Fourier Domain Mode Locking (FDML): A new laser operating regime and applications for optical coherence tomography

R. Huber, M. Wojtkowski, and J. G. Fujimoto

Department of Electrical Engineering and Computer Science
and Research Laboratory of Electronics,
Massachusetts Institute of Technology, Cambridge, MA 02139
Tel: 617-253-8920, Fax: 617-253-9611,
rhuber@mit.edu

Abstract: We demonstrate a new technique for frequency-swept laser operation--Fourier domain mode locking (FDML)--and its application for swept-source optical coherence tomography (OCT) imaging. FDML is analogous to active laser mode locking for short pulse generation, except that the spectrum rather than the amplitude of the light field is modulated. High-speed, narrowband optical frequency sweeps are generated with a repetition period equal to the fundamental or a harmonic of cavity round-trip time. An FDML laser is constructed using a long fiber ring cavity, a semiconductor optical amplifier, and a tunable fiber Fabry-Perot filter. Effective sweep rates of up to 290 kHz are demonstrated with a 105 nm tuning range at 1300 nm center wavelength. The average output power is 3 mW directly from the laser and 20 mW after post-amplification. Using the FDML laser for swept-source OCT, sensitivities of 108 dB are achieved and dynamic linewidths are narrow enough to enable imaging over a 7 mm depth with only a 7.5 dB decrease in sensitivity. We demonstrate swept-source OCT imaging with acquisition rates of up to 232,000 axial scans per second. This corresponds to 906 frames/second with 256 transverse pixel images, and 3.5 volumes/second with a 256x128x256 voxel element 3-D OCT data set. The FDML laser is ideal for swept-source OCT imaging, thus enabling high imaging speeds and large imaging depths.

©2006 Optical Society of America

OCIS codes: (110.4500) Optical coherence tomography; (140.3600) Lasers, tunable

References

1. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, "Optical coherence tomography," Science 254, 1178-1181 (1991).
2. A. F. Fercher, C. K. Hitzenberger, G. Kamp, and S. Y. Elzaiat, "Measurement of intraocular distances by backscattering spectral interferometry," Opt. Commun. 117, 43-48 (1995).
3. F. Lexer, C. K. Hitzenberger, A. F. Fercher, and M. Kulhavy, "Wavelength-tuning interferometry of intraocular distances," Appl. Opt. 36, 6548-6553 (1997).
4. B. Golubovic, B. E. Bouma, G. J. Tearney, and J. G. Fujimoto, "Optical frequency-domain reflectometry using rapid wavelength tuning of a Cr4+:forsterite laser," Opt. Lett. 22, 1704-1706 (1997).
5. S. R. Chinn, E. A. Swanson, and J. G. Fujimoto, "Optical coherence tomography using a frequency-tunable optical source," Opt. Lett. 22, 340-342 (1997).
6. S. H. Yun, G. J. Tearney, J. F. de Boer, N. Itinimia, and B. E. Bouma, "High-speed optical frequency-domain imaging," Opt. Express 11, 2953-2963 (2003).
http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-22-2953
7. S. H. Yun, C. Boudoux, G. J. Tearney, and B. E. Bouma, "High-speed wavelength-swept semiconductor laser with a polygon-scanner-based wavelength filter," Opt. Lett. 28, 1981-1983 (2003).
8. R. Huber, M. Wojtkowski, K. Taira, J. G. Fujimoto, and K. Hsu, "Amplified, frequency swept lasers for frequency domain reflectometry and OCT imaging: design and scaling principles," Opt. Express 13, 3513-3528 (2005).
http://www.opticsexpress.org/abstract.cfm?URI=OPEX-13-9-3513.
9. M. A. Choma, K. Hsu, and J. Izatt, "Swept source optical coherence tomography using an all-fiber 1300-nm ring laser source," J. Biomed. Opt. 10, 044009 (2005).
10. R. Huber, M. Wojtkowski, J. G. Fujimoto, Y. Y. Jiang, and A. E. Cable, "Three-dimensional and C-mode OCT imaging with a compact, frequency swept laser source at 1300 nm," *Opt. Express* 13, 10523-10538 (2005).
http://www.opticsexpress.org/abstract.cfm?URI=OPEX-13-26-10523.
11. Y. Yasuno, V. Madjarova, S. Makita, M. Akiba, A. Morosawa, C. Chong, T. Sakai, K. Chan, M. Itoh, and T. Yatagai, "Three-dimensional and high-speed swept-source optical coherence tomography for in vivo investigation of human anterior eye segments," Opt. Express 13, 10652-10664 (2005).
http://www.opticsexpress.org/abstract.cfm?id=86669.
12. W. Y. Oh, S. H. Yun, G. J. Tearney, and B. E. Bouma, "115 kHz tuning repetition rate ultrahigh-speed wavelength-swept semiconductor laser," Opt. Lett. 30, 3159-3161 (2005).
13. S. T. Sanders, J. A. Baldwin, T. P. Jenkins, D. S. Baer, and R. K. Hanson, "Diode-laser sensor for monitoring multiple combustion parameters in pulse detonation engines," P. Combust. Inst. 28, 587-594 (2000).
14. J. Wang, S. T. Sanders, J. B. Jeffries, and R. K. Hanson, "Oxygen measurements at high pressures with vertical cavity surface-emitting lasers," Appl. Phys. B 72, 865-872 (2001).
15. G. Totschnig, M. Lackner, R. Shau, M. Ortsiefer, J. Rosskopf, M. C. Amann, and F. Winter, "1.8 um m vertical-cavity surface-emitting laser absorption measurements of HCl, H2O and CH4," Meas. Sci. Technol. 14, 472-478 (2003).
16. A. A. Bol'shakov, B. A. Cruden, and S. P. Sharma, "Determination of gas temperature and thermometric species in inductively coupled plasmas by emission and diode laser absorption," Plasma Sci. Technol. 13, 691-700 (2004).
17. L. A. Kranendonk, R. J. Bartula, and S. T. Sanders, "Modeless operation of a wavelength-agile laser by high-speed cavity length changes," Opt. Express 13, 1498-1507 (2005).
http://www.opticsexpress.org/abstract.cfm?URI=OPEX-13-5-1498.
18. W. Eickhoff and R. Ulrich, "Optical frequency-domain reflectometry in single-mode fiber," Appl. Phys. Lett. 39, 693-695 (1981).
19. R. Passy, N. Gisin, J. P. Vonderweid, and H. H. Gilgen, "Experimental and theoretical investigations of coherent Ofdr with semiconductor-laser sources," J. Lightwave Technol. 12, 1622-1630 (1994).
20. U. Glombitza and E. Brinkmeyer, "Coherent frequency-domain reflectometry for characterization of single-mode integrated-optical wave-guides," J. Lightwave Technol. 11, 1377-1384 (1993).
21. H. Barfoss and E. Brinkmeyer, "Modified optical frequency-domain reflectometry with high spatial-resolution for components of integrated optic systems," J. Lightwave Technol. 7, 3-10 (1989).
22. M. A. Choma, M. V. Sarunic, C. Yang, and J. Izatt, "Sensitivity advantage of swept source and Fourier domain optical coherence tomography," Opt. Express 11, 2183-2189 (2003).
http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-18-2183.
23. M. Wojtkowski, R. Leitgeb, A. Kowalczyk, T. Bajraszewski, and A. F. Fercher, "In vivo human retinal imaging by Fourier domain optical coherence tomography," J. Biomed. Opt. 7, 457-463 (2002).
24. S. H. Yun, G. J. Tearney, B. E. Bouma, B. H. Park, and J. F. de Boer, "High-speed spectral-domain optical coherence tomography at 1.3 um m wavelength," Opt. Express 11, 3598-3604 (2003).
http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-26-3598.
25. N. A. Nassif, B. Cense, B. H. Park, M. C. Pierce, S. H. Yun, B. E. Bouma, G. J. Tearney, T. C. Chen, and J. F. de Boer, "In vivo high-resolution video-rate spectral-domain optical coherence tomography of the human retina and optic nerve," Opt. Express 12, 367-376 (2004).
http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-3-367.

1. Introduction

Laser mode locking has proven to be a powerful method for generating short optical pulses. To date, mode-locking techniques work by active or passive amplitude-modulation or phase-modulation, which is synchronous to the round-trip time of the pulse in the laser cavity. However, in addition to short laser pulse generation, there are applications where high-speed, narrowband, optical frequency-swept lasers are desired. In biomedical imaging with optical coherence tomography (OCT), [1] frequency-swept lasers have recently enabled imaging speeds of up to several ten thousand axial scans per second, which is 10 to 50 times faster than standard OCT detection techniques.[2-12] A further increase in the sweep rate is desired, because a broad range of promising applications can be envisioned with fast swept-source 3-D OCT.[10, 11] In addition to high-speed OCT imaging, narrowband optical frequency-swept lasers with broad tuning ranges have many other applications in fields such as spectroscopy [13-17] or photonic device characterization.[18-21]
In all of these applications, the narrowband, optical frequency-swept laser provides spectral encoding in time, and spectral information is obtained by recording the transient signal while the laser is frequency swept. Current high-speed, frequency-swept laser sources typically consist of a broadband gain medium with a tunable optical bandpass filter in the cavity. The maximum achievable frequency tuning rate is limited by the characteristic time constant for building up laser activity inside the cavity.[8] This non-stationary operation, corresponding to a temporally varying distribution of energy between the longitudinal modes of the laser cavity, has many drawbacks, including increased amplitude noise, low power, broad instantaneous linewidth, or short instantaneous coherence length. These problems can be overcome by extending the laser cavity and periodically driving the optical bandpass filter synchronously with the optical round-trip time of the propagating lightwave in the cavity. This produces a quasi-stationary operation where light from one frequency sweep propagates through the cavity and returns to the optical bandpass filter at the exact time when the transmission of the filter is at the same spectral position. In the frequency domain, this produces a fixed phase relation between the longitudinal cavity modes such that the transient electric field at the optical bandpass filter has only frequency components that match the transient filter transmission, while all other frequency components destructively interfere. We refer to this technique as Fourier domain mode locking (FDML). FDML is complementary to standard mode locking. In FDML, the spectrum, rather than the amplitude of the field, is modulated. A dynamic spectral window function (wavelength window which changes in time), rather than a temporal one (time window with no wavelength dependence), is applied. As a result, the laser generates a sequence of narrowband optical frequency sweeps at the cavity repetition rate or a harmonic thereof. This frequency-swept output can also be thought of as a sequence of highly chirped, long pulses, with a fixed phase relationship between successive frequency sweeps. Although the results presented in this manuscript were achieved with long-cavity fiber lasers, the principles of FDML can be scaled to any cavity length and frequency-sweep repetition rate.

In this paper, we describe Fourier domain mode locking (FDML) and demonstrate it for high-speed, frequency-swept operation of a semiconductor amplifier and fiber ring cavity laser. We demonstrate the FDML laser for high-speed, swept-source OCT imaging. Excellent instantaneous linewidth performance is achieved, which enables more than 7 mm imaging depths. High-speed OCT image acquisition of up to 232,000 axial scans per second, which corresponds to an acquisition rate of 908 frames/second for 256 transverse pixel images, is demonstrated. Three-dimensional data sets consisting of 256x128x256 voxels can be acquired at 3.5 volumes per second. To our knowledge, with the exception of full field OCT techniques, this is the highest acquisition speed achieved for OCT imaging to date.

2. Concept of Fourier Domain Mode Locking (FDML)

Figure 1 is a schematic showing the concept of an FDML laser compared to a standard frequency-swept laser. In a standard frequency-swept laser (Fig. 1 (left)), light from a broadband gain medium is spectrally filtered by a narrowband optical bandpass filter within the cavity and fed back to the gain medium.
Only longitudinal modes with frequencies that are transmitted through the narrowband optical filter can lase. When the center frequency of the narrowband optical filter is tuned during a frequency sweep, lasing must build up from spontaneous emission at each new frequency position of the filter. This significantly limits the performance of high-speed, frequency-swept lasers, imposing a trade-off between the speed of the frequency sweep versus linewidth, output power, and tuning range.[8]

In FDML, a dispersion managed delay line is incorporated into the laser cavity and the narrowband optical filter is tuned periodically at the cavity round-trip time, or a harmonic of the round-trip time (Fig. 1 (right)). This produces a quasi-stationary mode of operation. Light from one frequency sweep propagates through the cavity and returns to the filter at the exact time when the transmission window of the optical bandpass filter is tuned to the same optical frequency. Therefore, light from the previous round-trip is coupled back to the gain medium and lasing does not have to build up from spontaneous emission. In other words, an entire frequency sweep is optically stored within the dispersion managed delay line in the laser cavity. Under ideal operation, sequential frequency sweeps have the same phase evolution and are mutually coherent. The narrowband optical bandpass filter dissipates almost no energy because the backcoupled light contains only frequencies that are matched to the transmission window filter at each moment. In the frequency domain, this requires destructive interference of all longitudinal modes that are not transmitted through the narrowband filter at a given time. Thus, the phases of the longitudinal modes must be locked. Standard mode-locked lasers have longitudinal modes locked with constant phase, which corresponds to the generation of a train of short pulses at a repetition rate equal to the cavity round-trip time. Fourier domain mode-locked lasers have modes locked with a different phase relationship. The laser output is not a train of short pulses; instead, it is a train of frequency sweeps or highly chirped, very long pulses. The tunable narrowband filtering is equivalent to an infinite number of narrowband amplitude modulators that are slightly out of phase. Fourier domain mode locking is performed by periodic spectral modulation, rather than amplitude modulation. This can be viewed as the Fourier domain analog of mode locking for short-pulse generation. In an ideal system the FDML technique represents a completely new type of active mode locking mechanism.

3. Experimental setup

3.1 Design and operation of the FDML laser

Figure 2 is a schematic diagram of the FDML laser. The laser is based on a fiber-ring geometry with a semiconductor optical amplifier (SOA from InPhenix, Inc.) as a gain medium.
and a fiber Fabry-Perot filter (FFP-TF, Micron Optics, Inc.) as the tunable, narrowband optical bandpass filter. The SOA is polarization insensitive with a polarization dependent gain of ~0.5 dB. The fiber Fabry-Perot tunable filter had a free spectral range of ~200 nm at 1300 nm and a finesse of ~800.

In order to have FDML operation, light with a certain frequency or wavelength must be transmitted by the filter again after one round trip. The time duration $\tau_{\text{gate}}$, the filter transmits at a certain wavelength is approximately given by:

$$
\tau_{\text{gate}} = \frac{\Delta \lambda}{\eta \cdot f_{\text{drive}} \cdot \Delta \lambda_{\text{tuning range}}}
$$

(1)

where $\Delta \lambda$ is the spectral width of the optical filter, $f_{\text{drive}}$ is the drive frequency, $\Delta \lambda_{\text{tuning range}}$ is the bandwidth over which the filter is tuned and a factor $\eta = \pi$ accounts for the non-linearity and the bidirectionality of the sinusoidal sweep. The derivation of this formula is analogous to the discussions of the “single roundtrip limit” in Ref. [8]. The mismatch between the roundtrip time and the frequency sweep period, caused by various parasitic effects detailed below, must be smaller than the time $\tau_{\text{gate}}$.

To enable FDML operation, a Corning SMF28e fiber of several kilometers in length is incorporated into the laser, and the narrowband optical bandpass filter is driven periodically with a period matched to the optical round-trip time of the laser cavity, or a harmonic thereof. Dispersion must be minimized so that different frequencies or wavelengths within the frequency sweep will propagate with the same round trip time. In general, this can be accomplished using a “dispersion managed” delay, where fibers with different dispersion characteristics and lengths are combined in order to achieve a low dispersion across the wavelength range of operation. Dispersion management is achieved at 1300 nm by using SMF28e fiber. This fiber has zero dispersion at 1313 nm and a dispersion slope of 0.086 ps/km/nm$^2$. This produces a variation in round trip propagation time of $\Delta \tau_{\text{disp}}$ as a function of wavelength given by:

$$
\Delta \tau_{\text{disp}} = (\lambda - 1313\text{nm})^2 \cdot 0.086 \frac{\text{ps}}{\text{km} \cdot \text{nm}^2} \cdot L
$$

(2)
where $\lambda$ is the specific wavelength and $L$ is the physical length of the fiber. In this study, implementations of FDML lasers with physical cavity lengths of 7 km, 4.8 km and 3.3 km were investigated. These cavity lengths correspond to optical roundtrip frequencies of 29 kHz, 42 kHz and 62 kHz. The corresponding maximum mismatch in roundtrip time caused by the dispersion slope for wavelengths of $1313 \pm 50$ nm is 1.5 ns, 1 ns and 700 ps, respectively. These values are much smaller than the time $\tau_{\text{gate}}$, for which the filter transmits a certain frequency or wavelength under FDML operation. With a tuning range of $\Delta \lambda_{\text{tuningrange}} = 120$ nm, $\Delta \lambda = 0.25$ nm and $f_{\text{drive}} = 29$ kHz, 42 kHz and 62 kHz, $\tau_{\text{gate}}$ is calculated to be 22 ns, 15 ns and 10 ns respectively. This is more than one order of magnitude more than the time mismatch caused by dispersion. Time mismatch due to polarization mode dispersion can be estimated and is in the picosecond range for all of the above operating points. Therefore polarization mode dispersion can be neglected.

In the present investigation, we did not observe experimental evidence for a significant difference in performance between the operation of the laser with the 7 km fiber at the second harmonic of the cavity roundtrip frequency and the laser with the 3.3 km fiber at the fundamental of the cavity roundtrip frequency. Further studies are necessary to investigate these effects. However, in order to reduce loss and possible effects of dispersion, it is desirable to operate the laser with the shortest fiber length possible for a given round trip time or frequency sweep repetition rate.

The waveform driver for the fiber Fabry-Perot consisted of a digital function generator and an electric power amplifier for driving the low-impedance ~$2.2 \mu F$ capacitive load of the fiber Fabry-Perot lead zirconate titanate (PZT) actuator. With respect to thermal stability, the drift of the resonance frequency caused by temperature variations as well as drift in the PZT bias offset were minimal and a manual adjustment after about 15 minutes warm up time ensured stable operation for many hours. The isolators eliminated extraneous intracavity reflections and ensured the unidirectional lasing of the ring cavity. A 30% fiber splitter acted as the output coupler. After isolation, the laser output was amplified with a second fiber-coupled semiconductor amplifier (SOA from InPhenix, Inc.), which functions as a booster amplifier. The device is polarization insensitive with a polarization dependent gain of about 0.5 dB. The physics of post-amplification are discussed in detail in Ref. [8].

The losses throughout the cavity are typically 0.35 dB for each isolator, <2 dB for the fiber Fabry-Perot filter, 1.8 dB for the 30 % output coupler and 2.2 dB, 1.5 dB and 1 dB for 7 km, 4.8 km and 3.3 km lengths of fiber, respectively. Between -5 dB and -7 dB of the output of the SOA are coupled back into the SOA. The fiber-to-fiber small signal gain of the SOA is 20 dB.

3.2 OCT imaging setup

Figure 3 is a schematic diagram of the OCT system. The OCT Michelson interferometer uses a circulator and a dual-balanced detector in order to cancel background levels and excess laser noise, as well as to enable A/D detection with lower bit resolution. The photodiodes have a bandwidth of 80 MHz and a transimpedance gain of ~50,000 V/A. The photodiode responsivity at 1300 nm was estimated to be ~0.8 A/W from the given value of 1 A/W at a wavelength of 1550 nm. The interferometric fringe signal from the OCT interferometer was acquired on one channel of a two-channel, high-speed, 14-bit-resolution analog-to-digital converter (A/D) operating up to 200 Msamples/s (Gage Applied Technologies, Inc., model CS14200). The A/D card has an onboard memory of 2 Gb, enough to store several 3-D data sets in real-time acquisition mode. A portion of the signal from the frequency-swept laser was tapped off and coupled into a separate free-space Mach-Zehnder (MZ) interferometer with adjustable asymmetry in the arm lengths.
While the laser was frequency sweeping, a sinusoidal fringe signal was generated and recorded on the second channel of the A/D converter. This signal was used for the recalibration of time to optical frequency. For all data and images shown in this paper, signal recalibration prior to the Fast Fourier Transform (FFT) was performed with the fast next neighbor check algorithm presented in Ref. [8]. Recalibration with spline interpolation could be performed if improved accuracy is needed, but it has the disadvantage of being too slow for real-time preview mode and, therefore, was not used in this study. An aiming mode provides a real-time frame rate of approximately 2-4 frames per second with an image size of 512 axial and 256-512 transverse pixels. In the acquisition mode, the signal is recorded onto the large onboard buffer of the A/D converter card. This scheme circumvents limitations by the transfer speed of the computer PCI bus. The size of the onboard buffer is 2 Gb, which enables storage of entire 3-D data sets. The fast rearming time of the A/D card supports up to 500,000 trigger events per second. After data acquisition, the onboard buffer is read out to system memory at readout speeds of up to 160 Mb/s, which is limited by the peripheral component interconnect (PCI) bus v. 2.1 (32 bit, 66 MHz). The effective data acquisition rate with the onboard buffer is as high as 800 Mbytes/s, which can be maintained for several 3-D data sets.

4. Performance of the FDML laser

Figure 4 shows the transient intensity profiles of the frequency-swept laser for forward (shorter to longer wavelengths) and backward (longer to shorter wavelengths) frequency sweeps at different effective sweep rates. The data is shown for the direct laser output without post-amplification in order to ensure that the transient intensity profiles are not obscured or shaped by saturation effects (see Ref. [8]). The physical cavity length was 7 km, which corresponds to a 10-km optical path length. Resonances in the tunable filter drive frequency were observed at 29 kHz and at the higher harmonics. Because two frequency sweeps, one forward and one backward, were generated for each sinusoidal drive cycle, a 29 kHz filter drive frequency corresponds to an effective sweep rate of 58 kHz.

In contrast to other high-speed, frequency-swept lasers, in FDML lasers, the forward and backward frequency sweeps have the same intensity profile and the same maximum power. For most applications, the forward and backward sweeps show comparable parameters. However, when the calibration MZ interferometer is set for long delays (>>10 mm), the
forward frequency sweep shows more instabilities than the reverse frequency sweep, thus indicating an increased instantaneous linewidth. For the OCT imaging applications presented here, the forward and reverse frequency sweeps are equivalent.

![Graph of power vs. time for different frequencies](image1)

**Fig. 4.** Transient intensity profiles of the FDML laser for different effective sweep rates. The traces always show the transient intensity for one forward and one backward frequency sweep.

![Graph of integrated spectra vs. wavelength](image2)

**Fig. 5.** Integrated spectra of the FDML source for different effective sweep rates.

Figure 4 shows that neither the shape, nor the amplitude of the transient intensity profiles changes as the filter drive frequency is increased. The maximum filter drive frequency and frequency sweep rate (change of the optical frequency per time) are only limited by the mechanical response of the tunable narrowband optical filter. This enables very high-speed OCT imaging, as demonstrated in the following sections.

Figure 5 shows the integrated spectra of the frequency-swept laser source with post-amplification measured with an optical spectrum analyzer in peak hold mode. These measurements were performed using the FDML laser with post-amplification. The average power for these measurements was 18.5 mW, 19.7 mW, 17.6 mW and 17.0 mW for 58 kHz, 116 kHz, 232 kHz, and 290 kHz effective sweep rates, respectively. As noted previously, the shape of the spectra did not depend on the effective sweep rate. The spectra spanned a range from 1262 nm to 1368 nm, a full width of approximately 105 nm. The full-width at half-
maximum (FWHM) was ~74 nm. A Gaussian spectrum with a 74 nm FWHM corresponds to an axial OCT resolution of 10 μm in air.

The actual axial point spread function (PSF) at an effective sweep rate of 58 kHz from an isolated mirror reflection in the OCT imaging setup was obtained by: taking an interferometric signal consisting of 1600 A/D samples at 200 Msamples/s; applying the fast next neighbor check method to obtain approximately 1300 samples; zero padding the data to a length of 2048 samples; and Fourier transforming. One-half of the Fourier-transformed data is used to obtain an axial scan, which resulted in 1024 data points per axial scan. A numerical dispersion compensation was applied. The measured FWHM resolution of the point spread function (PSF of the FFT amplitude fitted by a Gaussian function) was 12.7 μm in air, which corresponds to ~9 μm in tissue (Fig. 6). The measured resolution slightly deviates from the theoretical value because of several factors, including: deviations of the sweep spectrum from Gaussian; imbalances in dispersion in the calibration of the MZ interferometer; an overpronounced spectral width of the output spectrum measured with an optical spectrum analyzer OSA (Fig. 5) due to the nonlinear, optical frequency sweep speed; wavelength calibration errors from the fast next neighbor check method; and a residual, uncompensated dispersion mismatch in the Michelson interferometer. The application of a higher performance, broader bandwidth SOA should enable an increased frequency sweep range and a better spatial resolution.

The instantaneous linewidth or instantaneous coherence length are other critical parameters for frequency-swept laser sources. In order to characterize the performance of the FDML laser, the sensitivity was measured for different path-length mismatches in the interferometer.

![PSF data](image_url)

**Fig. 6.** Axial OCT point spread function (PSF)-resolution in air 12.7 μm (FWHM of amplitude) corresponds to ~9 μm in tissue.

These measurements were performed using the FDML laser with post-amplification. Measurements were performed using a simplified interferometer sample arm, without scanning optics, which consisted of an aspheric collimating lens and a gold mirror reflector. The average power from the frequency-swept laser source after post-amplification was 17 mW, and the power on the sample reflector was 5.8 mW. The effective sweep rate was 58 kHz. In order to investigate the long instantaneous coherence length it was necessary to chose this slow sweep rate because of limitations from the 200 Msamples/s AD converter card. To characterize the sensitivity of the frequency-swept laser source for OCT, a calibrated -47 dB reflection was used. The reference arm power was attenuated to several tens of microwatts average power. Optimum sensitivity performance could be obtained over more
than one order of magnitude variation in reference arm power, before the heterodyne gain became too small, or the excess noise became too large.

![Graph showing depth vs. 20*log(amplitude)](image)

Fig. 7. Measured OCT PSFs on a logarithmic scale for different delays, which is relative to the interferometer reference arm length of the Michelson interferometer. The depth scale of 0 mm to 7 mm in the graph reflects actual imaging depth and corresponds to a optical roundtrip delay of 0 mm to 14 mm. The scale is adjusted by a constant, such that the peak values reflect the sensitivity values at the different depth positions.

The sensitivity values were measured by taking the ratio between the peak of the PSF amplitude after Fourier transformation, to the standard deviation of the noise floor, which was measured with the sample arm blocked. The quoted dB values are 20 times the decadic logarithm of this ratio. System losses of ~2.5 dB arising from losses in the optics, mirror reflectivity, and backcoupling were subtracted from the measured sensitivity values. Figure 7 shows the PSFs and sensitivities for depths of 1 mm to 7 mm measured in 1 mm steps. For these measurements, the asymmetry in the MZ interferometer was set to 14 mm. The displayed PSFs are for backward sweeps only. The measured sensitivity for depths of 1 mm to 7 mm were 107.9 dB, 107.6 dB, 107.7 dB, 106.5 dB, 104.3 dB, 102.6 dB, and 100.4 dB. For depths from 1 mm to 5 mm the FWHM of the PSFs did not significantly change, while for depths of 6 mm and 7 mm, it increased to 15 μm and 16 μm, respectively. The measured maximum sensitivity was 2.3 dB smaller than the calculated shot-noise limit of 110.2 dB for the experimental parameters of 5.8 mW power, a detection bandwidth of 100 MHz, a detector efficiency of 0.85 e/photon, Gaussian spectral shape, and 1300 sampling points (see Ref. [22]). Figure 7 shows that the FDML laser has a narrow instantaneous linewidth, and the sensitivity decreases by only 7.5 dB over a depth range of 7 mm. Some of the decrease in sensitivity with depth in these studies can also be attributed to the electronic bandwidth limit of the detectors and the anti-alias filter in the A/D converter. For conventional frequency-swept lasers or spectrometer-based OCT systems, a 10 dB or more drop in sensitivity over a 3 mm depth range is typical.[8, 10, 22-25] The superior performance of FDML is the result of quasi-stationary operation. A large number of effective round-trips of light within the cavity produces strong filtering and mode competition similar to nonswept or slow, frequency-swept continuous-wave lasers. The instantaneous optical bandwidth of the FDML laser is much narrower than the filter bandwidth of the optical bandpass inside the cavity that results in a longer coherence length, which yields a larger imaging depth.

5. High-speed, swept-source OCT imaging with FDML laser

The application of the frequency-swept laser for high-speed, swept-source OCT imaging is shown in the images and multimedia files in Figs. 8-10. Due to the limitations of the
200 Msamples/s AD converter card, the asymmetry in the calibration MZ interferometer had to be decreased for the higher sweep speeds to ensure the calibration fringe frequencies are below the Nyquist limit for a sampling rate of 200 Msamples/s (100 MHz). The number of acquired points per sweep changed accordingly.

OCT imaging was performed using two galvanometer steering mirrors and additional optics in the sample arm, when compared to the sensitivity measurements. Due to higher losses in the scanning optics, the incident power was reduced to 2.3 mW on the sample, and the effective sensitivity for the OCT imaging was ~96 dB. Figure 8 shows an image of a human finger in vivo. The data set is cropped in z-direction. The data set was acquired in 0.097 s and the image-size is 4096 transverse x 1024 axial pixels. The FDML laser was operated at a filter drive frequency of 42 kHz, with a physical cavity length of 4.8 km. For this imaging measurement, only one frequency sweep direction was recorded, so the effective acquisition rate was 42,000 axial scans per second. The calibration MZ interferometer was set to a path difference of 6 mm in air, thus resulting in a maximum image acquisition depth of 3 mm.

Imaging was performed on skin because it is a well accepted sample for evaluating the performance of OCT systems. In addition because skin is highly optically scattering, it provides a good metric for performance. The OCT image shows very good penetration well into the dermis and is comparable to state-of-the-art time domain systems. The background at the bottom of the image shows a slightly increased signal, when compared to the background in the region at the top of the image. This can be an indication that the detection reaches the multiple scattering limit and supports good dynamic range. In this limit, a higher sensitivity will not increase the effective image penetration depth.

Figure 9 shows a 3-D OCT data set of a fixed hamster cheek pouch specimen in vitro. All animal handling was performed according to protocols approved by the MIT Committee on Animal Care (CAC). The 3-D OCT data set was acquired in 0.8 s, the size of the final image data set was 512 axial pixels per line, 512 lines per frame, and 200 frames. The FDML laser was operated at a filter drive frequency of 62 kHz. The physical cavity length was 3.3 km. In this case, both the forward and backward frequency sweeps were acquired, which resulted in an effective acquisition rate of 124,000 axial scans per second. The calibration MZ interferometer was set to a path difference of 5 mm in air, which resulted in a maximum image acquisition depth of 2.5 mm. The data set in Fig. 9 is cropped in z-direction to facilitate display. The movie shows a fly-through in z-direction. The advantages of high-speed, 3-D OCT imaging are especially important for generating en face images that require
large numbers of axial scans. The 3-D OCT data set enables the precise registration of cross-sectional images within these \textit{en face} views. The deep structures show different layers occurring at various positions in one \textit{en face} view. The image penetration is good, and structures well into the connective tissue can be visualized. This example shows that very high-quality \textit{en face} images can be reconstructed from a 3-D OCT data set, and that such a data set can be acquired in less than one second.

Fig. 9. Formalin-fixed hamster cheek pouch specimen \textit{in vitro}. A 3-D OCT data set acquired in 0.8 s. The 512x512x200 pixel volume was recorded at 124,000 axial scans/s, 242 frames/s and 1.2 volumes/s. The animation shows a fly-through visualization of the 3-D OCT data set (2.0MB).

Fig. 10. Human finger \textit{in vivo}. 3-D data set acquired in 0.28 s. The 256x128x256 pixel volume was recorded at 232,000 axial scans/s, 906 frames/s, and 3.5 volumes/s. The animation shows a volume-rendered representation of the 3-D OCT data set (1.4MB).

Fig. 10 shows a 3-D OCT data set of a human finger \textit{in vivo}. The entire 3-D OCT data set was acquired in 0.28 s, and the size of the final image data set is 256x256x128 voxels. The FDML laser was operated at a filter drive frequency of 116 kHz. The physical cavity length was 7 km, which corresponds to a fundamental roundtrip frequency of 29 kHz. The FDML laser was operated with a filter drive frequency corresponding to the fourth harmonic of the cavity roundtrip frequency. Both frequency sweep directions were recorded, so the effective acquisition rate was 232,000 axial scans per second. The frame rate was 906 frames/s for...
images consisting of 256 transverse pixels. The calibration MZ interferometer was set to a path difference of 4 mm in air, which resulted in a maximum acquisition depth of 2 mm. The movie shows the rendered data set. The 3-D OCT data set of 256x256x128 voxels was acquired in 0.28 seconds, which corresponds to the acquisition of 3.5 volume 3-D OCT data sets per second. This example shows that in vivo volumetric 3-D OCT imaging will be feasible without motion artifacts and with reasonable image quality. Furthermore it demonstrates that FDML can enable 3-D, real-time acquisition with several volumes per second, which could be used for live preview or survey, with the goal of video-rate, 3-D OCT imaging.

6. Conclusion

In this study, we demonstrate a new operation regime for frequency-modulated lasers called Fourier domain mode locking (FDML). FDML enables the generation of high-speed, narrowband, optical frequency sweeps with unprecedented performance. The FDML laser source operates at up to 290 kHz effective sweep rates. The dynamic linewidth is narrow enough to enable OCT imaging over a 7 mm depth range. Using an amplified FDML laser, sensitivities as high as 108 dB were achieved, with only a 7.5 dB drop in sensitivity over 7 mm depth. The FDML laser sweeps over 105 nm full width at 1300 nm, and it achieves an axial resolution of ~9 μm in tissue. The application of the FDML laser is demonstrated for high-speed, swept-source OCT imaging. OCT imaging at acquisition rates of up to 232,000 axial scans/second, 906 frames/second and 3.5 volumes/second is demonstrated. To our knowledge, with the exception of full field OCT techniques, this is the fastest OCT image acquisition speed achieved to date. The FDML laser is promising for future high-speed, swept-source OCT imaging applications.

Acknowledgments

We would like to acknowledge scientific contributions and helpful advice from Kenji Taira, Aaron Aguirre, Vivek Srinivasan, and Shu-Wei Huang. Maciej Wojtkowski is currently an assistant professor at the Institute of Physics, Nicholas Copernicus University, Torun, Poland. This research was sponsored in part by the National Science Foundation BES-0522845 and ECS-0501478; the National Institutes of Health R01-CA75289-09 and R01-EY11289-20; the Air Force Office of Scientific Research FA9550-040-1-0011 and FA9550-010-0046; and the German Research Foundation (DFG) Hu 1006/1-1.