Real-time wavelength and bandwidth-independent optical integrator based on modal dispersion

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Abstract: High-throughput real-time optical integrators are of great importance for applications that require ultrafast optical information processing, such as real-time phase reconstruction of ultrashort optical pulses. In many of these applications, integration of wide optical bandwidth signals is required. Unfortunately, conventional all-optical integrators based on passive devices are usually sensitive to the wavelength and bandwidth of the optical carrier. Here, we propose and demonstrate a passive all-optical intensity integrator whose operation is independent of the optical signal wavelength and bandwidth. The integrator is implemented based on modal dispersion in a multimode waveguide. By controlling the launch conditions of the input beam, the device produces a rectangular temporal impulse response. Consequently, a temporal intensity integration of an arbitrary optical waveform input is performed within the rectangular time window. The key advantage of this device is that the integration operation can be performed independent of the input signal wavelength and optical carrier bandwidth. This is preferred in many applications where optical signals of different wavelengths are involved. Moreover, thanks to the use of a relatively short length of multimode waveguide, lower system latency is achieved compared to the systems using long dispersive fibers. To illustrate the versatility of the optical integrator, we demonstrate temporal intensity integration of optical waveforms with different wavelengths and optical carrier bandwidths. Finally, we use this device to perform high-throughput, single-shot, real-time optical phase reconstruction of phase-modulated signals at telecommunications bit rates.

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1. Introduction

An all-optical integrator offers significant promise for ultrafast optical information processing, optical memory, measurement and computing systems [1,2]. As expected for an all-optical technology, a photonic integrator can provide a processing speed which is orders of magnitude faster than its electronic counterpart [1]. Recent experimental demonstrations of all-optical temporal signal integration devices include a gain-assisted fiber grating resonant cavity [3], a uniform fiber Bragg grating (FBG) [4] and a CMOS-compatible photonic chip [1]. These all-optical integrators are designed by synthesizing their spectral response as opposed to the time domain response. Two major limitations associated with these devices are that strict wavelength matching between the input optical signal and the spectral response of the integrators is required and the operational optical bandwidth is typically small. A wavelength-independent photonic intensity integrator has been demonstrated recently [5], where the integration operation is based on the superposition of an infinite set of continuously delayed replicas of the input signal. The replicas are generated by intensity modulating a rectangular-like incoherent broadband optical spectrum with the input drive signal, and the time delay is introduced by first-order chromatic waveguide dispersion. While the system in [5] enables wavelength-independent integration operation, it still suffers from a few limitations. First, since an incoherent broadband light source is required, the integrated signal exhibits a low signal-to-noise ratio (SNR), and single-shot operation is not possible. Second, the system cannot integrate large-bandwidth signals, such as ultrashort optical waveforms, due to the use of an electro-optical modulator. Third, km-length dispersive fibers are required to produce a sufficient integration time windows, due to the relatively small chromatic waveguide dispersion coefficient associated with single mode fibers. This long length results in both high loss and high system latency, and may cause signal distortion due to the non-negligible higher-order chromatic dispersion and polarization mode dispersion [6].

Recently, we reported a new device for generating group velocity dispersion. The so called Chromo Modal Dispersion (CMD) device generates significant chromatic dispersion by employing spatial dispersion in a diffraction grating and the large modal dispersion in a short multimode waveguide [7]. Here, we propose and demonstrate a new optical intensity integrator that also exploits modal dispersion in a multimode waveguide. The system is simpler as no spatial gratings are required. Since modal dispersion has very weak dependence on optical wavelength and bandwidth, this all-optical integrator's functionality is almost independent of optical wavelength and bandwidth of the optical carrier, especially over limited bandwidth (tens of nm). Using modal dispersion in a multimode waveguide, we construct an optical integrator capable of high-throughput, single-shot, real-time intensity

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integration of arbitrary ultrashort optical waveforms. Whereas previous work in this area utilizes chromatic waveguide dispersion [5,6], our proposed integrator is implemented based on the modal dispersion in a multimode waveguide, which is typically much larger than chromatic waveguide dispersion per unit length and is nearly wavelength- and bandwidth-independent. When an optical waveform to be processed is sent to the proposed system, the waveform is copied into identical replicas, with each exciting the distinct spatial modes in the multimode waveguide. Temporal delay of the replicas is introduced by modal dispersion. Since modal dispersion in a multimode waveguide is much larger than chromatic waveguide dispersion in an optical fiber [7], it is easy to produce a long integration time window using a short multimode fiber (MMF). For example, an integration time window of 350ps can be achieved using only a 20-meter length of MMF. To obtain the same value of time delay using chromatic dispersion for an incoherent optical source with 20-nm bandwidth [5], more than 1 km of single mode fiber is required. Therefore, our system features a smaller device footprint and lower latency than one using single mode fiber. In addition, since no modulation of incoherent optical sources is required [5], the signal-to-noise ratio of the integrated signal is greatly improved, making single-shot real-time operation possible. The demonstrated wavelength- and bandwidth-independent optical intensity integrator provides a promising solution for applications where various light sources and optical devices with different wavelengths are involved.

2. Basic concept

The proposed photonic integrator is designed by synthesizing its time domain response. It is well known that the temporal impulse response of an ideal integrator is proportional to a unit-step function (0 for $t < 0$ and 1 for $t \geq 0$, where t is the time variable). In the design of a time-domain all-optical integrator, it is critical for the system to synthesize a unit-step impulse response. However, in practice, an integrator based on passive devices provides a unit-step response only over a finite time window [4]. In this work the unit-step function with a limited time window is generated using modal dispersion in a MMF instead of chromatic dispersion as used in the previous work [4–6], leading to wideband and wavelength insensitive integration with much lower latency and real-time operation.

Multimode fibers have been widely employed in local- and campus-area optical communications networks. However, modal dispersion can limit transmission length at high bit rates because of the temporal spread of light pulses. Although the inherent modal dispersion in multimode fibers cannot be avoided, it can also be exploited to achieve higher transmission bit rates using optical multiple-input multiple-output (MIMO) communication techniques [8]. The nature of modal dispersion comes from the different propagation velocity of optical signals that are coupled into different waveguide modes [9,10]. In a multimode waveguide, light rays propagating at small axial angles reach the output end much earlier than rays at larger angles. When the angular width of the excitation beam is as large as the acceptance angle of the multimode waveguide, the introduced time delay is maximized.

While modal dispersion is a limiting factor in optical communications systems, here we take advantage of MMF's large modal dispersion to generate a compact optical integrator with a long operational time window. It has been demonstrated that in a MMF different modes can be excited by different incident angles [11]. The output energy distribution as a function of input excitation angle in the presence of mode coupling can be obtained by numerically solving [11]

$$\varepsilon(\theta, z) = \sum_{n=1}^{\infty} a_n J_0\left(b_n \frac{\theta}{\theta_c}\right) \exp\left(-\frac{D b_n^2 z}{\theta_c}\right). \tag{1}$$

The coefficients a_n are given by

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$$a_n = \frac{2J_0\left(b_n \frac{\theta}{\theta_c}\right)}{\theta_c^2 J_1^2\left(b_n\right)} \tag{2}$$

where b_n are the zeros of the Bessel function J_0. In the case of oblique plane-wave excitation, θ is the propagation angle inside the fiber with respect to the fiber axis, θ_0 is the center angle of the angular distribution of excited modes in the fiber, θ_c is the critical angle inside the fiber, D is the mode coupling constant, and z is the length of the multimode fiber. The numerical aperture (NA) and the diameter of the core of this MMF are 0.37 and 200m, respectively. When the angular width of the input is equal to the acceptance angle of the fiber, optical pulses can be dispersed to their maximum width using modal dispersion. The maximum pulsewidth exiting a MMF with unit length is given by

$$\Delta\tau = \tau_2 - \tau_1 \approx \frac{n_1}{c\sin\theta_c} - \frac{n_1}{c} \tag{3}$$

To generate a rectangular impulse response (unit-step response with a limited time window), it is critical that optical power is distributed equally amongst the spatial modes. This is achieved by tailoring the launch condition of the input optical beam and using a spatial intensity mask [11]. Therefore, a rectangular impulse response can be obtained due to the combination of power distribution across different spatial modes and modal dispersion of the MMF. Furthermore, since the proposed integrator is only based on modal dispersion, it can operate in any wavelength range over which the MMF is transparent. The integrator performance is determined primarily by the modal dispersion of the fiber, as compared to its material dispersion. This yields the integrator performance largely wavelength-independent.

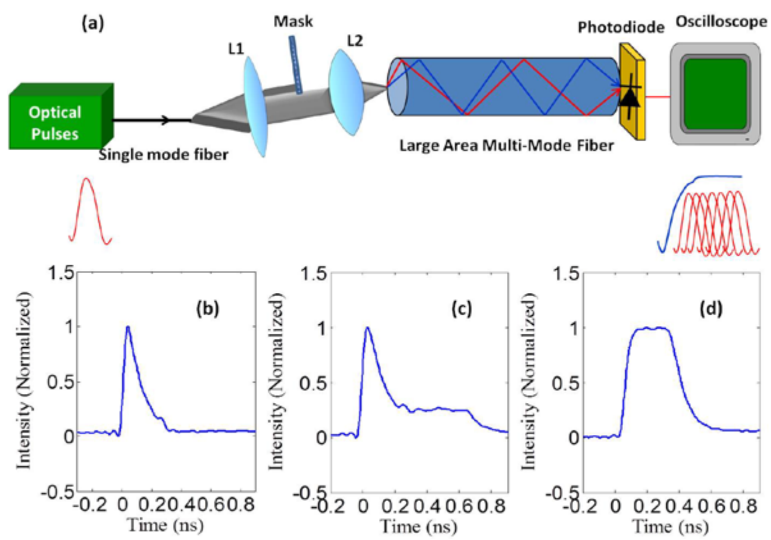

Fig. 1. (a) Schematic of the optical integrator. A beam is collimated and focused into the end of a MMF. The beam is tilted by an angle of approximately 15 degrees to shape the temporal impulse response. An intensity mask is also used to block the portion of the beam which excites low-order modes. The light is then detected by a high speed photodiode and oscilloscope. (b) The integrator output waveform generated by launching the input beam on-axis into the center of the fiber facet. (c) The integrator output waveform using an input beam tilted by 15 degrees. (d) The integrator output waveform generated by tilting the input beam by 15 degrees, using an intensity mask and offsetting the fiber in both the x- and y-directions.

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3. All-optical integrator experiment

We first demonstrate the wavelength- and bandwidth-independent intensity integration of optical signals using the experimental apparatus shown in Fig. 1(a). A fiber-coupled optical signal is collimated by lens L1 and focused into the MMF using lens L2. The focal lengths of L1 and L2 are 100 mm and 25 mm, respectively. The tip of a 20 m MMF is placed at the focus of L2. The signal can be coupled into a variety of different waveguide modes by adjusting the angular alignment of the fiber tip. The NA of the MMF is 0.37 and the fiber core diameter is 200 µm. According to Eq. (3), the maximum output pulse width produced by modal dispersion of the MMF is approximately 3 ns. This value represents the largest integration time window that can be produced by this device.

To characterize the optical intensity integrator, we use a 500-fs optical pulse to measure the impulse response. The pulse has a center wavelength of 1545 nm and a 3dB bandwidth of 20 nm. The output signal from the MMF is detected by a 17-GHz bandwidth photodiode and recorded by a 50 gigasample/second real-time oscilloscope. As shown in Fig. 1, the output waveform, or equivalently, the impulse response of the system, depends on the beam launch conditions, such as offset, tilt angle and width of the input beam [12].

To increase the total modal-dispersion-induced time delay, we tilt the input beam with a 15-degree angle in the y-direction and slightly offset the input beam waist with respect to the fiber core. In this case, pulse broadening is observed due to the modal dispersion. The output waveform has a 10dB pulse width of 700 ps, as shown in Fig. 1(c). Note that the obtained pulse width is smaller than the theoretical value because the diameter of the photodetector is only 62.5 µm, which is smaller than the core diameter of the MMF and a portion of the fiber output is truncated. A longer time window can be obtained by optimizing the light coupling between the MMF and the photodetector.

When an optical waveform is sent to the integrator, it is "copied" into a set of identical replicas by exciting various spatial modes in the MMF and tailoring power distribution among different modes using a spatial mask. Here, for simplicity, we use a fixed intensity mask to attenuate the portion of the beam corresponding to the fundamental modes, as shown

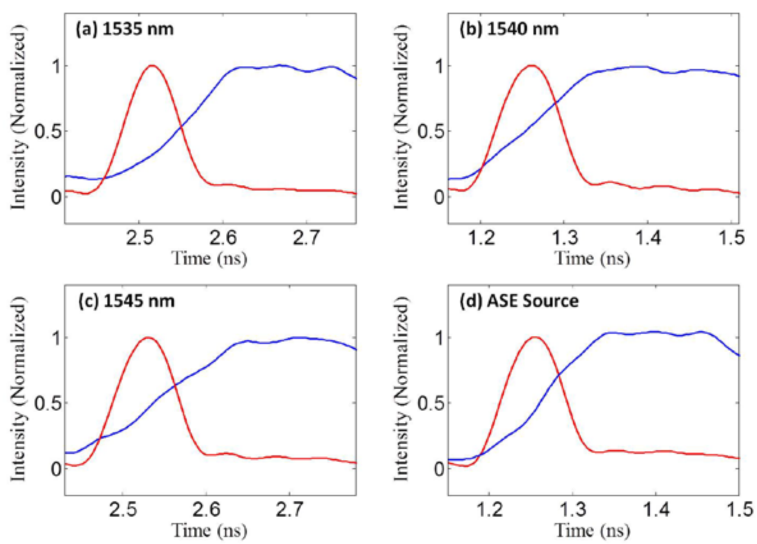

Fig. 2. Experimental demonstration of the wavelength and bandwidth independent operation of the MMF-based optical integrator. A tunable laser is modulated as the pulse source. The optical pulses are transmitted through the MMF based optical integrator. The red curves are the input temporal waveforms and the blue curves are the output. The wavelength of the laser is tuned to 1535nm, 1540nm and 1545nm, respectively, as shown in (a), (b) and (c). Modulated ASE is also used as a wideband source, and the waveform of the integrator's input and output is shown in (d).

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in Fig. 1(a). As these replicas propagate, they become time-delayed due to modal dispersion in the MMF. Finally, they are summed in intensity at the photodetector. As a result, a rectangular impulse response with a time window of approximately 350 ps is achieved, as shown in Fig. 1(d). Via this process, the integrator provides a cumulative time integral of the input intensity waveform. The time duration of the input signal that can be processed should be shorter than the time window of the impulse response of the integrator. While the insertion loss of the integrator is relative large (~10 dB) due to the use of a spatial mask, it can easily be compensated by an optical amplifier such as an erbium-doped fiber amplifier (EDFA).

To demonstrate the wavelength-independent operation of the proposed integrator, we choose the input optical waveforms with different carrier wavelengths, which are generated by intensity modulating continuous-wave (CW) optical carriers with three wavelengths of 1535, 1540 and 1545 nm. The generated optical waveforms have a pulse width of 80 ps and repetition rate of 780 MHz. The optical pulses are transmitted through the MMF-based optical integrator. The input pulses (red curves) and the integration results (blue curves) of the three cases are shown in Figs. 2(a), 2(b) and 2(c). As expected, the integrator performance remains invariant as a function of carrier wavelength. Broadband operation of the integrator is also verified by using a 30 nm broadband amplified spontaneous emission (ASE) source as the optical carrier. A similar integration result is obtained, as shown in Fig. 2(d).

4. Application 1: Integration of wavelength-division multiplexing (WDM) waveform

The wavelength- and bandwidth-independent nature of this integrator is usually desirable for performing the integration of a wavelength-division multiplexing (WDM) waveform. As an example of this application, we apply the optical intensity integrator to an input optical signal consisting of three successive optical pulses with different center wavelengths. The three pulses, each having a pulse width of 30 ps and temporal spacing of 130 ps, are generated by first shaping the broadband spectrum of a femtosecond laser using a three-channel optical bandpass filter (1540.5, 1543.7 and 1546.9 nm), and then temporally stretching the filtered pulses using a 500 meter long dispersive fiber. The optical power spectrum and the temporal intensity profile of the generated optical signal are shown in Figs. 3(a) and 3(b), respectively. Figure 3(c) shows the integration of this signal using the integrator. We use the data in Fig. 3(b) to perform a numerical integration for comparison. The results of this calculation are shown in Fig. 3(c) (red curve). The obtained experimental results (blue curve) show excellent agreement with the theoretical results over the entire integration time window.

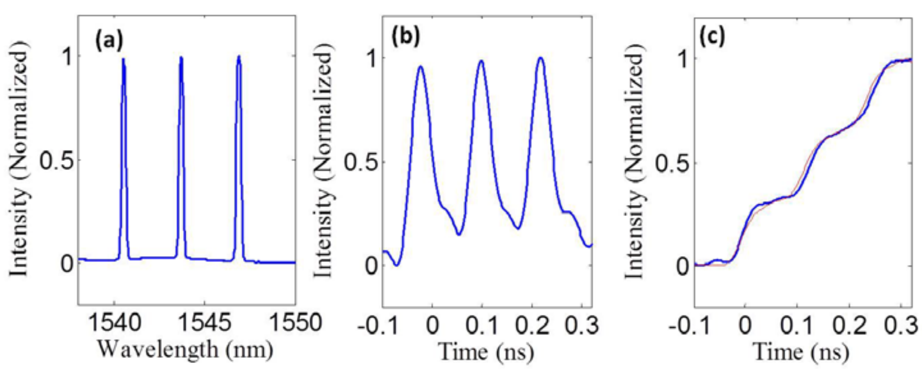

Fig. 3. Demonstration of optical integration of a WDM signal. (a) Spectrum of the input signal. The three peaks are centered at 1540.5, 1543.7 and 1546.9 nm. (b) Input signal waveform, with each pulse in time corresponding to a different center wavelength. (c) Integral of the WDM signal. The red curve is the simulation result and the blue curve is the experimental result.

5. Application 2: Real-time high-throughput optical phase reconstruction

To demonstrate the utility of the optical integrator for ultrafast optical data processing performed in real-time, we applied it to perform high-throughput optical phase reconstruction

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of phase-modulated signals at telecommunications bit rates. Optical phase reconstruction is critical to the performance of coherent optical communications systems and fiber-optic distributed sensing systems [13,14]. The temporal phase profile of an optical signal is typically monitored using a frequency-discriminator-based phase differentiator followed by an optical integrator. Due to the lack of wavelength-insensitive optical integrators, only the derivative of the phase (frequency chirp) can be characterized in real-time [15]. While the complete phase information can be obtained by performing the integration digitally, it is very challenging to implement ultrafast high-throughput real-time integration in the digital domain due to the limited bandwidth of the digitizer and the digital signal processor. Here, we demonstrate complete optical phase reconstruction in real-time by combining a phase differentiator with our optical intensity integrator.

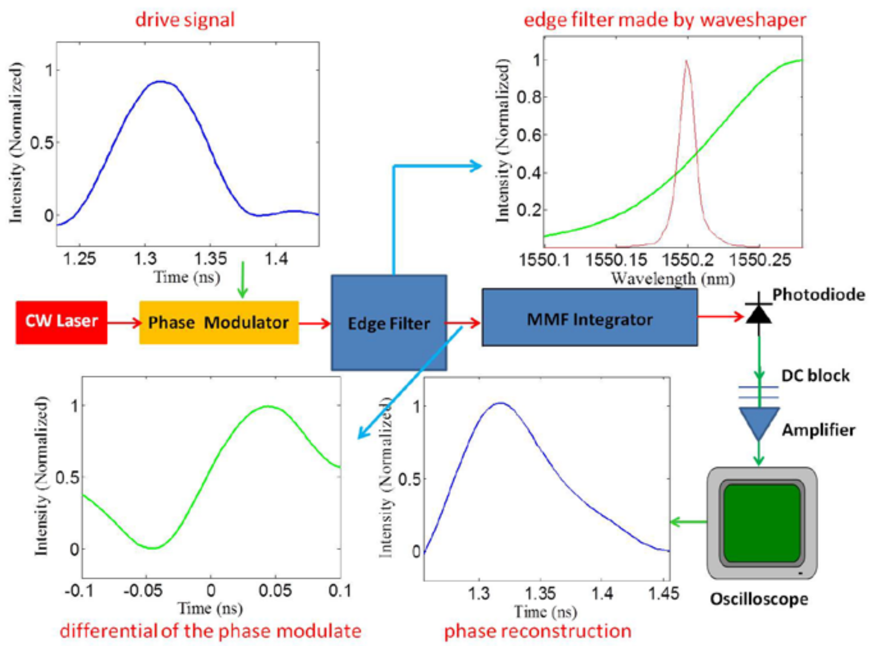

Fig. 4. Demonstration of real-time high-throughput optical phase reconstruction of phase-modulated signals. A CW laser (λ = 1550.02 nm) is phase modulated and transmitted through an edge filter, which serves as a differentiator. The beam is launched into the optical integrator and the phase is reconstructed. (a) The electrical drive signal. (b) Spectrum of the laser and spectral response of the edge filter. (c) Waveform of the output from the edge filter. (d) Waveform of the output from the optical integrator representing the reconstructed phase.

Figure 4 shows the experimental setup of the phase reconstruction system. An optical carrier from a CW laser source (λ = 1550.2 nm) is phase modulated by electrical pulses using a phase modulator. The drive electrical signal, as shown in Fig. 4(a), has a repetition rate of 7.8 GHz and pulse width of 80 ps. The phase modulated light is transmitted through an edge filter, which has a linear amplitude response. Figure 4(b) shows the spectrum of the laser (red curve) and the spectral response of the edge filter (green curve). The edge filter serves as a frequency discriminator, which converts the differential of the phase (instantaneous frequency) into the temporal intensity profile of the optical signal with a DC offset [15]. Figure 4(c) shows the measured temporal waveform at the output of the edge filter. This signal is then launched into the optical integrator. Figure 4(d) shows the output signal. The DC component of the integrated signal is blocked and a low-noise microwave amplifier with 20-dB gain amplifies the signal. The integration time window is reduced to 200 ps by offsetting the incident beam to increase the signal-to-noise ratio. The phase of the original optical signal is reconstructed in real-time using the edge filter and the developed optical integrator.

6. Conclusion

We have developed an all-optical intensity integrator based on multimode wave propagation inside a multimode waveguide. Since the integrator is based on modal dispersion, as opposed to chromatic dispersion, it is both wavelength- and bandwidth-independent, and offers great flexibility for ultra-fast real-time optical data processing. This integrator is simple and cost effective, eliminating the need for complicated optical filter design, optical spectral shaping and electro-optic modulation. We also demonstrated its applications in intensity integration of WDM signals and in real-time high-throughput optical phase reconstruction, with excellent agreement between theory and experiment.

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