-energy require larger beam size in nonlinear gain medium, the PFM scheme will become more important in OPCPAs. This PFM-OPCPA is a candidate for a visible and near-IR terawatt source.

References

[1] Dubietis A *et al* 1992 *Opt. Comm.* **88** 437
[2] Ross I N *et al* 1997 *Opt.Comm.* **144** 125
[3] Collier J *et al* 1999*Appl. Opt.* **38** 7486
[4] Xia J F *et al* 2000 *Acta Phys. Sin.* **49** 256 (in Chinese)
[5] Liu H J *et al* 2001 *Acta Phys. Sin.* **50** 1717 (in Chinese)
[6] Yang X *et al* 2001 *Appl. Phys.* B **73** 219
[7] Liu H J *et al* 2002 *Acta Opt. Sin.* **22** 1195 (in Chinese)
[8] Yang X D *et al* 2002 *Opt. Lett.* **27** 1135
[9] Jovanovic I *et al* 2002 *Opt. Lett.* **27** 1622.
[10] Jovanoic I *et al* 2003 *Appl. Phys. Lett.* **83** 4125
[11] Harimoto T *et al* 2003 *Opt. Express* **11** 393
[12] Liu H J *et al* 2004 *Chin. Phys. Lett.* **21** 94
[13] Arishom G *et al* 2004 *Opt. Express* **12** 518
[14] Zhu P F *et al* 2003 *Acta Phys. Sin.* **52** 587 (in Chinese)
[15] Liu H J *et al* 2002 *Chin. J. Laser* **29** 21 (in Chinese)
[16] Shirakawa A *et al* 1999 *Appl. Phys. Lett.* **74** 2268
[17] Liu H J *et al* 2004 *Acta Phys. Sin.* **53** 105 (in Chinese)
[18] Sun T *et al* 2002 *Acta Phys. Sin.* **51** 2281 (in Chinese)
[19] Shirakawa A *et al* 1998 *Opt. Lett.* **23** 1292
[20] Martiez O E 1986 *Opt. Commun.* **59** 229
[21] Kobayashi T *et al* 2002 *Meas. Sci. Technol.* **13** 1671
[22] Bor Zs *et al* 1985 *Opt. Commun.* **54** 165