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Compact Ultrafast Reflective Fabry-Perot Tunable Lasers For OCT Imaging Applications

Mark Kuznetsov*, Walid Atia, Bart Johnson, and Dale Flanders
Axsun Technologies Inc., 1 Fortune Dr, Billerica, MA 01821, USA
* mkuznetsov@volcanocorp.com; www.axsun.com

ABSTRACT

We demonstrate a novel reflective Fabry-Perot tunable laser (RFPTL) for high speed swept-source optical coherence tomography (OCT) imaging applications. This external cavity semiconductor laser uses a silicon MEMS tunable Fabry-Perot filter in a novel reflective mode of operation. The laser is packaged in a compact 25x15 mm fiber-pigtailed butterfly package. Lasers at 1060 and 1300 nm wavelengths have been demonstrated with tuning ranges up to 140 nm, fast scan rates of 100 kHz, and coherence lengths greater than 13 mm. We also describe OCT imaging with these lasers. RFPTL lasers with 1–2 µm wavelengths and tuning ranges of 250 nm have also been demonstrated for a wide range of applications.

Keywords: optical coherence tomography OCT, swept source, tunable semiconductor laser

1. INTRODUCTION

Optical coherence tomography (OCT) [1] imaging technology has emerged as an important tool for a wide range of medical applications, such as ophthalmology, cardiology, dentistry, cancer detection, etc. The initially demonstrated time-domain TD-OCT technique using broadband light sources has recently been dramatically improved upon with higher speeds, resolution, and sensitivity by frequency/Fourier domain OCT techniques: spectral or Fourier-domain FD-OCT using a broadband source and a dispersive grating with a detector array, and swept-source SS-OCT using a fast tunable laser and a detector. These three OCT techniques parallel the three spectroscopy approaches of Fourier Transform spectroscopy, dispersive grating with detector array spectrometer, and a tunable laser spectrometer. The dramatic improvement of the Fourier- over time-domain OCT technique is due to the noise filtering properties of the Fourier Transform operation that obtains the OCT image from the directly measured interference spectrum. Swept-source OCT has distinct advantages over FD-OCT because of its capability of balanced and polarization diversity detection. It has advantages as well for imaging in wavelength regions where inexpensive and fast large-pixel-count detector arrays are not available.

Existing approaches to fast swept sources for OCT include: semiconductor fiber ring lasers [2], grating-tuned external cavity semiconductor lasers [3], external cavity semiconductor lasers with polygonal scanning mirrors [4], and, potentially, multi-section super-structure-grating SSG-DBR semiconductor lasers [5]. A novel very fast swept source, the frequency-domain modelocked FDML laser [6], is capable of scan rates of 200–300 kHz, the high rates frequently aided by optical buffering [7]. In this paper we introduce a new reflective Fabry-Perot tunable laser (RFPTL), illustrated schematically in Figure 1. RFPTL is an external cavity semiconductor laser that uses a silicon micro-electro-mechanical system (MEMS) tunable Fabry-Perot filter in a novel reflective mode of operation. RFPTL has a very simple and compact cavity configuration with high OCT performance characteristics. Here we describe the RFPTL laser technology, laser performance characteristics, and laser applications to OCT imaging.

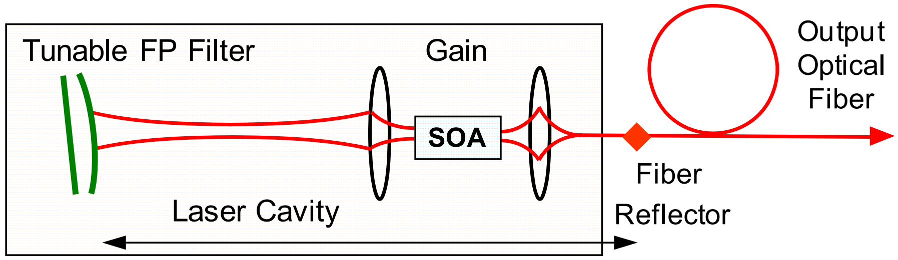

Figure 1. Reflective Fabry-Perot tunable laser RFPTL configuration.

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2. RFPTL LASER TECHNOLOGY

The key component of the RFPTL laser, Figure 1, is the silicon MEMS tunable Fabry-Perot (FP) filter [8], illustrated in Figure 2. Of the two Fabry-Perot mirrors, one is on an electro-statically actuated movable silicon membrane, shown in Figure 3, used for filter tuning. The filter size is ~2x1.5x0.5 mm; wafer scale fabrication produces several thousand tunable membranes on a single wafer, as shown in Figure 4, and allows for low device cost. We have demonstrated such MEMS filters with scan rates in excess of 100 kHz; operating wavelengths in the 1.0 – 2.0 μm range; filter free spectral range, and thus tuning range, adjustable by design between 40 and 350 nm; and filter linewidths between 1 and 150 GHz (0.008 to 1.2 nm).

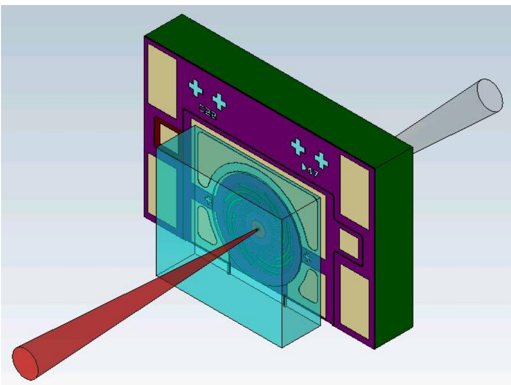

Figure 2. Silicon micro-electro-mechanical system (MEMS) tunable Fabry-Perot filter.

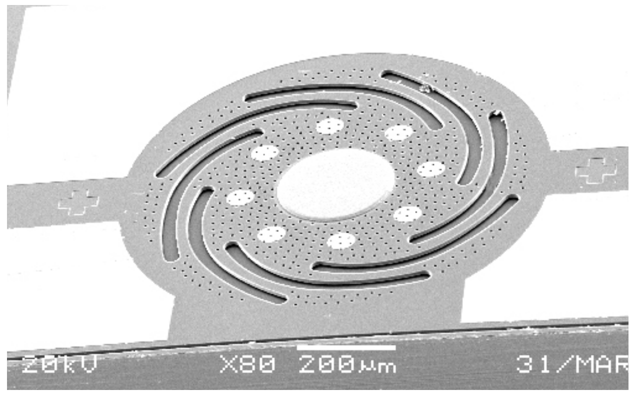

Figure 3. Electro-statically actuated movable silicon membrane with a high reflectivity coating mirror.

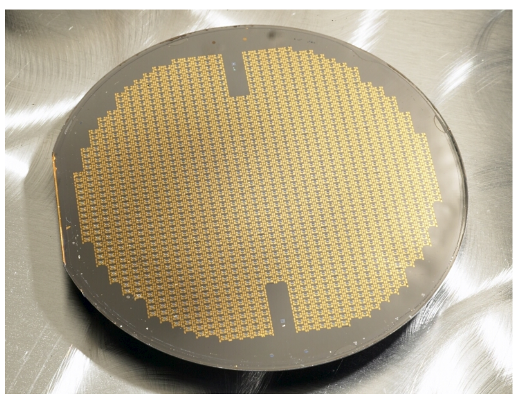

Figure 4. Silicon wafer with several thousand fabricated movable mirrors.

We use FP filters in a novel reflective operating regime. Conventional FP filters with an optical beam incident along the filter optical axis produce a narrow spectral peak in transmission and a spectral notch in reflection. We have discovered that a curved-mirror-cavity multi-spatial-mode FP resonator with its optical axis tilted relative to the incoming optical beam produces a narrow spectral peak both in transmission and retro-reflection [9]. Using asymmetric FP mirror reflectivity, such as the Gires-Tournois configuration, we can achieve retro-reflectivity in the 10 to 70 percent range. Such a filter is ideal for external cavity tunable semiconductor lasers: it is a fast tuning reflective filter that allows compact, e.g. 10-20 mm long, external cavities for ultrafast rate, >100 kHz, laser tuning. Longer cavity lengths in the multi-cm range can be easily achieved by using pigtailed optical fiber as part of the laser cavity, as shown for example in Figure 1, where a mirror coating is put on the fiber outside the laser package. The laser can emit from one to many tens of spectral modes within the tunable filter passband envelope, depending on the filter linewidth and laser cavity length. The laser output can be taken through the filter, with the filter operating simultaneously in transmission and reflection, thus filtering out amplified spontaneous emission (ASE); or through the gain chip, where ASE is unfiltered.

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Using a relatively short, 10 – 30 mm, laser cavity on the optical bench, only a single longitudinal spectral mode of the laser can fit under the filter passband envelope; the RFPTL laser then operates in a single mode regime and tunes discretely by hopping from mode to mode. Spectral measurements, and hence OCT imaging, can be performed by taking data at the discrete optical frequencies accessed by such a discretely tunable laser. Since optical power of the laser varies as it hops modes upon tuning, this power variation can be used for direct clocking of the spectral/OCT data acquisition. Alternatively, an external clocking interferometer can also be used to clock data acquisition. For such mode-hopping lasers, the maximum, at Nyquist condition, imaging depth is one half the laser optical cavity length. Excellent quality images have been demonstrated using such directly clocked mode-hopping RFPTL lasers.

We use a reliable telecom-class micro-optical-bench packaging platform for RFPTL lasers, as shown in Figure 5: Au/Sn hard solder is used for mounting components onto the bench; passive component placement achieves ~5 μm positional accuracy; deformable metal LIGA micro-alignment structures with robotic active alignment further give ~0.1 μm accuracy; finally the device is hermetically sealed in a fiber-pigtailed ~ 25 x 15 mm butterfly package. For system operation, the laser is mounted on an electronic circuit board with DSP processor dynamic control of the filter tuning voltage, laser drive current, and laser bench temperature. Axsun Technologies has been manufacturing tunable lasers based on this technology since 2004. Such lasers with operating wavelengths in the 1 to 2 μm range have been used for a variety of applications, such as industrial process spectroscopy, semiconductor processing metrology, and OCT.

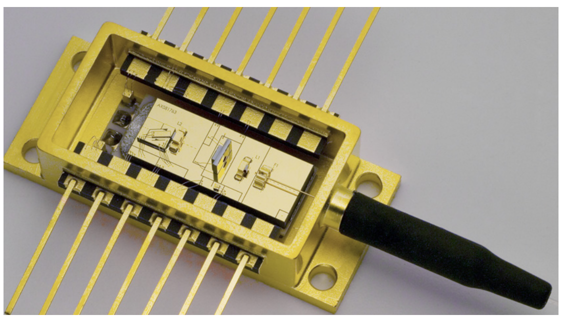

Figure 5. RFPTL laser micro-optical bench in a 14-pin butterfly package.

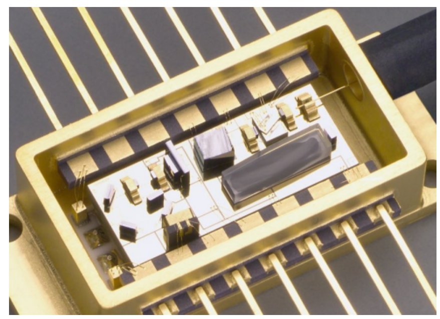

Figure 6. RFPTL laser micro-optical bench with an integrated, co-packaged, clocking etalon and detector.

Our micro-optical packaging platform also allows integration, or co-packaging, of additional functional optical components on the optical bench inside the laser package. Figure 6 shows an example of such integration: here an RFPTL laser is integrated with an optical-frequency-reference clocking etalon and a detector [10]. Output from the laser is taken through the optical fiber at one end of the laser cavity. At the other end of the laser cavity, residual light transmitted through the reflective Fabry-Perot tunable filter is first reflected from a glass etalon and then detected by a detector that produces the electrical signal for triggering and calibrating spectral data acquisition. We have fabricated integrated clock lasers at both 1060 and 1300 nm wavelengths and with scan rates up to 100 kHz.

3. RFPTL LASER PERFORMANCE

The simple RFPTL laser design and short laser cavity allow high laser performance characteristics. We have demonstrated OCT lasers at 1060 and 1300 nm wavelengths; tuning ranges of 100 to 140 nm; scan rates in excess of 100kHz, output powers in excess of 100 mW, and laser coherence lengths of 10 – 100 mm. Figure 7 shows dynamic laser power variation with wavelength tuning over 120 nm range near 1060 nm at 100 kHz scan rate; average power is ~30mW. Figure 8 shows the RFPTL laser point spread function for several values of the measurement interferometer full path length difference, which is twice the imaging depth. For this measurement the laser tunes over 110 nm near 1060nm at 100 kHz scan rate; laser frequency tuning is partially linearized to produce a 60% scan duty cycle; a single detector is used; and the Hann window apodization is used for the Fourier Transform. Point spread function decays in amplitude by a factor of 2, or 6 dB, when interferometer arms full path length difference changes from zero to L_c=13.5mm, which is the laser coherence length. Point spread function resolution here is 12 μm and is independent of length or imaging depth. Using 1060 nm RFPTL lasers in an OCT system with a balanced receiver gives sensitivity value of 100 dB at 4 mW sample illumination power; this value is within 7dB of the shot noise limit.

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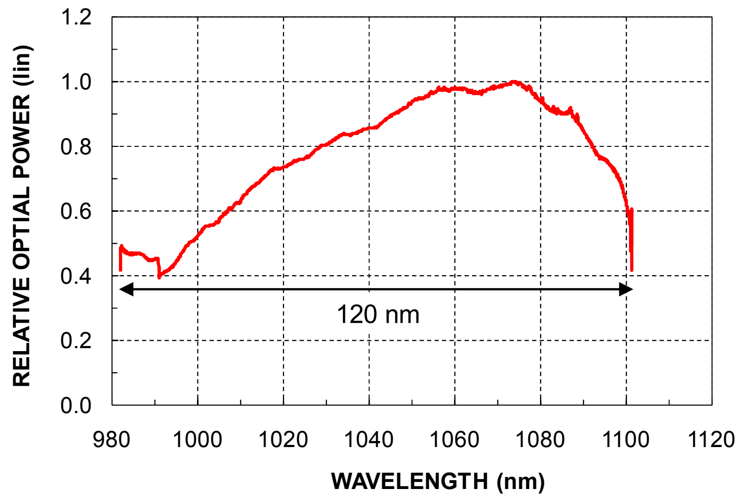

Figure 7. RFPTL dynamic laser power variation on tuning: 120 nm tuning range at 100 kHz scan rate.

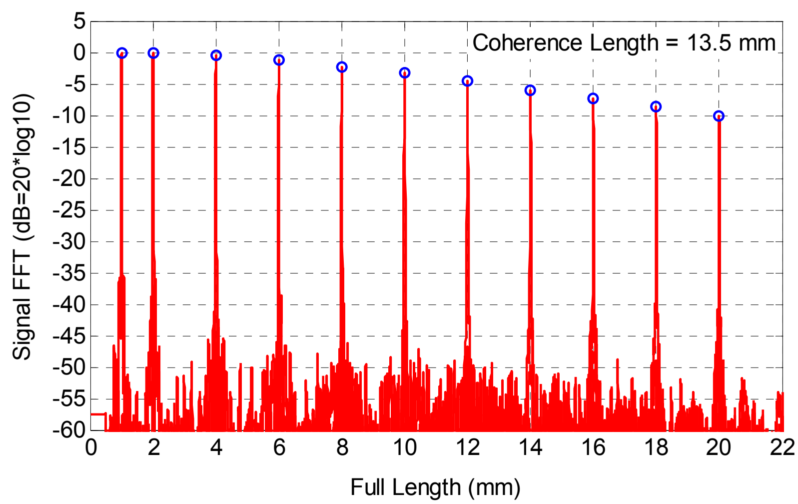

Figure 8. RFPTL laser coherence length measurement: laser point spread function, FFT of interferometer fringe amplitude, decays with increasing interferometer arms full path length difference. Here the coherence length is 13.5 mm for a tuning range of 110 nm near 1060 nm at 100 kHz scan rate.

4. OCT IMAGING WITH RFPTL LASERS

We have performed imaging experiments with RFPTL lasers at 1060 and 1300 nm, obtaining excellent quality images at scan rates up to 100 kHz. Imaging resolutions of 8.3 µm and 15 µm in air with Hann window apodization were demonstrated at 1060 and 1300 nm, respectively. Some OCT images obtained with RFPTL lasers are shown in Figures 9 – 15. Figure 9 shows an OCT image of a house fly measured at 1300 nm. Figure 10 shows an image of the finger skin at 1300 nm. Figures 11 and 12 show images of a tooth measured at 1300 nm: the first is a 3D OCT image of the tooth, and the second is a cross sectional OCT image. Figures 13 – 15 show OCT images of the anterior segment of the eye at 1300nm obtained using RFPTL laser at the Nicolaus Copernicus University, Torun, Poland. In particular, Figures 14 and 15 show an eye of a patient after corneal transplantation, penetrating keratoplasty, treatment. Scars at the junction between host and donor cornea are visible in Figure 15, and shadows from the stitches in the cornea are visible on the iris in Figure 14.

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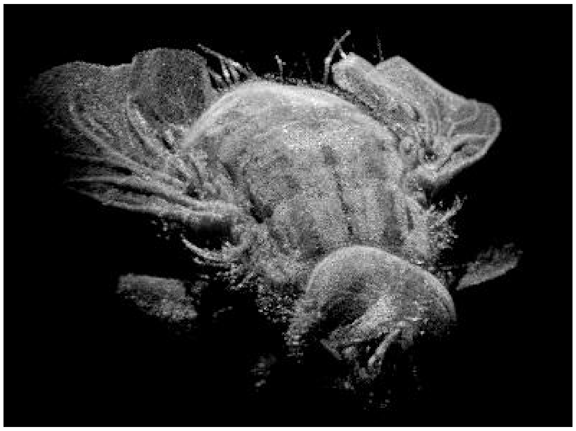

Figure 9. OCT image of a house fly.

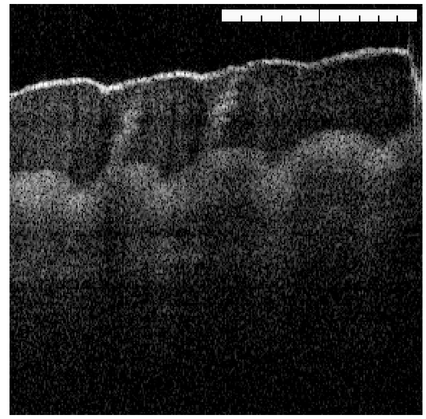

Figure 10. OCT image of back of finger with sweat glands; courtesy of Michelson Diagnostics Ltd

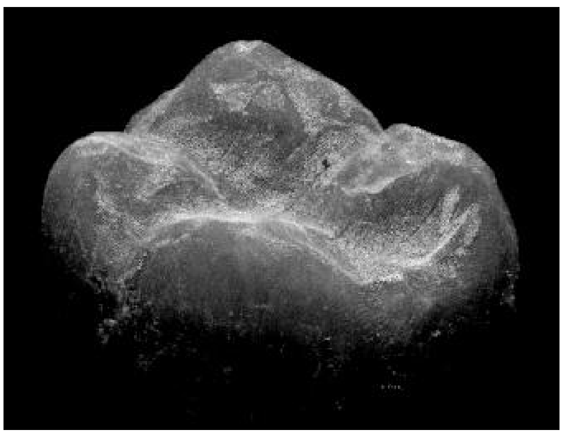

Figure 11. OCT image of a tooth.

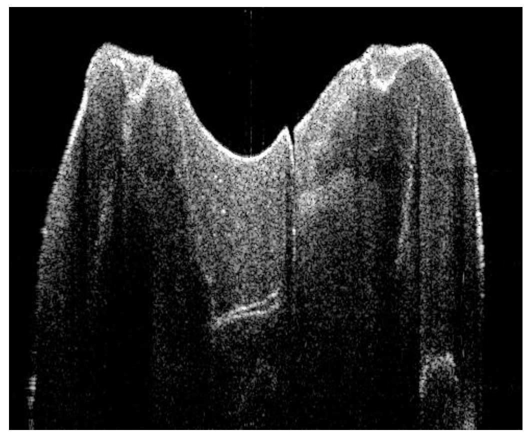

Figure 12. OCT image cross section of a tooth.

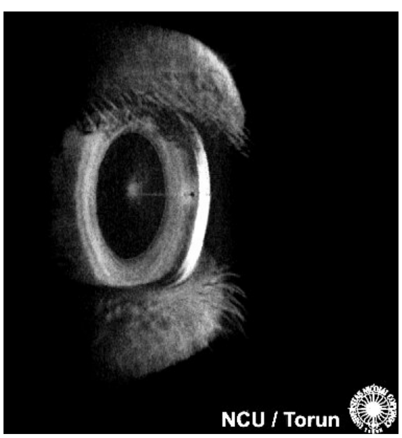

Figure 13. OCT image of an eye; courtesy of Nicolaus Copernicus University, Torun, Poland.

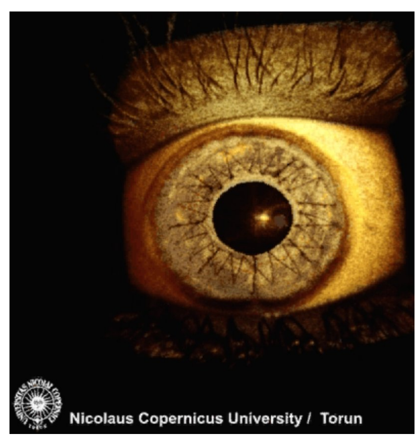

Figure 14. OCT image of an eye after corneal transplantation; courtesy of Nicolaus Copernicus University, Torun, Poland.

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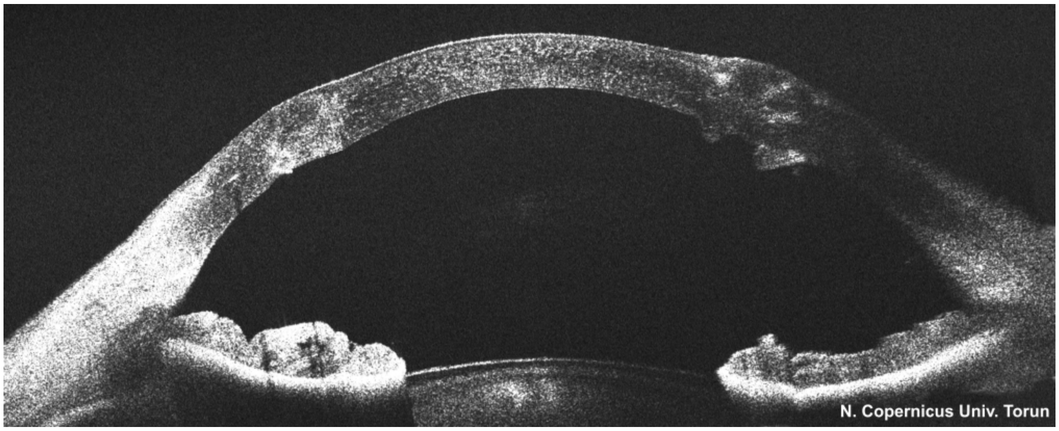

Figure 15. OCT image of anterior eye chamber after corneal transplantation; courtesy of Nicolaus Copernicus University, Torun, Poland.

In conclusion, we have described novel compact, ultrafast scanning, semiconductor tunable lasers with high performance characteristics for swept source optical coherence tomography. We have also illustrated OCT imaging capability of these lasers in several applications. These highly manufacturable lasers are finding broad use as sources for OCT imaging in medical and other applications.

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