Compact, flexible and versatile photonic differentiator using silicon Mach-Zehnder interferometers

Jianji Dong,1 Aoling Zheng,1 Dingshan Gao,1,* Lei Lei,1 Dexiu Huang,1 and Xinliang Zhang1

1Wuhan National Laboratory for Optoelectronics, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, 430074, China
*dsgao@mail.hust.edu.cn

Abstract: We propose and experimentally demonstrate the flexibility and versatility of photonic differentiators using a silicon-based Mach-Zehnder Interferometer (MZI) structure. Two differentiation schemes are investigated. In the first scheme, we demonstrate high-order photonic field differentiators using on-chip cascaded MZIs, including first-, second-, and third-order differentiators. For single Gaussian optical pulse injection, the average deviations of all differentiators are less than 6.5%. In the second scheme, we demonstrate multifunctional differentiators, including intensity differentiator and field differentiator, using an on-chip single MZI structure. These different differentiator forms rely on the relative shift between the probe wavelength and the MZI resonant notch. Our schemes show the advantages of compact footprint, flexible functions and versatile differentiation forms. For example, high order field differentiators can be used to generate complex temporal waveforms, such as high order Hermite-Gaussian waveforms. And intensity differentiators are useful for ultra-wideband pulse generation.

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References and links
1. Introduction

Similarly to the advantages of ultrafast optical signal processing aiming to overcome the electronic bottleneck, photonic differentiators can implement the differentiation (DIFF) of ultrafast optical signals in optical domain directly without electronic processing. Photonic DIFF is attracting lots of interests due to its potential wide applications in the optical digital processing and analog processing [1–5].

Currently, photonic DIFF can be mainly divided into two categories, the field DIFF and the intensity DIFF [6]. The intensity DIFF means both input signals and output differentiated signals are carried by the optical intensity or optical power regardless of signal phase, which is useful for ultra-wideband (UWB) microwave communications [7–9] and signal encoding [10]. Previously, we achieved such DIFFs by nonlinear effects of semiconductor optical amplifiers (SOAs) [8, 11]. The intensity DIFF could be also implemented by incoherent photonic processors [12] and highly nonlinear fibers [7], and so forth. On the other hand, the field DIFF means the output optical field (complex signal, including both amplitude and phase) is the differentiation of input field signals, which has potential applications in ultrashort pulse generation [3, 13], odd-symmetry Hermite-Gaussian waveform generation [2], and pulse edge recognition [14]. To date, the field DIFFs were implemented by fiber Bragg gratings [15, 16], long-period fiber gratings [2, 4], interferometers [17], SOAs [13], and silicon microring resonators [18, 19]. Even more interesting would be the implementation of high order DIFF, which could offer more complex temporal waveforms, such as high order Hermite-Gaussian waveforms. Besides, optical arbitrary waveforms can also be made of a family of arbitrary-order differentiations of a Gaussian pulse. The high-order differentiators were implemented by specially-designed fiber Bragg gratings (FBGs) [16], phase-shifted long-period fiber gratings [20], tilted FBGs [5], cascaded FBGs [21], programmable pulse shaper [22], silicon Bragg gratings [23], and so forth. Especially, Ref [23] demonstrated a high order differentiator with bandwidths in the THz range. However, most of the DIFFs were not versatile and showed a sole function. To meet multi-requirements in photonic signal processing, flexible and versatile DIFFs are required. Besides, these reported DIFFs were mainly implemented by fiber optics technologies without compactness. In fact, photonic
DIFF with silicon-based waveguide, can offer distinct advantages of increased stability and reliability, compactness, capability of integration with electronics.

In this paper, we present two schemes to demonstrate the flexibility and versatility of photonic DIFFs using a silicon-based Mach-Zehnder Interferometer (MZI) structure. In the first scheme, we demonstrate high-order photonic field DIFFs using on-chip cascaded MZIs, including first-, second-, and third-order DIFFs. In the second scheme, we simultaneously demonstrate intensity DIFF and field DIFF, using an on-chip single MZI structure. These different DIFF forms rely on the relative shift between the probe wavelength and the MZI resonant notch. Our schemes show the advantages of compact footprint, flexible functions and versatile DIFF forms.

2. High order DIFF by on-chip cascaded MZI

In this section, we aim to implement high-order photonic field DIFFs using on-chip cascaded MZIs, including first-, second-, and third-order DIFFs. An \( N \)th-order optical temporal differentiator provides the \( N \)th-time derivative of the complex envelope of an input optical signal. Therefore, the output differentiated signal in frequency domain can be written by

\[
E_{\text{out}}(\omega) = [j(\omega-\omega_0)]^NE_{\text{in}}(\omega)
\]  

(1)

where \( \omega_0 \) is the optical carrier frequency, and \( E_{\text{in}} \) and \( E_{\text{out}} \) are the input and output optical fields, respectively. Therefore, an optical filter should be designed with a spectral transfer function of the form \([j(\omega-\omega_0)]^N\). It has been proved that the MZI structure has a good linear frequency response near the MZI resonant notch [17], which can implement the first order DIFF. Therefore, to achieve \( N \)th-order differentiator, the MZI unit just needs to be cascaded by \( N \) times to achieve a frequency response of \([j(\omega-\omega_0)]^N\).

For an asymmetric MZI, the spectral transfer function is given by

\[
H(\omega) = 1 + \exp[j(\omega T + \phi_0)] = 2 \sin \left( \frac{\omega T + \phi_0 + \pi}{2} \right) \exp \left( -\frac{\omega T + \phi_0}{2} \right)
\]  

(2)

where \( \tau \) and \( \phi_0 \) are the relative time delay and phase difference between the two interferometer arms, respectively. When the MZI operates near its resonant frequency, we have

\[
\sin \left( \frac{\omega T + \phi_0 + \pi}{2} + m\pi \right) = \frac{\omega T + \phi_0 + \pi(1+2m)}{2} = 0
\]

where \( m \) is an integer. Thus Eq. (2) can be converted to

\[
H(\omega) = \left[ j(\omega T + (2m+1)\pi) \right] \exp \left( \frac{j(\omega T + \phi_0)}{2} \right)
\]  

(3)

From Eq. (3), one can see clearly that both the amplitude response and the phase response have a linear frequency response. At the same time, when the amplitude response shifts across the null, a \( \pi \) phase shift should appear at the resonant frequency. Therefore, the first order DIFF can be implemented using an MZI structure. Assume that \( m = 0 \) and \( \phi_0 = -\pi \). The time delay is set at 100 ps. According to Eq. (3), we calculate the spectral transfer function, as shown the dash lines of Figs. 1(a) and 1(b), which suggest that, the MZI can be regarded as a good differentiator near the resonant frequency. We also calculate the standard transfer function of the MZI without any approximation, as shown the solid lines of Figs. 1(a) and 1(b). For comparison, the phase responses are quite similar and a \( \pi \) phase shift appears at the resonant frequency. However the amplitude response has a large deviation far away from the resonant frequency region. Thus to implement photonic DIFF, the MZI should work only near the resonant frequency region.
Figure 1(a) suggests that the MZI has an accurate DIFF within a finite bandwidth. To explore the impact of input signal bandwidth on the DIFF accuracy, we simulate the DIFF waveforms of a Gaussian pulse with different pulsewidth, and $\tau$ is set at 100 ps. When the pulsewidth of input Gaussian pulse is 1000 ps, the MZI output waveform accords well with an ideal DIFF waveform, as shown in Fig. 2(a). When the input pulsewidth is decreased to 100 ps, one can see the DIFF waveform is broadened compared to an ideal DIFF waveform, as shown in Fig. 2(b). However, a large DIFF error occurs when the pulsewidth is decreased to 20 ps, as shown in Fig. 2(c), because the bandwidth of input Gaussian pulse becomes much larger than the MZI operation bandwidth.

We employ on-chip cascaded MZI structure for high-order DIFF. First we design and fabricate cascaded MZIs on commercial silicon-on-insulator (SOI) wafer. Figure 3 shows the microscope image of our on-chip MZIs. The top silicon thickness of SOI wafer is 340 nm and the buried oxide layer thickness is 2 $\mu$m. The device layout was transferred to ZEP520A photoresist by E-beam lithography. Then the upper silicon layer was etched downward for 240 nm to form silicon ridge waveguide and input/output grating couplers, through inductively coupled plasma (ICP) etching. The coupling loss of the grating coupler was measured to be 5 dB for single side. In order to reduce the loss unbalance between the two arms of MZI, the arm width of straight waveguides is broadened to 1 $\mu$m. But the width of curved waveguides is 500 nm and the bending radius is 15 $\mu$m. A 3 $\mu$m long linear taper is used to transform the wide straight waveguide to the narrow curved waveguide. This hybrid design makes the device compact and improves the loss uniformity of MZI arms as well. We have fabricated three typical MZI structures, i.e., one MZI (MZI-1), two cascaded MZIs (MZI-2) and three cascaded MZIs (MZI-3). The insets of Fig. 3(a) show the photos of these MZI structures. Figures 3(b)-3(d) show the scanning electron microscope (SEM) images of the grating coupler, Y branch and arc region, respectively.
Figures 4(a)-4(c) show the measured transfer functions of MZI-1, MZI-2 and MZI-3 for 1st-order, 2nd-order, and 3rd-order DIFFs, respectively. The ideal frequency responses for these differentiators are also shown for comparison. One can see that good agreements between the ideal and the measured transfer functions are achieved in a finite bandwidth. And a small deviation appears at the amplitude dip of 2nd-order DIFF, which is caused by the loss unbalance in silicon fabrication process. The chip losses for MZI-1, MZI-2, and MZI-3 are about 1 dB, 3.5 dB, and 10.5 dB, respectively. And the coupling losses for all chips are about 10 dB. The notch depth of MZI-1, MZI-2, and MZI-3 is 13.5 dB, 9.3 dB, and 16.6 dB, respectively. All the MZIs have a free spectral range (FSR) of 80 GHz. According to the definition of device operation bandwidth (DOB) in Ref [24], the DOB of MZI-1, MZI-2, and MZI-3 is measured to be 43 GHz, 40 GHz, and 35 GHz, respectively. The DOB informs the maximum operation speed of signals to be differentiated. Due to the hardware restraint, the phase response of the MZI chip was not measured. However, we can deduce from Fig. 1 that the MZI has a $\pi$ phase jump at the resonant frequency.

The experimental setup for high-order DIFF is shown in Fig. 5. A continuous wave (CW) beam is emitted from a tunable Laser diode (TLD) with a precisely tuning resolution of 1 pm. The CW beam is modulated by two cascaded Mach-Zehnder modulators (MZMs). The bit pattern generator (BPG) provides both data and clock electrical signals for these two MZMs. Both return-to-zero (RZ) and nonreturn-to-zero (NRZ) data can be generated optionally. The first erbium doped fiber amplifier (EDFA) is used to boost the input optical power. The second EDFA is used to compensate the power attenuation by the chip loss. A polarization controller (PC) is required since the silicon waveguide operates only in transverse electrical
(TE) mode. We employ the vertical grating coupling scheme to couple the optical signal from fiber to silicon waveguide. For different order DIFFs, we just change the chip type accordingly. Finally, the temporal waveform is analyzed through a digital communications analyzer (Agilent DCA86100C).

First, the laser wavelength is fixed at 1565.4 nm. And the BPG drives the two MZMs to generate a Gaussian pulse train with a pulsewidth of 18 ps, as shown in Fig. 6(a). The launched peak power before the chip is about 13dBm. When we employ the chips of MZI-1, MZI-2, and MZI-3, and fine tune the TLD wavelength to align with the resonant notch, we measure the temporal waveforms of 1st order, 2nd order, and 3rd order DIFFs, respectively, which are shown in Figs. 6(b)-6(d), respectively. It can be seen that the measured differentiated pulses fit well with the simulated pulses, except a small discrepancy in the pulse sidelobes, such as 2nd-order DIFF and 3rd-order DIFF. The deviation of the sidelobes may be caused by the finite DOB and the finite notch depth. To analyze the DIFF accuracy, the average deviation is defined as the mean absolute deviation of measured differentiation power from the calculated one on certain pulse period [22]. The calculated average deviations for 1st order, 2nd order, and 3rd order DIFFs are 3.35%, 4%, 6.5% respectively.
The cascaded MZI chip cannot only process the DIFF of periodic pulse trains, but also process intensity-modulated signals with pseudo random bit sequence (PRBS). Figure 7 shows the 1st order DIFF waveform of NRZ PRBS signals at the bit rate of 20 Gbit/s, where R1 is the input original bit sequence, R2 and R3 are the measured and simulated DIFF waveforms, respectively. One can see the measured waveform accords well with the simulated waveform. The calculated average deviation is 10.36%. Figure 8 show the 1st order DIFF result for 20Gbit/s RZ PRBS signal, where R1 is input RZ pulse train, R2 and R3 are the measured and simulated DIFF waveforms, respectively. The calculated average deviation is 13%. The insets of Fig. 7 and Fig. 8 are the eye patterns of input signals and differentiated signals. The clean eye patterns of differentiated signals indicate well DIFF results regardless of the data bit sequences. And all the measured waveforms are captured with single slot measurement. Figure 9(a) shows the spectra of input RZ pulse and the output DIFF pulse. One can see the input signal carrier is well aligned with the MZI resonant notch, and the carrier is suppressed in the output spectrum.

Fig. 8. R1: input RZ PRBS signals at 20Gbit/s, R2 and R3 are measured and simulated waveforms of 1st-order DIFF. Inset: eye pattern.

Fig. 9. Measured spectra of input RZ PRBS signals at 20Gbit/s and output DIFF signals with (a) MZI-1 and (b) MZI-2.
Now the chip is replaced by MZI-2, and the 2nd-order DIFF results of PRBS signals are shown in Fig. 10, where R1 is input RZ data stream at the bit rate of 20 Gbit/s, R2 and R3 are the measured and simulated DIFF waveforms, respectively. The calculated average deviation is 15.2%. One can see the measured and simulated waveforms have good agreements in the intermittent single pulse, but have large deviations in the consecutive pulses. Especially the pulse sidelobes of output waveforms are distorted to a single pulse. Therefore to achieve high order DIFF, it is stricter to design the transfer functions in terms of the notch depth and DOB. Figure 9(b) shows the spectra of input RZ pulse and the output 2nd order DIFF pulse. One can see the input signal carrier is well aligned with the MZI resonant notch, but the carrier is not deeply suppressed in the output spectrum due to the finite notch depth of MZI-2.

3. Multifunctional DIFF by on-chip single MZI

In this section, we aim to implement multifunctional DIFFs using on-chip single MZI, including field DIFF and intensity DIFF. Previously, we summarized the photonic DIFF types to four categories according to DIFF parameter (intensity or field) mapping of the input/output signals, namely, intensity-to-intensity DIFF, intensity-to-field DIFF, field-to-intensity DIFF, and field-to-field DIFF, respectively [25]. Especially, we demonstrated both intensity-to-intensity DIFF and intensity-to-field DIFF using an SOA and a fiber-based delay interferometer. Since silicon waveguide is more compact and stable than fiber-based system, we employ the on-chip single MZI instead. Besides, the silicon MZI chip has less power consumption than other active semiconductor devices. In the near future, the phase modulator may be replaced by nonlinear silicon waveguide, such as microring resonator, thus our concept of multifunctional DIFF can be integrated into a single silicon platform.

Assume that a CW beam is phase modulated by a temporal signal $s(t)$ first. The amplitude keeps constant, as shown in Fig. 11(a). Then the CW beam will have a frequency chirp of $\delta \omega(t) = -\partial s(t)/\partial t$, which is the differentiation of the input signal, as shown in Fig. 11(b). When the CW carrier is located at the notch of the MZI spectrum, the frequency chirp will be converted into intensity information with square magnitude of the differentiated signal, corresponding to intensity-to-field DIFF, labeled “⊗”, as shown in Fig. 11(c). The output optical field can be expressed by [25]

$$E_{\text{out}}(t) = K \partial s(t)/\partial t$$

(4)

where $K$ is constant. Equation (4) indicates that the output field is proportional to the differentiation of input signals, corresponding to the intensity-to-field DIFF. The detected optical power is given by $P_{\text{out}}(t) = |E_{\text{out}}(t)|^2$. 

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Fig. 10. R1: input RZ PRBS signals at 20Gbit/s, R2 and R3 are measured and simulated waveforms of 2nd-order DIFF.
However, when the CW carrier is slightly shifted from the MZI notch, the frequency chirp will be converted into intensity information approximately, corresponding to intensity-to-intensity DIFFs (+) and (-), labeled “2” and “3”, as shown in Fig. 11(c). In such a case, the approximation is satisfied only when the phase modulator operates with a small phase-modulation index and the optical carrier is near the MZI notch [25]. Then the output optical power can be approximately expressed by

$$P_{\text{out}}(t) = 2K^2(\omega_p - \omega_0)\frac{\partial s(t)}{\partial t} + \gamma_{\text{dc}}$$

(5)

where \( \gamma_{\text{dc}} \) is a constant, \( \omega_p \) is the optical frequency of the CW beam, \( \omega_0 \) is the MZI notch frequency. From Eq. (5), one can see that the output power is differentiation of input signals, corresponding to the intensity-to-intensity DIFF. Moreover, a pair of polarity-reversed DIFF, labeled with (+) and (-), can be obtained, dependent on whether \( \omega_p - \omega_0 > 0 \) or not. Therefore, simultaneous field and intensity DIFFs are achievable without altering the configuration.

The experimental setup for multifunctional DIFFs is shown in Fig. 12. The configuration is quite similar to Fig. 5 except that the cascaded MZMs are replaced by one phase modulator (PM). And only MZI-1 chip is employed. The BPG provides an electrical Gaussian pulse to drive the PM. Thus the input optical signal emitted from the TLD is phase modulated. The signal wavelength is fixed at 1565.4 nm first. By fine tuning the wavelength of the TLD, we can measure different DIFF types.
First, we set the BPG so that the input Gaussian pulse has a full width at half maximum (FWHM) of 50 ps. Figure 13(a) shows the different DIFF types when the central wavelength of the TLD is precisely tuned, where waveform R1 is the input Gaussian pulse, R2 is the measured waveform of intensity-to-field DIFF, R3 and R4 are a pair of polarity-reversed intensity DIFF waveform. The dash lines are the calculated DIFF waveforms accordingly. The calculated average deviations of R2 ~R4 are 5.5%, 8.2% and 10.1%, respectively. When the FWHM of input Gaussian pulse is set at 30 ps, we repeat the DIFF measurement. Figure 13(b) shows the different DIFF waveforms, where R1 is the input Gaussian pulse, R2 is the measured waveform of intensity-to-field DIFF, R3 and R4 are a pair of polarity-reversed intensity DIFF waveform. The dash lines are the calculated DIFF waveforms accordingly. The average deviations of R2 ~R4 are 11.1%, 13.8% and 14.5%, respectively. One can see that the intensity DIFF has a larger deviation than the field DIFF. The reason lies in that the MZI spectral characteristics shows a linear transfer function near the resonant notch, but a large deviation far from the notch. Besides, Eq. (5) is an approximate formula. When the central wavelength is far away from the resonant notch, the deviation becomes larger. Therefore the field DIFF is more accurate than the intensity DIFF in our scheme.

We have demonstrated two schemes to implement flexible and versatile DIFF using the silicon-based cascaded MZI structure. The silicon waveguide has the advantages of compactness, stability and scalability. Higher-order DIFF (such as 4th order DIFF) can be further achieved by cascading more MZI unit on the chip. Since the high order DIFF is very strict with the device transfer function, the practical fabrication of silicon-based MZI structure is facing some challenges. For example, the uniformity of each MZI unit cannot be maintained without additional controllers, such as thermal or electrical controllers. So the further work is to enhance the spectral adjustment by fabricating the heater or electrode. Besides, to increase the DOB, one may increase the FSR of the MZI chip or design a linear filter on SOI substrate.

4. Conclusions

We present two schemes to demonstrate the flexibility and versatility of photonic DIFFs using a silicon-based MZI structure. In the first scheme, we demonstrate first-, second-, and
third-order photonic field DIFFs using on-chip cascaded MZIs. For single Gaussian optical pulse injection, the average deviations of all differentiators are less than 6.5%. For pseudorandom signal injection at 20 Gbit/s, the average deviations are less than 15.2%. In the second scheme, we demonstrate multifunctional differentiators, including intensity DIFF and field DIFF, using an on-chip single MZI structure. These different DIFF types rely on the relative shift between the probe wavelength and the MZI resonant notch. Our schemes show the advantages of compact footprint, flexible functions and versatile differentiation forms. These different DIFF forms can offer different applications in optical data signal processing and analog signal processing. For example, high order field DIFFs can be used to generate complex temporal waveforms, such as high order Hermite-Gaussian waveforms. And intensity DIFFs are useful for UWB pulse generation.

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