Ultrashort optical pulse shaper based on complex-modulated long-period-grating coupler*

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In this paper, we present a novel ultrashort pulse shaper based on complex-modulated long-period-grating coupler (CM-LPGC). Temporal rectangular waveform with 2-ps full width at half maximum (FWHM) is obtained by transforming the input Gaussian pulse. Tolerances of the CM-LPGC-based shaper to various non-ideal excitation conditions and fabricating errors are investigated. Results confirm that CM-LPGC is stable and suitable for optical pulse shaping operation.

Keywords: ultrafast process, optical pulse shaper, complex-modulated long-period-grating coupler, rectangular waveform

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1. Introduction

Pulses on the time scales of picosecond and femtosecond have attracted considerable attention in many applications. The mode-locked lasers have by far been the most common sources of ultrashort pulses. But the temporal shapes generated by mode-locked lasers are typically sech^2 or Gaussian, which are unsuitable for some special applications. For example, an ultrashort pulse with square or rectangular form is highly desirable for a nonlinear optical switching system.[1] In order to obtain a customized optical pulse waveform, pulse shaping and processing technologies are indispensable.[2] The well-known approach is the 4f Fourier transform setup,[3] in which an appropriately designed amplitude or phase mask is used to reshape the spectrum of the incident pulse. However, devices employed by the 4f system are bulky, lossy, and expensive. These have prompted recent efforts to implement the waveguide-based optical shaping elements. For example, shaping filters based on superstructured Bragg gratings[4] or cascaded linearly chirped fiber Bragg gratings[5] have been reported. Compared with submicron-period Bragg grating, long period grating is easy to fabricate in the integrated platform.[6] In addition, long period grating is especially suited for processing pulses with shorter temporal features due to its broader operating bandwidth.[7] Therefore, in this paper, we present a novel ultrashort pulse shaper based on a complex-modulated long-period-grating coupler (CM-LPGC). Both theoretical analysis and numerical calculation about the spectral response and temporal shaping capability are shown in detailed.

2. Structural model and theoretical background

A grating coupler generally consists of two parallel waveguides with different structures as shown in Fig. 1.[8] The concept of a complex-modulated long-period-grating coupler was first proposed by Greenberg and Orenstein.[9] Unlike the conventional long-period-grating-based coupler, besides the real refractive index modulation, optical pumps are used to induce the gain perturbation. Therefore, a complex-modulated long-period grating coupler can be described as[10]

$$\Delta n = \Delta n_r \cos\left(\frac{2\pi}{\Lambda}z\right) - \mathrm{j}\Delta n_i \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right), \tag{1}$$

where Λ is grating period, Δn_r and Δn_i are refractive index and gain ($\Delta n_i > 0$) modulation, respectively, and $\Delta\varphi$ represents the additional phase difference between the real and imaginary parts. Since the modulation has a long-period beat length, the gratings given by Eq. (1) do not excite significant backward fields. The coupled-mode equations describing the slowly varying mode amplitudes can be expressed as

$$\frac{\mathrm{d}c_1}{\mathrm{d}z} = -\mathrm{j}\left[K_{21}^r \cos\left(\frac{2\pi}{\Lambda}z\right) - \mathrm{j}K_{21}^i \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right)\right] c_2 \times \exp\left[-\mathrm{j}(\beta_2 - \beta_1)z\right], \tag{2}$$

$$\frac{\mathrm{d}c_2}{\mathrm{d}z} = -\mathrm{j}\left[K_{12}^r \cos\left(\frac{2\pi}{\Lambda}z\right) - \mathrm{j}K_{12}^i \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right)\right] c_1 \times \exp\left[-\mathrm{j}(\beta_1 - \beta_2)z\right], \tag{3}$$

where β_1 and β_2 are the propagation constants of waveguides 1 and 2, and K_{vu}^r and K_{vu}^i are defined as

$$K_{vu}^r = \frac{\omega}{4}\iint_{\infty}\left[2\varepsilon_0 n \Delta n_r \cos\left(\frac{2\pi}{\Lambda}z\right)\right]\cdot E_v E_u^* \mathrm{d}S = 2k_n \cos\left(\frac{2\pi}{\Lambda}z\right), \tag{4}$$

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$$K_{vu}^{i} = \frac{\omega}{4}\iint_{\infty}\left[2\varepsilon_0 n\Delta n_i \cos\left(\frac{2\pi}{\Lambda}z+\Delta\varphi\right)\right]\cdot E_v E_u^* \,\mathrm{d}S$$
$$= 2k_\alpha \cos\left(\frac{2\pi}{\Lambda}z+\Delta\varphi\right), \quad (5)$$

where k_n and k_α are the real and imaginary coupling coefficients induced by the refractive index modulation or gain/loss perturbation, respectively.

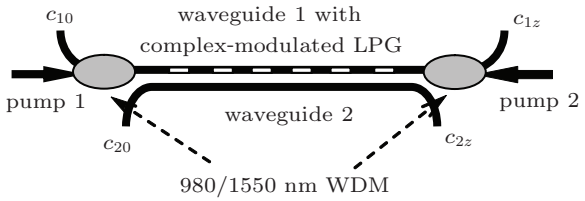


Fig. 1. Ultrashort optical pulse shaper based on complex-modulated long-period-grating-assisted-coupler.

On the assumption that only one input port is excited initially ($c_{10}=1$, $c_{20}=0$) and the additional phase difference $\Delta\varphi=\pi/2$, the closed-formed analytical solutions linking the input and output signals can be obtained as follows:

$$c_{1z} = \left(\cos(\gamma z)+\mathrm{j}\frac{\delta}{\gamma}\sin(\gamma z)\right)\exp(-\mathrm{j}\delta z)c_{10}, \quad (6)$$

$$c_{2z} = -\mathrm{j}\left(\frac{k_n+k_\alpha}{\gamma}\sin(\gamma z)\right)\exp(\mathrm{j}\delta z)c_{10}, \quad (7)$$

where $\gamma=\sqrt{\delta^2+k_n^2-k_\alpha^2}$ with $\delta=\pi/\Lambda-\Delta\beta/2$ as the mismatched phase factor. Taking into consideration the wavelength-dependency of the propagation constants ($\beta_i(\omega)=n_{\mathrm{eff},i}\omega_0/c+n_{g,i}(\omega-\omega_0)/c$, with $n_{\mathrm{eff},i}$ and $n_{g,i}$ used as the effective and group indices of the waveguide i ($i=1,2$), and ω_0 serving as the central angular frequency),[11] the above two equations can also describe the transmission spectral responses of the straight and cross waveguides, respectively. Thus, if an optical pulse $A(t)$ is injected into the CM-LPGC, the temporal response at the output port is the inverse Fourier transform of the product of input pulse spectrum $A(\omega)$ and CM-LPGC transmission spectral response $c_{1z}(\omega)$ or $c_{2z}(\omega)$, i.e.,

$$A_{1z}(t) = \int [A(\omega)c_{1z}(\omega)]\exp(\mathrm{i}\omega t)\,\mathrm{d}\omega, \quad (8)$$

$$A_{2z}(t) = \int [A(\omega)c_{2z}(\omega)]\exp(\mathrm{i}\omega t)\,\mathrm{d}\omega. \quad (9)$$

3. Numerical simulations and discussion

On the basis of the above theoretical analyses, the influences of imaginary perturbation on the power coupling characteristics are investigated first. To comply with contact lithography, InGaAs is used as the waveguide core and InP is adopted as buried cladding. The effective indices of waveguide 1 and waveguide 2 are set to $n_{\mathrm{eff1}}=3.59$ and $n_{\mathrm{eff2}}=3.554$. A grating with period $\Lambda=43$ μm is inscribed, so as to satisfy the phase-matching condition at a wavelength of 1550 nm. When $k_\alpha=0$, that is, a conventional long-period-grating coupler is used, the reciprocal and symmetric power exchange between the two waveguides is exhibited as can be seen from Fig. 2(a). The initial injected power is completely transferred to another waveguide by choosing the coupling length as $L=\pi/2k_n$. Comparatively, when CM-LPGC is used, an obviously different power coupling behavior is shown. Although the two waveguides can still be coupled alternately, the symmetry of transferring power is broken by controlling imaginary perturbation (Figs. 2(b) and 2(c)). In particular, in the case of matched complex-modulation ($k_\alpha=k_n$), the power in cross waveguide 2 will grow quadratically with the coupling length increasing, whereas, the power in straight waveguide 1 remains unaffected. Therefore, a nonreciprocal unidirectional coupling characteristic is achieved.

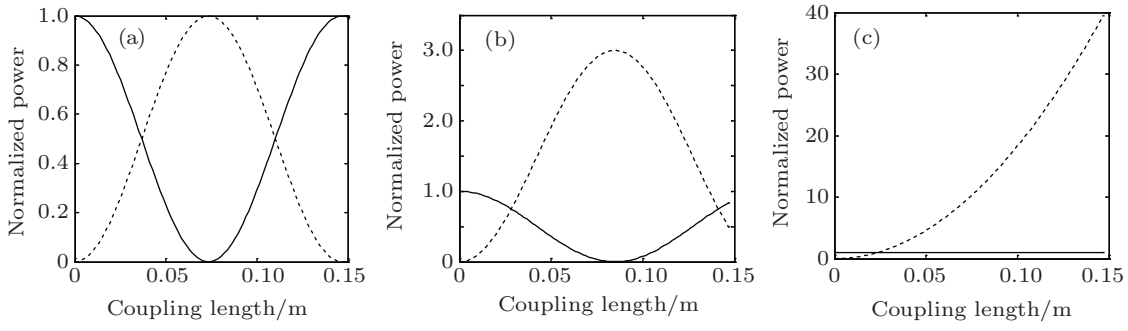


Fig. 2. Influences of imaginary perturbation on the power coupling characteristics. Solid curve: $|c_{1z}|^2$, dotted curve: $|c_{2z}|^2$) for (a) $k_a=0$, $k_n=k$; (b) $k_a=0.5k$, $k_n=k$; (c) $k_a=k_n=k$.

Next, we numerically simulate the pulse shaping capabilities of CM-LPGC with matched complex-modulation. The device length $L=\pi/2k_n$ is chosen so as to achieve complete signal coupling if the imaginary part is removed. A single transform-limited Gaussian pulse $A(t)=\exp(-t^2/\tau_0^2)$ with the central wavelength matching with CM-LPGC is used as the input signal. The spectral response of CM-LPGC is given in Fig. 3. When the full width at half maximum (FWHM) time-width of the input signal is 1 ps, temporal waveforms of the output pulse and the original input pulse are shown in

Fig. 4. The solid line, dashed line, and dotted line denote the output signals from cross waveguide and straight waveguide, and the original input signal, respectively. It can be seen that both the output signals from the two waveguides keep unchanged Gaussian waveforms, due to the bandwidth of input signal being much smaller than the spectral bandwidth of CM-LPGC. However, when an ultrashort Gaussian pulse with FWHM time-width 0.1 ps is injected, the output signal from cross waveguide is reshaped into a rectangular temporal waveform with 2-ps FWHM (Fig. 5). The explanation for this is that the spectrum of an ideal rectangular pulse is a sinc-function, which includes infinite sidelobes with alternating optical phase. In order to obtain fast rise and fall time, an ample number of sidelobes should be retained for the shaped pulses. When an ultrashort optical pulse with much larger spectral width than CM-LPGC is used, the product of $A(\omega)$ and $c_{2z}(\omega)$ equals $c_{2z}(\omega)$ itself. Under the condition of matched complex-modulation ($k_\alpha = k_n$), $c_{2z}(\omega)$ can be approximated by sinc-function around the center angular frequency ω_0 as can be seen from Eq. (7). Therefore, a rectangular waveform is obtained by taking the inverse Fourier transform of sinc-function. However, on the other hand, by retaining a significant number of sidelobes, spectral width of the main resonant peak around ω_0 is reduced, which results in the shaped pulse broadening in the time-domain. This can be solved by optical pulse compression[12] in the future. In addition, the output signal from straight waveguide 1 is not affected. By picking up both the output signals of straight waveguide 1 and cross waveguide 2, undistorted pulse transmission and shaping processing can be achieved simultaneously.

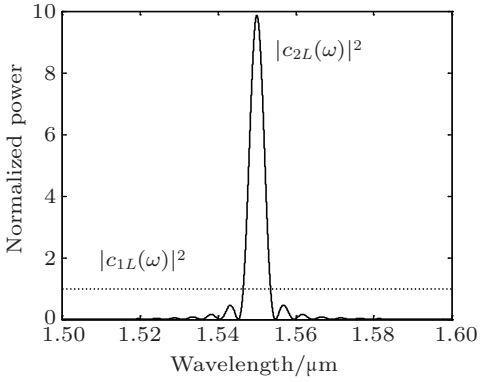


Fig. 3. Spectral response of CM-LPGC with matched complex modulation.

With the above results, the effect of CM-LPGC fabrication errors on the output waveform is numerically examined. As can be seen from Fig. 6, if the condition of matched complex-modulation ($k_\alpha = k_n$) cannot be satisfied, the sharp notch around the pulse center is formed. In the case of extreme mismatch=100% (that is, for conventional LPGC, $k_\alpha = 0$), the notch becomes so deep that two separated pulses can nearly be found. Therefore, if our target output waveform is the rectangular pulse, the tolerable error for the mismatch complex-modulation cannot exceed 5%. In addition, the grating-induced waveguide birefringence should be restrained to avoid shaped pulse distortion.[13]

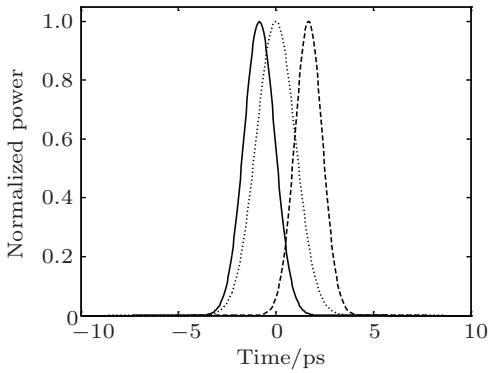


Fig. 4. Temporal output pulses from cross waveguide (solid line) and straight waveguide (dashed line) when original input pulse (dotted line) is 1 ps.

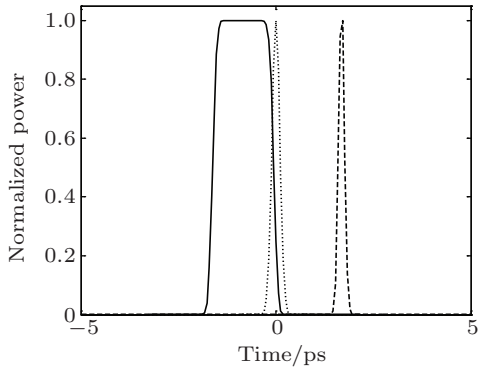


Fig. 5. Temporal output pulses from cross waveguide (solid line) and straight waveguide (dashed line) when original input pulse (dotted line) is 0.1 ps.

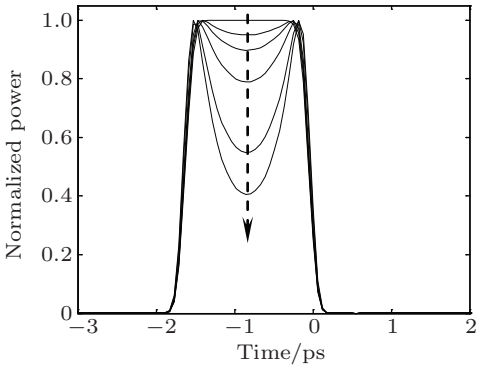


Fig. 6. Effects of the mismatch complex-modulation. Arrow: mismatch=0, 5%, 10%, 20%, 50%, 100% .

Then, we investigate the sensitivity of the shaping operation to a variety of non-ideal optical pulse excitations. When a Gaussian pulse with the central wavelength deviating from the phase-matching wavelength of CM-LPGC is injected, the influence of the wavelength mismatch on the output pulse is shown in Fig. 7. Deformations from the flat-top rectangular waveform are not obvious unless the central wavelength mismatch is greater than 5 nm, which is reasonably more robust than the superstructured-grating-based shaper reported in

Ref. [4]. In addition, since pulses generated by mode-locked laser are generally disturbed by non-ideal Gaussian noise,[14] we examine the output waveform if the input Gaussian signal has some sidelobes. As can be seen from Fig. 8(b), the significant narrowing of the flat-top is exhibited as the sidelobe extends.

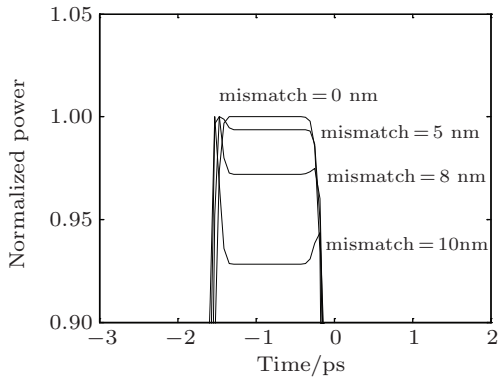


Fig. 7. Influences of central wavelength mismatch on the waveform of output pulse.

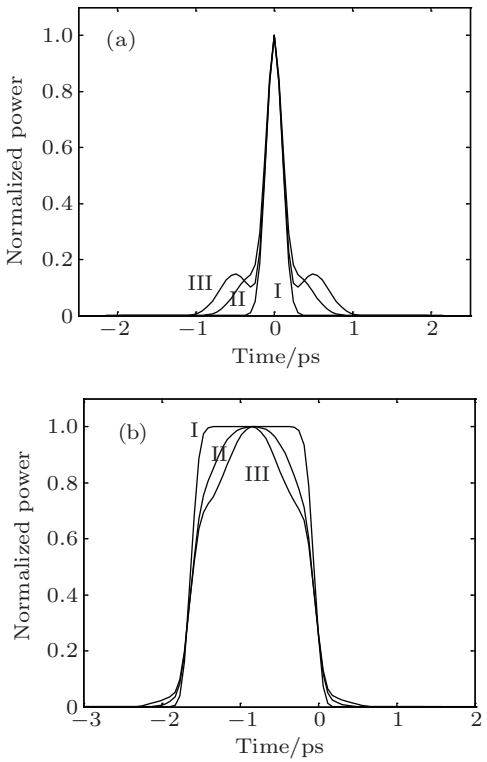


Fig. 8. Normalized powers versus time in the cases that (a) Gaussian pulses with sidelobes are input and (b) pulses deformed from the ideal rectangular waveform are output.

Finally, when the input signal is sequences of multiple Gaussian pulses, the pulse-shaping capability of CM-LPGC is tested numerically. Figure 9 gives the output signals for different time intervals of the input pulse sequences. The feasibility is confirmed as long as the time interval of neighboring pulses is not smaller than twentyfold FWHM of the single pulse.

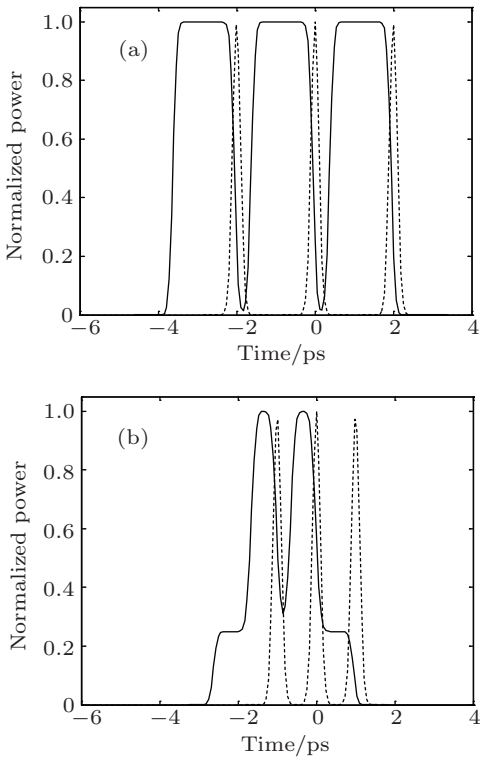


Fig. 9. Output waveforms (solid line) for the input Gaussian pulse sequences (dotted line) with time intervals of 2 ps (a) and 1 ps (b).

4. Conclusions

In this paper, we numerically investigated the power coupling behaviors and ultrashort pulse propagating characteristics of CM-LPGC. The pulse shaping capability of CM-LPGC is confirmed and temporal rectangular waveform is achieved by transforming the input Gaussian pulse. In addition, the sensitivity of the shaping operation to a variety of non-ideal excitation conditions and fabricating errors are examined. Results demonstrate that CM-LPGC is stable and suitable for ultrashort optical pulse shaping application.

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