# 1.7 MHz Fourier domain mode locked laser at 840 nm for retinal imaging

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## 1. Introduction

Thanks to its capabilities of producing cross-sectional images down to a micrometer scale, all without invasive procedure, optical coherence tomography (OCT) is particularly interesting for the field of retinal imaging [1-3]. Fourier domain mode locked (FDML) lasers have been widely used in swept-sources OCT for many years [4-7]. Their high A-Scan rate is one of their main characteristics making them attractive for OCT [8-10]. The increased speed mitigates motion artifacts induced by patient movement, thereby contributing to the overall image quality. Besides, they are known for their high stability and long coherence length [11], which facilitate improved visualization and analysis of tissues at greater depths within the sample. They are currently manufactured by Optores GmbH at 1.6 MHz and 3.2 MHz centered at 1060 nm, 1300 nm, or even 1550 nm. We recently developed an 840 nm FDML laser sweeping at 2×414 kHz [12]. Retinal images have been acquired at a rate of 828 kHz using the bidirectional sweeping of the FDML laser. These shorter wavelength lasers are especially interesting for eye imaging due to reduced water absorption, potential higher transverse resolution, and higher contrast.
In this work, we present an upgrade of the 840 nm FDML laser showing an A-Scan rate of 1.7 MHz by implementing a bufferstage. A characterization of the laser is given, including spectrum and roll-off. This laser is specifically designed for use in retinal imaging applications.

## 2. Methods and results

FDML lasers are mainly composed of a broadband gain medium, usually a semiconductor optical amplifier (SOA), an optical bandpass filter enabling the creation of the wavelength sweep, and a long fiber delay line. Due to their ability to generate narrow linewidth, wide free spectral range, and fast repetition rate, Fabry-Pérot filters are mostly used as optical bandpass filters. The fundamental working principle/idea of FDML lasers is to synchronize the inverse round trip time of the light field circulating in the cavity with the filter frequency. To optimize the synchronization of all wavelengths, chromatic dispersion must be compensated. As shown in Figure 1, three chirped fiber Bragg grating (cFBG) are introduced for this purpose. Polarization controllers are positioned at each input of the circulators to manage the polarization mode dispersion introduced by the latter. The whole laser is temperature-controlled to ensure a stable output power and a constant polarization state.

To increase the repetition rate of the laser from 2×425 kHz to unidirectional 1.7 MHz, optical buffering is used [9]. The FDML laser is modulated to a duty cycle of 25% to enable a four-time optical buffering. After having isolated the laser from the booster stage by using a PM-circulator, the light propagates through both buffering stages, copying the sweep four times. A second SOA is finally used to boost the output power to ~10 mW. Figure 1 left shows the whole FDML and booster setup.

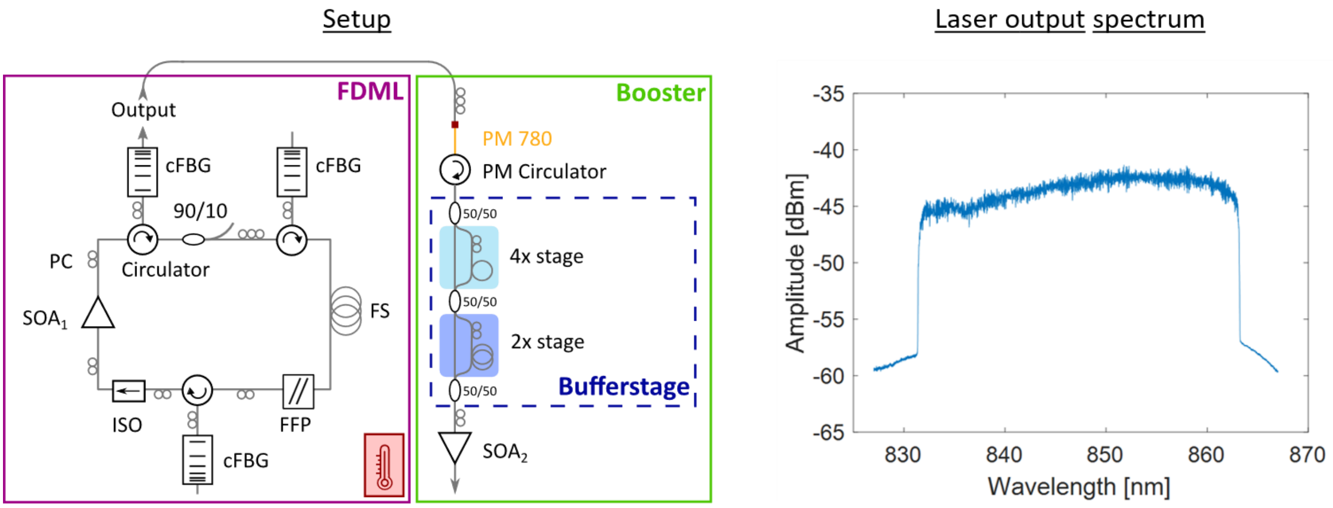


Figure 1. Left: FDML laser and booster stage setup. Right: FDML laser output spectrum.

The output spectrum of the laser is presented in Figure 1 right. A bandwidth of ~30 nm is obtained. The sweep range is currently limited by the mechanical restriction of the filter and might be improved to ~50 nm with the development of more performant filters. Specific care is taken with the power circulating in the laser due to the low catastrophic optical damage of the SOA of about 20 mW. This limitation can also restrict the maximum sweep bandwidth of the laser since the full operating current of the SOA cannot be exploited (~170 mA out of 250 mA possible).

The roll-off of the laser is measured by generating fringes with a Mach-Zehnder interferometer, which are acquired using a 30 GHz photodiode (Thorlabs, DMX30AF) and a 63 GHz, 80 GS/s real-time oscilloscope (Keysight, DSOZ634A). Figure 2 shows that the sensitivity roll-off decreases by 6 dB at ~15 mm, corresponding to a frequency of ~2.2 GHz. For the measurement, no second calibration channel was used. The fringe acquired at ~1.1 GHz, corresponding to ~8 mm imaging depth, is filtered with a bandpass filter (sampling frequency 80GS/s, low cutoff frequency: 0.960 GHz, high cutoff frequency: 1.6 GHz) and used for calibration for all other depths.

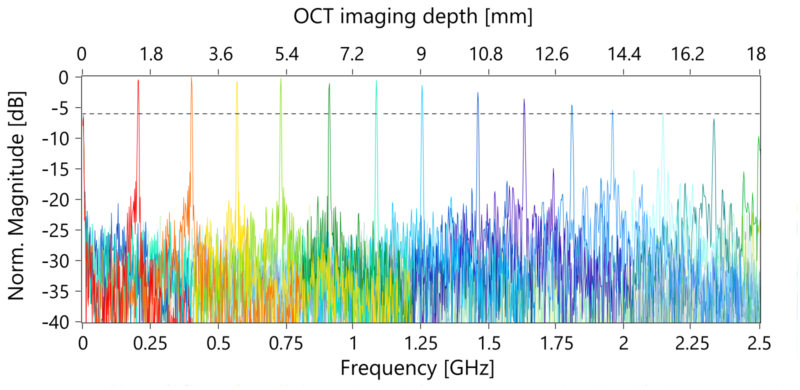


Figure 2. Sensitivity roll-off of more than 15 mm at -6 dB.

We showed that the laser presents promising performances for retinal imaging with 10 mW output power, a theoretical axial resolution in water of 10.7 µm, a repetition rate of 1.7 MHz, and a 6 dB roll-off at 2.2 GHz. Even so we observe a minor roll-off over 1 cm, considering that our imaging range is limited by the analog bandwidth of our Silicon photodiode, 600 MHz, there will be virtually no roll-off in the OCT. An ethical approval to image the human retina *in vivo* was obtained recently, and imaging sessions will be carried out in the future.

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