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Photonic compressive sensing with a micro-ring-resonator-based microwave photonic filter

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ABSTRACT

A novel approach to realize photonic compressive sensing (CS) with a multi-tap microwave photonic filter is proposed and demonstrated. The system takes both advantages of CS and photonics to capture wideband sparse signals with sub-Nyquist sampling rate. The low-pass filtering function required in the CS is realized in a photonic way by using a frequency comb and a dispersive element. The frequency comb is realized by shaping an amplified spontaneous emission (ASE) source with an on-chip micro-ring resonator, which is beneficial to the integration of photonic CS. A proof-of-concept experiment for a two-tone signal acquisition with frequencies of 350 MHz and 1.25 GHz is experimentally demonstrated with a compression factor up to 16.

1. Introduction

Microwave signals acquisition over a wide bandwidth has become an essential technique in advanced radar, radio astronomy and electronic warfare systems. The conventional way for signal acquisition is based on analog-to-digital converters (ADCs) with Nyquist sampling rate. However, the improvement in electronic techniques largely lags behind that of digital signal processing due to the limits in timing issues and other inherent device technologies. Photonic ADCs have attracted intensive research interests in recent decades owing to the availability of high-repetition-rate mode-locked lasers with ultra-low timing jitter and the advantage of wide-bandwidth offered by photonics [1]. Recently, compressive sensing (CS) with photonic techniques has been proposed to acquire sparse signals with sub-Nyquist sampling rate [2–17]. CS is a highly efficient way for sparse signal acquisition from a number of sampling points that is far less than the Nyquist sampling points [18–20]. Realizing CS in a photonic link takes both advantages of CS and photonics, which is a promising method for the acquisition of ultra-wideband sparse signals with a low sampling rate and a simple structure. CS realized in a photonic link provides the possibility to extend the system bandwidth compared to its electronic counterpart since the functions of signal modulation and mixing are implemented in the optical domain.

The initial work of photonic CS is to realize the random mixing of CS in the optical domain, including random mixing based on spatial light modulator (SLM) [2,3] and electro-optic modulators (EOMs) [4–6]. To further reduce the sampling rate of the system, the combination of the techniques of photonic time stretch and CS was proposed in [7]. In [8], time delayed pseudo-random bit sequences (PRBSs) with single PRBS source was realized to simplify the photonic CS with a multi-channel configuration. More recently, it has been demonstrated that the functions of low-pass filtering or integration in the CS can also be implemented in a photonic way. In [9], optical integration is achieved based on the compression of a chirped pulse propagating through a dispersive fiber. To simplify the realization of optical integration, delay-and-sum function of the random mixed signal is achieved with a configuration using multi-wavelength continuous-wave (CW) light source and dispersive fiber [10]. In [11], a microwave photonic filter with a single CW light source and a dispersive element is implemented in the photonic CS based on the dispersion-induced power fading of RF signal.

In this paper, we develop a novel architecture of photonic CS with a comb-based microwave photonic filter. The proposed system aims to acquire ultra-wideband sparse signals without using high speed electronics. A multi-tap microwave photonic filter is realized with dispersive medium and an optical frequency comb, which is achieved by spectrally shaping of an amplified spontaneous emission (ASE) source with a silicon micro-ring resonator.

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Compared with the previous approaches, the multi-tap filter presented here has higher side-lobe suppression and better frequency response due to the controllable comb number, which can improve the recovery performance of CS based signal acquisition. In addition, the use of compact on-chip component is beneficial to the integration of the system. Experimental and simulation results show a wide-band sparse signal can be captured with high performance even under a compression factor of 16.

2. Operation principle

A schematic of our proposed photonic CS is shown in Fig. 1. An ASE source with a polarizer, a polarization controller (PC) and a tunable optical band pass filter (OBPF) are placed before a micro-ring resonator, which acts as a comb-like filter. The number of optical frequencies can be selected with the tunable OBPF. A spectrally sparse signal $x(t)$ to be captured is modulated on the frequency comb via a Mach–Zehnder modulator (MZM) which is biased at the quadrature point. The modulated optical signal is mixed with PRBS $r(t)$ (alternating between 0 and 1) via another MZM which is biased at the null point.

The normalized optical power of the mixed signal at the output of the second MZM can be written as

$$P(t) = [1 + mx(t)]\cdot r(t) = x'(t)r(t) \tag{1}$$

where m is modulation depth of the MZM for signal modulation. According to the theory of CS, the bit rate of $r(t)$ should be equal to or above the Nyquist rate of $x(t)$. After passing though a length of dispersive fiber, a time delay is introduced to the randomly mixed signal between adjacent wavelength channels. As the multi-wavelength optical carrier is incoherent, the electrical signal after the photodetector (PD) is a delay-and-sum version of the mixed signal, which can be expressed as

$$I(t) = \sum_{k=0}^{L-1} a_k P(t - kT) = \sum_{k=0}^{L-1} a_k P(t - kD\Delta\lambda) \tag{2}$$

where a_k is the coefficient of the kth wavelength channel, D is the accumulated dispersion amount of the dispersive fiber in (ps/nm), $\Delta\lambda$ is the wavelength space of adjacent channels, L is the wavelength number. In the frequency domain, the frequency response of the sum-and-delay of the multiple channels is

$$H(f) = \sum_{k=0}^{L-1} a_k \exp(-jk2\pi fD\Delta\lambda) \tag{3}$$

It is seen from Eq. (3) that a multi-tap microwave photonic filter with a free spectral range (FSR) of $1/(D\Delta\lambda)$ is achieved which can be used as the low-pass filter (LPF) in the CS. The electrical signal $I(t)$ is then down-sampled via an electronic ADC and the acquired digital signal $\mathbf{y}$ is sent to a digital signal processing module for signal reconstruction with a sparse recovery algorithm. The recovery algorithm is operated by modeling all the processes with matrixes, which is expressed as $\mathbf{y}=\mathbf{\Phi x}=\mathbf{\Phi W\theta}$. The incoming spectrally sparse signal $\mathbf{x}$ can be expressed in an $N\times N$ Fourier basis $\mathbf{W}$ as $\mathbf{x}=\mathbf{W\theta}$, where $\boldsymbol{\theta}$ is an $N\times 1$ vector representing the Fourier coefficients of $\mathbf{x}$. $\mathbf{\Phi}$ represents the measurement process with random entries of dimension $M\times N$ $(M<<N)$ and $\mathbf{y}$ is the measurement result of dimension M. $\mathbf{\Phi}$ can be further modeled as $\mathbf{\Phi = DHR}$, where $\mathbf{R} = \mathrm{diag}[r(t)]$ is an $N\times N$ diagonal matrix denoting the random sequence, $\mathbf{H}$ is an $N\times N$ matrix representing the impulse response of the LPF, $\mathbf{D}$ is an $M\times N$ matrix denoting the down-sampling process of the digitizer. According to the theory of CS, $\boldsymbol{\theta}$ can be fully reconstructed by solving a minimization problem $\hat{\theta} = \arg\min \|\theta'\|_{\ell_1}$, subject to $\Phi W\theta' = y$ if the matrix product $\mathbf{\Phi W}$ satisfies the restricted isometry property.

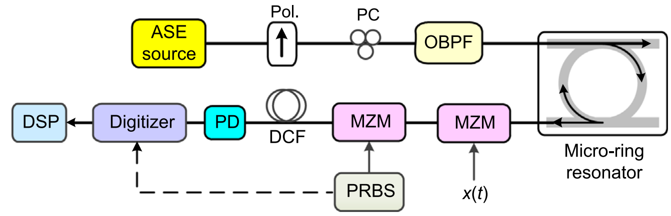

Fig. 1. Schematic illustration of the proposed photonic CS (ASE: amplified spontaneous-emission, Pol.: polarizer; PC: polarization controller; OBPF: optical band-pass filter, MZM: Mach–Zehnder modulator, PRBS: pseudo-random bit sequence, PD: photodetector, DSP: digital signal processing, DCF: dispersion compensating fiber).

3. Results and discussion

A proof-of-concept experiment with the setup shown in Fig. 1 is implemented. The ASE light (AGILENT 83438A) first passes through a polarizer to generate a polarized light, which is tuned to be transverse electric (TE) mode and coupled to the silicon chip by a photonic crystal grating coupler. The detailed fabrication process of the silicon chip can be found in [21]. An OBPF with a Gaussian-like profile and a 3 dB bandwidth of 5 nm is introduced before the micro-ring resonator. The silicon micro-ring resonator has an FSR of 0.8 nm and a Q factor of 1.7×10^5. The optical signal is amplified before entering the micro-ring resonator, and the available output optical power is around 4 dBm. The generated frequency comb with a resolution of 0.02 nm is shown in Fig. 2(a). Two MZMs with bandwidth of 40 GHz are used for signal modulation and PRBS modulation. The applied PRBS is generated by a pulse pattern generator and the sequence has periodical length of 2^7–1. By using a coil of dispersion compensation fiber (DCF), the function of low-pass filtering can be achieved. A typical frequency response with the frequency comb and a length of DCF is given in Fig. 2(b), which is measured in a system with a total dispersion amount of 90.7 ps/nm at 1550 nm. In this case an LPF with a 3-dB bandwidth of around 0.5 GHz is realized. The mismatch between the measured and predicted results is mainly due to the amplitude fluctuation of the optical frequency comb and the higher-order dispersion of the DCF. The impulse response of the LPF can be obtained from its frequency response by using the Fourier transform, which is employed to construct the matrix $\mathbf{H}$. To match the compression factor and the bit rate of the applied PRBS of the CS system, the impulse response of the LPF can be adjusted by changing the length of DCF.

In the experiment, a two-tone RF signal containing frequencies of 350 MHz and 1.25 GHz is employed as the spectrally sparse signal to be measured. The spectrum of the input signal is shown in Fig. 3(a). The bit rate of the applied PRBS is 2.5 Gb/s, equal to twice of the highest frequency component of the input sparse signal. The detected electrical signal from PD (HP 11982A) is captured by a real-time oscilloscope (Tektronix DPO4102B-L) with a sampling rate of 5 GS/s. The data length is set to be N=10,000 and the recorded data from the oscilloscope is down-sampled to M samples in a program according to the required compression factor of the CS process. The down-sampled signal with a compression factor of 8 is shown in Fig. 3(b). The equivalent sampling rate of the digitizer is 1/8 of the Nyquist rate of the signal, which is calculated to be 312.5 MS/s. The sparse recovery algorithm proposed in [22] is applied to reconstruct the input signal with the down-sampled data $\mathbf{y}$ and the measurement matrix $\mathbf{\Phi}$ calculated according to $\mathbf{\Phi = DHR}$. Figs. 3(c) and (d) compare the reconstructed spectra and the time domain signals with the original ones. It can be concluded from the results that both the time-domain and the frequency-domain information are successfully