2025

Fiber lasers for nonlinear microscopy. — This year we aimed at the development of sub-ps Er-fiber lasers and amplifiers operating in the optical telecommunication range around 1560 nm primarily with nonlinear microscopy and atmospheric laser radar applications in mind. In longer term, we wish to (1) replace femtosecond Ti-sapphire lasers [1] operating in the 760-780 nm range in NAD(P)H fluorescence lifetime imaging (FLIM) experiments investigating the metabolic state of cells for detection of cancer cells for instance, and (2) develop sub-ps fiber oscillators operating in the 1.7 micron range that penetrate deeper layers of tissues (like skin) for 3-photon excitation of fluorophores, which allows imaging of skin (especially melanoma) biopsies at a lower risk of laser absorption in melanin as well. The pulsed fiber laser system operating at around 1.7 micron is also a candidate for atmospheric laser radar applications, where they should be operated in “burst” mode rather than single pulses for better detectability.

A significant difference between Yb-fiber (operating at around 1030 nm) and Er-fiber laser systems is that in the former case the optical fibers used typically have normal dispersion, while in Er-fiber laser systems they have typically anomalous dispersion (negative GDD) at around 1560 nm. In our experiments we used an *ELMO* oscillator manufactured by MenloSystems GmbH (Germany) and an *EDFA 100S* Er-fiber amplifier manufactured by Thorlabs Inc. (N.J., USA). By using optical fibers with different dispersion properties spliced in front and behind the Er-fiber amplifier, and by optimizing the amplification of the fiber amplifier, we could produce amplified soliton laser pulses at around 1560 nm and 1680 nm with a typical pulse duration of ~100 fs before a second-harmonic generation (SHG) unit efficiently converting our laser pulses to 780 nm. The block diagram of the optimized experimental setup for second harmonic generation SHG is shown in Fig.1.

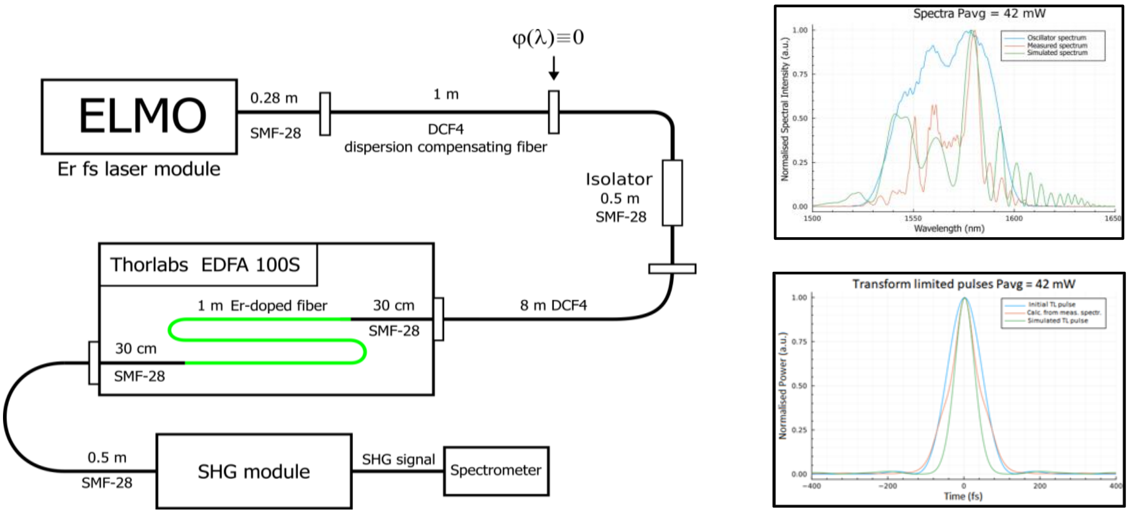

Figure 1. Left: Block diagram of the Er-fiber amplifier system optimized for SHG when using DCF4 dispersion-compensating fibers and SMF-28 anomalous dispersion optical fibers. Right up: spectrum of the Er-oscillator measured at the input of the Er-fiber amplifier (blue), measured spectrum of soliton pulses with energy of ~0.84 nJ arriving at the SHG unit (red), and corresponding model result (green). Right down: temporal shapes corresponding to spectra depicted above, assuming transform-limited laser pulses.

The ELMO Er-oscillator generates ultrashort laser pulses at a center wavelength of 1580 nm and at a repetition rate of 50 MHz with an average power of P_{avg} = 5 mW, the temporal length of which can be compressed to less than 150 fs using a dispersion-compensating fiber of appropriate length. In order to protect our oscillator, an optical isolator was placed behind it by setting the length of the optical fibers leading to it to the shortest experimentally feasible value using a fiber splicer. The type and length of the optical fibers used in the Thorlabs EDFA 100S Er-fiber amplifier were obtained from the manufacturer and were used in our model calculations. The length of the DCF4 dispersion-compensating fiber was chosen to be 8 m in front of the Er-fiber amplifier, while the length of the SMF-28 fiber, which transmits the amplified laser pulses exiting the amplifier to the SHG unit, was chosen to be 0.5 m. A detailed description of the SHG unit is omitted here due to lack of space. For our simulations we used a code written in Matlab using the "split-step Fourier" method. In addition to the second-order dispersion and Kerr nonlinearity, we also involved the effects of the third-order dispersion as well as self-steepening and stimulated Raman scattering in optical fibers. Simulation results together with corresponding experimental data are shown on the right side of Figure 1.

The continuous increase in the wavelength of the soliton-like pulses generated at the output of the Er-fiber amplifier can be achieved by using stimulated Raman scattering in optical fibers by continuously increasing the length of the fiber with anomalous dispersion. In our Raman experiments, we placed an approx. 1 m long SMF-28 fiber after the Er-amplifier and continuously increased the gain in our laser amplifier. Accordingly, our soliton pulses appeared at increasingly smaller distances compared to the amplifier output and thus they traveled increasingly larger distances in the SMF-28 fiber. On the left side of Figure 2, the laser output spectrum is shown for different Er-amplifier currents, which is continuously shifted towards longer wavelengths due to Raman scattering. On the right side, we see the graph of the wavelength values corresponding to the measured spectral intensity peaks. It is important to note that the energy of the Raman laser pulses propagating in the anomalous dispersion range above 1580 nm contain 50-70% of the total pulse energy, and that this part of the laser spectrum can be separated or compressed with appropriate spectral filters!

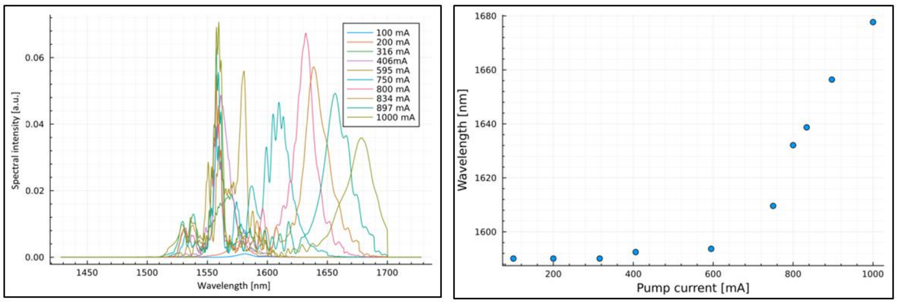

Figure 2. Left: output spectra of the Er-fiber amplifier, where the Raman shift in a 1 m long SMF-28 fiber can be observed. On the right are the wavelength values corresponding to the spectral intensity peaks to the right of 1580 nm as a function of the amplifier pump current.

References

[1] G. Szipőcs, Á. Krolopp, S.P. Chong, P. Török, R. Szipőcs, *Fiber-coupled, sub-ps Ti-sapphire laser for multi-excitation wavelength, head-mounted two-photon excitation fluorescence microscopy of the brain*, Proc. SPIE 13937, Advances in Microscopic Imaging V, 139371S (2025); https://doi.org/10.1117/12.3098083