Generation of near transform-limited ultrashort laser pulses in kilohertz chirped-pulse amplification system by compensating high order phase distortions

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The effects of gain narrowing and high order dispersions on the pulse duration in our kilohertz chirped-pulse amplification system have been compensated experimentally. Using an acousto-optic programmable dispersive filter (AOPDF), the spectral full-width at half-maximum (FWHM) is expanded from 30 to 50 nm. Stable laser pulses with the duration of 30 fs (FWHM), which is 1.07 times Fourier-transform-limitation, have been acquired by pre-compensating the high order phase distortions using the phase measured by spectral phase interferometry for direct electric-field reconstruction (SPIDER).

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Chirped-pulse amplification (CPA) technique has been widely used to generate ultra-intense femtosecond pulses. In this scheme, the seed pulses from an oscillator are stretched before amplification, usually by introducing a positive chirp, and afterwards compressed with an equally large negative chirp[1]. The stretched pulses, which have relatively low peak power with longer duration, can support more energy extraction and effectively decrease the nonlinear effects in the gain media.

Femtosecond oscillators can routinely deliver nearly transform-limited mode-locked laser pulses. However, subsequent amplification in a CPA chain will result in a broadening of the output compressed pulses in temporal domain owing to the gain narrowing and uncompensated phase distortions, especially high order dispersions. The beam propagation process in the amplification medium can be described by the following transmitting equation

$$\frac{\partial A}{\partial z}+\sum_{n=1}^{\infty} i^{(n-1)}\beta_n \frac{\partial^n A}{\partial t^n}=i\gamma\left|A\right|^2 A+\frac{g-\alpha}{2}A, \qquad (1)$$

where $A(z,t)$ is the complex envelope of the electric field under slowly varying pulse approximation, β_n is the nth order dispersion constant of the transparent media. For example, β_1 is the group delay (GD) constant, β_2 the group delay dispersion (GDD) constant, β_3 the third order dispersion (TOD) constant and β_4 the forth order dispersion (FOD) constant. The GD constant β_1 only leads to a shift on temporal domain and does not affect the pulse shape. When a reference frame with the group velocity v_{g} is used, β_1 can be eliminated from the equation. Parameter g is the gain coefficient and α is the absorption coefficient. The constant γ stands for the effect of self phase modulation (SPM).

Generally, the influence on the pulse width decreases with the dispersion order n. GDD is the main factor that stretches and compresses the pulse, and one of the most remarkable influences of TOD is to make some side-wings on the sides of the pulse shape. The compressor usually consists of a grating pair or a prism pair, which can effectively compensate most of the second order dispersion and part of the high order dispersions. But there will still be some high order phase distortions which cannot be compensated even when the stretcher and the compressor are carefully aligned. And the shorter the pulse is, the more difficult it will be to achieve perfect compensation. Femtosecond laser pulses which have broad spectra will also suffer considerable group velocity dispersion when propagating through transparent materials.

Gain narrowing is another primary limitation for the compressed pulse duration, which is caused by the nonuniform gain for different part of the spectra. This effect usually can be offset by introducing a spectral filter before or in the amplifier to suppress the higher part of the gain trace. Another undesired effect is the shift of the center wavelength after amplification.

Many methods have been used to correct the time aberrations introduced by the CPA laser chains, such as liquid crystal spatial light modulator (LC SLM)[2], mobile mirror (MM)[3], deformable mirror (DM)[4], etc.. Most of them have complicated structures and have to be used in space-time conversion $4f$ systems. In our experiment, an acousto-optic programmable dispersive filter (AOPDF) (Dazzler WB-800, Fastlite, France) was employed to compensate both gain narrowing effect and high order spectral distortions of the CPA chain. This device can separately control the amplitude and the phase of the pulses accurately. Another unique feature of the AOPDF is that it does not have to be positioned in the Fourier plane of a dispersion line. The device is compact, and its implementation in an existing CPA laser chain requires only minor changes[5]. The spectral resolution of our AOPDF is 0.6 nm. This device has been applied in 10-Hz CPA systems[6,7].

The experiment was carried out on our kilohertz, femtosecond laser system (Spitfire, Spectra-Physics, USA). The original pulse duration was about 51 fs (full-width at half maximum, FWHM), and the average output pulse energy was 700 μJ. The FWHM of the spectra from the oscillator (Millennia, Spectra-Physics) was about 35 nm. After the regenerative amplifier, the width was reduced to 30 nm because of the gain narrowing. A spectral phase interferometer for direct electric-field reconstruction (SPIDER) (APE, Germany) was used to measure both the pulse intensity and the spectral phase.

The AOPDF was settled between the oscillator and the stretcher, as shown in Fig. 1. By introducing a nonlinear modulation on the intensity of the spectra, the spectral FWHM was expanded from 30 to 50 nm (Fig. 2), which means that much shorter pulses can be delivered in the optimized system. In our experiment, the pulse duration can be compressed from 51 to 39 fs only using spectral modulation. Because the seed pulse was weaker after modulation, more pump energy was needed to maintain the original output power. The system stability was not affected in our experiment.

The phase of seed pulse Φ is the function of spectral frequency ω, and it can be expanded into Taylor series:

$$\Phi(\omega)=\sum_{n=1}^{\infty}\frac{1}{n!}a_n(\omega-\omega_0)^n+\Phi(\omega_0). \qquad (2)$$

From the transmitting equation we can conclude that if an appropriate additional phase was modulated on the initial pulse, the high order dispersions brought by the latter processes, including stretching, amplification and compression, will be effectively compensated.

For near-infrared (NIR) and visible (VIS) pulses with <50 fs durations, at least the effect of TOD has to be taken into account[7]. By changing the four dispersion parameters of system, the AOPDF can exactly control the first four terms of the pulse phase. It can also use the output phase file of SPIDER or frequency-resolved optical gating (FROG) to modulate the laser phase, and in this mode linear interpolation will be used to determine the additional phase of each point of the spectra.

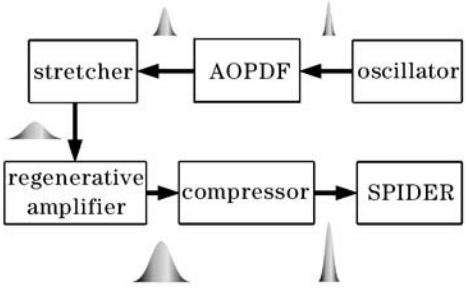

Fig. 1. Schematic of the CPA laser system.

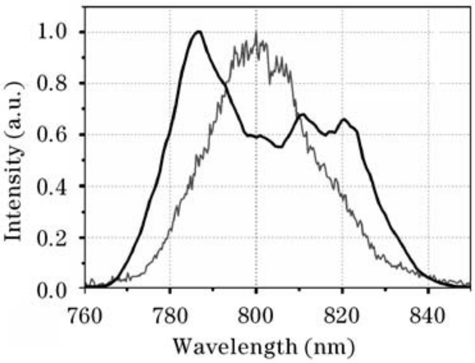

Fig. 2. Output spectra before (thin line) and after (thick line) modulation.

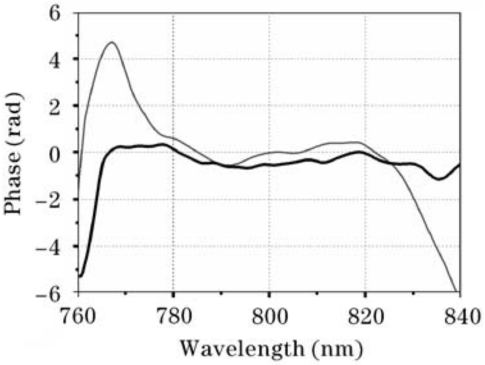

Fig. 3. Output phases measured before (thin line) and after (thick line) phase optimization.

The phase curve of the amplified 51-fs pulse measured by SPIDER before optimization is shown in Fig. 3. There is quite a large phase distortion on the edge of the original pulse phase. Firstly, the effects of GDD, TOD, and FOD were investigated by scanning the four dispersion parameters respectively. We find that the third phase term is the main factor that limits the output pulse width in our system, which means that there is quite a large TOD (about 10^5 fs^3) needs to be compensated. The change of the second phase term can be approximately compensated by tuning the compressor, and obvious influence of the forth term has been observed. The best result we achieved here was 34 fs.

For further optimization, a phase feedback was used to make compensation for the residual high order phase distortions. Stable output duration of 30 fs (FWHM) was acquired. The phase trace after optimization is also shown in Fig. 3. Compared with the original phase, we can see that the side distortion has been remarkably reduced. The phase fluctuation can be restrained between ±0.5 rad in the effective spectral range. The residual phase distortion is possibly due to the measurement error of SPIDER and the intrinsic fluctuation of the amplifier system.

The original pulse intensity (51 fs) and the optimized pulse intensity (30 fs) are compared in Fig. 4(a). There is a sequence of small wings on the right side of the original pulse, which is mainly due to the un-compensated TOD. The side peaks on both sides of the optimized main pulse are caused by the anomalous spectral envelope. Smoother pulse form should be obtained by regulating the spectral shape.

The Fourier-transform-limited temporal waveform was calculated with the optimized spectra using fast Fourier transform (FFT) method, as shown in Fig. 4(b). The transform limitation for the output pulse width is 28 fs (FWHM), and this means that 1.07 times the transform-limited duration has been achieved in our system. The measured intensity trace is fairly consistent with the simulation.

We also find that the optimized pulse width has been limited basically by the full spectral width of the amplifier. Although we have successfully expanded the

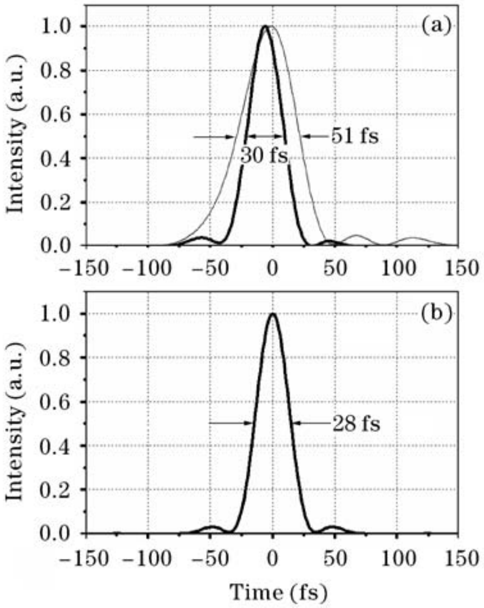

Fig. 4. Measured intensity forms (a) and the Fourier transform (b) of the optimized spectra.

spectral FWHM from 30 to 50 nm, the transform limitation has not been so obviously improved due to the unideal square-like spectral form.

In summary, using spectral modulation and phase precompensation, we have successfully optimized the output duration from 51 to 30 fs. We find that TOD is the primary limitation for the output duration in our CPA system. The high order phase distortions can be reasonably corrected using the measured phase file. The optimized intensity trace detected by SPIDER is considerably consistent with the Fourier transform of the spectra, and 1.07 times the transform-limited duration has been achieved. The optimized CPA system has been used to investigate the pulse compression process through filamentation in an argon-filled cell, and 12-fs output of good spatial quality has been obtained. This technique can also be used in other ultrashort laser systems.

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