Ultrahigh-speed optical coherence tomography utilizing all-optical 40 MHz swept-source

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Abstract. We present an ultrahigh-speed optical coherence tomography (OCT) based on an all-optical swept-source with an A-scan rate of 40 MHz. The inertia-free swept-source, which has its output power of 41.2 mW and tuning range of 40 nm and high scan linearity in wave-number with Pearson’s correlation coefficients $r$ of 0.9996, consists of a supercontinuum laser, an optical band-pass filter, a linearly chirped fiber Bragg grating, and two buffer stages. With sensitivity of 87 dB, high-speed OCT imaging of biological tissue in vivo is also demonstrated. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.

Keywords: optical coherence tomography; swept-source; linearly chirped fiber Bragg grating.

Ultrahigh-speed OCT imaging of biological tissue in vivo can improve the diagnostic accuracy of medical procedures. In this paper, we introduce an ultrahigh-speed OCT system based on a 40 MHz swept-source, achieving a sensitivity of 87 dB and an axial resolution of 19.8 ns. The system utilizes an all-optical swept-source with a bandwidth of 40 nm and a tuning range of 40 MHz. The sweep rate is limited by the group velocity dispersion (GVD) of the low-cost fiber Bragg grating (LCFGB) used in the system. However, the swept-source achieves a high A-scan rate of 40 MHz, enabling rapid imaging of biological tissues.

Optical coherence tomography (OCT) has been a valuable tool in medical imaging for its ability to provide high-resolution, cross-sectional images of tissues. The use of a swept-source with a high A-scan rate allows for faster imaging and improved resolution compared to traditional OCT systems. In this work, we demonstrate the integration of an all-optical swept-source with an A-scan rate of 40 MHz to enhance the imaging speed and sensitivity of OCT. This approach promises to improve the diagnostic capability of OCT in real-world applications.

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Journal of Biomedical Optics 030503-1 March 2015 • Vol. 20(3)
With \( \sim 38 \, \mu W \) power input in EDFA, the output of the 40 MHz swept-source is 41.2 mW.

We use a flat mirror at the sample position of 50 \( \mu m \) to evaluate the point spread function (PSF). The optical power incident on the specimen is \( \sim 25.5 \, mW \) for 40 MHz SS-OCT with a theoretical sensitivity of 90 dB. The measured axial resolution of 26.9 \( \mu m \), almost the same, except that the LCFBG2 in the 40 MHz swept-source is replaced by LCFBG 3 and the buffered stage is removed in the 10 MHz swept-source. With an input power of \( \sim 38 \, \mu W \) in the EDFA, the output power of the 10 MHz swept-source is 40.5 mW. The optical power incident on the specimen is \( \sim 25.1 \, mW \) for 10 MHz SS-OCT with the theoretical sensitivity of 90 dB. With a total GVD of \( -2312 \, ps \cdot nm^{-1} \), its full-swept range of 40 nm is mapped into a time span of 91.2 ns. The axial resolution, \( -6 \, dB \) imaging depth, and sensitivity of the 10 MHz SS-OCT are 27 \( \mu m \), 1.95 mm, and 85.5 dB, respectively.

Because LCFBGs provide a practically flat gain and linear group delay, \( \beta_2 \) is almost a constant. Therefore, the swept-source scans the wavenumber linearly with time. In Fig. 3(b), the wavenumber versus time curve (dashed line) is obtained from the fringes (solid line) at a 40 MHz swept rate with a fiber-based Mach–Zehnder interferometer, in which the arm difference is set to be \( \sim 0.1 \, mm \). The Pearson’s \( r \) is 0.9996 in the fitted linear curve (short dotted line). The integrated relative frequency error \( \chi \), defined as a measure for the sweep linearity, is 0.0002, as shown in Fig. 3(a).

To illustrate the performance of the 40 MHz swept-source, SS-OCT imaging of the intralipid injected into a glass tube and human palm is implemented, as shown in Figs. 5(d) and 5(c). Due to the analog bandwidth upper limit of the acquisition system, the recordable imaging depth is not enough for viewing the whole cross section of the tube. Therefore, in comparison, a 10 MHz swept-source-based SS-OCT imaging with a fourfold larger imaging depth is also given, as shown in Figs. 5(a) and 5(b). The configuration of the 10 and 40 MHz swept-source is almost the same, except that the LCFBG2 in the 40 MHz swept-source is replaced by LCFBG 3 and the buffered stage is removed in the 10 MHz swept-source. With an input power of \( \sim 38 \, \mu W \) in the EDFA, the output power of the 10 MHz swept-source is 40.5 mW. The optical power incident on the specimen is \( \sim 25.1 \, mW \) for 10 MHz SS-OCT with the theoretical sensitivity of 90 dB. With a total GVD of \( -2312 \, ps \cdot nm^{-1} \), its full-swept range of 40 nm is mapped into a time span of 91.2 ns. The axial resolution, \( -6 \, dB \) imaging depth, and sensitivity of the 10 MHz SS-OCT are 27 \( \mu m \), 1.95 mm, and 85.5 dB, respectively.

It is worthwhile to mention that all imaging is implemented without any averaging of the consecutive A-scan signal. As shown in Fig. 5(a), our ultrahigh-speed SS-OCT can clearly reveal the structure of the epidermis and dermis layers. With a faster photo-detector and data acquisition card, the maximum imaging
Two-dimensional (2-D) cross-sectional imaging of intralipid injected into a glass cube by (a) (423 × 200 pixels) 10 MHz swept-source and (c) (423 × 50 pixels) 40 MHz swept-source. The scale bar represents 500 μm. (e) Schematic for the sample in (a) and (c). The intralipid was injected into a glass tube with an outer diameter of 1.2 mm and inner diameter of ~1 mm.

depth could reach ~7 mm, as implied by the quality of the image in Fig. 4 because the signal in the deep depth does not have much falloff. Meanwhile, it is possible to superimpose more LCFBGs to enlarge the spectral range and to achieve higher axial resolution.

In summary, a 40 MHz all-optical swept-source at 1545 nm with a 3 dB tuning range of 40 nm, output power of 41.2 mW, and EDFA amplification is developed and achieves good wave-number-linearity with Pearson’s r of 0.9996 and integrated relative frequency error of 0.0002. With a sensitivity of 87 dB, 6 dB fall-off depth of 0.42 mm, and A-scan rate of 40 MHz, ultrahigh-speed SS-OCT imaging of biological tissue in vivo is demonstrated.

Acknowledgments
This work is supported in part by the National Natural Science Foundation of China under Grant No. 61227807 and by the Tsinghua Initiative Scientific Research Program under Grant No. 2013THZ02-3.

References