250 fs, 130 mW Laser With Tunable Pulse Repetition Rate From 0.5 to 1.3 GHz

Roger Wüst, Daniel Hug, Benjamin Rudin, Florian Emaury, and Bojan Resan

***Abstract*—We report a compact ultrafast solid-state laser source with a pulse repetition rate continuously tunable in the range of 0.56–1.23 GHz. The optical cavity design allows a user to vary the repetition rate only by moving positions of two optical components inside the resonator, without a need to exchange components or realignment. The Yb:KYW crystal based cavity emits 250 femtosecond pulses at a central wavelength around 1040 nm, with a self-starting SESAM modelocking. In a robust modelocked operation mode, an average power up to 130 mW is achieved using a stabilized single mode pump diode at a wavelength of 981 nm, while the laser in continuous wave (CW) mode delivers up to 270 mW. Atmospheric air cooling was sufficient for both CW and modelocked laser operation. Quite low noise performance was observed, with carrier frequency SNR higher than 80 dB, although the measurements were taken with the open breadboard setup.**

***Index Terms*—GHz lasers, high pulse repetition rate, modelocked lasers, solid state lasers, ultrafast lasers.**

I. Introduction

In the recent years the demand for ultrafast laser systems with various parameters in terms of wavelength, power, pulse repetition rate and noise level has risen continuously, as one can remarkably improve the minimal processed feature size and resolution with various laser parameters for different materials and diverse processes [1].

In some applications such as the field of frequency comb generation at various wavelengths, a low noise level is required [2], [3], [4]. By using a fiber Bragg grating (FBG)-stabilized laser diode with a single mode fiber output as a pump source, solid-state lasers have demonstrated quite low noise levels [5], [6]. The lower output power level of a single mode fiber delivered pump diode has advantages in thermal management of the laser, while limiting the fs laser output power. An all-air-cooled solution is sufficient for cooling a <1 W pump laser diode enabling 100–200 mW output power from the fs laser and leading to a simpler opto-mechanical design.

Recently, the concept of Ablation-cooling was introduced by Fatih Ömer Ilday and his team in the field of laser micromachining [7], [8]. Using femtosecond pulses and very high pulse repetition rates in GHz range, which make the Ablation-cooling process possible, material removal was demonstrated with an extremely low thermal damage. This principle reduces the single pulse energy required for the process and has a broad range of possible scientific [8], [9], medical [9], [10] and industrial applications [11]. Excellent results have been demonstrated especially with materials like copper [12], [13], silicium [14], glass and water-rich soft tissues [7], each material being processed with an appropriate laser wavelength.

Different approaches for cavities in the GHz pulse repetition rate were pursued over the last years including a ring cavity [15], a Kerr-lens modelocked laser [16], a SESAM modelocked laser [17], [18] or a principle with a seed signal in the MHz range which is multiplied by cascaded 50/50 coupler into the GHz range [19], [20]. These lasers show pulse repetition rates from 1–10 GHz [21] with laser output power from 14.6 mW [16], [22] to 2.2 W [2] or 3.4 W [17] with high peak power. As single mode pump diodes are limited in pump power, all of the higher output power laser setups were pumped with commercial multimode diode laser(s) [17], [23].

As in large part of the laser applications including medical and micromachining, typical wavelengths are around 1 micron, we are focusing our efforts on that wavelength. Most laser companies are selling established ultrafast laser oscillators with up to approximately 100 MHz pulse repetition rate [24].

Compared to other commercially available materials hosting ytterbium, Yb:KYW crystal exhibits broader and smoother emission spectrum around 1 micron, enabling generation of shorter fs pulses. Therefore, this was our material of choice to build this laser cavity. Yb:KYW crystal was claimed to be very suitable as a pulsed laser source [25], as well as it features very high slope efficiency of over 85% [26].

Specific pulse repetition rates are required for different applications [20] and large tunability of the pulse repetition rate would be a huge benefit. Acousto-optic modulators (AOMs) as pulse pickers are still limited in speed to ∼100 MHz and can only lower the repetition rate, while tuning with a piezo actuator enables just a few 100s of kHz around a fixed pulse repetition rate is not providing the targeted broader range of tunability. Increasing the pulse repetition rate by multiple stages of 50/50 beam splitters

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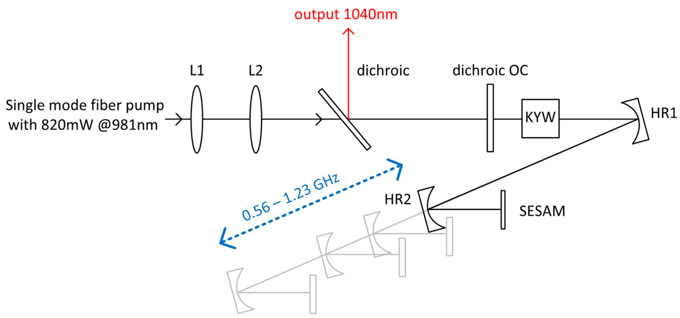


Fig. 1. Layout of the Z-shaped tunable modelocked laser cavity.

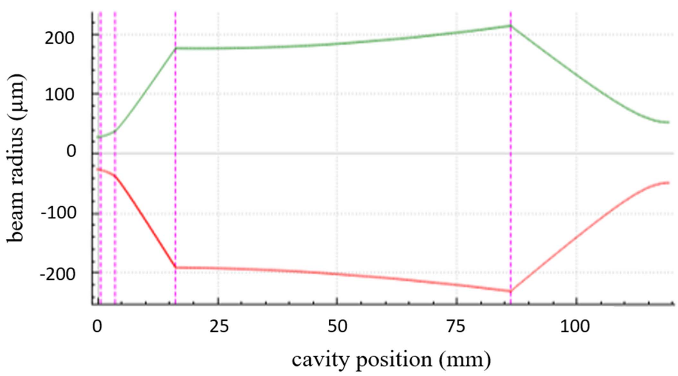


Fig. 2. Simulation of the Gaussian beam cavity propagation (diameter versus position in the cavity) for the 1.003 GHz Z-shape cavity, with 5° AOI at HR1 and HR2. Green curve shows tangential dimension and red curve shows sagittal dimension.

and combiners has drawbacks in size, complexity and mechanical long-term stability with free-space optics or cost with fiber optics components. An opto-mechanical concept enabling significantly different pulse repetitions rates without changing the cavity components or realignment, would therefore be very interesting from a scientific and commercial point of view.

Single and multimode diode pumped solid state ultrafast lasers in the GHz regime have been demonstrated previously, but each of them with very different laser cavity [15], [22], [27], [28]. In our work, we demonstrate a new concept of a fundamentally modelocked laser cavity, which allows to continuously tune the pulse repetition rate from 0.56 to 1.23 GHz with the same optical components on a simple movable mechanical platform, without realignment. Furthermore, with measured RF spectra we demonstrate quite low noise level of our femtosecond laser cavity, especially considering that we worked with an open breadboard setup.

II. Simulations

Initially extensive simulations and calculations were performed using a publicly available ABCD matrix simulation software, and the stability of the cavity was investigated. The laser simulation model was built up with two 100% reflective end mirrors (AOI = 0°), a crystal with defined length and refractive index, and two curved HR mirrors, where the AOIs were varied to simulate a wide range of angles of the Z-shaped cavity (see Fig. 2). V-cavities did not work for this widely tunable laser, as a z-shape with collimated middle section was required. By varying the radii of curvature of the HR mirrors as well as tuning the distances between the optics, a setup was found where only the distance between the HR-mirrors and the distance from HR2 to the SESAM had to be adapted for different pulse repetition rates.

According to the simulation, stable cavities with lower or higher pulse repetition rates than 0.5 or 1.3 GHz respectively, are also possible. This is because the simulations describe continuous wave (CW) mode, gaussian beam propagation, and do not take into account the required fluence on the SESAM for stable modelocking.

For large tunability of the pulse repetition rate, a cavity with a focused beam waist in a crystal positioned between the two curved HR mirrors was not possible. Therefore, we placed the gain crystal just next to the dichroic output coupler. This also led to a simpler pump arrangement as there was more space for the 45-degree dichroic mirror between the focusing pump optic and the output coupler (see Fig. 1).

An important insight from the simulations was the strong influence of the angle of incidence (AOI) on the curved mirrors on the laser performance. As the software only allows to simulate in CW mode, we can only state that the simulation result become very asymmetric and the targeted spot size on SESASM (HR in simulation) and crystal become too large and deformed, but still deliver a stable cavity with high AOI. AOI up to 5 degrees on both curved mirrors have no big impact on the asymmetry of the beam and only small impact on the mode size diameter (see Fig. 2). With lager AOIs the deviation from a symmetric beam increases exponentially, while the maximum output power decreases [29].

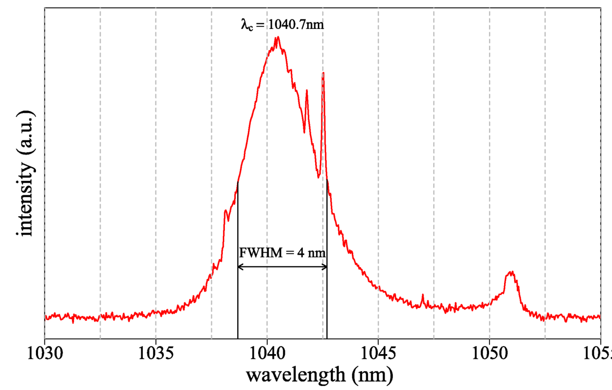
Our experience is that stable modelocking is only possible with AOI $< 10°$ and CW lasing was only achieved with AOI less than 15°. At some point, mechanical restrictions due to the optics sizes and optic holders prevented us from further decreasing the AOI in the small cavity (see Fig. 1). Generally, one can say that larger AOIs lead to too strong aberrations, astigmatism [30] and beam deformation and prevent the laser operation. As we were using highly curved mirrors, the beam size on these two mirrors must be relatively small too.

III. Experimental Setup

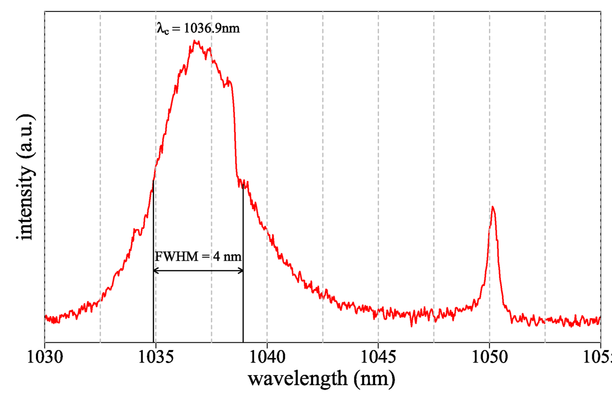
The laser gain media was an antireflection coated Yb^{3+}-doped $KY(WO_4)_2$ monoclinic crystal with 3 mm thickness in N_g cut orientation (light propagates in N_g axis direction), AOI = 0 degree, and 3% doping concentration. The absorption peak at 981 nm [31] and its ability to support high efficiency lasers with a low lasing threshold makes it favorable for our application in a high repetition rate solid-state diode pumped laser [32]. For the current laser we used a commercially available single mode fiberized pump diode (3SP Technologies, model 1999CHP) with a FBG stabilized output at a measured wavelength of 980.8 nm and a maximum pump power of 820 mW. With the appropriate pump lenses (f = 20mm/150mm), the 6.6 μm mode field diameter from the pump diode fiber was focused to a gain mode size diameter of 45 μm ($1/e^2$) in the Yb:KYW crystal.

The laser cavity is a Z-shape with an adjustable middle section with collimated beam between the two curved high reflection mirrors HR1 and HR2 (see Figs. 1 and 2). For this reason, one of the curved reflective mirrors (HR2) and the semiconductor saturable absorber mirror (SESAM) were placed on a mechanically movable platform. The mechanical platform can be placed with hand with around 0.5 mm accuracy in beam direction using a side rail with the possibility to optimize modelocking with a micrometer translation stage where the SESAM is put on. In a future prototype the accuracy of tuning can be improved using an additional micrometer translation stage if an exact pulse repetition rate is needed. The commercially available GaAs based SESAM SAM-1040-1-1ps from Batop GmbH, enabling the self-starting passive fundamental modelocking, is placed as an end mirror, with an incident mode size diameter of 75–94 μm, depending on the actual set pulse repetition rate (position of the movable platform). The SESAM has a modulation depth of 0.9%, non-saturable loss of 0.4%, relaxation time constant of ~1 ps and a saturation fluence of 50 μJ/cm^2. The curved high reflection coated mirrors HR1 and HR2 of this ultrafast laser system provide a negative group delay dispersion (GDD) of -550 fs^2 each leading to a net cavity dispersion of -2200 fs^2 per roundtrip [33]. The dichroic mirror acts also as an output coupler. The reason for that was to avoid extra optics, which would lead to difficulties in tuning the pulse repetition rate and would lower the efficiency if more optical components were used. Another 45-degree dichroic mirror was used to separate the pulsed output beam from the incoming CW pump light.

Starting from a cavity with a pulse repetition rate of 0.5 GHz the movable platform was stepwise moved closer to the first curved mirror (HR1).



(a)



(b)

Fig. 3. Optical spectrum of the 0.56 (a) and the 1.23 GHz (b) cavity.

IV. Results

In CW mode, using an HR mirror instead of the SESAM, in all four characterized cavity distances (for 0.56, 1.00, 1.12 and 1.23 GHz) the laser generated an output power >200 mW. The highest output power of 273 mW was measured at 1.003 GHz pulse repetition rate, which corresponds to an optical-to-optical efficiency of over 33%. Initially, 0.5 GHz modelocked cavity with SESAM, showed Q-switching instabilities [34] due to a too small mode size diameter on the SESAM. This was improved by enlarging the SESAM spot diameter according to the revised simulations. With an appropriate spot size diameter of 75 μm (1/e^2) for the 0.56 GHz cavity (in the simulations), damaging the SESAM due to too high energy density and over-saturation were avoided. A vertically polarized modelocked output power of 78 mW was measured at this pulse repetition rate. The light polarization was in N_p direction using the N_g cut crystal.

The optical spectrum is 4 nm in FWHM. As we did not have a polarization filter in the cavity (e.g., Brewster window), even by rotating the crystal by 90 degrees around the N_g axis the lasing occurred in the N_p direction (now horizontal). The output power in this configuration was significantly lower and therefore we continued our experiments with the initial orientation of the crystal. We think that the high curvature of the two HR mirrors and relatively large AOI in horizontal plane led to high aberrations if lasing was obtained with horizontal polarization (P-polarization) parallel to N_m crystal axis. For this crystal orientation, only 20–30 mW of output power was obtained. Our reported higher power of >100 mW was obtained only with vertical laser output polarization (S-polarization) parallel to crystal N_p axis.

Two slightly different central wavelengths occurred in each of the four pulse repetition rates, depending on the lateral position of the SESAM in the sub-millimeter range. All of them were in the range of the emission around 1040 nm from the N_p direction. We observed the tendency that with the higher central wavelength around 1042 nm a higher output power was possible. In the setup with a central wavelength of 1042 nm a small CW breakthrough could be detected (see Fig. 3(a)). This could not be prevented by any adjustments of the cavity or reducing the pump power and the origin is still under investigation. As the area from the CW part in the spectrum is small in comparison to the area of the modelocked spectrum, we conclude that this CW background is negligible compared to the modelocked pulse's energy. The peak slightly above 1050 nm is due to a mismatch in dispersion at that wavelength [35], [36], [37]. These peaks, called Kelly sidebands, are typical at the edges of broad spectra.

The second-harmonic generation (SHG) intensity autocorrelation trace, measured with Femtochrome FR-103XL, demonstrates optical pulse durations from 291 to 251 fs (see Fig. 4), assuming sech^2- shaped pulse profile. The spectrum is 3% broader than from bandwidth-limited sech2- shaped pulses, with a time bandwidth product (TBP) of 0.323 at a pulse repetition rate of 0.56 GHz. Therefore, the temporal pulses are slightly chirped. The autocorrelation trace shows clean modelocked pulse without shoulders or sub-pulses. The shortest pules were

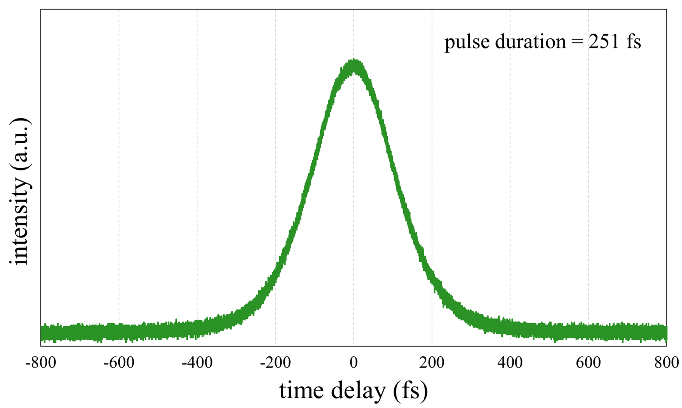


Fig. 4. SHG intensity autocorrelation trace for 1.23 GHz cavity corresponding to 251 fs pulse duration, assuming sech^2-shaped pulses.

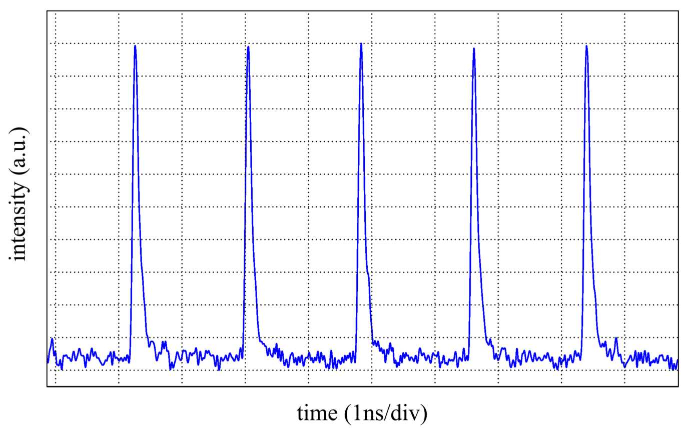


Fig. 5. Pulse train of the 0.56 GHz setup measured with a photodiode and a fast oscilloscope in stable CW modelocking.

measured at a pulse repetition rate of 1.228 GHz with 251 fs pulse duration.

By observing the pulsed output with a fast photodiode (model Picometrix D-15ir) coupled with a 16 GHz sampling oscilloscope (model Tektronix DSA71604) we observed the pulse repetition rate and prevented eventual Q-switching and SESAM damage. We proved that the laser is in CW modelocking regime and not in Q-switching regime by observing ns to ms time scales on the oscilloscope (see Fig. 5).

The radio frequency (RF) spectra were measured using the Picometrix D-15ir photodiode and the RF spectrum analyzer Hewlett Packard 8563E. No side peaks were detected between zero and the second harmonic frequency demonstrating stable, single spatial mode, modelocked lasing (see Figs. 6 and 7). RF spectra demonstrate very low noise level for a breadboard setup with carrier frequency SNR >80 dB (see Fig. 7(b)). Detailed phase (timing jitter) and amplitude noise (RIN) characterization is under way and is the subject of the next publication.

Once the laser is in stable CW modelocking, the influence of gain filtering and soliton-shaping effects [38] help to stabilize modelocking and avoid Q-switching instabilities [34].

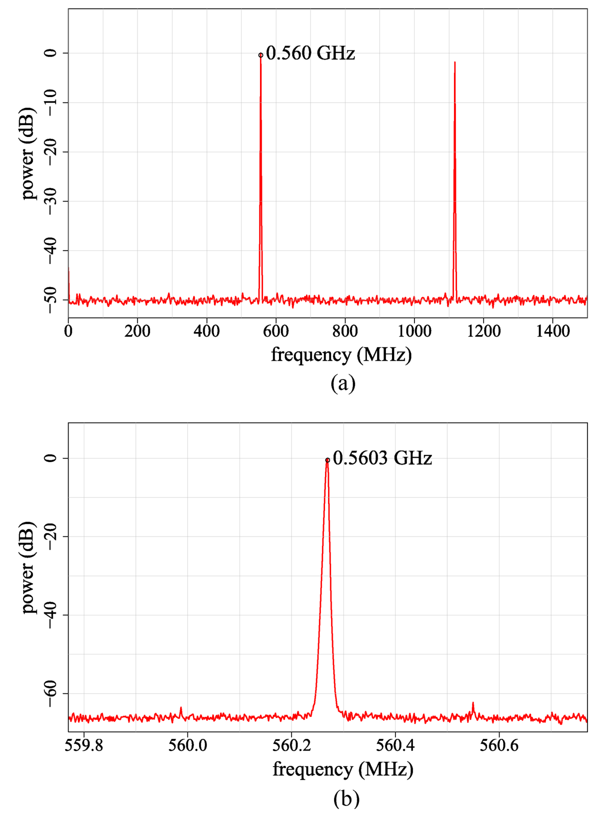


Fig. 6. RF spectrum of the 0.56 GHz cavity (span = 1.5 GHz and RBW = 1 MHz) (a) and 0.56 GHz cavity (span = 1 MHz and RBW = 3 kHz) (b).

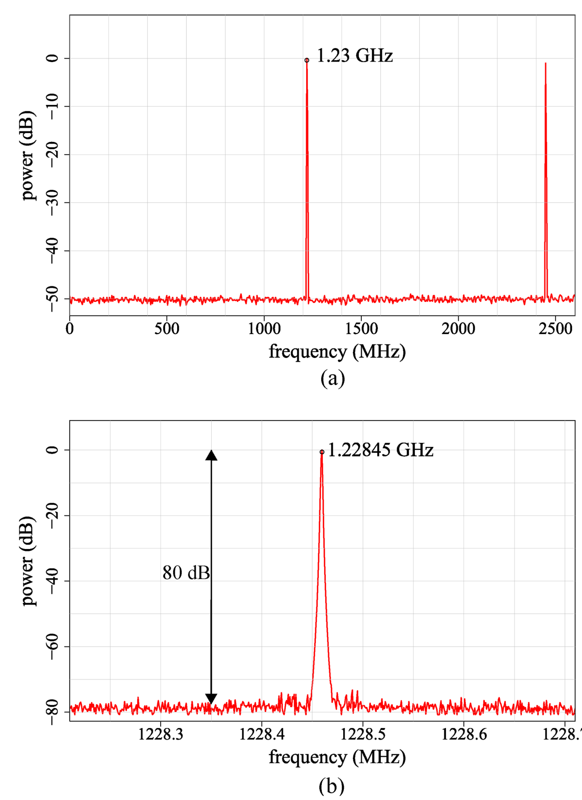


Fig. 7. RF spectrum of the 1.23 GHz cavity (span = 2.6 GHz and RBW = 2 MHz) (a) and 1.23 GHz cavity (span = 500 kHz and RBW = 1 kHz) (b).

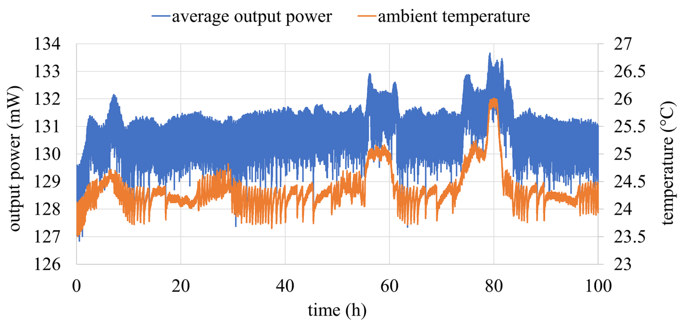


Fig. 8. Long-term power stability and ambient temperature of the 1.12 GHz cavity over 100 hours.

TABLE I
RESULT SUMMARY FOR FOUR PULSE REPETITION RATES

Pulse repetition rate	f_p	[GHz]	0.558	1.003	1.120	1.228
Pulse duration	τ_p	[fs]	292	252	255	251
Optical pump power	P_{pump}	[mW]	650	650	820	735
Average output power	P_{avg}	[mW]	78	81	127	98
Central wavelength	λ_c	[nm]	1040.4	1036.9	1042.1	1036.7
CW output power	P_{cw}	[mW]	270	273	209	197
FWHM spectrum	$\Delta\lambda$	[nm]	4.0	4.2	3.1	4.0
Simulated spot size SESAM	d_{SESAM}	[µm]	75	88	91	94
Saturation ratio	R_S	[-]	2.5	1.07	1.42	0.92

A clear single-mode TEM_{00} operation of the laser is confirmed with an M^2 values of 1.11 in both x and y direction, measured with Ophir-Spiricon LLC M2-200s-FW. The long-term stability of the optical output power, showing minor oscillations following the fluctuations of the ambient temperature in the lab is shown in Fig. 8. No degradation of the power was observed in over 100 hours of permanent laser run.

V. DISCUSSION

In the cavity numerical simulations, the modelocking stability restrictions were not incorporated and therefore, the pulse repetition rate could be adjusted in simulations far beyond the range that we could demonstrate in the experiment. From the practical experience with the modelocked cavity we know the limit of the AOI is around 10° and the limiting factor for the obtained range of the pulse repetition rates is the mode size diameter on the SESAM. As we use the same optics, at some point the spot on the SESAM does not fit in the required energy density range for stable modelocking. A too small spot on the SESAM leads to damages on the SESAM incident area and a too big spot leads to Q-switching and instable modelocking due to insufficient saturation of the irradiated surface. For this reason, we are limited in the tunability from 0.56 GHz to 1.23 GHz pulse repetition rate or 122 mm to 268 mm in cavity length. With this insight, we assume that our cavity principle can be implemented for other pulse repetition rate ranges with an appropriately designed spot on the SESAM, which eventually requires appropriate combination of distances and optical curvatures.

No spatial hole burning effect [39] was detected in the laser performance, although the gain medium is placed very close to the end of this cavity.

The formula for calculating the Q-switching instability threshold [34] was missed by a factor of 300, i.e., we were in Q-switching regime 300 times below the Q-switching threshold. This underlines the importance and influence of other factors including soliton shaping when working with ultrafast lasers with high repetition rates. Due to the lack of information about all the parameters needed for the extended formula described in [34], we cannot evaluate its value for our laser.

AOI and spot size on the HR optics are crucial due to high curvature of HR mirrors and associated aberrations. AOI should be kept below 5° and beam diameters below 1 mm, in order to obtain stable modelocking. Those conditions prevented cavity designs with the gain crystal in the middle and were met only with gain crystal at the end of the cavity.

The maximum achievable modelocked output power was limited by the available pump power from a single mode fiber delivered laser diode. With the available maximum pump power, the modelocked laser did not show increasing CW-breakthroughs, double-pulsing, or Q-switching instabilities. Additionally, the CW-breakthrough in the left optical spectrum of Fig. 3 could not be reduced or fully avoided by lowering the pump power, as one might have expected. With more available single mode pump power and/or lower SESAM non-saturated losses [28], one should be able to obtain higher output power and shorter pulses.

VI. CONCLUSION

We demonstrated a single mode, fiberized output diode pumped solid state laser with ultrashort pulses of 250 fs and a tunable pulse repetition rate in the range of 0.56 to 1.23 GHz with an output power up to 130 mW. While tuning the pulse repetition rate, the same passive optical components remained in the cavity. The different repetition rates were realized by just moving the two optics, without additional realignment. As mentioned, with the same components, a broad range of different pulse repetition rates (see Table I) can be achieved with the novel laser cavity concept with collimated beam and crystal near the end of the cavity.

One of the next steps is to construct a boxed prototype laser delivering the same output power and pulse duration, but lower noise performance and simplified handling. We will further characterize the timing jitter (phase noise) and amplitude noise (RIN) from this prototype laser. Furthermore, this laser will be used for future investigation of the performance of 100 W level amplifiers [40] and GHz-bandwidth fast modulators to achieve 100 W, GHz repetition rate, fs laser with single pulse switching capability. Moreover, this fs oscillator featuring widely tunable pulse repetition rate, with 100 W amplifier, will be used for in-depth studies of micro-machining in the regime of Ablation-cooling, and other applications where continuous tunability of the pulse repetition rate is beneficial. In addition, the low noise laser oscillator seems promising as clocking signal for synchronization of other signal sources, optical sampling and other optical communication applications.

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