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Published in:
Optical Coherence Tomography and Coherence Domain Optical Methods in Biomedicine XXVII

Link to article, DOI:
10.1117/12.2649142

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Proano Grijalva, E. A., Martínez Jiménez, A., Bradu, A., Fernandez, A., Meyer, B. O., Jensen, A., Semenova, E., Ansbæk, T., Yvind, K., & Podoleanu, A. (2023). Novel 1.6 MHz Swept Source for real-time, volumetric in-vivo OCT imaging of the human retina. In J. A. Izatt, & J. G. Fujimoto (Eds.), *Optical Coherence Tomography and Coherence Domain Optical Methods in Biomedicine XXVII* Article 1236704 SPIE - International Society for Optical Engineering. https://doi.org/10.1117/12.2649142

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Event: SPIE BiOS, 2023, San Francisco, California, United States

Novel 1.6 MHz Swept Source for real-time, volumetric in-vivo OCT imaging of the human retina

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ABSTRACT

In this report, a swept source optical coherence tomography (SS-OCT) instrument, equipped with a novel, multi-MHz tuning range swept source is presented. The source, based on an electrically pumped Micro Electro Mechanical System Vertical Cavity Surface Emitting Laser (MEMS-VCSEL) technology, is able to operate at 1.6 MHz with bidirectional sweeping, and emits light at a central wavelength of 1060 nm with a wavelength tuning range of 30 nm at -3 dB. The capabilities of the SS are investigated, and characterized, using an OCT instrument equipped with pupil tracking capabilities. The source provides an experimental axial resolution of 30 μm measured in air. From measuring the sensitivity drop-off, an axial imaging range longer than 90 mm was inferred. To estimate the wavenumber tuning non-linearities of the source and generate images, the Complex Master-Slave (CMS) method was employed. CMS also allowed for real-time visualization of the *en-face* images of the human retina, *in-vivo*, without computing the whole volume. By using the novel SS, *in-vivo* real-time images of the human retina are produced at 4 Hz volume rate when paired with a 2-D orthogonal galvanometer scanner. The increase in speed for A-scan and volume acquisition tends to reduce fragmented and blurry images. Apart from a montage of *en-face* images generated in real-time from various axial positions, we also present B-scans produced with a galvanometer scanner driven at 1 kHz from the optic nerve area.

Keywords: micro electro mechanical system; vertical cavity surface emitting laser; swept source; optical coherence tomography;

1. INTRODUCTION

Swept source optical coherence tomography (SS-OCT) is an imaging technique for the acquisition of cross-section images, usually used on the eye and other kinds of tissues. In ophthalmology, it is used for the diagnosis of different conditions like choroidal neovascularization, drusen, and diabetic macular edema[1]. SS-OCT uses a light source that sweeps a narrow linewidth over a continuous range and a fast photodetector that captures the interference signal from the reference and sample arm[2]. The scanning speed is limited by the sweep rate of the source. High repetition rates are important for the reduction of motion artifacts and for the acquisition of dense volumes of data to generate 3D images[3]. This has motivated the current trend of developing sources with higher repetition rates. For example, a sweep rate of 80MHz was demonstrated by using all-normal dispersion super continuum generation[4]. Another type of source is the Fourier Domain Mode Locked Laser where the tuning filter is driven in synchronism with the round-trip time in the laser cavity. In this way SS-OCT at a rate of 1.64MHz has been achieved[5].

Micro-Electro-Mechanical System with Vertical-Cavity Surface Emitting Laser (MEMS VCSEL) are a type of tunable source that has the advantage over other tunable sources of a very short cavity; this allows single mode operation and narrow instantaneous linewidths that are essential for achieving a long axial range in the OCT images. In comparison with FDML or time stretched lasers, MEMS-VCSELs are more compact and in addition, their sweeping rate can be adjusted according to the application[6]. Volumetric SS-OCT has been previously demonstrated at a central wavelength of 1300 nm for the imaging of gastrointestinal tissue[7].

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Optical Coherence Tomography and Coherence Domain Optical Methods in Biomedicine XXVII,
edited by Joseph A. Izatt, James G. Fujimoto, Proc. of SPIE Vol. 12367,
1236704 · © 2023 SPIE · 1605-7422 · doi: 10.1117/12.2649142

Complex Master-Slave (CMS-OCT) is used to improve the accuracy and processing speed of the imaging process over conventional methods such as software-based or k-clock resampling[8]. CMS-OCT consists in comparing each channeled spectrum (CS) to a set of stored, filtered CSs (masks). Each mask corresponds to a point in the axial range and these are calculated in advance from CS at different optical path differences (OPD) using a mirror in the sample arm. Such calculation takes into account the effects of nonlinearities in the sweep source and dispersion from the interferometer[9]. Another advantage of CMS-OCT over using FFT is that it allows the generation of an *en-face* image without processing the whole volume of data[10]. In this report we use a MHz tuning rate SS based on a MEMS VCSEL for the acquisition of images of the human retina. CMS-OCT is used for faster processing and computation of the *en-face* images.

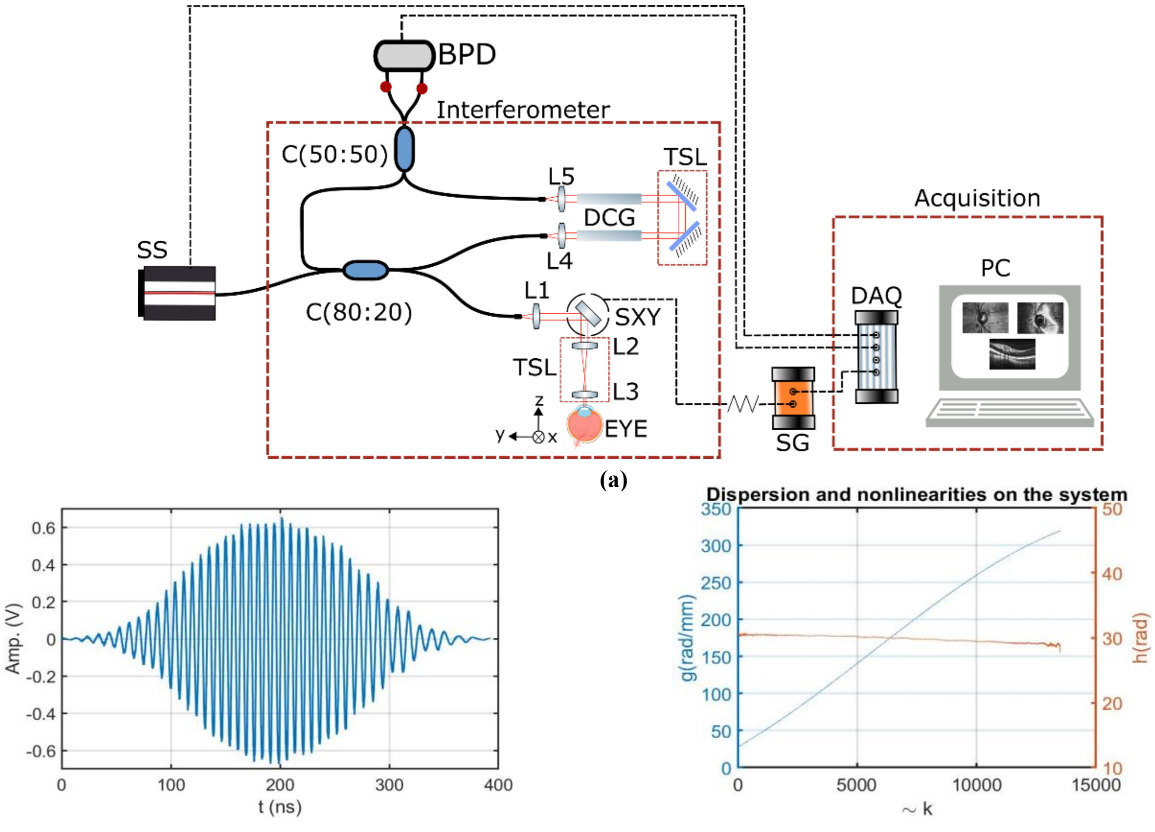
Table 1. Specifications of the SS-OCT system and scanning parameters during imaging.

Laser centre wavelength	1060 nm
Spectral bandwidth (FWHM)	30 nm
Axial range (6 dB)	>90 mm
Bidirectional sweeping time	1/[0.8 MHz]
Equivalent unidirectional sweep time	1/[1.6 MHz]
B-Scan rate	1 kHz
Volume rate	4 Hz
Optical power at the cornea	2.3 mW
Axial resolution in air	29 µm
Lateral resolution using USAF Target	15 µm
Measured sensitivity	-90 dB

2. METHODS

In the present work, a bidirectional 1.6 MHz swept source with 100% duty cycle based on an electrically pumped MEMS-VCSEL devised at OCTLIGHT and the Technical University of Denmark is presented. The laser is a monolithic GaAs based structure with a bottom AlGaAs/GaAs mirror, quantum well gain, anti-reflective coating, and a top photonic crystal mirror. The detailed structure and fabrication of the laser is given in [11] except that the airgap in the present device is 1170 nm. The laser is packaged in vacuum, fiber-coupled and assembled with an isolator, semiconductor optical amplifier (SOA), and control electronics. Resonant excitation of the MEMS in vacuum is used to lower the noise and increase the tuning range of the VCSEL[12]. To investigate the capability of this source to produce high resolution images of the human eye, an OCT instrument whose schematic diagram is shown in Fig.1 (a) has been developed. The instrument is based on a Michelson interferometer composed of an 80:20 directional coupler where 20% of the light is guided towards the sample arm, and 80% towards the reference arm. The light back scattered by the sample and from reference arm is coupled in a 50:50 directional coupler driving a balanced photodetector.

Since the light source has a built-in SOA booster, it can deliver optical powers superior to 20 mW. A sensitivity of the system of -90 dB was measured when the optical power on the sample was 1.8 mW. For the high scanning speed used in this report, the optical power used on the eye was 2.3 mW. In the sample arm, the light is conveyed via a Galvanometer head composed of 2-D orthogonal scanners. A chin rest is used equipped with a camera that tracks the pupil and continuously aligns the platform holding the OCT system with the eye. For measurements, a high-speed oscilloscope (Teledyne Lecroy, WaveMaster 820Zi-B) was used to digitize the signal at the output of a 23 GHz bandwidth balanced photodetector (Optilab, BPR-23-M). For imaging purposes however, the photo-detected signal was digitized at 500 MS/s (AlazarTech, ATS9350) which limited the imaging range of the instrument to ~ 2 mm. In this case, a lower bandwidth, higher gain detector with lower noise was employed (Thorlabs, PDB481-AC, 1 GHz). A LabView software employing the Master Slave approach was developed for real-time display of the OCT images. The program displays three images simultaneously: a confocal, an *en-face* (C-scan) and a cross sectional (B-Scan). For synchronization, the swept source triggers the acquisition card with a TTL signal that is used together with the signal driving the galvanometer scanners. Some of the specifications of the OCT system are presented in the Table 1.



(a)

(b)

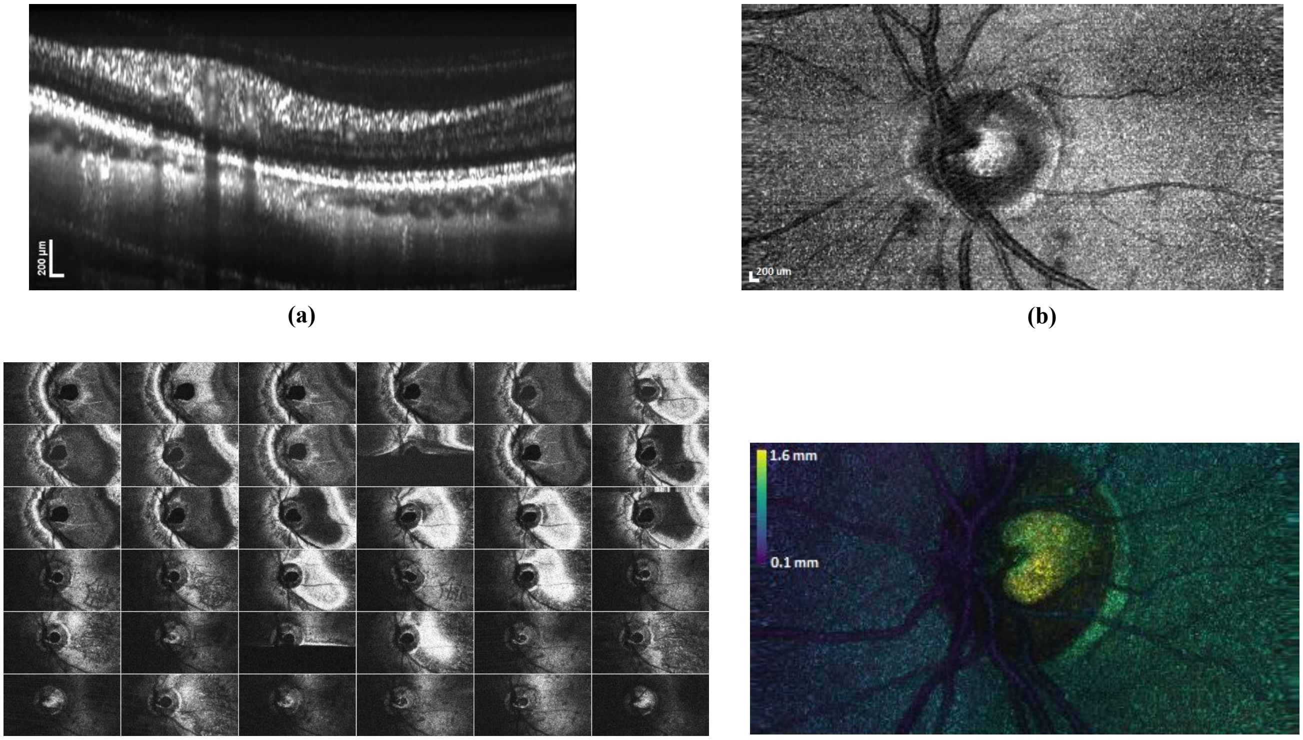
(c)

Figure 1. (a) Schematic of the SS-OCT system. SS: MEMS-VCSEL swept source, Interferometer (C: couplers, TSL: translation stage launcher, DCG: dispersion compensating glass, SXY: 2-D Lateral scanning head, L1-5: lenses), Acquisition (DAQ: digitizer, BPD: balanced photodetector, PC: Computer), SG: Dual signal generator. (b) Channel spectrum at an OPD of 1.7 mm (c) Computed the parameters g and h per each sweep.

Although the tuning of the source is bidirectional, only forward sweeping is used to generate images, therefore only half of the signal was used, making the effective repetition rate 800 kHz. The *en-face* image is displayed at a specified depth position that could be modified at any time. CMS is used as part of the calibration procedure for the computation of *en-face* images at a specific depth. In order to compute the masks, the calibration procedure consists in using a mirror in the sample arm to generate a single layer reflection. Then, the OPD is changed at fixed intervals between the axial range by changing the position of the TSL. The CSs at every position are used to calculate the coefficients h and g, Fig.1 (c). From these coefficients the masks can be obtained for any number of points within a given range as it is shown in the algorithm in [9]. Confocal images are computed based on integration of the ac signal, $\sum_k |S(k)|$ where S(k) is the channel spectrum, for each coordinate (x, y) in the image. 3D volumes are acquired by grouping together 400 sweeps per each lateral scan with 200 such lines in each frame.

3. RESULTS

To produce the OCT images, the channel spectrum acquired per each sweep was processed based on the CMS procedure. Corrected channel spectra are presented in Fig.1 (b) at an OPD of 0.85 mm, corresponding to a frequency of 120 MHz. A slope of 0.068 dB/mm was obtained. Measuring the decay of sensitivity with OPD, an axial range of 90 mm at 6 dB was obtained. In Fig.1 (c), the functions $g(k)$ and $h(k)$ describing the tuning non-linearities of the source with the wavenumber and the unbalanced dispersion in the interferometer respectively are shown. Sweeping exhibits almost linear sweeping (g almost linear) while dispersion is minimal ($h(k)$ almost constant). Several samples have been imaged, such as an IR card, thumb, nails, and a USAF target. Using the latter, a lateral resolution of 15 µm was experimentally measured when an achromatic lens of 2 cm focal length was employed to focus the light on the USAF target. Fig.2 (a) shows an averaged B-scan composed of 200 B-scans, continuously acquired at a line rate of 1 kHz.



(a) **(b)**

(c) **(d)**

Figure 2. OCT images acquired in real time. a) B-Scan OCT image of the retina obtained by averaging 200 B-scans. (b) Confocal image centered on the optic nerve. (c) *En-face* images recorded in sequence at 2 Hz, in which the depth of the image displayed was varied from 0.1 to 1.6mm using different masks. (d) Depth-color encoded projection on *en-face* from 3D volume.

Fig.2 (b) shows the confocal image obtained simultaneously with the *en-face* and B-scans. The montage presented in Fig.2 (c) is composed of 36 *en-face* images recorded sequentially in real-time at a rate of 4 Hz (0.2 s to acquire the volumetric data and 50 ms to process it). To produce it, the axial position of the eye was fixed, while the selection of the axial position where the *en-face* was produced, performed by the CMS processing, was varied from OPD = 0.1 mm up to 1.6 mm. For the lateral *x*-direction, the line (fast) lateral scanner is driven with a triangular shape at 1 kHz and an amplitude of 1.5 V. The corresponding lateral size covers approximately 3.7 mm in the retina. In the y-direction, 200 points were used, corresponding to an amplitude of 0.85 V applied to the frame galvanometer scanner corresponding to 1.8 mm. Fig.2 (d) is a depth color-coded image projection of all *en-face* images generated in a 3D volume acquired at 4 Hz.

4. CONCLUSIONS

In this work, a compact OCT system for fast acquisition of *en-face* images is demonstrated. This exhibits an effective A-scan rate of 800 kHz. Each sweep however is acquired in half time of the sweeping period, hence corresponds to sweeping in an equivalent period to that of sweeping at 1.6 MHz. B-Scans are obtained at a rate of 1 kHz with 400 A-scans per B-scan. The images were obtained *in-vivo* at a display rate of 4 Hz, with lateral and axial resolutions of 15 µm and 30 µm, respectively. As a result, we were able to observe the optic nerve and the fovea over an area of 3.7 x 1.8 mm. Further improvements can be made by using a higher speed digitizer that would allow the acquisition of a larger axial range, and the implementation of the bidirectional scanning would allow doubling the A-scan rates.

ACKNOWLEDGMENTS

The authors thank the European Commission for the Innovative Training Networks “NExt generation of Tunable LASer for optical coherence tomography” (ITN-NETLAS) program of the Marie Sklodowska-Curie actions (H2020-EU.1.3.1., grant agreement no.860807). AP also acknowledges the support of the NIHR Biomedical Research Centre at Moorfields Eye Hospital NHS Foundation Trust and UCL Institute of Ophthalmology, BRC3, BBSRC BB/S0166431 and NIHR202879 grant to the i4i Call 21. KY acknowledges the support from the Independent research fund Denmark (STEPS project 8022-00110A). AB acknowledges the support of the Royal Society, project PARSOCT, RGS/R1/221324 and the support of the Academy of Medical Sciences/the Welcome Trust/the Government Department of Business, Energy and Industrial Strategy/the British Heart Foundation/Diabetes UK Spring-board Award SBF007\100162.

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