Practical Short Cavity Fabry-Perot Fiber Ring Lasers for OCT Systems

TODD C HABER
Chief Technical Officer

Micron Optics, Inc
Atlanta, GA
tchaber@micronoptics.com

Abstract

A new generation high reliability, all-fiber, short cavity, and high performance swept wavelength laser sources designed for Optical Coherence Tomography (OCT) applications is discussed. These simple short cavity Fabry-Perot (SCFP) ring lasers offer a highly functional and attractive combination of fast 100kHz scan rates, high output power powers, and polarization stable, wide wavelength range lasing at 1060, 1310, and 1550 nm. Supporting tissue imaging depths of 6 – 10 mm, resulting scans are free from the types of sweep rate harmonic and spectral sideband distortions that are common among other high speed swept sources and known to adversely affect high quality OCT images.

An overview and comparative analysis of available commercial sources is presented, as well as visibility into the commercialization path for this new generation of OCT swept wavelength laser source.

I. INTRODUCTION

Since the first introductions of the greatly enhanced SNR afforded by swept source optical coherence tomography (SS-OCT) in 2003, numerous optical technologies have vied for a prominent place in the academic development and commercial deployment of the technology [1]. Over the years following, great strides have been made in improving key operating parameters such as laser line width, output power, sweep speed, sweep range, and sweep rate linearity.

Today, there are multiple swept source products on the market that offer researchers and commercial system integrators several options representing varying price and performance tradeoffs. This paper will endeavor to offer an overview of those technology choices and introduce a new option available to the marketplace in that context.

II. BACKGROUND

The first practical implementations of swept source OCT were realized using a high performance, rapidly tuned swept laser based upon scanning polygon technology [2]. Combining mature Semiconductor Optical Amplifier (SOA) gain chip technology from the telecommunications industry with a novel highly linear and repeatable mechanical cavity tuning mechanism, these scanning polygon laser set the stage, if not the bar, for all other aspiring technologies.

In the years that followed, great efforts have been made in the development of economically viable and technologically enabling optical sources for use in swept source OCT. As the utility and sophistication of the measurement technique advanced, so did the field of lasers and other swept sources made available for deployment in those systems. The following two sections will highlight some of the early successes of Fabry-Perot based short cavity lasers, and give context for their current "re-introduction" into the market place.

III. FFP-TF History in OCT

Fiber Fabry-Perot tunable filters (FFP-TFs) have long been key enabling devices in the research and development of swept wavelength sources for OCT. Early short cavity prototypes using tunable filters from Micron Optics and LambdaQuest demonstrated scan rate, wavelength range, and coherence length design flexibility that is inherent in the technology and have been of of great use in the development of several key seminal SS-OCT programs [3, 4, 5]. Many swept source laser prototypes were developed by Micron Optics in cooperation with many of the leading research and development centers around the world in the years spanning 2004 – 2009.

Results of once such cooperative effort are seen as the 3D reconstruction of pig retina tissue in Figure 1 below, as imaged by a 2kHz 1060nm short cavity Fabry-Perot ring laser based upon a Micron Optics FFP-TF.

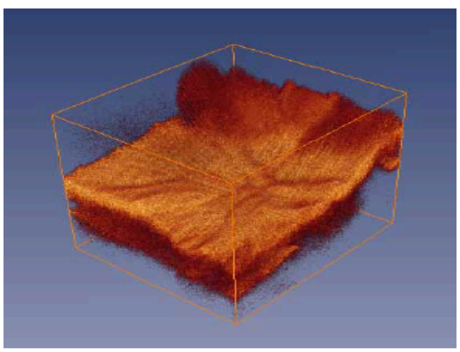

Figure 1. Pig Retina as imaged by 1 μm SCFP laser.

Reproduced from Applied Physics Lett. **89**, p.073901-1 (2006).
J. Zhang, Q. Wang, B. Rao, Z. Chen, and K. Hsu.

In addition to SCFP ring laser architectures, FFP-TFs have also been deployed in much higher speed configurations, taking advantage of simultaneous resonances of both TF actuator and ring cavities, in a technique know as Fourier Domain Mode Locking (FDML). In FDML lasers, the round trip time for circulating photons is intentionally delayed by the addition of long lengths of intra-cavity fiber to match the sweep rate of the tunable filter, as seen in Figure 2. This adaptation effectively allows the laser to support all desired lasing frequencies simultaneously within the ring cavity. This technique enabled the development and use of much higher frequency swept wavelength lasers than the limited 2 – 10 kHz speed SCFP ring lasers before them.

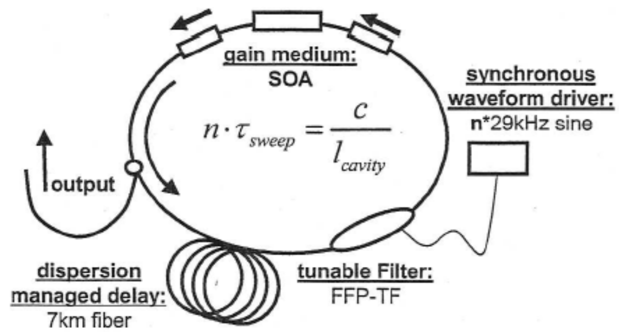

Figure 2. Simple FDML ring architecture employing an FFP-TF

Courtesy of the European Conference on Bio-Medical Optics, PDA3, (2005). R. Huber, K. Taira, M. Wojtkowski, and J. G. Fujimoto.

As with the SCFP ring lasers, FFP-TF technology supports implementations of FDML at both 1.0 and 1.3 μm ranges. Figure 4 shows a sample 3D reconstruction of a human finger imaged by a Micron Optics FFP-TF based FDML ring laser at 232kHz sweep rate.

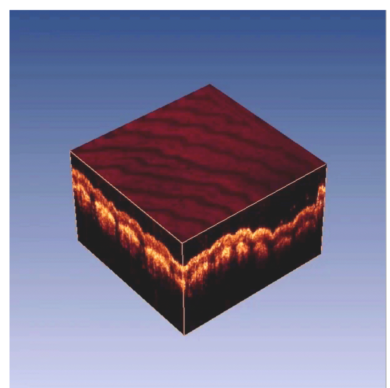

Figure 3. Human Finger imaged at 232,000 scans/second with FFP-TF based FDML laser.

Reproduced from Optics Express, **13**, p.3513 (2005).
R. Huber, M. Wojtkowski, K. Taira, J. G. Fujimoto, and K. Hsu

Although the speeds, imaging depths, and image resolution performance of FDML lasers are indeed impressive, the complexity of maintaining optimal synchronization of two simultaneously resonant systems (as well as the need to mitigate extraneous noise issues that present at true resonance) have thus far precluded wide spread use of the technology outside of less cost-sensitive research and development applications.

IV. THE SOURCE FIELD ADVANCES

The years 2009 through 2015 saw accelerated investment into and advances of several exciting technology platforms, all eager to become the principal supplier of SL sources for the growing number of commercial OCT companies reaching towards the market. In fact, some of the perceived successes of these efforts were enough to overshadow (at least for a time) any additional significant advances in SCFP technology.

Far and away, the most visible activity in the OCT swept source space took place in the integrated optics/MEMS area. Several key vendors with rich experience in developing gain media solutions and/or tunable MEMS elements invested heavily into integrating both into their product packages, and the OCT world responded enthusiastically in the form of development partnerships, supply agreements, and acquisitions.

As with many technologies, though, the MEMS-based laser architecture has not been without tradeoffs. Perhaps the greatest and most material disadvantage related to these otherwise seemingly ideal sources is the presence of artifacts in the scan that perform in ways that are averse to high quality imaging, specifically a line at twice the base oscillator rate that advances twice as fast, as well as sidebands in the resulting point spread function (PSF), each issue causing echoes or shadow effects in the images of biological tissues with epithelial surfaces. While these types of artifacts can be ignored in academic or research settings, they are certainly not conducive to a clinical use environment or use by physicians.

MEMS based OCT lasers have been the most broadly promoted and evaluated technology. However, due to the artifact issues outlined above, as well as some field reliability issues, the technology has not been universally recognized as a suitable long term supply solution.

Equally exciting to watch has been the development story surrounding "programmable" semiconductor lasers, based upon tunable DBR architectures. These sources report as supporting 400kHz, >100 mm coherence length, and highly linearized sweep outputs over a 1.0, 1.3, and 1.5 μm wavelength regions. However, to date, and for reasons not entirely clear from marketing materials, this technology has yet to gain a foothold in the commercial space as a reliable and economically viable solution for OCT imaging sources.

Yet a third area of investment and excitement is that of the vertical cavity surface emitting laser (VSCEL). Tunable VCSEL technology has made incredible strides over the last several years, particularly at 1.0μm wavelengths and is helping to drive advances in deep retinal scanning application beyond where traditional 800 nm systems can penetrate. Even so, VCSELs have yet to gain commercial traction, especially at 1.3μm wavelengths where most commercial medical systems activity is taking place.

Thus far, the most technically and economically successful in technology the field of commercial OCT systems has been that of the "original" high speed swept wavelength laser in the form of the scanning polygon swept wavelength laser. These lasers are known in the field to work exceptionally well, offering product solutions of sufficient power, coherence length, and sweep rate linearity to support the development and deployment of several key industry leading commercial OCT systems. Unlike MEMS based swept wavelength lasers, scanning polygon lasers have been demonstrated to image tissues with clean scans and PSFs, resulting in high quality, echo free images. In fact, due to availability, price, and performance, scanning polygon lasers have proven to be the ideal sources for first generation medical OCT systems.

Now what about 2nd generation systems?

Despite all of these strengths, the limits of scanning polygon technology is currently being challenged by the advancements of their users. Now that many pioneering medical SS-OCT firms have secured real application and market successes, the time has come to look towards second generation systems with requirements for higher speed, lower cost, and enhanced mechanical reliability. At the core of each scanning polygon laser is a high speed spinning

mechanical disk, and it is broadly expected that over time and in volume, this moving part will result in undesirable reliability and/or lifetime issues.
If another technology were able to match the scanning polygon in terms of wavelength range, output power, and coherence length while offering advantages in speed, cost, and reliability, it would be well positioned to help propel the industry (at least from the optical source side) to manufacturable maturity.

V. The Return of SCFP Lasers

In part due to the successes realized by scanning polygon, and in equal part due to the intermittent performance and image artifact issues of MEMS technology, short cavity Fabry-Perot cavity ring lasers are getting a hard second look.

Perhaps the most impactful event in this trend has been a 2014 publication by Jun, et al, from the Wellman Center for Photomedicine, a medical photonics research cooperative between Harvard Medical School and Massachusetts General Hospital [6].

In this work, Jun and his team present a simplified architecture for fiber ring laser, optimizing cavity length, SOA gain, and intra-cavity isolation such that high power, high speed, and wide wavelength range lasing is supported with a manufacturable set of commercially available optical components. The configuration is shown in Figure 4.

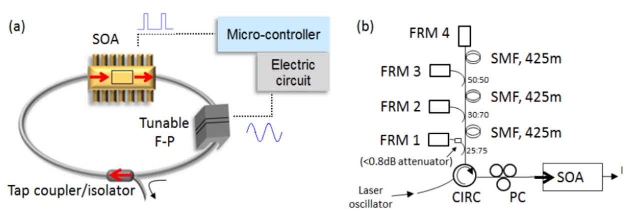

Figure 4. Simplified SCFP ring laser architecture and buffer-multiplier network

Reproduced from Optics Express, **22**, p.25807 (2014).
C. Jun, M. Villiger, W.l Oh, and B. Bouma

By first optimizing lasing parameters to match the fundamental resonance mode of the TF piezoelectric actuator, then utilizing a network of subsequent buffer stages to multiply the repetition rate of the laser, current market requirements for 100 – 200kHz scan rates can be achieved with 150nm range and over 90 mW of output power, as shown in the same spectral trace of Figure 5 below.

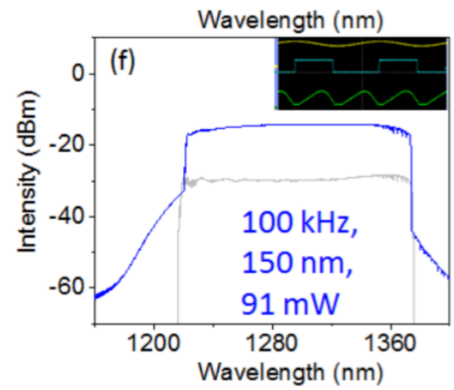

Figure 5. Spectral characterization of SCFP ring laser

Reproduced courtesy of the Wellman Center for Photomedicine.
C. Jun.

VI. Results and Effects

In addition to meeting application requirements for sweep rate, power, sweep range and coherence length, this new incarnation of SCFP ring laser addresses the three current shortcomings of competitive technologies.

First, as the laser tuning mechanism is based upon field proven piezoelectric actuators and not macro-scale mechanical motion, scanning polygon concerns about durability do not carry forward to this design. With an MTBF of > 3000 years at specified operating conditions, piezo actuators of this design have been built into 1000's of Micron Optics lasers over the past 10 years, representing over 100 million hours of field reliable operation.

Second, the scan purity of the SCFP ring laser design has been demonstrated and confirmed over multiple systems to generate high quality OCT images, free from the types of sweep rate harmonic and spectral sideband distortions that are perpetually evident in MEMS swept laser products. Figure 6 below shows such an image taken by the Wellman Center system.

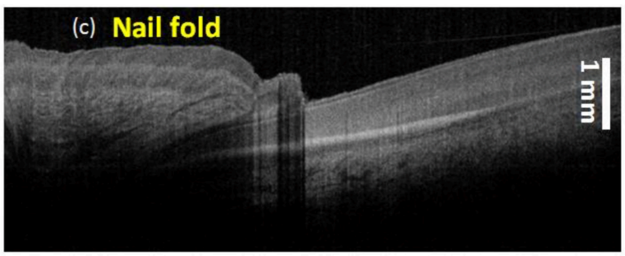

Figure 6. Artifact-free OCT image taken with 100kHz SCFP laser.

Reproduced from Optics Express, **22**, p.25815 (2014).
C. Jun, M. Villiger, W.l Oh, and B. Bouma.

The third barrier to broad market adoption for all prior offerings has been price. Though suitable for first generation systems, the mechanical tolerances and manufacturing requirements associated with scanning polygon lasers may ultimately preclude them from inclusion of future, cost reduced versions commercial OCT systems. While price points of MEMS lasers have not been outwardly prohibitive, there is also broad concern in the market regarding the sustainability of the price points as volume requirements increase and yield/manufacturing consistency challenges multiply.

In contrast, the SCFP ring laser is comprised of commercially available, OTS parts which are all already deployed commercially, in volume, together in fiber ring laser architectures that have been serving the telecom and optical sensing markets over the last 10 – 15 years. There is both a clear commercialization path and proven cost/yield framework surrounding lasers of very similar designs, thereby greatly reducing both technical and commercial risks as they pertain to market pricing.

In terms of pricing, this architecture will come to market with all of the aforementioned strengths at a price point at least 25% below current market pricing for the largely incumbent scanning polygon lasers.

Figure 7 below graphically represents how this new generation of SCFP ring lasers (denoted as "this work") compares to earlier scanning polygon, MEMS, VCSEL, and FDML technologies.

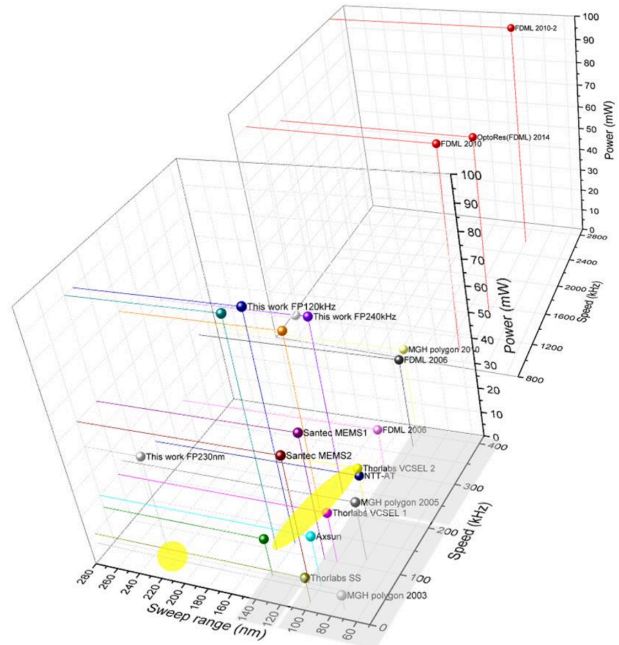

Figure 7. Performance map of swept wavelength lasers

Reproduced courtesy of the Wellman Center for Photomedicine.
C. Jun.

This new generation of SCFP ring laser does in fact offer a combination of output power, sweep rate, sweep range, coherence length, sweep frequency purity, and manufacturing cost/market price that together position such a product well for inclusion in next generation structural OCT imaging systems.

VII. Product Development

Micron Optics is today the recognized leader in high-speed swept wavelength laser manufacturing world wide, having built, sold, and distributed thousands of lasers into the optical sensing space over the past 10 years.

It is on this base of manufacturing experience and record proven reliability that Micron Optics endeavors to help propel the field of OCT swept wavelength lasers into a new phase of reliable, cost effective, and requirements compliant supply.

As of today, work is underway to bring this technology to market in the form of the Micron Optics slm388 swept laser module, the next offering in the SOLARITY line of high speed swept wavelength laser sources.

Figure 8. slm388 1310nm swept wavelength laser module from Micron Optics, Inc.

Alpha prototypes/evaluation kits can be made available through special arrangements.

Beta prototypes of the slm388 will be available for sale and customer evaluation in Q3 of 2016, and will represent the GA products' final fit, form, and function. Final product certification and GA release is schedules for Q1 of 2017.

Please contact sriggi@micronoptics for details.

VIII. References

[1] 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).

[2] 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)

[3] 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)

[4] J. Zhang, Q. Wang, B. Rao, Z. Chen, and K. Hsu, "Swept laser source at 1 μm for Fourier domain optical coherence tomography," Applied Physics Lett. **89**, p.073901-1 (2006).

[5] R. Huber, M. Wojtkowski, K. Taira, J. G. Fujimoto, and K. Hsu "Amplified, frequency swept lasers for OCT imaging: design and scaling principles," Optics Express, **13**, p.3513 (2005)

[6] C. Jun, M. Villiger, W.l Oh, and B. Bouma. "All-fiber wavelength swept ring laser based on Fabry-Perot filter for optical frequency domain imaging," Reproduced from Optics Express, **22**, p.25815 (2014).