Dual-Band FDML laser for Swept Source Spectroscopic OCT

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Abstract: We report a synchronized dual-band-swept, Fourier domain mode locking (FDML) laser with sweeping rate of 97.6 kHz. It is the first time to achieve spectroscopic OCT based on dual-band FDML swept laser.

OCIS codes: (300.6360)Spectroscopy, laser; (140.4050) Mode-locked lasers

1. Introduction

The wavelength-swept lasers have driven the development of biomedical imaging techniques such as optical coherence tomography (OCT) and spectrally encoded (SE) imaging. And in fast spectroscopic OCT imaging, swept laser covering two or more bands is especially desirable. Recently the simultaneous dual wavelength band swept laser is realized with a single polygon mirror scanner at swept rate of 65 kHz [1]. However, the speed and bandwidth are still limited because of the non-mode-locking configuration. The Fourier domain mode locking (FDML) laser has helped to overcome physical limitations of traditional swept laser in the aspects of sweep repetition rate and output power [2]. To the best of our knowledge, the FDML laser used in the previous study was single band in all cases. In this paper, we demonstrate the first dual-band FDML swept-laser based on a custom-designed driver. It generates a simultaneous 1310 nm/1550 nm mode-locked laser at the sweeping speed of 97.6 kHz which allows for *in vivo* high-speed biomedical imaging with potential application in spectroscopic investigations.

2. Principle and Design

In FDML, the long fiber delay line optically stores the entire sweeping frequency range within the cavity, while the tunable filter is periodically driven with a period that matches the round-trip time of the cavity or its harmonics. The dual-band swept-source comprises of two extended ring cavity lasers, two individual fiber Fabry-Perot tunable filters (FFP-TF) and one common spool of fiber delay line as shown in Fig. 1 (a). Here the custom-designed dual-channel driver generates two sinusoidal signals with the same frequency which ensures the synchronization between the two FFP-TFs. In our configuration, the main part of the delay line is shared by two bands with the help of two wavelength-division multiplexing couplers (WDMC). Due to the difference of group velocity at two bands, an additional length of delay-compensated fiber is mandatory for the band with higher velocity. The difference in cavity length is caused by different refractive indices between the two bands, as described in ref [2]. The compensating length ΔL is given by

$$\Delta L = L \times \frac{f_1 - f_2}{f_1} \tag{1}$$

where f_1 and f_2 represent each band's resonant frequency before compensation. L is length of the long fiber delay line. As a result, the two bands achieve a common resonant frequency of f_1.

The complete system of 1310/1550 nm dual-band FDML laser was built as presented in Fig. 1(a). A 4.2-km long SMF-28e fiber was used as the main fiber delay line in our setup, and the fundamental longitudinal frequency of the total laser cavity was 48.8 kHz, which gave equivalent wavelength sweeping rate of 97.6 kHz. In the two ring cavities, there were two SOAs (*InPhenix Co.*) which were centered at wavelengths of 1310 nm and 1550 nm, respectively. The common frequency applied on the FFP-TF was 48.8 kHz which can be increased further in our case if a higher frequency FFP-TF driver was used. According to Eq. 1, the mismatched length between the two laser cavities was calculated to be 4 m. Thus a 4-m long fiber patchcord was inserted into the 1310-nm ring cavity. Then in the time-multiplexing part [3], a length of 1-km SMF-28e fiber was added after the 1550 nm band end as the delay line. Finally, the time-shifted 1550 nm band was combined with the 1310 nm band by a WDM coupler. The output from the dual-band wavelength swept laser was monitored with an optical spectrum analyzer (OSA). Fig. 1(b) shows the source's integration with the OCT imaging setup.

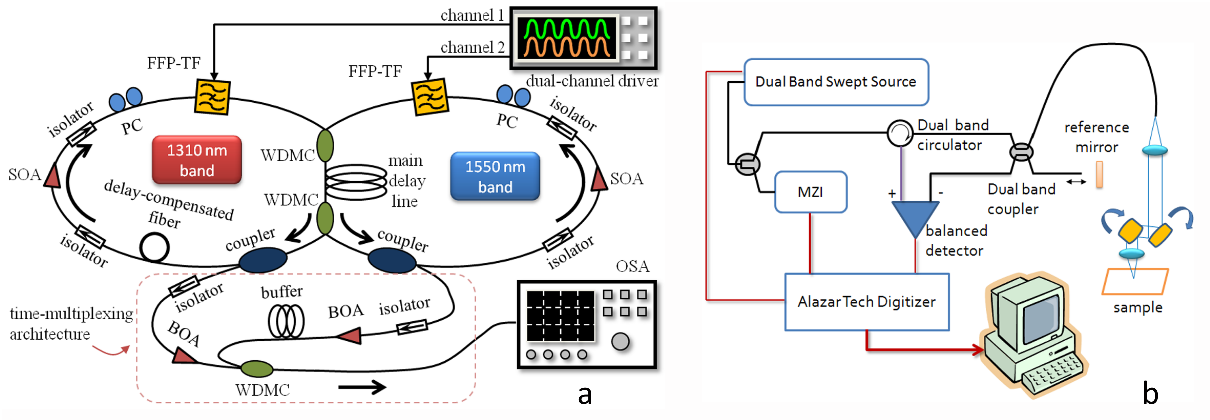

Fig. 1. Schematic diagram of dual-band FDML laser setup (a) and OCT imaging setup (b). PC: polarization control; SOA: semiconductor optical amplifier; WDMC: wavelength-division multiplexing coupler; BOA: booster SOA; FFP-TF: fiber Fabry-Perot tunable filter; OSA: optical spectra analyzer; MZI: Mach-Zehnder interferometer.

3. Experimental Results

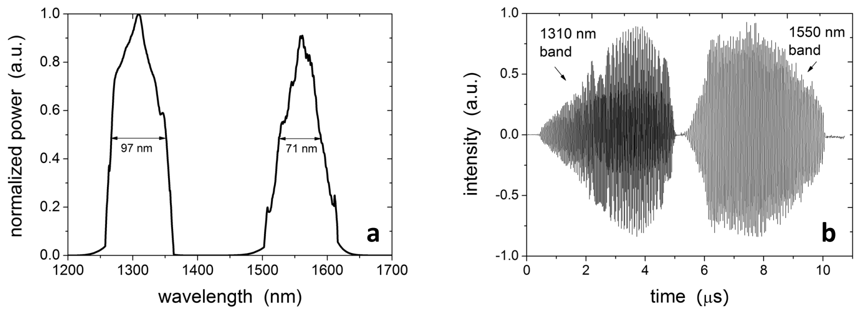

Fig. 2. (a) Measured spectrum of dual-band-swept FDML laser by OSA. (b) Time domain interference pattern measured by balanced detector and oscilloscope after the time-multiplexing architecture.

Fig. 2 shows the measured spectrum of the output laser. The shorter wavelength band FDML laser had an output power of 11 mW centered at 1310 nm with a 120-nm bandwidth (97 nm full wave at half maximum (FWHM)), while the longer wavelength FDML was centered at 1560 nm with a 10 mW output and 130-nm bandwidth (71 nm FWHM). The swept wavelength range at 1550 nm band was increased by 70 nm in comparison with the previous study by a polygon mirror based dual-band swept laser [1]. With the help of custom-designed dual-channel driver, the amplitude and offset parameters were individually and flexibly adjustable, which can optimize each band to its maximum swept range. The achieved wavelength swept rate was 97.6 kHz, which is 30 kHz higher than the speed in Ref. [1]. Moreover, the speed in FDML setup will not restrict the laser's power output. It is only determined by the mechanical properties of piezoelectric crystal based tunable filter.

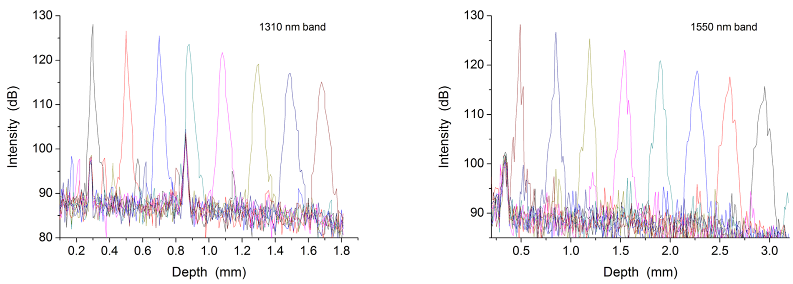

Fig. 3. Point spread functions for 1310 nm band (left) and 1550 nm band (right).

The coherence length of the laser was measured by evaluating the amplitude rolloff in OCT point spread functions as the imaging range was increased. Fig. 3 shows the rolloff curve for the 1310 nm band and 1550 nm band. In comparison with the results by the non-FDML scheme [1], the sensitivity rolloff of the laser is improved by 45% for 1310 nm band and 80% for 1550 nm band when the two sources are FDML scheme.

4. OCT imaging

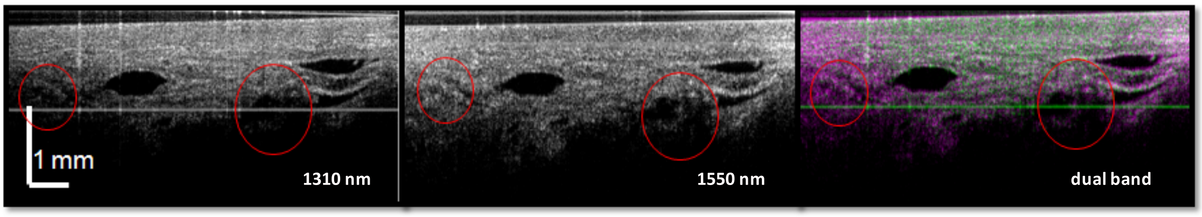

Fig. 4. SS-OCT images of a sow's ovary tissue (*ex vivo*).

Fig. 4 shows the *ex vivo* OCT images (2.5mm $\times$ 10 mm) of sow's ovary tissue by the dual band FDML laser based swept-source OCT system. The OCT images at individual center wavelength of 1310 nm and 1550 nm are respectively processed. In agreement with the absorption and scattering properties, the left and middle images in Fig. 4 demonstrate that, the penetration depth at 1550 nm is slightly larger than that at 1310 nm, and axial imaging resolution in the image at 1310 nm is obviously higher than that at 1550 nm wavelength band. Fig. 4 (right) shows the combined spectroscopic OCT image processed using the color encoded method. By comparing the circled regions, it is indicated that the spectroscopic image maintains the larger penetration depth at 1550 nm and higher resolution at 1310 nm. Though there is no obvious functional pattern difference in this image, if using some specific sample (such as the tissue with high water concentration), significant differences would be obtained in the spectroscopic image.

5. Conclusion

In conclusion, a 97.6-kHz fast-swept, 1310/1550 nm dual-band, Fourier domain mode locking laser was firstly demonstrated. The laser used a custom-designed dual-channel driver for the two FFP-TF filters. The accurate compensation for delay fiber enabled the simultaneous oscillation in both bands' ring cavities. The instantaneous output power of 11 mW at 1310 nm band and 10 mW at 1550 nm band were achieved in the experiment. And the scanning ranges for the two bands were 120 nm and 130 nm, respectively. Such high-speed, dual-band wavelength-swept laser is promising to be applied to spectroscopy related imaging such as spectroscopic OCT or wavelength encoded imaging. Simultaneous OCT imaging of human finger at 1310 and 1550 nm at an A-scan rate up to 97.6 kHz was demonstrated. The novel method allows potentially for instantaneous high-quality OCT spectroscopic analysis and stable phase measurements in simultaneous two wavelength bands. By integrating it with microscopy, this technique allows for high resolution 3-D optical coherence microscopic imaging with potential application in functional (spectroscopic) investigations.

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