Diode-Pumped Passively Mode-Locked Nd:YVO_4 Lasers With 40-GHz Repetition Rate

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***Abstract*—We present two different diode-pumped passively mode-locked Nd:YVO_4 lasers with a repetition rate of 40 GHz. This is the highest repetition rate demonstrated so far with diode-pumped 1-μm solid-state lasers. The first laser design allows short pulses of 2.7-ps duration whereas the second laser design is optimized for high average output power of up to 288 mW. We compare both design approaches and show that there is a tradeoff between output power and pulse duration.**

***Index Terms*—Diode-pumped lasers, high-pulse repetition rates, mode-locked lasers, semiconductor absorbers.**

I. Introduction

PROGRESS over the last decade in ultrafast all-solid-state lasers has pushed performance in average power and pulse repetition rate by 2–3 orders of magnitude [1]. Trains of picosecond or femtosecond mode-locked pulses at repetition rates of several gigahertz are required for various applications like telecommunications [2], optical clocking of very fast computer processors [3], high-speed electro-optic sampling [4], analog-to-digital conversion, time-resolved spectroscopy with high signal-to-noise ratio [5], generation of polarized electron beams for particle accelerators [6], and pumping of optical parametric oscillators [7], [8]. Such pulse trains should be generated with compact, efficient and reliable lasers delivering at least a few picojoules of pulse energy (e.g., 1 pJ of pulse energy with a pulse repetition rate of 40 GHz corresponds to an average output power of 40 mW). The noise properties are also very important, and timing stabilization of the laser using an external microwave reference oscillator may be required [9]. Depending on the application, the emission wavelength can be of concern and might ideally be tunable. For example, for telecommunication through optical fibers, the often used C-band has a wavelength region between 1530 and 1565 nm. Optical parametric oscillators allow coverage of even much wider wavelength ranges [8]; for multigigahertz pulse repetition rates, they require solid-state pump lasers with optimized output power.

Several approaches are currently being explored to generate mode-locked pulses at gigahertz repetition rates. One common approach is represented by actively and passively mode-locked fiber lasers. These lasers can produce very high repetition rates of up to 200 GHz [10] but at the cost of a high complexity due to harmonic mode locking and relatively low output powers of at most a few tens of milliwatts. Even higher repetition rates of more than 1 THz can be reached with mode-locked edge-emitting semiconductor lasers [11]. In general, the pulses from such laser diodes are strongly chirped, and the average output power is typically only a few milliwatts or even below 1 mW. Optically pumped vertical-external cavity surface-emitting semiconductor lasers (VECSELs) that are passively mode-locked with a semiconductor saturable absorber (SESAM) [12], [13], can generate high average output powers in picosecond pulses of good quality [14], [15], and close to transform-limited femtosecond pulses [16]. Recently, a 10-GHz device of this kind with 1.4 W average output power has been demonstrated [17], and higher repetition rates should be possible.

Here we present another class of lasers based on a Nd:YVO_4 crystal and on passive mode locking using a SESAM. This concept has been demonstrated with up to a 157-GHz repetition rate [18], but so far repetition rates higher than 13 GHz [19] have required the use of a Ti:sapphire laser as a pump source with high brightness. A 10-GHz diode-pumped laser was optimized for a high average output power of 2.1 W [18]. Table I presents a summary of 1-μm solid-state lasers with repetition rates above 1 GHz. Similar lasers with Er:Yb:glass as gain medium, emitting within the telecom C-band, have been demonstrated with repetition rates of up to 50 GHz [20]. Both types of lasers produced pulses of some picosecond durations and of very high quality.

In this paper, we present diode-pumped passively mode-locked Nd:YVO_4 lasers with repetition rates around 40 GHz. This is the highest repetition rate achieved so far for diode-pumped 1-μm lasers (see Table I). A key point was the use of novel high-brightness pump diodes. We demonstrate two different laser designs meeting different goals. In Section II, we describe a laser optimized for short pulses of 2.7-ps duration with an average output power of 49 mW, whereas in Section III we present a second laser producing longer pulses with 6.5-ps

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TABLE I
1-μm SOLID-STATE LASERS WITH REPETITION RATES ABOVE 1 GHz

Laser Material	ML technique	λ_0	τ_p	$P_{av, out}$	f_{rep}	Pumping	Ref.
Nd:YLF	Active AOM	1.047 μm	7 ps	135 mW	2 GHz	Diode pumped	[21]
Nd:YLF	Active EOM	1.053 μm	4.5 ps	400 mW	2.85 GHz	Diode pumped	[22]
Nd:YLF	Active EOM	1.053 μm	13 ps	350 mW	5 GHz	Ti:sapphire laser pumped	[23]
Nd:BEL	Active EOM	1.070 μm	3.9 ps	30 mW	20 GHz	Diode pumped	[24]
$Nd:GdVO_4$	Passive SESAM	1.063 μm	12 ps	500 mW	10 GHz	Diode pumped	[9]
$Nd:YVO_4$	Passive SESAM	1.064 μm	14 ps	2100 mW	10 GHz	Diode pumped	[18]
$Nd:YVO_4$	Passive SESAM	1.064 μm	8.3 ps	198 mW	13 GHz	Diode pumped	[19]
$Nd:YVO_4$	Passive SESAM	1.064 μm	≈ 5.3 ps	≈ 60 mW	39, 49, 59 GHz	Ti:sapphire laser pumped	[25]
$Nd:YVO_4$	Passive SESAM	1.064 μm	2.7 ps	≈ 50 mW	77, 157 GHz	Ti:sapphire laser pumped	[26, 18]
$Nd:YVO_4$	Passive SESAM	1.064 μm	6.5 ps	288 mW	40 GHz	Diode pumped	This publication
$Nd:YVO_4$	Passive SESAM	1.064 μm	2.7 ps	49 mW	39 GHz	Diode pumped	This publication

ML technique: mode-locking technique. λ_0: center lasing wavelength. τ_p: measured pulse duration. $P_{av, out}$: average output power. f_{rep}: pulse repetition rate. AOM: acousto-optic modulator. EOM: electro-optic phase modulator. SESAM: semiconductor saturable absorber mirror.

duration but at a much higher average output power of 288 mW. We compare both approaches and discuss a tradeoff between output power and pulse duration.

II. 39-GHz $Nd:YVO_4$ Laser for Short Pulses

A. Concept and Previous State of the Art

Passively mode-locked $Nd:YVO_4$ lasers pumped with Ti:sapphire lasers have already been demonstrated with repetition rates up to 157 GHz [18]. The laser with a 157-GHz repetition rate emitted 2.7-ps pulses with 45 mW of average output power for 500 mW of pump power. A laser of the same type with a repetition rate of 39 GHz emitted longer pulses of 5.5 ps with 60 mW of average output power [25]. In both cases, a quasi-monolithic laser design was used where basically the whole intracavity path length is within the $Nd:YVO_4$ crystal (see Fig. 1). The crystal thickness is, e.g., 1.74 mm for the 39-GHz laser presented here, or 0.44 mm for the 157-GHz laser. One crystal facet, which acts as the output coupler, is curved and dielectrically coated. The other facet is flat, polished and can be antireflection coated or uncoated. The SESAM is mounted close to the flat crystal facet with an air gap of a few micrometers thickness between crystal and SESAM. For fine adjustment of the air gap, the SESAM is mounted on a piezoelectric transducer. To suppress Q-switching instabilities [27] for the typical intracavity powers of such lasers, the laser mode radius in the gain medium has to be in the order of 20 μm. This is achieved e.g., with a radius of curvature of the crystal facet of 10 mm for a 40-GHz laser.

Because this kind of laser has to be operated very far above the pump threshold in order to suppress Q-switching instabilities, great care has to be taken to avoid the excitation of higher-order transverse cavity modes, which would destabilize the mode-locking process. Therefore, the pump beam radius should be at most about 3/4 of the laser beam radius over the whole crystal length. (Even after a propagation length corresponding to several pump absorption lengths, a larger pump beam radius is not acceptable.) As a consequence, the pump beam quality factor M^2 must be smaller than ≈2, while ≈300 mW of power is required. Until recently, the resulting high pump brightness could be achieved only by using a Ti:sapphire pump laser, but in the meantime, semiconductor diode lasers with sufficient brightness have been developed.

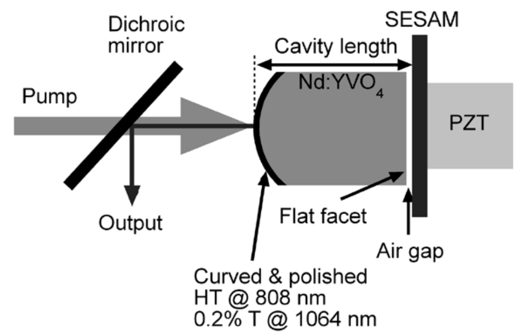

Fig. 1. Laser setup of the 39-GHz laser optimized for short pulses. The pump and laser beam are separated with a dichroic mirror. PZT stands for piezoelectric transducer.

B. Experimental Setup

Our pump diode is a single-mode AlGaAs–GaAs device provided by Bookham (Switzerland) AG. It can emit up to 500 mW in a close to diffraction-limited beam $(M^2 < 1.3)$. To avoid catastrophic damage, we run the diode with 400 mA, obtaining 379 mW incident on the $Nd:YVO_4$ crystal. Due to the E2-facet passivation technology [28], this single-mode laser reveals an excellent reliability at high-power densities. For a mount temperature of 24 °C, the optical spectrum is centered at 808.7 nm and has a spectral linewidth below 1 nm. The slightly asymmetric beam of the diode was shaped to a nearly circular beam at the laser crystal using two cylindrical lenses. Using an achromatic lens with 35-mm focal length, we obtained a beam radius in the laser crystal of ≈17 μm.

We used a $Nd:YVO_4$ crystal with 3% neodymium doping. This doping level might appear to be higher than necessary for good pump absorption, but it reduces the sensitivity to the pump wavelength and bandwidth without introducing thermal problems at this power level. The curved side of the crystal was polished with a radius of 10 mm. It was coated for high transmission at the pump wavelength and ≈0.2% transmission at the laser wavelength. The flat facet remained uncoated. This aspect is important and will be discussed below. The SESAM is similar to the one used in the 157-GHz laser [18]. It consists of a high-reflecting AlAs–GaAs Bragg mirror followed by a single InGaAs quantum well absorber in an antiresonant structure. Three Bragg pairs of AlAs–GaAs were deposited on the top of the structure to reduce the nonsaturable losses to less than 0.1% at the expanse

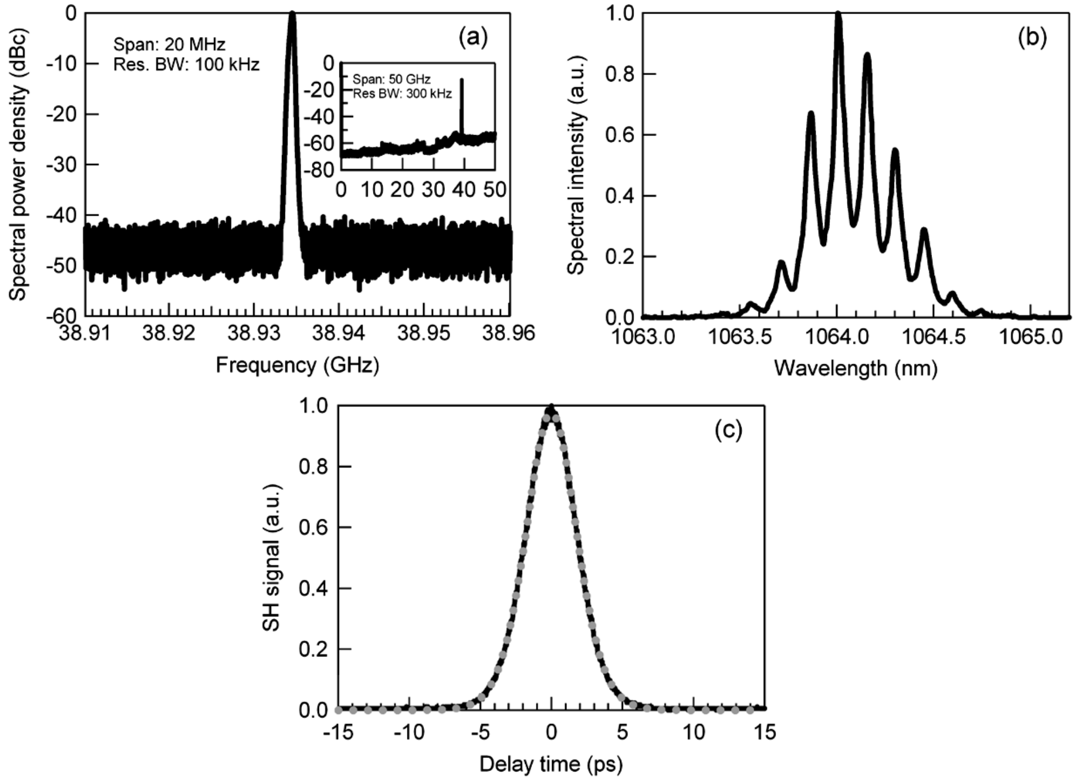

Fig. 2. (a) Radio frequency spectra of the 39-GHz short pulse laser, showing stable mode locking. (b) Optical spectrum measured with 0.08 nm resolution bandwidth. The longitudinal modes with 39-GHz spacing are partly resolved. (c) Autocorrelation trace. The sech^2 fit (dots) fully overlaps with the autocorrelation trace (line). The pulse length is 2.7 ps.

of a lower modulation depth of 0.3% and a higher saturation fluence of 60 μJ/cm^2. The absorber recovery time is 28 ps.

C. Experimental Results

With 379 mW of pump power, the laser produced 49 mW of output power at a repetition rate of 38.9 GHz. The pulse energy was 1.3 pJ. The laser operated on a single transverse mode with $M^2 < 1.15$. The relaxation oscillations are firmly suppressed as shown in the RF spectrum [Fig. 2(a)]. The optical spectrum [Fig. 2(b)] has a linewidth of about 0.35 nm. The autocorrelation [Fig. 2(c)] is well fitted for sech^2-shaped pulses and indicates a pulse length of 2.7-ps, which agrees with the transform limit for the measured optical spectrum.

D. Effect of the Air Gap Between Crystal and SESAM

While the previous 39-GHz laser [25] had an antireflection coating on the flat side of the crystal, the laser described here has an uncoated flat side. Due to the strong Fresnel reflection of this surface and the air gap between the crystal and the SESAM, we effectively have a Fabry–Perot resonator. When the resonance condition of this Fabry–Perot resonator is tuned with the piezo below the SESAM, the pulse duration, pulse stability and output power change with a $\lambda/2$ period. Stable pulses with the shortest duration of 2.7 ps are reached when the average power has its maximum. This observation first appeared to be rather surprising, because one should expect the strongest pulse shaping effect in the SESAM (and thus the shortest pulses) to occur in resonance of the Fabry–Perot resonator, where however the losses are highest and thus the output power is in a minimum. We conclude that the "good" operation points (with highest output power and shortest pulses) correspond to antiresonances of the Fabry–Perot resonator, although in these points the laser field hardly penetrates into the SESAM and hardly saturates the absorber. Although the general understanding is that significant absorber action is required to form short pulses, this is different in the concrete case due to the effect of spatial hole burning in the gain medium [29]. As this laser is operated far above the laser threshold (in order to suppress Q-switching instabilities), spatial hole burning is very strong. Experimentally this is apparent from the fact that even without a SESAM such lasers generate an output spectrum with a width comparable to the one obtained in mode-locked operation. While without this effect the spectral width of the laser output requires a balance between SESAM action and spectral narrowing in the gain medium, spatial hole burning alone can lead to a spectral width on the order of 0.3 nm. Thus, the SESAM then only has to phase-synchronize the longitudinal cavity modes, but is not required to stabilize their intensity pattern. Note that the phase synchronization becomes more difficult outside the antiresonance due to the dispersion of the Fabry–Perot cavity under these conditions.

Note that we have previously observed a similar behavior in a 77-GHz Nd:YVO_4 miniature laser where the rear flat crystal facet was also uncoated [18], [26]. At that time we interpreted these effects as resulting from dispersion generated in the Fabry–Perot resonator, acting together with the nonlinearity of the crystal to form soliton-like pulses. However, we found that the nonlinearity is actually too weak for soliton pulse shaping, as we later confirmed with numerical simulations.

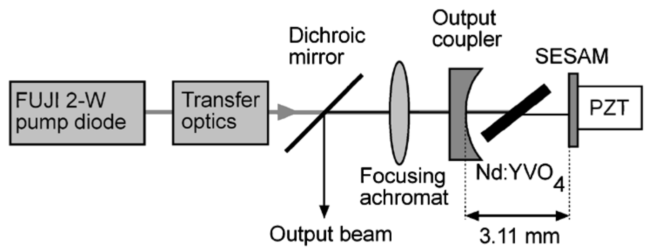

Fig. 3. Experimental setup of the 40-GHz laser with higher power. The pump and laser wavelengths are separated with a dichroic mirror. PZT stands for piezoelectric transducer.

We also did experiments using antireflection coated Nd:YVO_4 crystals, where the resonance effects are significantly weaker [25]. This, however, leads to roughly two times longer pulses. Also note that the shortest pulses from Nd:YVO_4 lasers have always been achieved with quasi-monolithic laser cavities, where spatial hole burning is strong, while lasers with a thin gain medium (not extending to the ends of the cavity) have always generated significantly longer pulses. Such a laser is also described in the following section.

III. High-Power 40-GHz Laser

A. Concept and Previous State of the Art

By carefully optimizing a laser based on the presented quasi-monolithic design, it should be possible to reach a higher average output power. However, this would require a pump diode with higher power but not with lower brightness, because the mode area should not be increased by a larger factor than the intracavity power. It turns out that the currently available laser diodes with higher powers (> 0.5 W) have a lower brightness and thus can not be used for a quasi-monolithic 40-GHz laser. A tapered amplifier could have the required brightness, but is more complex and expensive. For a given repetition rate, the demands on the pump brightness can be reduced by reducing the length of the pump-absorbing crystal, so that the pump beam divergence is less important. One possibility would be to use a quasi-monolithic design with a composite crystal that has a neodymium-doped section and an undoped section. However, we have used a design that is no longer quasi-monolithic: a Brewster-angled flat crystal of shorter length is placed between a SESAM and a curved output coupler (Fig. 3).

In 2002 we published a diode-pumped Nd:YVO_4 laser of this kind with a repetition rate of 10 GHz, an average output power of 2.1 W, and a pulse length of 14 ps [18]. This device was pumped with a 5-W diode that had an M^2 of about 22 in both directions. Despite the high power, the brightness of this source is not suitable for a 40-GHz laser. In the following we describe a 40-GHz laser based on the same approach, but using a 2-W laser diode with higher brightness.

B. Experimental Setup

Fig. 3 shows a schematic of the complete laser setup. The pump source, provided by Fuji Photo Film Company, Ltd., is a 50-μm stripe Al-free laser diode emitting up to 2 W of power at a wavelength of 807 nm for a mount temperature of 30 °C. This device proved to be very reliable with more than 2000 h of continuous operation at room temperature without degradation [30]. The beam quality factor is 12 for the slow axis and 2 for the fast axis. Two cylindrical lenses, an anamorphic prism pair and an achromatic lens with 30-mm focal length are used to focus the beam to a spot of 24×51 μm radius with 1.83 W in the crystal.

The laser cavity has a total physical length of 3.11 mm. The output coupler with a 3.8-mm radius of curvature has more than 90% transmission for the pump wavelength and a transmission of 0.25% at the laser wavelength. A crystal with 2% neodymium doping was chosen for maximum pump absorption without fracture or quenching effects at this power level. A pump absorption efficiency of roughly 50% is achieved with 0.5-mm crystal thickness. A longer crystal would allow for higher output power, but would increase the demands on the pump beam quality.

To avoid thermal quenching, the laser crystal was mounted on a copper block between indium foils. The SESAM is the same as used in the short pulse laser described in Section II.

C. Experimental Results

For 1.83 W of incident pump power on the crystal (0.8 W was absorbed), we obtain stable mode locking at a repetition rate of 40 GHz with 288 mW of average output power. The pulse energy was 7.2 pJ. Fig. 4 shows the radio frequency spectra from a fast photodiode, the optical spectrum and the autocorrelation. Although the autocorrelation trace shows some overlap of neighboring peaks, the 6.5-ps pulses at 40 GHz (corresponding to a period of 25 ps) are still well separated. The longer pulse duration compared to the laser of Section II can be explained by the fact that spatial hole burning has a weaker influence in this laser [29].

The saturation energy of the gain medium was independently calculated from the relaxation oscillations frequency and from the emission cross section of the Nd:YVO_4 crystal, and we obtained 6.8 and 4.5 μJ, respectively. The agreement is satisfactory since the mode size in the laser crystal and the total cavity losses are not precisely known.

D. Stability Versus Cavity Length

A somewhat unexpected observation is that the behavior of the laser changes periodically when the cavity length is changed. In general, the RF spectrum exhibits two lines rather than a single one; only for certain cavity lengths, which occur with a period of ≈ 1 μm, do the two lines merge to a single one, and the autocorrelation shows the minimum width. The performance described above was obtained at these optimum points. This dependence on the cavity length is normally not observed in mode-locked lasers but was seen in an even stronger form in a similar laser with an antireflection coated crystal (with a smaller angle toward the beam) and in less clear form in the 10-GHz laser [18]. These effects are related to spurious intracavity reflections from the laser crystal. One can easily show that such reflections, even at a very low level of e.g., 10^{-8} of the power, can slightly modify the frequencies of the longitudinal cavity modes. These variations are periodic with the cavity length. Only for certain cavity lengths, occurring with a period of ≈ 1 μm (assuming that the gain medium is near the middle of the cavity), are the frequencies equidistant,

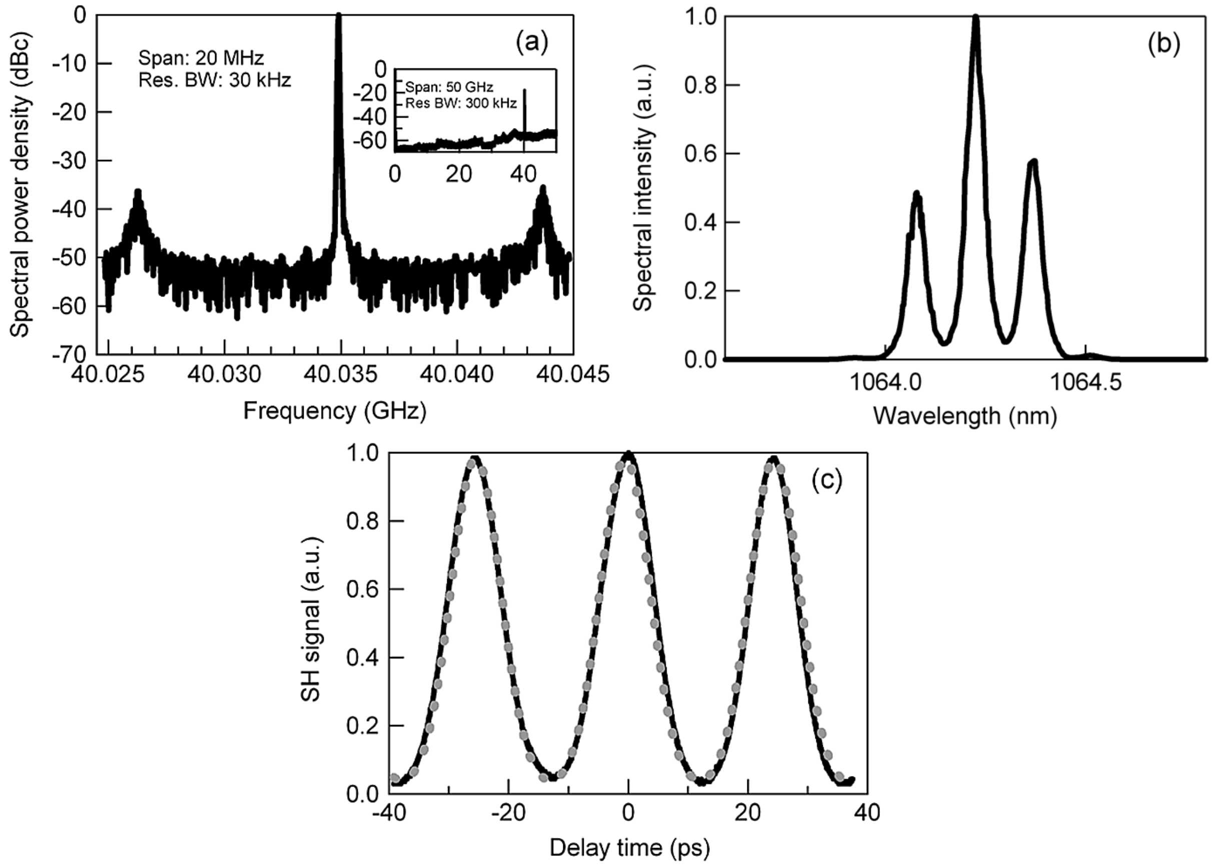

Fig. 4. (a) Radio frequency spectra of the 40-GHz high average output power laser. (b) Optical spectrum measured with 0.08 nm resolution bandwidth. The longitudinal modes with 40-GHz spacing are partly resolved. (c) Autocorrelation trace. The $sech^2$ fit (dots) overlaps with the autocorrelation trace (line). The pulse length is 6.5 ps.

so that the SESAM can easily lock the phases of the modes for generation of short pulses. Indeed we have experimentally verified this variation of the mode frequencies with the cavity length, making our explanation of the observed periodicity highly plausible and consistent.

IV. Conclusion and Outlook

We have demonstrated two different diode-pumped Nd:YVO_4 lasers with 40-GHz repetition rate, which is the highest repetition rate demonstrated so far with passively mode-locked 1-μm lasers. One laser was optimized for short pulses of 2.7-ps duration, while the other laser was optimized for a high output power of 288 mW.

We see some room for improvements with optimized SESAMs. A reduced saturation fluence would allow the realization of a higher repetition rate, or an increase in the modulation depth and thus a decrease in the pulse duration. In principle, this could also be achieved with stronger focusing on the absorber, but this could lead to overheating. A faster absorber recovery could be beneficial for high repetition rates. A factor of crucial importance is low nonsaturable losses, allowing low cavity losses, high slope efficiency, and leading to weaker heating.

Our discussion showed that high repetition rates from passively mode-locked lasers require a high pump brightness, because we need to operate far above threshold with a small laser mode radius in the gain medium in order to suppress Q-switching instabilities. The following properties of the gain medium can help to reduce the demands on pump brightness: large laser cross sections, a high-amplification bandwidth (allow one to work with a SESAM with lower modulation depth), a high pump absorption (i.e., a high pump absorption cross section, a high absorption bandwidth, and a high doping density), and low parasitic losses. Good thermal properties are also important because they allow maximization of the doping level and thus the pump absorption. Compared to many other gain media, Nd:YVO_4 has excellent properties in these respects. Recently, some new gain materials of a similar kind, namely Nd:$GdVO_4$ [9], [31] and Nd:$LuVO_4$ [32], [33], have been shown to have even slightly superior properties and might therefore allow the performance levels of passively mode-locked 1-μm laser to be raised somewhat further.

Laser diodes with higher powers tend to have a smaller brightness than low-power devices. For this reason, we are forced to use pump diodes with lower powers when constructing lasers with higher repetition rates, and the output powers get correspondingly smaller. Of course, the further development of high brightness pump diodes should help to improve the laser performance. Note that apart from the brightness, a small optical bandwidth is also important because it improves the pump absorption efficiency for small crystal lengths.

Passively mode-locked solid-state lasers can be used for pumping parametric oscillators (OPOs) in the multigigahertz regime. At higher repetition rates, it becomes more difficult to achieve a high laser output power, while OPOs need even higher pump powers. Currently, optimized Nd:YVO_4 lasers can be used for direct OPO pumping up to a repetition rate of $\approx$10 GHz. For significantly higher repetition rate of e.g., 40 GHz, a pump laser with sufficient output power is not feasible with the currently available laser crystals and pump diodes, and it is then necessary to use an amplifier between laser and OPO [34].

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