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Photonic compressive sensing for analog-to-information conversion with a delay-line based microwave photonic filter

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ABSTRACT

Compressive sensing (CS) in the photonic domain is highly promising for analog-to-information conversion of sparse signals due to its potential capability of high input bandwidth and digitization with sub-Nyquist sampling. In this paper, we suggest that the concept of delay-line based microwave photonic filter be used in photonic CS to realize the low-pass filtering (LPF) function which is required in CS. A microwave photonic filter (MPF) with a dispersive element and fiber delay lines is applied in photonic CS to achieve better performance and flexibility. In the approach, the input radio-frequency signal and the pseudorandom bit sequence (PRBS) are modulated on a multi-wavelength optical carrier and propagate through a dispersive element. The modulated optical signal is split into multiple channels with tunable delay lines. The multiple wavelengths, dispersive element and multiple channels constitute a reconfigurable low-pass microwave filter. Experiment and simulations are presented to demonstrate the feasibility and potentials of this approach.

1. Introduction

Compressive sensing (CS) in the photonic domain is highly promising for analog-to-digital conversion of wideband sparse signals due to the advantages of sub-Nyquist sampling enabled by CS and extremely high input bandwidth enabled by photonic technologies and components [1,2]. According to the CS theory, sparse signals, for example, multiband sparse signals which occupy only a few spectra in a large bandwidth can be captured by a digitizer with a sampling rate far below the Nyquist rate. The implementation of photonic CS was firstly proposed by Valley and his colleagues [3,4]. In their scheme, an optical pulse source and a spatial light modulator (SLM) based pulse shaper are employed to implement the mixing of the radio-frequency (RF) signal and the random sequence in the photonic domain. In recent years, several approaches to implementing CS with photonic techniques have been proposed, which include the CS in a photonic link [5,6], the CS with improved mixing performance [7–9], the CS with the technique of photonic time stretch [10–12], the photonic multi-channel CS [13–15], and the CS in nanophotonic structures [16]. Basis mismatch in the photonic CS system has also been investigated [17]. A photonics-enabled scheme using CS and temporal channelization was proposed [18]. In order to realize the function of low-pass filtering required in CS, the technique of microwave photonic filter has been incorporated into the photonic CS system [19–21], in which the LPF function can be implemented by using a multi-wavelength source and a dispersive element.

In this paper, we present an approach to achieving the function of LPF in CS, which is simpler and more flexible than former approaches. Benefitting from the dispersive element and the delay-line pattern, the system uses fewer wavelengths to achieve the required compression factor, remarkably reducing the number of required laser sources and the wavelength tuning range. The applied tunable delay-line based approach is proposed according to the structure of optical fiber delay lines to achieve time delay differences in microwave photonic filter [22–24], which can largely reduce the necessary wavelength number to assure the required frequency response and improve the performance in realizing the low-pass filtering function, and also offer better flexibility in the filter design.

2. Theory

Compressive sensing aims at reducing the number of measurements to fully capture a signal by using its sparsity [25], which helps reduce the pressure of storing, transmitting and receiving the data. As shown in Fig. 1, a sparse signal is measured and compressed before being transmitted, and after being received the original signal can be reconstructed by using a recovery algorithm.

In detail, the measurement process of the CS, which is shown in Fig. 2, can be modeled as $\mathbf{y} = \mathbf{F}\mathbf{x}$, where the input sparse signal $\mathbf{x}$ is

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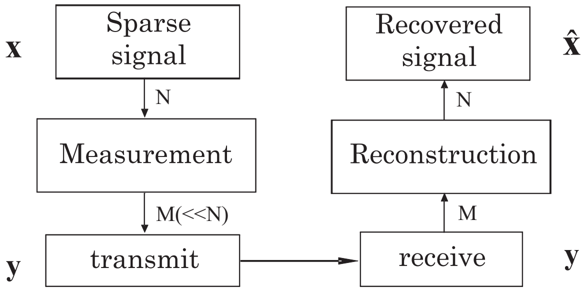

Fig. 1. The basic concept of CS ($\mathbf{x}$: input signal, $\mathbf{y}$: measurement results, $\hat{\mathbf{x}}$: recovered signal).

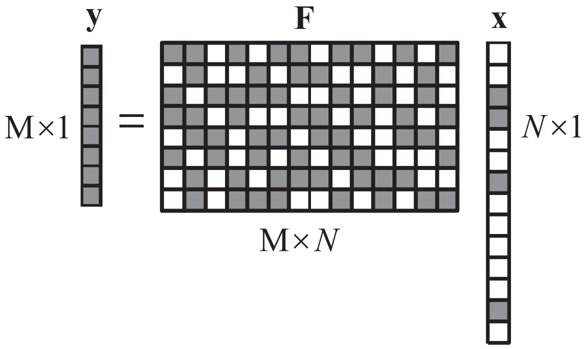

Fig. 2. Illustration of the CS measurement process [25].

represented by an $N \times 1$ vector, the measurement results $\mathbf{y}$ is an $M \times 1$ vector ($M < < N$), and $\mathbf{F}$ is an $M \times N$ matrix representing the measurement process. To the CS scheme for the analog-to-information conversion of time-domain signal, such as the random demodulator, the measurement matrix can be modeled as $\mathbf{F} = \mathbf{DIR}$, in which the matrix $\mathbf{R}$ is a diagonal $N \times N$ matrix representing a random sequence, $\mathbf{I}$ is an $N \times N$ matrix denoting the impulse response of a low-pass filter, and the $M \times N$ matrix $\mathbf{D}$ means a down-sampling process. In the proposed scheme, the low-pass filtering function is realized by a multi-tap microwave photonic filter and the digitizer operates with a sampling rate of M/N of the Nyquist rate of the input signal. Therefore the compression factor of the CS is $L = N/M$.

In theory, the method to reconstruct the input signal is to solve the minimization problem.

$$\hat{\mathbf{x}} = \arg\min \|\mathbf{v}\|_0 \text{ subject to } \mathbf{Fv} = \mathbf{y} \tag{1}$$

where the l_0 function $\|\mathbf{v}\|_0$ represents the number of nonzero entries in the vector $\mathbf{v}$ [26]. A number of algorithms, such as the orthogonal matching pursuit algorithm, are available now for signal reconstruction.

Our approach to realizing photonic CS with a delay-line based filter is shown in Fig. 3. The optical carrier is provided by a multi-wavelength laser source and the input RF sparse signal is modulated on it through a Mach–Zehnder modulator (MZM1). Then the signal is modulated by another MZM (MZM2) which is driven by the PRBS. The mixed optical signal propagates through a dispersive element and is split by an optical coupler into multiple channels. After passing through the multiple optical channels, the delayed signals are combined together after O/E conversion and then digitized by an analog-to-digital converter (ADC) at a sampling rate largely lower than the Nyquist rate. The measurement results are sent to the digital signal processor to reconstruct the signal with a reconstruction algorithm. In our approach, the low-pass filtering function is realized with the help of a multi-wavelength carrier, a dispersive element and tunable delay lines, in place of an electrical low-pass filter. Note that the wavelength space of the optical carrier, the dispersion amount and the lengths of tunable delay lines are precisely set according to the bit duration of the random sequence. In detail, the wavelength space and the dispersion amount of the dispersive element should be set in accordance with the bit duration of the random sequence to ensure the group delay between adjacent wavelength channels is equal to the bit duration. And the tunable delay lines should be adjusted to assure the time delay between adjacent channels is $i \times B$, where i is the number of wavelengths and B is the bit duration of the random sequence. Benefitting from this structure, this approach uses fewer tunable laser sources and reduces the requirement for the wavelength tuning range of the laser source. The performance of low-pass filtering function is improved and the number of delay-line channels can be adjusted according to the compression factor, making the system configurable.

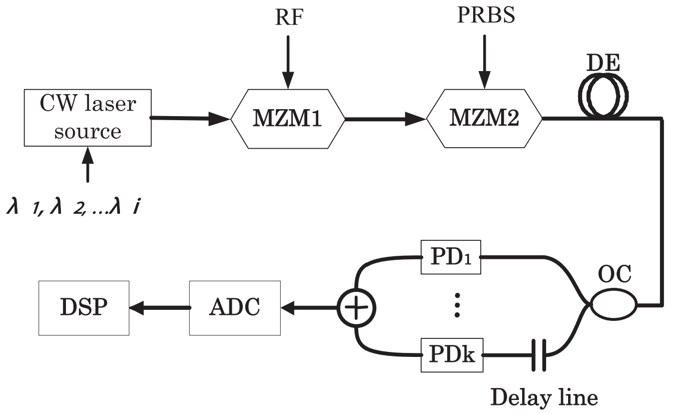

Fig. 3. Schematic of the photonic CS structure with a delay-line based microwave photonic filter (RF: radio-frequency signal, PRBS: pseudorandom bit sequence, DE: dispersive element, MZM: Mach–Zehnder modulator, PD: photodetector, OC: optical coupler, ADC: analog-to-digital converter, DSP: digital signal processor).

The microwave photonic filter applied here consists of two stages. In the first stage, the optical signal which is modulated on the multi-wavelength optical carrier propagates through a dispersive element, and due to the group delay between the adjacent wavelength channels, the low-pass filtering function is realized. Then the signals pass through a delay-line pattern and are combined together after O/E conversion, which realizes the second stage of the MPF. As the function of the first and second stage can be regarded as an i-tap filter and a k-tap filter respectively, the frequency response of the filter can be expressed as $H(\omega) = H_0(\omega)\sum_{n=0}^{i*k-1} e^{-j\omega nB}$, where $H_0(\omega) = \cos(\frac{DZ\lambda^2\omega^2}{4\pi c})$ is the frequency response of the frequency-dependent RF power fading, which can be neglected in our scheme, D is the dispersion coefficient, Z is the fiber length, λ is the wavelength of the optical carrier, c is the velocity of light in vacuum, k is the number of delay-line channels, i is the number of wavelengths and B is the bit duration of the random sequence, which ensures the required response precisely and improves the performance of the low-pass filtering function. In this case, the compression factor of the CS is $L = N/M = i \times k$. The measured frequency response of a typical filter with two wavelengths and two delay-line channels, as well as the predicted one, is shown in Fig. 4. This configuration can be used as a reconfigurable low-pass microwave filter and enables us to use fewer wavelengths to achieve the required compression factor. For example, to achieve the compression factor of 16, by using 2 tunable delay-line channels in the second stage, 8 wavelengths are needed, leading to a result that 8 tunable laser sources are reduced, which is of great benefit to the cost and power consumption of the system. Consider 2 or 3 delay-line channels are applied, the number of laser sources can be reduced by 50% or 67%, respectively. The number of delay-line channels in the second