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High-speed and wide bandwidth Fourier domain mode-locked wavelength swept laser with multiple SOAs

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Abstract: We report on the development of a high-speed, wide bandwidth Fourier domain mode-locked (FDML) wavelength swept laser of around 1300 nm using two gain media for high-resolution and high-speed Fourier domain optical coherence tomography. The wavelength swept laser is capable of FWHM scanning range of more than 135 nm at 45.6 kHz sweeping rate. The measured axial resolution of the forward scan is 6.6 μm in air and 4.7 μm in tissue. The peak power is 11.4 mW for both the forward and backward scans. The measured system sensitivity is achieved up to 100.7 dB. We also demonstrate OCT imaging using the FDML wavelength swept laser with two semiconductor optical amplifiers.

OCIS codes: (140.3600) Lasers, tunable; (140.3510) lasers, fiber; (120.3180) Interferometry; (110.4500) Optical coherence tomography

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1. Introduction

Optical coherence tomography (OCT) is an emerging technology for biomedical imaging [1]. Recent development of Fourier domain OCT has significantly increased the imaging speed and sensitivity [2]. Two methods have been developed to employ the Fourier domain techniques: a spectrometer based system that uses a high speed line scan camera [3,4], or a swept laser source based system that uses a fast wavelength scanning laser [5,6]. Although a high speed imaging line scan camera is readily available at 800 nm, the large array line scan camera at 1.3 μm has to be custom made, which makes the swept light source based system a better choice at 1.3 μm. In addition, swept source OCT (SSOCT) has the advantage of a simple system design since no spectrometer is required. Furthermore, narrow spectral line width can be achieved without crosstalk, which results in a larger imaging range.

A key component in high-resolution OCT imaging is an optical source with a broad bandwidth because the axial resolution is inversely proportional to the bandwidth of the light source. Although a number of broadband optical light sources have been developed to improve resolution in time domain and spectrometer based Fourier domain OCT, few broadband high-speed swept light sources have been reported [2,7,8].

The speed of the conventional swept light source is limited by both the tuning speed of the filter and laser cavity lifetime. Recently, R. Huber et al. [9] demonstrated a high-speed wavelength swept laser called a Fourier domain mode-locked (FDML) laser in order to increase the sweeping speed of the swept laser. This FDML laser is not limited by the laser lifetime because a long dispersion delay line fiber is inserted into the laser cavity, and one or more wavelength sweeps are stored in the laser cavity [9,10]. The FDML laser provides a sweeping rate of up to 370 kHz [10]. The FDML based swept source has the advantage of high-speed, narrow linewidth, and high phase stability [11,12]. However, the current reported FDML swept source has limited bandwidth (< 100 nm at FWHM bandwidths), which corresponds to an axial resolution of 10 μm in air [9]. More recently, three-dimensional endomicroscopy using FDML laser has been reported. The reported FDML use a single SOA with a full tuning range of 160 nm and FWHM bandwidth of less than 100 nm, corresponding to an of axial resolution of 7.1 μm. [13] In this paper, we design a FDML laser by combining two SOAs as gain media [14]. We successfully demonstrate a FDML wavelength swept laser which has an over 136.5 nm FWHM bandwidth and an over 160 nm edge-to-edge spectral bandwidth with a scanning rate of 45.6 kHz. The measured axial resolution of the system is 6.6 μm in air. The maximum sensitivity of the swept laser system is measured with 100.7 dB and is decreased by 8.6 dB at a 2 mm imaging depth. We demonstrate OCT imaging using an SSOCT system, which is built based on the developed FDML swept laser.

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2. Experimental setup

Figure 1 shows the experimental setup for a wide-bandwidth, high-speed FDML wavelength swept laser and an SSOCT system. The FDML laser is similar to the conventional wavelength swept laser using a scanning filter except with an addition of a long dispersion-managed fiber [9]. The scanning fiber Fabry-Perot tunable filter (FFP-TF) is driven with a frequency that matches the longitudinal frequency of the laser cavity. Thus, the traveling light from one frequency sweep propagates through the laser cavity. A 4.5 km long SMF-28e fiber is used in our set up, and the corresponding mismatched dispersion is less than 2.1 ns for a wavelength range from 1240 nm to 1380 nm [9].

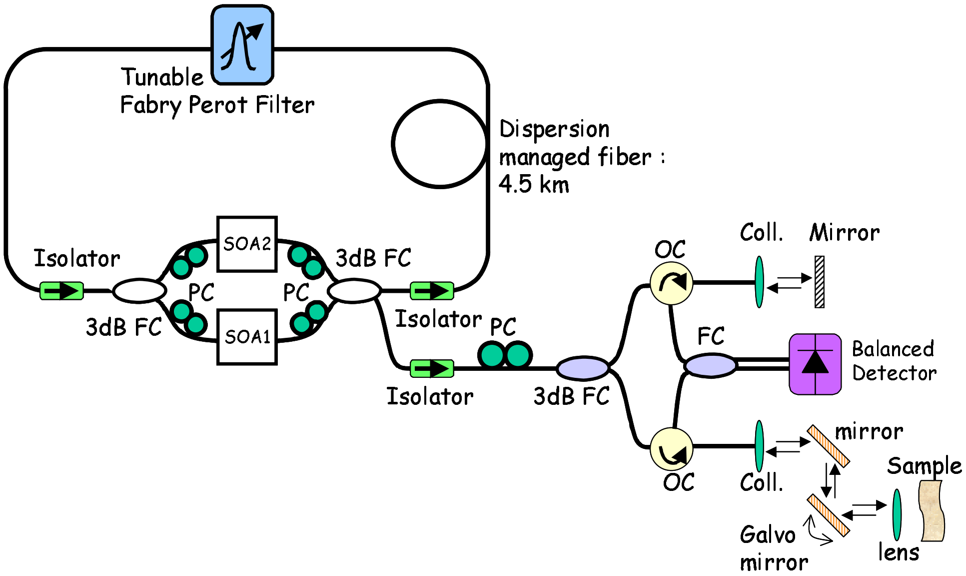

Fig. 1. Experimental setup for a wide-bandwidth, high-speed of a FDML wavelength swept laser and an SSOCT system. (PC: polarization controller; FC: fiber coupler; OC: optical circulator; SOA: semiconductor optical amplifier; Coll.: collimator)

The FDML wavelength swept laser consists of two SOAs, two isolators, two 3 dB fiber couplers, two polarization controllers, a scanning FFP-TF (Micron Optics Inc.), and a 4.5 km long SMF-28e dispersion managed fiber. There are two laser cavities with two SOAs. In this experiment, the parallel scheme is adopted because the serial configuration has a problem in which each SOA exhibits absorption in the portion of the spectrum outside of its unique gain band [14]. The center wavelengths of the SOAs are 1272 nm and 1322 nm, respectively. Both SOAs are produced by InPhenix Co. (model number :IPSAD 1301). The FFP-TF has a free spectral range of ~ 210 nm at 1300 nm and a linewidth of ~ 0.2 nm. The applied frequency of the FFP-TF is 45.6 kHz, which is the same as the fundamental longitudinal frequency of the total laser cavity. The sweeping speed can be increased in our case if a higher frequency PZT driver is used. The current system can be scaled to high frequency with the high frequency driver. Furthermore, since both the forward and backward scans can be used, 45.6 kHz sweeping source can achieve 91.2 kHz A-scan speed. Polarization controllers are inserted into the laser cavity because both SOAs are polarization dependent. It is better to match the length between the two laser cavities in order to match the longitudinal frequency of each laser cavity. In this experiment, however, the mismatched length was within 4 cm for both laser cavities. The frequency difference corresponding to the mismatched length is 0.5 Hz. The performance of FDML with two SOAs was almost the same if the mismatch frequency is less than 1 Hz. Two isolators are used to operate

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unidirectional propagation in the laser cavities. The output from the wavelength swept laser is monitored with an optical spectrum analyzer and an oscilloscope via 3dB fiber coupler. The output of the FDML laser is coupled into a Fourier domain OCT imaging system. The basic configuration of the OCT system is based on a Michelson interferometer. The output light from the FDML laser source is split into reference and sample arms by a 1 × 2 coupler. Ninety percent of the incident power is coupled into the sample arm while ten percent is fed into the reference arm. The reference power is attenuated by an adjustable neutral density attenuator for maximum sensitivity. Two circulators are used in both reference and sample arms to redirect the back-reflected light to a 2x2 fiber coupler (50/50 split ratio) for balanced detection. A balanced detection configuration is used to increase the signal-to-noise ratio of the OCT system [15].

In the detection arm, the time fringe signal collected by the photodetectors with detection bandwidth of 75 MHz (PDB120C, Thorlabs) is digitized by a 14 bit data acquisition board (high speed digitizer 5122, National Instrument) sampling at 100 M samples/s, and the number of data points for each A-line data acquisition is 800. The control signal driving the FFP-TF generates an A-line trigger signal that is used to initiate the data acquisition process for each A-line. The complex analytical depth encoded signal is converted from the collected time fringe signal by fast Fourier transform. The structure image is reconstructed from the amplitude term of the complex depth encoded signal.

3. Experimental results

Figure 2 shows the normalized amplified spontaneous emission optical spectra of two SOAs. The wide bandwidth output could be obtained by combining these SOAs because each SOA generates its own spectrum independently. Figure 3 shows the laser output spectra and its transient intensity profiles of the FDML wavelength swept laser for using different SOAs. The spectra are measured with peak hold mode in an optical spectrum analyzer at 2 nm resolution bandwidths. When the second SOA is disconnected in the laser cavity, the output spectrum of the wavelength swept laser with only the first SOA is shown in Fig. 3(a). The FWHM of the tuning range of cavity 1 is 81nm from 1237 to 1318 nm. The edge-to-edge tuning range is 108 nm from 1220 to 1328 nm. Figure 3(b) shows the transient intensity profile of Fig. 3(a). The peak power is more than 7.8 mW for both forward and backward scans. Figures 3(c) and 3(d) show the optical spectrum and the transient intensity profile of laser cavity 2. The FWHM of the tuning range of cavity 2 is 59 nm from 1316 to 1375 nm. The edge-to-edge tuning range is 102 nm from 1278 to 1380 nm. The temporal peak power of laser cavity 2 is 8.2 mW for both forward and backward scans.

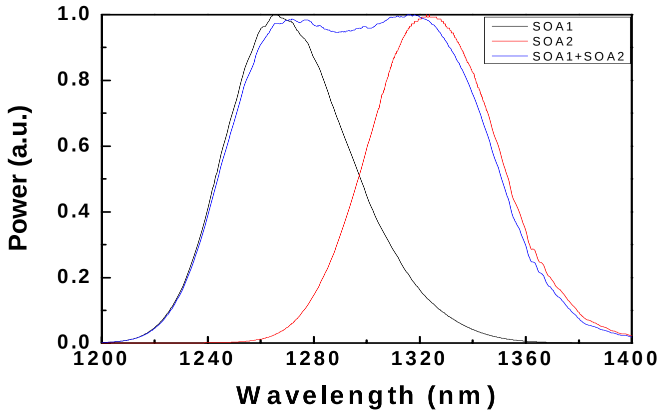

Fig. 2. ASE spectrum of two SOAs used in a FDML wavelength swept laser.

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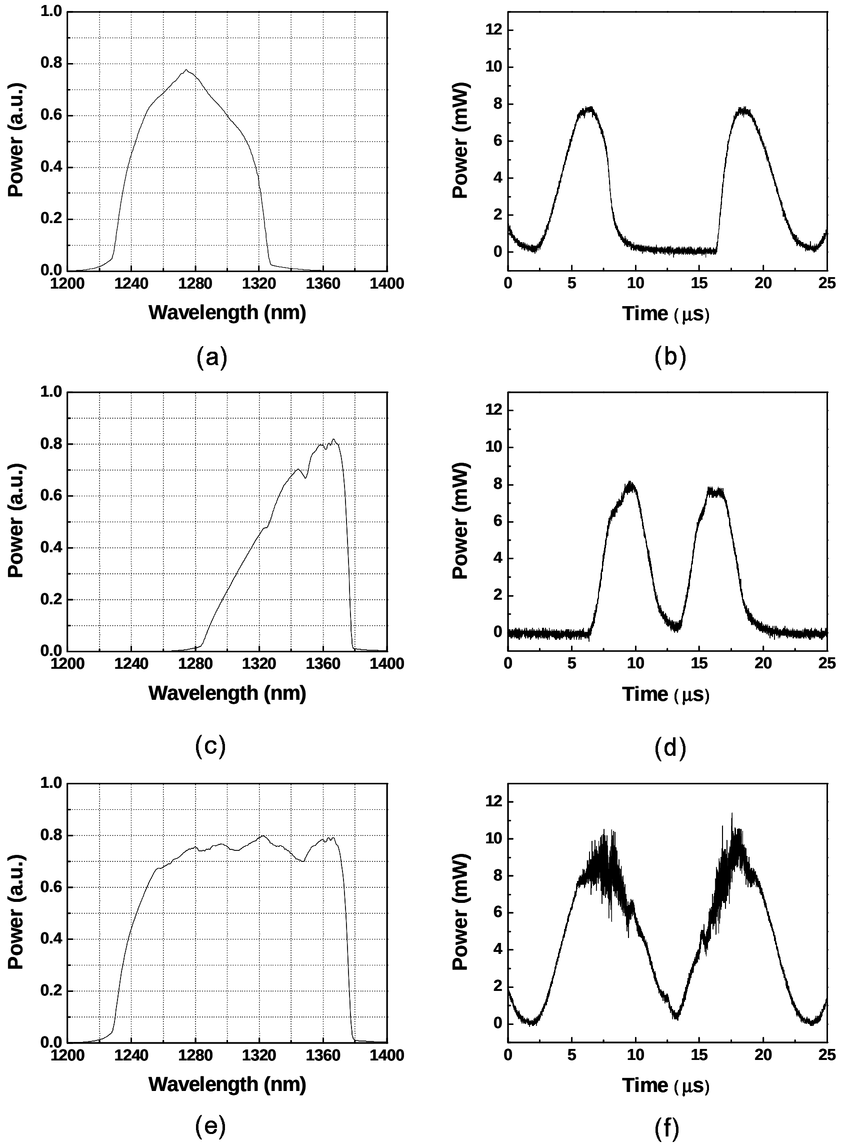
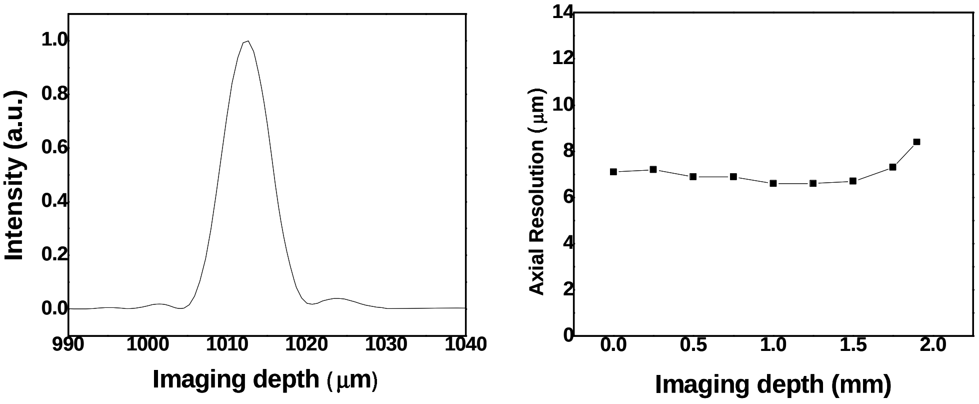


Fig. 3. Optical spectra and transient intensity profiles : (a) optical spectrum of laser cavity 1 and its transient intensity profile (b); (c) optical spectrum of laser cavity 2 and its transient. intensity profile (d); (e) optical spectrum of combined laser cavity and its transient intensity profile (f).

Figures 3(e) and 3(f) show the optical spectrum and the transient intensity profile of the combined wavelength swept laser. The total scanning range of the edge-to-edge is over 160 nm from 1220 to 1380 nm, and the FWHM bandwidths of the laser is 136.5 nm from 1238.5 to 1375 nm. There is an amplitude fluctuation that is due to the polarization dependence of the SOAs. The temporal intensity profile of the combined swept laser is shown in Fig. 3(f). Even though there is an additional cavity loss from the two 3 dB fiber couplers, the peak power is over 11.4 mW for both forward and backward scans.The amplitude noise in the temporal domain is observed. It is due to a slight mismatch length between laser cavity 1 and laser cavity 2. The mismatched length between the two laser cavities is less than 4 cm. Coherent interference between the two laser cavities generates additional coherent beat noise in the temporal power profile which can be suppressed by use of balance detection in an OCT system. In order to avoid the beat noise, properly designed WDM couplers can be used.

The theoretical resolution corresponding to a Gaussian shape with a 136.5 nm FWHM bandwidth is 5.4 μm in air. Dispersion should be compensated in order to get an OCT image since dispersion mismatch in the sample and reference arms would broaden the coherence function. Dispersion mismatch will cause degradation of the axial resolution of the system. In our swept source OCT system, calibrating the nonlinear phase function in wave number space with a sample reflector compensates for dispersion. Figure 4(a) shows the point spread function (PSF) measured with a partial reflector. The measured axial resolution of the FDML wavelength swept laser is 6.6 μm in air for the forward scan. It corresponds to the effective axial resolution of 4.7 μm in tissue (n=1.4). The instantaneous linewidth is determined to be 0.18 nm by measuring the coherence length of the laser output. Axial resolution and imaging depth are important to understand imaging performance in the OCT system. The axial resolutions with imaging depth are measured by the PSF. Figure 4(b) shows the axial resolution at different imaging depth in air. The mean axial resolution within 1.5 mm imaging depth range is about 6.8 μm.



(a) (b)

Fig. 4. Forward scan point spread function (PSF) of the FDML laser system: (a) axial resolution and (b) axial resolution as a function of depth.

In order to characterize the system performance of the swept laser, the sensitivity is measured by placing a partial reflector with a measured attenuation of 56.7 dB in the sample arm. Figure 5 shows the axial point spread function for different delays. The side-lobes in the main mirror peaks are observed due to the asymmetric spectral modulation in the light source [2]. The system sensitivity roll-off at the different imaging depths is shown in Fig. 5. Maximum sensitivity is 100.7 dB including the system insertion loss of ~ 3 dB and an attenuation of a partial reflector of 56.7 dB; sensitivity at a depth of 2 mm is decreased by 8.6 dB. The –6dB roll-off depends on the linewidth of the filter. [16] The linewidth of the used fiber Fabry-Perot tunable filter (FFP-TF) is 0.2 nm.

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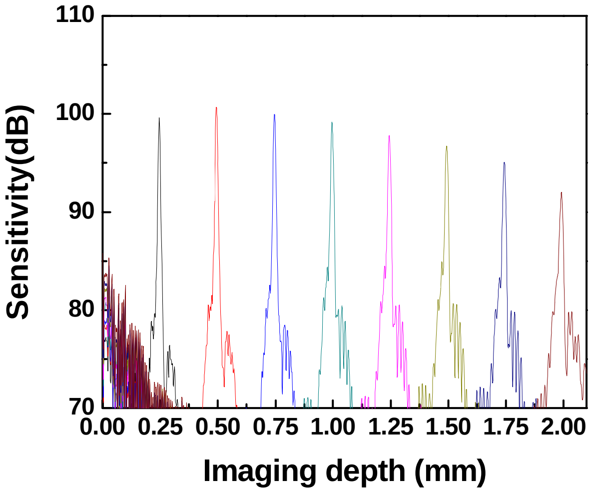

Fig. 5.Sensitivity of the FDML laser system as a function of depth.

To evaluate the FDML wavelength swept laser, human skin was imaged with the SSOCT system. Figure 6(a) shows an OCT image of a human finger in vivo. Figure 6(b) shows an OCT image of a human nail fold in vivo. The number of data points for each A-line data acquisition is 800. The sampling rate of analog-to-digital converter is 100 M samples/s for the A scan rate of 45.6 kHz.

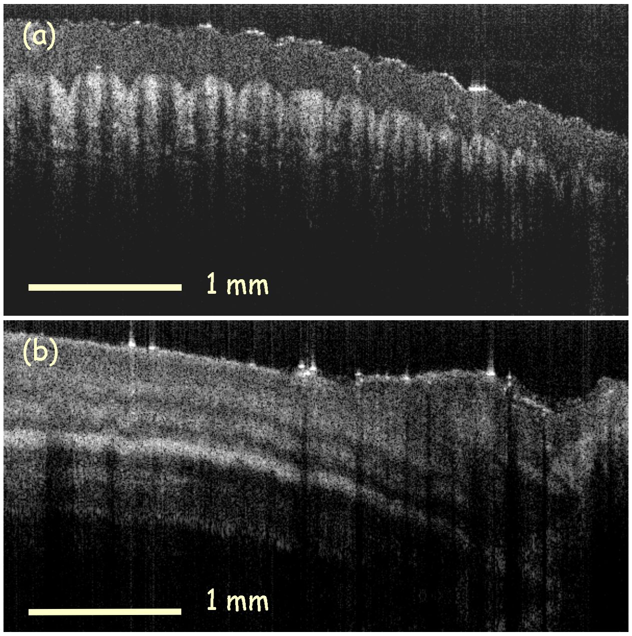

Fig. 6. OCT images of (a) human finger and (b) nail fold in vivo with FDML wavelength swept laser at 45.6 kHz sweep rate.

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4. Conclusion

We have successfully demonstrated a wide-bandwidth, high-speed Fourier domain mode-locked (FDML) wavelength swept laser using two semiconductor optical amplifiers. The axial scan rate of the laser was 45.6 kHz which corresponded to the round trip time of the laser cavity. The FWHM scanning range of the FDML wavelength swept laser was over 135 nm and an over 160 nm edge-to-edge spectral bandwidth around 1300 nm. The measured axial resolution of the forward scan was 6.6 μm in air and 4.7 μm in tissue. The detection sensitivity achieved up to 100.7 dB with FDML swept laser using two SOAs. The dispersion mismatch in roundtrip time caused by the dispersion slope for a wavelength from 1240 nm to 1380 nm was less than 2.1 ns. We also demonstrated OCT imaging using the wide-bandwidth, high-speed FDML wavelength swept laser. We expect that a wide-bandwidth FDML swept laser will have the potential to achieve high quality 3-D OCT imaging.

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