All-PM coherent 2.05 µm Thulium/Holmium fiber frequency comb source at 100 MHz with up to 0.5 W average power and pulse duration down to 135 fs

H. Hoogland,[1,*] A. Thai,[1,2] D. Sánchez,[2] S. L. Cousin,[2] M. Hemmer,[2] M. Engelbrecht,[1] J. Biegert,[2,4] and R. Holzwarth[1,3]

[1] *Menlo Systems GmbH, Am Klopferspitz 19a, 82152 Martinsried, Germany*
[2] *ICFO-Institut de Ciences Fotoniques, Castelldefels, Barcelona 08860, Spain*
[3] *Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[4] *ICREA – Institucio Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain*
[*] *h.hoogland@menlosystems.com*

Abstract: We report on a dual output all-PM fiber laser system running at 100 MHz repetition rate offering coherent broadband and narrowband pulses centered at 2.05 µm with a spectral FWHM bandwidth of 60 nm and 1.5 nm at up to 360 mW and 500 mW, respectively. The broadband pulses are compressed down to 135 fs. The multi-stage double-clad amplifier based on Tm/Ho codoping is seeded by a supercontinuum light source, spanning from around 1 µm up to 2.4 µm.

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1. Introduction

In recent time, a high interest in fiber laser systems with wavelengths beyond the 1.55 µm region, covered by Erbium-Laser devices, has developed. Numerous applications using 2 µm light are given in the fields of spectroscopy, medicine, defense and security in the eye-safe laser regime [1] or driving Ho-based solid state amplifiers [2]. Furthermore, light sources at 2 µm are used to pump optical parametric systems to generate light in the mid-IR [3]. Thulium based modelocked oscillators emitting femtosecond pulses at MHz repetition rates are typically operating at central wavelengths well below 2 µm [4]. Central wavelengths above 2 µm have been demonstrated by use of a Thulium based frontend laser for subsequent Raman soliton generation [5]. By use of Holmium doping, oscillators with emission wavelengths above 2 µm and FWHM bandwidths of sub 10 nm, avoiding strong spectral absorption lines around 1.9 µm [6], have been investigated [7]. Another approach is to amplify the 2 µm region of a supercontinuum (SC) or Raman shifted seed source [8–10] or to generate SC in Thulium or Holmium doped fibers [11,12]. However, those amplifiers are mostly bound to wavelengths fairly below 2 µm or to the necessity of combinations of free-space and fiber optics.

We present, for the first time to our knowledge, an entirely polarization maintaining (PM) fiber based coherent light source around 2.05 µm with average powers of several hundred mW and FWHM pulse durations down to 135 fs. To cover a wide range of applications, the system is designed to support both broadband (BB) as well as narrowband (NB) pulses with a FWHM bandwidth of 60 nm and 1.5 nm, respectively.

2. System performance

The setup of the entire system is depicted in Fig. 1. The light of an inhouse built all-PM femtosecond fiberlaser centered at 1550 nm with 100 MHz pulse repetition rate was amplified in subsequent Erbium-based amplifier stages to boost the pulse energy to about 4 nJ at a pulse duration around 100 fs. The light is coupled into a highly nonlinear fiber (HNLF) for SC generation, with a resulting span from 1 µm up to 2.4 µm. To further increase the signal at 2050 nm, we used the effect of self-amplification [13] by coupling the SC into 8 cm of unpumped polarization maintaining (PM) Tm/Ho gain fiber, resulting in additional gain of up to 10 dB on the spectral region spanning the 1.9 µm – 2.16 µm range.

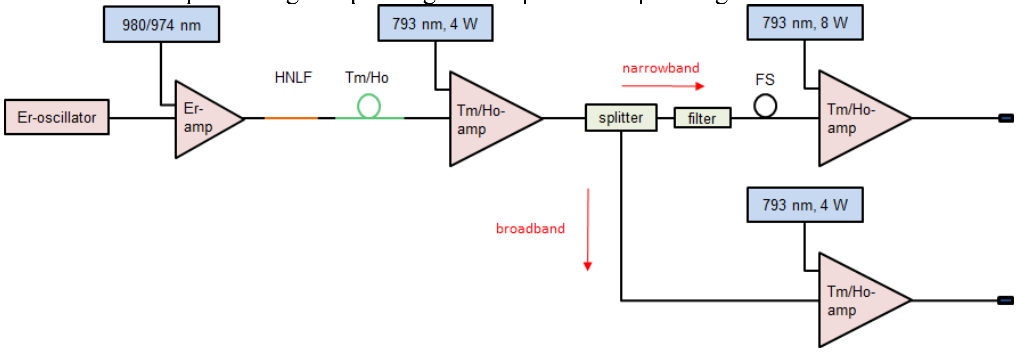

Fig. 1. Schematic setup of the multi-stage 2.05 µm amplifier system; HNLF: highly nonlinear fiber, FS: fiber stretcher.

For a first investigation, a non-PM amplifier was set up consisting of 2.6 m of Tm/Ho gain fiber pumped with up to 4.5 W at 793 nm. The gain fiber was specified with a double-clad absorption of 3.2 dB/m with a core radius of 6 µm. Amplification of the 2.05 µm signal resulted in up to 670 mW average output power with a slope efficiency of 23.5%. The output pulses had a spectral FWHM bandwidth of up to 126 nm (Fig. 2(a)) with optimized pump settings of the Er-amplifier for broadest spectrum. This optical bandwidth supported a transform limited (TL) pulse duration of 63 fs. By additional cooling of the active fiber the change of gain per °C was observed to be 0.07 dB/°C when pumping at 4 W and changing temperature between 15 °C and 25 °C. Figure 2(b) depicts an optical spectrum at fixed pump power but tuning the temperature within above mentioned range. No significant changes in spectral shape could be observed.

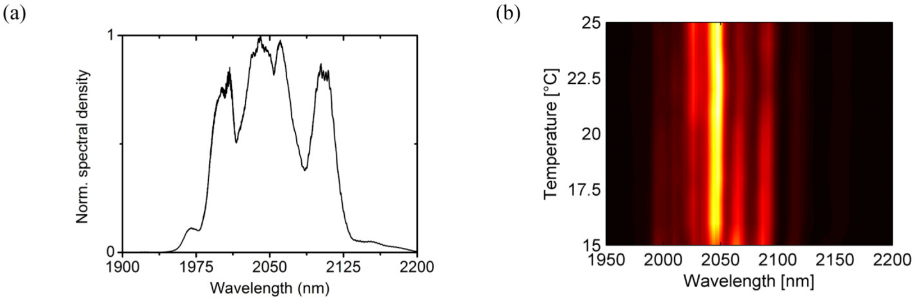

Fig. 2. (a) Output spectrum of the pulses behind single stage preliminary Tm/Ho amplifier; (b) preliminary investigation on the optical output spectrum when tuning the temperature of the amplifiers gain fiber between 25°C and 15°C.

The non-PM gain fiber of the Tm/Ho based amplifier was replaced with a similar fiber, but fabricated in PM-design. Extension to 3m further increased the pump absorption. For following applications, the signal path was split. Around 95% of the light was used to seed a NB amplifier. To achieve a narrowband signal, the beam was spectrally filtered. The filter device was based on spatially chirping the beam by use of a reflective grating and recollection of only a part of the refracted beam. The output of this filter device delivered pulses at 3 mW average power with a FWHM bandwidth of 3 nm. To avoid nonlinearities in the following amplifier induced by high peak intensities inside the gain fiber, an additional 22 m of passive PM fiber were spliced directly behind the filter device. The pulse energy was further amplified in 3.6 m of Tm/Ho gain fiber pumped by 8 W at 793 nm. Amplification by 22 dB was achieved yielding an average output power of 0.5 W. As a result of gain narrowing, the spectral FWHM bandwidth on the NB output was measured to be 1.5 nm, as shown in Fig. 3. Furthermore, the onset of nonlinearities could be observed indicated by sidelobes in the output spectrum at 2049 nm and 2053 nm.

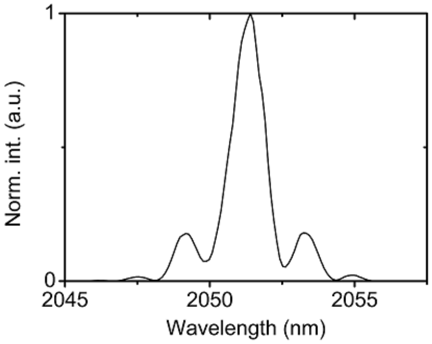

Fig. 3. Output spectrum of NB port at 500 mW average output power.

The remaining 5% of signal light behind the splitter were used to seed the BB amplifier arm. An additional amplifier, pumped by 4W at 793 nm, boosted the average output power to 360 mW. The FWHM duration of the uncompressed BB pulses was measured to be 25 ps at a spectral FWHM bandwidth of 60 nm, showing again gain narrowing similar to the NB amplifier. The central wavelength shifted to 2030 nm due to the amplification process towards the Thulium gain region and due to the transmission function induced by the used splitter. To achieve information on the additional noise induced by the amplification process, the relative intensity noise (RIN) of the pulses on the output of the BB channel was measured and compared to the RIN of the oscillator. The integrated RIN from 500 kHz to 1 kHz on the BB output, as shown in Fig. 4(a), yielding $2.29 \cdot 10^{-3}$, indicated a 57 times higher integrated RIN compared to the integrated RIN of the pulses behind the oscillator and a first Er-doped preamplifier with $0.04 \cdot 10^{-3}$, as depicted in Fig. 4(b). This additional intensity noise contribution can be explained by the nonlinear SC generation based on four-wave-mixing, resulting in higher intensity noise in the outer spectral regions of the SC at 1 µm and 2 µm [14,15]. A contribution by polarization drifting of the signal inside the fiber path could be neglected since an all-PM design was used.

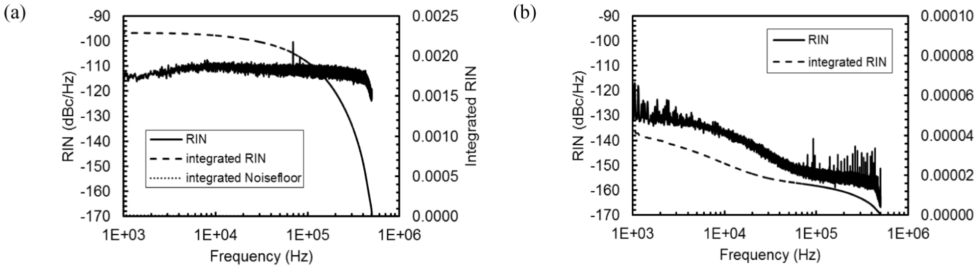

Fig. 4. RIN measurement of the broadband pulses depicting RIN, integrated RIN and integrated noisefloor of the pulses on the output of the broadband channel (a) and of the SC seed on the output of the HNLF (b).

To prove coherence of the output pulses, the second harmonic of the BB output signal was generated in a suitable PPLN based setup and a beat signal with a commercial continuous wave (cw) laser at 1025 nm was recorded. The cw laser was phaselocked to the SHG signal of the BB pulses. The phaselocked beat signal exhibited a signal-to-noise-ratio (SNR) in the radio-frequency spectrum (RF) of ~32 dB, as shown in Fig. 5 with 10 kHz resolution bandwidth.

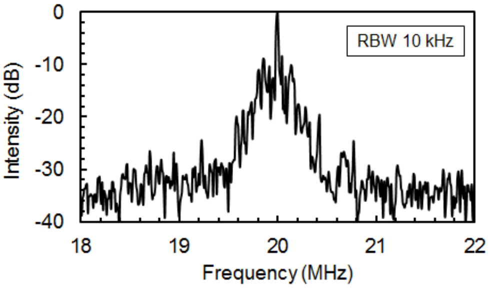

Fig. 5. RF spectrum of the phaselocked beat signal with a SNR of 32 dB.

The BB pulses were subsequently temporally compressed using a Martinez-type free-space compressor on the output of the BB amplifier arm. The setup of the compressor is depicted in Fig. 6(a) [16]. The compressor consisted of an Al-coated reflection grating with 360 lines/mm and a concave mirror with a focal length of 30 cm. The overall transmission through the compressor was limited to ~20% by the availability of gratings at the date of measurement. For spectral and temporal measurements we used an Ocean Optics NIR256 spectrometer and a home-built SH-FROG. The optical output spectrum and resolved pulse duration are depicted in Figs. 6(b) and 6(c), respectively. The phase over the pulses on the output of the compressor could be retrieved as almost linear, resulting in a pulse duration of 135 fs with a calculated transform limited (TL) pulse duration of around 123 fs. This result indicated that group-velocity dispersion as well as third order dispersion of the output pulses are nearly canceled out by the dispersion induced by the compressor.

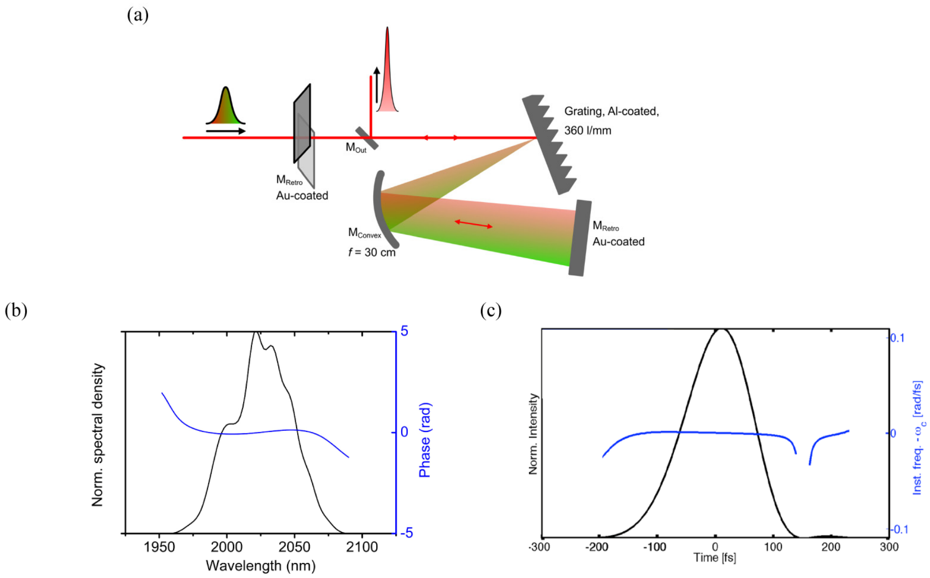

Fig. 6. (a) Setup of the Martinez style compressor unit, based on Al-coated grating and convex mirror with a focal length of 30 cm; (b) output spectrum and phase of the BB pulses on the output of the compressor measured by SH-FROG; (c) FROG resolved pulse duration and instantaneous frequency over the pulse (inset: measured FROG trace).

3. Conclusion

We have demonstrated a 2.05 µm fiber laser amplifier system in a robust all-PM structure for long term stable operation. The 2 µm part of a SC light source is used to seed multi-stage amplifiers based on Tm/Ho codoped gain fibers. Behind a first amplifier, the signal was split and coupled into a NB and a BB amplifier arm, respectively. We achieved up to 22 dB gain for NB amplification, resulting in a 1.5 nm broad spectrum at 2.05 µm with an average power of 500 mW. The average output power of the BB pulses was up to 360 mW with a spectral FWHM bandwidth of 60 nm. For a single stage Tm/Ho based amplifier, we observed FWHM bandwidths of up to 126 nm at 670 mW average output power. For each amplifier, we observed gain narrowing and a slight onset of sidelobes on the output spectrum of the NB pulses by nonlinearities inside the amplifier. The RIN and the phase noise of the broadband pulses were measured and are in good agreement with literature values. A Martinez-type based free-space temporal compressor was setup on the output of the double stage BB amplifier, delivering pulse durations of 135 fs at an average output power of 55 mW.

Upcoming work will focus on scaling the pulse energy by integration of higher pump power diodes. To maintain the pulse characteristics, further temporal stretching will reduce arising nonlinearities. A change in the amplifier design will be performed to reduce the gain narrowing effect. To optimize the transmission of the compressor, a more suitable grating will be used to achieve an efficiency of ~75%.

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