Optics and Laser Technology 111 (2019) 66–74

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Temporal analog optical computing using an on-chip fully reconfigurable photonic signal processor

Hossein Babashah[a], Zahra Kavehvash[a,*], Amin Khavasi[a], Somayyeh Koohi[b]

[a] Sharif University of Technology, Department of Electrical Engineering, Azadi Ave., Tehran, Iran
[b] Sharif University of Technology, Department of Computer Engineering, Azadi Ave., Tehran, Iran

HIGHLIGHTS

- A fully reconfigurable on-chip photonic signal processor.
- Dispersive Fourier transform and linearly chirp modulation are used for operation.
- Arbitrary mathematical operation is performed on incident optical signal.
- Operation time of 200 ps with high resolution of 300 fs.

ARTICLE INFO

Keywords:
Integrated optics
Integrability
Optoelectronics
Nonlinear optics
Dispersion
Fourier optics

ABSTRACT

This paper introduces the concept of on-chip temporal optical computing, based on dispersive Fourier transform and suitably designed modulation module, to perform mathematical operations of interest, such as differentiation, integration, or convolution in time domain. The desired mathematical operation is performed as signal propagates through a fully reconfigurable on-chip photonic signal processor. Although a few numbers of photonic temporal signal processors have been introduced recently, they are usually bulky or they suffer from limited reconfigurability which is of great importance to implement large-scale general-purpose photonic signal processors. To address these limitations, this paper demonstrates a fully reconfigurable photonic integrated signal processing system. As the key point, the reconfigurability is achieved by taking advantages of dispersive Fourier transformation, linearly chirp modulation using four-wave mixing, and applying the desired arbitrary transfer function through a cascaded Mach-Zehnder modulator and a phase modulator. Numerical simulations of the proposed structure reveal a great potential for chip-scale fully reconfigurable all-optical signal processing through a bandwidth of 400 GHz.

1. Introduction

It is more convenient for an integrated photonic structure to perform any mathematical operations, such as convolution with an arbitrary function and pulse shaping, in time domain [1–7]. Therefore, analog optical computing has gained widespread applications in optical communication and real-time spectroscopy for processing optical signals in time domain.

One of the most important features in digital signal processing (DSP) is the processing speed, mostly restricted by the electronic sampling rate. In an optical network, signal processing is carried out by DSP, which is responsible for electronic sampling, as well as optical-to-electrical (OE) and electrical-to-optical (EO) conversions. As an approach to achieve power-efficient and high-speed signal processing capability in an optical network, we can implement signal processing unit directly in the optical domain using a photonic signal processor to avoid the need for electronic sampling and OE and EO conversions [8–10].

So far, numerous photonic signal processors have been proposed based on either discrete components or photonic integrated circuits [8–11,7,12–18]. Photonic signal processors based on discrete components, such as fiber Bragg grating [3,17,18], usually have good programming abilities but are bulkier and less power efficient, whereas a photonic integrated signal processor has a much smaller footprint and a higher power efficiency. A photonic signal processor can be used to implement various types of applications, such as optical pulse shaping [19], arbitrary waveform generation [8], temporal integration [14], temporal differentiation [15], optical dispersion compensation [13],

* Corresponding author.
E-mail address: kavehvash@sharif.edu (Z. Kavehvash).

https://doi.org/10.1016/j.optlastec.2018.09.027
Received 10 December 2017; Received in revised form 10 July 2018; Accepted 15 September 2018

Optics and Laser Technology 111 (2019) 66–74

and Hilbert transformation [20]. These functions are basically the building blocks of a general-purpose signal processor performing signal generation and fast computing. Fast computing processes, such as temporal integration, temporal differentiation, and convolution facilitate important applications [20–31]. For example, a photonic integrator, as a device that able to perform time integral of an optical signal, has a key role in dark soliton generation [21], optical memory [22], and optical analog-digital conversion [23]. Moreover, a photonic temporal differentiator [26], as a device performing temporal differentiation of an optical signal, is employed for all-optical Fourier transform [27,28], temporal pulse characterization [29], and the demultiplexing of an optical time division multiplexed (OTDM) signal [30], for example. Although the photonic implementations of these functions have been reported so far [14–16,24,26], an optical signal processor is usually designed to perform a specific function with no or very limited reconfigurability. For general-purpose signal processing, however, a photonic signal processor is desired to perform multiple functions with high reconfigurability [1]. In [1], the reconfigurability is achieved by controlling the injection currents to the active components (i.e. semiconductor-optical-amplifiers) of the signal processor which still yields specific functionality such as differentiation, integration, and Hilbert transform. Consequently, applying any new frequency transfer function or spatial transformation requires a new complicated design of the structure. Therefore, implementing arbitrary transfer function in time domain is worth to be noticed. Pulse shaping has been performed before by transferring the signal from time domain to spatial domain and applying appropriate filters in spatial domain [7]. Nevertheless, as the main drawback of these structures, they necessitate precise optical alignment procedure for fiber optic applications, in which light must be coupled with low loss out of and back into single-mode optical fiber.

To address above limitations, in this paper, a general time-domain analog optical computing structure is proposed which can be implemented in an integrated photonic system. The proposed structure which is of a very small size, provides the possibility of highly compact, potentially integrable architectures within much smaller volumes and, in some cases, over sub-wavelength length, ensuring controlled manipulation and processing of the incoming signal. As a novel idea, we proposed a structure that takes advantages of dispersive Fourier transformation to implement any arbitrary transfer function by a simple time-modulation in the frequency domain. In other words, our work is the time domain counterpart to the idea proposed in [32–34] which performs analog optical computing in spatial domain using lenses and metasurfaces.

Dispersive Fourier transformation has thus far been utilized for separating the frequency components in time domain in order to overcome the slow response of the detector [35] or low speed of the electro-optic phase modulator used for pulse shaping [17,18]. Nevertheless, no analog optical computing, i.e., computational Fourier transformation, has been performed based on a dispersive Fourier transform structure. Still, the use of dispersive Fourier transformation in analog optical computing requires specific considerations. To make the structure implementable in an integrated photonic system, we implemented the dispersive Fourier transformation [35–37] with an on-chip structure with high group-delay-dispersion (GDD) benefiting from time lens for chirp modulation [38]. Moreover, time-domain modulation for multiplying the signal and arbitrary transfer function in frequency domain can be performed through a cascaded Mach-Zehnder modulator and a phase modulator [39,40].

The paper is organized as follows: A review on dispersive Fourier transformation and time lens is discussed in Section 2. Section 3 present the proposed temporal analog optical computing structure. Simulation results are discussed in Section 4; Section 5 concludes the paper.

2. A review on dispersive Fourier transformation and time lens

Time-domain Fourier transformation has been implemented through passing light via dispersive media [36]. Dispersive Fourier transformation (DFT) maps the broadband spectrum of a conventionally ultrashort optical pulse into a time stretched waveform with its intensity profile mirroring the spectrum using chromatic dispersion. It is known that a dispersive element can be modeled as a linear time-invariant (LTI) system with a transfer function given by $H(\omega) = |H(\omega)|\, e^{j\varphi(\omega)}$, where $|H(\omega)|$ and $\varphi(\omega)$ are the magnitude and phase response of the dispersive element at angular frequency ω, respectively. Mathematically, the phase response $\varphi(\omega)$ can be expanded in Taylor series. This dispersive element is conventionally a long length single mode fiber [35]. The propagation of an optical pulse through a dielectric element with up to the second-order dispersion coefficients (assuming negligible higher-order dispersion coefficients within the bandwidth of interest) can be described with the following transfer function and impulse response:

$$H(\omega) = |H(\omega)|\, e^{j\varphi_0} e^{j\dot{\varphi}_0\omega} e^{j\frac{1}{2}\ddot{\varphi}_0\omega^2} \xrightarrow{\Im^{-1}} h(t) = e^{j\varphi_0} e^{-j\frac{1}{2\ddot{\varphi}_0}(t-\dot{\varphi}_0)^2} \quad (1)$$

where $|H(\omega)|$ is engineered to be constant or have weak dependence to the angular frequency and $\varphi(\omega)$ equals to $\beta(\omega)L$ where $\beta(\omega)$ and L are propagation constant and waveguide's length, respectively. The stretched pulse can be therefore approximated by [41]:

$$y(t) = x(t)*h(t) = \int_{-\infty}^{\infty} x(\tau) e^{j\beta_0 L} e^{-j\frac{1}{2\ddot{\beta}_0 L}(t-\tau-\dot{\beta}_0 L)^2} d\tau \quad (2)$$

setting $\tau_R = \tau + \dot{\beta}_0 L$ we have:

$$y(t) = e^{j\beta_0 L} \int_{-\infty}^{\infty} x(\tau_R - \dot{\beta}_0 L) e^{-j\frac{1}{2\ddot{\beta}_0 L}(t-\tau_R)^2} d\tau_R = e^{j\beta_0 L} e^{-j\frac{1}{2\ddot{\beta}_0 L}t^2} \int_{-\infty}^{\infty} x(\tau_R - \dot{\beta}_0 L) e^{-j\frac{1}{2\ddot{\beta}_0 L}\tau_R^2} e^{+j\frac{1}{\ddot{\beta}_0 L}t\tau_R} d\tau_R \quad (3)$$

to compensate for the term $e^{j\frac{1}{2\ddot{\beta}_0 L}\tau_R^2}$, the input signal, $x(t)$, is modulated with a quadratic phase modulation as follows:

$$x(\tau) = x_0(\tau) e^{+ja(\tau+\dot{\beta}_0 L)^2} \quad (4)$$

where a is the chirp factor. By considering $a = \frac{1}{2\ddot{\beta}_0 L}$ we yield the following equation for $y(t)$:

$$\tilde{y}(t) = e^{j(\beta_0 L - \frac{1}{2\ddot{\beta}_0 L}t^2)} \int_{-\infty}^{\infty} x_0(\tau_R - \dot{\beta}_0 L) e^{j\frac{1}{\ddot{\beta}_0 L}t\tau_R} d\tau_R = e^{j(\beta_0 L + \frac{t+\dot{\beta}_0 L}{\ddot{\beta}_0 L}\dot{\beta}_0 L - \frac{1}{2\ddot{\beta}_0 L}t^2)} X_0(\omega)\Big|_{\omega=\frac{t+\dot{\beta}_0 L}{-\ddot{\beta}_0 L}} \quad (5)$$

where $X(\omega) = \Im\{x(t)\}$, is the Fourier transform of the input pulse. This phase modulation is significantly larger than the 10π possible phase shift using an electro-optical phase modulator, and therefore an alternative scheme can be realized using a parametric nonlinear wave mixing process such as four wave mixing [38]. In this approach, a Gaussian pump pulse propagates through a dispersive medium with a GVD equals to $\ddot{\beta}_p$ and length of L_p that is much longer than the dispersion length of the pulse. As a result, the pulse undergoes temporal broadening and is linearly chirped. The broadened linearly chirped signal which is proportional to $e^{j\frac{\tau^2}{2\ddot{\beta}_p L_p}}$ is then used in the four wave mixing process as the pump pulse. The output signal denoted as idler in the four wave mixing can be filtered and it is calculated as follows:

$$E_{idler}(t) = E_{pump}^2(t) E_{input}^*(t) \quad (6)$$

where $E_{idler}(t)$, $E_{pump}(t)$, and $E_{input}(t)$ are the output, pump and input electric field amplitude in the four wave mixing process. The output electric field frequency, $\omega_{idler} = 2\omega_{pump} - \omega_{input}$, is obviously different from the input and the pump frequency. This frequency could be separated in the output through using a band-pass Bragg filter. It should be here mentioned that, the chirp phase modulation could be avoided by making the term $\tau_R^2/2\ddot{\beta}_0 L \ll 1$, for all values of τ_R between 0 and pulse duration, T. This is possible if and only if a long length of the