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Design of Linearly Chirped-Fiber-Bragg-Grating for Ultrashort Optical Pulse Shaping and Coding

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Abstract A simplified signal-transform technique is utilized to map the output pulse temporal waveform into the spectral response of the shaper or coder. By designing the apodization profile of linearly chirped-fiber-Bragg-grating, a transform-limit Gaussian ultrashort optical pulse is shaped into a rectangular or triangular temporal output waveform. In addition, in order to demonstrate the feasibility for coding a train of optical pulses, non-return-zero (NRZ) or return-zero (RZ) pulse with 1011 codes are generated.

Key words ultrafast optics; pulse shaping; pulse coding; linearly chirped-fiber-Bragg-grating

OCIS codes 320.5540; 070.6020; 060.2340; 050.2770

设计线性啁啾光纤布拉格光栅进行超短光脉冲整形和编码

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摘要 利用一种简单的信号变换技术，将输出脉冲的瞬时波形映射成整形器或编码器的光谱响应，从而通过线性啁啾光纤布拉格光栅的切趾设计，将变换限高斯超短光脉冲整形为方型或三角型脉冲。为了证实该方法对光脉冲串编码的有效性，产生了具有 1011 码字的非归零和归零脉冲码。

关键词 超快光学；脉冲整形；脉冲编码；线性啁啾光纤布拉格光栅

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1 Introduction

Ultrashort pulses with the time scales of picosecond and femtosecond have attracted considerable attention. The mode-locked lasers are by far the most common sources of ultrashort pulses. But the temporal shapes generated by mode-locked lasers are typically sech or Gaussian, which are unsuitable for some special applications[1-2]. For example, the ultrashort pulse with flat-top waveform is highly desirable for nonlinear optical switching system[3], and ultrashort pulse trains with controlled coding amplitude are necessary for all-optical code-division multiple access communication systems[4]. Therefore, optical pulse shaping and coding techniques become increasing important. The well-known approach is the 4f Fourier transform setup[5-6], in which liquid-crystal spatial light modulators are usually utilized as the amplitude or phase mask to reshape the spectrum of incident pulse in the spatial domain[7-8]. However, devices employed by the 4f system are bulky, lossy, and expensive. This has prompted recent efforts on the implementation of waveguide-based optical shaping or coding elements. For example, pulse shaper and pulse-code generator based on fiber Bragg gratings[9], superstructured Bragg gratings[10] or long-period-gratings[11] have been demonstrated. However, pulse shaper or coder mentioned above is usually involved complex synthesis algorithms, such as inverse-scattering or layer-peeling techniques[12], which does not always ensure the feasibility in some particular pulse shaping or coding. In this paper, we utilize a simplified signal-transform technique to map the output pulse temporal waveform into the spectral response of

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作者简介： 董小伟(1978—)，副教授，主要从事光纤通信及光电子等方面的研究。E-mail：way7803@163.com the transfer function, and arbitrary customized pulse waveform or code can be obtained flexibly by designing the apodization profile of linearly chirped fiber Bragg grating (LCFBG).

2 Theory backgrounds

The incident pulse signal is described as $a_{\mathrm{in}}(t) = \hat{a}_{\mathrm{in}}(t) \cdot \exp(\mathrm{j}\omega_0 t)$, where $\hat{a}_{\mathrm{in}}(t)$ represents the complex envelop of the signal and ω_0 is the central angular frequency. By taking the Fourier transform, the corresponding spectral response can be obtained as $A_{\mathrm{in}}(\omega) = \hat{A}_{\mathrm{in}}(\omega - \omega_0) = \hat{A}_{\mathrm{in}}(\omega')$.

The transfer function of the shaper or coder is defined as $H(\omega) = \hat{H}(\omega)\exp[-\mathrm{j}\Phi(\omega)]$. By assuming phase factor $\Phi(\omega)$ characterized by the quadratic phase response, the third-order and higher-order differentiation of $\Phi(\omega)$ will be zero. Therefore, the transfer function $H(\omega)$ can be described as $H(\omega) = H(\omega_0 + \omega') = \hat{H}(\omega')\exp\left[-\mathrm{j}\left(\Phi_0 + \dot{\Phi}_0\omega' + \frac{1}{2}\ddot{\Phi}_0\omega'^2\right)\right]$, where $\Phi_0 = \Phi(\omega_0)$, $\dot{\Phi}_0 = \partial\Phi/\partial\omega$, $\ddot{\Phi}_0 = \partial^2\Phi/\partial\omega^2$ are the Taylor expansions of phase function $\Phi(\omega)$ in the vicinity of ω_0.

When the incident signal propagates through the shaper or coder, the spectral response function of output signal can be expressed as

$$A_{\mathrm{out}}(\omega) = A_{\mathrm{in}}(\omega)H(\omega) = \hat{A}_{\mathrm{in}}(\omega')\hat{H}(\omega')\exp(-\mathrm{j}\Phi_0) \times \exp(-\mathrm{j}\dot{\Phi}_0\omega')\exp\left(-\mathrm{j}\,\frac{1}{2}\ddot{\Phi}_0\omega'^2\right). \tag{1}$$

For an ultrashort temporal pulse waveform, its Fourier spectrum is usually very broad. By designing the parameters of the shaper or coder, the spectral bandwidth of the injected ultrashort pulse can be made much larger than bandwidth of the shaper or coder. Therefore, the signal amplitude is approximately constant $[\hat{A}_{\mathrm{in}}(\omega') = \hat{A}_0]$ corresponding to spectral response of the shaper or coder. Thus, by taking inverse Fourier transform of Eq. (1), the output pulse can be obtained as

$$\begin{aligned}
A_{\mathrm{out}}(t) = {} & \mathscr{F}^{-1}[A_0(\omega)] \approx \\
& \mathscr{F}^{-1}\left[\hat{A}_0\hat{H}(\omega')\exp(-\mathrm{j}\Phi_0)\exp(-\mathrm{j}\dot{\Phi}_0\omega')\exp\left(-\mathrm{j}\,\frac{1}{2}\ddot{\Phi}_0\omega'^2\right)\right] \propto && \text{(2a)} \\
& \mathscr{F}^{-1}[\hat{H}(\omega')] \otimes \mathscr{F}^{-1}\left[\exp\left(-\mathrm{j}\,\frac{1}{2}\ddot{\Phi}_0\omega'^2\right)\right] \propto \\
& h(t) \otimes \exp\left(\mathrm{j}\,\frac{1}{2\ddot{\Phi}_0}t^2\right) \propto \\
& \int_{-\infty}^{+\infty} h(t')\exp\left[\mathrm{j}\,\frac{1}{2\ddot{\Phi}_0}(t - t')^2\right]\mathrm{d}t' \propto \\
& \exp\left(\mathrm{j}\,\frac{1}{2\ddot{\Phi}_0}t^2\right)\int_{-\infty}^{+\infty} h(t')\exp\left(-\mathrm{j}\,\frac{1}{\ddot{\Phi}_0}tt'\right)\mathrm{d}t' \propto && \text{(2b)} \\
& \hat{H}(\omega')\big|_{\omega' = t/\ddot{\Phi}_0}. && \text{(2)}
\end{aligned}$$

Note: In the step (2a), $\hat{A}_0\exp(-\mathrm{j}\Phi_0)\exp(-\mathrm{j}\dot{\Phi}_0\omega')$ is neglected because only a constant amplitude and an average delay are introduced. In the step (2b), $\exp\left(\mathrm{j}\,\frac{1}{2\ddot{\Phi}_0}t'^2\right)$ is negligible if the dispersion coefficient $\ddot{\Phi}_0$ is sufficiently large so that $\ddot{\Phi}_0 \gg t'^2/2$[13]. Eq. (2) shows that the ultrashort pulse can be shaped into the waveform proportional to spectral response of the transfer function $\hat{H}(\omega')$ at $\omega' = t/\ddot{\Phi}_0$. Therefore, by designing the spectral response of shaper or coder with high-enough dispersion, arbitrary temporal pulse waveform can be obtained.

Linearly chirped fiber Bragg gratings are well-known passive devices, whose dispersions and spectra can be synthesized flexibly. In the weak modulation and high-dispersion limit, the grating's spectral response can be linearly mapped by its normalized apodization profile $G(z)$ [14],

$$\hat{H}(\omega')\big|_{\omega' = \Delta\omega_g(z - L/2)/L} = G(z), \tag{3}$$

where $\Delta\omega_g$ denotes as the grating's angular frequency chirp, and L is the grating's length. Form Eq. (2) and Eq. (3), it is shown that arbitrary waveform or code can be achieved by linearly chirped fiber Bragg grating based on a direct space (z) to time (t) mapping.

3 Numerical analyses and discussions

In the following numerical simulations, we focus on pulse shaping and coding for transform-limited Gaussian ultrashort pulse $A(t) = \exp(-t^2/\tau_0^2)$, whose full-width at half maximum (FWHM) is 2 ps and its carrier center wavelength is 1550 nm. LCFBG is synthesized to reshape the input transform-limited ultrashort Gaussian pulse into rectangular or triangular output pulse waveform. Under the weak-coupling condition, the grating modulation is mapped into constant rectangular or triangular apodization profile according to Eq. (3). Fig. 1 and Fig. 2 give the grating's apodization profiles, the grating spectral responses and the corresponding rectangular or triangular temporal output pulse waveforms, respectively.

The grating is designed to coding a train of pulses. In order to generate a train of non-return-zero (NRZ) or return-zero (RZ) codes of 1011, the grating apodization profiles are shown in Fig. 3(a) and Fig. 4(a). According to the coupling-mode theory and the Fourier-transform signal process, the calculated grating spectral responses and the output pulse codes are shown in Fig. 3(b), (c) and Fig. 4(b), (c), respectively.

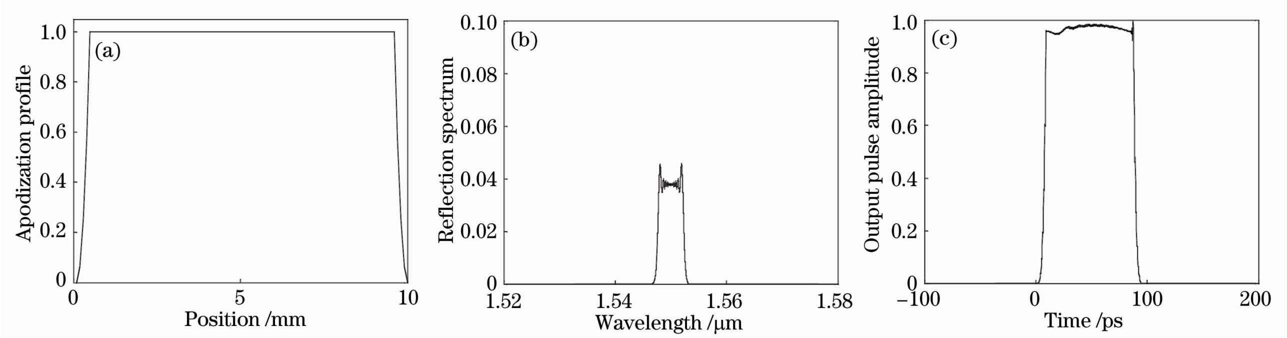

Fig. 1 Pulse shaping for a rectangular output waveform. (a) Grating apodization profile; (b) grating reflection spectral response; (c) output pulse temporal waveform

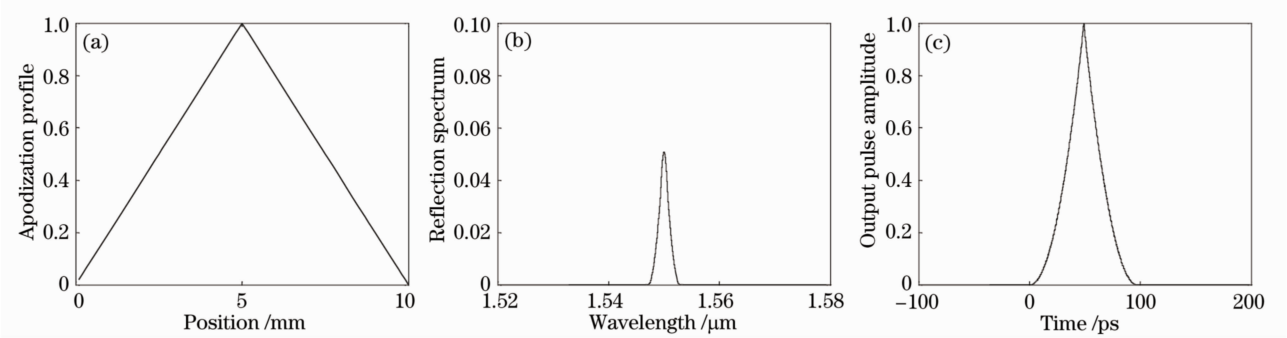

Fig. 2 Pulse shaping for a triangular output waveform. (a) Grating apodization profile; (b) grating reflection spectral response; (c) output pulse temporal waveform

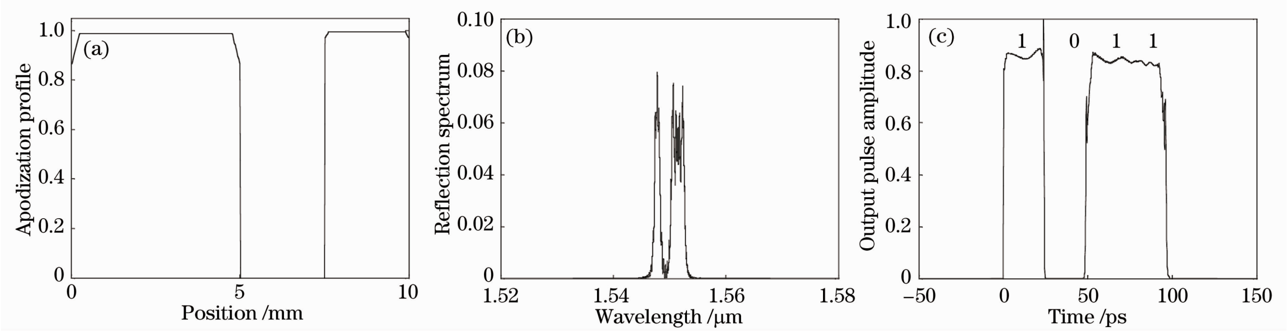

Fig. 3 Pulse coding for NRZ generation. (a) Grating apodization profile; (b) grating reflection spectral response; (c) output NRZ 1011 codes

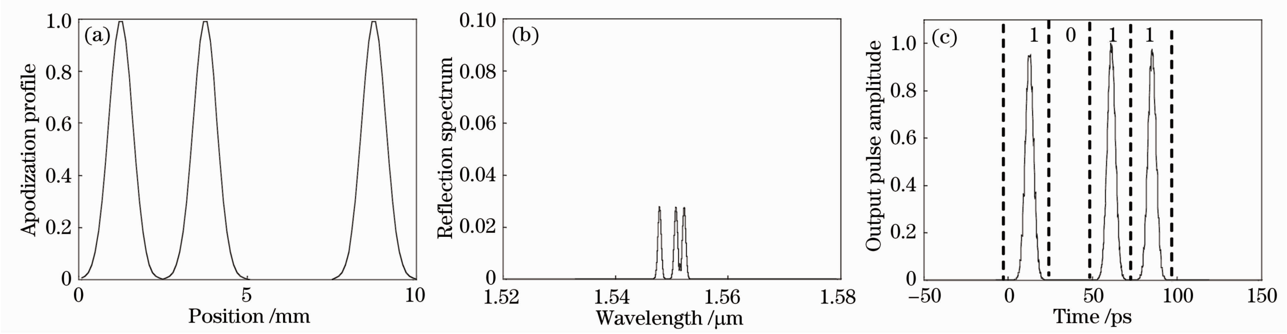

Fig. 4 Pulse coding for RZ generation. (a) Grating apodization profile; (b) grating reflection spectral response; (c) output RZ 1011 codes

4 Conclusions

A simplified signal-transform technique to map the output pulse temporal waveform into the spectral response of the shaper or coder transfer function is utilized. In the weak modulation and high-dispersion limit, the grating′s spectral response is proportional to its normalized apodization profile. Thus, arbitrary customized pulse waveform and code are obtained by flexibly designing the apodization profile of the linearly chirped fiber Bragg grating.

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