Frequency comb swept lasers for optical coherence tomography

Frequency Comb Swept Lasers for Optical Coherence Tomography

Tsung-Han Tsai[a], Chao Zhou[a], Desmond Adler[a], and James G. Fujimoto[a]

[a]*Department of Electrical Engineering & Computer Science and*
Research Laboratory of Electronics,
Massachusetts Institute of Technology, Cambridge, MA

Abstract

We demonstrate a frequency comb (FC) swept laser and a frequency comb Fourier domain mode locked (FC-FDML) laser for applications in optical coherence tomography (OCT). The fiber-based FC swept lasers operate at a sweep rate of 1kHz and 120kHz, respectively, over a 135nm tuning range centered at 1310nm with average output powers of 50mW. A 25GHz free spectral range frequency comb filter in the cavity of swept lasers causes the lasers to generate a series of well defined frequency steps, which are equally spaced in frequency-space (linear in k-space). The narrow bandwidth (0.015nm) of the frequency comb filter enables a ~-1.2dB sensitivity roll off over ~3mm range, compared to conventional swept source and FDML lasers which have -10dB and -5dB roll offs, respectively. Measurements at very long ranges are possible with minimal sensitivity loss. The filtered laser output can be used to self-clock the OCT interference signal sampling, enabling direct fast Fourier transformation of the fringe signals, without the need for fringe recalibration procedures. The design and operation principles of FC swept lasers are discussed and interferometric measurement applications are proposed.

Keywords: Optical coherence tomography; Interferometry; Frequency comb; Swept laser; Fiber laser.

1. INTRODUCTION

Optical coherence tomography (OCT) generates cross-sectional and three-dimensional images of tissues *in situ* with micron scale resolution by measuring time delay of backscattered or back reflected light [1]. The recent development of Fourier domain detection techniques with spectrometer based systems (spectral / Fourier domain OCT, or SD/FD-OCT) or frequency swept lasers based systems (swept source / Fourier domain OCT or SS-OCT) enables imaging speeds 10 to 100 times faster than standard time domain OCT techniques [2-13]. Compared to SD/FD-OCT, SS-OCT can have improved overall sensitivity if operated in shot-noise-limit because there are no spectrometer losses and the photodetectors used are more sensitive than cameras [8, 14-16]. SS-OCT also enables operation at long wavelength ranges without the need for expensive InGaAs cameras. Improved system dynamic range can also be achieved in SS-OCT because it uses dual-balanced detection and higher bit depth data acquisition (DAQ) systems than cameras. In addition, swept source / Fourier domain detection can provide very large number of axial samples, as determined by the speed of DAQ system.

Typical swept lasers consist of a broadband gain medium with a tunable optical bandpass filter in the cavity. The tunable filter is swept so that the transmission frequency varies in time. Sufficient time is needed to allow lasing in the transmission bandwidth to build up from spontaneous emission inside the cavity. This limits the maximum tuning rate of the laser and also results in lower power, broader instantaneous linewidth or shorter instantaneous coherence length. Fourier domain mode-locking (FDML) is a new mode of operation for frequency swept lasers that overcomes these problems and is especially promising for high speed OCT imaging [17, 18]. An FDML laser uses a cavity with a long fiber delay line and a fiber Fabry-Perot tunable filter (FFP-TF) whose sweep rate is synchronized with the round-trip time of light inside the cavity. The long fiber delay line stores the entire frequency sweep inside the laser cavity and different frequencies in the sweep return to the FFP-TF at the time when the filter is tuned to transmit the corresponding wavelength. The laser

Optical Coherence Tomography and Coherence Domain Optical Methods in Biomedicine XIV, edited by
Joseph A. Izatt, James G. Fujimoto, Valery V. Tuchin, Proc. of SPIE Vol. 7554, 75541E · © 2010 SPIE
CCC code: 1605-7422/10/$18 · doi: 10.1117/12.842589

generates a sequence of optical frequency sweeps at the cavity repetition rate. However, the coherence length of standard FDML lasers is limited by the instantaneous bandwidth of the FFP-TF and a 5dB~10dB drop in sensitivity over a 3mm depth range is typically observed [19-22]. For OCT imaging applications, it is desirable to have uniform imaging sensitivity over a large depth range.

At the same time, most Fourier domain OCT systems require re-sampling or recalibrating the OCT interference fringe signals in order to provide data evenly sampled in frequency domain prior to fast Fourier transformation (FFT). This recalibration process is computationally expensive and limits the real-time operation of OCT. For SS-OCT, Eigenwillig *et al.* have successfully demonstrated an approach to linearize frequency sweeps in FDML lasers by incorporating the second and third harmonics of the drive waveform to FFP-TF [21]. However, this approach requires that the FFP-TF have a high frequency response and is also sensitive to thermal drift in the FFP-TF.

In this manuscript, we demonstrate frequency comb (FC) lasers, a new type of swept laser incorporating a fixed narrowband frequency comb fiber Fabry-Perot (FFP-FC) filter inside the cavity of conventional swept lasers and FDML lasers. FC swept lasers generate a sweep of discrete steps in frequency, rather than a continuous sweep. The narrow bandwidth of the frequency steps generated by FC lasers improves the sensitivity roll off in OCT compared to conventional swept source and FDML lasers, enabling imaging over a longer depth range. The comb frequencies are equally separated in k-space, providing a clock signal which can potentially be used to trigger the OCT interference fringe acquisition. This self-clocking method outperforms standard frequency calibration methods using reference Mach-Zehnder interferometer signals.

2. OPERATING PRINCIPLES

In a conventional swept laser or FDML laser, the frequency is continuously varying during one sweep. In an FC laser, a fixed frequency comb filter FFP-FC with small free spectral range (FSR) and narrow transmission bandwidth is used in the cavity in addition to a tunable filter FFP-TF. The transmission function of the FFP-FC is defined as: $T = (1-R)^2/[1-2R\cos(2kL)+R^2]$, where R and L are the reflection coefficients and the cavity length in the Fabry-Perot resonator respectively and k is the wavevector of the incident light. This filter thus provides a series of transmission peaks with an equal frequency spacing of $\Delta f = c/2nL$, also known as the FSR. However it is important to note that if the material n in the Fabry-Perot resonator has dispersion, the transmission resonances will no longer be uniformly spaced. Figure 1 shows the operating principle of FC lasers [23]. During operation, the FFP-TF is continuously tuned across the sweep range and frequency components which pass through both the FFP-TF and FFP-FC filters can be amplified by the gain medium, while other frequency components are suppressed. The laser operates at frequencies given by the product of the transmissions of these two cascaded filters. As the FFP-TF is swept in time, the laser generates a series of fixed frequency steps with varying amplitudes. If the bandwidth of the tunable FFP-TF is less than the FSR of the frequency comb FFP-FC, the laser will generate only a single frequency at a time and the intensity output will be strongly modulated. If the bandwidth of the tunable FFP-TF is comparable to the FSR of FFP-FC, then the laser can operate in a superposition of FFP-FC frequencies and is partially modulated in intensity (Figure 1 bottom). The instantaneous linewidth of the FC laser is determined by the bandwidth of FFP-FC, which is much narrower than the bandwidth of the FFP-TF. This produces a longer coherence length output because the laser tunes in a discrete series of steps each of which have narrow linewidth. This produces less sensitivity roll-off over large imaging depths compared to conventional swept lasers.

Moreover, since the peaks in the intensity modulation are equally spaced in frequency, they can be used as a clock signal to sample the OCT interference signal. This results in a calibrated OCT interference signal which is equally sampled in k-space and can be directly Fourier transformed to obtain axial scan information. The OCT interferometric signal obtained using an FC laser can be considered as a discrete version of interferometric signal obtained using a standard swept laser, and the discrete spacing is determined by the FSR of FFP-FC because it determines the frequency comb spacing of the laser.

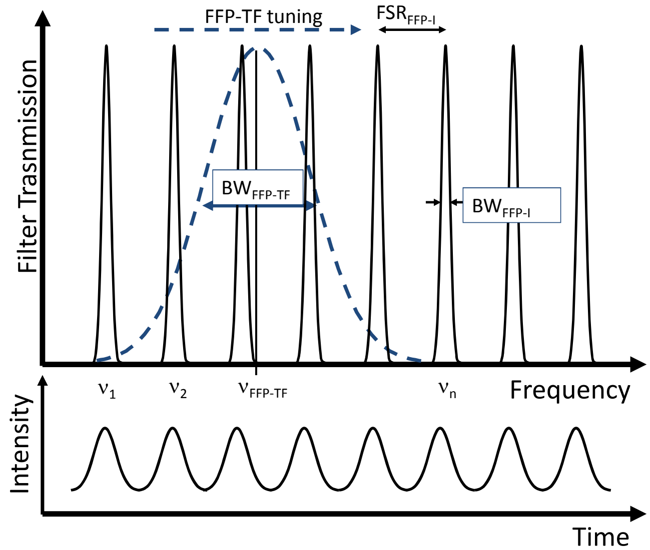


Figure. 1. Operating principles of a frequency comb swept laser.

The FSR of the frequency comb filter also determines the number of samples that can be generated as the laser is swept across its tuning range. An interferometric signal which has a frequency higher than one half of this sampling rate will be aliased. This means that OCT signals from reflections at a range larger than the principal range 0 to $2nL$ will be aliased so that the measurement appears at depths from 0 to $2nL$. Therefore, it is important to choose the FSR of the frequency comb filter FFP-FC so that the frequency comb spacing is small enough to provide a large enough measurement depth range and sufficient numbers of samples during the frequency sweep.

3. METHODS

The detailed experiment methods were described in [23]. Figure 2 (a) shows a schematic diagram of the FC swept laser. The laser is based on a ring resonator geometry with a semiconductor optical amplifier (SOA, Covega, Inc.) as the gain medium, a tunable filter (FFP-TF, Micron Optics, Inc.), and a fixed frequency filter (FFP-FC, Micron Optics, Inc.) in a cavity with physical path length of 15m. The laser output is amplified with a second SOA outside the cavity which serves as a booster amplifier. The FSR of FFP-FC is ~25GHz, corresponding to a maximum imaging depth of 3mm. The transmission bandwidth of FFP-FC is ~0.015nm at a center wavelength of 1310nm. A sinusoidal waveform of 1kHz is used to drive the FFP-TF. Figure 2 (b) shows a schematic diagram of the single buffered FC-FDML laser [17], using the same FFP-TF and FFP-FC filter. The FFP-TF is driven with a sinusoidal waveform at 59.8427kHz, synchronous to the optical round-trip time of the 3,416m long cavity. The average output power after the booster was 50mW. To compare performance, the FFP-FC was removed from the cavities in Figures 2 (a) and (b) to enable conventional swept source and FDML laser operation.

The OCT system used to measure the point spread functions (PSFs) of these lasers is shown in Figure 3. A small portion of the laser output was coupled to an asymmetric Mach-Zehnder interferometer (MZI) that produces interference fringes with zero crossing evenly spaced in frequency. The MZI fringes were detected by a dual-balanced photodetector and used to generate a clock to recalibrate the interference fringe signals from the OCT system. The OCT system consisted of a dual-balanced Michelson interferometer with a pair of optical circulators and a 50/50 fiber-optic splitter [17, 19]. The MZI and OCT fringes were recorded simultaneously using a high speed oscilloscope. The nonlinear frequency sweep in the OCT fringe data was recalibrated using the MZI fringe data and a fast Fourier transform was performed to obtain the PSFs.

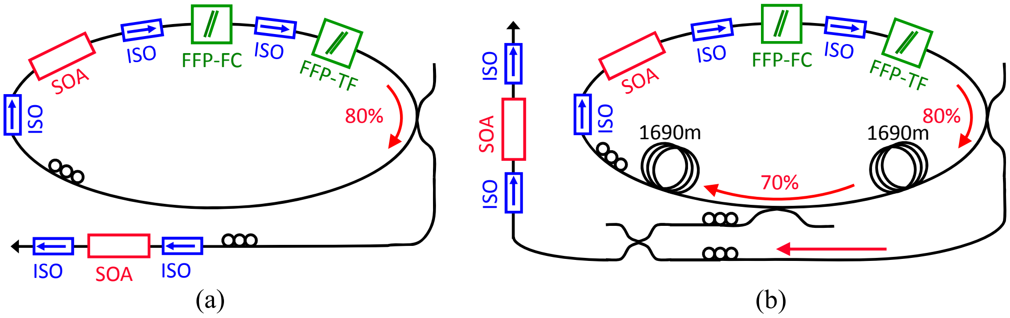


Figure. 2. Schematic diagrams of the frequency comb (FC) swept laser (a) and frequency comb Fourier domain mode-locked (FDML) laser (b).

To test the feasibility of self-clocking, the A/D clocking process was simulated by post processing the OCT interference data. A portion of the output from the laser in Figure 3 was detected by a photodetector and the intensity modulation was recorded. A low pass filter at 200MHz was used on the intensity signal to remove high frequency electronic noise. The filtered laser intensity output and OCT interference signals were recorded simultaneously using a high speed oscilloscope. The data was post processed using a custom MATLAB script to find the peak positions of the laser intensity output and sample the OCT interference signal at these times. In this case, with total tuning range of 135nm and 0.15nm FSR of the FFP-FC, there were about 900 peaks. The sampled OCT interference fringes were then zero-padded to 2048 points and directly Fourier transformed. Therefore, the final OCT A-line data contained 1024 points over the principal imaging range. No other calibration or dispersion compensation procedures were applied for the analysis of these data.

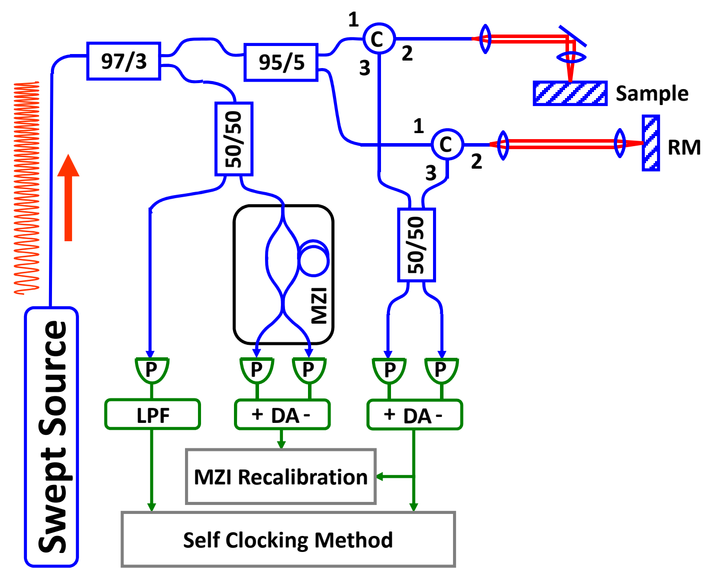
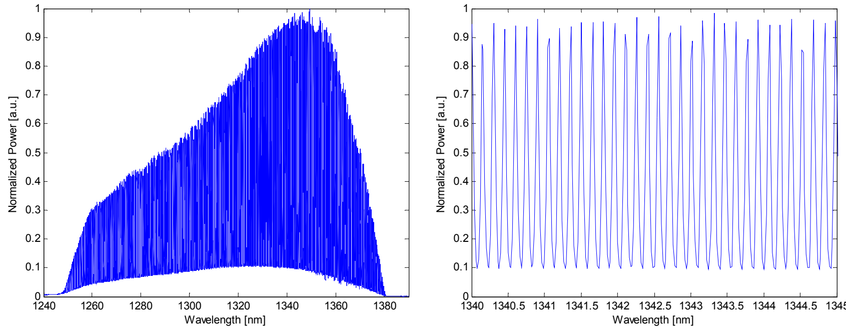


Figure. 3. Schematic of the swept source OCT system (optics: blue; electronics: green; recalibration clock mechanism: gray). C: circulator; MZI: Mach-Zehnder interferometer; RM: reference mirror; DA: differential amplifier; P: photodetector; LPF: lowpass filter.

4. RESULTS

Figure 4 shows the output spectra of the FC swept laser. The total tuning range of the spectrum is 135nm, with full width half maximum (FWHM) of 70nm. As mentioned in Section 3, the transmission bandwidth of

FFP-FC is ~0.015nm at a center wavelength of 1310nm. Therefore, the frequency bandwidth of individual frequency steps in the frequency comb cannot be resolved because of the limited resolution of the optical spectrum analyzer. The zoomed view in figure 4 (b) shows the ~0.15nm spacing between each frequency step, corresponding to the FSR of the frequency comb filter FFP-FC. The background underneath the frequency modulation is produced by the amplified spontaneous emission (ASE) of the booster SOA.



(a) (b)

Figure. 4. (a) Output spectrum and (b) the zoomed view from 1340nm to 1345nm of the FC swept laser.

Figure 5 compares transient intensity outputs of the conventional swept source, FDML and FC swept lasers. The zoomed view in figure 5 (c) and (f) is similar to what was expected from figure 1b. The frequency comb filter FFP-FC in the cavity generates a modulated intensity output. Each peak in the modulation represents an individual frequency step. The time spacing between each peak in the intensity is determined by the instantaneous tuning speed of FFP-TF. The time between peaks in central part of the frequency sweep is smaller than that at the edge of the sweep because the tunable filter FFP-TF is driven sinusoidally.

Figure 6 shows an example OCT interferometric signal at a delay of 0.7mm using the FC and FC-FDML lasers. The modulation in the laser output intensity can be seen superposed on the OCT interferometric signals. Each peak in the modulation is an individual frequency step, indicating that the interference traces can be precisely calibrated to frequency (linear in k-space) if they are sampled at the peaks of the modulations.

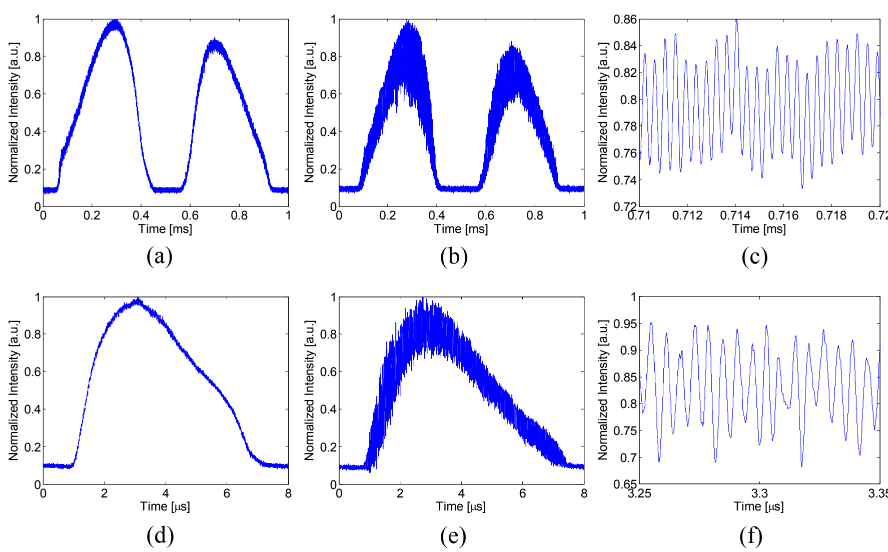


Figure. 5. Transient intensity output traces of different lasers: (a) conventional swept laser; (b) FC swept laser; (c) zoomed view from 0.71ms to 0.72ms of (b); (d) FDML laser; (e) FC-FDML laser; (f) zoom-in view from 3.25µs to 3.35µs of (e).

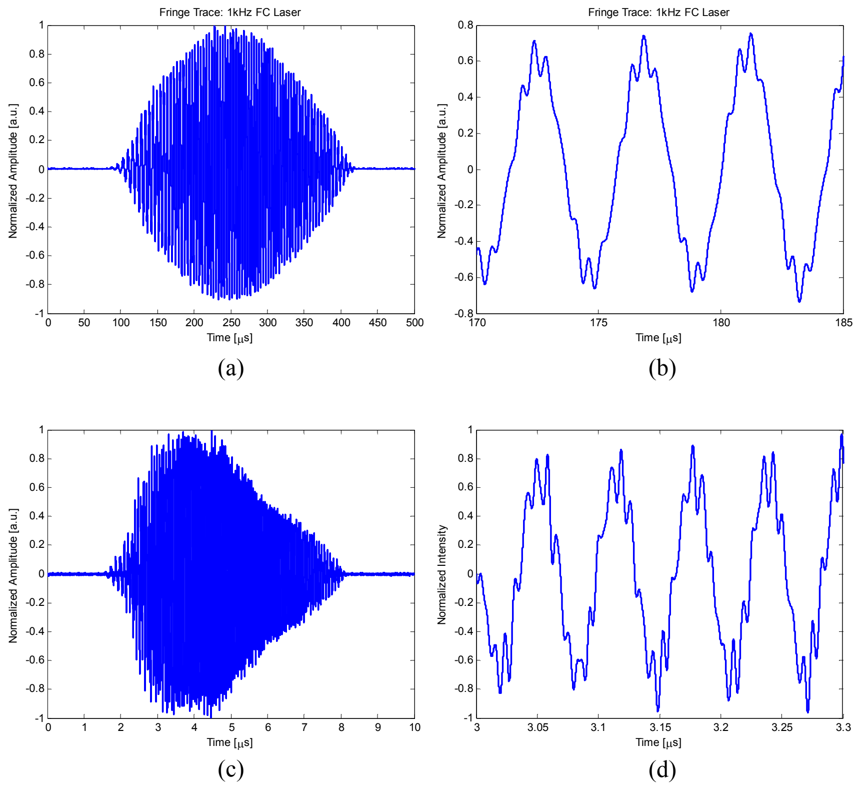
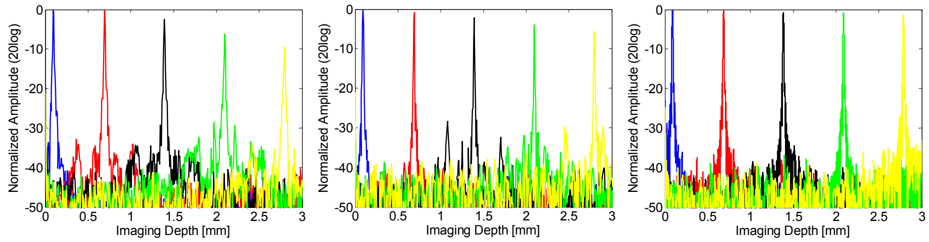


Figure. 6. OCT interferometric traces at 0.7mm imaging depth using a (a) FC swept laser and (c) FC-FDML laser. (b) and (d) are the zoomed views of (a) from 170μs to 185μs and (c) from 3μs and 3.3μs respectively.

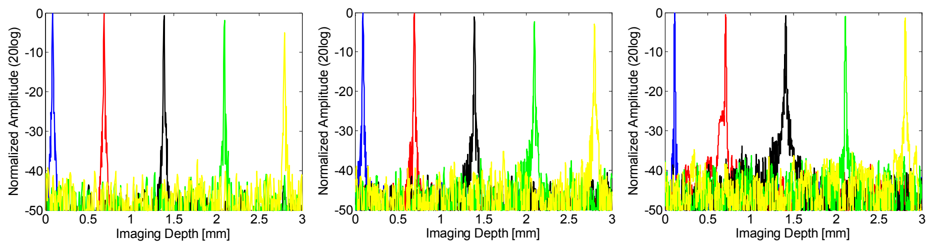
The point spread functions of the conventional and FC swept lasers were measured at different imaging depths from 0.1mm to 2.8mm. For comparison, the OCT interference traces of FC laser were recalibrated using MZI signal and the self-clocking method separately. From figure 7, the measured roll off is -10dB for the conventional swept laser versus -5dB for FC laser using the MZI recalibration method and only -1.2dB using the self-clocking method. Using the same MZI recalibration method, the FC laser shows less sensitivity roll off compared with the conventional swept laser, indicating the instantaneous coherence length of the frequency steps in the FC laser are longer. Furthermore, the self-clocking method calibrates the interference data to linear k-space more accurately compared to the MZI recalibration method, achieving much less sensitivity roll-off over the 2.8mm imaging depth. The measured FWHM resolution of the point spread function was 11μm in air, which corresponds to ~8μm in tissue, while the theoretical value of the resolution was 10.8μm in air. The measured resolution is slightly worse than the theoretical value because of several factors such as the electronic bandwidth limit of the detectors, spectral shape and residual sampling errors. The axial resolution using the FC swept laser is the same as that from conventional frequency swept and FDML lasers operating with the same bandwidth.

The same comparison was also performed between a FDML and FC-FDML laser. Figure 8 shows the sensitivity roll-off over 2.8mm depth for an FDML laser, a FC-FDML laser with MZI recalibration, and a FC-FDML laser with self-clocking. The sensitivity using the FDML laser rolls off by -5dB which shows that the instantaneous linewidth of FDML laser is narrower than conventional swept laser. Using MZI recalibration, the sensitivity roll off of FC-FDML laser is -3dB, which is slightly improved compared to the standard FDML laser. However, using the self-clocking method, a sensitivity roll-off of only -1.3dB can be achieved. Figures 8 (b-c) also show a slightly elevated noise floor as discussed previously. These results show that FC lasers have superior linewidth and coherence length compared with standard swept lasers or FDML lasers.



(a) (b) (c)

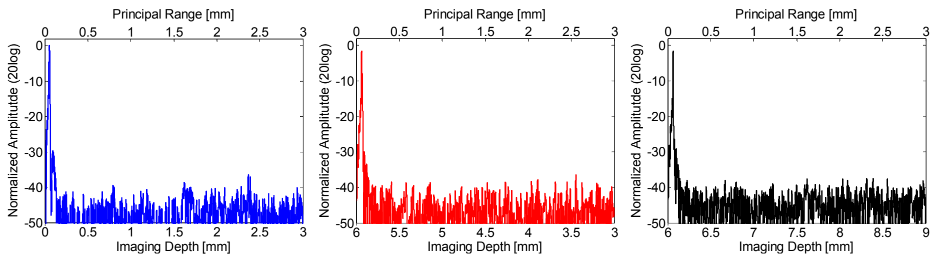
Figure. 7. Sensitivity roll-off from 0.1mm to 2.8mm imaging depth: (a) conventional swept laser; (b) FC swept laser with MZI calibration; (c) FC swept laser with self-clocking calibration.



(a) (b) (c)

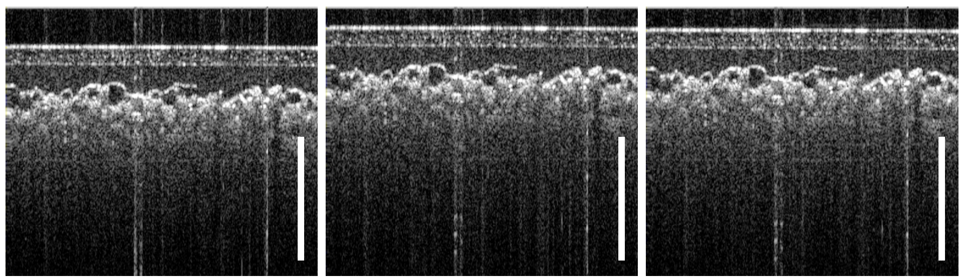
Figure. 8. Sensitivity roll off from 0.1mm to 2.8mm imaging depth: (a) FDML laser; (b) FC-FDML laser with MZI calibration; (c) FC-FDML laser with self-clocking calibration.

As mentioned above, aliasing occurs if the OCT signal is outside the principal measurement range set by the frequency comb filter FFP-FC. The same aliasing phenomenon was also reported by Jung *et al.* using a light source with an external frequency comb filter [24]. Figure 9 (a) shows the PSF when reflection is at 0.06mm depth. Figure 9 (b) shows a reflection from a depth of 5.94mm, which appears as if it is at the 0.06mm delay. Reflections at a position z between 3mm to 6mm range appear as if they are between 3mm to 0mm, at a position (3mm – z), mirrored about the 3mm position. When the reflection is at the edge of the principal measurement range, 3mm in this case, the corresponding PSF and its mirror PSF would overlap and it would not be possible to distinguish if the reflection were from the edge of the imaging range or near zero delay. Figure 9 (c) shows the PSF when the reflection is at 6.06mm. Because of the 25 GHz FSR of the frequency comb filter FFP-FC, the signal from a reflection at 6.06mm appears as if it is at 0.06mm depth because the measurement range repeats every 6mm. Reflections which are at a position z between 6mm to 9mm range appear as if they are between 0mm and 3mm, at a position (z – 6mm). Note that the sensitivity for the reflection at 6.06mm delay is decreased by only -1.5dB, demonstrating the narrow linewidth of the frequency steps generated by the FC laser. Although the aliasing occurs at deeper depths, this implies that it is possible to see signals at very long delays with very little loss of sensitivity. At the same time, imaging structures which extend over a very large range of depths would require techniques to remove aliasing. The large imaging depths could be very useful for applications such as profilometry, where the measured signals can be easily de-aliased. Figure 10 shows the example images of an IR card taken from different principal imaging range using the FC-FDML laser. The overall imaging quality from the three images are almost the same, again indicating that the instantaneous coherent length of the FC-FDML laser is remarkably long.



(a) (b) (c)

Figure. 9. Sensitivity roll off at imaging depth deeper than the principal imaging range. (a) Reflection is at 0.06mm depth. (b) Reflection is at 5.94mm depth. (c) Reflection is at 6.06mm. Each amplitude is normalized by the peak value in (a).



(a) (b) (c)

Figure 10. OCT images of an IR cards taken from different principal imaging range using the 120kHz FC-FDML laser. (a) Principal range from 0mm to 3mm. (b) Principal range from 6mm to 9mm. (c) Principal range from -6mm to -3mm. Scale bar: 1mm.

5. DISCUSSION

Frequency comb operation can improve performance for both conventional swept lasers as well as FDML lasers. The frequency comb filter inside the laser cavity causes the laser to generate a sweep of frequency steps with narrow instantaneous linewidth, producing longer instantaneous coherence length output. As demonstrated in Section 4, this property of FC swept lasers improves sensitivity roll-off, enabling measurements over a longer depth range with both conventional swept and FDML lasers.

The intensity modulation in the laser output also enables self-clocking to precisely sample the OCT interferometric signal into linear k-space (equal frequency intervals) without additional recalibration. Compared to typical MZI recalibration methods [19-22], using self-clocking achieves better sensitivity roll-off. In addition, self-clocking should simplify the DAQ system requirements since a separate high speed channel is no longer required to detect an MZI signal. Moreover, precise sampling of the OCT interferometric data allows phase information to be recorded more accurately, which should enable FC lasers to achieve improved sensitivity for phase sensitive applications, such as Doppler OCT. The self-clocking method demonstrated in this study was performed using software sampling. Future implementations will require that special electronics be developed to enable direct clocking of high speed A/D acquisition using the filtered intensity modulated output of the frequency comb laser. Similar improvements in performance to those reported here should be obtainable. The frequency comb filter FFC-FC could also be frequency locked to an external frequency standard if the generation of absolute frequencies is needed. These approaches are analogous to frequency comb methods that have been demonstrated with broadband femtosecond lasers [25].

6. CONCLUSION

In this study, a new type of swept laser, called a frequency comb (FC) swept laser is demonstrated which improves performance for both conventional swept lasers and FDML lasers. The frequency comb laser generates a frequency sweep consisting of a series of frequency steps determined by an intracavity frequency comb filter. Because the frequency steps have narrower instantaneous linewidths then conventional frequency sweeping, sensitivity roll-off of the laser is significantly improved. It is also possible to use the filtered intensity output of the laser for self-clocking the OCT interference signal acquisition to generate a signal that is sampled with constant frequency spacing (linear in k-space).

Operation of a FC swept laser and FC-FDML laser are demonstrated at 1kHz and 120kHz sweep rates respectively over at 135nm tuning range with an average output power of 50mW. Using frequency comb operation with self-clocking, the sensitivity roll-off at 2.8mm delay is improved from -10dB to -1.2dB for the conventional swept laser and from -5dB to -1.3dB for the FDML laser [23]. Measurements at longer ranges are possible with minimum sensitivity roll-off, however, reflections at depths outside the principal measurement range from 0mm to 3mm appear aliased back into the principal range [23]. Frequency combs also improve the performance of swept source OCT for phase measurement and Doppler applications, since the frequency steps in the swept laser output are precisely determined by the frequency comb filter.

ACKNOWLEDGEMENTS

We gratefully acknowledge the technical contributions of Drs. Benjamin Potsaid, Robert Huber and Yueli Chen. Dr. Adler is currently at LightLab Imaging, Inc. We also gratefully acknowledge technical discussions and information from Mr. Alex Cable of Thorlabs, Inc. The research was sponsored in part by the National Institute of Health R01-CA75289-12 and R01-EY011289-24; the Air Force Office of Scientific Research FA9550-07-1-0014 and Medical Free Electron Laser Program FA9550-07-1-0101. The author acknowledges support from Taiwan Merit Scholarship from the National Science Council of Taiwan and the Center for Integration of Medicine and Innovation Technology.

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,* vol. 254, pp. 1178-1181, Nov 22 1991.

[2] A. F. Fercher, C. K. Hitzenberger, G. Kamp, and S. Y. Elzaiat, "Measurement of Intraocular Distances by Backscattering Spectral Interferometry," *Optics Communications,* vol. 117, pp. 43-48, MAY 15 1995.

[3] S. R. Chinn, E. A. Swanson, and J. G. Fujimoto, "Optical coherence tomography using a frequency-tunable optical source," *Optics Letters,* vol. 22, pp. 340-342, Mar 1 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," *Optics Letters,* vol. 22, pp. 1704-1706, Nov 15 1997.

[5] F. Lexer, C. K. Hitzenberger, A. F. Fercher, and M. Kulhavy, "Wavelength-tuning interferometry of intraocular distances," *Applied Optics,* vol. 36, pp. 6548-6553, Sep 1 1997.

[6] 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," *Optics Letters,* vol. 28, pp. 1981-1983, Oct 15 2003.

[7] S. H. Yun, G. J. Tearney, J. F. de Boer, N. Iftimia, and B. E. Bouma, "High-speed optical frequency-domain imaging," *Optics Express,* vol. 11, pp. 2953-2963, Nov 3 2003.

[8] M. A. Choma, K. Hsu, and J. A. Izatt, "Swept source optical coherence tomography using an all-fiber 1300-nm ring laser source," *Journal of Biomedical Optics,* vol. 10, p. no. 044009 Jul-Aug 2005.

[9] R. Huber, M. Wojtkowski, J. G. Fujimoto, J. Y. Jiang, and A. E. Cable, "Three-dimensional and C-mode OCT imaging with a compact, frequency swept laser source at 1300 nm," *Optics Express,* vol. 13, pp. 10523-10538, Dec 22 2005.

[10] 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," *Optics Express,* vol. 13, pp. 3513-3528, May 2 2005.

[11] W. Y. Oh, S. H. Yun, G. J. Tearney, and B. E. Bouma, "115 kHz tuning repetition rate ultrahigh-speed wavelength-swept semiconductor laser," *Optics Letters,* vol. 30, pp. 3159-3161, DEC 1 2005.

[12] Y. Yasuno, V. D. Madjarova, S. Makita, M. Akiba, A. Morosawa, C. Chong, T. Sakai, K. P. 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," *Optics Express,* vol. 13, pp. 10652-10664, Dec 22 2005.

[13] S. Yun, G. Tearney, B. Bouma, B. Park, and J. de Boer, "High-speed spectral-domain optical coherence tomography at 1.3 um wavelength," *Opt. Express,* vol. 11, pp. 3598-3604, 2003.

[14] K. Takada, "Fiber-optic frequency encoder for high-resolution OFDR," *Photonics Technology Letters, IEEE,* vol. 4, pp. 1174-1177, 1992.

[15] R. Passy, N. Gisin, J. P. von der Weid, and H. H. Gilgen, "Experimental and theoretical investigations of coherent OFDR with semiconductor laser sources," *Journal of Lightwave Technology,* vol. 12, pp. 1622-1630, 1994.

[16] S. Moon and D. Y. Kim, "Normalization detection scheme for high-speed optical frequency-domain imaging and reflectometry," *Opt. Express,* vol. 15, pp. 15129-15146, 2007.

[17] R. Huber, D. C. Adler, and J. G. Fujimoto, "Buffered Fourier domain mode locking: unidirectional swept laser sources for optical coherence tomography imaging at 370,000 lines/s," *Opt. Lett.,* vol. 31, pp. 2975-2977, 2006.

[18] R. Huber, M. Wojtkowski, and J. G. Fujimoto, "Fourier Domain Mode Locking (FDML): A new laser operating regime and applications for optical coherence tomography," *Optics Express,* vol. 14, pp. 3225-3237, Apr 17 2006.

[19] D. C. Adler, Y. Chen, R. Huber, J. Schmitt, J. Connolly, and J. G. Fujimoto, "Three-dimensional endomicroscopy using optical coherence tomography," *Nature Photonics,* vol. 1, pp. 709-716, Dec 2007.

[20] D. C. Adler, S.-W. Huang, R. Huber, and J. G. Fujimoto, "Photothermal detection of gold nanoparticlesusing phase-sensitive optical coherencetomography," *Opt. Express,* vol. 16, pp. 4376-4393, 2008.

[21] C. M. Eigenwillig, B. R. Biedermann, G. Palte, and R. Huber, "K-space linear Fourier domain mode locked laser and applications for optical coherence tomography," *Opt. Express,* vol. 16, pp. 8916-8937, 2008.

[22] M. Y. Jeon, J. Zhang, and Z. Chen, "Characterization of Fourier domain modelocked wavelength swept laser for optical coherence tomography imaging," *Opt. Express,* vol. 16, pp. 3727-3737, 2008.

[23] T.-H. Tsai, C. Zhou, D. C. Adler, and J. G. Fujimoto, "Frequency Comb Swept Lasers," *Optics Express,* vol. 17, pp. 21257-21270, 2009.

[24] E. J. Jung, J.-S. Park, M. Y. Jeong, C.-S. Kim, T. J. Eom, B.-A. Yu, S. Gee, J. Lee, and M. K. Kim, "Spectrally-sampled OCT for sensitivity improvement from limited optical power," *Opt. Express,* vol. 16, pp. 17457-17467, 2008.

[25] T. R. Schibli, HartlI, D. C. Yost, M. J. Martin, MarcinkeviciusA, M. E. Fermann, and J. Ye, "Optical frequency comb with submillihertz linewidth and more than 10 W average power," *Nat Photon,* vol. 2, pp. 355-359, 2008.