# Ultrafast and broadband inertia-free swept source for optical coherence tomography

**Jiqiang Kang, Pingping Feng, Xiaoming Wei, Edmund Y. Lam, Kevin K. Tsia, and Kenneth K. Y. Wong,***
*Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong SAR*
*kywong@eee.hku.hk

**Abstract:** We demonstrate an optical coherence tomography system with a 44.5-MHz repetition rate, 102-nm optical bandwidth inertia-free swept source. Two- and three-dimensional mud-fish eye anterior segment imaging was conducted with 10-μm resolution in tissue.
**OCIS codes:** 180.1655, 140.3560, 110.4500.

## 1. Introduction

Optical coherence tomography (OCT) [1] is a well-recognized cross-section imaging modality featured with label-free, non-invasive, deep-issue, and micrometer resolution, etc. For an OCT system, one key performance indicator is its imaging speed, i.e. A-scan rate, because high imaging speed paves the way to real-time volumetric imaging and to minimize motion artifacts. Different with spectral-domain OCT (SD OCT) where imaging speed is normally limited by the line scan camera [2], the imaging speed of swept-source OCT (SS-OCT) is limited by the swept rate of the broadband swept source [3]. To develop high speed swept source for SS OCT application, a variety of optical frequency scanning technologies were proposed, such as rotating polygon mirror lasers [4], Fourier-domain mode locking lasers [5], short-cavity MEMS-tunable lasers [6], and mode locked fiber lasers [7], etc. Among all those optical frequency scanning technologies, the scheme of applying fiber mode locked laser together with time-stretch technology provides a promising solution to achieve ultrafast (> MHz) swept rate sources since no mechanical vibration components exist anymore and thus remove the speed limitation from mechanical inertia.

In this paper, we demonstrate an inertia-free swept source OCT system based on a fiber ring laser which was passively mode locked by nonlinear polarization rotation (NPR) technology. Two-dimensional (2D) and three-dimensional (3D) OCT images on a mud-fish eye anterior segment was exhibited. Although this system works at 1.5-μm window, it can be extended to other optical wavelength regime, say 1.0-μm for lower water absorption and thus for higher penetration depth [8].

## 2. Experimental setup and results

The experimental setup is shown in Fig. 1.

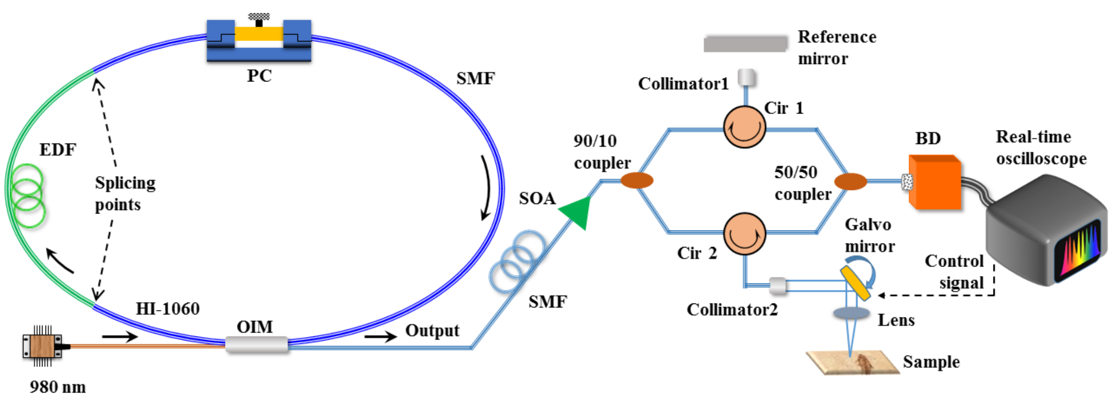


Fig. 1. Experimental setup. EDF: erbium-doped fiber; PC: polarization controller; OIM: optical integrated module; SMF: single mode fiber; SOA: semiconductor optical amplifier; Cir: circulator; BD: balanced detector.

The NPR mode locked fiber ring laser consisted of 3.5-m lowly-doped EDF, 0.5-m single-mode fiber (SMF), and 0.5-m HI-1060 fiber corresponding to 44.5 MHz repetition rate. In mode-locked state, the pump power at 980 nm was 112 mW and the direct output power from the laser was 22 mW. The 10-dB optical spectrum bandwidth was 102 nm measured by an optical spectrum analyzer (OSA, Yokogawa AQ6375) with 0.05-nm resolution, as is shown in Fig. 2(a). Fig 2(b) is the time domain pulse chain measured with a 10-GHz electrical bandwidth photodetector (PD, HP 11982A) and a real time oscilloscope (Lecroy SDA 820Zi-B) with with 80GS/sec sampling rate and 20 GHz electrical bandwidth. Here, the 44.5 MHz repetition rate is clearly shown.

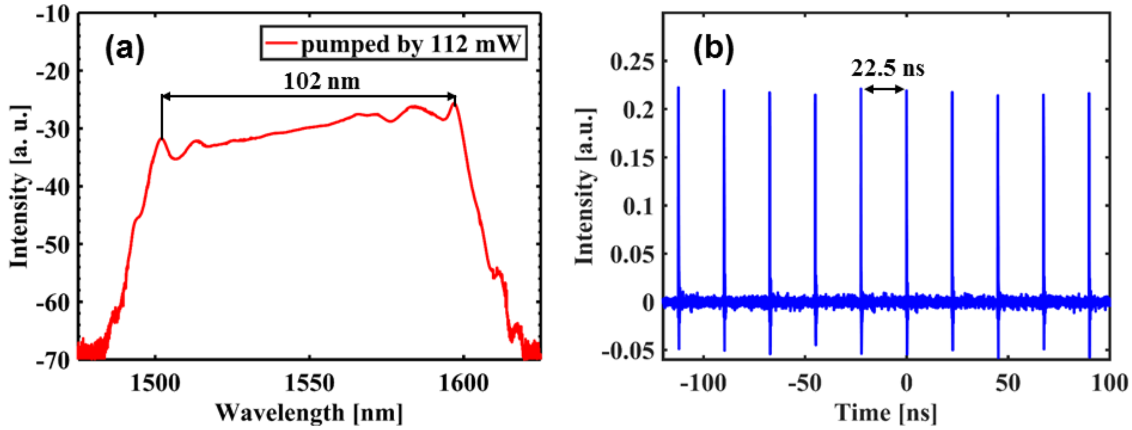


Fig. 2. (a): direct output optical spectrum from the fiber laser; (b): direct output time domain waveform from the fiber laser

The direct output pulse chain was first chirped by a spool of 10-km SMF to ~21 ns with 95% duty ratio, and a semiconductor optical amplifier (SOA, SOA-1140 Covega) was afterwards used to amplify and reshape the time-stretched pulse chain. The original and reshaped optical spectrum are compared in Fig. 3(a) where the short wavelength regime has larger gain than the longer wavelength counterpart which reshaped the spectrum to flatten profile. The average power after the SOA was 32.8 mW. Fig. 3(b) is the time-stretched waveform after the SOA.

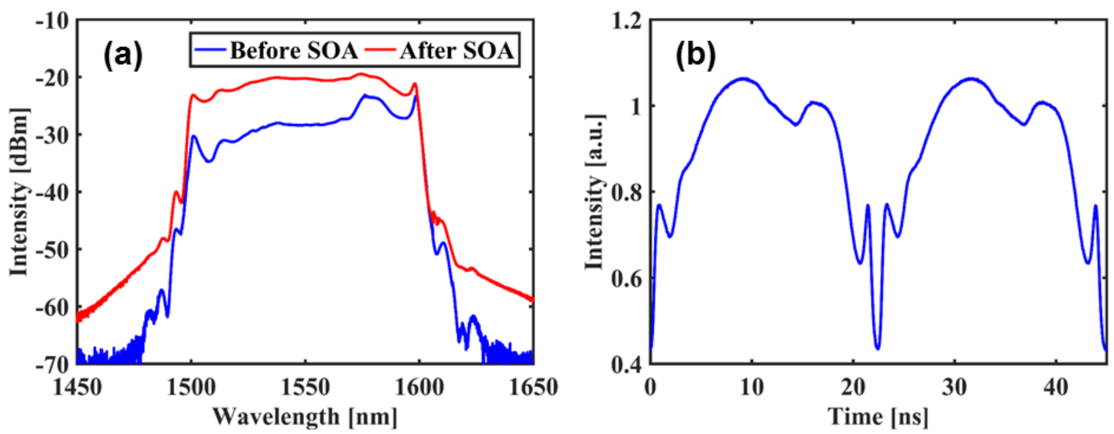


Fig. 3. (a): time-stretched optical spectrum before SOA (in blue) and after SOA (in red); (b): time stretched waveform after SOA.

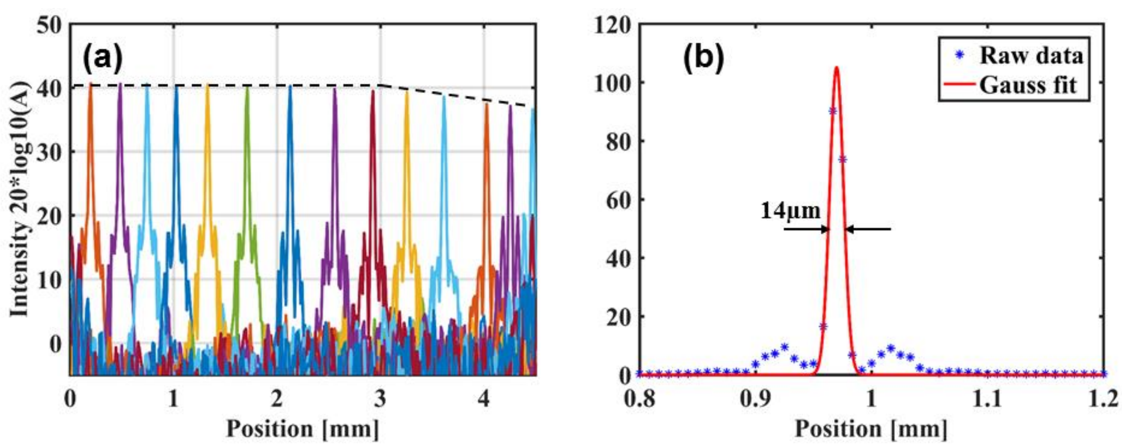


Fig. 4. (a): Sensitivity roll-off; (b): axial resolution.

A Michaelson interferometer was implemented after the SOA for OCT imaging and a balanced detector (BD, DSC-R212 Discovery) with maximum 18 GHz electrical bandwidth and 0.8 A/W responsivity at 1550 nm was used to detect the interference signal and the signal processing was conducted on MATLAB platform operated at the real time oscilloscope. The sensitivity roll-off curves is shown in Fig. 4(a). The sensitivity has no obvious change within 3mm range which shows good coherence performance of the swept source and the measured sensitivity of the system is 86 dB. The axial resolution of the system is shown in Fig. 4(b) and it is 14 µm in air corresponding to 10 µm in tissue which matches well with the theory resolution, i.e. 9.7 µm, with 102 nm spectrum center at 1550 nm.

To demonstrate practical OCT imaging capability by this swept source, a mud-fish eye was used as the sample and the 2D and 3D OCT images are shown in Fig. 5. From those images, the structures of the eye anterior segment are clear shown which proves the high performance of the ultrafast broadband inertia-free SS-OCT system.

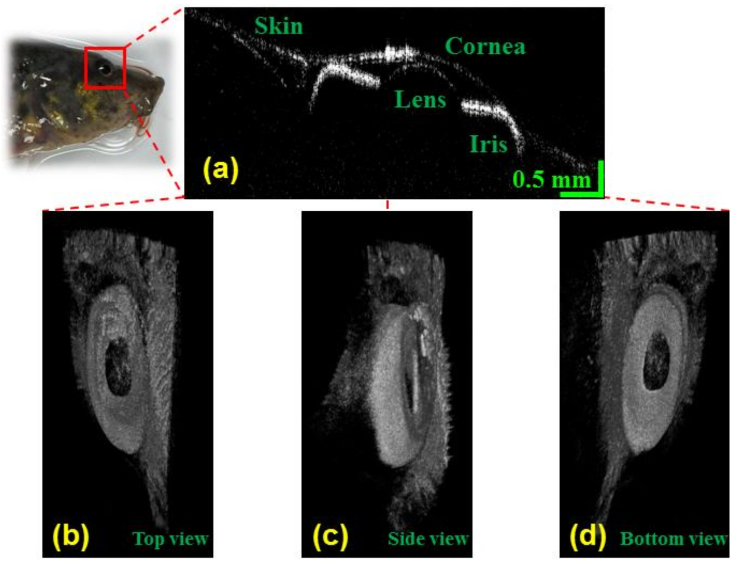


Fig. 5. (a): 2D image of a mud fish eye; (b)~(d): top, side, and bottom view of the 3D mud-fish eye image.

## 3. Summary

In this paper, we demonstrate an OCT system with a 44.5-MHz repetition rate, 102-nm optical bandwidth inertia-free swept source. Comparing with current SS-OCT system, this scheme is a promising solution to realize video rate 3D OCT with high-speed signal processing.

## 4. Acknowledgment

Research Grants Council of the Hong Kong Special Administrative Region, China (Project Nos. HKU 17205215, HKU 17208414, and CityU T42-103/16-N) and National Natural Science Foundation of China (N_HKU712/16). Innovation and Technology Fund (GHP/050/14GD); and University Development Fund of HKU.

## 5. References

[1] W. Drexler and J. G. Fujimoto, "Optical Coherence Tomography: Technology and Applications (Biological and Medical Physics, Biomedical Engineering)," Springer (2008).

[2] T. Bajraszewski, M. Wojtkowski, M. Szkulmowski, A. Szkulmowska, R. Huber, and A. Kowalczyk, "Improved spectral optical coherence tomography using optical frequency comb," Opt. Express **16**(6), 4163–4176 (2008).

[3] I. Grulkowski, J. J. Liu, B. Potsaid, V. Jayaraman, C. D. Lu, J. Jiang, A. E. Cable, J. S. Duker, and J. G. Fujimoto, "Retinal, anterior segment and full eye imaging using ultrahigh speed swept source OCT with vertical-cavity surface emitting lasers," Biomed. Opt. Express **3**(11), 2733-2751 (2012).

[4] W. Y. Oh, B. J. Vakoc, M. Shishkov, G. J. Tearney, and B. E. Bouma, ">400 kHz repetition rate wavelength- swept laser and application to high-speed optical frequency domain imaging," Opt. Lett. **35**(17), 2919–2921 (2010).

[5] R. Huber, M. Wojtkowski, and J. G. Fujimoto, "Fourier Domain Mode Locking (FDML): A new laser operating regime and applications for optical coherence tomography," Opt. Express **14**(8), 3225–3237 (2006).

[6] B. Potsaid, V. Jayaraman, J. G. Fujimoto, J. Jiang, P. J. S. Heim, and A. E. Cable, "MEMS tunable VCSEL light source for ultrahigh speed 60 kHz-1 MHz axial scan rate and long range centimeter class OCT imaging," Proc. SPIE 8213, 82130M, 82130M-8 (2012).

[7] J. Xu, X. Wei, L. Yu, C. Zhang, J. Xu, K. K. Y. Wong, and K. K. Tsia, "High-performance multi-megahertz optical coherence tomography based on amplified optical time-stretch," Biomed. Opt. Express **6**(4), 1340-1350 (2015).

[8] S. A. Filatova, I. A. Shcherbakov, V. B. Tsvetkov, "Optical properties of animal tissues in the wavelength range from 350 to 2600 nm," J. Biomed. Opt. 22(3), 035009 (2017)