All-fiber wavelength swept ring laser based on Fabry-Perot filter for optical frequency domain imaging

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Abstract: Innovations in laser engineering have yielded several novel configurations for high repetition rate, broad sweep range, and long coherence length wavelength swept lasers. Although these lasers have enabled high performance frequency-domain optical coherence tomography, they are typically complicated and costly and many require access to proprietary materials or devices. Here, we demonstrate a simplified ring resonator configuration that is straightforward to construct from readily available materials at a low total cost. It was enabled by an insight regarding the significance of isolation against bidirectional operation and by configuring the sweep range of the intracavity filter to exceed its free spectral range. The design can easily be optimized to meet a range of operating specifications while yielding robust and stable performance. As an example, we demonstrate 240 kHz operation with 125 nm sweep range and >70 mW of average output power and demonstrate high quality frequency domain OCT imaging. The complete component list and directions for assembly of the laser are posted on-line at www.octresearch.org.

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References and links
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(5035), 1178–1181 (1991).
2. M. Wojtkowski, “High-speed optical coherence tomography: basics and applications,” Appl. Opt. 49(16), D30–D61 (2010).
3. R. Leitgeb, C. Hitzenberger, and A. Färber, “Performance of Fourier domain vs. time domain optical coherence tomography,” Opt. Express 11(8), 889–894 (2003).
4. M. Choma, M. Sarunic, C. Yang, and J. Izatt, “Sensitivity advantage of swept source and Fourier domain optical coherence tomography,” Opt. Express 11(18), 2183–2189 (2003).
5. S. Yun, G. Tearney, J. de Boer, N. Iftimia, and B. Bouma, “High-speed optical frequency-domain imaging,” Opt. Express 11(22), 2953–2963 (2003).
6. I. Grukowski, J.-J. Liu, B. Potsaid, V. Jayaraman, C. D. Lu, J. Jiang, A. E. Cable, J. S. Duker, and J. G. Fujimoto, “Retinal, anterior segment and full eye imaging using ultrahigh speed swept source OCT with vertical-cavity surface emitting lasers,” Biomed. Opt. Express 3(11), 2733–2751 (2012).
7. S. H. Yun, C. Boudoux, M. C. Pierce, J. F. de Boer, G. J. Tearney, and B. E. Bouma, “Extended-cavity semiconductor wavelength-swept laser for biomedical imaging,” IEEE Photon. Technol. Lett. 16(1), 293–295 (2004).
8. 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(20), 1981–1983 (2003).
9. 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(23), 3159–3161 (2005).
10. W.-Y. Oh, B. J. Vakoc, M. Shishkov, G. J. Tearney, and B. E. Bouma, “>400 kHz repetition rate wavelength-swept laser and application to high-speed optical frequency domain imaging,” Opt. Lett. 35(17), 2919–2921 (2010).
Since optical interferometry was first applied for cross-sectional imaging of biological samples [1], optical coherence tomography (OCT) has evolved over more than two decades yielding better resolution, imaging depth, imaging speed and expanded functionality [2]. Up to the present, swept-source (SS) OCT, or optical frequency domain imaging (OFDI), has proven advantageous over time-domain (TD) OCT in terms of imaging speed [3–5], detection sensitivity, and thus effective imaging range [2,5,6]. This has motivated concentrated efforts to develop higher performance wavelength-swept light sources over the recent ten years [2,6]. Resonant galvanometers and polygon-scanners were applied in early wavelength-scanning filters for high speed OFDI systems, resulting in sweep frequencies of tens of kHz [7,8]. With advances in filter optical design and polygon parameters, subsequent filters enabled broader wavelength sweep range, narrower instantaneous linewidth, and higher sweep frequency, exceeding 400 kHz [9,10]. Fabry-Perot (F-P) tunable filters have played another prominent role [4,11,12]. The fiber pigtailed design of the F-P filter has the advantage of alignment-free operation and early systems generated up to 20 kHz sweep rates [12]. Fourier-domain model-locking (FDML) was introduced to overcome the low quality factor, and commensurate broadened output linewidth and decreased coherence length, that arose from high-speed filter operation in conventional laser resonators [13]. FDML has an attractive advantage that as sweep speed increases, the resonator fiber length can be reduced and the resonant frequency

11. M. A. Choma, K. Hsu, and J. A. Izatt, “Swept source optical coherence tomography using an all-fiber 1300-nm ring laser source,” J. Biomed. Opt. 10(4), 044009 (2005).
12. R. Huber, M. Wojtkowski, K. Taira, J. Fujimoto, and K. Hsu, “Amplified, frequency swept lasers for frequency domain reflectometry and OCT imaging: design and scaling principles,” Opt. Express 13(9), 3513–3528 (2005).
13. R. Huber, M. Wojtkowski, and J. G. Fujimoto, “Fourier Domain Mode Locking (FDML): A new laser operating regime and applications for optical coherence tomography,” Opt. Express 14(8), 3225–3237 (2006).
14. R. Huber, D. C. Adler, and J. G. Fujimoto, “Buffered Fourier domain locking: unidirectional swept laser sources for optical coherence tomography imaging at 370,000 lines/s,” Opt. Lett. 31(20), 2975–2977 (2006).
15. W. Wieser, B. R. Biedermann, T. Klein, C. M. Eigenwillig, and R. Huber, “Multi-Megahertz OCT: High quality 3D imaging at 20 million A-scans and 4.5 G Voxel per second,” Opt. Express 18(14), 14685–14704 (2010).
16. Corning SMF28+ “http://www.corning.com/opticalfiber/products/SMF-28e+_fiber.aspx.
17. H. S. Cho, S.-J. Kang, K. Kim, A. V. Dan-Chin-Yu, M. Shishkov, B. E. Bouma, and W.-Y. Oh, “High frame-rate intravascular optical frequency-domain imaging in vivo,” Biomed. Opt. Express 5(1), 223–232 (2014).
18. S. C. Schlachter, D. Kang, M. J. Gora, P. Vacas-Jacques, T. Wu, R. W. Carruth, E. J. Wilsterman, B. E. Bouma, K. Woods, and G. J. Tearney, “Spectrally encoded confocal microscopy of esophageal tissues at 100 kHz line rate,” Biomed. Opt. Express 4(9), 1636–1645 (2013).
19. Arduino,” http://arduin.cc/.
20. A. E. Siegman, Lasers (University Science Books, 1986).
21. K. Inoue, T. Mukai, and T. Saitoh, “Nearly degenerate four-wave mixing in a traveling-wave semiconductor laser amplifier,” Appl. Phys. Lett. 51(14), 1051–1053 (1987).
22. G. P. Agrawal, “Population pulsations and nondegenerate four-wave mixing in semiconductor lasers and amplifiers,” J. Opt. Soc. Am. B 5(1), 147–159 (1988).
23. S. S. Girard, M. M. Piche, H. Chen, G. G. Schinn, W.-Y. Oh, and B. B. Bouma, “SOA Fiber Ring Lasers: Single- Versus Multiple-Mode Oscillation,” IEEE J. Sel. Top. Quantum Electron. 17(6), 1513–1520 (2011).
24. R. Langenhorst, M. Eiselt, W. Pieper, G. Grosskopf, R. Ludwig, L. Küller, E. Dietrich, and H.-G. Weber, “Fiber loop optical buffer,” J. Lightwave Technol. 14(3), 324–335 (1996).
25. M. R. N. Avanaki, A. Bradu, I. Trifanov, A. B. L. Ribeiro, A. Hojjatoleslami, and A. G. Podoleanu, “Algorithm for Excitation Optimization of Fabry-Perot Filters Used in Swept Sources,” IEEE Photon. Technol. Lett. 25(5), 472–475 (2013).
26. S. Yun, G. Tearney, J. de Boer, and B. Bouma, “Removing the depth-degeneracy in optical frequency domain imaging with frequency shifting,” Opt. Express 12(20), 4822–4828 (2004).
27. E. Brinkmeyer and R. Ulrich, “High-resolution OCDR in dispersive waveguides,” Electron. Lett. 26(6), 413–414 (1990).
28. M. Villiger, E. Z. Zhang, S. K. Nadkarni, W.-Y. Oh, B. J. Vakoc, and B. E. Bouma, “Spectral binning for mitigation of polarization mode dispersion artifacts in catheter-based optical frequency domain imaging,” Opt. Express 21(14), 16353–16369 (2013).
29. D. Veri, “Fiber Optic Test and Measurement (Prentice Hall PTR, 1998).
30. B. R. Biedermann, W. Wieser, C. M. Eigenwillig, T. Klein, and R. Huber, “Dispersion, coherence and noise of Fourier domain mode locked lasers,” Opt. Express 17(12), 9947–9961 (2009).
31. R. Steiner, “Laser-Tissue Interactions,” in Laser and IPL Technology in Dermatology and Aesthetic Medicine, C. Raulin and S. Karsai, eds. (Springer Berlin Heidelberg, 2011), pp. 23–36.
32. ImageJ,” http://rsbweb.nih.gov/ij/.

1. Introduction
of the tunable filter then limits performance. This unique advantage resulted in multi-MHz sweep frequency by combining an interleaver for multiplexing [14,15]. More recently, several companies have launched prospective technologies by transferring bulk laser schemes into micro-cavity configuration with the help of semiconductor fabrication and micro-packaging technologies, for example, sampled-grating distributed-Bragg-reflector laser with current control (Insight Inc.), external cavity laser (ECL) using micro-electromechanical system (MEMS) mirror and grating (Exalos AG, Santec Co.), ECL using MEMS F-P (Axsun Inc.) and integrated vertical-cavity surface emitting laser (VCSEL) with MEMS mirror (Thorlabs Inc.). Each of these commercial lasers achieves performance specifications required for high quality, high speed imaging. However, they are expensive and it would be extremely difficult, if possible, to customize their performance and specifications. While lab-built wavelength swept lasers are more flexible in this regard, previous designs have been complex, requiring precise alignment, dispersion compensation, and polarization control in order to achieve performance targets. Therefore, there remains a need for an inexpensive alternative design capable of being reconfigured and optimized for different performance metrics and simple enough to be adopted broadly in order to facilitate OCT research. In this manuscript, we describe a filter and laser design that meets these objectives. Key to our design is a short, ~0.5 m, all-fiber, ring resonator based on a semiconductor optical amplifier (SOA) and F-P tunable filter. The resonator design allows only three components to be directly fusion spliced and requires no polarization controllers. We demonstrate the critical importance of strong isolation against bi-directional operation, which results in versatile, high speed operation. In addition, we demonstrate that by overdriving the FP filter and modulating the SOA gain, this laser can produce high quality, nearly linear, broadband wavelength sweeps. In combination with a 4-fold interleaver, we demonstrate 125 nm sweep range with >70 mW of output power at 240 kHz repetition rate in the ~1.3 µm wavelength region.

2. Wavelength-swept laser

In this section, we describe the wavelength-swept laser oscillator and interleaver. The effect of cavity isolation and overdriven F-P operation are also discussed.

![Fig. 1. Schematic setup of (a) 60 kHz laser oscillator and (b) interleaver for 4 x frequency multiplication followed by an amplifier SOA. (SOA: semiconductor optical amplifier, F-P: Fabry-Perot filter, CIRC: circulator, FRM: Faraday rotating mirror, SMF: single-mode fiber, PC: polarization controller).](image)

2.1 Laser setup

Figure 1(a) is the schematic of the specific configuration utilized in this manuscript. The laser oscillator comprised a SOA gain medium, a F-P tunable filter and a hybrid output coupler/isolator. The SOA (Thorlabs Inc., BOA1130S3) had a small signal gain of ~28 dB and a saturated output power of ~18 dBm. The 3-dB bandwidth of amplified spontaneous emission (ASE) was 92 nm with 1280 nm center wavelength. Each built-in isolator, positioned at opposite ends of the SOA, provided ~20 dB isolation over the full sweep range and ~50 dB at the design wavelength. The isolator on right-side of the SOA in Fig. 1(a) is to prevent the back-reflection of forward propagating ASE, and the isolator on left-side of the
SOA is to suppress the backward propagating ASE from the beginning. Although in our previous research [5,8–10], we have found that a single isolator meeting these specifications was sufficient in conventional laser designs, we demonstrate below that it was insufficient when simplifying the resonator design including the highly reflective component like the F-P filter and optimizing its performance. The F-P tunable filter (LambdaQuest LLC.) had a free spectral range (FSR) of ~160 nm and filter linewidth of ~0.16 nm at 3-dB, corresponding to a Finesse of 1000. The broad resonance of the F-P allowed a ~150 nm wavelength sweep range for drive frequencies from 55 kHz to 65 kHz by adjusting the offset voltage ($V_{\text{offset}}$) and peak-to-peak voltage ($V_{\text{p-p}}$). Since the resonance frequency bandwidth of tunable F-P filters is determined by lead zirconate titanate (PZT) and mechanical load, we anticipate that it should be similar per product unless the material and fabrication process are changed; we have tested 6 units and found consistent resonance responses. Outside the resonance range, the filter still achieved a sweep range of 91 nm (50 kHz), 94 nm (68 kHz) and 30 nm (180 kHz). In this work, we used a 60 kHz drive frequency. The output coupler (DPM Photonics, TAPI) was a hybrid between a tap coupler and isolator, which were integrated in a single package. The tap ratio was 50:50 and the isolator was a broadband, dual-stage design providing >35 dB isolation over the full sweep range (> ± 50 nm). The hybrid coupler/isolator played an important role in satisfying isolation and short cavity length simultaneously. The SOA, F-P, and output coupler were fusion spliced, resulting in ~0.51 m physical cavity length (~0.75 m optical cavity length by n = 1.4676 @ 1310 nm [16]).

The final output repetition rate can be increased over that of the master oscillator and filter by reducing the duty cycle of the oscillator and using an interleaver, such as a Mach-Zehnder type [15] or parallel-split delay line [17,18]. The interleaver design used in this work, Fig. 1(b), is a modified version of that used in Refs. 17 and 18. It includes a tandem structure, which reduces the total fiber length 2-fold. While the F-P was driven with a 60 kHz sinusoidal wave, the cavity SOA was modulated with a 25% duty cycle square wave that was synchronized with the sinusoidal wave driving the F-P so that the SOA provided gain at the most linear portion of the sinusoid. Following the interleaver, the sweep repetition rate was 240 kHz and the duty cycle approached 100%. With these parameters, the oscillator’s sweep range was approximately 71% of the FSR of the filter and the sweep was linearized relative to the sinusoidal response of the filter at resonance. An inexpensive and compact microcontroller, e.g., Arduino [19], combined with an electronic circuit provided the synchronized drive signals for the F-P and SOA. The frequency and duty cycle of the square wave provided by the microcontroller were set by adjusting the internal clock and a voltage divider circuit was used to adjust the voltage level. A sinusoidal wave for the F-P was generated by electrically band-pass filtering the square wave from the micro-controller and an op-amp and clamper circuit was used to adjust $V_{\text{p-p}}$ and $V_{\text{offset}}$, respectively. The SMF delay fibers were loose-wound, without plastic spools to minimize size.

2.2 Effect of cavity isolation

Unidirectional isolation in a ring laser cavity is essential to avoid spatial hole burning and counter-propagating lasing which partitions the gain and induces spectral and intensity noise [20]. Especially when the laser cavity includes any reflective component like the F-P filter, the level of isolation needs to be verified to avoid undesired lasing.
Fig. 2. Effect of laser cavity isolation. (a) Temporary setup to separately measure the swept spectrum (yellow dash) and the ASE back-reflect ed by the F-P (blue dash). (b) Yellow-filled spectrum is the desired swept spectrum and blue-colored spectrum is the reflected ASE. Thick red spectrum is the combined output. With sufficient isolation of >55 dB between F-P and SOA 2, the backward-propagating ASE no longer exists (black spectrum at bottom). The output spectra for various fixed (not swept) F-P voltages are depicted in with different colors (c) for 20 dB isolation and (d) for >55 dB isolation. The inset of Fig. 2(c) is the evolution of ASE up to 49 roundtrips. The swept spectrum is displayed in (e) for 20 dB isolation and (f) for >55 dB isolation. The evolved ASE is hidden as a spectral noise in Fig. 2(e) (grey spectrum).

Figure 2 shows the difference of lasing spectra with and without sufficient isolation. Figure 2(a) depicts the temporary configuration for testing isolation and measuring the forward- and backward-propagating light separately. In this setup, two SOAs have the same specification but SOA 1 has a built-in isolator only on the right-side to represent the forward propagating ASE of Fig. 1(a) and SOA 2 only on the left-side for backward propagating ASE, and thus only ~20 dB isolation in backward direction is provided by the built-in isolator in SOA 2. The yellow dashed curve represents the forward propagating light and the blue dashed curve designates the SOA ASE reflected from the F-P filter. The spectrum of the ASE reflected by the F-P is independent of whether the F-P is sweeping or not. With both SOAs turned on and the F-P driven at resonance, the swept spectrum is mixed with the reflected ASE as shown by the thick red line in Fig. 2(b). After many roundtrips or reflections, the ASE reflected by the F-P evolves into a narrower, red-shifted spectrum due to gain narrowing and self-phase modulation with nearly-degenerate four-wave mixing [21–23]. The inset of Fig. 2(c) is the experimental confirmation of ASE evolution up to 49 roundtrips which was measured via the function generator’s pulse burst mode, and it shows the same tendency with simulation [24]. Characteristic lasing spectra for fixed F-P voltages in a ring resonator are depicted in Fig. 2(c) (up to 14 V_{DC}). As shown in Fig. 2(b), the residual ASE overwhelms the
swept intensity, partitioning much of the SOA gain. Therefore, the evolved ASE occupied most of the spectra while the filtered spectra by the F-P had low intensity in Fig. 2(c). On the other hand, when the filter was positioned around 1320 nm which was the design wavelength of the built-in isolator in SOA (50 dB isolation), we could observe the desired spectra without an influential ASE noise. The swept spectral width was also severely affected as shown in Fig. 2(e), and the ASE evolution was hidden as a spectral noise (gray spectrum). In comparison, Fig. 2(d) and 2(f) show the results when >55 dB isolation over the full sweep range was provided by adding a tap coupler/isolator. In these cases, the backward propagating ASE was completely removed (black line at bottom of Fig. 2(b)), allowing only the swept spectrum to circulate the cavity. The DC-tuned spectra in Fig. 2(d) show extinction ratios of up to 80 dB and saturated output power of 40 mW per channel within the FSR. The swept spectrum in Fig. 2(f) indicated no residual ASE. From the result, we concluded that the isolation between the backward propagating ASE of the SOA and the F-P was required to be at least 40 dB over the entire sweep range which corresponds to the intensity difference between the ASE and swept spectrum of Fig. 2(b). The combination of the built-in isolators in the SOA and the tap coupler/isolator met this criterion, resulting in the desired wavelength-swept output with excellent extinction ratio and output power.

We note that the laser configuration of Fig. 1(a) requires no polarization controllers. From our measurements, we conclude that previous laser schemes, such as in Ref. 17 and 25, with fewer isolator components may have required polarization control in order to introduce additional isolation. A polarization controller located between the F-P and SOA could result in isolation by distorting the polarization state of back-reflected ASE so that it was misaligned with the gain axis of the SOA. A second polarization controller, located on the other side of the F-P would then compensate the retardance of the first polarization controller so that forward propagating light was aligned with the SOA preferred polarization state. By providing greater isolation, through input and output isolators within the SOA package and through the hybrid output coupler/isolator, we verified that unidirectional operation can be ensured and that explicit polarization control is not required. This greatly simplifies the construction of a ring resonator having a short perimeter.
2.3 Fabry-Perot filter operation

As depicted in Fig. 3(a) with the grey line, a F-P filter incorporated into a wavelength swept laser is normally driven so that the transmission peak is swept over a wavelength range less than the FSR of the F-P etalon. So the sweep range is expected to be reduced if the cavity SOA is modulated with a low duty cycle to be interleaved for higher laser frequency (red line in Fig. 3(a)). For example, SOA modulation with 25% duty cycle reduces the sweep range to 71% of the maximum (150 → 107 nm), and 20% duty cycle to 59% of the maximum (150 → 89 nm). By overdriving the F-P, however, the sweep range can be maintained close to the maximum even though the SOA is modulated with a low duty cycle. Exceeding the FSR by overdriving the F-P can result in lasing through multiple transmission orders of the filter. The mixed time and spectral traces are designated with brown color at the bottom of “Overdriven” in Fig. 3(a) and Fig. 3(d), respectively. However, by controlling the time window of the SOA gain, lasing can be constrained to a single order, thereby resulting in a larger, more linearized sweep as shown in Fig. 3(a). With the laser configuration of Fig. 1 and the components described above, we observed a ~130 nm sweep range while operating the SOA with a 25% duty cycle. Resulting spectra are shown in Fig. 3(b)-3(e) for duty cycles of 46%, 31%, 25%, and 20%, corresponding to 120 kHz, 180 kHz, 240 kHz and 300 kHz operation, respectively. In all cases, the voltage applied to the F-P was less than 20 V. In the case of 46% duty cycle, 120 kHz operation, the output average power was 80-100 mW, which is around the SOA saturation output power. At every duty cycle, the sweep range can be close to 150 nm unless
the displacement of an overdriven F-P mirror exceeds the F-P spacing and the sinusoidal PZT response to high \( V_{pp} \) becomes unstable. However, high speed wavelength sweep results in output power loss due to the reduced number of roundtrip of each instantaneous linewidth. That is, there is a tradeoff between the output power (or sweep range) and laser speed to maintain maximum sweep range (or high output power). Nonetheless, sweep range of >110 nm with the output power of >50 mW can be achieved within 300 kHz laser speed, which can be sampled with the common 340 Ms/s digitizer for 4-5 mm imaging depth.

3. OFDI result at 240 kHz

In this section, we describe an OFDI system using the aforementioned swept laser, and discuss the performance including numerical calibration of laser chirp, sensitivity, axial resolution and imaging depth for 240 kHz axial scan rate operation. Imaging results of a human fingertip and a nail fold are presented.

![Figure 4](image-url)

**Fig. 4.** (a) Schematic of 240 kHz OFDI system. (b) Swept spectra at laser output (red), at detector coming from the sample arm mirror (green dot) and at detector coming from the reference arm mirror (blue dot). Spectra at detectors were measured with the reduced resolution of 0.5 nm to better display the spectral shape. (c) Relation of functions and signals in the time domain. (AO FS: acousto-optic frequency shifter, PD: photodiode, FBG: fiber Bragg grating, Pol: polarizer, BS: beam splitter, PBS: polarizing beam splitter).

Figure 4(a) presents a schematic of the OFDI system incorporating the 240 kHz swept laser. Figure 4(b) depicts the final spectrum of the laser, indicating a 112 nm 3-dB bandwidth (125 nm at full sweep range) and 70.5 mW of average output power. The spectra incident on the detectors, respectively coming from reference arm and ~60-dB-attenuated sample arm are also displayed with blue and green dots for reference. The laser sweep trace is shown with a thick red line in Fig. 4(c). The imperfect spacing of traces from the interleaver, evident in the figure, has no consequence for imaging since the acquisition of each A-line is triggered by a pulse resulting from the reflection of laser light from a fiber Bragg grating as shown in Fig. 4(a). Double-passing the acousto-optic frequency shifter (Brimrose Co.) in the reference arm
shifts the fringe frequency so that the zero delay point of the interferometer corresponded to
100 MHz [26]. The dual-balanced detectors (Exalos AG) had 350 MHz bandwidth and the
effective sampling rate of digitizer (Signatec, PX14400A) was 340 MS/s, limited by the
transfer rate over PCI-Express. The 14 bit-depth resolution of the digitizer provided 84 dB
dynamic range. Due to the Nyquist frequency of 170 MHz, ~4.8 mm was the digitizer-limited
imaging depth in this system. The imaging depth when using 100 MHz frequency shifter in
this setup will then be from ~2.8 mm to 2 mm around the sample depth of zero delay between
two interferometer arms. When doing a calibration and measuring system performance, a
mirror was placed in sample arm, which was later replaced with a galvanometric scanner for
2D scanning of sample.

In OFDI, the signal containing depth information results from beating between the
reference light and a time-delayed sweep from the sample like Fig. 5(a). Therefore, if the
frequency sweep is perfectly linear, each depth generates a single tone that is proportional to
depth. However, in the case of a nonlinear frequency sweep like Fig. 5(a), reflection from a
discrete depth in the sample generates a frequency band chirped over a period, as seen in Fig.
5(b), which becomes broader as the sweep frequency increases, the sweep range increases, or
the sweep nonlinearity increases. Here we calculated Fig. 5(a) and 5(b) by assuming the
wavelength was linearly swept ($\lambda(t) = \lambda_0 + \alpha t$, where $\alpha$ is the swept speed of 29.9 nm/µs at
240 kHz) as described in Fig. 3(a). The resulting chirp in the fringe signal impairs the
theoretical imaging depth. As shown in Fig. 5(b), a signal corresponding to the theoretical
maximum positive delay of 2 mm differential delay results in a beating frequency exceeding
70 MHz in the beginning of the sweep. Considering the 100 MHz modulation of the reference
signal in the current configuration, 70 MHz is the Nyquist limit. The gray lines in Fig. 5(c)
show the system axial response before calibration, evidencing significant broadening due to
the nonlinear sweep. After sampling 1296 points of the interference fringe signal with a fixed-
rate digitizer, we first isolate one of the two mirror terms and demodulate its fringe signal by
the reference carrier frequency. This complex valued fringe signal is then linearly interpolated
with our calibrated mapping to obtain 648 sample points corresponding to this one mirror
term, which are then zero-padded to a length of 1024. Additionally, we compensated for
remaining dispersion imbalance [5,27,28]. Representative point-spread functions at various
delays are shown as red traces in Fig. 5(c). Regarding the stability of F-P filter and
calibration, we did not observe any noticeable degradation of the point-spread-function during
hours of operation, even though the F-P is not thermally controlled.
To quantify system sensitivity, we used a $-60.8$ dB attenuator in the sample arm and the system loss from the sample mirror to detector was $3.3$ dB. The power incident on sample was $\sim50$ mW and the reference arm power on detector was $60-90 \mu$W. Figure 6(a) is the theoretical sensitivity as a function of reference arm power on detector [2,3,5], which was calculated with the measured noise current of $18.7$ pA/sqrt(Hz), common-mode rejection ratio (CMRR) of $-25$ dB and relative intensity noise (RIN) of $-130$ dB/Hz [29,30]. The theoretical maximum value of sensitivity was $107.3$ dB which is slightly lower than the shot-noise-limited value of $111.3$ dB due to the laser RIN. Detector saturation ($-4$ dBm) further limits the maximum sensitivity to $106.9$ dB. The measured sensitivity values (red dots) were lower than the calculations by 4-9 dB. The difference is due to: (1) the polarization mode dispersion (PMD) which degrades the signal-to-noise ratio (SNR) even in the polarization-diversity setup, (2) the Hanning windowing which loses the number of sampling points, (3) the incomplete calibration which degrades the SNR, and (4) the CMRR reduction due to the optical power imbalances in the balanced detectors. The actual maximum sensitivity was measured to be $93.3$ dB at zero delay. It should be noted that $170$ MHz band pass filter will increase the sensitivity by $3.1$ dB and improved power balance in the balanced detectors and reduced system loss will also gain several dB sensitivity. Figure 6(b) shows the sensitivity roll-off and the SNR at each depth with one of the unaveraged noise. The horizontal-axis is denoted by both imaging depth and the corresponding signal frequency. The SNR is calculated from the PSF data in the lower part of Fig. 6(b), to which is then added the attenuation value to result in the sensitivity in the upper part of Fig. 6(b). The full range imaging depth measured at the 6-dB roll-off point was $1.9 \times 2.0 = 3.8$ mm. Theoretically, the F-P instantaneous linewidth, $0.16$ nm should correspond to $4.6$ mm full range imaging depth. In the current setup, as described previously, the Nyquist frequency of $170$ MHz determined by the digitizer and signal broadening due to the nonlinear chirp of the laser, limit the imaging depth. Figure 6(c) indicates the axial resolution per depth, defined as full width at half maximum (FWHM) of each trace. For a better precision like the inset of Fig. 6(c), $10 \times 1024$ pixels of discrete Fourier transform (DFT) are generated in this measurement. The measured axial resolution was $11.4$ µm in air and $8.1$ µm in tissue ($n = 1.4$ [31]), which is comparable with the theoretical value of $10.7$ µm in air.
Figure 7 presents images acquired with the system in vivo at 240 kHz A-line scan rate. The transverse resolution was 17 µm, defined as the 1/e² spot size of the beam relayed by the XY galvanometer-scanner (Cambridge Technology Inc. 6215H, Thorlabs LSM02) to the sample. The fingertip image was composed of 1024 pixels (Z) × 1024 A-lines (Y) × 512 frames (X), corresponding to 4.5 mm × 10 mm × 5 mm at the sample. The image was simply rescaled to 512 (Z) × 1136 (Y) × 568 (X) voxels to have the same pixel size of 8.8 µm in X-Y-Z directions, which includes 2-fold averaging when downsizing in Z dimension and interpolation in X and Y dimensions, and then cropped for display. The nail fold image of Fig. 7(c) followed the same procedure while 256 frames were imaged. Both images have the same unit length for actual comparison. Image preparation, including the 3D rendering of Fig. 7(b) and 7(d), was performed using ImageJ [32]. No additional averaging/filtering was performed. In these examples, the B-scans, with 1024 A-lines, were acquired with a frame rate of 234 per second. The images show sweat ducts, stratum corneum, epidermis, epidermal-dermal junction, and the nail structure quite clearly with high penetration depth and sensitivity.

4. Conclusion
We demonstrated an all-fiber wavelength-swept laser based on a Fabry-Perot filter and a short-length ring cavity for optical frequency domain imaging. The most significant characteristics of the laser are simplicity of assembly, low cost of materials, and robust operation without polarization control, all while providing high performance in terms of repetition rate, average power, coherence length, and resolution. In addition, the design can readily be optimized with respect to the axial resolution and the sweep rate to target various applications, or tailored for alternative wavelength ranges using appropriate components. The primary insights that enabled this result were the requirement of high intracavity isolation against counter-propagating light and the unique operation of the F-P filter with a sweep range exceeding its intrinsic free spectral range. The laser sweep range was 125 nm and the output power was >70 mW at 240 kHz repetition rate. Integrating the laser with an OFDI system, we demonstrated high quality imaging with 8.1 µm axial resolution in tissue, 93.3 dB sensitivity and 3.8 mm imaging depth at 240 kHz axial scan rate.
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