OPTOELECTRONICS LETTERS Vol.8 No.6, 1 November 2012

All-optical buffer and shaper based on complex-modulated long-period-grating coupler and self-closed fiber loop*

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(Received 8 June 2012)

We propose a novel all-optical buffer and shaper based on the adjustable power transferring characteristics of the complex-modulated long-period-grating coupler (CM-LPGC) and the multiple circulations of the self-closed fiber loop. By turning on the external optical pumps, the signals can be stored by utilizing the nonreciprocal power transferring of the CM-LPGC. When the buffer time is satisfied, the signals can be extracted discretionarily by turning off the external optical pumps. In addition, by controlling the spectral bandwidth of the CM-LPGC, the temporal rectangular pulse can be obtained by reshaping the Gaussian input signal.

Document code: A **Article ID:** 1673-1905(2012)06-0418-4
DOI 10.1007/s11801-012-2286-6

Optical buffer is one of the most important technologies for the realization of high-speed all-optical networks[1]. They can be used for contention resolution and rate conversion. Optical buffers are conventionally made of variable delay lines[2]. But these architectures require multiple switches to connect the delay lines, which increases the physical size and the cost of overall system badly. Contrastively, optical buffers based on recirculating or regenerative fiber loops are compact[3]. And the maximum storage time as long as 50 μs has been reported[4]. However, in order to store the data into the loop or extract them out of the loop, some controllable switches or logic gates are needed[5]. In addition, due to the buffer time is directly proportional to the number of optical circulations, power and waveform of the output signals are degraded as the storage time increasing[6]. Therefore, recent efforts have been focused on designing and fabricating high-quality optical buffers with pulse reshaping capability. In this paper, we propose a novel all-optical buffer and shaper, in which the controllable optical delay mechanism is employed, and the output pulse waveform is adjusted discretionarily.

Fig.1 illustrates the structure of the proposed optical buffer and shaper, which is based on the complex-modulated long-period grating coupler (CM-LPGC) and self-closed fiber loop. The CM-LPGC is formed by inscribing a complex-modulated long-period grating into two unequal parallel waveguides. Due to the propagating constants of the two waveguides are mismatched, a grating with periodical modulation can facilitate the power coupling. According to the definition given in Ref.[7], a complex-modulated grating with the simultaneous modulation on real refractive index and imaginary gain/loss perturbation can be described as

$$\Delta n = \Delta n_{\mathrm{r}} \cos(\frac{2\pi}{\Lambda} z) - \mathrm{j}\Delta n_{\mathrm{i}} \cos(\frac{2\pi}{\Lambda} z + \Delta\varphi) \ , \tag{1}$$

where Λ is grating period. Δn_{r} and Δn_{i} are refractive index and gain ($\Delta n_{\mathrm{i}}>0$) or loss ($\Delta n_{\mathrm{i}}<0$) modulation, respectively. $\Delta\varphi$ represents the additional phase difference between the real part and imaginary part. Since the modulation has a long-period beat length, the grating given by Eq.(1) doesn't excite significant backward fields. Therefore, the coupled-mode equations of the CM-LPGC can be obtained after a series of complicated operations as

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

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

where β_1 and β_2 are the propagation constants of waveguide 1 and 2, and K_{vu}^{r} and K_{vu}^{i} (v, u = 1 or 2) are defined as

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* This work has been supported by the National Natural Science Foundation of China (Nos.61007007, 11002018 and 61101110).

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

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

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

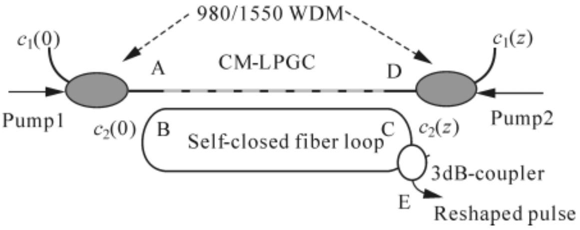


Fig.1 Optical buffer and shaper based on CM-LPGC and self-closed fiber loop

With the assumption that the additional phase difference $\Delta\varphi=\pi/2$ and only one input port is excited initially, the closed-form analytical solutions of the above coupled-mode equations can be obtained by taking the second differential c_1'' of Eq.(2) and eliminating c_2 and c_2' according to Eq.(3).

When the waveguide 1 is excited, which means that the initial condition is $c_1(0)=1$ and $c_2(0)=0$, the outputs from the waveguide 1 and waveguide 2 can be expressed as

$$c_1(z)=\left[\cos(\gamma z)+\mathrm{j}\frac{\delta}{\gamma}\sin(\gamma z)\right]\exp(-\mathrm{j}\delta z) \ , \tag{6}$$

$$c_2(z)=-\mathrm{j}\left[\frac{k_n+k_\alpha}{\gamma}\sin(\gamma z)\right]\exp(\mathrm{j}\delta z) \ . \tag{7}$$

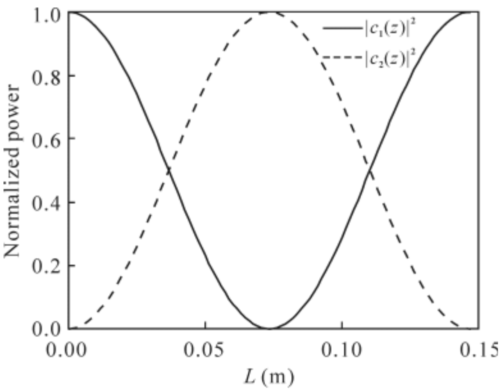
Similarly, when the waveguide 2 is excited initially ($c_1(0)=0$, $c_2(0)=1$), the outputs can be expressed as

$$c_1(z)=-\mathrm{j}\left[\frac{k_n-k_\alpha}{\gamma}\sin(\gamma z)\right]\exp(-\mathrm{j}\delta z) \ , \tag{8}$$

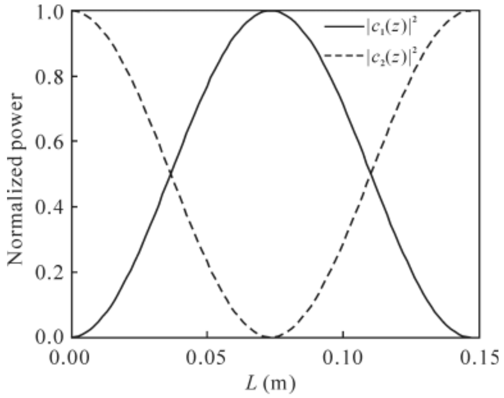
$$c_2(z)=\left[\cos(\gamma z)-\mathrm{j}\frac{\delta}{\gamma}\sin(\gamma z)\right]\exp(\mathrm{j}\delta z) \ , \tag{9}$$

where $\gamma=\sqrt{\delta^2+k_n{}^2-k_\alpha{}^2}$ with $\delta=\pi/\Lambda-(\beta_1-\beta_2)/2$ as the phase-mismatch factor.

Based on the theoretical analyses above, the power coupling characteristics of the CM-LPGC are investigated firstly. When $k_\alpha=0$, i.e., a conventional long-period grating without the gain/loss modulation is inscribed into the coupler, the normalized output powers of $|c_1(z)|^2$ and $|c_2(z)|^2$ varying with the coupling length are depicted in Fig.2. It can be seen that the reciprocal and symmetric power exchanges can be achieved regardless of which waveguide is initially excited. By choosing the proper coupling length as $L=\frac{\pi}{2k_n}$, signals at port A (or port B) can be transferred into port C (or port D). Contrastively, when the complex-modulated long-period grating with matched perturbation of refractive index and gain/loss ($k_\alpha=k_n$) is used, an obviously different power coupling behavior is shown. As can be seen from Fig.3, when the waveguide 1 is initially excited, the power in the cross waveguide 2 can grow quadratically as the coupling length increasing. Whereas, if the waveguide 2 is initially excited, the power exchanging behavior is checked, and the output power in the cross waveguide remains zero. Therefore, a nonreciprocal unidirectional coupling characteristic is shown by the matched CM-LPGC[8]. The signals injected into port A can be transferred to port C. But the signals injected into port B can not

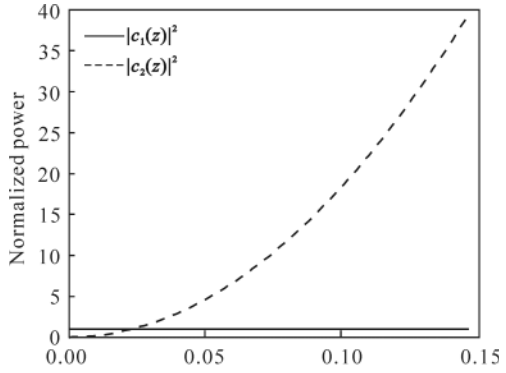


(a) Signals injected into port A of waveguide 1

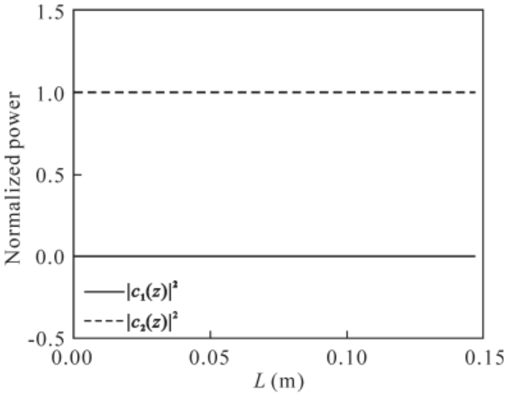


(b) Signals injected into port B of waveguide 2

Fig.2 Power coupling characteristics of the CM-LPGC without gain/loss modulation ($k_\alpha=0$)



(a) Signals injected into port A of waveguide 1



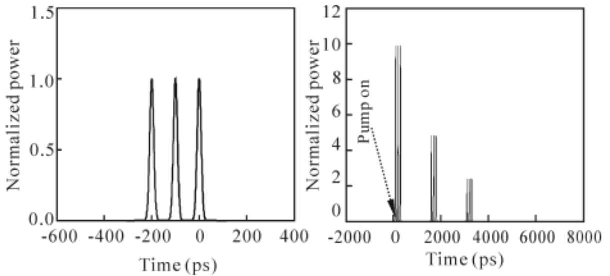
(b) Signals injected into port B of waveguide 2

Fig.3 Power coupling of the CM-LPGC with matched gain/loss and refractive index modulation (k_α=k_n)

be transferred to port D.

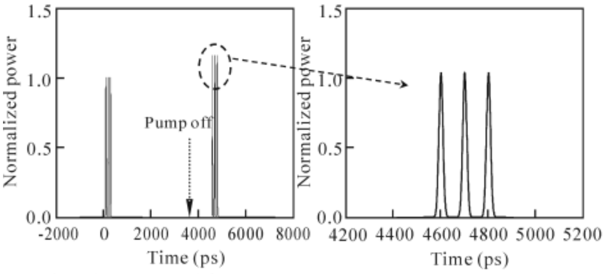
Due to the gain/loss can be controlled accurately by introducing external optical pumps[9], the power coupling behavior of CM-LPGC can be adjusted flexibly. Taking advantage of the adjustable coupling characteristics, a novel optical signal buffer and shaper is constructed by connecting the output port C with the input port B of waveguide 2. When the external optical pumps are turned on, and the induced gain is matched with the refractive index modulation (k_α= k_n), the CM-LPGC performs the nonreciprocal coupling. Signals injected into port A are transferred to port C. After one roundtrip along the self-closed fiber loop, the signals arrive at port B. Due to the cross-coupling is prohibited, the signals cannot be transferred to port D. Therefore, the signals are stored and circulated within the self-closed fiber loop. When the buffer time is satisfied, the signals can be extracted discretionarily by turning off the external optical pumps (k_α= 0). The symmetric reciprocal power coupling operation enables the signals at port B to be transferred to port D.

In order to verify the feasibility of optical buffering operation based on CM-LPGC, three Gaussian pulse signals with spectral width much smaller than that of the CM-LPGC are injected into port A, as shown in Fig.4(a). By turning on the optical pump, the signals are stored. Fig.4(b) gives the signals after circulating two roundtrips. When the optical pumps are turned off, the stored signals are extracted from port D, as depicted in Fig.4(c). Fig.4(d) gives the output signals with zoomed time-axis.



(a) Input signals at port A

(b) Signals stored in the self-closed loop when the pumps are turned on



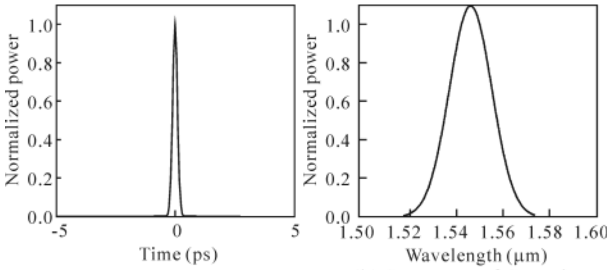
(c) Signals extracted from port D when the pumps are turned off

(d) Output signals with zoomed time-axis

Fig.4 Buffering performance of the CM-LPGC

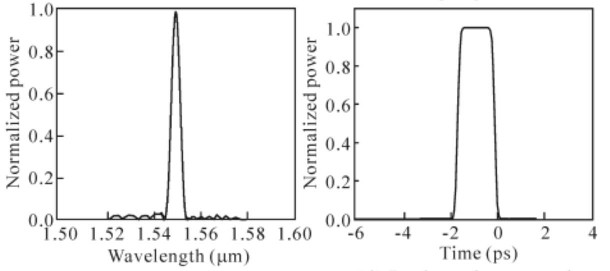
In addition, in some special applications, pulses with temporal Gaussian waveform are unsuitable. For example, pulses with square or rectangular waveform are highly desirable for nonlinear optical switching system[10]. In order to obtain a customized optical pulse waveform, pulse shaping and processing technologies have attracted considerable attention. Compared with submicron-period Bragg grating, long period grating is specially suited for processing pulse with shorter temporal feature due to its broader operating bandwidth[11]. By adjusting the relative bandwidth of the CM-LPGC with the input signal, the Gaussian input pulse can be shaped into rectangular temporal waveform. As can be seen from Fig.5, when an ultrashort Gaussian pulse with FWHM time-width of 0.1 ps is injected, a reshaped rectangular pulse is output from port E by adding a wideband 3 dB-coupler.

In this paper, we numerically investigate the power coupling behaviors of CM-LPGC. Results demonstrate that when the gain perturbation is removed, the symmetrical reciprocal coupling is obtained. Whereas, if the gain perturbation is matched with the refractive index modulation, the unidirectional nonreciprocal coupling is exhibited. By adjusting the external optical pump and controlling the gain perturbation,



(a) Gaussian input pulse at port A

(b) Spectrum of Gaussian input pulse



(c) Spectral response of CM-LPGC

(d) Reshaped rectangular output pulse at port E

Fig.5 Pulse reshaping performance of the CM-LPGC

a novel all-optical buffer and shaper is exploited by combining the CM-LPGC with a self-closed fiber loop. And the buffering capability is validated by storing Gaussian input pulses with two circulations. In addition, by adjusting the relative bandwidth of the CM-LPGC with the input signal, an ultrashort Gaussian input pulse is shaped into rectangular temporal waveform. This novel all-optical buffer and shaper can find promising applications in future all-optical networks.

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