Data Compressed Photonic Time-Stretch Optical Coherence Tomography

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***Abstract*—Photonic time stretch enables real-time optical coherence tomography, but at the cost of extreme requirement for high-speed signal acquisition and massive data set. This work reports a data compressed real-time Fourier-domain optical coherence tomography based on photonics-assisted compressive sensing. Compression ratio of 66% is achieved.**

Keywords—compressive sensing; dispersion; optical coherence tomography; photonic time stretch

I. Introduction

Optical coherence tomography (OCT) has developed widespread applications across a variety of disciplines in engineering and medical diagnostics. High-throughput real-time OCT based on photonic time stretch (PTS) technique with MHz axial scan rate is an indispensable tool for investigating fast-changing and transient dynamics as it is immune to motion artifacts [1, 2]. However, the main difficulty associated with PTS-OCT is that high-speed data acquisition up to tens of GS/s is always required to capture the temporal interferogram. Moreover, an inherent consequence of this is that a torrent of data is continuously generated. On the other hand, compressive sensing enables detection of sparse signal with sampling rate far below the normally required Nyquist rate [3]. It holds great potential in data compression of real-time OCT systems.

In this paper, we propose and experimentally demonstrate a data-compressed PTS-OCT system based on photonics-assisted time-domain compressive sensing [4]. Compressive sensing spectral domain OCT has been previously reported [5]. This paper reports the first demonstration of compressive sensing real-time PTS-OCT system. A high axial scan rate of 50MHz is achieved using low-speed signal acquisition with greatly reduced sampling rate of 50 MS/s. The compression ratio is 66% for a single-layer measurement.

II. Principle

PTS-OCT achieves real-time Fourier-domain OCT by mapping the optical spectrum to a temporal waveform using chromatic dispersion. Here the temporal waveform is usually sparse in Fourier domain corresponding to particular reflection layers along the depth of the object.

Figure 1 shows the schematic diagram of the proposed compressive sensing PTS-OCT system. A passive mode-locked fibre laser generates ultrashort optical pulse train. A dispersion compensating fibre (DCF) stretches the optical pulses to achieve spectrum-to-time mapping and reduces the peak optical power to avoid unwanted supercontinuum generation due to nonlinear optical effects. The time stretched optical pulses are directed via an optical circulator to a simple Michelson-type interferometer OCT setup. One arm of the interferometer has a fixed fibre Faraday mirror serving as the reference and the other arm is focused onto a movable mirror acting as a single-layer sample. The time stretched and encoded optical pulses are sent to a Mach Zehnder Modulator (MZM), where photonic-assisted random mixing is implemented by modulating the pulses with pseudo-random bit sequences (PRBS). Optical integration is implemented by pulse compression using single-mode fibres (SMF) with opposite dispersion to the DCF. A photodetector (PD) measures the power of each compressed optical pulse, generating one element in the measurement matrix. Only low-speed signal acquisition with sampling rate identical to the pulse repetition rate, which is 50 MHz in our case, is required to obtain multiple measurements.

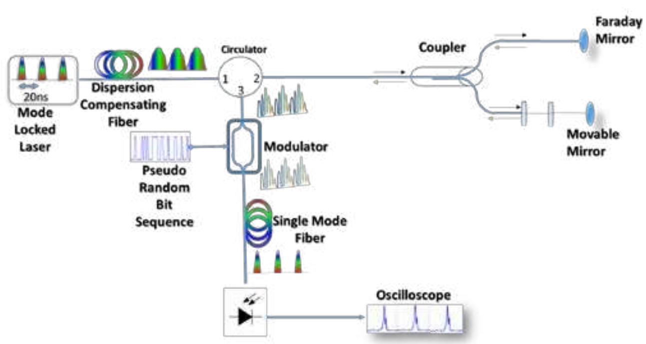

Fig.1. Schematic diagram of the proposed compressive sensing real-time OCT system.

In compressive sensing model, the signal to be measured $\boldsymbol{x}$[N], which is sparse in domain $\boldsymbol{\Psi}$, is modulated by the PRBS $\boldsymbol{\Phi}$ at Nyquist rate with length N. After obtaining the measurement vector $\boldsymbol{y}$ with length M (M<N) for each PRBS pattern, considering the target information, we can write $\boldsymbol{y} = \boldsymbol{\Phi x} = \boldsymbol{\Phi}\times(\boldsymbol{\varphi}^{-1}\boldsymbol{s})=\boldsymbol{\theta}\times\boldsymbol{s}$, where $\boldsymbol{s}$ denotes the sparse coefficients in domain $\boldsymbol{\Psi}$. In reconstruction process, we can retrieve $\boldsymbol{s}$ from $\boldsymbol{y}$ and $\boldsymbol{\theta}$. The obtained $\boldsymbol{s}$ can be used as initial guess for $\boldsymbol{L}$-1

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minimization program which solves the algorithm of min(||s||)$_1$) subject to $\boldsymbol{y}=\boldsymbol{\theta}\times\boldsymbol{s}$. As the equation converges, we can get more accurate solution for $\boldsymbol{s}$. Finally, the signal x is calculated from its $\boldsymbol{\Psi}$ domain representation $\boldsymbol{s}$.

III. EXPERIMENT

To demonstrate the utility of the proposed compressive sensing TPS-OCT system, we constructed the experimental apparatus as shown in Fig. 1. The ultrashort optical pulses have a repetition rate of 50 MHz, central wavelength of 1550 nm with a full width at half maximum (FWHM) spectral bandwidth of ~12 nm. The total dispersion of the DCF is -1000 ps/nm. The interferometer has an initial path difference of 1 mm in air, which produces a uniform interference fringes in the optical spectrum. Thanks to dispersion-induced wavelength-to-time mapping, a temporal waveform with its interference frequency of 750 MHz is obtained. Fig. 2(a) shows the waveform captured by a fast real-time oscilloscope.

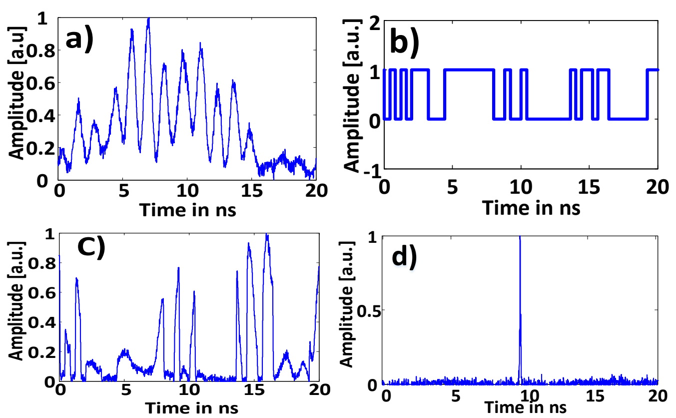

Fig. 2. Measured results for photonic-assisted compressive sensing. (a) Temporal wavaeform with 0.833 GHz intereference pattern, (b) one of PRBS patterns, (c) the modulated waveform, d) the compressed optical pulse using single mode fibers.

In order to detect this waveform using normal uniform sampling, 1.5 GS/s sampling rate is required at the least. However, as the signal is very sparse in its Fourier domain, it can be detected using a much slower sampling rate thanks to compressive sensing. In our system, the time-stretched and encoded waveform is modulated by PRBS patterns with a bit rate of 2.5 Gb/s, generated by an arbitrary waveform generator. Figs. 2(b) and (c) show one of the PRBS patterns and the modulated waveform, respectively. To achieve integration for compressive sensing in the optical domain, a SMF with a total dispersion of 933 ps/nm is used to compress the modulated optical pulse. The compressed pulse has a FWHM pulse-width of 30 ps as shown in Fig. 2(d).

The optical power of each compressed pulse measured by a PD produces one measurement. Using a low-speed real-time oscilloscope (50 MHz), totally 33 measurements are taken. A sparse signal recovery algorithm based on random demodulation [6] is used to reconstruct the original temporal waveform. Fig. 3(a) shows the discrete cosine transform (DCT) representation of the signal and Fig. 3(b) is the reconstructed temporal waveform with a 738 MHz carrier frequency (blue solid). The original waveform measured by the fast oscilloscope is also shown in red dashed for comparison. A good agreement has been achieved. Considering that the original signal has a length of 50 bits and 33 measurements are used to achieve the signal reconstruction, compression ratio of 66% is achieved. The effective axial scan rate of our compressive sensing PTS-OCT system is 1.51 MHz.

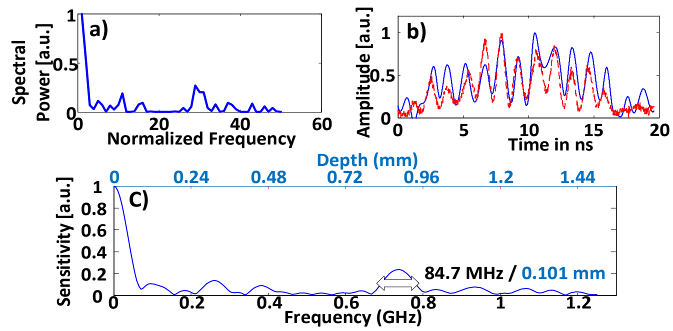

Fig. 3.a) DCT of the reconstructed signal from L-1 minimization algorithm, b) the reconstructed signal, c) FFT of the reconstructed signal showing the single-lay reflection.

Finally, by calculating the Fourier transform of the reconstructed temporal waveform, Fig. 3(c) shows the single-shot point-spread function (PSF) of depth measurement for the single-layer sample. The measured axial resolution is estimated to be 101 µm.

IV. CONCLUSION

We have proposed and experimentally demonstrated a compressive sensing real-time PTS-OCT system. Random mixing and integration processes are implemented in the optical domain directly. High-throughput axial scanning at 1.51 MHz is achieved using low-speed data acquisition at 50 MS/s thanks to a high compression ratio of 66%.

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