Optik 124 (2013) 1211–1214

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Study on broadband third harmonic conversion efficiency with angular spectral dispersion

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ARTICLE INFO

Article history:
Received 18 October 2011
Accepted 6 March 2012

Keywords:
Broadband laser
Third harmonic generation
Conversion efficiency
Angular spectral dispersion

ABSTRACT

Broadband third harmonic conversion efficiencies of temporal phase modulation (TPM), linear chirped (LC) and chirped pulse stacking (CPS) lasers have been analyzed by adopting the schemes of type I/II KDP angle-detune and angular spectral dispersion (ASD) quantitatively. The result shows that the conversion efficiency of broadband lasers would be improved obviously by angular spectral dispersion and the suitable thickness of type II KDP crystal. Meanwhile, the conversion efficiency of the linear chirped laser is the largest when the broadband laser with the spectral bandwidth of 10–17 nm, and the chirped pulse stacking laser will exhibit the largest conversion efficiency among these three kinds of broadband lasers when the spectral bandwidth is broader.

1. Introduction

Broadband lasers as fundamental lights could be sorted into the following forms by generative mechanism, such as temporal phase modulation (TPM) broadband lasers [1,2], linear chirped (LC) broadband lasers [3] and chirped pulse stacking (CPS) broadband lasers [4,5], etc. However, efficient frequency doubling and tripling occurs under the condition of the phase matching. Therefore, obtaining the third harmonic generation (THG) output with a high efficiency is the main difficulty in the field of broadband lasers under the high power condition.

The scheme of cascaded crystals [6,7] or angular spectral dispersion (ASD) [8,9] could be adopted to achieve efficient broadband third harmonic frequency conversion. For the available bandwidth of KDP crystals is very narrow [10], the cascaded crystals method is not suitable for the broader spectral bandwidth which is more than 2 nm (the THG efficiency is less than 40% when spectral bandwidth is 2 nm). To the broader spectral bandwidth, different frequency compositions of the fundamental light could be injected into KDP crystals with relevant phase matching angles by ASD to achieve the efficient THG conversion.

In this paper, the THG efficiencies of three kinds of broadband flattened lasers mentioned above are discussed by the harmonic conversion theory and optimized by ASD method to analyze the third harmonic characteristics of each broadband flattened laser.

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doi:10.1016/j.ijleo.2012.03.006

2. THG conversion efficiency of broadband flattened laser

2.1. Theoretical model

TPM broadband lasers could be generated by changing the refractive index of nonlinear crystals periodically, and the expression of temporal shape is given by [2]

$$E = \frac{E_0}{2} \exp\left[-\frac{1}{2}\left(\frac{t}{\tau}\right)^{2m}\right] \exp[i\omega_0 t + i\sigma \sin(\omega_m t)] + c.c \quad (1)$$

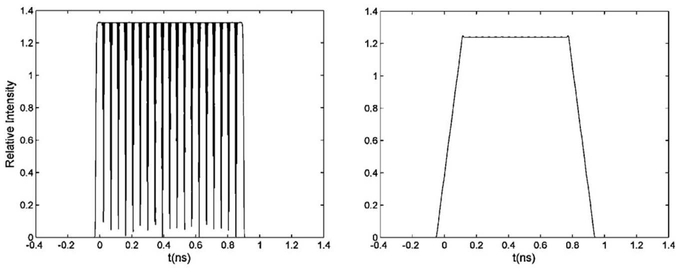
Here m is the order of super-Gaussian beam; τ is the temporal half width where the peak intensity decreases to 1/e; σ is phase modulating coefficient; ω_0 is the carrier frequency; ω_m is the modulating frequency; the full width half maximum (FWHM) of the spectrum $\Delta\omega \approx 2\sigma\omega_m$; the FWHM of the pulse $T = 2\tau \ln 2^{1/2m}$; and the instantaneous frequency $\omega(t) = \omega_0 + \sigma\omega_m \cos(\omega_m t)$.

The expression of LC broadband lasers can be expressed as [3]

$$E = \frac{E_0}{2} \exp\left[-\frac{1}{2}\left(\frac{t}{\tau}\right)^{2m}\right] \exp\left[i\omega_0 t + i\frac{C}{2}\left(\frac{t}{\tau}\right)^2\right] + c.c \quad (2)$$

Here C is chirp coefficient. According to the Fourier analysis, the FWHM of the spectrum $\Delta\omega = \ln 2^{1/2m}(1 + C^2)^{1/2}/(\pi\tau)$; the FWHM of the pulse $T = 2\tau \ln 2^{1/2m}$; and the instantaneous frequency $\omega(t) = \omega_0 + Ct/\tau^2$.

An integrated optical modulator or an optical fiber pulse stacker can be used to generate CPS broadband lasers, and the temporal



(a) instantaneous distribution (b) average distribution

Fig. 1. Temporal shape of the pulse stacked by 20 chirped pulses.

distribution could be expressed as [4]

$$E_{\mathrm{sum}}(t)=\sum_{n=0}^{N-1}\frac{E_0(n)}{2}\exp\left[\frac{(t-nkT)^{2m}}{2\tau^{2m}}+i\Phi_0(n)\right]$$

$$\exp\left[i\omega_0(t-nkT)+iC\frac{(t-nkT)^2}{2\tau^2}\right]+c.c \qquad (3)$$

Here T is the FWHM of sub-pulses; k is the retardation coefficient; Φ_0 is the initial phase. To the CPS broadband laser which is constituted by several sub-pulses, the FWHM of the spectrum $\Delta\omega=\ln 2^{1/2m}(1+C^2)^{1/2}/(\pi\tau)$, the overall FWHM of the pulse $T_{\mathrm{sum}}\approx(nk+1)T$, and the instantaneous frequency $\omega_n(t)=\omega_0+C(t-nkT)/\tau^2$. According to the partial coherence theory, there would be the beat frequency in the stacked pulses making the stacked temporal distribution coherent because of the constant phase difference among each sub-pulse. Therefore, the optical limiting technology can be adopted to cut the coherent peak off.

Fig. 1(a) shows the instantaneous distribution of the flattened CPS broadband laser stacked by 20 sub-pulses. The FWHM of these 5th order super-Gaussian sub-pulses is 50 ps, the spectral bandwidth is 15 nm (the corresponding FWHM of the spectrum is 22.5 THz), the central wavelength is 1053 nm, and the retardation coefficient is 0.92 in this calculation. The modulating cycle of the flattened CPS broadband laser is 0.27 ps.

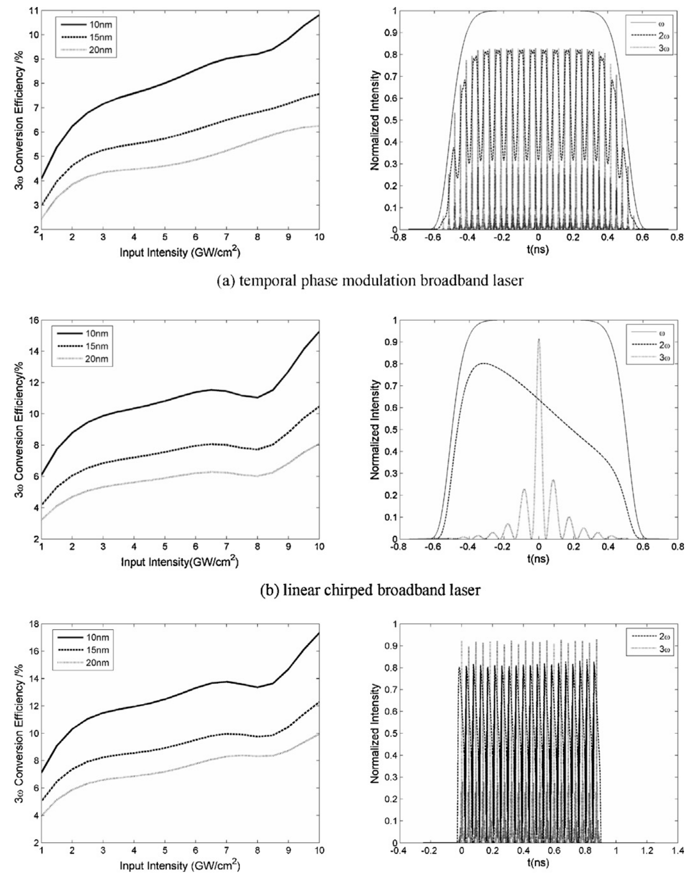
The intensity modulation with a high frequency is hardly detected, so the stacked temporal distribution is equivalent to the time-interval averaging distribution shown in Fig. 1(b). Because of the favorable uniformity, it can be regarded that the flattened pulse is generated by the several sub-pulses.

2.2. Conversion efficiency of the third harmonic generation

For type I/II KDP angle-detuning method, the equations of harmonic conversion can be expressed as [11]

$$\begin{aligned}
&\frac{\partial^2E_1}{\partial x^2}+\frac{\partial^2E_1}{\partial y^2}+i2n_1\frac{\omega_1}{c}\left[\frac{\partial E_1}{\partial z}+\rho_\omega(\theta)\frac{\partial E_1}{\partial y}+a_1\frac{\partial E_1}{\partial t}\right]\\
&\quad=-\frac{\omega_1^2}{c^2}d_{eff}E_2^*E_3\exp(i\Delta kz)-i\frac{n_1\omega_1}{c}\alpha_1E_1\\
&\frac{\partial^2E_2}{\partial x^2}+\frac{\partial^2E_2}{\partial y^2}+i2n_2\frac{\omega_2}{c}\left[\frac{\partial E_2}{\partial z}+\rho_{2\omega}(\theta)\frac{\partial E_2}{\partial y}+a_2\frac{\partial E_2}{\partial t}\right]\\
&\quad=-\frac{\omega_2^2}{c^2}d_{eff}E_1^*E_3\exp(i\Delta kz)-i\frac{n_2\omega_2}{c}\alpha_2E_2\\
&\frac{\partial^2E_3}{\partial x^2}+\frac{\partial^2E_3}{\partial y^2}+i2n_3\frac{\omega_3}{c}\left[\frac{\partial E_3}{\partial z}+\rho_{3\omega}(\theta)\frac{\partial E_3}{\partial y}+a_3\frac{\partial E_3}{\partial t}\right]\\
&\quad=-\frac{\omega_3^2}{c^2}d_{eff}E_1E_2\exp(-i\Delta kz)-i\frac{n_3\omega_3}{c}\alpha_3E_3
\end{aligned}\qquad (4)$$

Here ρ is the walk-off coefficient of the extraordinary light; $a_j=1/v_{gj}-1/v_{g1}$ (j = 1, 2, 3 represent the fundamental light, the



(a) temporal phase modulation broadband laser

(b) linear chirped broadband laser

(c) chirped pluses stacking broadband laser

Fig. 2. 3ω conversion efficiency and temporal shape adopting type I/II KDP angle-detuning method.

second harmonic generation (SHG) and the THG, respectively); v_{gj} is group velocity; Δk is phase mismatch; c is the velocity of light in the vacuum; α_j is linear absorbing coefficient of KDP crystal.

To the second harmonic frequency conversion, $E_1=E_2=E_{1o}/2$ and E_{1o} is the ordinary light amplitude of the fundamental light; $E_3=E_{2e}$, and E_{2e} is the extraordinary light amplitude of the SHG; $n_1=n_2=n_o$, and n_o represents the ordinary refractive index of the fundamental light; $n_3=n_{2e}$, and n_{2e} is the extraordinary refractive index of the SHG; the effective nonlinear coefficient $d_{eff}=-\chi^{(2)}\sin\theta\sin 2\phi$, θ is the angle between the optical axis and the propagation direction, the azimuth $\phi=45^\circ$ and the nonlinear coefficient $\chi^{(2)}=7.8\times10^{-13}$ m/V in Eq. (4).

And about the third harmonic frequency conversion, $E_1=E_{1e}$, and E_{1e} is the extraordinary light amplitude of the fundamental light; $E_2=E_{2o}$, and E_{2o} is the ordinary light amplitude of the SHG; $E_3=E_{3e}$, and E_{3e} is the extraordinary light amplitude of the THG; $n_1=n_e$ represents the extraordinary refractive index of the fundamental light; $n_2=n_{2o}$ represents the ordinary refractive index of the SHG; $n_3=n_{3e}$ represents the extraordinary refractive index of the THG; $d_{eff}=\chi^{(2)}\sin\theta\cos 2\phi$, and $\phi=0^\circ$.

The third harmonic characteristics of these three kinds of broadband flattened laser have been analyzed under the same condition in this paper. Fig. 2 shows the relationships between the THG efficiency and the intensity of the fundamental light adopting type I/II KDP angle-detuning method, and the temporal shapes of each flattened broadband laser when the intensity of the fundamental light is 4 GW/cm^2 and the spectral width is 15 nm. Fig. 2(a) shows the TPM broadband laser, Fig. 2(b) shows the LC broadband laser and Fig. 2(c) shows the CPS broadband laser, respectively. Besides, the calculating parameters are: the thickness of type I KDP crystal is