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Programmable wavelength-tunable second-order optical temporal differentiator based on a linearly chirped fiber Bragg grating and a digital thermal controller

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We proposed and experimentally demonstrated an all-fiber structured wavelength-tunable second-order optical temporal differentiator based on a linearly chirped fiber Bragg grating and a digital-controlled thermal array. The central frequency of the differentiation can be reconfigured from 192.141 to 192.616 THz by a programmable circuit. In the experiment, a second-order differentiator with 3 dB bandwidth of 0.086 THz is achieved with a root mean square error of 4.89%. © 2014 Optical Society of America

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All-optical circuits for signal processing and communication could overcome the inherent electronic bottleneck of increasing operation speed and bandwidth in ultrafast communication systems [1]. As one of the basic building blocks, optical temporal differentiators (OTDs) that can provide real-time derivation in the optical domain have attracted considerable interest during the past few years due to their potential in the future all-optical information processing systems [2–4].

Several schemes of OTDs have been previously proposed and experimentally demonstrated. OTDs were realized by utilizing π phase shift fiber Bragg gratings (PS-FBGs) [5,6], long-period fiber gratings (LPFGs) [1], an interferometer [4,7], spatial diffraction and a liquid crystal modulation-based programmable optical pulse shaper [8], a silicon-based microring resonator [9], and so forth. A temporal differentiator can also be obtained based on cross-gain modulation in a semiconductor optical amplifier (SOA) [10]. Generally, all the OTDs can be mainly classified into two categories, namely field differentiators and intensity differentiators [4–7]. Among all the above methods, fiber gratings filter-based field differentiators are of great convenience due to the all-fiber structure and are naturally compatible with optical fiber communication systems. What's more, they present negligible insertion loss and low costs thus are favorable for applications. However, all previous fiber-grating-based differentiators fixed bandwidth at a certain wavelength for differentiation operation. Wavelength-tunable differentiators have potential applications in wavelength-division multiplexing (WDM) systems and flex-grid-supported optical networks. To accomplish a wavelength-tunable differentiator for various optical pulses at different wavelengths, an arbitrarily program-

mable optical filter is required to configure the spectrum characteristics flexibly.

Recently, we proposed and demonstrated an all-fiber structured bandwidth-tunable and wavelength-variable optical filter based on a linearly chirped fiber Bragg grating (LCFBG) and a thermal printhead (TPH) [11]. With its reconfigurable filtering performance, this all-fiber waveshaper technology is ideal to perform temporal differentiation operation for incoming optical pulses with any given central wavelength.

In this Letter, by utilizing our developed digitally controlled waveshaper, we experimentally demonstrate a wavelength-tunable second-order OTD with a suitable pulse width. To the best of our knowledge, this is the first time to implement a reconfigurable OTD based on a LCFBG and a TPH.

An N th-order OTD ($N = 1, 2, \dots$) provides the N th time derivative of the complex envelope of an input optical signal waveform [12]. In principle, an N th-order OTD can be obtained by concatenating N first-order OTDs, however, this method will result in much less energy efficiency (the ratio between the output pulse energy and the input pulse energy) and increased implementation complexity [13,14]. We assume that the complex envelope of an input optical signal is $u_{in}(t)$, and the corresponding optical field is $U_{in}(\omega - \omega_0)$, where ω and ω_0 are the optical frequency variable and the central optical frequency of the input signal, respectively. The N th time derivative of the complex envelope is mathematically described as $\partial^N u_{in}(t)/\partial t^N$, and the differentiated signal in the frequency domain can be expressed as $[j(\omega - \omega_0)]^N U_{in}(\omega - \omega_0)$ [14,15]. Therefore, an N th-order OTD can be realized through a filter providing a spectral transfer function in the form

Fig. 1. Experimental setup of the proposed OTD.

of $H_N(\omega) \propto [j(\omega - \omega_0)]^N$. It can be easily seen that only the optical signal's amplitude needs to be modified for even-order differentiators ($N = 2, 4, \dots$).

The proposed experimental system for second-order differentiator is illustrated in Fig. 1. A mode-locked fiber laser (MLFL) is used to generate an ultrashort optical pulse with a repetition frequency of 558 MHz and a pulse-width of 1.2 ps. In order to obtain a Gaussian pulse with well-defined bandwidth as the input signal, a wave-shaper produced by Finisar is employed to carve the MLFL-generated soliton spectrum. The output of the differentiator is measured by an optical spectrum analyzer (OSA) (Ando, AQ6371B), which has a best resolution of 0.01 nm. The inset in Fig. 1 shows the block diagram of the constructed second-order OTD. For programmable thermo-optic filtering, a TPH is connected to a program-controlled circuit, which can configure the heating elements array dynamically. The purpose of placing a heat sink is to alleviate the unwanted heat diffusion and improve the stability.

Any standard TPH has a program-controlled heating elements array and each element can work independently. The TPH used in this work is FTP-628MCL701 manufactured by Fujitsu. The heating array consists of 384 heating elements, its total length and the element pitch are 48 and 0.125 mm, respectively. The heating configuration is controlled by a 384-bit serial data, each bit determines the heating state of the corresponding heating element.

A piece of 1.5 cm long LCFBG is fixed tightly with the heating element array, as shown in Fig. 2 [11]. A notch filter having a transfer function of a second-order differentiator can be implemented with this method. As the local Bragg wavelength changes linearly with position along the LCFBG axis, wavelength-tunable notch filtering can be obtained by controlling the corresponding local heating elements. When an input signal with optical carrier wavelength is located right within the notch, the optical pulse will be differentiated.

To measure the transmission of the LCFBG, a SOA is used as the broadband light source. The transmission spectrum of the LCFBG without heating is illustrated in Fig. 3(a) (red line). When two local regions (with widths of 1.000 and 1.375 mm, respectively) of the

Fig. 2. Schematic diagram of the proposed OTD.

Fig. 3. (a) Transmission spectrum of the LCFBG. (b) Transfer functions of a second-order differentiator.

LCFBG with 1.000 mm separation are heated simultaneously, two notches are obtained within the stop band of the LCFBG, as shown in Fig. 3(a) (blue line). It is worth noting that the purpose of heating two local regions simultaneously for one channel differentiation is to keep balance on both sides of the differentiator notch. Only one heated region will result in that the short-wavelength edge of the notch is much higher than the long-wavelength. It can be seen that the normalized amplitude (absolute value) transmission spectrum corresponding to the short-wavelength notch (blue line) coincides well with the ideal transfer function of a second-order differentiator (red line), as shown in Fig. 3(b). The center of the ideal transfer function is located at 192.561 THz.

Figure 4(a) shows the original optical spectrum of the optical pulse generated by the MLFL. A preshaper (Finisar, WaveShaper 4000s) is used to modify the spectrum of the MLFL output into a Gaussian shape with suitable bandwidth. The central frequency and 3 dB bandwidth of this Gaussian pulse are 192.561 and 0.086 THz, respectively, as shown in Fig. 4(b). Since the time-bandwidth product of a transform-limited Gaussian optical pulse is 0.441, the corresponding temporal full width at half-maximum (FWHM) of the filtered pulse after the preshaper is approximately 5.13 ps. As the input optical signal, the Gaussian pulse is directed

Fig. 4. Spectrum of the optical pulse. (a) The initial MLFL output. (b) Optical pulse filtered by the pre-shaper.

Fig. 5. Normalized output pulse spectrum of the OTD.

Fig. 6. Waveforms of the optical pulses.

to the designed differentiator. Figure 5 shows the normalized transmission spectrum (intensity) of the signal after transmitting through the differentiator. The energy efficiency of our proposed differentiator is measured to be 3.23%, which is relatively higher than that of previously published second-order OTD schemes [7,13].

Through inverse Fourier transform, the input optical pulse and output differentiated optical pulse in the time domain can be obtained, as shown in Fig. 6 with the dashed blue line and solid red line, respectively. For comparison, the ideal second-order differentiation of the input optical pulse is also illustrated in Fig. 6 with a solid blue line. The root mean square error (RMSE) between the experimental time-domain-differentiated pulse and the ideal second-order differentiation is about 4.89%, which indicates that the accuracy of the proposed second-order differentiator is satisfied.

To further investigate the systematic OTD errors of our system, we measured the output spectrum and recover the corresponding temporal waveform for an input Gaussian pulse located at 192.561 THz with different 3 dB bandwidth from 0.062 to 0.110 THz, by keeping the same heating configurations. Meanwhile, the ideal second-order time derivative of the input pulse with different bandwidth is calculated for comparison. Figure 7 shows the relationship between the obtained RMSE and the 3 dB bandwidth of the input pulse. As can be seen, there exists an optimal operation bandwidth (0.086 THz) for the designed second-order OTD, where the root RMSE is minimized to ~4.89%. The performance

Fig. 7. Processing error as a function of the 3 dB bandwidth of the input pulse

Fig. 8. Relationship between the notch center and the heating position.

Fig. 9. Transmission spectra of the notches with three different heating positions.

of the designed second-order OTD degrades significantly when the input pulse bandwidth is less than 0.08 THz.

Keeping the heating widths and the separation between the two heated local regions unchanged, the heated positions are scanned along the LCFBG axis over a distance of 2.625 mm in a step of 0.125 mm without moving any components. The obtained central frequency of the notch ranges from 192.141 to 192.616 THz and can be well-fitted with a linear relationship, as shown in Fig. 8. The slope of the linear fitting is about -0.19 THz/mm. Figure 9 shows the transmission spectrum of the notch with different heating configurations. It can be seen that the shapes of the three notches match the ideal transfer function of a second-order differentiator well, which

indicates that a wavelength-tunable second-order OTD can be realized with good stability. It is worth noting that the notch shown in Fig. 3(b) corresponds to the notch with the heating position of 5.875 mm in Fig. 9.

In conclusion, we have proposed and experimentally demonstrated a programmable wavelength-tunable second-order OTD based on a LCFBG and a TPH. The optimal RMSE and the energy efficiency of the second-order temporal differentiation are 4.89% and 3.23%, respectively, under the condition that the 3 dB bandwidth of the input optical Gaussian pulse is 0.086 THz. The central frequency of the differentiator can be reconfigured flexibly from 192.141 to 192.616 THz by a program-controlled circuit.

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References

1. R. Slavik, Y. Park, M. Kulishov, R. Morandotti, and J. Azaña, *Opt. Express* **14**, 10699 (2006).
2. C. Cuadrado-Laborde and M. V. Andrés, *Opt. Lett.* **34**, 833 (2009).
3. L. M. Rivas, K. Singh, A. Carballar, and J. Azaña, *IEEE Photon. Technol. Lett.* **19**, 1209 (2007).
4. J. Dong, A. Zheng, D. Gao, L. Lei, D. Huang, and X. Zhang, *Opt. Express* **21**, 7014 (2013).
5. M. Li, D. Janner, J. Yao, and V. Pruneri, *Opt. Express* **17**, 19798 (2009).
6. N. K. Berger, B. Levit, B. Fischer, M. Kulishov, D. V. Plant, and J. Azaña, *Opt. Express* **15**, 371 (2007).
7. Y. Park, J. Azaña, and R. Slavík, *Opt. Lett.* **32**, 710 (2007).
8. J. Dong, Y. Yu, Y. Zhang, B. Luo, T. Yang, and X. Zhang, *IEEE Photon. Technol. Lett.* **3**, 996 (2011).
9. F. Liu, T. Wang, L. Qiang, T. Ye, Z. Zhang, M. Qiu, and Y. Su, *Opt. Express* **16**, 15880 (2008).
10. J. Xu, X. Zhang, J. Dong, D. Liu, and D. Huang, *Opt. Lett.* **32**, 1872 (2007).
11. H. Zhang, M. Tang, Y. Xie, H. Liao, S. Fu, P. P. Shum, and D. Liu, *Appl. Phys. B* **112**, 479 (2013).
12. N. Q. Ngo, S. F. Yu, S. C. Tjin, and C. H. Kam, *Opt. Commun.* **230**, 115 (2004).
13. L. M. Rivas, S. Boudreau, Y. Park, R. Slavik, S. LaRochelle, A. Carballar, and J. Azana, *Opt. Lett.* **34**, 1792 (2009).
14. M. Kulishov and J. Azaña, *Opt. Express* **15**, 6152 (2007).
15. M. Kulishov, D. Krcmarík, and R. Slavík, *Opt. Lett.* **32**, 2978 (2007).