Research Article | Vol. 32, No. 9 / 22 Apr 2024 / Optics Express 15555

Optics EXPRESS

Diode-pumped passively mode-locked femtosecond Yb:YLF laser at 1.1 GHz

SERDAR OKUYUCU,[1,2,*] UMIT DEMIRBAS,[1,2,3] JELTO THESINGA,[1] MARVIN EDELMANN,[1,4] MIKHAIL PERGAMENT,[1] AND FRANZ KÄRTNER[1,4,5]

[1] Center for Free-Electron Laser Science CFEL, Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
[2] Laser Technology Laboratory, Department of Electrical and Electronics Engineering, Antalya Bilim University, 07190, Antalya, Turkey
[3] Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[4] Physics Department, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[5] The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany
[*] serdar.okuyucu@gmail.com

Abstract: We report femtosecond pulse generation at GHz repetition rates with the Yb:YLF gain medium for the first time. A simple, low-cost, and compact architecture is implemented for the potential usage of the system as a low-noise timing jitter source. The system is pumped by 250 mW, 960 nm single-mode diodes from both sides. The semiconductor saturable absorber mirror (SESAM) mode-locked laser is self-starting and generates transform-limited 210 fs long pulses near 1050 nm. The laser's average output power is 40 mW, corresponding to a pulse energy of 36 pJ at 1.1 GHz repetition rate. The measured laser relative intensity noise (RIN) from 1 Hz to 1 MHz is 0.42‰. The performance obtained in this initial work is limited by the specifications of the available optics and could be improved significantly by employing custom-designed optical elements.

1. Introduction

Compact, low-cost ultrafast laser systems with suitable parameters such as wavelength, power, pulse repetition rate, and noise level are needed for a variety of industrial and scientific applications. In this respect, femtosecond lasers with high repetition rates (>500 MHz) have been widely investigated and utilized as practical tools in a vast variety of fields such as optical frequency metrology [1], high bit-rate optical communication [2,3], arbitrary waveform generation [4], low-jitter synchronization of large facilities [5,6], high-resolution spectroscopy [7,8], medical imaging [9,10], laser micromachining [11], quantum optics [12], optical clock distribution [13], absolute distance measurement [14], and precision calibration of astronomical spectrograms in the search for Earth-like exoplanets [15]. Utilizing high repetition rates in certain applications offers advantages such as: (i) easier use of individual lines in frequency-comb-based spectroscopy with a larger comb-mode spacing and a higher power per comb [16], (ii) improved nonlinear bio-imaging with enhanced signal rate and imaging speed, along with reduced photobleaching and photodamage of fluorescent protein [17], and (iii) increased signal to noise ratio through higher entangled-photon flux in quantum applications [18].

Various techniques have been employed for generating ultrafast laser sources with repetition rates in the gigahertz range, including fiber lasers [19,20], diode-pumped solid-state lasers (DPSSL) [21,22], semiconductors lasers [23], and waveguide lasers [24,25]. Among these, diode-pumped bulk and waveguide solid-state lasers have the potential to provide the best performance in terms of laser noise, such as timing jitter, due to their ability to generate/handle high intracavity peak powers via the usage of high-Q-cavities [26–28]. Amongst the diode-pumped solid-state

#518081 https://doi.org/10.1364/OE.518081
Journal © 2024 Received 8 Jan 2024; revised 13 Mar 2024; accepted 14 Mar 2024; published 12 Apr 2024

Optics EXPRESS

lasers, Yb-doped gain media possesses broad enough emission bands of around 1 μm to enable sub-50-fs pulse generation [29–32]. Possession of simple energy diagrams with near-unity quantum efficiency and the absence of undesired processes such as temperature quenching of fluorescence lifetime, upconversion, and excited-state absorption help to minimize thermal effects and promotes power scaling in Yb-systems [33,34]. Moreover, absorption bands of Yb-ions around 960-990 nm match perfectly with the preferred emission spectrum of InGaAs laser diodes, which are regarded as the most reliable and powerful laser diodes available in the market [35]. This in turn enables direct in-band diode pumping with minimal quantum defect and advantages of cost reduction, compactness, low noise, and high electrical-to-optical conversion efficiency [36]. Hence, there has been significant interest to develop ultrafast Yb-oscillators with GHz repetition rates over the last decades as summarized in Table 1. From Table 1, we see that, pulse durations as short as 48 fs [37], repetition rates as high as 10.6 GHz [38] and average powers as high as 6.9 W [37] have been demonstrated from GHz repetition Yb-lasers via Kerr-lens mode-locking (KLM) or SESAM mode-locking.

In this work, we aim to develop a simple GHz laser system with low-cost, and low power consumption in a rather compact cavity scheme that can potentially fit into the palm of a hand. Hence, use of single-mode diodes is preferred as the pump source which can be driven by simple and compact battery powered diode drivers. As the laser gain medium, we choose to work with Yb-doped Yttrium Lithium Fluoride (Yb:YLF) due to several advantages. First of all, Yb:YLF can be grown with very high quality and minimal passive losses [57,58], enabling construction of very high-Q-cavities that is beneficial in reducing quantum-noise limited laser timing jitter. Second of all, Yb:YLF has relatively small linear and nonlinear refractive index, minimizing intracavity nonlinearities and reducing the amount of negative dispersion required for soliton pulse shaping, which is also beneficial for reducing the quantum noise limited timing jitter noise of laser systems. Moreover, due to its negative dn/dT coefficient, thermal lensing is quite small in Yb:YLF compared to well-known alternatives such as Yb:YAG [59,60], hence, potentially one can design a system where the laser crystal does not need active cooling. Lastly, Yb:YLF has relatively broad emission bands enabling generation of sub-50-fs pulses in mode-locked operation, a pulse width that is reachable only by a few Yb-doped crystals.

Yb:YLF gain media have been used in lasing studies for more than 20 years, and has already shown some significant results. The first report of continuous-wave (CW) lasing with Yb:YLF goes back in 2001 by Kawanaka et al., where 50 mW of output power was achieved with 400 mW of diode pump power [61]. Later on, by use of more powerful pumping schemes in improved geometries, CW output power exceeding 5 W and a CW tuning range extending from 993 nm to 1110 nm is demonstrated [62–65]. In mode-locked operation, 196 fs pulses with average power up to 120 mW at 55 MHz [66], 87 fs pulses with 35 mW average power at 100 MHz [67], 40 fs pulses with 265 mW average power at 87.3 MHz [68], and 380-fs pulses with 1.85 W average power at 190.4 MHz [68] have been reported. Note that, all the earlier mode-locking results are focused on standard repetition rates of ~100 MHz.

In this work, two low-cost 250 mW single-mode diodes are employed as the pump source, and mode-locking of Yb:YLF lasers is demonstrated at GHz repetition rates for the first time. Dispersion compensation is achieved via chirped mirrors and mode-locking is initiated and sustained using a SESAM. Mode-locking was self-starting, and the laser produced transform-limited 210 fs long pulses with 40 mW average power at a repetition rate of 1.1 GHz. The relative intensity noise of the laser is measured as 0.42% within a bandwidth from 1 Hz to 1 MHz. The results obtained in this initial study were limited by the commercially available optics and could be significantly improved by usage of customized SESAM and dispersion compensating mirrors. Nevertheless, the initial results demonstrate the potential of Yb:YLF oscillators in providing fs pulse trains at GHz repetition rates from compact and low-cost laser setups.

Optics EXPRESS

Table 1. Performance Summary of Yb-doped Bulk and Waveguide Solid-State Mode-locked Lasers with GHz Repetition Rates

Gain Media	Method	$P_{pump}(W)$	$\tau_p(fs)$	$f_{rep}(GHz)$	$P_{avg}(W)$	$\lambda_c(nm)$	Reference
Yb:YAG[b]	SESAM	14	606	1.09	2.5	1031	[39]
Yb:CYA[a]	KLM	8.5	99	1.04	1.46	1048	[40]
Yb:KGW[b]	KLM	22.3	296	1.64	3.3	1049	[41]
Yb:KGW[b]	SESAM	0.82	250	0.56-1.23	0.13	1040-1036	[42]
Yb:KGW[a]	SESAM	13	125	1.06	3.4	1046	[43]
Yb:KGW[d]	SESAM	6	290	1	2.2	1042	[44]
Yb:KGW[d]	SESAM	5.3	396	4.8	1.9	1043	[45]
Yb:KGW[d]	SESAM	5.5	281	1	1.1	1041	[46]
Yb:CALGO[b]	KLM	18.5	93	1	6.9	1045	[37]
Yb:CALGO[b]	KLM	19.5	48	1	4.1	1052	[37]
Yb:CALGO[c]	SESAM	5.5	166	10.6	1.2	1050	[38]
Yb:CALGO[b]	SESAM	15	95	5	4.1	1060	[47]
Yb:CALGO[b]	SESAM	9	60	1.8	2.95	1059	[48]
Yb:KYW[a]	CNT	0.75	168	1.2	0.05	1047	[49]
Yb:KYW[b]	SESAM	1.3	278	1.02	0.8	1042	[50]
Yb:KYW[a]	KLM	0.75	-	4.6	0.015	1046	[51]
Yb:KYW[c]	SESAM	2.5	162	2.8	0.7	1045	[52]
$Yb:LU_2O_3$[a]	KLM	1	148	6	0.01	1076	[53]
Yb^{3+}-glass waveguide[b]	SESAM	0.5	738-824	4.9-15.2	0.06	1045	[54]
Yb:YAG waveguide[f]	SWCNT-SAM	3.2	0.002	2.08	0.32	1030	[55]
Yb:KLuW waveguide[g]	SWCNT-SAM	1.4	736-876	2.27-3.55	0.21	1030	[56]
Yb:YLF[e]	SESAM	0.57	210	1.1	0.04	1050	This work

[a] *Pumped with:* Single-mode fiber laser
[b] Fiber-coupled laser diode
[c] MMD laser diode
[d] Distributed Bragg reflector tapered diode laser
[e] Single-mode diode
[f] Optically-pumped semiconductor laser
[g] Tapered amplified diode laser.

The paper is organized as follows: Section 2 describes the cavity layout, specifications of the optical elements used and the pumping method. Section 3 describes the measured characteristics of the oscillator, and lastly the results are summarized in Section 4.

2. Experimental setup

Figure 1(a) shows the z-folded laser cavity used in CW and CW mode-locked lasing experiments. For stable mode-locking at different repetition rates, careful adjustment of cavity arm lengths, selection of dichroic mirrors (M1 and M2) with appropriate radii of curvature (RoC) was necessary. Femtosecond pulse generation through stable CW mode-locking was achieved at several discrete frequencies within the 0.3-1.1 GHz range. Here we present details of the CW

Optics EXPRESS

mode-locked laser at highest repetition rate of 1.1 GHz (physical setup shown in Fig. 1(b)) achieved with moderate output power levels.

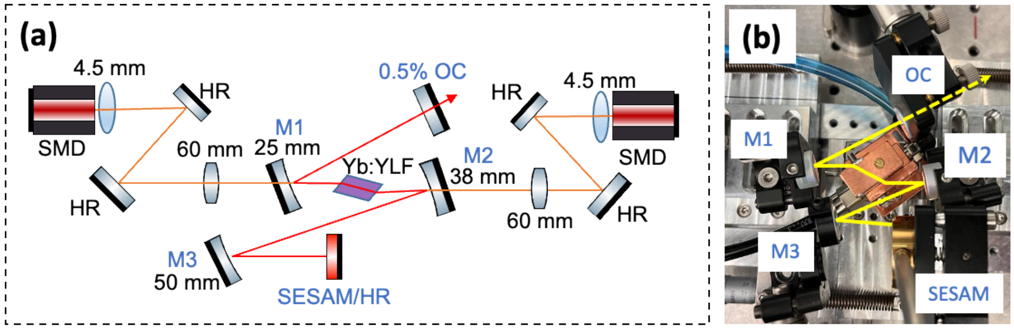

Fig. 1. (a) Schematic of the double-side single-mode diode-pumped Yb:YLF laser oscillator used in CW and CW mode-locked experiments. The high reflecting (HR) end mirror is replaced with the SESAM in mode-locking experiments. (b) Photograph of the z-folded 1.1-GHz repetition rate Yb:YLF laser. The intracavity laser beam path is shown with yellow solid lines.

The laser cavity consists of two concave dichroic mirrors (M1, M2), Yb:YLF crystal, SESAM and a focusing mirror (M3) on one arm and the 0.5% output coupler on the other arm. The 10 mm long, Brewster-Brewster a-cut Yb:YLF crystal (5 mm wide, 2 mm thick) has a specified doping level of 2 mol% and measured passive losses of only 0.06% per cm [62]. The crystal is mounted in a copper holder (water cooled to 15 °C). In doing so, two thin pieces of indium foil are placed at the top and bottom faces of the crystal for good thermal contact. The crystal is placed at Brewster angle to minimize Fresnel reflection losses for pump and lasing beams. The commercial SESAM (Reflekron, RK177D) has a company specified modulation depth of 1.5%, a non-saturable loss of around 0.5%, a reflectivity range covering the 1000–1080 nm region, and a saturation fluence of 35 μJ/cm^2. M1 and M2 are dichroic mirrors with high reflectivity ($R > 99.95\%$) in the 1000-1200 nm range and high transmission ($R < 0.2\%$) in the 900-970 nm range. 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 fs^2 (± 125 fs^2) per bounce (for 10° angle of incidence) over the 1015-1090 nm range. M3 (RoC = 50 mm) is used to generate a second focus on the SESAM and it is highly reflective ($R > 99.9$) in the range 860-1110 nm and has a specified GDD of -80 fs^2 (±20 fs^2) at zero-degree incidence. Astigmatism originating from intracavity Brewster element and other curved mirrors is compensated by folding the cavity around M1 and M2 at the incidence angle of ~25° (ideal value is calculated as 26°). Angle of incidence at M3 is at ~15°. The laser performance is insensitive to slight variations (±5°) of these incidence angles at M1, M2, and M3.

By use of two single-emitter, single-mode diodes (SMD) with up to 282 mW power at 450 mA current at 960 nm (Thorlabs L960H1), the Yb:YLF crystal is pumped on both sides in π-polarization (E//c) [66]. At room-temperature, the absorption cross-section of Yb:YLF covers the 880-1030 nm range where absorption in E//c is 2-3 fold higher with respect to E//a with peaks at 960 nm and 994 nm, which justifies the selection of E//c for pumping in this work [35]. For optimal control and stability of the emission wavelength and output power, pump laser diodes are mounted on thermoelectrically cooled holders. The diodes are in turn cooled to 15 °C for increased overlap of emission peak with the 960 nm absorption line to achieve improved conversion efficiency and low lasing thresholds. The pump beam is first collimated with an aspheric lens (f = 4.5 mm) and then focused by a 60 mm achromatic doublet to an

Optics EXPRESS

estimated beam waist of ~25 μm inside the Yb:YLF crystal. With the given pump configuration, a single pass absorption of more than 90% in the gain medium is estimated [62]. The respective ~130 mm-long standing wave cavity corresponds to the pulse repetition rate of 1.1 GHz in mode-locked operation. In mode-locking experiments, the cavity was optimized in terms of (i) fine tuning of net intracavity GDD, (ii) optimization of OC reflectivity, (iii) fine tuning of pump power and mode area on the gain element and SESAM. The cavity is operated in the negative dispersion regime with a total GDD of around -500 fs^2, and soliton pulse formation is employed for pulse-shaping [69]. By placing the SESAM at 18 mm distance from M3 (a few mm away from the position where excessive focusing on the SESAM occurs, which leads to damage of the SESAM), the intracavity beam is focused to an estimated beam waist of 32 μm on the SESAM.

3. Results and discussion

Figure 2(a) shows the laser efficiency curves taken in CW (red markers) and CW mode-locked (blue markers) regimes, respectively. In CW operation, we have measured a lasing threshold of around 100 mW and a slope efficiency of 27% with the 0.5% transmitting output coupler. The laser provided around 90 mW of output power at a total incident pump power of 565 mW. The roll-over in output power measured at incident pump power exceeding ~430 mW is related with the spectral shift of the pump diode emission away from the absorption peak of the Yb:YLF crystal due to heating of the diode. When the HR-mirror is replaced by the SESAM, the lasing threshold is increased to 170 mW due to the additional losses introduced by the SESAM and the slope efficiency is reduced to 11%. Stable CW mode-locking (shown with green colored diamond markers in Fig. 2(a)) is self-starting for pump powers above 550 mW. At this CW mode-locking threshold, the intracavity pulse fluence on the absorber is estimated to be ~225 $\mu J/cm^2$ which is around 6.4 times the saturation fluence of the SESAM. At this operating point full saturation of the SESAM is achieved and the condition for self-starting is satisfied (Eq. (9.3) in [70]). At the highest incident pump power of 564 mW, the output power in CW ML operation is 40 mW with a corresponding pulse energy of 36 pJ. At this pump power, the CW mode-locked laser output with TEM_{00} beam profile did not show any CW breakthrough, double-pulsing, or Q-switching instabilities. By use of a higher transmission (T_{OC}) output coupler (i.e., 1%), we could achieve a higher average output power (~60 mW) in CW mode-locked operation at lower repetition rates (750 MHz), where cavity arms are lengthened in a symmetrical fashion. For scaling of the repetition rate above 1 GHz, the critical intracavity pulse energy for stable CW mode locking could only be achieved by use of $T_{OC} \leq 0.5\%$ which results in lower output power levels. However, the intracavity average laser power is as high as 8 W, which helps to reduce quantum limited noise levels of the system. In future studies, using optimized SESAMs with lower saturation fluence and lower passive intracavity losses, it should be possible to significantly scale up the average output power demonstrated in this study.

At the total incident pump power of 560 mW, the CW mode locked laser output at 1.1 GHz is first characterized by measurement of the transverse beam profile at a caustic generated by focusing the laser output with a 175 mm focal length lens (Fig. 2(b)). Sample beam profiles measured along the caustic is also shown in Fig. 2(b).

A least squares fit to the measurement data is then performed, and the M^2 beam quality factor is determined as 1.03 and 1.15 for the horizontal and vertical axes, respectively. The optical spectrum (recorded with Ocean Optics HR4000 at 0.27 nm resolution) and auto-correlation trace (measured with APE, Pulse Check) of CW mode locked laser output with respective hyperbolic secant ($sech^2$) profile fits are shown in Fig. 3(a) and Fig. 3(b), respectively. The measured optical spectrum of the CW ML laser output is centered at 1050 nm, and the full width at half-maximum (FWHM) is 5.6 nm, which corresponds to a Fourier transform-limited pulse duration of 207 fs ($sech^2$-fitting). The autocorrelation trace in Fig. 3(b) shows a clean pulse without a pedestal or sub-pulses. Assuming a $sech^2$-pulse profile with a deconvolution factor of

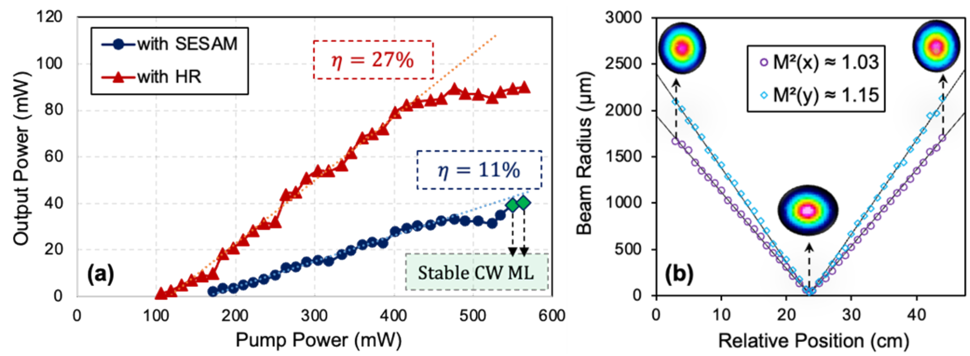

Fig. 2. (a) Output power versus pump power curves of the Yb:YLF laser operated with HR (red) or SESAM (blue) as an end mirror for CW and CW mode-locked operation, respectively. The data is taken using a 0.5% transmitting output coupler. The slope efficiencies are indicated for each case. (b) Beam quality parameter (M^2) measurement of the Yb:YLF laser in mode-locked regime for both axes. Inset pictures show beam profiles at selected caustic positions.

1.54 in the autocorrelation trace, the pulse duration is measured as 210 fs. This corresponds to a time-bandwidth product is 0.32, which is consistent with the expected soliton pulse shaping mechanism. The pulse width that is achieved is limited by the dispersion settings of the mirrors at hand and could ideally be reduced below 50-fs by using customized dispersion mirrors.

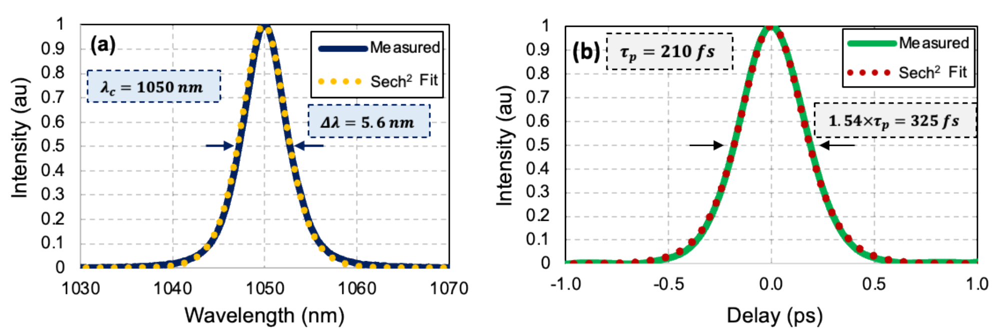

Fig. 3. (a) Normalized optical spectrum of the Yb:YLF laser measured at 40 mW average output power in CW mode-locked operation. (b) Autocorrelation trace of the 1.1 GHz pulse train measured at 40 mW average output power.

Figure 4(a) shows the radio frequency (RF) spectra of the mode-locked laser output measured with a fast photodetector (Thorlabs DET08CFC/M, rise time: 70 ps and RF signal analyzer (Agilent Technologies, N9000A, 9 kHz-3 GHz) with 5.1 kHz resolution bandwidth (RBW). The noise floor of the detection system is at -70 dB relative to the signal's maximum located at 1.11 GHz. Figure 4(b) shows the RF spectrum measured over a wider frequency range (0-3 GHz) with an RBW of 100 kHz which also shows the second harmonic at 2.22 GHz. No side peaks were detected, demonstrating stable, single spatial mode, mode-locked operation.

We have further characterized the relative intensity noise (RIN) of the CW mode-locked laser as shown in Fig. 5. The pulse train is detected with a low-noise InGaAs photodetector (ET-3000) and subsequently amplified with a low-noise trans-impedance amplifier after filtering. All measurements are taken at a constant RF-power of -10 dBm, corresponding to a shot-noise limit (SNL) of -142.3 dBc/Hz. The AM-Noise is measured with the signal-source analyzer (SSA,

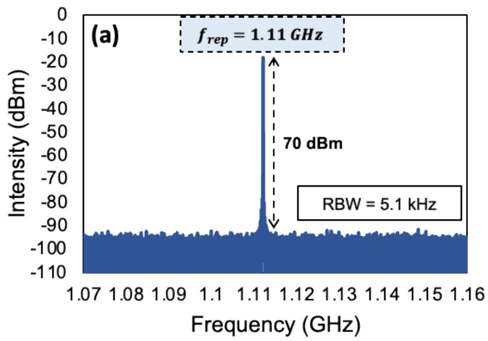

Fig. 4. Measured radio frequency spectrum of CW mode-locked output at 1.11 GHz over (a) narrow and (b) wide frequency span ranges.

Keysight E5052B) on the first harmonic (~1 GHz) of the Yb:YLF laser, filtered out via a proper bandpass-filter. The integrated RIN (red line) shown in Fig. 5, shows that the high-frequency range from 190 Hz-1 MHz contributes negligible noise due to the very long upper state lifetime of Yb:YLF at ~2 ms, which effectively filters out most of the intensity noise for frequencies >500 Hz. We see that, the relaxation oscillations are not visible as they are damped by the nonlinear loss of the saturable absorber in this stable mode-locked regime [71]. For frequencies <200 Hz, the laser noise is mostly dominated by mechanical perturbations (i.e. cooling) or power supply noise. Further reduction of the laser noise may be possible by use of better covers around the laser and by reducing pump intensity noise (e.g., by powering the diodes with batteries).

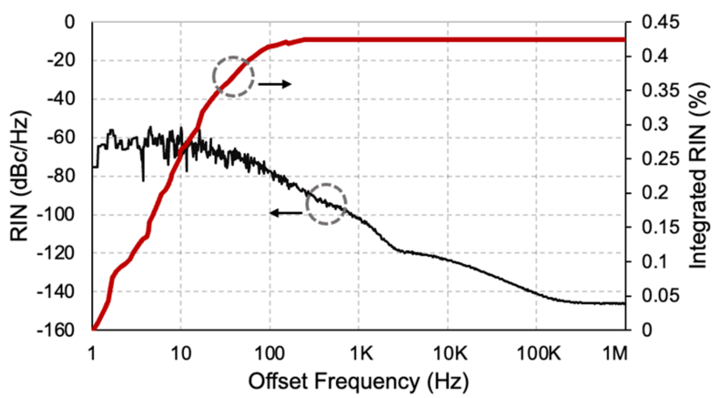

Fig. 5. Measured intensity noise of the cw mode-locked 1.1 GHz Yb:YLF laser. The relative intensity noise of the laser is measured as 0.42% within a bandwidth from 1 Hz to 1 MHz.

4. Conclusion

In conclusion, we report the first diode-pumped femtosecond Yb:YLF laser operating at GHz repetition rates. A simple two-sided pumping scheme with low-cost SMDs at 960 nm is used to generate 210 fs pulses with 40 mW average power at 1.1 GHz repetition rate. Soliton pulse shaping is implemented by using proper dispersion compensating mirrors creating a small cavity mode size in a relatively long Yb:YLF crystal (for self-phase modulation and avoiding Q-switching instabilities). The SESAM mode-locked laser was self-starting and immune to environmental fluctuations. The integrated RIN up to 1 MHz is only 0.42% without any feedback stabilization, use of covers around the laser and reduction of pump intensity noise. The output

Optics EXPRESS

power is limited by the available pump power and may be scaled up by use of a more appropriate SESAM design with lower saturation fluence and passive losses and/or by using more powerful pumping schemes (i.e., fiber coupled laser diodes).

Funding. Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (1059B142100385); Deutsche Forschungsgemeinschaft (390715994).

Acknowledgments. This work has been supported by Deutsches Elektronen-Synchrotron DESY, a member of the Helmholtz Association (HGF), POF IV DMC and the Cluster of Excellence 'Advanced Imaging of Matter' of the Deutsche Forschungsgemeinschaft (DFG).

Disclosures. The authors declare no conflict of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

1. H. R. Telle, G. Steinmeyer, A. E. Dunlop, *et al.*, "Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation," Appl Phys B **69**(4), 327–332 (1999).
2. R. Kaiser and B. Huttl, "Monolithic 40-GHz mode-locked MQW DBR lasers for high-speed optical communication systems," IEEE J. Sel. Top. Quantum Electron. **13**(1), 125–135 (2007).
3. D. Hillerkuss, R. Schmogrow, T. Schellinger, *et al.*, "26 Tbit s-1 line-rate super-channel transmission utilizing all-optical fast Fourier transform processing," Nat. Photonics **5**(6), 364–371 (2011).
4. S. T. Cundiff and A. M. Weiner, "Optical arbitrary waveform generation," Nat. Photonics **4**(11), 760–766 (2010).
5. J. Kim, J. A. Cox, J. Chen, *et al.*, "Drift-free femtosecond timing synchronization of remote optical and microwave sources," Nat. Photonics **2**(12), 733–736 (2008).
6. M. Xin, K. Şafak, and F. X. Kärtner, "Ultra-precise timing and synchronization for large-scale scientific instruments," Optica **5**(12), 1564 (2018).
7. M. Maiuri, M. Garavelli, and G. Cerullo, "Ultrafast spectroscopy: state of the art and open challenges," J. Am. Chem. Soc. **142**(1), 3–15 (2020).
8. C. R. Phillips, B. Willenberg, A. Nussbaum-Lapping, *et al.*, "Coherently averaged dual-comb spectroscopy with a low-noise and high-power free-running gigahertz dual-comb laser," Opt. Express **31**(5), 7103–7119 (2023).
9. F. F. Voigt, F. Emaury, P. Bethge, *et al.*, "Multiphoton in vivo imaging with a femtosecond semiconductor disk laser," Biomed. Opt. Express **8**(7), 3213 (2017).
10. B. Resan, R. Aviles-Espinosa, S. Kurmulis, *et al.*, "Two-photon fluorescence imaging with 30 fs laser system tunable around 1 micron," Opt. Express **22**(13), 16456–16461 (2014).
11. S. Kawabata, S. Bai, K. Obata, *et al.*, "Two-dimensional laser-induced periodic surface structures formed on crystalline silicon by GHz burst mode femtosecond laser pulses," Int. J. Extrem. Manuf. **5**(1), 015004 (2023).
12. R. I. Woodward, Y. S. Lo, M. Pittaluga, *et al.*, "Gigahertz measurement-device-independent quantum key distribution using directly modulated lasers," npj Quantum Inf **7**(1), 58 (2021).
13. C. Debaes, A. Bhatnagar, D. Agarwal, *et al.*, "Receiver-less optical clock injection for clock distribution networks," IEEE J. Sel. Top. Quantum Electron. **9**(2), 400–409 (2003).
14. Y. S. Jang, W. Kim, H. Jang, *et al.*, "Absolute distance meter operating on a free-running mode-locked laser for space mission," Int. J. Precis. Eng. Manuf. **19**(7), 975–981 (2018).
15. C. H. Li, A. J. Benedick, P. Fendel, *et al.*, "A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}," Nature **452**(7187), 610–612 (2008).
16. S. A. Diddams, "The evolving optical frequency comb [Invited]," J. Opt. Soc. Am. B **27**(11), B51 (2010).
17. T. A. G. Bondaz, J. G. McInerney, J. V Moloney, *et al.*, "Broadband 1.5 GHz VECSEL-based laser system for high speed multicontrast nonlinear imaging," IEEE Photonics Technol. Lett. **35**(11), 589–592 (2023).
18. A. Anwar, C. Perumangatt, F. Steinlechner, *et al.*, "Entangled photon-pair sources based on three-wave mixing in bulk crystals," Rev. Sci. Instrum. **92**(4), 1 (2021).
19. H. Cheng, W. Wang, Y. Zhou, *et al.*, "5 GHz fundamental repetition rate, wavelength tunable, all-fiber passively mode-locked Yb-fiber laser," Opt. Express **25**(22), 27646 (2017).
20. Z. Zhao, L. Jin, S. Y. Set, *et al.*, "2.5 GHz harmonic mode locking from a femtosecond Yb-doped fiber laser with high fundamental repetition rate," Opt. Lett. **46**(15), 3621–3624 (2021).
21. A. Bartels, D. Heinecke, and S. A. Diddams, "Passively mode-locked 10 GHz femtosecond Ti:sapphire laser," Opt. Lett. **33**(16), 1905–1907 (2008).
22. D. Li, U. Demirbas, J. R. Birge, *et al.*, "Diode-pumped passively mode-locked GHz femtosecond Cr:LiSAF laser with kW peak power," Opt. Lett. **35**(9), 1446 (2010).
23. A. Aschwanden, D. Lorenser, H. J. Unold, *et al.*, "10 GHz passively mode-locked external-cavity semiconductor laser with 1.4W average output power," Appl. Phys. Lett. **86**(13), 131102 (2005).
24. A. G. Okhrimchuk and P. A. Obraztsov, "11-GHz waveguide Nd: YAG laser CW mode-locked with single-layer graphene," Sci. Rep. **5**(1), 11172 (2015).
25. A. Choudhary, A. A. Lagatsky, P. Kannan, *et al.*, "Diode-pumped femtosecond solid-state waveguide laser with a 49 GHz pulse repetition rate," Opt. Lett. **37**(21), 4416 (2012).

26. H. A. Haus and A. Mecozzi, "Noise of mode-locked lasers," IEEE J. Quantum Electron. **29**(3), 983–996 (1993).
27. R. Paschotta, "Noise of mode-locked lasers (Part I): numerical model," Appl. Phys. B **79**(2), 153–162 (2004).
28. D. Li, U. Demirbas, A. Benedick, *et al.*, "Attosecond timing jitter pulse trains from semiconductor saturable absorber mode-locked Cr:LiSAF lasers," Opt. Express **20**(21), 23422–23435 (2012).
29. F. Pirzio, S. D. D. D. Cafiso, M. Kemnitzer, *et al.*, "Sub-50-fs widely tunable Yb:$CaYAlO_4$ laser pumped by 400-mW single-mode fiber-coupled laser diode," Opt. Express **23**(8), 9790 (2015).
30. Y. Wang, X. Su, Y. Xie, *et al.*, "17.8 fs broadband Kerr-lens mode-locked Yb:CALGO oscillator," Opt. Lett. **46**(8), 1892–1895 (2021).
31. Z. Gao, J. Zhu, J. Wang, *et al.*, "Generation of 33 fs pulses directly from a Kerr-lens mode-locked Yb:$CaYAlO_4$ laser," Photonics Res. **3**(6), 335 (2015).
32. W. Chen, Z.-L. Lin, W.-Z. Xue, *et al.*, "Kerr-lens mode-locked Yb:$YAlO_3$ laser generating 24-fs pulses at 1085 nm," Opt. Lett. **47**(18), 4728–4731 (2022).
33. G. Boulon, Y. Guyot, M. Ito, *et al.*, "From optical spectroscopy to a concentration quenching model and a theoretical approach to laser optimization for Yb^{3+}-doped $YLiF_4$ crystals," Mol. Phys. **102**(11-12), 1119–1132 (2004).
34. L. D. DeLoach, S. A. Payne, L. L. Chase, *et al.*, "Evaluation of absorption and emission properties of Yb^{3+} doped crystals for laser applications," IEEE J. Quantum Electron. **29**(4), 1179–1191 (1993).
35. U. Demirbas, J. Thesinga, M. Kellert, *et al.*, "Detailed investigation of absorption, emission and gain in Yb:YLF in the 78–300 K range," Opt. Mater. Express **11**(2), 250–272 (2021).
36. A. A. Lagatsky, C. T. A. Brown, and W. Sibbett, "Highly efficient and low threshold diode-pumped Kerr-lens mode-locked Yb:KYW laser," Opt. Express **12**(17), 3928 (2004).
37. M. Hamrouni, F. Labaye, N. Modsching, *et al.*, "Efficient high-power sub-50-fs gigahertz repetition rate diode-pumped solid-state laser," Opt. Express **30**(17), 30012 (2022).
38. A. S. Mayer, C. R. Phillips, and U. Keller, "Watt-level 10-gigahertz solid-state laser enabled by self-defocusing nonlinearities in an aperiodically poled crystal," Nat. Commun. **8**(1), 1673 (2017).
39. M. Seidel, J. Pilat, L. Lang, *et al.*, "Ultrafast Yb:YAG laser oscillator with gigahertz repetition rate," Opt. Express **31**(21), 34313 (2023).
40. Z. Zhang, J. Ma, G. Zhao, *et al.*, "Sub-100 fs watt-level Kerr-lens mode-locked Yb:$CaYAlO_4$ laser with a gigahertz repetition rate," Front. Phys. **11**(01), 1–5 (2023).
41. L. Zheng, Y. Chen, W. Tian, *et al.*, "1.6-GHz, 3.3-W Kerr-lens mode-locked Yb:KGW oscillator pumped by a multimode laser diode," in *2022 Conference on Lasers and Electro-Optics (CLEO)* (OSA, 2022), pp. 2022–2023.
42. R. Wust, D. Hug, B. Rudin, *et al.*, "250 fs, 130 mW laser with tunable pulse repetition rate from 0.5 to 1.3 GHz," IEEE Photonics J. **14**(5), 1–6 (2022).
43. A. Klenner, M. Golling, and U. Keller, "A gigahertz multimode-diode-pumped Yb:KGW enables a strong frequency comb offset beat signal," Opt. Express **21**(8), 10351 (2013).
44. S. Pekarek, T. Südmeyer, S. Lecomte, *et al.*, "Self-referenceable frequency comb from a gigahertz diode-pumped solid-state laser," Opt. Express **19**(17), 16491 (2011).
45. S. Pekarek, A. Klenner, T. Südmeyer, *et al.*, "Femtosecond diode-pumped solid-state laser with a repetition rate of 4.8 GHz," Opt. Express **20**(4), 4248 (2012).
46. S. Pekarek, C. Fiebig, M. C. Stumpf, *et al.*, "Diode-pumped gigahertz femtosecond Yb:KGW laser with a peak power of 3.9 kW," Opt. Express **18**(16), 16320 (2010).
47. A. Klenner and U. Keller, "All-optical Q-switching limiter for high-power gigahertz modelocked diode-pumped solid-state lasers," Opt. Express **23**(7), 8532 (2015).
48. A. Klenner, M. Golling, and U. Keller, "High peak power gigahertz Yb:CALGO laser," Opt. Express **22**(10), 11884 (2014).
49. H. Yang, C. Kim, S. Y. Choi, *et al.*, "femtosecond Yb : KYW laser mode-locked by a carbon nanotube saturable absorber mirror," Opt. Express **20**(28), 29518–29523 (2012).
50. T. C. Schratwieser, C. G. Leburn, and D. T. Reid, "Highly efficient 1 GHz repetition-frequency femtosecond Yb^{3+}:$KY(WO_4)_2$ laser," Opt. Lett. **37**(6), 1133 (2012).
51. M. Endo, A. Ozawa, and Y. Kobayashi, "Kerr-lens mode-locked Yb:KYW laser at 4.6- GHz .pdf," Opt. Express **20**(11), 12191–12197 (2012).
52. S. Yamazoe, M. Katou, T. Adachi, *et al.*, "Palm-top-size, 15 kW peak-power, and femtosecond (160 fs) diode-pumped mode-locked Yb^{+3}:$KY(WO_4)_2$ solid-state laser with a semiconductor saturable absorber mirror," Opt. Lett. **35**(5), 748 (2010).
53. M. Endo, A. Ozawa, and Y. Kobayashi, "6-GHz, Kerr-lens mode-locked Yb:Lu_2O_3 ceramic laser for comb-resolved broadband spectroscopy," Opt. Lett. **38**(21), 4502–4505 (2013).
54. A. A. Lagatsky, A. Choudhary, P. Kannan, *et al.*, "Fundamentally mode-locked, femtosecond waveguide oscillators with multi-gigahertz repetition frequencies up to 15 GHz," Opt. Express **21**(17), 19608–19614 (2013).
55. S. Y. Choi, T. Calmano, F. Rotermund, *et al.*, "2-GHz carbon nanotube mode-locked Yb:YAG channel waveguide laser," Opt. Express **26**(5), 5140–5145 (2018).
56. J. E. Bae, X. Mateos, M. Aguiló, *et al.*, "Multi-gigahertz mode-locked femtosecond Yb:KLuW waveguide lasers," Photonics Res. **10**(11), 2584–2589 (2022).
57. G. Brasse, P. Loiko, C. Grygiel, *et al.*, "Liquid Phase Epitaxy growth, structure and spectroscopy of highly-doped 20 at.% Yb^{3+}:$LiYF_4$ thin films," J. Lumin. **236**(11), 118071 (2021).

58. S. Püschel, S. Kalusniak, C. Kränkel, *et al.*, "Temperature-dependent radiative lifetime of Yb:YLF: refined cross sections and potential for laser cooling," Opt. Express **29**(7), 11106–11120 (2021).
59. U. Demirbas, M. Kellert, J. Thesinga, *et al.*, "Advantages of YLF host over YAG in power scaling at cryogenic temperatures: direct comparison of Yb-doped systems," Opt. Mater. Express **12**(7), 2508–2528 (2022).
60. M. Kilinc, U. Demirbas, J. B. Gonzalez-Diaz, *et al.*, "Thermal and population lensing of Yb:YLF at cryogenic temperature," Opt. Mater. Express **13**(11), 3200–3216 (2023).
61. J. Kawanaka, H. Nishioka, N. Inoue, *et al.*, "Tunable continuous-wave Yb:YLF laser operation with a diode-pumped chirped-pulse amplification system," Appl. Opt. **40**(21), 3542–3546 (2001).
62. U. Demirbas, J. Thesinga, M. Kellert, *et al.*, "Broadly tunable (993–1110 nm) Yb:YLF laser," Appl. Opt. **61**(13), 3702–3710 (2022).
63. M. Vannini, G. Toci, D. Alderighi, *et al.*, "High efficiency room temperature laser emission in heavily doped Yb:YLF," Opt. Express **15**(13), 7994–8002 (2007).
64. A. Pirri, G. Toci, D. Alderighi, *et al.*, "Yb-doped YLF and CaF_2 crystal laser at room temperature," Opt. Mater. (Amst). **33**(2), 200–204 (2010).
65. W. Bolaños, F. Starecki, A. Braud, *et al.*, "2.8 W end-pumped Yb^{3+}:$LiYF_4$ waveguide laser," Opt. Lett. **38**(24), 5377–5380 (2013).
66. N. Coluccelli, G. Galzerano, L. Bonelli, *et al.*, "Diode-pumped passively mode-locked Yb:YLF laser," Opt. Express **16**(5), 2922–2927 (2008).
67. F. Pirzio, L. Fregnani, A. Volpi, *et al.*, "87 fs pulse generation in a diode-pumped semiconductor saturable absorber mirror mode-locked Yb:YLF laser," Appl. Opt. **55**(16), 4414–4417 (2016).
68. U. Demirbas, J. Thesinga, M. Kellert, *et al.*, "Semiconductor saturable absorber mirror mode-locked Yb:YLF laser with pulses of 40 fs," Opt. Lett. **47**(4), 933 (2022).
69. F. X. Kartner, I. D. Jung, and U. Keller, "Soliton mode-locking with saturable absorbers," IEEE J. Sel. Top. Quantum Electron. **2**(3), 540–556 (1996).
70. U. Keller, "*Passive Modelocking BT - Ultrafast Lasers: A Comprehensive Introduction to Fundamental Principles with Practical Applications*," in U. Keller, ed. (Springer International Publishing, 2021), pp. 419–546.
71. A. Schlatter, S. C. Zeller, R. Grange, *et al.*, "Pulse-energy dynamics of passively mode-locked solid-state lasers above the Q-switching threshold," J. Opt. Soc. Am. B **21**(8), 1469–1478 (2004).