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Compressive Sensing Detection of RF Signals by All-Optically Generated Binary Random Patterns

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***Abstract*—High-speed random bit sequences are crucially important in temporal compressive sensing applications. In this work, we propose a new all-optical binary random patterns generation method for compressive sensing, completely eliminating the use of high-speed electronic circuits. This approach uses photonic time stretched optical pulses as the optical carrier. Spectrum slicing using a tunable ring resonator produces a train of uniformly spaced optical pulses (bits) due to spectrum-to-time mapping in photonic time stretch. Two cascaded dispersive devices with particularly designed nonlinear dispersion profiles are employed to introduce random time delays among optical pulses, leading to a quasi-random binary sequence. The random sampling pulse sequence can be updated by changing the free-spectral range of the ring resonator. The proposed method is verified by numerical simulations. The photonic generated random pulse sequences are used in compressive sensing detection of high-frequency RF signals. In a proof-of-concept demonstration, one-tone and multi-tone microwave signals are successfully reconstructed from four-time compressed measurement data.**

Keywords*—*RF signal detection; compressive sensing; random sequence generation;

I. INTRODUCTION

Compressive sensing is a signal processing technology to explore and utilize the sparse signal detection [1]. In the detection progress, pseudo-random bit sequences (PRBS) are always needed to mix the RF signal to be detected before down-sampled at a lower sampling rate. The equivalent Nyquist rate of the system is essentially determined by the bit rate of PRBS. Therefore, the main difficulties associated with conventional electronic solutions are high cost and limited bandwidth in generating high speed electronic PRBS [2]. Thanks to unique advantages offered by optics, such as broad bandwidth, low-loss propagation and inherent immunity to electromagnetic interference, great efforts have been made to investigate photonics-assisted methods to generating high-speed PRBS. Generally, those methods require high speed optical clock signal along with complicated dual-drive differential Mach-Zehnder modulator (MZM) [3]. So, those high-speed PRBS generation and mixing schemes still suffer from electronics bottleneck, not from the detection end, but the mixing process.

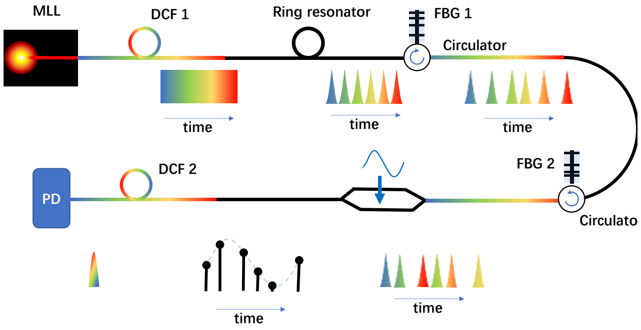


Fig. 1. Conceptual diagram of proposed setup for all-optical random binary random sequence generator

On the other hand, all-optical approaches to generating random bit sequences would feature large bandwidth and inherent mixing in optical domain as well, hence completely eliminating electronic bottlenecks. Therefore, there are many researchers trying to utilize optical methods for PRBS generation and mixing. Generally, the mixing process is implemented using a Mach-Zehnder modulator (MZM). There are various all-optical PRBS generation methods developed in recent years, including those based on photonic time stretch [4,5], a spatial light modulator (SLM) [6], spectrally encoded laser [7], cascaded Mach-Zehnder interferometers (MZIs) [8] and so on. Most recently, we reported an all-optical random sequence generation approach based on spectral filtering using cascaded unbalanced dispersion MZIs followed by spectrum-to-time conversion [8,9],which not only generates high-speed optical random patterns but also implements all-optical mixing via spectral filtering, hence eliminating the need of high speed MZM or electronics PRBS generator. However, the generated random sequence is not binary but with arbitrary bit levels, which is not desirable for compressive sensing applications as the existing reconstruction algorithms are optimized for binary random mixing signal.

In this work, we propose and demonstrate a binary all-optical random pattern generation method, which is based on uniform spectrum slicing followed by nonlinear photonic time stretch using two cascaded nonlinear dispersion devices. Here we utilized a tunable ring resonator for spectrum shaping and the concept of nonlinear photonic time stretch to rearrange the time delays among optical sub-pulses (bits). The method is verified by numerical simulations and its utility in compressive sensing detection of single-tone and multi-tone microwave signals is also presented.

II. PRINCIPLE

The proposed setup is shown in Fig.1. A mode-locked laser (MLL) is used to generate optical pulses with 50MHz and full-width half-maximum (FWHM) pulse of 800 fs. After passing through a dispersion compensation fiber (DCF) with dispersion value of D (ps^2), the pulse will be stretched in time lead to spectral-to-time linear and continuous mapping. A ring resonator acts as an optical comb filter and produces uniformly spectrum-sliced pulses. Thanks to the one-to-tone mapping from spectrum to time, this equivalently generates a burst of sub pulses with uniform temporal delays within one original pules period. The pulse train serves as the uniformly spaced "one" bits.

To generate random binary bits, the uniform delays among sub pulses are rearranged by a nonlinear dispersive element with specially designed group delay response. The nonlinear dispersion can be implemented using two cascaded chirped fibre Bragg gratings (CFBGs) with different group delay profiles. Accordingly, nonlinear spectrum to time mappings at the two CFBGs can be described as,

$$t_{1,v} = t_{0,v} + \left(v - v_1\right) D_1{}' \tag{1}$$

$$t_{2,v} = t_{1,v} + \left(v - v_2\right) D_2{}' \tag{2}$$

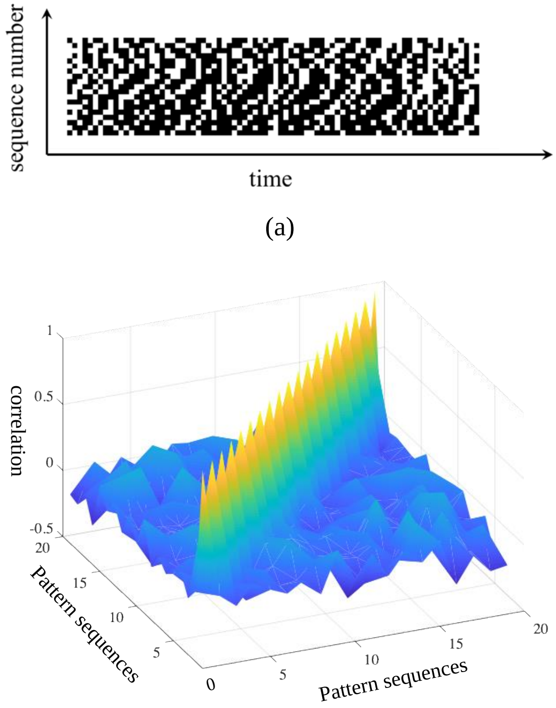
where, $t_{1,v}$, $t_{2,v}$ are the time delay of pulse with frequency of v through the $CFBG_1$ and $CFBG_2$, respectively. v_1 , v_2 and D_1', D_2' are the zero-dispersion point and dispersion coefficient of the CFBG1 and CFBG2, respectively.

In this work, the dispersion parameters of the two CFBGs are linear and quadratic with respect to the frequency variation, respectively, as shown in Equ.3 and 4.

$$D_1{}' = D_1\left(v - v_1\right) \tag{3}$$

$$D_2{}' = D_2\left(v - v_2\right)^2 \tag{4}$$

It can be seen from the Eqs.1 and 2 that cascaded CFBGs can be seen as an optical pulse shifter. The optical sub pulses with different central wavelengths can be radically rearranged in the time domain due to strong nonlinear spectrum-to-time mapping. By carefully design the dispersion profiles of the two cascaded CBFGs, reshaped optical sub pulses will have random time delays among them, leading to a quasi-random binary sequence. Equivalent sequence bit rate is determined by the frequency spectral range (FSR) of the ring resonator and the dispersion profiles of two CFBGs. To fulfil the required for compressive sensing, the generated random sampling pulse sequence can be updated by slightly changing the FSR of the ring resonator. Note that the mixing of modulated microwave signal with the generated random bit sequence is completely achieved in optical domain via spectral filtering. No extra high-speed modulator is required.



(a)

(b)

Fig. 2. (a) 20×80 Binary random patterns, and (b) the Correlation matrix of self- and cross-correlation between the generated patterns.

III. BINARY PATTERN GENERATION

To verify the proposed principle, numerical simulations have been performed. The spectral bandwidth of the ultrafast optical pulses is selected from 193.5 to 193.8 THz, and dispersion parameters D_1, D_2 are 1000 ps^2 and -2000 ps^3 for the two CFBGs, respectively. FSR of the ring resonator is adjusted from 20 to 40 GHz. A given FSR will produce a specific random bit sequence. As shown in Fig. 2(a), 20 binary patterns are generated by adjusting FSR with a step of 1 GHz, and the length of the random sequences is 80 points. Considering that time window of the random bit sequence generation is 80 ps, the equivalent sampling rate is 1 TS/s.

It is required in the compressive sensing applications that the generated bit sequences should be as random as possible with low cross-correlation. Correlation matrix showing self- and cross-correlation between the generated patterns are shown in Fig. 2(b). An average cross-correlation coefficient as low as 9.28 % has been achieved.

IV. COMPRESSIVE SENSING AND RECONSTRUCTION

To verify the utility of the proposed random bit sequence generation method in compressive sensing system, we investigate the compressive sensing detection of RF signals using the generated random patterns. As shown in Fig. 1, the generated random pattern is modulated by the RF signal to be tested using an MZM. This is also equivalent to random non-uniform sampling of the RF signal using the optical pulses. After

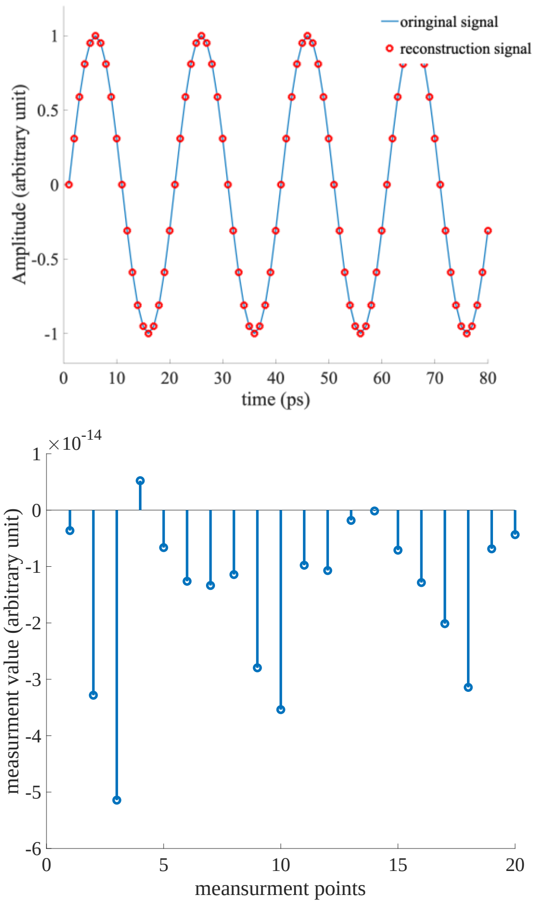


Fig. 3. Single-tone 40 GHz microwave signal detection via compressive sensing. (a) The original signal and reconstruction result, and (b) compressed measurement results.

this mixing process, integration of microwave signal with mixed random patterns is implemented in the optical domain as well based on optical pulse compression using another dispersive element with exactly opposite dispersion value to the first dispersion for pulse stretching. At the end, a low-speed photodetector (PD) is used to detect the fully compressed optical signal. Only one sample is captured during the entire pulse period. This will be repeated by multiple times to obtain the measurement date set. In our case, 20 single-pixel measurements have been taken for the incoming RF signals. Considering 80 points in the mixed original signal, a compression ratio of 25% is obtained. Then standard ℓ1-MAGIC signal recovery algorithm is used for reconstruction of the original signals.

In this work, two RF signals are tested. The first is a single tone signal with carrier frequency of 40 GHz, as shown in Fig. 3(a). As the signal is so sparse in the frequency domain, it can be perfectly reconstructed using the generated random patterns from down-sampled measurements, with the results shown in Fig. 3(a) in red circles. Fig. 3(b) presents the 20 measurement results. Dramatic variations in amplitude is a clear indication of proper random mixing and integration. In a second example, a multi-tone microwave frequency with carrier frequencies of 25 and 50 GHz is selected, as shown in Fig. 4(a). The reconstructed signal using the proposed approach is shown as well in red circles. Slightly degraded reconstruction accuracy is evident, which is due to the higher frequency component involved. Fig.4 (b) shows the measured compressed data set for each single-pixel detection.

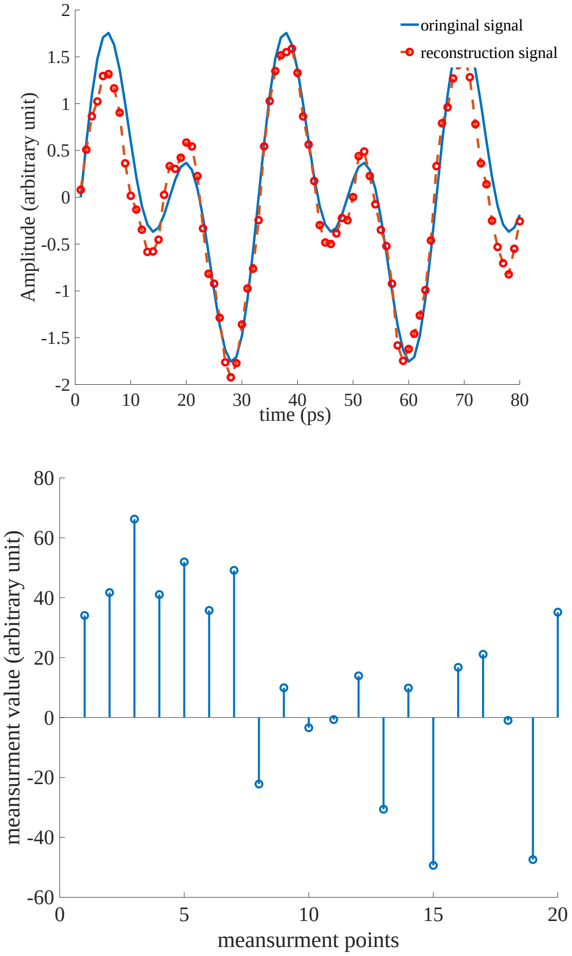


Fig. 4. Compressive sensing detection of multi-tone microwave signal with carrier frequencies of 25 and 50 GHz. (a) The original signal and reconstruction result, and (b) the compressed measurement results.

V. CONCLUSION

Generation and mixing of high-speed random sequences are bottlenecks for compressive sensing technology. In this work, we proposed and demonstrated an all-optical binary random sequences generation method based on spectrum slicing and nonlinear photonic time stretch using two cascaded CFBGs. The binary sequences were mixed with input RF signals by an MZM for compressing sensing detection of the signals. In proof-of concept experiments, successful reconstruction of single-tone RF signal of 40 GHz and two-tone signal of 25 and 50 GHz have been demonstrated. The proposed approach avoids electronics bottleneck in compressive sensing system and have a great potential for high-speed signal compressing sensing.

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