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Tailoring Wavelength Sweep for SS-OCT with a Programmable Picosecond Laser

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ABSTRACT

This paper presents a unique and novel picosecond laser source that offers complete tailoring of the wavelength sweep and that benefits swept-source optical coherence tomography (SS-OCT) applications. Along with the advantages of a fiber-based architecture, the source is a fully programmable, electronically controlled actively mode-locked laser capable of rapidly tuning the wavelength and pulse characteristics. Furthermore, several sweep modes and configurations are available which can be defined by range, with linear sweeps in wavelength or *k*-space, or by arbitrary wavelengths. The source design is discussed and its use in SS-OCT with a prototype using a semiconductor optical amplifier as a gain medium is illustrated.

Keywords: Optical Coherence Tomography, Swept Sources, Tunable Lasers, Fiber lasers, Programmable Lasers

1. INTRODUCTION

This paper presents a new source for swept-source optical coherence tomography (SS-OCT). The laser source is based on a dispersion-tuned actively mode-locked fiber-based laser. It possesses two unique features: a chirped fiber Bragg grating (CFBG) that provides the dispersion and advanced high-speed electronics that offer programmability of all the source's parameters. The CFBG provides the basis for fast sweep rates and large imaging depths in SS-OCT. The programmability allows the user to tailor the wavelength sweep at will. In particular, one can perform a true linear *k*-space sweep at a selected sweep rate.

Section 2 provides more details about these unique features. Section 3 illustrates the source at work, presenting point-spread functions and OCT images obtained with a prototype using a semiconductor optical amplifier (SOA) as a gain medium.

2. PROGRAMMABLE LASER SOURCE

The programmable laser source is based on a dispersion-tuned actively mode-locked fiber laser. The basic operating principle of such a laser has been well described in previous papers from Genia Photonics and other groups [1-3]. Figure 1 illustrates the layout of the programmable laser source. The gain medium is a semiconductor optical amplifier (SOA), although a doped fiber could also be used. The cavity is dispersive and generates different round-trip times for each wavelength within the cavity. The repetition rate of the laser is defined by the actively mode-locker, which is an electro-optic modulator (EOM) in our source design. Thus, the wavelength can be tuned by electronically changing the frequency or repetition rate of the signal driving the EOM. Our laser source presents two unique features: a chirped fiber Bragg grating (CFBG) that provides the dispersion and specialized electronics that ensures the full programmability and operation of the source.

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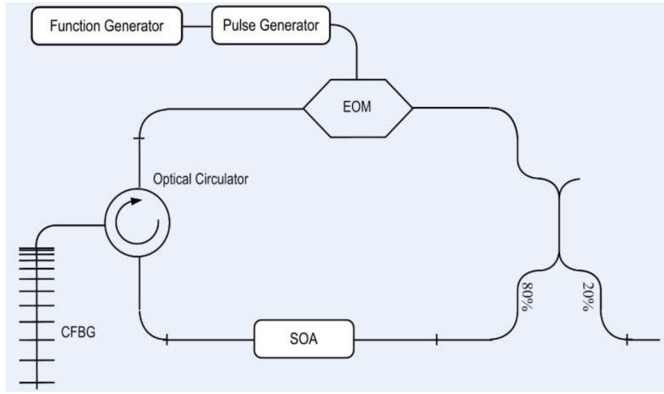

Figure 1. Layout of the programmable laser source. The CFBG provides the high dispersion necessary for long coherence lengths while maintaining a short cavity length for rapid sweeping.

A CFBG is a very efficient method to induce dispersion within the cavity: it can provide high dispersion over a short length. The high dispersion allows a fine linewidth, thus high coherence, which translates to a large imaging depth in SS-OCT. The short cavity allows fast tuning, an essential element for achieving fast sweeping rates in SS-OCT. For comparison, 14 cm of CFBG with a dispersion of -10 ps/nm replaces 100 m of dispersion compensating fiber. This comparison illustrates the great advantage of a CFBG-based design.

Specialized electronics is the key element to the enhanced programmability of the laser source. This programmability is best illustrated by a quick overview of the user interface. Figure 2 presents the main panel. On the left side of the panel, one can adjust the power, the delay value (to be discussed further below), and the wavelength in a fixed-wavelength non-sweeping operation mode. On the right side of the panel, the selected sweep mode is displayed. Many sweep modes are available, including a custom sweep mode where one can select the number of wavelengths, the wavelength sequence, and the number of pulses to deliver for each wavelength in the sweep. SS-OCT is better performed with a linear in *k*-space (wavenumber space) sweep mode. Figure 2 presents the panel "Equal pulse count in optical frequency" which corresponds to the linear in *k*-space sweep mode. The sweep can be fully customized by adjusting many parameters: the initial and final wavelengths, the number of wavelengths, and the number of pulses per wavelength. One can also select a

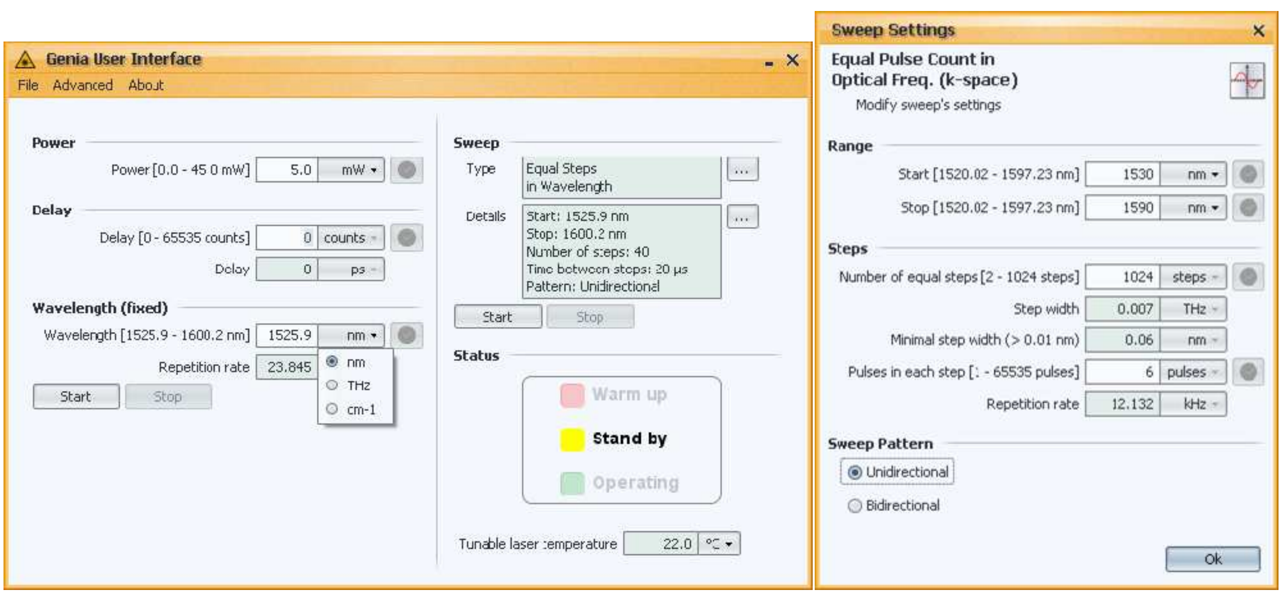

Figure 2. Main panel (left) of the user interface along with the "Sweep Settings" panel (right) for the linear in *k*-

directional or bidirectional sweep.

Since the programmable laser source can operate in variable sweep modes, multiple trigger signals are provided to allow precise signal digitization and efficient data processing for SS-OCT. These trigger signals are made available through the back panel as illustrated in Figure 3. Figure 4 presents a diagram of the trigger sequence. One trigger signal is provided at the beginning of the sweep cycle, another one being provided at the beginning of each subsequent sweeps. To allow triggered digitization, one trigger signal is given for each pulse. Using a fast photodetector, the pulses can be well resolved, thus the exact timing of the digitization is of utmost importance. Consequently, a delayed trigger signal per pulse is also given. This is the delay value that was previously presented as adjustable on the main panel of Figure 2. Finally, a trigger signal for each wavelength change is also provided, so the wavelength sweep can be precisely monitored. Figure 4 shows relationships between the different trigger signals. The five triggers thus allow the user to keep track of all the properties of the optical sweep in real time.

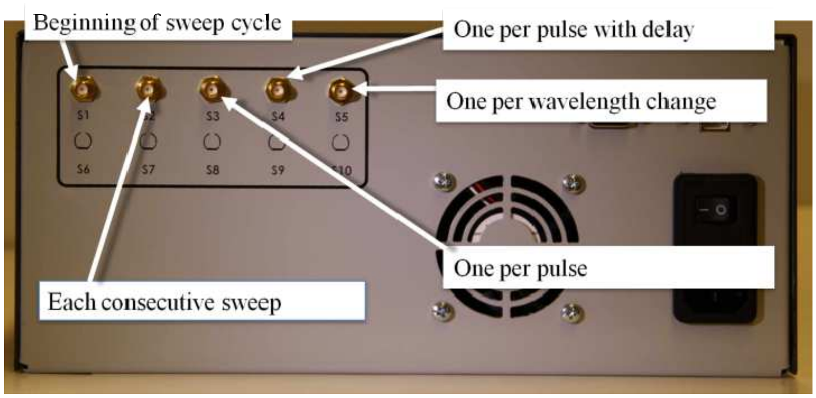

Figure 3. Trigger signals available through the back panel of the source. All the optical properties of the optical sweeps are represented in the trigger signals.

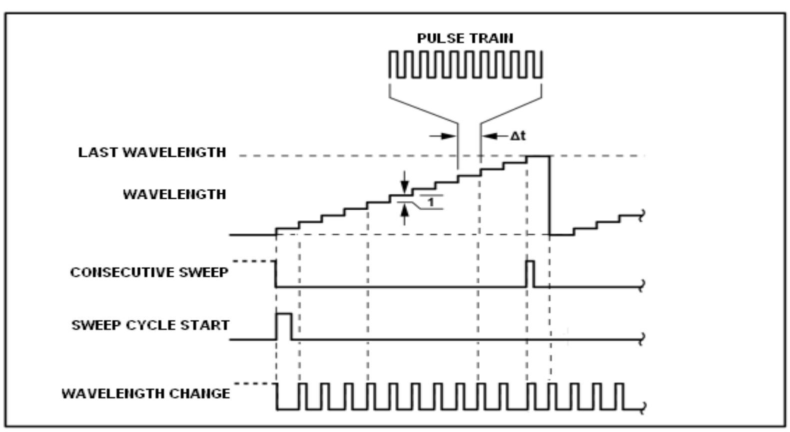

Figure 4 Sequence of trigger signals provided by the source.

3. SOA PROTOTYPE

A prototype has been assembled using the layout shown in Figure 1. The laser has -10 ps/nm of anomalous dispersion coming from a CFBG. The modulator is driven by a 100 ps pulser with a fundamental repetition rate of approximately 25 MHz. For our experiments, the laser was run at the third harmonic, 75 MHz, in order to reduce the ASE in the SOA gain medium. The laser tuning range and spectra are shown in Figure 5. The OSNR of the laser varies between 20 and 40 dB across the wavelength tuning range due to the almost Gaussian gain shape of the SOA and noise variation upon the wavelengths. The 3 dB tuning range is about 20 nm but the laser emits light over a 75 nm range. The 3 dB sweeping range is slightly larger, about 30 nm.

The programmable source was integrated in a custom-built SS-OCT system. The SS-OCT system was built around a Mach-Zehnder configuration and included a balanced detector. An Alazar Tech ATS-9462 waveform digitizer card insured the triggered digitization. Figure 6 presents point-spread functions (PSF) measured with a reflector located at various depths from the zero-delay position. All curves were obtained with a linear in *k*-space sweep composed of 1024 wavelengths between 1530 nm and 1590 nm. Thanks to the linear in *k*-space sweep, a simple fast Fourier transform provided the PSFs, no resampling was performed. Avoiding resampling not only simplifies the data processing, but also avoids the introduction of unwanted artifacts [4]. Figure 6 presents three sets of results representing a different number of pulses for each wavelength. The graphic titles provide the approximate sweep rate, obtained by dividing the pulse repetition rate (75 MHz) by the product of the number of wavelengths (1024) and the number of pulses per wavelength (3,12, or 96).

The prototype was operated with a non-optimized SOA when these measurements were performed. This SOA had only 65 nm bandwidth and a narrow gain bandwidth, giving only 20-30 nm of swept optical bandwidth, which impacts the quality of the results. Nevertheless, the measured PSFs demonstrate that the source will provide good SS-OCT imaging, even if operated with a non-optimized SOA. At a sweep rate of 6 kHz, each pulse completes 4 roundtrips in the cavity between wavelength changes. The resulting PSFs are well shaped. Similar PSFs are obtained at a sweep rate of 25 kHz, where each pulse completes a single roundtrip between wavelength changes. At a sweep rate of 0.8 kHz, each pulse completes 32 roundtrips between wavelength changes. This ensures a narrower linewidth, thus a larger coherence, which results in a larger amplitude of the PSFs at larger depths.

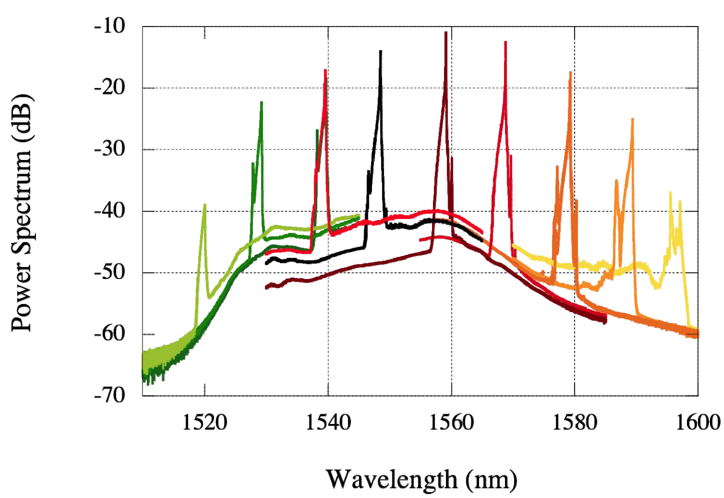

Figure 5. Tuning range of the prototype SOA in the programmable laser. The laser tunes over 75 nm.

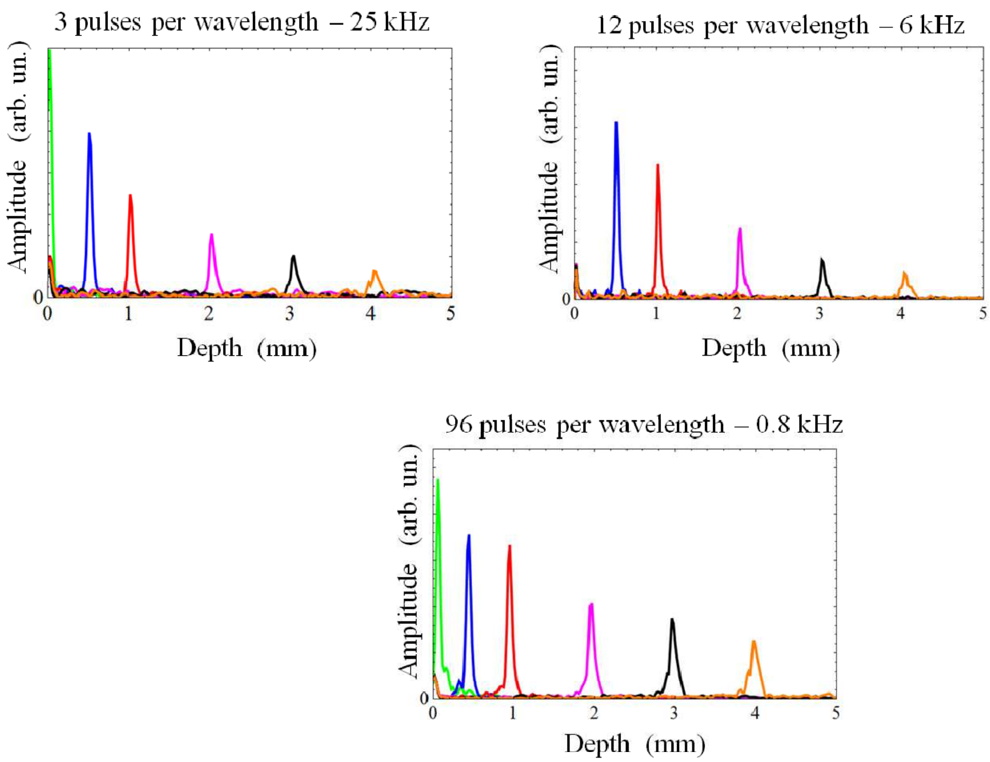

Figure 6. Point-spread functions in linear scale obtained with a reflector located at various depths relative to the zero-delay position. All curves were obtained with a sweep over 1024 wavelengths. The title of each figure indicates the number of pulses per wavelength and the resulting sweep rate.

Figure 7 presents OCT images recorded with the custom-built SS-OCT system using the programmable source. Again, the programmable source operated with a non-optimized SOA. Figure 7a) shows the OCT image of a glass slide tilted over another glass slide suspended in air. OCT imaging was performed with a sweep rate of 6 kHz with a linear in *k*-space sweep. Figure 7c) presents a photograph of the sample where the lower glass slide is lying on a table instead of being suspended in air. The OCT image provides a very clear image of the glass surfaces. Figure 7b) shows the OCT image recorded from the top of a tubular silicon structure with internal ridges. It was acquired with 3 kHz sweep rate. Figure 7d) provides a photograph of the structure. In the OCT image of Figure 7b), not only is the shape of the structure well defined, the internal scattering structure is also revealed.

Next step regarding the source is to use an optimized SOA inside the laser cavity and further characterize it through OCT. We show in Figure 8 a glimpse of the preliminary results using a better yet still not optimal SOA in the laser cavity. This SOA yields an 80 nm 3dB bandwidth at sweeping rate up to 50 kHz, or 50 Mλ/s.

4. CONCLUSION

We have presented a new source for SS-OCT. The programmable laser source is based on dispersion-tuning active mode locking. It possesses two very unique features. First, the dispersion is provided by a CFBG, which is a key element for faster tuning and for a good imaging depth. Second, the laser source is programmable, allowing the user to customize the sweep at will, especially for a linear in *k*-space sweep where all parameters can be selected offering faster data processing. A proof of concept of the source has been provided by measurements performed with a prototype using a SOA as a gain medium. Even if obtained with a non-optimized SOA, OCT images showed that the source is performing well for SS-OCT imaging. Better performance is still expected with the introduction of an optimized SOA: better signal-to-noise ratio, better imaging depth, and better OCT resolution. Much higher sweep rates than those presented are

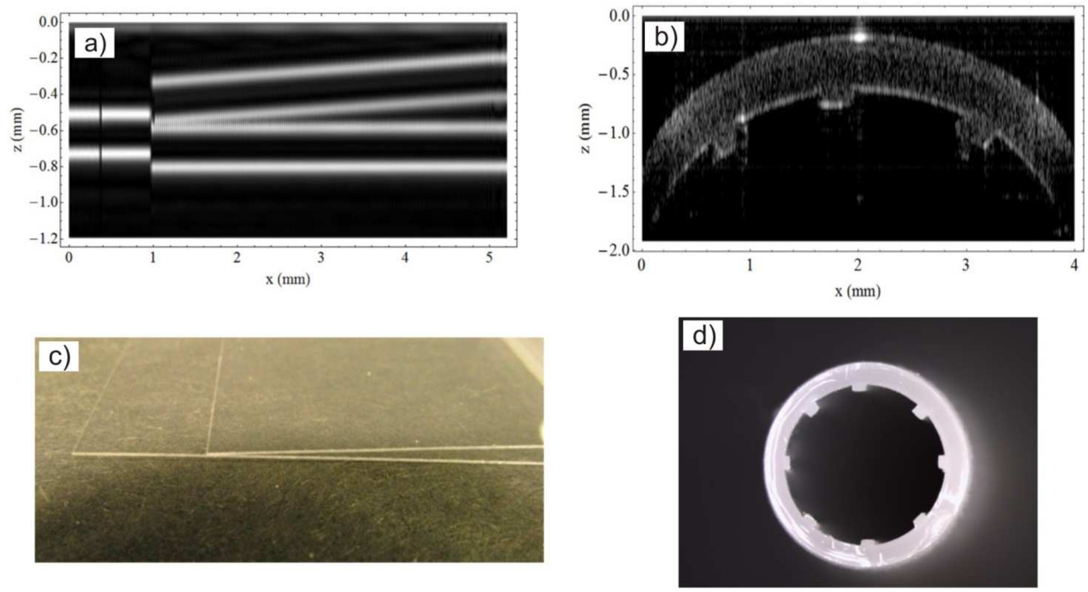

Figure 7. a) OCT image of a tilted glass slide over another glass slide and b) OCT image of a tubular silicon structure with ridges on the inside. Photos of the samples are provided in c) and d). Glass slides in the OCT image a) were suspended in air and not lying on a table as in c).

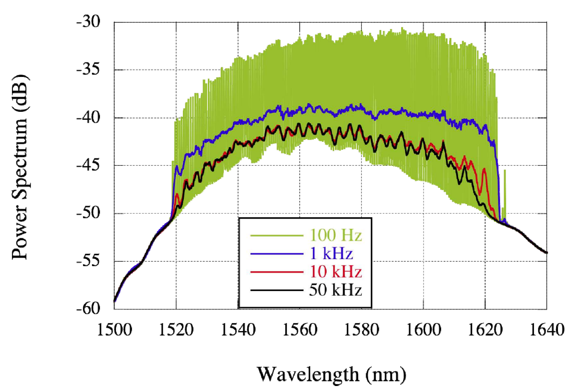

Figure 8. Wavelength sweeps of a programmable laser with a SOA that is more optimized. The 3dB bandwidth of the sweeps is 80 nm at rate going up to 50 kHz. Note that at 100 Hz the lines actually show pulse spectra.

currently being developed, by shortening the laser cavity and by operating the programmable laser source in higher harmonics.

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