Wideband Photonic Compressive Sensing System Based on Bipolar Optical Chaos

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***Abstract*—We propose a wideband photonic compressive sensing system based on bipolar wideband optical chaos, which supports simultaneous reconstruction for multiple frequency components in the range of 0-40GHz with only a 2GS/s down-sampling rate.**

***Keywords*—optical chaos, photonic compressive sensing, digital signal processing**

I. Introduction

Compressive sensing (CS) is a novel technology for the acquisition of sparse signals. It can reconstruct sparse signals with a sampling rate much less than the Nyquist sampling rate [1]. In recent years, CS has been widely used in many areas, such as detection imaging, radar sensing, satellite remote sensing, et al. [3]. Up to present, random demodulator (RD) and modulated wideband converter (MWC) are two main frameworks in CS [6]. The RD-based structure of CS focuses on recognizing sparse multi-tone signals while the MWC-based structure applies to identifying multi-band signals. Both schemes adopt random mixing, low-pass filtering, and down-sampling to get a measurement vector. Recently, photon-assisted CS systems have been proposed to get rid of the bandwidth limitation of electronic devices [8].

Nichols first mixed sparse signals and measurement signals in a photonic link by using two cascaded Mach-Zehnder modulators (MZM), which largely improved the system bandwidth [8]. Due to the characteristic of intensity modulation and direct detection of optical links, this scheme cannot get a zero-mean measurement matrix, which would deteriorate the recovery performance. To solve this problem, an optical random mixing scheme with three MZMs and a balanced structure was proposed, and multi-tone signals can be reconstructed in this scheme [9]. To further enhance the bandwidth of CS systems, researchers introduce a technology of time stretch, which can slow down the rate of the sparse signal to reduce the requirement of the rate of pseudo-random binary sequence (PRBS) [10]. Nevertheless, in RD-based systems, it is a great challenge to require the PRBS rate to meet or exceed the Nyquist rate of the sparse signal. Therefore, it is necessary to seek a novel random sequence to improve the bandwidth of such a system.

In this paper, a wideband compressed sensing system based on bipolar optical chaos is proposed. Wideband chaos is emitted from a chaotic source. Then we adopt a scheme of delay subtraction to get bipolar signals. The randomness is enhanced by optimizing the bandwidth of the chaotic signal and therefore improves the quality of signal reconstruction. This CS system avoids generating high-speed PRBS and an all-optical mixing is achieved to enhance the system's bandwidth.

II. Principle

The proposed scheme is schematically illustrated in Fig 1. This system is composed of two parts. The first part is a wideband chaotic generation system. Phase modulation and dispersion are used to produce wideband chaos [12]. The feedback optical signal is modulated by a phase modulator (PM), which can generate more frequency components, and the signal is broadened over the spectrum. Next, the output signal propagates through a single-mode fiber (SMF) after modulation. Dispersion can motivate nonlinear effects and make the power spectrum flatter, which improves the bandwidth of the chaotic laser. Since the photodetector is not sensitive to phase, dispersion also enables PM-IM conversion. In the system, the wideband chaotic signal acts as a measurement signal and an optical carrier signal. The second part is an RD-based CS system. The wideband chaos is divided into two channels by a 50:50 fiber coupler (FC), and the sparse signal $x(t)$ is modulated to the optical paths via MZMs, which work at the quadrature point. Unlike the upper channel, the chaos in the lower channel is delayed by a delay line (DL) before being modulated. Sufficient delay time can ensure the chaotic signals from different paths are uncorrelated. The signals from the two channels are detected by a balanced photodetector (BPD). The parameters are the same except for the chaotic signals on the upper and lower

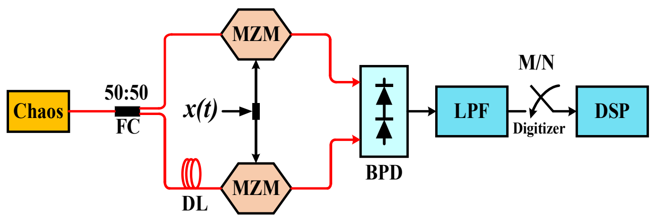

Fig. 1. Photonic compressive sensing system based on wideband optical chaos. FC, fiber coupler; DL, optical delay line; MZM, Mach-Zehnder modulator; BPD, balanced photodetector; LPF, low-pass filter; DSP, digital signal processing.

channels, so we get the subtraction term from the two channels and a bipolar mixed signal is acquired. Moreover, the amplitude distribution of the chaotic signal is optimized with the delay subtraction and obeys the zero-mean Gaussian distribution. Then the signal passes through a low-pass filter (LPF) and is down-sampled with an analog-digital converter (ADC). So we can get an $M\times 1$ ($M<<N$) vector $\mathbf{y}$, which is the observed value after down-sampling. The whole system model refers to the CS structure based on RD, so it is supposed to construct a measurement matrix $\mathbf{\Phi}$, which is consisted of three parts: a down-sampling matrix $\mathbf{D}$ with dimension $M\times N$, an $N\times N$ matrix $\mathbf{H}$ representing the impulse response of the LPF and an $N\times N$ diagonal matrix $\mathbf{R}$ denoting measurement signal. The measurement matrix $\mathbf{\Phi}=\mathbf{DHR}$. At last, the sparse signal is reconstructed with the BP algorithm by using measurement matrix $\mathbf{\Phi}$ and observed vector $\mathbf{y}$.

III. Results And Discussions

The parameters used in the simulations are set as: the feedback strength of the optical signal is chosen to be -20dB, the PM modulation depth is 2, and the feedback delay is 5ns. The fiber length is set as 25km and the dispersion coefficient is 16ps/nm/km, as such the cumulative dispersion is 400ps/nm. The half-wave voltage of the MZM is set to be 3.5V. The LPF cut-off frequency is 500MHz, the sample length N of the signal $x(t)$ is 8000 and the observation length M is 200. So the compressive ratio is N/M=40. The original signal $x(t)$ is set with frequencies 1.2, 13.4, 18, 23.3, and 38.6GHz within the bandwidth of 40 GHz, and its SNR is set as 20dB. So the sparsity of the signal is K=5.

Fig. 2 shows the amplitude distribution of the chaotic signal before and after delay subtraction and their reconstruction results of the sparse signal. The blue line represents the original signal while the red line denotes the reconstructed signal. In fact, due to the nonnegativity of optical signals, the amplitude distribution of optical chaos should all be greater than zero, (a1) and (b1) are the estimated values of the probability density of amplitude. It shows that the delay subtraction scheme converts a unipolar signal into a bipolar signal, and the amplitude of the signal obeys zero-mean Gaussian distribution. Therefore it improves the reconstruction performance of the CS system. Fig. 2 (a2)-(b3) compare the quality of reconstruction of single-tone signals between unipolar and bipolar chaotic signals. The single frequency is set to 18GHz. Both of the two chaotic signals can recover $x(t)$. To evaluate the effect of signal reconstruction, we consider relative root mean square error (RRMSE) and error energy ratio (EER). It is necessary to increase measurement times to reduce the error as much as possible. The RRMSE and EER of unipolar chaos are 0.0652 and 0.0083, while for the bipolar chaos case, the values are 0.0384 and 0.0021. Fig. 2 (a4)-(b5) compare the reconstruction performance of multi-tone signals between unipolar and bipolar chaotic signals. The unipolar chaotic signal cannot reconstruct multi-tone signals while the signal after delay subtraction can successfully reconstruct $x(t)$ with acceptable performance (the spectrum of the signal is at least 5dB higher than the level of the noise [13]). These phenomena straightforwardly confirm that the CS system with bipolar chaos shows a better performance in the reconstruction than the unipolar chaos-based ones, which is especially apparent in the recognition of multi-tone signals.

Fig. 3 illustrates the system reconstruction performance before and after bandwidth enhancement of the chaotic signal. The first and second columns show the time-domain wave,

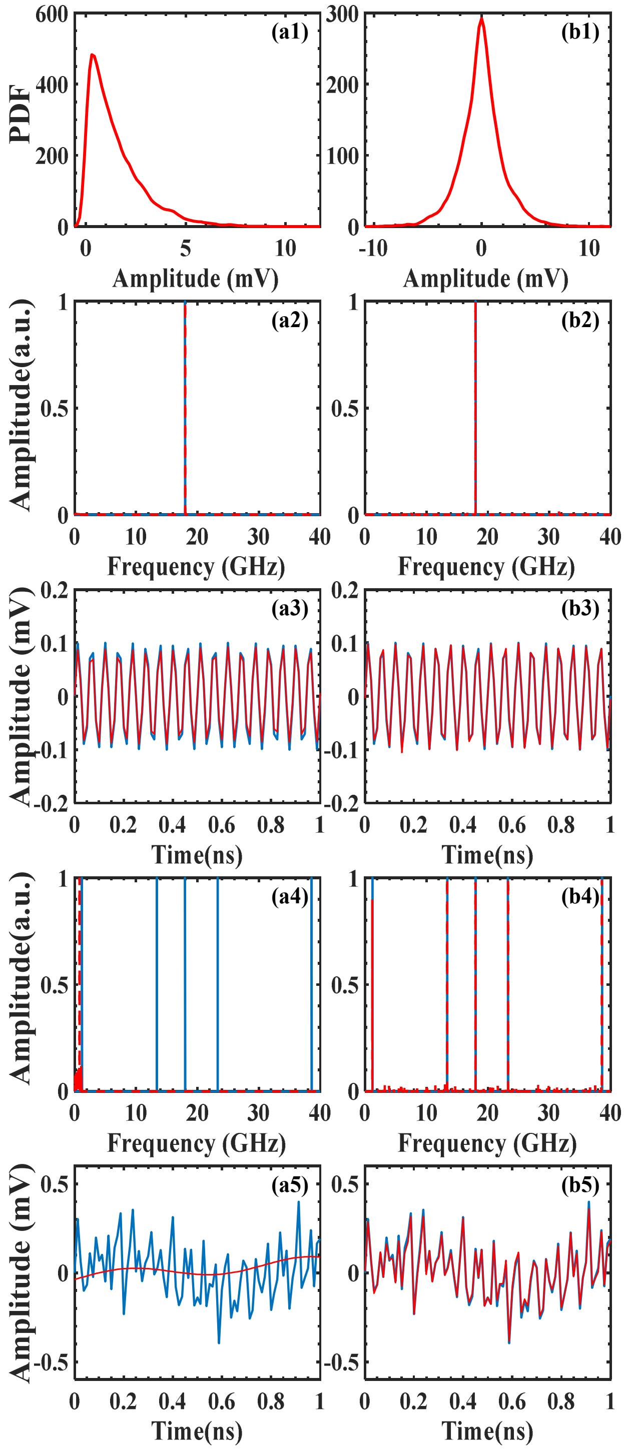

Fig. 2. Chaotic signal before (a) and after (b) delay subtraction. Amplitude distribution (first row), spectrum reconstruction of single-tone signal (second row), time-domain reconstruction of single-tone signal (third row), spectrum reconstruction of multi-tone signal (fourth row) and time-domain reconstruction of multi-tone signal (fifth row)

spectrum, and reconstruction effect of the conventional optical feedback (COF) and of the wideband chaotic signal. Fig. 3 (a1) and (b1) show that the time domain of chaos produced by the PM+SMF scheme changes faster than the COF scheme. Fig. 3 (a2) and (b2) indicate that the PM+SMF scheme has a flatter power spectrum, which means the bandwidth of the chaos is enhanced, proving the randomness of the wideband chaotic signal is better than traditional optical feedback.

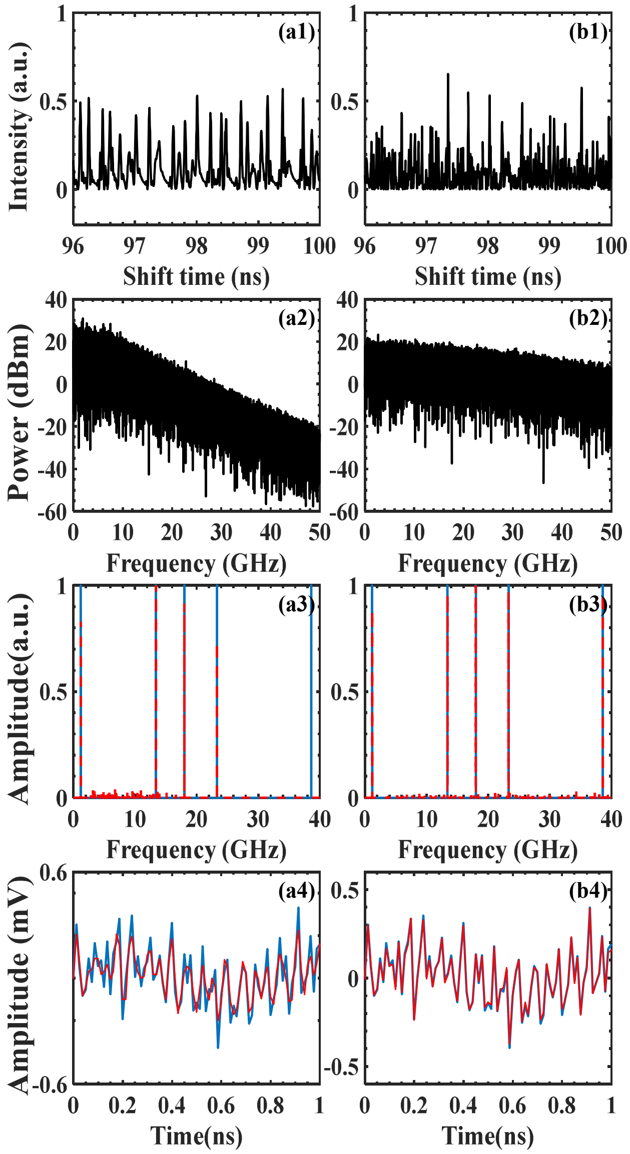

Fig. 3. Conventional optical feedback (first column) and optical feedback with phase modulation and dispersion (second column). Time-domain of chaotic signals (first row), power spectrum of chaotic signals (second row), spectrum reconstruction (third row) and time-domain reconstruction (fourth row)

Therefore, better reconstruction performance can be achieved owing to the enhancement of chaos bandwidth.

Figs. 3 (a3)-(b4) present the reconstruction performance of multi-tone signals. It is clear that the CS system based on COF fails to reconstruct the high-frequency component of 38.6GHz, and the amplitude of the component of 23.3GHz is decayed. We usually use the effective bandwidth, a frequency range corresponding to 80% of the total energy of the spectrum from the DC component [14], to measure the bandwidth of the chaotic signal. In CS systems, the bandwidth of the COF scheme is 16.05GHz, while the bandwidth of the PM+SMF scheme is 30.5GHz. The RRMSE and EER of the COF scheme are 0.1669 and 0.1221, while the PM+SMF scheme are 0.0350 and 0.0063. Moreover, all reconstructions are successful within the acceptable limit in the PM+SMF scheme. The result illustrates that the enhanced bandwidth of the chaotic signal can improve the range of the compressive sensing and the reconstruction effect.

IV. Conclusion

A wideband photonic compressive sensing system based on bipolar optical chaos is proposed. A wideband and complexity-enhanced optical chaos signal is used as a measurement signal to replace PRBS, which provides a novel alternative to measurement signals. We propose a bipolar chaos generation scheme in virtue of the delay subtraction to improve the reconstruction performance. Based on this, an exemplary reconstruction for multi-tone sparse signals in the range from 0 to 40 GHz by using a 2 GS/s down-sampling rate is numerically demonstrated. Compared with the CS systems using chaos generated with the COF scheme, both the quality of the reconstruction performance and the sensing frequency range of the proposed CS scheme with wideband and complexity-enhanced optical chaos are obviously enhanced.

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