High-Speed Dual-Band-Swept Fourier Domain Mode Locking Laser

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Abstract: We report a dual-band-swept, Fourier domain mode locking (FDML) laser with sweeping rate of 97.6 kHz. The laser uses a custom-designed dual-channel driver to achieve synchronization between two tunable filters. It is the first time to achieve simultaneous dual-band FDML laser.

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1. Introduction

The wavelength-swept lasers have driven the development of biomedical imaging techniques such as optical coherence tomography (OCT) [1] and spectrally encoded (SE) imaging [2]. And in fast spectroscopic OCT imaging, swept laser covering two or more bands is especially demanded. Recently the simultaneous dual wavelength band swept laser is realized with a single polygon mirror scanner at swept rate of 65 kHz [3]. However, the speed and bandwidth are still limited because of the traditional configuration. The Fourier domain mode locking (FDML) laser has helped to overcome physical limitations of traditional swept laser on the aspects of sweep repetition rate and output power [4]. To the best of our knowledge, the FDML laser used in previous study is in all cases single band. In this paper, we here 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. Here the custom-designed dual-channel driver generates two sinusoidal signals with same frequency which ensures the synchronization between the two FFP-TFs. Nevertheless, the amplitude and offset on each filter are individually adjustable within a rated voltage range. Other than the synchronization in repetition rate, the length of optical delay line for each ring cavity is also required to be precisely matched. 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). However, considering the difference of group velocity at two bands, an additional length of delay-compensated fiber is compulsory for the band with higher velocity. Different from the long distance delay fiber, the short length of delay-compensated fiber is specifically used to compensate the cavity length to match the resonant frequency. The difference in cavity length is caused by different refractive indices between the two bands, as described in ref [4]. The compensating length \( \Delta L \) is given by

\[
\Delta L = L \times \frac{f_1 - f_2}{f_1}
\]

where \( f_1 \) and \( f_2 \) represent each band’s resonant frequency before compensation. \( L \) is length of the long fiber delay line and it exhibits the length of delay-compensated fiber. As a result the two bands achieve a common resonant frequency of \( f_1 \).

Considering the two outputs are simultaneously generated, if they are combined directly, for some detection instruments such as digital communication analyzer (DCA), oscilloscope or the balanced detectors in OCT, signals will overlap. Therefore, it is essential to separate the two bands in time domain. In Fig. 1 the schematic diagram shows the time-multiplexing architecture [5]. In this configuration, a length of fiber as the time-delay buffer is added into one band. The respective time-shift in time is prepared for the final combination. With the help of a
WDMC, the buffered and unbuffered bands are finally combined together into a common-path output. By this time-multiplexing technique, the sweeps with different wavelength are separated and a tailored laser output is generated.

The complete system of 1310/1550 nm dual-band FDML laser was built as presented in Fig. 1. 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. One FFP-TF had a free spectral range (FSR) of 200 nm at 1310 nm and a linewidth of 0.15 nm and another had a FSR of 200 nm at 1550 nm with a linewidth of 0.1 nm. Each FFP-TF introduced a loss less than 2.5 dB at single wavelength. The measured total cavity loss in respective ring was 7.5 dB at 1310 nm band and 10 dB at 1550 nm band. The common frequency applied on the FFP-TF was 48.8 kHz which can be increased in our case if a higher frequency FFP-TF driver was used. Each band employed two isolators in order to operate unidirectional propagation in the laser cavities. Polarization controllers were also inserted into the laser cavities to maintain the shape of spectra. Before inserting the delay-compensated fiber, resonant frequency at 1310 nm band was 46 Hz higher than that at 1550 nm band. According to the previous equation, the mismatched length between the two laser cavities was calculated to be 4 m for both laser cavities. Thus a 4-m long fiber patchcord was inserted into the 1310-nm ring cavity. Then the outputs from the two ring cavities were connected to two booster SOAs, respectively. The laser power was amplified by 15-17 dB during the post amplification. In the time-multiplexing architecture, a 1-km SMF-28e fiber was added after the 1550 nm band end as the buffer. 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).

3. Experimental Results and Discussion

Fig. 2 shows the measured spectrum of the output laser. The shorter wavelength band FDML laser had an output power of 11.2 mW centered at 1320 nm with a 98-nm bandwidth, while the longer wavelength FDML was centered at 1566 nm with a 10.6 mW output and 131-nm bandwidth. 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 [3]. 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. [3]. Moreover, the speed in FDML setup will not restrict the laser’s power output. By changing for high-powered tunable filter driver, swept speed can be dramatically improved to more than 300 kHz [6]. It is only determined by the mechanical properties of piezoelectric crystal based tunable filter.

It is important to note that the 1310 nm band had a bandwidth of 98 nm which was not as wide as that described in Ref. [3] (i.e. 160 nm). The narrower bandwidth was due to the amplification characteristics of the SOA utilized.
in our setup. In contrast, the amplifier in the previous work was actually a BOA with a gain bandwidth of over 80 nm. Our polarization-independent SOA is superior in polarization control but has a narrower gain bandwidth (53 nm) than the polarization-dependent BOA. Therefore, for the system utilizing SOAs, gain bandwidth is usually narrower than that of BOAs. One way that can overcome the trade-off between polarization sensitivity and gain bandwidth is to replace the SMF fiber in the cavity with polarization maintaining fiber (PMF). In that case, the spectrum of the output laser will not be influenced by the polarization state even when a BOA is used as the amplifier. As a result, both wide scanning range and polarization stability can be achieved.

4. Conclusion

In conclusion, a 97.6-kHz fast-swept, 1310/1550 nm dual-band, Fourier domain mode locking laser is 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 11.2 mW at 1310 nm band and 10.6 mW at 1550 nm band were achieved in the experiment. And the scanning ranges for the two bands were 94 nm and 107 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.

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