A rapid, dispersion-based wavelength-stepped and wavelength-swept laser for optical coherence tomography

Serhat Tozburun,1,2,* Meena Siddiqui,3 and Benjamin J. Vakoc1,2,3

1Harvard Medical School, Boston, Massachusetts 02115, USA
2Wellman Center for Photomedicine, Massachusetts General Hospital, Boston, Massachusetts 02114, USA
3Harvard-MIT Division of Health Sciences and Technology, Cambridge, Massachusetts 02139, USA

tozburun.serhat@mgh.harvard.edu

Abstract: Optical-domain subsampling enables Fourier-domain OCT imaging at high-speeds and extended depth ranges while limiting the required acquisition bandwidth. To perform optical-domain subsampling, a wavelength-stepped rather than a wavelength-swept source is required. This preliminary study introduces a novel design for a rapid wavelength-stepped laser source that uses dispersive fibers in combination with a fast lithium-niobate modulator to achieve wavelength selection. A laser with 200 GHz wavelength-stepping and a sweep rate of 9 MHz over a 94 nm range at a center wavelength of 1550 nm is demonstrated. A reconfiguration of this source design to a continuous wavelength-swept light for conventional Fourier-domain OCT is also demonstrated.

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1. Introduction

Many technologies have been used to build high-speed swept-wavelength sources for optical coherence tomography (OCT) [1–16]. In 2003, Yun et al. presented a wavelength-swept semiconductor laser utilizing a polygon scanner-based wavelength filter with a sweep repetition rate of ~16 kHz [1]. By utilizing cascaded delay lines, this approach was extended to A-line rates exceeding 400 kHz [2]. Buffered Fourier-domain mode-locking lasers with fiber Fabry-Perot tunable filters prove sweep rates ranging from 370 kHz to 5 MHz, depending on the specific configuration [3–6]. Dispersion tuning or dispersion mode-locking techniques have been demonstrated that provide wide gain to speeds up to 200 kHz [7–10]. More recently, VCSEL-based laser has been demonstrated at 1 MHz and additionally support extremely long imaging ranges [11]. These and other source designs allow OCT imaging at higher speeds and over longer imaging ranges. However, to take advantage of these speed and imaging range increases, the data acquisition bandwidth of the OCT receiver must scale up accordingly. For some very high speed and long range imaging sources, impractical receiver bandwidths are required.

To address this challenge, we have recently described optical-domain subsampled OCT as a method for passively reducing acquisition and data transfer bandwidth [12]. In subsampled OCT, a wavelength-stepped source, i.e., one that jumps discretely in fixed k-space increments, is used in place of a continuously swept-wavelength laser. It was shown that this approach allows imaging over large depth ranges with reduced bandwidth. In the aforementioned work, a wavelength-stepped laser was constructed by incorporating a Fabry-Perot (FP) etalon into a relatively slow polygon-filter based laser. While this source was sufficient to demonstrate the principle of optical-domain subsampling in OCT, significantly faster wavelength-swept lasers are needed to take full advantage of the subsampling approach.

In this work, we demonstrate a novel design for a wavelength-stepped laser for optical-domain subsampled OCT. The source achieves wavelength tuning through incorporation of positive and negative dispersion within the cavity and the use of a fast intensity modulator. It is similar in operating principle to a laser previously demonstrated for time-division multiplexed addressing of fiber Bragg grating (FBG) sensors [17]. However, in our proposed laser, wavelength selection is performed by a fixed Fabry Perot etalon rather than FBGs, which ensures wavelength-steps are equally spaced in wavenumber. Further, we have used...
fibers to provide continuous positive and negative dispersion. As a result, we achieve a very rapid wavelength stepping and sweeping to support high speed subsampled OCT. In a wavelength-stepped configuration with 200 GHz step size, we obtained a tuning range of 94 nm centered at 1550nm with a coherence length of 3.2 cm (double-pass). The sweep rate was approximately 9 MHz, and could be straightforwardly extended to 20 MHz with a change in drive electronics. While this laser design was motivated by the need for rapid wavelength-stepped laser sources for subsampled OCT, it can also enable rapid lasers for conventional OCT. A continuous wavelength-swept source with 87 nm bandwidth and a coherence length (double-pass) exceeding 1.75 mm is presented. This configuration operates at the same 9 MHz sweep rate as the subsampled configuration. In this report, we first describe the operating principle of the laser (section 2). Next the experimental design of our prototype laser (section 3) is detailed. Finally, the performance of the laser for both wavelength-stepped and wavelength-swept configurations is summarized (section 4).

2. Laser operating principle

The laser design is based on intracavity pulse stretching and compression (Fig. 1). Within a ring laser cavity, a broadband gain element (e.g., semiconductor optical amplifier (SOA)) is coupled to a first dispersive element, a fast intensity modulator, and then a second dispersive element with opposite dispersion. A FP etalon is included to force wavelength-stepped operation. By matching cavity dispersion, the cavity round trip time is made approximately constant across a large optical bandwidth. The intensity modulator is driven by short electrical pulses at a repetition rate equal to a harmonic of this round trip time. This allows resonant accumulation of power. The first dispersive fiber temporally separates the optical wavelengths at the SOA to avoid gain saturation effects that would narrow the lasing bandwidth. The second dispersive fiber temporally realigns the pulses at the intensity modulator. The driving pulse train for the modulator is synchronized to the return time of the compressed pulse (or a harmonic). Light is output through a coupler placed after the SOA, providing access to the wavelength-stepped pulse train.

For wavelength-stepped operation, it is important to fully separate (in time) the optical pulses at the SOA to avoid non-linear mixing. There exists therefore a relationship between the pulse width (set by the drive signal to the intensity modulator), the free spectral range (FSR) of the etalon (which gives the wavelength spacing of spectrally and temporally adjacent signals), and the required dispersion. As the pulse width increases, larger dispersions are required to separate pulses. As the FSR increases, smaller dispersions are required (because the wavelengths are further spectrally separated). From these relationships, one can note that this design is more appropriate for rapid sources using short pulses (and therefore requiring less dispersion) than for slow sources. The sweep rate of the laser is limited by the product of the lasing bandwidth and the dispersion provided by each dispersive element, and is independent of the overall cavity round trip time (when operated in a harmonic resonant mode).
The laser design is composed of positive and negative chromatically dispersive elements, a fast intensity modulator and a Fabry Perot etalon to generate a rapid wavelength-stepped laser output.

One technical challenge associated with this laser design is the dispersion engineering of the laser cavity. A large dispersion is required to temporally separate closely spaced wavelengths. For example, 1000 ps/nm is required to separate 1 ns pulses spaced 1 nm apart. Also, in order to match the cavity round trip time across the full lasing bandwidth, the large positive and negative dispersive elements must be matched to higher orders. In principle, the variation in cavity round trip time across the lasing bandwidth should be less than the intensity modulator pulse width. For these reasons, single-mode fibers dispersive coils are perhaps best suited to provide the positive and negative dispersion for this design.

3. Experimental setup

3.1 Laser design

A schematic of the prototype laser design is presented in Fig. 2. Positive dispersion was generated by a 39.394 km SMF-28e + fiber spool, providing approximately 655.7 ps/nm at 1550 nm. The measured loss of this fiber spool was 8.38 dB. Negative dispersion was provided by a dispersion-compensating fiber designed to be dispersion slope matched to SMF-28e + . The dispersion compensating module was 5.26 km in length, and loss was measured at 2.96 dB. A high-extension lithium niobate intensity modulator (MXER-LN, Photline Technologies, >30 dB extinction at 1550 nm) was used. Pulses were generated by an analog pulse generator (AVM-1-C, Avtech) providing approximately 0.50 ns full-width at half-maximum (FWHM) pulse profiles (the final pulse width was modified slightly during lasing to obtain optimal performance). The pulse generator was externally triggered by a digital delay generator (DG645, Stanford Research System). A fused silica FP etalon (custom part from Light Machinery) with FSR of 200 GHz and finesse of ~100 was included in a free-space path in the laser. At 200 GHz (1.6 nm) spectral spacing, the included dispersion (655.7 ps/nm) provided ~1.12 ns group delay between adjacent wavelengths, sufficient to temporally separate the 0.50 ns FWHM pulses at the SOA. Two SOAs (Covega, BOA1004S) were used as gain elements in the laser to overcome high losses due to long dispersive fiber lengths. The SOAs included integrated optical isolators. A 10% tap coupler provided the laser output, which was further amplified outside the laser (Covega, BOA1004S) to increase power and reduce intensity noise through gain saturation effects.

The total optical loss within the laser cavity was dominated by the two dispersive fibers (11.34 dB), with contributions additionally from the intensity modulator (4.3 dB at maximum transmission), and the etalon (5.27 dB fiber-to-fiber coupling loss at transmission peak).
3.2 Chromatic dispersion

The dispersion matching must be sufficient to maintain a constant cavity round trip time across a large optical bandwidth. To achieve this matching, we measured the group delay for each dispersive fiber element separately and in combination using the phase-shift method [18,19]. Briefly, a narrowband tunable laser source (TSL-510, Santec) produced optical signals at wavelengths tunable from 1500 nm and 1630 nm. A vector network analyzer (MS2036C, Anritsu) provided an intensity modulation signal to the laser at 97 MHz. The light was passed through the device under test, detected, and provided to the network analyzer. By measuring the phase-shift of the modulating 97 MHz signal as a function of wavelength, the relative group delay was calculated. By changing modulation frequency at a fixed wavelength, the absolute group delay was determined. Figure 3 presents group delay measurements of the combined dispersive fibers (not including the SOA, output coupler, and FP). Fast variations in group delay across wavelength are due to measurement noise. The blue curve provides a 3rd-order polynomial fitting to this data. From this curve, the group delay was measured to be 216.9 µs across the 100 nm range from 1500 nm to 1600 nm, and variations in group delay were on the order of ±0.45 ns. This meets the criteria for providing group delay variations that are less than the pulse width (0.50 ns), although with minimal margin. Reducing group delay variation by higher order dispersion engineering may be a path to further improve laser performance.

Fig. 2. A schematic of the wavelength-stepped laser (PC: polarization controller; FP: Fabry Perot etalon; SOA: semiconductor optical amplifier; IM: intensity modulator; DCF: dispersion compensating fiber; CDF: 39.394 km SMF-28e + chromatic dispersion fiber (655.7 ps/nm at 1550 nm); DDG: digital delay generator; PG: pulse generator).

Fig. 3. The absolute group delay of the combined positive and negative dispersion fibers as a function of wavelength. Red squares: measured data. Blue curve: 3rd-order polynomial fitting. The group delay averaged 216.9 µs across the lasing bandwidth with variations of approximately 0.45 ns.
3.3 Timing noise and jitter

The timing accuracy of the electrical pulse generator is critical to the successful operation of the laser. To ensure that multiple circulations of the optical pulses arrive during the open window of the optical modulator, the electrical pulse driving the modulator must have timing jitter at least less than the pulse width (~0.50 ns), and ideally a significant factor below this level. This jitter is relevant across a time-scale defined by the laser cavity round trip time of 219.4 µs. Thus, timing jitter significantly less than 1 ns over a millisecond time-scale is needed. To achieve this timing accuracy, we used a low-jitter digital delay generator (Stanford Research Systems DG645) to trigger an analog pulse generator (AVM-1-C, Avtech) that provided pulses directly (unamplified) to the lithium-niobate modulator. To limit jitter from external triggering of the AVM-1-C, a fast rise time modules (Stanford Research Systems SRD1) reduced the trigger signal risetime to less than 100 ps. To confirm jitter performance, we measured the analog pulse on a fast oscilloscope (Tektronix MSO 5204, 2 GHz, 10 GS/s) relative to a second clock signal generated by an RF signal generator (Stanford Research Systems SG384). Briefly, a first SG384 generated a 1 GHz clock signal (ECL signals with risetimes < 35 ps). This SG384 was phase-locked to a second SG384, which provided a lower frequency signal (e.g., 10 MHz) used to trigger the oscilloscope. This trigger frequency of the second SG384 was matched to the pulse frequency generated by the DG645 by the front panel (but the systems were not phase locked or physically coupled). Figure 4 shows a jitter histogram between the 1 GHz clock signal (used as true clock) and the analog signal generated over 4900 frames. Jitter values (defined as twice the standard deviation) were measured to be ~80 ps. We note that similar measurements using standard signal generators provided significantly higher jitter, and that the low-jitter high-performance clocks in the digital delay generator (DG645) were critical to achieving lasing operation. We also note that while the 1 GHz clock signal may have timing jitter, but this jitter would be uncorrelated to that of the pulse generator system (DG645 + AVM-1-C). Therefore, the measured jitter is an upper limit. Actual jitter of the pulse signal is likely somewhat smaller.

![Fig. 4. Measured jitter of the pulses driving the laser intensity modulator. Blue bars: histogram. Red curve: normal fit. Jitter (defined as twice the standard deviation) was measured to be approximately 80 ps.](image)

3.4 Polarization-mode dispersion

Because long fiber lengths were used as dispersive elements, significant polarization mode dispersion (PMD) was induced. We measured the PMD from each fiber using a wavelength-scanning method [19]. The measured differential group delays of the 40-km single-mode fiber and that of the dispersion compensating fiber were 0.46 ps and 0.16 ps respectively, each at a center wavelength of 1550 nm. The accumulated PMD, and especially that from the SMF-28e + spool, induces some instability in the source. In principle, this can be eliminated by
replacing the single-pass SMF-28e + spool with a double-pass design (of half the length) and using a Faraday rotator mirror. This design will be investigated in future work to enhance stability.

4. Laser performance

4.1 Wavelength-stepped configuration

In the wavelength-stepped configuration (with the FP included), the laser was operated at a pulse repetition frequency of 9061618.513 Hz (approximately the 1989th-order harmonic of the laser cavity). The output spectrum at the laser output after the external booster amplifier shows the expected spectral comb structure (Fig. 5(a)) forced by the 200 GHz (~1.6 nm) FSR FP etalon. The lasing bandwidth was measured to be 94 nm. It was determined that this bandwidth was limited by a combination of high cavity loss, variations in cavity group delay (see Fig. 3), and (to a lesser degree) PMD. The laser output in the time domain (Fig. 5(b)) was detected with an amplified photodetector (Thorlabs PDA8GS, bandwidth of 9.5 GHz) and digitized by a high-speed oscilloscope (Tektronix MSO 5204, 2 GHz, 10 GS/s). The generation of temporally separated optical pulses for each wavelength is apparent. The measured pulse shape (see expanded ROI in Fig. 5(b)) reflects this separation within the limitations of the 2 GHz bandwidth of the oscilloscope. The output power of the laser was 7.80 dBm. If the device were operated at 100% duty cycle (current source is 54% duty cycle), this power would increase to 10.46 dBm. The duty cycle in these experiments was limited by a 10 MHz ceiling on externally triggered pulse generation in the analog pulse generator (AVM-1-C). Without this limitation, the source could have been run at approximately 20 MHz repetition rates (with a duty cycle near 100%). The source RIN was measured to be approximately white (aside from structures attributed to A-line and pulse repetitions) across a 1 GHz spectral range, with a value of –106.18 dB/Hz at 501.3 MHz.

The source coherence length was measured with a variable-delay Michelson interferometer. The fringe signal was measured with a single-ended receiver as a function of the interferometer delay. We note that while it is difficult to confirm long coherence lengths with rapid wavelength-swept sources due to electronic and receiver bandwidth limitations [11], the wavelength-stepped laser aliases fringe power to a lower baseband [12], making these measurements more straightforward. The detected fringe amplitude is plotted as a function of mirror distance (half the optical path difference) in Fig. 5(c). The fringe visibility dropped to (1/e) of its path-matched value at a mirror displacement of approximately 32 mm. This demonstrates the ability of the FP etalon to force the laser to operate with relatively long instantaneous linewidth.

To evaluate the performance of the wavelength-stepped source for an OCT application, the point spread functions (PSFs) were measured for multiple mirror distances within the subsampled depth window (approximately 500 µm at 200 GHz stepping) (Fig. 5(d)). A polarization controller was used on the sample arm to tune the polarization state and a neutral density filter with an optical density value of 2.0 (introducing 40-dB attenuation in double-pass configuration) was fixed in place in front of the mirror in the sample arm. The measured OCT signal was obtained by use of a balanced photodetector (New Focus, 1617-AC) in combination with a 2 GHz bandwidth oscilloscope. The axial resolution (the full-width half-maximum of the PSF) at a distance of 0.125 mm was measured to be 27.4 µm in air.
Fig. 5. (a) Typical spectrum output of the wavelength-stepped laser source. The total tuning range is approximately 94 nm. (b) Laser output in the time domain at a repetition rate of over 9 MHz. The generation of temporally separated optical pulses for each wavelength are also shown with 2 GHz receiver bandwidth limitations. (c) The double-pass coherence length of the wavelength-stepped (optical-domain subsampled) laser was measured to be 32 mm (1/e). (d) Measured point spread functions at different mirror distance in air. The measured axial resolution in air was 27.4 µm at 0.125 mm mirror distance.
4.2 Wavelength-swept configuration

While the laser design was motivated by the need for a rapid wavelength-stepped laser source for optically subsampled OCT, it is also able to provide a rapid wavelength-swept source for conventional Fourier-domain OCT. Removal of the intracavity FP etalon allows continuous spectral operation. We note that operation in this conventional mode was found to be slightly more stable than in wavelength-stepped mode, which we preliminary attribute to reduced nonlinear effects that are efficiently seeded by the spectral comb-structure of the wavelength-stepped configuration. In addition, the stability of the continuously swept operation (i.e., without the FP) is preserved even when cavity loss is purposely increased, suggesting that other mechanisms in addition to cavity loss are of relevance.

The lasing bandwidth in the wavelength-swept configuration was measured to be 87 nm at a sweep rate of 9062493.112 Hz (Fig. 6(a)). This bandwidth is slightly smaller than the 94 nm of the wavelength-stepped configuration despite the reduction in cavity loss from removing the FP etalon. Nonlinear gain effects may be responsible for the increased bandwidth of the wavelength-stepped configuration. The time-domain laser output shows the expected continuous shape (Fig. 6(b)). The measured average output power of the laser and the corresponding peak power was over 12.66 and 15.32 dBm, respectively. The source RIN was measured to be $-114.1$ dB/Hz at 498.9 MHz.

The coherence length of the wavelength-swept source was investigated by measuring the fringe amplitude as a function of optical path difference. These measurements are limited by the large electrical bandwidth required to visualize fringes of the 9 MHz source at large path delays. Fringe amplitudes were measured to the oscilloscope limit of 2 GHz (corresponding to 1.75 mm mirror translation) (Fig. 6(c)). At optimal pulse width settings, the best fringe amplitude decay showed a drop to approximately 70% of its path-matched value at 1.75 mm, suggesting a double-pass coherence length on the order of 2 mm. We note that coherence length in the wavelength-swept configuration is greatly dependent on the modulator pulse width; smaller pulses provide greater wavelength discrimination and increase coherence length but narrow lasing bandwidth and reduce stability (likely due in part to the effects of timing jitter). To measure the source PSF, we operated the laser with slightly reduced coherence length (slightly increased pulse-widths) (Fig. 6(d)). The measured axial resolution in air was determined to be 25 µm at a distance of 0.1mm in a double-pass sample arm configuration. The FWHM of the PSFs did not significantly vary within 1.7 mm mirror displacement. The decreased coherence length evident in Fig. 6(d) relative to that of Fig. 6(c) can be attributed to the sensitivity of the source to the electrical pulse characteristics.
Fig. 6. (a) The lasing spectrum of the wavelength-swept laser was measured to be 87 nm. (b) The laser output in the time domain with a sweep time of approximately 60 ns. (c) The coherence length measurements were limited to 1.75 mm distance by the 2 GHz bandwidth of the oscilloscope. The measured double-pass coherence length of the laser is extrapolated to approximately 2 mm. (d) Point spread functions measured at various distances in air. The axial resolution at a mirror distance of 0.1 mm was measured to be 25 µm. The difference in coherence lengths between panels (c) and (d) is due to a high sensitivity of the laser (in the continuous sweep configuration) to variations in the electrical pulse parameters. A more stable and repeatable pulse generator is likely to improve overall source stability and performance in this configuration.
5. Conclusion

In this study, we have presented a novel laser design that utilizes two chromatically dispersive fibers for stretching and compressing optical pulses in time along with a fast lithium-niobate intensity modulator to produce rapidly wavelength-stepped laser output. This source could be an enabling technology for development of high-speed optical-domain subsampled OCT or very high-speed conventional OCT. In its current form, the source has a large form factor and some instability, and as such is more appropriate as a research tool. With improvements to the design including more practical dispersion engineering solutions, this laser design could find application in commercial and medical imaging instruments. Fundamentally, this dispersive approach or variations of it could be used to enable very fast lasers both in wavelength-stepped and wavelength-swept configurations.

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