Laser pulse spectral shaping based on electro-optic modulation

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A new spectrum shaping method, based on electro-optic modulation, to alleviate gain narrowing in chirped pulse amplification (CPA) system, is described and numerically simulated. Near-Fourier transform-limited seed laser pulse is chirped linearly through optical stretcher. Then the chirped laser pulse is coupled into integrated waveguide electro-optic modulator driven by an aperture-coupled-stripline (ACSL) electrical-waveform generator, and the pulse shape and amplitude are shaped in time domain. Because of the direct relationship between frequency interval and time interval of the linearly chirped pulse, the laser pulse spectrum is shaped correspondingly. Spectrum-shaping examples are modeled numerically to determine the spectral resolution of this technique. The phase error introduced in this method is also discussed.

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Chirped-pulse amplification (CPA) technique has been used to create damage-free amplification of short-duration optical pulses to terawatt and even petawatt laser levels[1]. Successful amplification of ultra-broadband optical pulses is limited by two effects: high-order phase errors in the amplification chain and gain narrowing in the high-gain amplifying medium. The dispersive optical systems that are capable of controlling dispersion up to the fifth order have been demonstrated[2]. In picosecond high power laser systems, the extent of spectral narrowing associated with gain narrowing is of the highest importance in pre-amplifiers, which typically possess the highest gain in the laser system. Because of the direct relationship between frequency interval and time interval of the linearly chirped pulses, gain narrowing results in laser temporal narrowing. The broadband seed pulses after spectral shaping can reduce time and spectrum narrowing in the regenerative amplifier, and help extract more energy in the power amplifier. In femtosecond high-peak-power laser systems, the spectral shaping helps produce shortest-duration high-peak-power laser pulses.

Spectral shaping techniques, such as intracavity etalon, birefringent crystals, and prism-waveguide coupler (PWC), have been adopted widely to broaden the bandwidths of the amplified pulses effectively in high-power pulsed laser systems[2−4]. PWC spectral shaping experiments have been demonstrated[5,6]. In this paper, we report a new spectral shaping scheme based on electro-optic modulation of linearly chirped ultra-short pulses. In a CPA system, because the seed optical pulses are linearly chirped, there exists a one-to-one correspondence between time duration and linearly chirped frequency. So, if the temporal shapes of seed laser pulses are modulated in time domain, their spectral shapes are also changed correspondingly in frequency domain. The new spectral shaping scheme, put forward in this paper, is based on this one-to-one correspondence. We focus on the theory research and numerical simulation here.

The spectral shaping scheme is illustrated in Fig. 1. Firstly, the seed laser pulses emitted from a mode-locked Nd:glass laser are chirped linearly and stretched from about 200 fs to 1 − 3 ns through a stretcher. So the laser pulse frequency is almost a linear function of time. Secondly, the stretched optical pulses are coupled into an optical fiber, so that a single pulse is picked out in the sampler which consists of a gate electrical pulse generator and an integrated electro-optic waveguide modulator. Thirdly, the single chirped optical pulse is divided into two pulses by a fiber splitter. The smaller power pulse, after amplification, is used to create a triggering electrical pulse by the Si photoconductive switch, to trigger the electrical pulse generator. The other optical pulse is sent to the second electro-optic waveguide modulator. This optical path arrangement assures the high-precision synchronization of the linearly chirped optical pulse and the shaped electrical pulse (the root-mean-square (RMS) time jitter is less than 5 ps)[7]. Finally, the linearly chirped pulse is shaped in the second waveguide electro-optic modulator driven by an aperture-coupled-

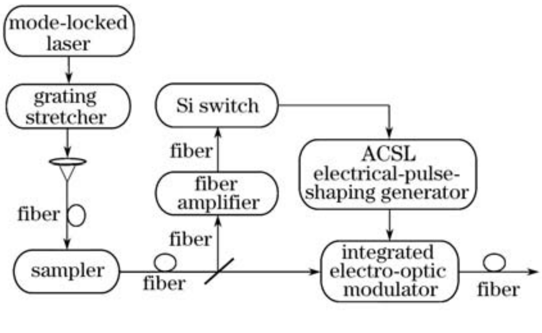

Fig. 1. Spectral shaping scheme.

stripline (ACSL) electrical pulse generator[8−10]. Because of the linear relationship between the laser pulse frequency and time duration, the amplitude modulation in time domain corresponds to amplitude modulation in frequency domain and spectral intensity modulation. The electro-optic modulation techniques have been used to shape long pulse waveform with a few nanoseconds duration[9−11], but have not been used to shape linearly chirped ultrashort pulses yet.

The field of seed laser pulse from the oscillator can be written as

$$\varepsilon_{\mathrm{in}}(t) = E(t)\mathrm{e}^{i[\omega_0 t - \beta(\omega_0)z]}, \tag{1}$$

where ω_0 is the carrier frequency for the seed pulse signal, $\beta(\omega_0)$ is the propagation constant, and $E(t)$ is taken to be the complex envelope.

After being linearly chirped through the optical stretcher (grating pairs or fiber), the stretched optical pulse field can be expressed as

$$\varepsilon(t) = \int_{-\infty}^{\infty} \varepsilon_{\mathrm{in}}(\omega)\exp\left[i\phi(\omega)\right]\exp(i\omega t)\mathrm{d}\omega, \tag{2}$$

$$\phi(\omega) = \phi(\omega_0) + \phi'(\omega_0)(\omega-\omega_0) + \frac{1}{2}\phi''(\omega_0)(\omega-\omega_0)^2 + \frac{1}{6}\phi'''(\omega_0)(\omega-\omega_0)^3 + \cdots, \tag{3}$$

where ϕ', ϕ'', and ϕ''' are the derivatives of the phase with respect to frequency, and are known as the group delay, the second-order dispersion (or group velocity dispersion (GVD)), the third-order dispersion (TOD), respectively. $\phi(\omega)$ is the phase introduced by the stretcher. Usually, the short laser pulse is stretched in time duration by a factor of $10^3 - 10^4$.

The stretched seed pulse is then coupled into the integrated electro-optic waveguide modulator driven by an ACSL electrical-waveform generator. The temporally shaped electrical pulse is synchronized with the passage of the stretched optical pulse through the modulator. This amplitude modulation technique makes use of the electrical pulse directly to manipulate the laser pulse amplitude in time domain. The optical pulse is split into two pulses with equal power in the modulator[12]. The field of the two pulses at the first fiber coupler of the electro-optic modulator can be expressed as

$$\varepsilon_1(t) = \varepsilon_2(t) = \frac{1}{\sqrt{2}}\varepsilon(t). \tag{4}$$

The output superposed field of the two laser pulses at the second fiber coupler, because of the electrical pulse modulation, is given by

$$\varepsilon'(t) = \frac{1}{\sqrt{2}}\left[\frac{1}{\sqrt{2}}\varepsilon(t)\exp(i\Delta\varphi) + \frac{1}{\sqrt{2}}\varepsilon(t)\exp(-i\Delta\varphi)\right] = \varepsilon(t)\cos(\Delta\varphi). \tag{5}$$

The relative phase shift is

$$\Delta\varphi(t) = \frac{\pi}{2}\{[V(t) + V_{\mathrm{dc}} + V_{\pi/2}J/V_\pi + \varphi_0\}, \tag{6}$$

where V_π and $V_{\pi/2}$ are the half-wave and quarter-wave voltages of the modulator, V_{dc} is the direct current (DC) bias voltage applied to the modulator to cancel the constant phase shift, and $V(t)$ is the voltage waveform applied to the radio frequency (RF) port of the modulator, $\Delta\varphi(t)$ is the phase shift introduced by $V(t)$, and φ_0 is the constant phase shift introduced by device manufacturing tolerances.

The Fourier transform of Eq. (5) gives us, in frequency domain or spectral domain, the corresponding amplitude and phase distribution of the temporally shaped optical pulse is given by

$$\varepsilon(\omega) = \int_{-\infty}^{\infty} \{\varepsilon(t)\cos[\Delta\varphi(t)]\}\exp(-i\omega t)\mathrm{d}t. \tag{7}$$

The shaped optical pulse waveform in frequency domain is obtained by

$$I(\omega) \propto |\varepsilon(\omega)|^2. \tag{8}$$

Generally, to obtain a linearly chirped pulse with a specified spectral shape, several design steps have to be obeyed: 1) the electric field of the seed laser pulse, in frequency domain, is calculated from the Fourier transform; 2) the electric field of the chirped pulse output from stretcher, in time domain, is obtained by the inverse Fourier transform, because the pulse stretcher is only represented by a quadratic phase; 3) the electrical pulse with special voltage shape is generated in ACSL generator; 4) the electric field of the optical pulse after being modulated, is calculated by Eq. (5); 5) the spectral shape of the optical pulse after being modulated, is calculated by Eqs. (7) and (8).

Consider that the seed laser pulse is Gaussian-shape and near-bandwidth-limited. The field of the seed laser pulse can be written as

$$\varepsilon(t) = \varepsilon_0 \exp\left[-\frac{2\ln 2t^2}{\tau_0^2} + i\omega_0 t\right], \tag{9}$$

where ε_0 is the peak value of the laser pulse field, τ_0 is the full-width at half-maximum (FWHM) of the seed pulse. The pulse shapes in time domain and frequency domain of the laser pulses after being stretched are simulated with the parameters of $\tau_0 = 220$ fs, $\Delta\lambda_{\mathrm{FWHM}} = 7.4$ nm, $\lambda_0 = 1053$ nm, the optical pulse duration FWHM after grating stretcher $\tau = 1.2$ ns.

The simulated chirped optical pulse shapes in time domain, before and after being shaped, are plotted in Fig. 2. The time modulation functions $M(t) = \cos[\Delta\varphi(t)]$ with different modulation depths are also shown in Fig. 2. The corresponding modulated optical pulse shapes in spectral space are plotted in Fig. 3. Different shapes with $\Delta\lambda_{\mathrm{FWHM}}$ values of 7.4, 8.6, 10.4, and 11.2 nm correspond to the original optical pulse and the modulated pulses by modulation functions with different modulation depths are shown in the figure. Figure 3 shows that the spectral bandwidth of the chirped optical pulse can be broadened by spectral shaping.

The electrical pulse voltage $V(t)$ shapes are calculated from the time modulation function $M(t)$, and the results

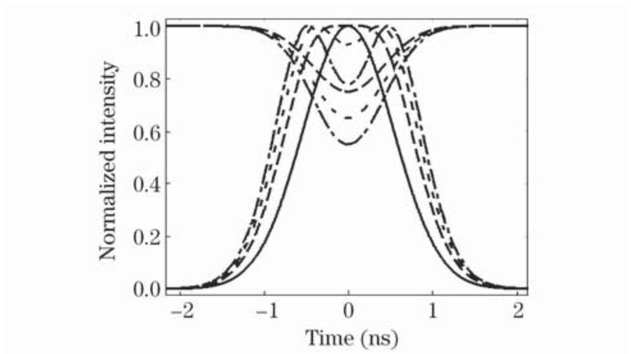

Fig. 2. Pulse shapes in time domain. The original optical chirped pulse (solid curve), three modulation function curves and modulated optical pulse intensity curves with different modulation depths (dotted, dashed, and dash-dotted curves).

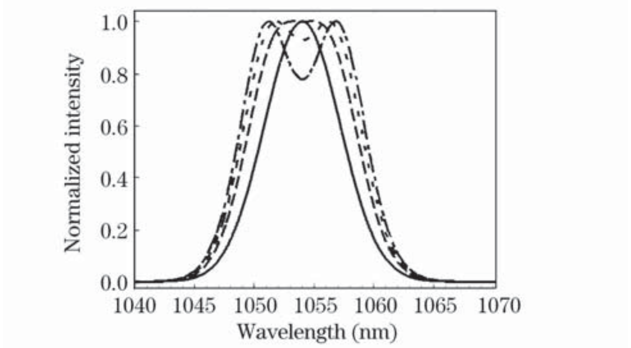

Fig. 3. Pulse shapes in spectral domain. The original chirped optical pulse shape (solid curve, $\Delta\lambda_{\mathrm{FWHM}} = 7.4$ nm) and three spectral pulse shapes (dashed curve: $\Delta\lambda_{\mathrm{FWHM}} = 8.6$ nm; dotted curve: $\Delta\lambda_{\mathrm{FWHM}} = 10.4$ nm; dash-dotted curve: $\Delta\lambda_{\mathrm{FWHM}} = 11.2$ nm) after being modulated.

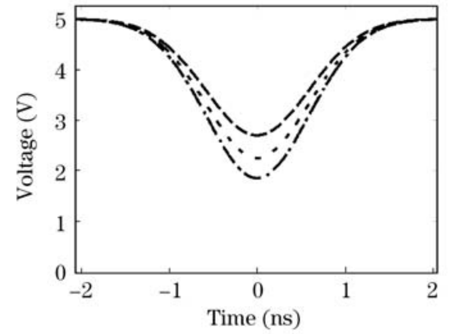

Fig. 4. Voltage shapes of three shaped electrical pulses with different modulation depths.

are plotted in Fig. 4. Since the electrical pulse with arbitrary waveform can be generated easily in ACSL generator, using this spectral shaping system, we can achieve broadband optical pulses with different spectral shapes.

In CPA systems, the gain coefficient dependence of the frequency results in distortion and exponential narrowing of the spectrum of an initially broadband pulse subjected to strong amplification. Perry *et al.* have studied this problem in detail[3]. In order to alleviate the gain narrowing, the chirped pulse spectral shapes are usually reshaped to be center-flat, or even center-sunken.

The basic requirement for spectral shaping by electro-optic modulation of linearly chirped pulse is to create a one-to-one correspondence between time interval and linearly chirped frequency. An exact frequency-time mapping is not possible because of the amount of spectral chirp rate b imposed on the optical pulse by stretcher and the shaped electric pulse fine structure Δt generated by ACSL generator. The larger the frequency chirp rate, the better a small frequency interval can be manipulated. The smaller the electric pulse fine structure, the smaller the frequency interval can be reshaped.

The spectral linear chirp rate b, the instantaneous frequency $f(t)$, and the wavelength $\lambda(t)$ are defined as

$$b = \frac{1}{2\pi}\frac{\mathrm{d}^2\phi(t)}{\mathrm{d}t^2},$$

$$f(t) = \frac{1}{2\pi}\frac{\mathrm{d}\phi(t)}{\mathrm{d}t} = f_0 + bt,$$

$$\lambda(t) = c/f(t) = 2\pi c/\left[\frac{\mathrm{d}\phi(t)}{\mathrm{d}t}\right] = c/(f_0 + bt). \quad (10)$$

The minimal spectral interval (spectral resolution) is $\lambda_{\mathrm{m}} \approx cb\Delta t/f_0^2$. As an example, considering the laser pulse with the parameters given above. The shaped electric pulse fine structure Δt is about 100 ps. The bandwidth of the modulators is approximately 8 GHz, which is sufficient for generating 100-ps structure on the shaped optical pulse[10]. These yield the spectral resolution $\lambda_{\mathrm{m}} = 0.6$ nm. It is obvious that, the smaller the electric pulse fine structure, the higher the spectral resolution can be achieved.

The phase accumulated in the electro-optic modulator is calculated by $\Delta\varphi(t)$. We plot the results for modulated pulses with different modulation depths in Fig. 5. The extra phase error introduced by electro-optic modulation can be compensated by grating compressor. The phase accumulated in spectral shaping system, compared with that introduced in materials dispersion, is quite small and can be compensated for by adjusting the incident angle of either the stretcher or the compressor[1].

The spectral shaping scheme based on the shaping of chirped pulse in time domain is demonstrated numerically in this paper. Numerical simulations indicate that spectral shapes can be reshaped by electro-optic modulation. Because of the high-precision synchronization between the seed laser pulse and the shaped electrical pulse, the steady and smooth shaped spectral shapes can be achieved. The shaped chirped pulse can reduce the

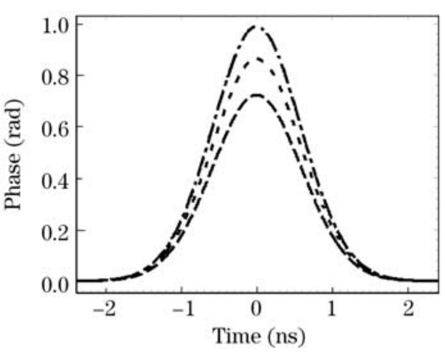

Fig. 5. Phase accumulated in spectral shaping by electro-optic modulation with different modulation depths.

gain narrowing in amplification, especially in high-gain regenerative amplifier. This also helps to generate the shortest laser pulse in CPA systems.

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