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Photonic Compressive Sensing Enabled Data Efficient Time Stretch Optical Coherence Tomography

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ABSTRACT

Photonic time stretch (PTS) has enabled real time spectral domain optical coherence tomography (OCT). However, this method generates a torrent of massive data at GHz stream rate, which requires capturing as per Nyquist principle. If the OCT interferogram signal is sparse in Fourier domain, which is always true for samples with limited number of layers, it can be captured at lower (sub-Nyquist) acquisition rate as per compressive sensing method. In this work we report a data compressed PTS-OCT system based on photonic compressive sensing with 66% compression with low acquisition rate of 50MHz and measurement speed of 1.51MHz per depth profile. A new method has also been proposed to improve the system with all-optical random pattern generation, which completely avoids electronic bottleneck in traditional binary pseudorandom binary sequence (PRBS) generators.

Keywords: Optical Coherence Tomography, Compressive sensing, Dispersion, Time stretch

1. INTRODUCTION

Optical coherence tomography (OCT)[1,2] has widespread applications in medicine and engineering. Time domain OCT (TD-OCT) was first demonstrated[3] followed by spectral domain OCT (SD-OCT), which offers superior sensitivity and higher scanning rate compromising axial scanning range. Swept source OCT (SS-OCT), another variant of SD-OCT has been demonstrated, which has achieved MHz scanning rate by rapidly sweeping the optical wavelengths across a broad bandwidth. The wavelength sweeping speed is further improved by photonic time stretch (PTS) method[4]. PTS-OCT has enabled detection of transient and fast changing dynamics[5] with an unprecedented A-scan rate of 90 MHz.

However, the PTS-OCT systems[5,6] always suffer from continuous massive data generation and the requirement of high speed acquisition equipment. On the other hand, compressive sensing (CS) enables detection of spectrally sparse signals with low acquisition speed[7,8]. Photonic compressive sensing[9] have wide spread applications in single-pixel optical imaging[10], gas sensing[11], and blind spectrum sensing[12,13]. There has been a demonstration of compressive sensing to study the effectiveness in optical coherence tomography system by direct sampling the OCT data with SD-OCT method followed by digital compressive sensing approach[14]. In this work, we reported and experimentally demonstrated data efficient PTS-OCT system based on photonic compressive sensing achieving 66% compression ratio with A-scan rate of 1.51MHz for a single layer measurement[15,16].

Figure 1 shows the schematic diagram of the proposed system. A passively mode-locked laser (MLL) generates ultrashort optical pulse train at a specific repetition rate. Dispersion compensating fibre (DCF) is used as a dispersion stretcher to disperse the broadband optical pulses and hence achieves frequency-to-time mapping. The time stretched optical pulses are then directed via an optical circulator to a Michelson OCT set up, which emulates a single layer sample. The layer depth profile is set up by optical path length difference between a fixed mirror in one arm and a movable mirror in the other arm. The spatial depth of the sample is first mapped to free spectral range (FSR) of optical spectral interferogram and further to the period of a temporal waveform due to dispersion-induced one-to-one mapping between frequency and time domain.

Each encoded optical pulse is then electro-optically mixed with a unique binary pseudorandom binary sequence (PRBS) using a Mach-Zehnder modulator (MZM). Integration of the mixed optical pulse to produce a single measurement is optically implemented by using a length of single mode fiber (SMF) with opposite dispersion profile to that of dispersion stretcher. This process compresses the encoded and mixed optical pulse to picosecond pulse width, which represents a linear combination of PRBS and the encoded optical pulse. A low speed PD with bandwidth identical to the pulse train repetition rate is used to measure the power of compressed pulse, generating one element in the measurement matrix.

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Considering total M distinct PRBS sequences, M measurements are recorded and sampled at the repetition rate of MLL using a real-time oscilloscope.

In compressive sensing model, the original signal x[N], sparse in domain Ψ, is modulated by the PRBS Φ at a Nyquist rate with length N. After obtaining the measurement vector y with length M (M<N) with each of M PRBS patterns, the measurement vector can be represented as $y = \Phi x = \Phi\times(\Psi^{-1}\boldsymbol{s}) = \theta\times s$, where s denotes the representation of input signal x in domain Ψ. In reconstruction process, we can retrieve s from y and θ by solving the algorithm of $\min(\|s\|_1)$ subject to $y=\theta\times s$. Finally, the signal x is calculated from its Ψ domain representation s.

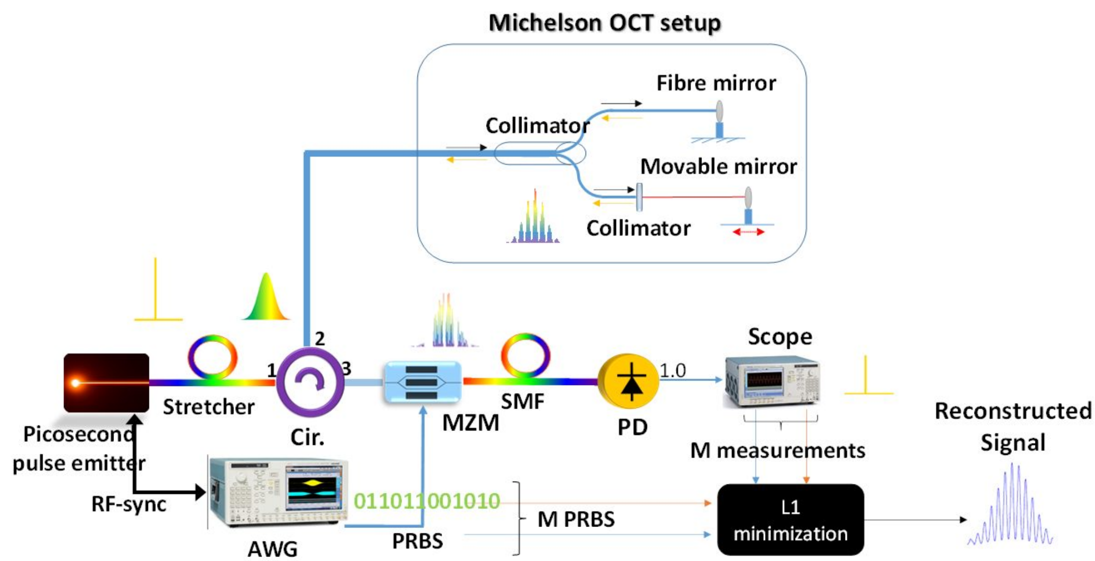

Figure 1. Schematic diagram of the proposed compressive sensing PTS-OCT system. AWG: arbitrary waveform generator, PRBS: pseudo random bit sequence, Cir.: Circulator, MZM: Mach-Zehnder modulator, SMF: Single mode fibre, PD: Photodetector.

2. RESULTS

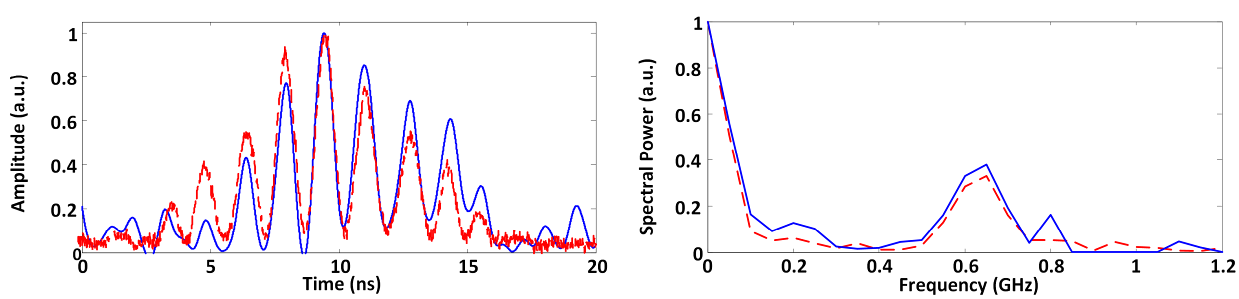

Figure 2. a) Time domain waveform of encoded pulse shown in red and the waveform obtained after compressive sensing is shown in blue. b) RF spectral domain of input (red) and reconstructed (blue)

To demonstrate the system, an experimental set up has been constructed as per Figure. 1. The MLL (Calmar Mendocino) generates ultrashort optical pulses at 50 MHz repetition rate with pulse width 800 fs and optical bandwidth of 12 nm at 1550 nm central wavelength. The total dispersion of the DCF stretcher is -1040ps/nm. The interferometer has been configured to have optical path length difference of 0.81 mm, which is mapped to a temporal waveform with RF carrier frequency of 650 MHz, as shown in Figure 2.a. in red color. The corresponding electrical spectrum is shown in Figure 2.b in red color. To detect this signal using uniform sampling, it would require 1.3 GS/s acquisition speed according to

Shannon-Nyquist sampling theorem. However, since the signal is sparse in frequency domain, it can be detected at a lower acquisition speed thanks to compressive sensing.

In our system, we used an arbitrary waveform generator (AWG) to generate PRBS sequences at 2.5 GS/s for random mixing. Considering the pulse train period of 20 ns, the overall sequence length is N = 50 per single optical pulse. Integration of mixed optical pulses is implemented in the optical domain based on pulse compression using opposite dispersion profile by 60 km single mode fibre. Therefore, a high-speed sample-and-hold electronic integrator is avoided. The AWG is synchronized to repetition rate of MLL to establish a deterministic electro-optic mixing process so that one to one mapping can be achieved for compressed measurement with a given binary PRBS pattern. Optical integration results in compressed pulse and a low speed detector is sufficient to capture the single-element power measurement for each individual pulses. In this case, since the repetition rate of the MLL is 50 MHz, the measured optical power would represent linear combination of PRBS and encoded signal. After compressive sensing and reconstruction, the resultant temporal waveform is shown in Figure 2.a. in blue color with corresponding FFT is shown in Figure 2.b in blue color which is in well agreement with the given input tone. Since only 33 measurements are required to reconstruct one depth profile with size of 50, compression ratio of 66% is obtained. At the same time, the overall axial scanning rate is reduced to 1.51 MHz.

3. DISCUSSION

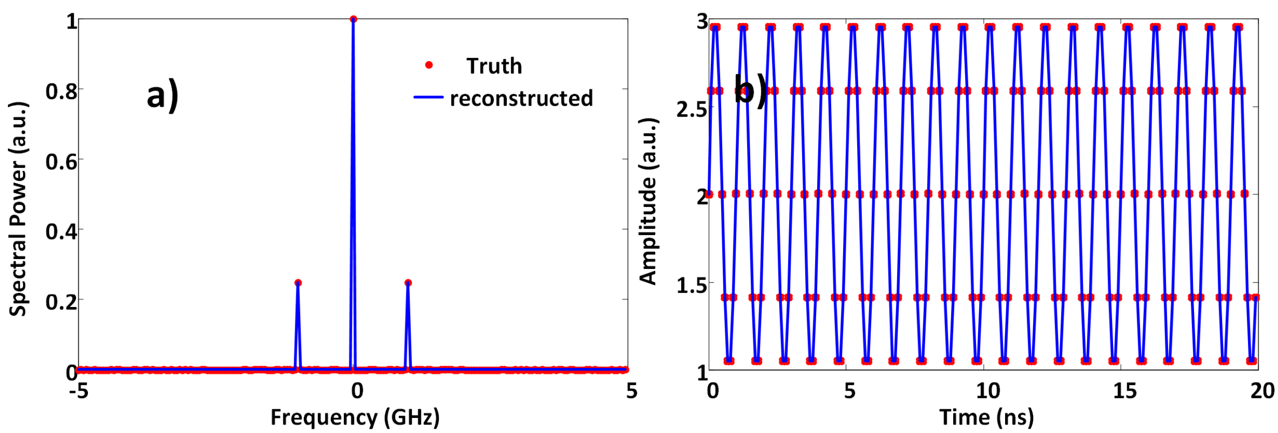

Figure 3. Simulation results of compressive sensing of single tone signal 1GHz with L1 reconstruction algorithm. a) FFT spectrum of the original (red) and the reconstructed (blue) signals; b) Time domain of original(red) and reconstructed(blue) signal

The results have been obtained with low speed photo detector which is independent of RF frequency. However, the compression ratio for a single tone reconstruction is expected to be less than 10%. Considering a single tone 1 GHz signal at 10 Gb/s sampling rate, the overall signal length is N = 200 as shown in Figure 3 in both frequency and time domains in red dots. A set of binary random sequences have been mixed and integrated with the signal. Using L1 reconstruction, the reconstructed signal in FFT and time domains are shown in Figure 3 in blue color. As observed, the bandwidth occupied by the single tone is 50MHz and the number of non-zero tones are 3 and the number of measurements are as low as 10 making the compression ratio 5% whereas the signal in the schematic is a convolution of single tone signal with time stretched MLL Gaussian pulses, which results in semi sparse signal with more non zero frequency tones, 27 in this case, which need to be retrieved. Figure 2 shows the single tone signal convoluted with time stretched MLL Gaussian pulses. As the number of measurements required linearly dependent on sparse tones, the number of measurements required are higher in this case[17].

Secondly, the A-scan range or the maximum RF frequency retrieved by the system dependant on the maximum analog bandwidth of the digital to analog converter (DAC) in AWG in this case, which is around 1.25 GHz for proper generation of PRBS sequences. In addition, to achieve random mixing with PRBS patterns, a high-frequency Mach-Zehnder modulator (MZM) is always required. To compensate the loss involved in electro-optic modulation we need to employ an additional optical amplifier. This whole equipment would make the system bulky and costly.

There have been several approaches in sensing and imaging with all-optically generated random patterns. An optical image is reconstructed with multiply scattering medium[18] and spectral resonance modulation[19] where the scattering medium in this case is a conglomeration of multiple cavities of various lengths, followed by demonstration of wavelength dependant scattering of TiO2 tipped fibre[20]. Here we proposed a new all-fiber technique for optical random pattern generation using a cascaded dispersion unbalanced Mach-Zehnder interferometer (MZI) structure. By varying the optical delay in one of the arms, the frequency chirp profiles of the MZI can be changed and the cascaded response would produce distinct patterns after wavelength-to-time mapping. The cross correlation between any two generated random patterns has been estimated to be less than 75% through numerical simulations[16].

The cascaded MZI structure in our proposed system replaces traditional AWG and MZM and produces random patterns in optical domain directly as shown in Figure 4. As this is a linear system, the interchangeability of mixing and encoding stages doesn't affect the performance of our compressive sensing system.

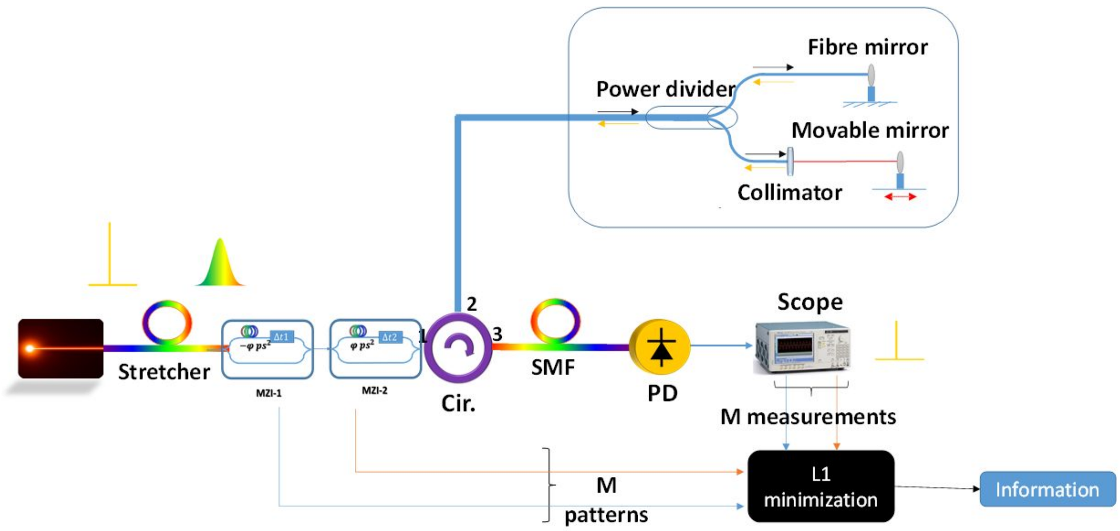

Figure 4. Proposed all-optical random patterns based OCT system that can sense the OCT image

4. CONCLUSION

We experimentally demonstrated data efficient real-time PTS-OCT system based on photonic compressive sensing, which achieved 66% compression ratio at 50 MHz acquisition speed with 1.51 MHz axial scanning rate. We also proposed a cost effective solution for capturing profile information through all optical random pattern generation based on cascaded MZI structure with opposite dispersion profile, which completely eliminate the electronic bottleneck in conventional photonic compressive sensing systems.

5. ACKNOWLEDGEMENTS

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