Multichannel Arbitrary-Order Photonic Temporal Differentiator for Wavelength-Division-Multiplexed Signal Processing Using a Single Fiber Bragg Grating

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***Abstract*—A multichannel photonic temporal differentiator implemented based on a single multichannel fiber Bragg grating (FBG) for wavelength-division-multiplexed (WDM) signal processing is proposed for the first time to our knowledge. The multichannel FBG is designed using the discrete layer peeling (DLP) algorithm together with the spatial sampling technique. Specifically, the DLP algorithm is used to design the spectral response of an individual channel, while the spatial sampling is employed to generate a multichannel response. The key feature of the proposed temporal differentiator is that WDM signals at multiple optical wavelengths can be simultaneously processed. Two sampling techniques, the phase-only and the amplitude-only, are employed. The use of the phase-only sampling technique to design a 45-channel first-order and second-order temporal differentiator is performed, and the use of the amplitude sampling technique to design a 3-channel first-order and second-order temporal differentiator is also performed. A proof-of-concept experiment is then carried out. A 3-channel first-order differentiator with a bandwidth of 33.75 GHz and a channel spacing of 100 GHz is fabricated. The use of the fabricated 3-channel FBG to perform first-order temporal differentiation of a 13.2-GHz Gaussian-like optical pulse with different optical carrier wavelength is demonstrated.**

***Index Terms*—Multichannel, photonic differentiator, photonic signal processing, sampled fiber Bragg grating, wavelength-division-multiplexed network.**

I. Introduction

In the past few years, with the rapid development of photonics technology, the implementation of basic signal processing functions in the optical domain has attracted great interests. Compared with a pure electronic temporal operator, a photonic temporal operator implemented in the optical domain would provide a much higher speed and wider bandwidth [1]. A few fundamental photonic signal processing operators and transformers, such as photonic temporal differentiators [2]–[10], integrators [11], [12] and Hilbert transformers [13]–[15], have been theoretically designed or practically realized.

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A temporal photonic differentiator is a basic operator that performs real-time differentiation of an optical signal in the optical domain [2], which can find applications in numerous fields such as ultrafast signal generation [16] and pulse characterization [17]. In general, a photonic temporal differentiation can be realized using an optical device that has a transfer function with the form $[j(\omega-\omega_0)]^N$, where N is the differentiation order, ω is the optical frequency and ω_0 is the optical carrier frequency of the optical signal. A temporal differentiator can be realized based on cross-gain modulation in a semiconductor optical amplifier (SOA) [3]. A temporal differentiator can also be realized using a π phase shifted fiber Bragg grating (PS-FBG) [4]–[6], a tilted fiber Bragg grating (TFBG) [7], or a long period fiber grating (LPFG) [8], [9]. A temporal differentiator can also be implemented based on a silicon micro-ring resonator [10].

A fiber-grating-based temporal differentiator has the intrinsic advantages such as simple structure and good compatibility with other fiber-optic devices. Different temporal differentiators based on a fiber grating have been proposed, however, the channel number is always one. A multichannel temporal differentiator could be used to improve the bandwidth capabilities in signal-processing platforms in a similar manner to that widely proved for optical telecommunication systems.

For ultrafast signal processing and characterization in a wavelength-division-multiplexed (WDM) network, an all-optical differentiator that can perform temporal differentiation of multichannel signals carried by multiple wavelengths is required. Recently, multi-channel optical differentiators have been proposed and demonstrated based on the use of optical interferometers. The response of an interferometer is intrinsically periodic in frequency. This fact has been exploited for the measurement and characterization of multi-wavelength high-speed signals in the context of WDM communications [18]. The main limitation of this solution is the instability due to the high sensitivity of an interferometer to environmental fluctuations. The other solution is to use multiple independent differentiators based on multiple fiber gratings, but at a high cost.

In this paper, a multichannel arbitrary-order photonic temporal differentiator based on a multichannel FBG is proposed and demonstrated for the first time to the best of our knowledge. The multichannel FBG is designed based on the discrete layer peeling (DLP) algorithm [19] together with the spatial sampling technique [20]–[22]. That is, the spectral response of an individual channel is designed by using the DLP algorithm, while the multichannel response is generated through spatial sampling. A preliminary study of the technique has recently been presented by us in [23], a detailed analysis, such as the design of a multichannel second-order photonic differentiator and the limitation of the proposed approach, has not been addressed. In this paper, a 45-channel first-order and second-order differentiator are designed based on the phase-only sampling technique. A 3-channel first-order and second-order differentiator based on the amplitude-only sampling technique are also designed. As a proof-of-concept experiment, the designed 3-channel temporal first-order differentiator with a channel spacing of 100 GHz is fabricated and its function as a multichannel temporal differentiator is experimentally demonstrated. The proposed multichannel photonic differentiators have important applications in the characterization of optical pulses in WDM systems.

II. Principle

An Nth-order temporal differentiator can be implemented by using an FBG that provides a transfer function of the form given by $[j(\omega-\omega_0)]^N$. Recently, a single-channel arbitrary-order photonic temporal differentiator has been designed with the DLP algorithm based on the desired phase and magnitude responses [6]. The design strategy of a single-channel temporal differentiator in this paper is the same as the one employed in [6]. Mathematically, the designed index modulation $n_s(z)$ of a single-channel photonic differentiator can be written as

$$n_s(z) = \mathrm{Re}\left\{\frac{\Delta n(z)}{2}\exp\left\{i\left[\frac{2\pi z}{\Lambda}+\phi_g(z)\right]\right\}\right\}, \quad (1)$$

where z is the position along the grating, and $\Delta n(z)$ denotes the maximum index modulation, Λ and $\phi_g(z)$ are the central pitch and the local phase of the single-channel seed grating, respectively.

A multichannel photonic temporal differentiator can be achieved using a single FBG with spatial sampling. The theory of spatial sampling is introduced as follows. In general, a sampled FBG is a grating with its index profile modulated along the fiber by a periodic sampling function $s(z)$, which can be expressed as

$$s(z) = \sum_{m=-\infty}^{\infty} g(z-mP), \quad (2)$$

where P is the period of the sampling function, $g(z)$ is the sampling function in one period. The sampling period P is determined by the required neighboring channel spacing $\Delta\omega$, which is, according to (2), $\Delta\omega = c\pi/n_{\mathrm{eff}}P$, where n_{eff} is the effective refractive index of the fiber core, and c is the light velocity in vacuum. For a sampled FBG with a central wavelength of 1550 nm, an effective refractive index $n_{\mathrm{eff}} \approx 1.45$ and a channel spacing 100 GHz, the sampling period is $P \approx 1$ mm. By using an optimization algorithm such as the simulated annealing algorithm (SAA) [24] and the genetic algorithm (GA) [25], the sampling function can be optimized to best fit the desired frequency response. For example, to design an FBG with $2M+1$ channels and all channels have an identical magnitude response, the Fourier transform of the sampling function within the $2M+1$ channels can be expressed as $S(\omega) \propto \sum_{m=-M}^{M}\delta(\omega-m\Delta\omega)$, where δ is the Dirac delta function.

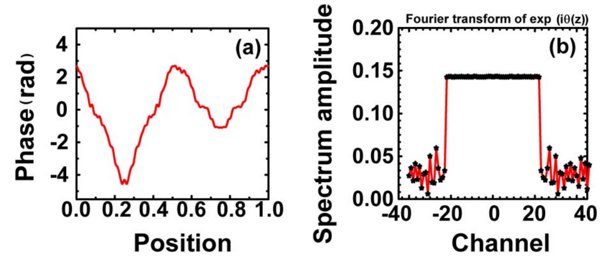

Fig. 1. A 45-channel continuous phase-only sampling function in one period and its spectrum. (a) The phase distribution, and (b) the spectrum.

When the index modulation of a single-channel FBG is modulated by a sampling function, the index modulation of the sampled FBG is expressed as [20], [21]

$$n(z) = \mathrm{Re}\left\{\frac{\Delta n(z)}{2}\times\exp\left\{i\left[\frac{2\pi z}{\Lambda}+\phi_g(z)\right]\right\}\times s(z)\right\}. \quad (3)$$

Based on the first-order Born approximation for the spectrum design of an FBG, the Fourier transform of the index modulation of the FBG represents its reflection spectrum. From (3), we have

$$r_M(\omega) \propto r_s(\omega) * \sum_{m=-M}^{M}\delta(\omega-m\Delta\omega), \quad (4)$$

where $r_s(\omega)$ is the reflection spectrum of a single channel, and $r_M(\omega)$ is reflection spectrum of a sampled FBG, and $*$ denotes the convolution operation.

From (4), it can be seen that a multichannel arbitrary-order photonic temporal differentiator can be realized based on a single FBG, when the index modulation of the single-channel seed grating is modulated by a periodic sampling function $s(z)$. In this paper, two sampling techniques, the phase-only and the amplitude-only, are applied to achieve a multichannel photonic temporal differentiator.

III. Design

A. Based on Phase-Only Sampling

To verify the above proposal, a 45-channel first-order and second-order photonic temporal differentiator is designed firstly based on the phase-only sampling technique. Then, a 3-channel first-order and second- order photonic temporal differentiator is designed based on the amplitude-only sampling method.

In the first design, a continuous phase-only sampling function is used. The phase-only sampling function in one period is given by $g(z) = \exp[i\theta(z)]$, which can be optimized by using the SAA. Fig. 1(a) shows a 45-channel continuous phase-only sampling function. The Fourier transform of the sampling function is shown in Fig. 1(b). The diffraction efficiencies is 92%, and the non-uniformity of the channel amplitudes is less than 0.8%.

Fig. 2(a) shows the desired magnitude and phase responses of the synthesized single-channel first-order photonic temporal differentiator. The operation bandwidth is 0.6 nm or 75 GHz. The central wavelength is 1550 nm. The index modulation of the designed single-channel temporal differentiator is shown in Fig. 2(b). When the phase-only sampling function with a sampling period of 1 mm is multiplied with the index modulation of

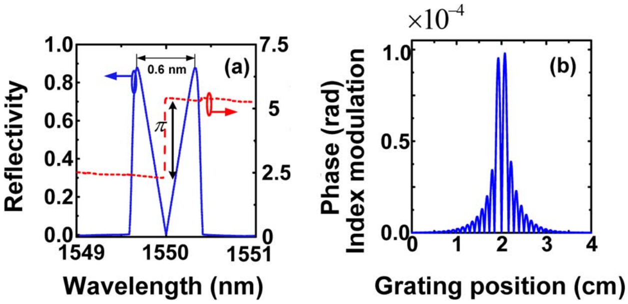

Fig. 2. (a) Magnitude and phase responses of the synthesized single-channel first-order photonic temporal differentiator. (b) Index modulation of the single-channel temporal differentiator.

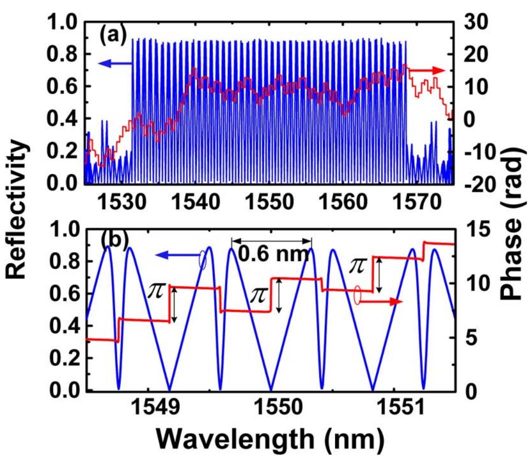

Fig. 3. Magnitude and phase spectra of the designed 45-channel first-order photonic temporal differentiator. (a) The full-view of the 45 channels, and (b) the zoom-in view of the central three channels.

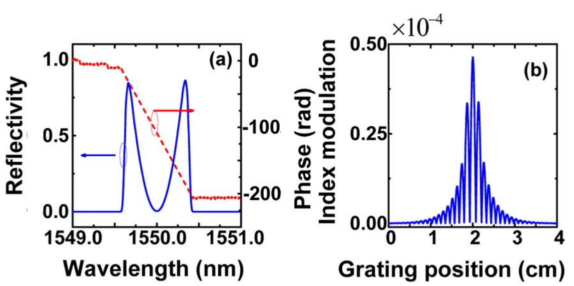

Fig. 4. (a) Magnitude and phase responses of the synthesized single-channel second-order photonic temporal differentiator. (b) Index modulation of the single-channel temporal differentiator.

the single-channel FBG, a 45-channel temporal differentiator with a channel spacing of 100 GHz is obtained, as shown in Fig. 3(a). A zoom-in view of the three central channels is given in Fig. 3(b). It can be seen from Fig. 3 that the desirable multichannel magnitude and phase responses (i.e., π phase shift) are successfully achieved. The energetic efficiency, defined as the output-to-input pulse energy ratio, for the first-order differentiation of a Gaussian pulse with a bandwidth of 75 GHz, is calculated to be 5.4%.

Fig. 4(a) shows the magnitude and phase responses of the synthesized single-channel second-order photonic temporal differentiator. The operation bandwidth and the central wavelength is the same as those of the single-channel first-order photonic

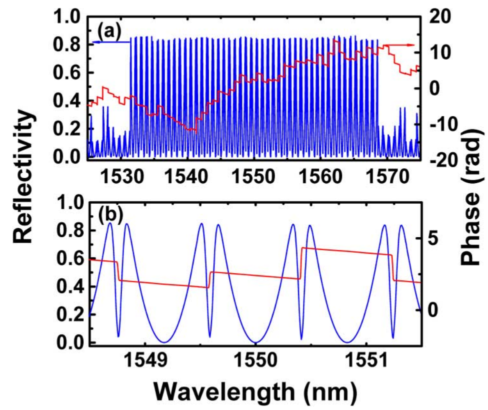

Fig. 5. Magnitude and phase spectra of the designed 45-channel second-order photonic temporal differentiator. (a) The full-view of the 45-channel, and (b) the zoom-in view of the central three channels.

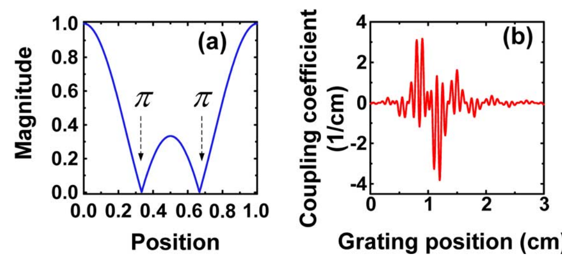

Fig. 6. (a) Amplitude-only sampling function in one period and (b) coupling coefficient of the 3-channel photonic first-order temporal differentiator.

temporal differentiator. The index modulation of the designed single-channel temporal differentiator is shown in Fig. 4(b). When the phase-only sampling function with a sampling period of 1 mm is multiplied with the index modulation of the single-channel FBG, a 45-channel second-order photonic temporal differentiator with a channel spacing of 100 GHz is obtained, as shown in Fig. 5(a). A zoom-in view of the three central channels is given in Fig. 5(b). It can be seen from Fig. 5 that the desirable multichannel magnitude and phase responses are successfully achieved. There is not phase jump existing in the phase profile in each channel which agrees well with the ideal phase response of a second-order photonic temporal differentiator. In addition, the energetic efficiency for the second-order differentiation of a Gaussian pulse with a bandwidth of 75 GHz is calculated to be about 0.4%.

B. *Amplitude-Only Sampling*

In the second design, a 3-channel temporal first-order photonic temporal differentiator with a channel spacing of 100 GHz is designed based on the amplitude-only sampling technique. The operation bandwidth is 0.27 nm or 33.75 GHz. The sampling function is a periodic sinc function, as shown in Fig. 6(a) [21]. By modulating the index modulation of the single-channel FBG with the periodic sampling function, a photonic first-order temporal differentiator with three identical channels that are equally spaced is achieved. The coupling coefficient of the amplitude-only sampled FBG is shown in Fig. 6(b). The magnitude and phase spectra of the designed 3-channel first-order photonic temporal differentiator are shown in Fig. 7. It can be seen from

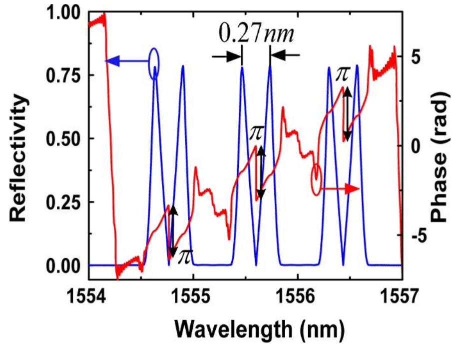

Fig. 7. Reflectivity and phase responses of the designed 3-channel photonic first-order temporal differentiator.

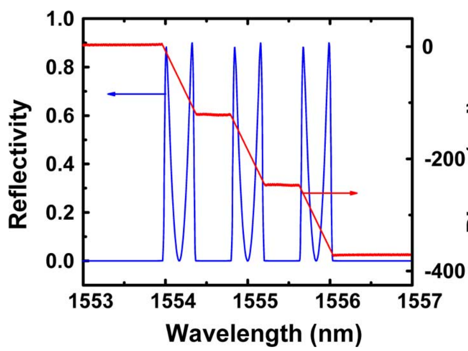

Fig. 8. Reflectivity and phase responses of the designed 3-channel second-order photonic temporal differentiator.

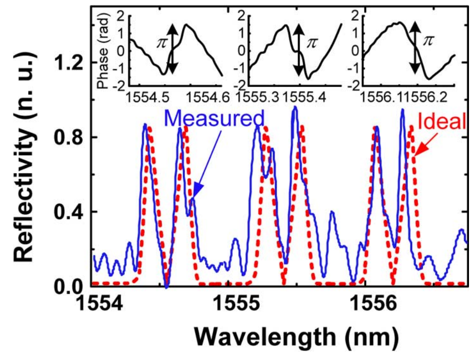

Fig. 9. Measured reflectivity and phase response of the fabricated 3-channel first-order temporal differentiator. The ideal reflectivity response (dotted line) is added for comparison.

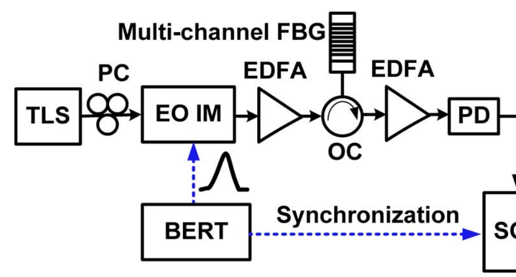

Fig. 10. Experimental setup. TLS, tunable laser source; PC, polarization controller; EO IM, electro-optic intensity modulator; FBG, fiber Bragg grating; OC, optical circulator; EDFA, erbium-doped fiber amplifier; PD, photodetector; SO, sampling oscilloscope; BERT, bit error rate tester.

Fig. 7 that the first-order photonic temporal differentiator has three identical channels spaced by 100 GHz with an operation bandwidth of 33.75 GHz.

By changing the index modulation of the single-channel first-order photonic temporal differentiator to a second-order differentiator, a second-order photonic temporal differentiator with three identical channels that are equally spaced is achieved. It can be seen from Figs. 7 and 8 that the desired multichannel photonic temporal differentiator can be successfully realized based on the amplitude-only sampling technique. In addition, the energetic efficiencies for the first-order and second-order differentiations of a Gaussian pulse with a bandwidth of 33.75 GHz are calculated to be about 4.6% and 0.3%, respectively.

IV. Proof-of-Concept Experiment

Since a phase mask for the fabrication of the 45-channel phase-only sampled FBG is not available (which should be customer-designed and fabricated at a very high cost), only the 3-channel amplitude-only sampled FBG is fabricated, which is done using an existing uniform phase mask via UV illumination by a frequency-doubled argon-ion laser operating at 244 nm. Based on the calculated coupling coefficient shown in Fig. 6(b), an apodization is applied which is implemented by dephasing the subsequent exposures while the UV beam is scanning the mask, a technique similar to the one employed in [26]. Note that, although the 3-channel second-order photonic temporal differentiator is not fabricated, the experimental result of a first-order differentiator is sufficient to verify the proposed multichannel photonic differentiators based on a sampled FBG.

Fig. 9 shows the measured magnitude and phase responses of the fabricated 3-channel 33.75-GHz temporal differentiator, obtained using an optical vector analyzer (OVA). The central wavelengths of the three channels are 1554.518, 1555.380 and 1556.175 nm with a channel spacing close to 0.8 nm. A π phase shift is observed at the central wavelength of each channel, as shown in the inset of Fig. 9.

To verify that the fabricated FBG can be used to implement the first-order temporal differentiation within the three channels, an experiment is then carried out based on the experimental setup shown in Fig. 10. A CW light wave from a tunable laser source (TLS) is directed to an intensity modulator (IM). An electrical pulse train with a bit rate of 13.5 Gbit/s from a bit error rate tester (BERT, Agilent 4901B), as shown in Fig. 10, is applied to modulate the optical carrier at the IM. The pulse from the BERT has a shape close to a Gaussian with a full width at half maximum of about 56.1 ps. The bandwidth of the input pulse is about 13.2 GHz, as shown in the inset of Fig. 11(a). The optical signal is then sent to the FBG through an optical circulator (OC). Since the central portion of the input signal spectrum is filtered out in the FBG-based differentiator, the temporal differentiation is an operation with an inherently low energetic efficiency. To compensate for the large loss, the optical signal is amplified before and after the temporal differentiator using two erbium-doped fiber amplifiers (EDFAs). Finally, the output optical pulse is detected by a high-speed photodetector (PD) with

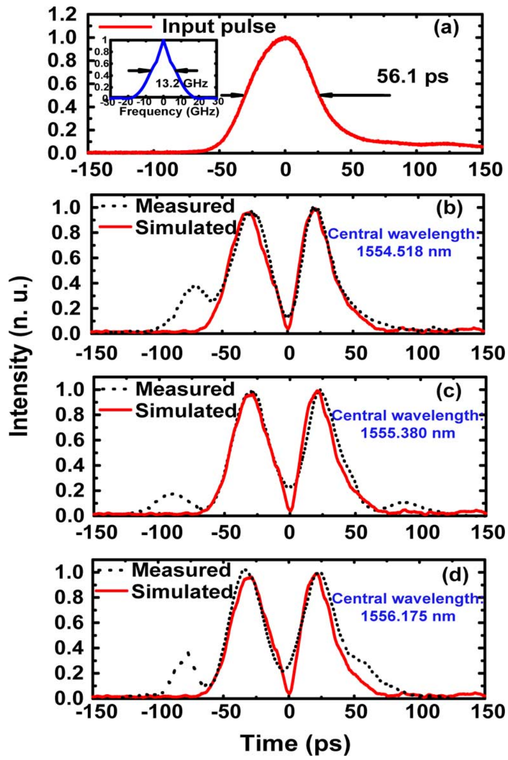

Fig. 11. Experimental results. (a) The input pulse from the BERT, the inset shows the spectrum of the input pulse. The simulated (solid+red line) and measured (dot+black line) pulses at the output of the first-order temporal differentiator with for three optical wavelengths at (b) 1554.518 nm, (c) 1555.380 nm, and (d) 1556.175 nm.

its waveform observed by a high-speed sampling oscilloscope (SO, Agilent 86116A).

Fig. 11 shows the measured pulses at the output of the 3-channel first-order temporal differentiator for three optical wavelengths of 1554.518, 1555.380 and 1556.175 nm. The simulated output pulses are also shown in Fig. 11. As can be seen, the simulation and experimental results agree well. The root mean square (RMS) errors are calculated to be about 8.3%, 9.6% and 12.1%, for the optical wavelengths at 1554.518, 1555.380, and 1556.175 nm. The energetic efficiency for the first-order differentiation are measured to be about 3.6%, 2.1% and 1.7%, for the optical wavelengths at 1554.518, 1555.380, and 1556.175 nm, respectively.

Finally, the processing error as a function of the input pulse bandwidth is estimated for each channel based on the measured magnitude and phase responses of the fabricated 3-channel first-order photonic temporal differentiator. To implement this evaluation, the amplitude and phase responses of the fabricated 3-channel optical differentiator are first measured using the OVA, and then the output pulse for an input Gaussian pulse with different bandwidths is calculated. The processing error is then obtained by calculating the RMS errors for the Gaussian pulse with a bandwidth from 0 to 120 GHz, as shown in Fig. 12.

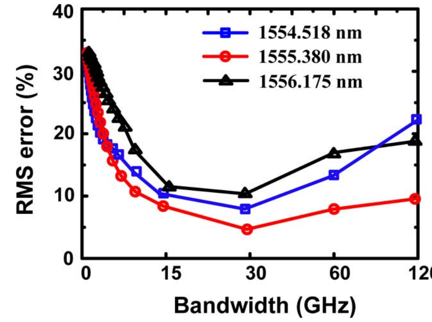

Fig. 12. Estimated processing error as a function of the input pulse bandwidth for the fabricated 3-channel first-order differentiator. RMS: root mean square.

V. Conclusion

A multichannel photonic temporal differentiator to implement arbitrary-order temporal differentiation of WDM signals was proposed and experimentally demonstrated. The differentiator was designed based on the DLP algorithm together with the spatial sampling technique to generate multichannel spectral response with each channel corresponding to a temporal differentiator at a specific optical wavelength. A 45-channel first-order and second-order temporal differentiator were designed based on the phase-only sampling technique, and a 3-channel first-order and second-order temporal differentiator were designed based on the amplitude-only sampling technique. The 3-channel first-order temporal differentiator was then fabricated. The use of the fabricated 3-channel differentiator to perform temporal differentiation of a 13.2-GHz Gaussian-like optical pulse with an optical carrier at three different optical wavelengths was demonstrated. The proposed multichannel photonic differentiators can be used for optical signal characterization in WDM networks.

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