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High-Speed Multi-channel Signal Acquisition in Photonic Time Stretch Optical Coherence Tomography through Frequency Division Multiplexing

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***Abstract*— Photonic time stretch optical coherence tomography (OCT) has achieved unprecedented A-scan rates of tens of MHz in previous studies. However, the slower lateral scan rate remains a bottleneck for volume imaging speed. In this work, we propose and demonstrate a novel data acquisition method that enables simultaneous ultrafast multi-channel A-scans in photonic time stretch OCT. Utilizing frequency-division multiplexing, our approach maintains the high A-scan rate and the same axial resolution, while significantly improving the overall imaging throughput. This advancement addresses the existing limitations and represents a significant step forward in high-speed and high-throughput OCT imaging.**

Keywords—optical coherence tomography, frequency-division multiplexing, photonic time stretch

I. INTRODUCTION

Since its inception, Optical Coherence Tomography (OCT) technology [1] has been extensively applied for non-destructive testing of biological tissues and materials [2-3]. In recent years, with the advancements in OCT technology and its non-invasive and high-resolution advantages, OCT applications have expanded from early ophthalmology use to a wide range of biomedical applications, including cardiovascular imaging, hair follicle analysis, and early caries detection. With the increasing range of applications, there is a growing demand for higher imaging speeds and larger imaging ranges in OCT. Consequently, ultra-high-speed OCT has emerged [4], achieving axial scanning (A-scan) rates approaching or exceeding the megahertz (MHz) level using fast wavelength-swept laser sources.

High-speed OCT offers several advantages. Firstly, it can detect rapid dynamics and is less affected by motion artifacts caused by moving samples or environmental changes in biomedical settings [5-8]. Secondly, in industrial applications, there is a need to rapidly acquire images to inspect large numbers of samples within a short period and to image large fields of view [9].

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In recent years, photonic time-stretch dispersive Fourier transform has been proven to be a significant method for increasing OCT scanning speed [10-12]. In photonic time stretch OCT, a dispersive medium, such as a dispersive fiber, stretches the incident ultrashort optical pulse in the time domain. Due to dispersion, different wavelength components of the light propagate at varying speeds, causing the pulse to stretch during transmission. This results in the temporal separation of wavelengths and essentially a ultrafast passively wavelength-swept optical source, which is the key for a high-speed OCT system.

To further enhance imaging system performance, various advanced photonic time stretch OCT systems have been developed. A dual-comb-based time-stretch OCT technology has been developed [13], which achieved an enhanced imaging depth of 1.5 meters and an A-scan rate of 200 kHz. In another work, to tackle the massive data volume generated from ultrafast photonic time-stretch OCT systems, a photonic compressive sensing approach has been demonstrated [14] to compress overall data size.

Despite that photonic time stretch optical coherence tomography (OCT) has achieved unprecedented A-scan rates of tens of MHz in previous studies, much slower lateral scan (usually via mechanical means) remains a bottleneck for volume imaging speed in OCT. A multi-probe photonic time-stretch OCT system based on wavelength division multiplexing [15] has been demonstrated to improve imaging throughput without any mechanical scanning. However, as the optical spectral bandwidth for each probe has been reduced, the axial resolution in this design is greatly sacrificed.

In this paper, we propose and demonstrate a frequency division multiplexing photonic time-stretch optical coherence tomography (FDM-PTS-OCT) system that enables simultaneous ultrafast multi-channel A-scans in photonic time stretch OCT. The whole optical spectral bandwidth is available for all the A-scan channels. Therefore, the axial resolution is the same as the single channel photonic time stretch OCT system. Simultaneous multi-channel A-scan is achieved based on frequency division multiplexing. Fixed time delays are introduced into multiple parallel channels

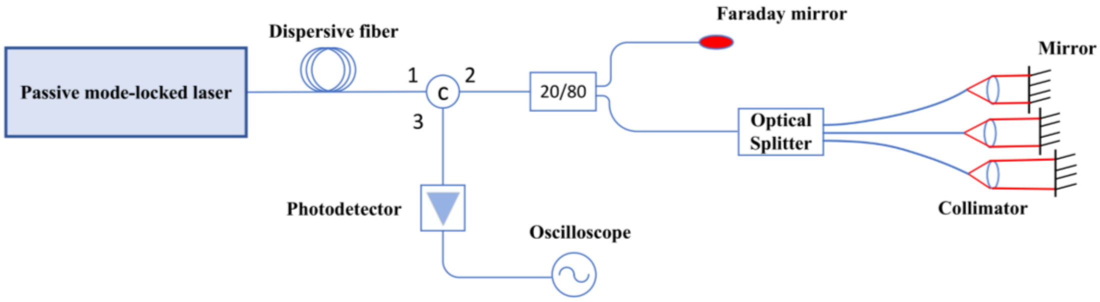

Fig. 1. Schematic of the proposed Frequency-division multiplexing photonic time-stretch OCT.

using an FDM component based on fiber optics. This parallel imaging technique splits the sample arm light into multiple channels, each illuminating different positions on the sample, allowing simultaneous signal acquisition from multiple locations and thus significantly improving the overall imaging throughput and maintaining the same A-scan rate and axial resolution.

II. PRINCIPL

The schematic diagram of our proposed FDM-PTS-OCT system is shown in Figure 1. The experimental setup utilizes a passively mode-locked laser (Calmar Mendocino FP laser) as the light source, generating a series of ultrashort broadband pulses with a repetition rate of 50 MHz. The light pulses are first transmitted into a dispersion-compensating fiber (DCF) with a dispersion of -615 ps/nm., stretching the pulses from 800 fs to 8 ns, thereby producing a broadband passive wavelength-swept optical carrier at 50 MHz.

After passing through an optical circulator, the optical carrier is split in an 80:20 ratio, with 20% entering a fiber Faraday mirror as the reference arm of a Michelson interferometer, and 80% entering the sample arm. In the sample arm, a 1×3 spatial division multiplexing (SDM) fiber splitter is used, where each path is collimated into free space using individual collimators. The backscattered light returns through the 1×3 SDM splitter, with each of the three channels illuminating the sample sequentially with different spectral components in time.

The back-reflected pulses from the sample interfere with the unmodulated pulses reflected from the reference mirror at the optical coupler, generating interference fringes in the time domain that contain axial information of the sample. This process is facilitated by the high group velocity dispersion (GVD) of the DCF, which converts the spectrum of each broadband pulse into a time waveform. Thus, frequency-domain OCT measurement is realized in the time domain using a high-speed single-pixel photodetector (PD), enabling the FDM-TS-OCT to operate at an axial scanning rate equivalent to the laser pulse repetition rate. Finally, the temporal interferogram is obtained at the output of the PD and collected by a high-speed oscilloscope.

The key to the FDM-OCT technology is the simultaneous generation of multiple illumination beams on the sample, each with different optical delays with respect to the reference arm, allocating different interference frequency bands to different A-scan channels. Only a single detection channel is needed to collect signals from all beams concurrently. This approach significantly enhances the signal acquisition throughputs while maintaining imaging speed and axial resolution. Note that imaging depth will be sacrificed in the proposed approach. Therefore, it is desired for applications where high throughput OCT detection is needed for thin samples.

III. EXPERIMENT RESULTS

To validate the performance of the proposed FDM-PTS-OCT technology, an experimental system was constructed based on the schematic diagram shown in Figure 1, and a proof-of-concept experiment was conducted.

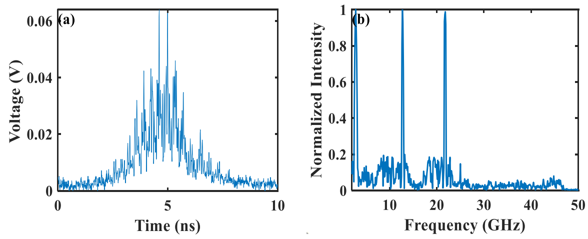

Fig. 2 System characterization. (a) The measured time domain waveform for multi-channel signal acquisition, and (b) Fast Fourier Transform showing multiple beating frequencies for FDM.

A. *Basic performance*

Characterization of the proposed system is completed using a silver mirror as a sample is shown in Figure 2. The time dispersed pulse sequence displayed on the high-speed oscilloscope is a mixed result of three reference arms, as shown in Figure 2 (a). The signals from different beams (different A-scan channels) are presented in different frequency ranges (i.e. imaging depths) as shown in Figure 2 (b). Therefore frequency division demultiplexing can be utilized to simultaneously demodulate depth information at different A-scan channels.

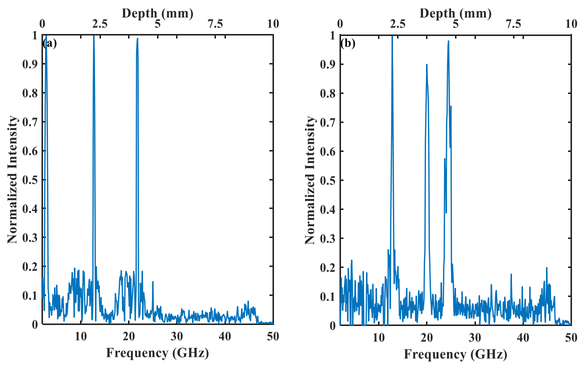

Fig. 3 Before adjusting the silver mirror (a) and (b) after adjusting silver mirror.

B. *Performance of the tomographic detection ability*

To demonstrate the multi-channel A-scan capability of the developed FDM-PTS-OCT system, a series of experiments were conducted using a mirror as the sample. By finely adjusting the axial distance of the mirrors , we controlled the time delay of each channel, thereby simulating different depths of the sample. Figure 3(a) shows the multi-channel OCT depths measurement results obtained using mirror samples within a depth range of 10 mm. In a second experiment, the mirrors' positions were adjusted to acquire multi-channel OCT spectra representing different depths, as shown in Figure 3(b).

To further verify the system's functionality, we conducted multi-depth A-scan on a two-layer sample, which is a 0.1 mm thick glass plate in the reference arm. The obtained OCT spectrum (depth information) is shown in Figure 4. The scan revealed two distinct peaks corresponding to reflections from the front and rear glass surfaces, separated by the corresponding Optical Path Delay (OPD). This experiment confirmed the system's ability to perform A-scan across multiple depths simultaneously. Note that only the first channel was used for this experiment. OCT spectrum is still available for other A-scan channels, as shown in Figure (4).

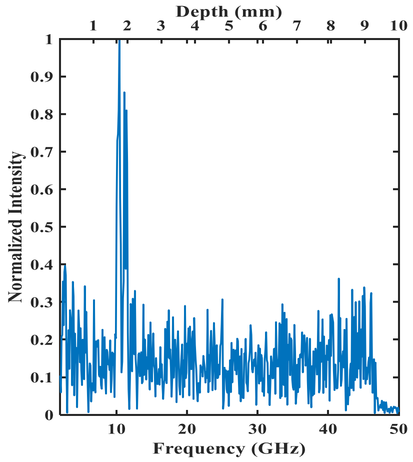

Fig. 4 A-Scans obtained from a thin glass plate in the reference arm. Two peaks regarding to each surface are shown.

IV. CONCLUSION

In this paper, we have introduced a novel FDM-PTS-OCT system based on frequency division multiplexing technology. This innovative approach leverages the principle of photonic time stretch combined with frequency division multiplexing technology to achieve simultaneous multi-channel A-scans without sacrificing A-scan speed and axial imaging resolution. The experimental validation confirmed the system's capability to perform Multi channel high-speed signal acquisition without compromising the integrity of the acquired data.

Our results demonstrate advancements over existing time-stretch OCT methods by enabling higher-throughput data acquisition and broader application potential in both biomedical and industrial fields. The FDM-PTS-OCT system's ability to simultaneously collect signals from multiple channels marks a significant step forward in the development of ultra-fast imaging technologies.

Future work will focus on further optimizing the system for various practical applications, including detailed biomedical imaging and industrial inspection processes. Additionally, exploring the integration of more advanced FDM components and higher repetition rate lasers may further enhance the system's performance.

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