Birefringent plate design for broadband spectral shaping in a Ti:sapphire regenerative amplifier

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A method to design a birefringent plate (BP) for broadening spectrum in a regenerative amplifier is presented. Using this method, we design a quartz BP with thickness of 761 μm inserted into a Ti:sapphire regenerative amplifier. The gain narrowing effect is reduced efficiently, and the experimental results agree with the calculation well. The bandwidth is broadened from 28 to 62 nm using the designed quartz BP and the pulses are compressed to $\sim$ 23 fs.

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In the passed decades, the chirped pulse amplification (CPA) technique developed rapidly. Several sub-30-fs multi-terawatt Ti:sapphire laser systems have been built[1−3]. To achieve sub-30-fs high power, one key is to obtain high energy gain with broad bandwidth. The bandwidth of the high-energy amplified pulse is usually far less than 100 nm for gain narrowing effect in the amplification process, especially in a regenerative amplifier. The bandwidth is only 20−30 nm (full-width at half maximum (FWHM)) typically. Therefore, several methods to broaden spectrum in the regenerative amplifier have been developed to compensate the gain narrowing effect[4,5]. Barty *et al.*[5] used two thin angle-tuned etalons to obtain more than 80-nm bandwidth. However, etalons in the regenerative cavity are sensitive to thermal and mechanical drifts and are complicated in alignment[6]. Takada *et al.*[7] adopted a multiple-dielectric-layer component to get more than 120-nm bandwidth. But designing and fabricating such a component is a complex job, and it is also difficult to adjust the attenuation depth of the transmission curve. Utilizing a birefringent plate (BP), Bagnoud *et al.*[6] obtained $\sim$ 82-nm bandwidth under lower gain condition. Leng *et al.*[8] designed a quartz BP based on a simplified formula given by Preuss *et al.*[9] to broaden the spectrum from 18 to 35 nm in the regenerative amplifier, and obtained a compressed 35-fs pulse finally. Compared with the multiple-dielectric-layer component and etalons, BP is much easier to be aligned and control the attenuation depth and position, besides its insensitivity to the thermal and mechanical drifts.

In this letter, we design a BP used in a regenerative cavity to compensate the gain narrowing effect in a laser system. A precise formula about the BP's single-pass transmission without simplification is used in BP design, and the amplified process in Ti:sapphire regenerative cavity is considered. Compared with the simplified formula[9], the simulation results based on the modified formula agree with the experimental results better. By controlling the BP in the regenerative cavity, the bandwidth of the amplified pulse is broadened from original $\sim$ 28 to $\sim$ 62 nm with a gain of about 10^7. After the following multi-pass amplification and compression, the compressed pulse duration (FWHM) reaches $\sim$ 23 fs.

In the regenerative amplifier with a BP inserted in, every time after the pulse passes through the whole cavity, the amplified intensity in the cavity is

$$I_{\text{out}} = I_{\text{in}} \cdot [(1-R)\cdot T \cdot G_{\text{E}}], \tag{1}$$

where I_{in} is the intensity of the seed pulse, T is the transmission produced from the interference of the ordinary (o-) and the extraordinary (e-) lights in the BP and polarizers, and R is the loss in the cavity. G_{E} is the single-pass energy gain of the crystal and calculated from the Frantz-Nodvik model[10]

$$G_{\text{E}} = \frac{1}{2\sigma(\lambda) v N \tau} \times \ln\{1 + [\exp(2\sigma(\lambda) v N\tau) - 1]\exp(\sigma(\lambda)\Delta n_0 L)\}, \tag{2}$$

where v is the velocity of the light in gain medium, L is the length of the gain medium, Δn_0 is the inversion population density, $\sigma(\lambda)$ is the emission cross-section, N and τ are the photon density and the duration of the pulse to be amplified, respectively. In the recursive calculation, the amplified pulse (I_{out}) in the current pass acts as the seed (I_{in}) in the next pass, and the increase of the photon density and the decrease of the inversion population density after every pass of amplification should also be considered.

Different from the previous work[8,9], our calculation uses a single-pass transmission formula considering not only the o- and e- lights along different ways inside the crystal BP, but also the birefringent splitting effect out of the plate[11], and the single-pass transmission T of the BP is

$$T = 1 - \sin^2(2\phi)\frac{n_{\text{o}}^4 - n_{\text{o}}^2\cos^2\theta}{(n_{\text{o}}^2 - \cos^2\theta\cos^2\phi)^2} \times \sin^2\frac{\pi t}{\lambda}\left\{\frac{n_{\text{o}}^2}{\sqrt{(n_{\text{o}}^2-\cos^2\theta)}} - \left[\frac{n_{\text{e}}^2(\theta,\phi)}{\sqrt{n_{\text{e}}^2(\theta,\phi)-\cos^2\theta}} + \cos^2\theta\left(\frac{1}{\sqrt{n_{\text{o}}^2-\cos^2\theta}} - \frac{1}{\sqrt{n_{\text{e}}^2(\theta,\phi)-\cos^2\theta}}\right)\right]\right\}, \tag{3}$$

where $n_e(\theta,\phi)$ is the extraordinary refractive index[9]

$$n_e(\theta,\phi) = n_e\sqrt{\left(1+\frac{\cos^2\theta\sin^2\phi}{n_e^2}-\frac{\cos^2\theta\sin^2\phi}{n_o^2}\right)}, \quad (4)$$

where n_o and n_e are the principal refractive indexes of the o- and e- lights of the crystalline quartz BP for the pulse with wavelength λ, respectively, t is the thickness of the BP, θ is the angle between the BP plate and the transmitted light, and ϕ is the rotation angle of the optical axis which lies in the plane of the BP plate[9].

Before designing BP, we compare the single-pass transmission curves calculated by the modified formula and the simplified formula[9] in a Ti:sapphire regenerative amplifier (see Fig. 1). In our simulation, the values $n_o = 1.53848$ and $n_e = 1.54739$ at 794.8 nm[12] are used, and the influence of different wavelengths on the refractive index differences in the region of about 100 nm is so small that it could be neglected. Figure 1 shows that the attenuation center of the solid line is red-shifted about 10 nm because the neglected phase is added into the modified formula in Eq. (3). Therefore, we could infer that the attenuation curve of BP designed by the simplified formula will disagree with the experimental one under the condition of the same BP parameters. Additionally, the move of center attenuation position with the increasing value θ becomes slow when the value of θ approaches 90°. All these calculated results from the modified formula agree well with the experimental results. Therefore, the modified formula (Eq. (3)) is used to design the BP inserted in the regenerative amplifier to compensate for the gain narrowing effect.

The scheme of the regenerative amplifier is shown in Fig. 2. The pump energy used in the regenerative amplifier is about 60 mJ. The recursive method is used in the simulation. When the seed pulse passes through the Ti:sapphire crystal from the right to the left of the crystal, the loss R of the amplified pulse is estimated to 0. On the contrary, when the seed pulse passes through the crystal from the left to the right of the crystal and R is estimated to be 0.25. Figure 3 shows the simulated results after 19 round trips with a 761-μm-thick BP inserted in the cavity. Without the spectrum limiting of the seed pulse, the bandwidth of the amplified pulse can reach 81.2 nm (FWHM). While the finite spectrum of the actual seed is considered, the bandwidth of the amplified pulse calculated by the seed spectrum is only 69.9 nm against 72.4-nm seed pulse bandwidth (FWHM). This indicates that the BP with 761-μm thickness in our regenerative amplifier can compensate the gain narrowing effect. Both these two calculated results neglect the fact that the central wavelength of the amplified spontaneous emission (ASE) spectrum in our regenerative amplifier is at 785 nm different from the calculated central wavelength of 793 nm. If we assume that the only influence that the regenerative cavity imposes on the the emission cross-section of the Ti: sapphire is to make the spectrum shape translate 8 nm to shorter wavelength in its entirety, the result is 71.4° which agrees with the experimental value of 72.0° (see Fig. 4) well. We also calculate the amplified spectrum by the simplified formula[9]. To get the similar figure, the value of θ is 82.2° when the seed is considered and 79.2° if the fact that the real regenerative central wavelength is 785 nm is considered further. It is evident that the calculated result from Eq. (3) agrees with the experimental result better than that from the simplified formula.

The experiment is carried out in our 10 Hz/17 TW Ti:sapphire laser system, and the scheme of the regenerative amplifier is shown in Fig. 2. The quartz BP is inserted between the polarizers P1 and P2 in the cavity. The energy of a single seed pulse is about 300 pJ, and

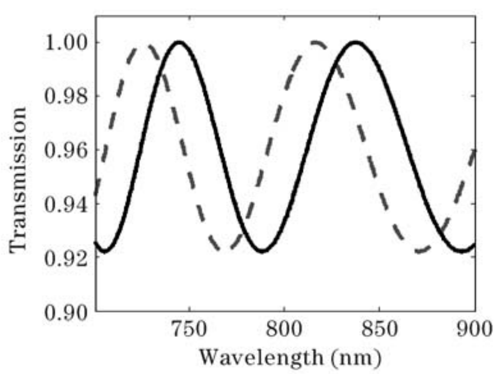

Fig. 1. Single-pass transmission curves of BP in regenerative cavity. $\theta = 76.0°$, $\phi = 8.0°$, $t = 761$ μm calculated by the simplified formula (dot) and modified formula (solid).

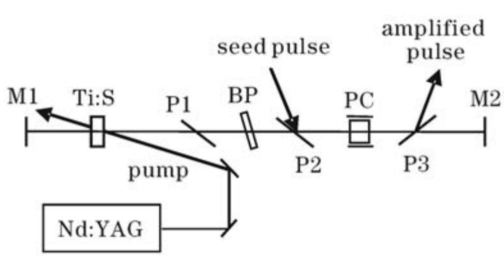

Fig. 2. Scheme of the regenerative amplifier. M1, M2: cavity mirrors; P1, P2, P3: polarizers; PC: Pockels cell.

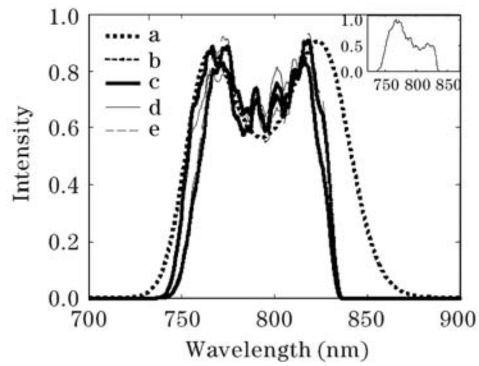

Fig. 3. Simulated results after 19 round trips. (a) Without the spectrum limit of the seed pulse: $\theta = 80.5°$, $\phi = 9.0°$, and $t = 761$ μm; (b) with the spectrum limit of the seed pulse: $\theta = 76.0°$, $\phi = 9.0°$, and $t = 761$ μm; (c) considering the real regenerative central wavelength further: $\theta = 71.4°$, $\phi = 10.0°$, and $t = 761$ μm. These results are calculated by the modified formula and the small figure is the initial injected seed spectrum. (d) With the spectrum limit of the seed pulse: $\theta = 82.2°$, $\phi = 9.0°$, and $t = 761$ μm; and (e) considering the real regenerative central wavelength further: $\theta = 79.2°$, $\phi = 10.0°$, and $t = 761$ μm. These results are calculated by the simplified formula.

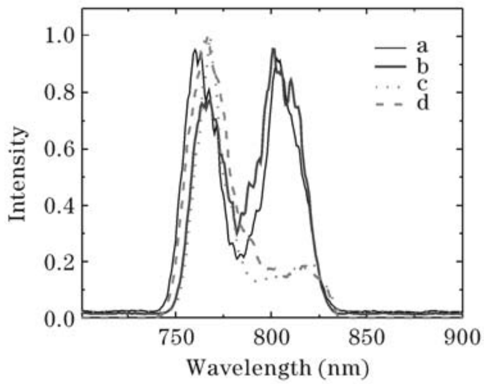

Fig. 4. Experimental spectra from regenerative amplifier. (a) The ASE spectrum; (b) the amplified spectrum with seed injected, $\theta = 72°$ and $t = 761$ μm; (c) the amplified spectrum, $\theta = 79.2°$ and $t = 761$ μm; and (d) the calculated amplified spectrum by the modified formula, $\theta = 79.2°$, $\phi = 10°$, and $t = 761$ μm.

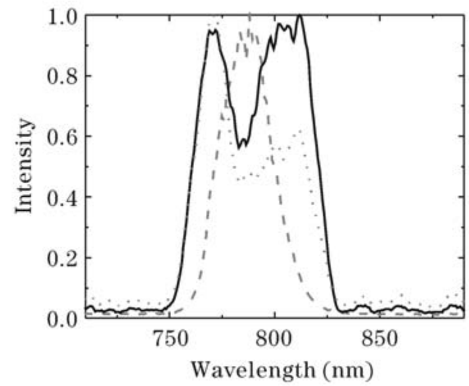

Fig. 5. Measured spectrum from the regenerative amplifier with (dot, considering the following amplification) and without (dash) 761-μm BP, and the amplified pulse spectrum from following five-pass amplifier (solid) with $\sim$ 62-nm bandwidth (FWHM).

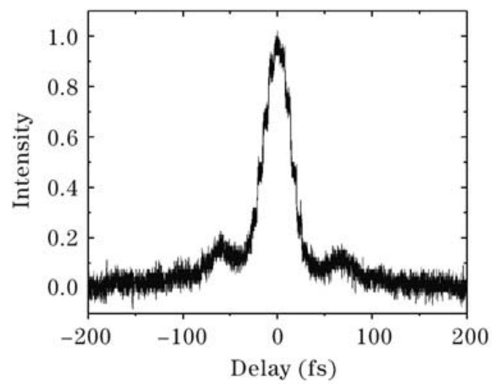

Fig. 6. Measured autocorrelation trace of the compressed 23-fs pulse.

the amplification ratio is $\sim 10^7$ to achieve an amplified pulse of about 3 mJ after 19 round trips. Because of the spectral clipping in the stretcher, the full bandwidth of the seed pulse is less than 90 nm as shown in Fig. 3. According to our simulation, a thinner BP could produce a broader spectrum. However, the thinner BP will affect the stability of the cavity and need stronger laser pump because of its greater energy loss. Additionally, the amplified spectrum is also limited by the initial injecting seed spectrum and the bandwidth of the optical components. To design a BP, the value of θ should be selected properly. Typically the value of θ is set between 70° and 80° by considering the stability of the amplified spectrum, effective BP's aperture, and the tunable wavelength range. Considering the influences of both the seed light and the fact that the central wavelength of the ASE spectrum of our regenerative amplifier is 785 nm, setting the value of θ to be 71.4° at the same time, the BP with the thickness of 761 μm is designed.

We fabricated a 761-μm-thick BP according to our design. Figure 4 shows the experimental spectra of the ASE and the amplified pulse, respectively. To validate the result calculated by modified formula, we set the BP values according to the above simplified calculated result, i.e., $\theta = 79.2°$, $\phi = 10°$, and $t = 761$ μm, to get the experimental spectrum and the calculated spectrum by the modified formula. Though the thickness of the BP affects the attenuation position, it could be corrected by changing the value of θ a little when the error of the fabrication is small, for example, in our case, it could get a similar figure by changing the value of θ about 1.5° for a thickness error of 2 μm. The bandwidth of the ASE spectrum is $\sim$ 69 nm, broader than $\sim$ 64 nm of the amplified spectrum. The real bandwidth is narrower than the calculated bandwidth, which could be attributed to the spectrum limit of the optical components, esp. the cavity mirrors and the polarizers. To get better simulated results, the details of the regenerative amplifier should be known, such as the space distribution of the pump energy, the reflective spectrum or transmitted spectrum of every optical component in the cavity.

The amplified pulse from the regenerative amplifier is injected into a 5-pass amplifier, and is amplified to $\sim$ 800 mJ. Then the amplified pulse is delivered into a grating compressor. Figure 5 shows the gain spectral bandwidth is 28 nm (FWHM) without the BP in the cavity. Because of the red shift effect of the following multi-pass amplifier, the spectrum of the regenerative amplifier is set to an asymmetric profile by adjusting the angle of θ. And the spectral width out of the multi-pass amplifier is $\sim$ 62 nm (FWHM) which is much broader than the situation without the BP in the cavity. A fraction of the compressor output is sent to a single-shot autocorrelator to measure the pulse duration. A typical autocorrelator trace is shown in Fig. 6 and the measured pulse duration is $\sim$ 23 fs (FWHM). The wings at both sides of the main peak result from that residual high orders of dispersion which are not compensated completely.

In summery, we presented a method to design a BP for spectral shaping in a Ti:sapphire regenerative amplifier. In the simulation the single-pass transmission formula of the BP without simplification is used. Utilizing the method, a BP with thickness of 761 μm is designed and displayed in the 10Hz/17TW Ti:sapphire laser system. The experimental results agree with the design well, and the gain narrowing effect in the laser system is reduced efficiently. After two stages of amplification and a compressor, the spectrum of the amplified pulse is broadened from original $\sim$ 28 to $\sim$ 62 nm, and the compressed pulse duration is $\sim$ 23 fs. According to the calculation, the bandwidth of the pulse is expected to be above 80 nm if the seed of the regenerative amplifier and the optical component in the regenerative amplifier can support broader bandwidth. This method is also easy to be used to design the BP in other regenerative amplifiers.

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