Generation of 60 fs pulses at 780 nm by frequency doubling of Er-doped fiber laser with tunable repetition rate for TPEF imaging

***D. Stachowiak*[1], *J. Bogusławski*[2], *A. Głuszek*[1], *A. Hudzikowski*[1], *Z. Łaszczych*[1], *M. Wojtkowski*[2], *G. Soboń*[1]**
1. Laser & Fiber Electronics Group, Wrocław University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
2. International Centre for Translational Eye Research, Institute of Physical Chemistry, Polish Academy of Sciences, Kasprzaka 44/52, 01-224 Warsaw, Poland

Femtosecond lasers have found an interesting application in the field of biophotonics, in particular in noninvasive diagnostics as optical imaging and multiphoton microscopy, of which example is two-photon excited fluorescent (TPEF) imaging process [1]. Currently, state-of-art TPEF imaging systems utilize commercially-available femtosecond Ti:Sapphire lasers, delivering pulses in the 700-800 nm window, which are quite expensive, complex and large devices [2]. As an alternative one can use a compact Erbium-doped fiber laser which is more simple, robust, maintenance free and cost-effective. By adding a frequency-doubling stage for the second harmonic generation (SHG), femtosecond pulses at 1560 nm wavelength can be converted to ultrashort pulses at 780 nm wavelength, ideally matching two-photon absorption spectra of many fluorophores [3]. Here we demonstrate a frequency-doubled Er-doped fiber laser with tunable repetition rate, optimized for TPEF imaging [4].

The laser system setup is depicted in Fig. 1. The system consists of two stages. The first one is a femtosecond Er-doped fiber laser providing 22 fs pulses with a chosen repetition rate from a range 1÷12 MHz. At the setting of f_{rep} = 1.02 MHz, we have obtained an average power of 6.5 mW corresponding to pulse energy of ~6.37 nJ. Subsequently, those pulses were launched into the second system stage: SHG module. Fig. 2 a) and b) shows the optical second harmonic spectrum and the pulse temporal intensity at f_{rep}=1.02 MHz. Measured central wavelength is 782.6 nm and pulse duration is 60 fs with 1.4 mW of an average power, corresponding to a pulse energy of 1.37 nJ. With increasing the f_{rep} from 1.02 MHz up to 11.9 MHz, we have observed a linear increase of the average power (while preserved pulse energy) and only 2 fs change of the pulse duration.

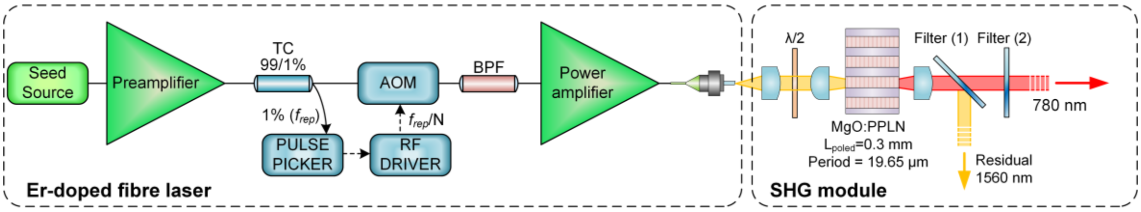

Fig. 1 Scheme of a frequency-doubled fiber laser (TC: tap coupler; AOM: acusto-optic modulator; BPF: bandpass filter).

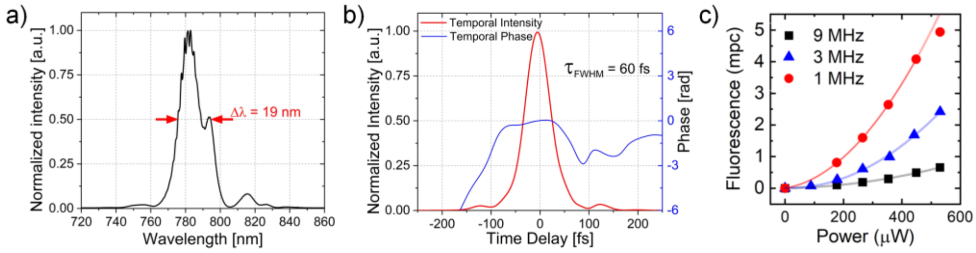

Fig. 2 a) second harmonic spectrum, b) FROG temporal 780 nm pulse intensity (solid red line) and its temporal phase (solid blue line), c) Fluorescence intensity of ex vivo rat skin in mean photon counts per pixel (mpc) as a function of excitation average power for 1, 3, and 9 MHz repetition rates.

Thanks to the built-in pulse-picker, the laser can be used in a wide range of repetition frequencies with preserved pulse energy and duration. It is an important feature allowing for custom setup optimization for specific requirements of the experiment (e.g. lifetime of fluorophores). Additionally, as it can be seen in Fig. 2c), the fluorescence intensity of rat skin sample increases with decreased pulse repetition rate, indicating that it is possible to obtain the same fluorescence intensity with 1 MHz excitation using ~3 times less power compared with 9 MHz excitation, thus reducing the thermal damage probability. The system was successfully applied for TPEF imaging of various biological samples confirming the benefit from adjustable pulse repetition rate function. This work was financed by Foundation for Polish Science (First TEAM/2017-4/39, TEAM TECH/2016-3/20, MAB/2019/12).

References

[1] W. Denk, J. H Strickler, W. W. Webb, "Two-photon laser scanning fluorescence microscopy," Science 248(4951), 73-76 (1990).
[2] G. Palczewska, et al., "Two-photon imaging of the mammalian retina with ultrafast pulsing laser," JCI Insight 3, e121555 (2018).
[3] S. Boivinet, P. Morin, J. P. Yehouessi, S. Vidal, G. Machinet, J. Boullet, "3.5nJ femtosecond pulses at 792 nm generated by frequency doubling of an all-PM fiber high energy 48 fs laser," Proc. SPIE 10897, Fiber Lasers XVI: Technology and Systems, 108971J (2019).
[4] D. Stachowiak, J. Bogusławski, A. Głuszek, Z. Łaszczych, M. Wojtkowski, G. Soboń, "Frequency-doubled femtosecond Er-doped fiber laser for two-photon excited fluorescence imaging", arXiv:2005.00927 [physics.optics] (2020).