

# Diode-pumped mode-locked Holmium fiber laser at 2.138 $\mu\text{m}$

*Nikolai Tolstik<sup>1,2,3</sup>, Evgeni Sorokin<sup>2</sup>, Ignac Bugar<sup>2</sup>, and Irina T. Sorokina<sup>1,3</sup>*

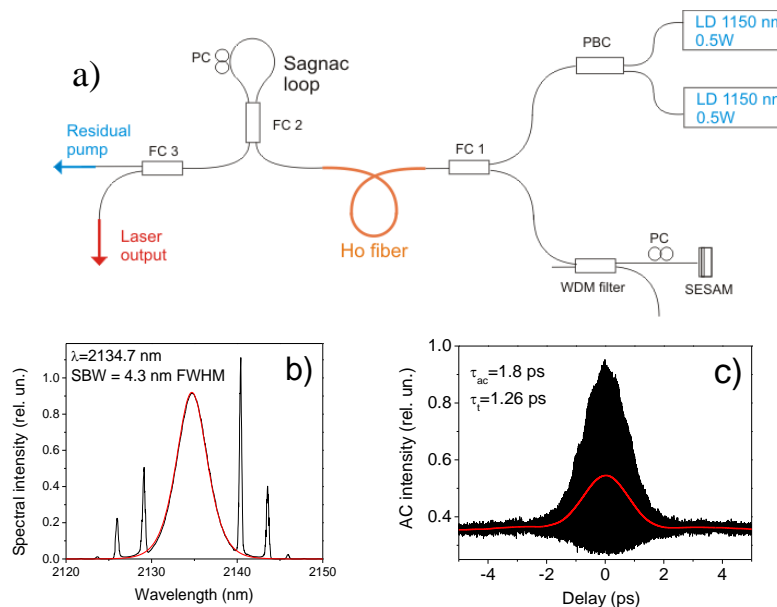
1. Department of Physics, Norwegian University of Science and Technology, Trondheim, Norway

2. Photonics institute, TU Wien - Vienna University of Technology, Vienna, Austria

3. Atla Lasers AS, Trondheim, Norway

Mode-locked fiber lasers emitting in the wavelength range beyond 2  $\mu\text{m}$  [1] are promising for a number of applications including environmental sensing, material processing, medicine etc. Mode-locked holmium fiber lasers tend to operate below 2.1  $\mu\text{m}$  wavelength. For some applications it is important to shift the laser wavelength further to the infrared. Previous demonstration of a 2107-nm mode-locked Ho-fiber laser used Tm-fiber laser pumping and graphene-based saturable absorber. Here we report the longest-wavelength operation of a mode-locked holmium fiber laser, realized in a compact diode-pumped setup.

The laser cavity setup is shown in Fig.1(a). Pumping was provided by the two FBG-stabilized 0.5 W laser diodes at 1150 nm, combined in the polarization beam combiner (PBC). Double-clad holmium-doped fiber with 10  $\mu\text{m}$  core diameter and  $\sim 20$  dB/m core absorption at 1150 nm was used as an active fiber, Thorlabs SM2000 served as a basis for all the intracavity fiber components. Two intracavity polarization controllers (PC) were implemented. Stable self-starting mode-locking regime was initiated and supported by a butt-coupled GaSb-based SESAM with modulation depth about 5%. Fiber loop acted as an output coupler with the estimated reflectance of 10% at 2135 nm. Specially designed fused fiber WDMs were introduced to the fiber laser cavity to ensure the long-wavelength operation. WDMs acted as a broadband wavelength filter, efficiently suppressing laser emission at 1.98 - 2.12  $\mu\text{m}$  and shifting it to 2.12 - 2.14  $\mu\text{m}$ . Residual pump suppressor FC3 and a fiber isolator were installed at laser output.



**Fig. 1** The experimental setup of a holmium fiber laser (a); the optical spectrum (b) and autocorrelation trace (c) of a laser emission.

The laser operated at a pulse repetition rate of 15.22 MHz. The mode-locking could be obtained at the wavelengths up to 2.138  $\mu\text{m}$ , however with rather limited output power typically below 2 mW after the isolator. A higher average output power of 6.3 mW was measured at the central wavelength of 2134.7 nm corresponding to the pulse energy of 0.41 nJ. Series of Kelly sidebands are visible in the spectrum (Fig. 1b), clearly indicating fundamental soliton mode-locking at anomalous cavity GDD. Spectral positions of the sidebands corresponded to the predictions of the theory, confirming the assumed intracavity parameters. The pulse duration of 1.26 ps (Fig. 1c) resulted in a time-bandwidth product of 0.356 and laser peak power of about 250 W.

Summarizing, we have demonstrated the longest-wavelength mode-locked operation of a holmium fiber laser. The laser is very compact, the optical head was packed to 15x18x9 cm size. The work was supported by the grants: EU-FET GRAPHENICS (618086), FWF P24916 and ENERGIX 255003/E20.

## References

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