

1.1-GHz SESAM-Modelocked Femtosecond Yb:YLF Laser

Serdar Okuyucu,^{1,2,3,*} Umit Demirbas,^{1,2} Jelto Thesinga,¹ Marvin Edelmann,^{1,4} Mikhail Pergament,¹ Franz X. Kärtner^{1,4,5}

¹Center for Free-Electron Laser Science CFEL, Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

²Laser Technology Laboratory, Department of Electrical and Electronics Engineering, Antalya Bilim University, 07190, Antalya, Turkey

³Akdeniz University, Department of Electrical-Electronics Engineering, Antalya, Turkey

⁴Physics Department, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

⁵The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany
serdar.okuyucu@gmail.com

Abstract: We report the first GHz Yb:YLF laser generating 210 fs long pulses at 40 mW average power output from a low-cost, self-starting, single-mode diode pumped cavity with integrated relative intensity noise <0.45%. © 2023 The Author(s)

Ultrafast oscillators with repetition rates in the GHz range have received widespread attention in various applications due to their advantages, such as (i) larger comb-mode spacing and higher power per comb in frequency comb-based spectroscopy, (ii) increased signal-to-noise ratio (SNR) in optical frequency metrology, and (iii) accurate calibration of spectroscopic instruments for measuring astronomical spectrograms in the search for Earth-like exoplanets. In the implementation of low-cost GHz femtosecond oscillators, diode-pumped solid-state lasers (DPSSL) based on Yb-doped media stand as attractive sources offering efficient pumping with reliable InGaAs laser diodes (preferred diode spectrum is well matched to the efficient absorption bands of Yb³⁺) and low quantum defect laser operation without temperature quenching, upconversion, and excited-state absorption [1]. In recent decades, passively mode-locked (ML) femtosecond GHz oscillators were demonstrated in various Yb-doped media, including Yb:CYA, Yb:KGW, Yb:CALGO, Yb:KYW, and Yb:Lu₂O₃ under various pumping schemes (Table 9.13 in [2]). Among various Yb-doped gain media, Yb:YLF exhibits distinctive properties such as broad emission-spectrum, naturally polarized output, weak thermal lensing, longer fluorescence lifetime (~2 ms), and possibility of crystal growth with minimal passive losses [3,4]. Earlier studies with Yb:YLF demonstrated (i) average output powers up to 5.87 W and broad tuning range (993-1110 nm) in continuous-wave (CW) and (ii) generation of pulses as short as 40 fs and watt-level femtosecond output (1.85 W, 380 fs) by passive mode-locking [5]. However, previous reports of mode-locking with Yb:YLF were in the MHz frequency range, indicating undiscovered potential with this gain medium in the GHz frequency range. In this work, we report the first GHz femtosecond Yb:YLF laser by SESAM mode-locking in a compact cavity pumped by two low-cost single-mode diodes (SMD). Fig. 1(a) describes the laser cavity where a 10 mm long, Brewster-Brewster cut, 2 mol% Yb-doped YLF sample (5 mm wide, 2 mm thick) is double-sided pumped in π -polarization (E//c) by two SMDs (Thorlabs L960H1, each outputs up to 282 mW at 450 mA) with emission peaks at ~960 nm.

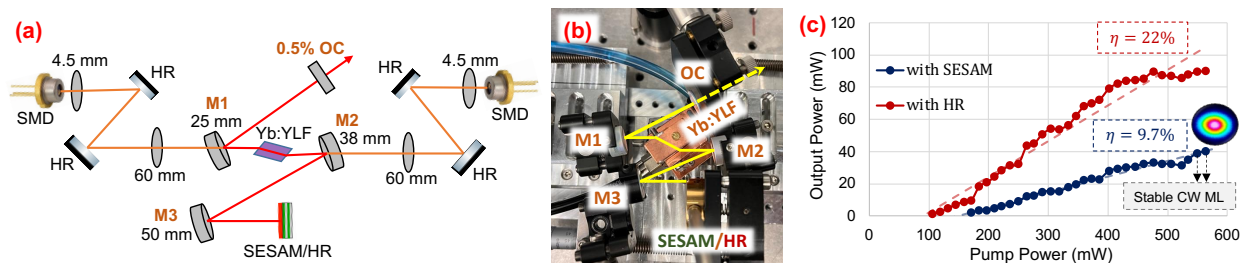


Fig. 1. (a) Schematic of 130 mm-long standing-wave Yb:YLF laser cavity used in CW and mode-locking by a SESAM at 1.1 GHz, (b) Picture of compact physical setup employing 4 mirrors, Yb:YLF crystal, and SESAM, (c) Power scaling performance in CW ML (beam profile shown as inset) and CW (with SESAM replaced with a high reflector) operation.

The pump beams on both sides are first collimated with aspheric lenses ($f=4.5$ mm) and then focused by 60 mm achromatic doublets to an estimated beam waist of ~ 25 μm inside the Yb:YLF crystal. A firm thermal contact between the copper holder (water cooled to 15 °C) and Yb:YLF crystal is maintained by use of thin indium foil pieces placed on top and bottom faces of the crystal. In a single pass, more than 90% of incident pump power is absorbed by the Yb:YLF crystal. In CW operation, the laser provided around 90 mW of CW output power at a total incident pump power of 565 mW, and with a slope efficiency of around 22%. In mode-locking, since the small footprint cavity limits the use of additional components for dispersion compensation, M1(ROC=25 mm) and M2(ROC=38 mm) are specifically designed to provide a group delay dispersion (GDD) of -200 fs² (± 125 fs²) per bounce (for 10° angle of

incidence) over the 1015-1090 nm range. M1 and M2 are highly reflective ($R > 99.95\%$) between 1000-1200 nm and are antireflection coated ($R < 0.2\%$) between 900-970 nm. M3 (ROC=50 mm) is highly reflective ($R > 99.9$) in the 860-1110 nm range with -80 fs^2 ($\pm 20 \text{ fs}^2$) GDD specified for zero-degree incidence. The total intracavity GDD is calculated as -500 fs^2 per round trip and the CW ML operation is initiated and sustained by the SESAM (Reflekron RK177D, $\Delta R = 1.5\%$, $\Delta R_{ns} = 0.5\%$, $F_{sat} = 35 \mu\text{J}/\text{cm}^2$) placed at 18 mm distance from M₃ (resulting in an estimated $32 \mu\text{m}$ beam waist on the SESAM). Stable CW mode-locking is self-starting at $P_{pump} \geq 550 \text{ mW}$ (with pulse fluence on SESAM at $\sim 225 \mu\text{J}/\text{cm}^2$ ($\approx 6.4 \times F_{sat}$) indicating full saturation). At the maximum incident power of 564 mW and use of 0.5% output coupling, 210 fs long pulses (autocorrelation is shown as inset in Fig. 2 (a)) at 40 mW average power ($E_p = 35.04 \text{ pJ}$) are generated. The respective optical spectrum is 5.6 nm wide, centered at 1050 nm (Fig. 2(a)). The resulting time-bandwidth product equals 0.32 which is consistent with the expected soliton pulse shaping mechanism. The measured radio frequency (RF) spectrum in Fig. 2(b) shows fundamental peak at $f_{rep} = 1.11 \text{ GHz}$ with 70 dBm signal-to-background ratio. The wider RF spectrum in the inset exhibits the fundamental and second harmonic frequency with no side peaks, demonstrating stable, single spatial mode ML operation. Fig. 2(c) shows the relative noise intensity of the CW ML laser at 40 mW output where the pulse train is detected by a low-noise InGaAs photodetector and then amplified using a low-noise trans-impedance amplifier after filtering. The signal-source analyzer utilizes AM-Noise measurement on the first harmonic (1.11 GHz) of the Yb solid-state laser with the aid of band-pass filters for isolation.

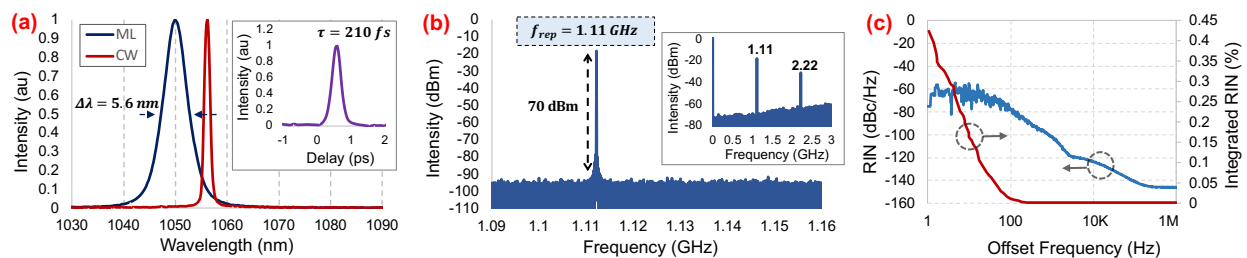


Fig. 2. (a) Optical spectrum of CW and CW ML operation. The inset shows the autocorrelation (sech^2 profile) measured at maximum pump power. (b) RF spectrum ($RBW = 5.1 \text{ kHz}$) of CW ML output (inset shows the wide-range RF spectrum with $RBW = 100 \text{ kHz}$), (c) Relative intensity noise of the CW ML laser (Measured at a constant RF-power of -10 dBm, corresponding to a shot-noise limit of -142.3 dBc/Hz).

By virtue of the integrated noise (red line) shown in Fig. 2, there exists no noise contribution in the high frequency range in 190 Hz-1MHz. In that respect, the lifetime ($\sim 2 \text{ ms}$) of Yb:YLF plays a partial role in suppression of noise factors with $f > 500 \text{ Hz}$. For frequencies $< 190 \text{ Hz}$, the laser noise is dominated by possible noise sources such as mechanical perturbations (i.e. cooling) and pump noise. Further reduction of the laser noise may be maintained by use of isolative covers around the laser and by reducing pump intensity noise (e.g. by powering the diodes with batteries). In conclusion, we achieve 210 fs pulses with an average power of 40 mW at a repetition rate of 1.1 GHz which stands as the first report of GHz mode-locking with the Yb:YLF crystal. By employing specific mirror designs for dispersion management and creating a compact cavity mode within a relatively long Yb:YLF crystal by low-cost SMD pumping, we attain soliton pulse shaping mechanism that mitigates self-phase modulation and Q-switching instabilities. As a result, the mode-locked laser demonstrates self-starting capability and resilience to environmental fluctuations. The output power is presently limited by the available pump power but can be increased by utilizing more powerful pumping methods such as fiber-coupled laser diodes and higher output coupler transmissions. Practical considerations of (i) fine tuning of net intracavity GDD, (ii) optimization of OC reflectivity, (iii) fine tuning of pump power and pump focusing on the gain element and SESAM for implementation of this low-cost setup are to be discussed.

3. References

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