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FDML swept source at 1060 nm using a tapered amplifier

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ABSTRACT

We present a novel frequency-swept light source working at 1060 nm that utilizes a *tapered amplifier* as gain medium. These devices feature significantly higher saturation power than conventional semiconductor optical amplifiers and can thus improve the limited output power of swept sources in this wavelength range. We demonstrate that a tapered amplifier can be integrated into a fiber-based swept source and allows for high-speed FDML operation. The developed light source operates at a sweep rate of 116 kHz with an effective average output power in excess of 30 mW. With a total sweep range of 70 nm an axial resolution of 15 μm in air (∼11μm in tissue) for OCT applications can be achieved.

Keywords: optical coherence tomography, swept source, tunable laser, tapered amplifier, fourier domain mode-locking

1. INTRODUCTION

Optical coherence tomography (OCT) has become an important instrument for biomedical imaging. During the last years, the development of frequency domain-OCT was promoted, which increases the imaging speed significantly[1] and brings a sensitivity advantage.[2] While in the visible range fast line cameras, which can record the spectrometric response of the sample at high resolution, are readily available, suitable devices for the near-infrared are still difficult to find. Therefore, swept source-OCT is the preferred method for wavelengths above 1 μm, since it requires only a single photo detector. It gives the option to use balanced detection, and allows for higher ranging depth. In order to obtain the spectral information, one needs a narrowband light source, that can be tuned over a broad wavelength range. One typical implementation of these so-called swept sources is a laser based on a fiber ring resonator comprising a semiconductor optical amplifier (SOA) as gain medium and a tunable filter for wavelength selection.[3]

The wavelength region around 1060 nm has been reported to be well suited for retinal imaging due to low absorption and dispersion in water.[4] SOAs for this wavelength have limited saturation power, so that one often needs to post-amplify the laser light with a second SOA. We propose a *tapered amplifier* as an alternative gain medium in a high-speed swept source for OCT. Tapered amplifiers are semiconductor gain media which due to their particular waveguide architecture are capable of delivering far higher output power than conventional SOAs. It was shown earlier that they can be used to implement a high power wavelength-swept laser.[5] Here, we demonstrate that a tapered amplifier can be integrated into a fiber-based resonator, which opens the possibility to implement the *Fourier domain mode-locking* (FDML) technique. Thus, one can overcome the limitation in sweep velocity given by the time needed to build up coherent light.[6]

The idea of FDML is to synchronize the sweep frequency of the tunable filter with the resonator round trip frequency. For this purpose, the round trip frequency must be decreased with a delay line of typically several kilometers length. Using standard fiber at 1060 nm, the achievable bandwidth of the light source is limited by chromatic dispersion in the delay line, because frequency synchronization cannot be achieved for all wavelengths.[7] We show that increased gain in the laser resonator (from an additional conventional SOA) counteracts the dispersion effects and helps to utilize the full gain bandwidth of the tapered amplifier.

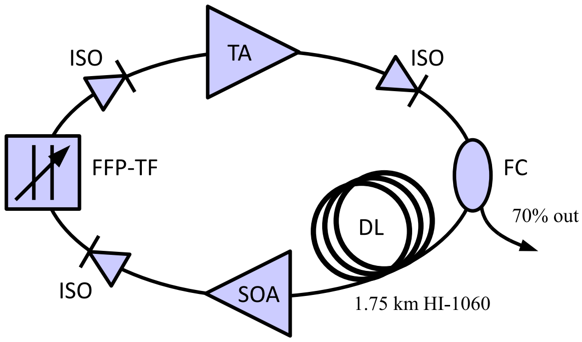

Figure 1. Schematic setup of the light source. TA: tapered amplifier, including fiber coupling optics, SOA: semiconductor optical amplifier, FFP-TF: fiber Fabry-Perot tunable filter, DL: delay line, ISO: optical isolator, FC: fiber coupler.

2. SETUP

The basic setup of the implemented light source is shown in Figure 1. Light emitted from the tapered amplifier (TA, Ferdinand-Braun-Institut) is focused into the single-mode fiber cavity. 70% of the intra-cavity power are coupled out, while the remaining fraction passes through the delay line (1.75 km HI-1060) to an additional SOA (InPhenix). A fiber-coupled Fabry-Perot tunable filter (FFP-TF, Micron Optics, 150 pm linewidth) selects the part of the spectrum that is fed back to the tapered amplifier. Optical isolators ensure unidirectional lasing in the resonator and suppress back-reflections from the Fabry-Perot filter. The length of the fiber delay line is chosen so that the resonator round trip frequency is close to a mechanical resonance of the tunable filter. The resulting FDML operating sweep rate of the light source is 116.8 kHz.

Conventional SOAs with a single-mode waveguide allow for drive currents of not more than a few hundred milliamperes, and have thus limited saturation power. Broad-area diodes, on the other hand, can be driven with several amperes, but emit highly multi-moded light, that cannot be coupled efficiently into a single-mode fiber. The tapered amplifier combines advantages of both architectures. In a narrow waveguide section single-mode "seed light" is generated. The waveguide is then slowly broadened, so that the mode field expands while keeping its original single-mode profile. Thus, tapered amplifiers can be driven with comparably large currents—and therefore deliver high saturated output power—but nevertheless maintain a good beam quality.

Figure 2 shows and illustration of the tapered amplifier an the fiber coupling optics. The emitted light is highly astigmatic. Along the fast axis (perpendicular to the taper structure) the aperture is narrow, so that the focal point is situated on the crystal facet. The aperture along the slow axis is typically about hundred

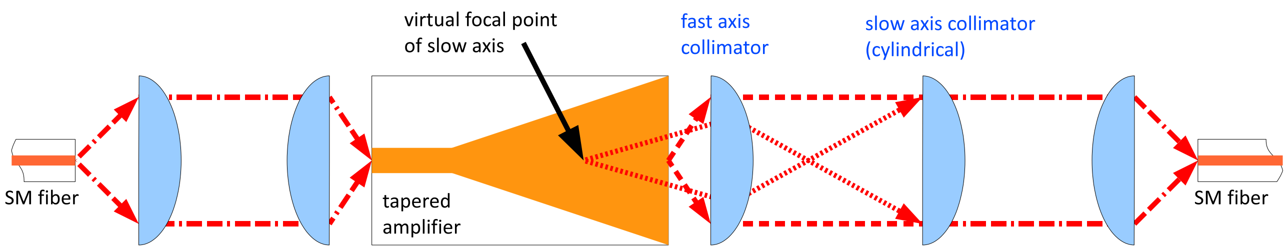

Figure 2. Schematic of the tapered amplifier and the fiber coupling optics. Dashed arrows: fast axis rays, dotted arrows: slow axis rays.

micrometers wide, and the beam emerges from a virtual focal point inside the crystal. In our experimental setup the fiber coupling was done in free-space optics, as depicted.

The additional SOA is inserted into the resonator in order to increase the total gain per round trip. In earlier experiments with non-FDML swept sources we demonstrated that increased gain can significantly improve the available bandwidth of a swept source.[8] This principle applies also to FDML when the chromatic dispersion in the delay line is so high that it cannot be neglected. If that is the case, extended photon cavity lifetime occurs only in the narrow wavelength band where the round trip frequency coincides with the filter sweep rate. Light of the wavelengths that do not fulfill the frequency matching condition gets interrupted after a certain number of round trips. Due to the extra gain of the SOA, all light is amplified faster and coherent laser light can be built up in a broader wavelength range, even though the frequencies are not perfectly matched.

3. RESULTS

Figure 3 (left) shows the time-resolved output power during one sweep cycle for drive currents $I_{TA} = 2.3$ A and $I_{SOA} = 0.3$ A. The first remarkable observation is the strong asymmetry between the operation performance of the forward scan (wavelength increasing, $t < 4.2\mu$s) and the backward scan ($t > 4.2\mu$s), which has not been reported for FDML light sources working at 1300 nm. By tuning the sweep frequency f_{sw} within a range of 100 Hz, one can adjust either the forward or the backward scan to run stable with high output power, while the other scan direction is affected by a severe drop in power and strong amplitude fluctuations. This phenomenon can be explained as a combined effect of chromatic dispersion in the fiber delay line and frequency up-conversion due to non-linearities in the semiconductor crystals. In the wavelength range of interest HI-1060 fiber exhibits normal dispersion, so that the resonator round trip frequency f_{res} is higher for longer wavelengths. Jeon et. al. previously showed that positive detuning of the sweep frequency ($f_{sw} > f_{res}$) impairs the laser performance significantly stronger during the backward scan than during the forward scan, and vice versa for negative detuning.[9] If one adjusts $f_{sw} = f_{res}(\lambda_{max})$, where λ_{max} is the highest wavelength of the laser sweep spectrum, the laser is positively detuned for the entire sweep range, and thus the performance deteriorates strongly only during the backward scan. Correspondingly, for $f_{sw} = f_{res}(\lambda_{min})$ the output power decreases and fluctuates during the forward scan. For $f_{res}(\lambda_{min}) < f_{sw} < f_{res}(\lambda_{max})$ both scan directions are partially affected. In terms of power and stability the light source performance appears slightly better when tuned for optimal forward sweep operation. Even if only one sweep direction is used, an A-scan rate of $2 \cdot f_{sw}$ (here: 233 kHz) can be achieved by buffered FDML operation.[10]

The average output power measured with the parameters as stated above is 20 – 25 mW. During the forward scan—which would be used for imaging—the average power is approximately 30 – 35 mW. These levels seem comparably low, given the fact that a tapered amplifier in a free-space non-swept external cavity laser can emit several watts. Apparently, the feedback in the given configuration is not sufficient to saturate the gain. Due to weaker confinement of the optical field, tapered amplifiers have lower small-signal gain than conventional SOAs.

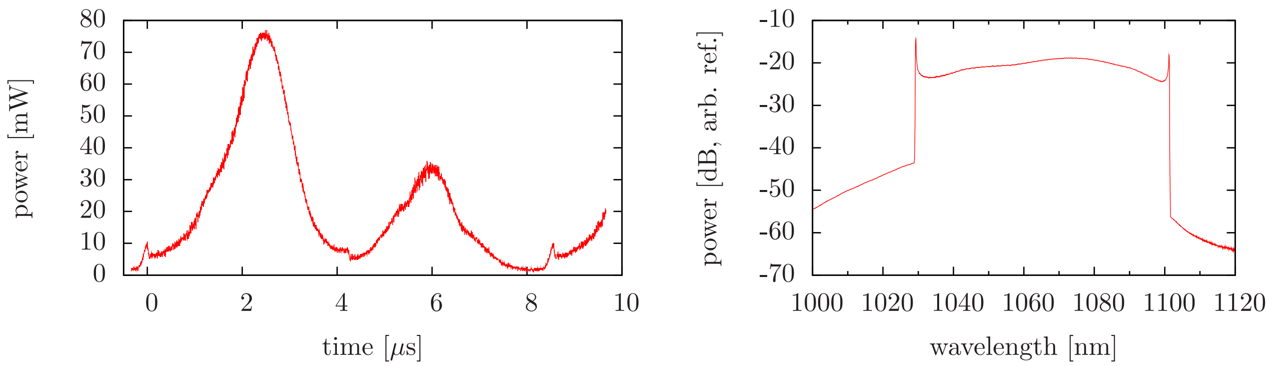

Figure 3. Left: output power during one sweep cycle (data acquisition 500 MS/s, 125 MHz detector bandwidth). Right: averaged power spectral density (0.2 nm OSA resolution).

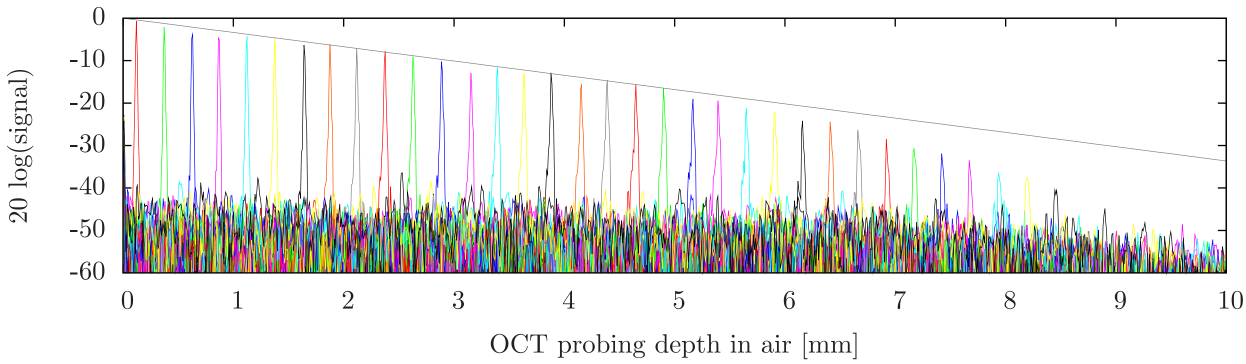

Figure 4. Point spread functions for varying OCT probing depth. (The length scale corresponds to the sample mirror position in a Michelson interferometer. Acquisition of the interferograms with 2.5 GS/s, 350 MHz detector bandwidth)

In conjunction with losses caused by the fiber-coupling optics, the tunable filter and the isolators, this leads here to the relatively low output. Possible ways to increase the power are to optimize the fiber-coupling, to use an SOA with higher saturation power, or to drive the tapered amplifier with higher current.

The averaged power spectrum (Fig. 3, right) shows the available bandwidth of the light source. A total sweep range of 70 nm can be maintained with good long-term stability, the FWHM of the spectrum after linearization in the optical frequency domain is 11.5 GHz (∼42 nm). This corresponds very well with the tuning range of the tapered amplifier when used at low sweep frequency in a non-FDML tunable laser, indicating that its gain bandwidth is nearly optimally exploited. A gain spectrum allowing for a tuning range of $60 - 70$ nm is currently state of the art for tapered amplifiers. The bandwidth of the light source can possibly be increased even further by modulating I_{SOA} during the sweep, so that the resulting output spectrum is shaped flatter and broader.

Using the output during the forward scan, point spread functions (PSF) were generated in a Mach-Zehnder interferometer (MZI). The PSF FWHM of 15 μm (theoretical ideal value: 12 μm*), and allows for an axial resolution of 11 μm in biological tissue. Figure 4 shows the evolution of the PSFs for increasing delay z (the length scale corresponds to the probing depth in an imaging setup). A linear fit through the PSF peaks up to $z = 6$ mm results in an R-number of ∼0.3 mm/dB (6 dB roll-off at $z \approx 1.8$ mm). The faster drop of the PSF amplitudes for $z > 6$ mm is presumably caused by a change in the coupling efficiency of the MZI. For a delay close to zero and 10 mW sample arm power in the MZI, we measured a sensitivity of 107 dB (not accounting for $2-3$ dB interferometer coupling loss).

*Assuming a Gaussian spectrum of equal 3 dB-bandwidth.

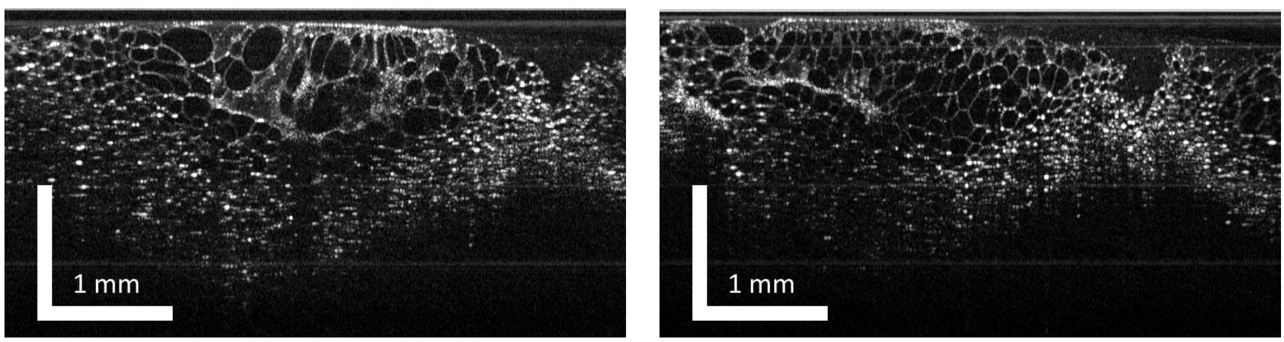

Figure 5. OCT images of a slice of cucumber. (Sliding average over 10 images; data acquisition with 400 MS/s, 200 MHz analog bandwidth; $n = 1.33$ assumed for the vertical scale bar.)

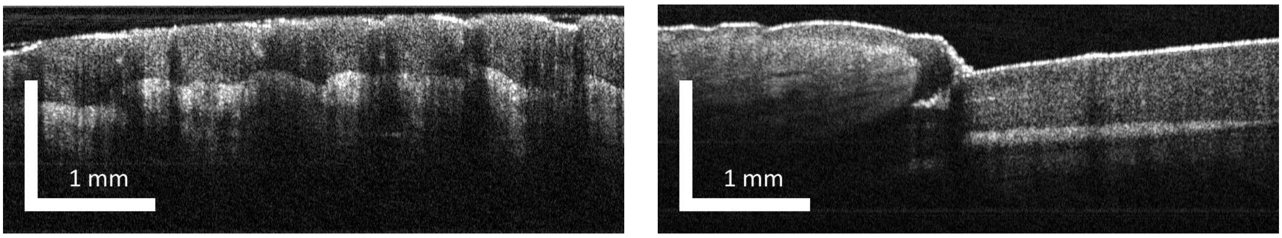

Figure 6. OCT images the skin at the finger tip (left) and the nail fold (right). (Sliding average over 3 images; data acquisition with 400 MS/s, 200 MHz analog bandwidth; $n = 1.4$ assumed for the vertical scale bar.)

Figures 5 and 6 show OCT images of a slice of cucumber and of human skin that were recorded to demonstrate the imaging performance of the light source. The light of the forward sweep was used for the image acquisition. The incident power on the sample placed in a Michelson interferometer was approximately 2.5 mW.

4. DISCUSSION AND OUTLOOK

We demonstrated successfully that a tapered amplifier can be used as gain medium in an FDML laser in order to construct 1060 nm-swept sources with increased output power. We implemented a light source, allowing for A-scan rates of 233 kHz, with an average output power of more than 30 mW during the forward scan. Although it exhibits a strong asymmetry in output power between the two sweep directions, the depth scan acquisition at twice the sweep frequency is possible by buffering. With a total sweep bandwidth of 70 nm an axial resolution of 15 μm in air (11 μm in tissue) can be achieved. The measured values for sensitivity ($\sim$110 dB) and signal roll-off (0.3 mm/dB) indicate that OCT images of good quality can be generated, which is confirmed by a series of images acquired with this light source.

Even though the gain spectrum of the tapered amplifier is very well exploited, the bandwidth of the light source can likely be broadened further by an adequate modulation of the SOA drive current. Furthermore, optimizing the feedback to the tapered amplifier will increase the achievable output power, and it can be expected that this will also lead to lower intensity noise and higher sensitivity. The integration of a tapered amplifier into a fiber-pigtailed package has been demonstrated,[11] thus the fiber-coupling can be compact and stable, with minimized losses. All this opens the possibility for high-speed swept source applications at 1060 nm with increased power requirements, such as buffered FDML or imaging with multiple beams.

ACKNOWLEDGMENTS

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