Compact $Nd:YVO_4$ Lasers With Pulse Repetition Rates up to 160 GHz

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***Abstract*—We present a comprehensive study on multigigahertz repetition rate $Nd:YVO_4$ lasers, passively mode-locked with semiconductor saturable absorber mirrors. A brief review of Q-switching instabilities with special emphasis on high repetition rate is given. We then present basic design guidelines, and experimentally show that one can push the pulse repetition rate of a $Nd:YVO_4$ laser up to 157 GHz, reaching the fundamental limit to the repetition rate which is given by the pulse duration and thus by the amplification bandwidth. We also demonstrate an air-cooled diode-pumped 10-GHz $Nd:YVO_4$ laser with 2.1-W average output power and 13% electrical-to-optical efficiency, showing the potential of solid-state lasers generating multiwatt, multigigahertz pulse trains with high efficiency.**

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

I. INTRODUCTION

LASERS with multigigahertz repetition rates are needed as key components in a big variety of applications. High-capacity telecommunication systems [1], photonic switching devices [2] and high speed electrooptic sampling techniques [3] rely on the availability of multigigahertz pulse trains with short pulses, low phase and amplitude noise, and pulse energies in the order of at least a few picojoules [4]. The signal-to-noise ratio in time-resolved spectroscopy can also be improved with such laser sources [5]. High-repetition-rate lasers are also used to generate polarized electron beams [6] for electron accelerators. Although the field of current and potential applications is rather diversified, all laser sources for these applications have to meet common requirements. Compactness and reliable and efficient lasing operation are key goals. Wavelength tunability and/or phase locking to an external microwave reference source are also often desired. Depending on the specific type of application, multigigahertz pulse trains with average output powers between tens of milliwatts and several watts in a diffraction-limited beam are required.

Different approaches have been developed so far to achieve these goals. Actively mode-locked fiber lasers can generate pulse repetition rates up to 200 GHz [7], but only with harmonic modelocking, and good pulse stability is then only achieved by using quite complex means for stabilization. Edge-emitting semiconductor lasers, passively or actively mode-locked, can generate repetition rates of more than 1 THz [8], but with fairly limited average output power due to the limited mode area. Recently developed optically pumped vertical-cavity surface-emitting lasers (VCSELs) which can be passively mode-locked with SESAMs [9], [10] do not suffer from this power limitation, have generated, e.g., 950 mW of average power in 15-ps pulses with a 6-GHz repetition rate [11], and promise to generate even higher powers in the multigigahertz regime. However, this concept needs further development for product maturity, and here we concentrate on ion-doped solid-state lasers.

Diode-pumped ion-doped solid-state lasers are well known for their potential to deliver high-power mode-locked pulse trains in diffraction-limited beams [12], [13]. They feature efficient, robust, compact, and reliable operation. However, because of their relatively low laser cross sections, they exhibit a strong tendency for Q-switched modelocking (QML) when they are operated with short cavities for high repetition rates. In the QML regime, the mode-locked pulse train is amplitude-modulated with a long Q-switched envelope [14], [15]. For this reason, the repetition rates of passively mode-locked ion-doped solid-state lasers were limited to a few gigahertz until recently. Passively mode-locked Cr : YAG lasers produced only a 2.6-GHz repetition rate with a 115-fs pulse duration [16]. Repetition rates around 2 GHz have been demonstrated with Kerr lens mode-locked Ti : sapphire lasers [5]. Actively mode-locked Nd : YLF [17] and Nd : BEL [18] lasers produced 5 and 20 GHz, respectively, but the required modulators and their drivers add complexity to the setup and limit the maximum achievable repetition rate.

Note that harmonic modelocking (with multiple pulses circulating in the laser cavity) can also be used to increase the repetition rate of a solid-state laser [19]. An advantage of this approach is that the QML tendency, which depends on the cavity length, is then weaker compared to the case of a short fundamentally mode-locked laser with the same repetition rate [15]. However, a stable interpulse spacing is not easy to achieve. We, therefore, concentrate on the simpler approach of fundamental modelocking, i.e., with only a single pulse circulating in the laser cavity.

In this paper, we summarize the main issues and challenges for passively mode-locked high-repetition rate lasers. We give basic design guidelines and selection rules for the gain medium, cavity design, and choice of SESAM parameters. Based on these guidelines, we demonstrate $Nd:YVO_4$ lasers reaching extreme operation parameters.

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II. DESIGN GUIDELINES

Passive modelocking of a solid-state laser by incorporating a saturable absorber is a well-known technique. However, saturable absorbers introduce a Q-switching tendency that can drive the laser into the regime of Q-switched modelocking [15], [20]. As the output pulse train then no longer consists of pulses with constant energy, this is an unwanted regime of operation for most applications. The physical picture of the QML dynamics can be understood as follows. If, for some reason, the pulse energy rises slightly above its steady-state value, this pulse energy fluctuation can initially grow because the stronger bleaching of the absorber increases the net round-trip gain. However, eventually the increased pulse energy will saturate the gain. If the gain saturation is strong enough, this will lead to a damped oscillation of the pulse energy, soon returning to the steady state. Otherwise, the relaxation oscillations are undamped or even growing in amplitude, and we obtain Q-switched mode-locked operation. From the analysis of this process in [15], one can draw the following simple relation. A saturable-absorber mode-locked laser (without soliton effects) is stable against QML if

$$E_{p,\,\mathrm{crit}}^2 \geq E_{\mathrm{sat},\,L} E_{\mathrm{sat},\,A} \Delta R \qquad (1)$$

where $E_{p,\,\mathrm{crit}}$ is the intracavity pulse energy, $E_{\mathrm{sat},\,L}$ is the saturation energy of the gain medium, $E_{\mathrm{sat},\,A}$ is the saturation energy, and ΔR is the modulation depth of the absorber. Here, one assumes that the absorber recovery is slow compared to a pulse duration but complete between consecutive pulses, i.e., within one round trip. Also, the absorber is assumed to be operated a few times above its saturation fluence.

Rewriting the inequality gives

$$P_{\mathrm{out},\,\mathrm{crit}} \geq f_{\mathrm{rep}} T_{\mathrm{oc}} \sqrt{F_{\mathrm{sat},\,L} F_{\mathrm{sat},\,A} A_L A_S \Delta R} \qquad (2)$$

where $P_{\mathrm{out},\,\mathrm{crit}}$ is the average output power, f_{rep} is the repetition rate, T_{oc} is the output coupler transmission at the lasing wavelength, $F_{\mathrm{sat},\,L}$ and $F_{\mathrm{sat},\,A}$ are the saturation fluences of the gain medium and the saturable absorber, respectively, and A_L and A_S are the mode areas in the gain medium and on the absorber.

The saturation fluence of the gain medium is $F_{\mathrm{sat},\,L} = h\nu/(m(\sigma_L + \sigma_A))$, where σ_L and σ_A are the emission and absorption cross sections, respectively, at the laser wavelength. In a four-level laser (like $\mathrm{Nd:YVO_4}$), $\sigma_A = 0$. m stands for the number of passes through the gain medium within one round trip, e.g., $m = 2$ for simple standing-wave cavities. Note that the relevant parameters of the gain medium are the laser cross sections, but not the upper-state lifetime as is often believed. This means, e.g., that any lifetime-quenching effects would not decrease the QML tendency, but even increase it due to the decreased achievable pulse energy. Note also that for quasi-three-level lasers, the absorption cross section must not be neglected in the calculation of the saturation fluence.

Equation (2) also reveals that the higher the repetition rate, the harder it is to fulfill the inequality and to obtain stable continuous-wave (CW) modelocking. Basically, three different aspects then have to be considered in obtaining design guidelines for high repetition rate solid-state lasers: 1) choice of gain medium; 2) cavity design; and 3) SESAM parameters.

A. Choice of Gain Medium

As the stimulated cross section can be found in the denominator of (2), gain media with large σ_L are desirable. For operation near 1 μm, $\mathrm{Nd:YVO_4}$ is the material of choice. Its emission cross-section σ_L of $114 \cdot 10^{-20}$ cm^2 [21] is the largest of all to-date known ion-doped solid-state lasers (e.g., ~2–3 times higher than Nd:YAG at 1.06 μm). Its short absorption length (e.g., 90 μm for 3 at.% Nd doping) and its birefringence are favorable characteristics for diode-pumped laser setups.

Unfortunately, the choice of suitable gain media for 1.5-μm operation is much less favorable. Er:Yb-doped glasses and crystals typically have much smaller laser cross-sections (order of 10^{-20} cm^2); nevertheless, we recently managed to demonstrate a 10-GHz laser at 1.5 μm based on Er:Yb-doped phosphate glass [22]. Cr:YAG offers significantly higher cross-sections ($\sim 30 \cdot 10^{-20}$ cm^2), but particularly for high doping levels (as required for multigigahertz lasers) it is difficult to obtain good crystal quality with low optical losses.

B. Cavity Design and Pumping Considerations

The cavity design of high repetition rate lasers is important because the modes sizes in the gain medium and on the SESAM both influence the QML threshold [see (2)]. The small dimensions of multigigahertz cavities limit the number of cavity components and exclude the use of too bulky optics. For a standing-wave cavity, a 100-GHz free spectral range corresponds to only 1.48-mm separation of the end mirrors in air or even less with a gain medium in the cavity. Ring cavities are usually difficult to build for this regime.

For highest repetition rates, the mode size in the gain medium should be as small as possible [see (2)]. This puts stringent limits on the beam quality of the pump source, because the pump beam must stay within the laser medium throughout the gain medium. It is important to realize that an increased pump mode size is unacceptable even after propagation by several absorption lengths because these lasers are typically operated far above threshold, and higher order transverse modes would easily start lasing and destabilize the modelocking process. For this reason, the highest repetition rates [23] have been achieved with a Ti : sapphire laser as pump source, although single transverse mode diode lasers with sufficient power might soon be available.

Without a diffraction-limited pump source (as e.g., a high-brightness diode laser), mode-matching considerations set a lower limit to the mode size in the gain medium. Additional limiting factors may be thermal fracture of the gain material or a roll-off in output power due to quenching effects [24]. The doping density of the laser crystal should be carefully chosen: high enough to allow efficient pump absorption in a short enough crystal and thus also to relax the requirements on the pump beam quality, but also low enough to avoid strong quenching effects.

For a given pump power, such limiting factors for the pump mode size will then directly translate into limitations for the repetition rate, because they can make it difficult to overcome the QML threshold. However, one can increase the intracavity power by reducing the output coupler transmission, although this might compromise the power efficiency, and by minimizing all additional intracavity losses (e.g., at optical surfaces or in the absorber). Also, it helps to operate the absorber in the regime of strong saturation (see below) by using a small mode area on the absorber.

C. SESAM

The parameters of the SESAM [25], [26] play a key role in obtaining stable self-starting CW mode-locked operation with a high repetition rate. Here, we discuss several important aspects.

The modulation depth (i.e., the maximum change of reflectivity) of the SESAM must be large enough to obtain stable and self-starting modelocking. For cavity losses in the order of 0.5%–1%, a modulation depth in the order of 0.2%–0.4% is typically sufficient. This is usually achieved with a quantum-well absorber layer of $\approx$5–10 nm thickness. A larger modulation depth may be desirable for generating shorter pulses [27], but it increases the QML tendency [see (2)]. In addition, this would tend to increase the nonsaturable losses, decreasing the intracavity power and thus further increasing the QML tendency. High nonsaturable losses may also lead to too-strong heating.

Another factor is the saturation energy, given as the product of saturation fluence and mode area. Operation with an intracavity pulse energy of at least two to three times the saturation energy has been assumed in the derivation of (2), but with the small pulse energies in multigigahertz lasers, this requires fairly small mode areas which are sometimes difficult to achieve due to geometrical restrictions [(2) is then somewhat on the pessimistic site]. Therefore, SESAM designs with low saturation fluence are desirable. Note that typical designs (“low-finesse designs”) are anti-resonant, utilizing the Fresnel reflectivity from the semiconductor-air interface [14], [26]. The field intensity in the absorber can be further reduced by increasing the top layer reflectivity with an additional dielectric coating [28]. This decreases the modulation depth and the nonsaturable losses, but also increases the saturation fluence. Therefore, it is usually better to use a design without additional coating, or possibly even an anti-reflection coated device [29], and reduce the modulation depth and nonsaturable losses by using a rather thin absorber layer. However, starting with a given semiconductor device (with thicker absorber) it may be useful to modify its properties with an additional reflective coating.

The QML tendency could, in principle, be reduced by operating the absorber far above the saturation fluence (i.e., with a very small saturation energy achieved, e.g., with a very small mode area). Absorber damage or modelocking instabilities might set limits to this approach. In practice, this regime would be difficult to reach in a multigigahertz laser anyway.

The recovery time of the SESAM is usually longer than the pulse duration. It has been shown to have little direct influence on the obtainable pulse duration, except that it determines a minimum pulse duration below which the pulses would become unstable [27]. In most multigigahertz lasers, this minimum is not relevant, and the resulting pulse duration depends mainly on the modulation depth relative to the total cavity loss and on the gain bandwidth, but not much on the SESAM recovery time. Nevertheless, the recovery time does become important when it becomes comparable with the round-trip time or even larger; the SESAM recovery during one round-trip time is then incomplete. For two reasons, this can easily happen in multigigahertz lasers. First, the round-trip times are rather short (e.g., 20 ps for 50 GHz). Second, SESAMs which are optimized for low nonsaturable losses tend to have relatively long recovery times, e.g., in the order of 50–100 ps for MOCVD-grown devices. With low-temperature (LT) MBE growth, significantly faster recovery could be achieved, but at the cost of higher nonsaturable losses. However, we have demonstrated at a wavelength of 800 nm with LT GaAs absorbers, that post-growth annealing results in an improved saturable absorber with small nonsaturable absorption [30]. We expect that LT InGaAs should show similar improvements. The effect of incomplete absorber recovery can be modeled numerically, but we can’t give a simple analytical equation in this case. As a simple guideline, the incomplete absorber recovery tends to increase the degree of saturation and typically decrease the effective reflectivity change during a pulse. As a consequence, the QML tendency is reduced, so that incomplete recovery would appear to be advantageous for high repetition rate lasers. However, it would seem to be better to use a faster absorber with reduced modulation depth, thus also reduced nonsaturable losses, and reduced saturation fluence, if such a device were available.

Despite the moderate output power, the laser spot on the SESAM in a multigigahertz laser can easily be heated by a few tens of Kelvin. This can be tolerated but is significant and comparable to the typical temperature rise in a SESAM of a high-power laser. The reason for this is that the intracavity power is relatively high and a small spot on the SESAM is used. In other words, each time the SESAM is saturated, a certain energy is dissipated in the absorber layer, and this happens with a repetition rate which is much larger than in typical passively mode-locked lasers.

It has been shown [31], [32] that two-photon absorption (TPA) in a SESAM can be exploited to reduce the QML tendency. Effectively, it reduces the increase of reflectivity for increasing pulse energy. However, this solution has not yet been demonstrated for a multigigahertz laser. The moderate peak intensities which are practically achievable in such lasers make the TPA effect in a normal SESAM very weak. However, it may be possible to increase it sufficiently by adding a relatively thick transparent semiconductor layer to the design in which TPA can occur.

D. Soliton Mode-Locked Operation

It has been shown [15] that operation in the soliton mode-locked regime, i.e., with an appropriate amount of negative anomalous dispersion in the laser cavity, can substantially reduce the QML tendency of the laser. Typically, the critical pulse energy for stable modelocking can be increased by a factor in the order of four. The physical mechanism behind this is that any increase of pulse energy increases the soliton bandwidth, and thus reduces the gain, as the gain bandwidth is limited.

Multigigahertz lasers, as we have demonstrated [23], [33], typically operate with pulse durations of a few picoseconds. Despite the high average intensity in the gain medium, the peak powers are moderate, and thus the influence of the Kerr nonlinearity is weak. For this reason, a moderate amount of negative anomalous group delay dispersion is sufficient for formation of soliton-like pulses, despite the relatively long pulse duration. On the other hand, this means that the soliton shaping effects are weak, and thus these solitons are less stable against perturbations than those usually encountered in femtosecond solid-state lasers. Nevertheless, we have demonstrated (see below) that soliton mode-locked operation allows substantially higher repetition rates to be reached because it reduces the QML tendency and the pulse duration, thus reducing the problem of overlap of consecutive pulses at very high repetition rates [23].

III. NEW EXPERIMENTAL RESULTS

Based on the design guidelines discussed above, we now describe two different Nd : YVO_4 lasers for extreme parameter regimes. The first has been optimized for high output power with a 10-GHz repetition rate. The second laser was designed to demonstrate an extremely high repetition rate of nearly 160 GHz, which is at the fundamental limit given by the gain bandwidth of Nd : YVO_4.

A. 10-GHz, 2.1-W Nd : YVO_4 Laser

Compared to mode-locked edge-emitting semiconductor lasers, mode-locked lasers based on ion-doped crystals can deliver much higher output powers. This makes such devices useful, e.g., as pump sources for various kinds of nonlinear optics experiments. As an example, we demonstrate here a 10-GHz laser with high output power for synchronous pumping of a parametric oscillator which generates a 10-GHz output in the 1.5-μm spectral region [34] for telecom applications.

The laser setup, shown in Fig. 1, is similar to the setup of a previously demonstrated 13-GHz laser [35]. As a pump source, we use a high-brightness diode laser (unique-m.o.d.e.) delivering 5.6 W at 808 nm with a beam quality factor M^2 of $\approx$20 in both directions. This beam is focused through an 18-mm radius cavity mirror to a spot with $\approx$50-μm radius in air. The FWHM linewidth of the pump source is $\approx$1.5 nm, slightly compromising the pump absorption efficiency in the 1-mm-long and 0.5% Nd-doped YVO_4 laser crystal which is aligned under Brewster's angle and placed $\approx$7-mm away from the output coupler. The output coupler has >95% transmission for the pump and has 1.8% transmission for the output beam. The calculated laser mode radii in the crystal are 67 μm by 143 μm and 50 μm on the SESAM, respectively. For precise tuning of the repetition rate in the range 9–11 GHz, the SESAM mount was stacked on a motor-driven translation stage. On the back side of the SESAM mount a small cooling fin was attached, because otherwise absorption of residual pump and laser radiation in the SESAM would raise the SESAM temperature too much. Note that the whole system is completely air-cooled.

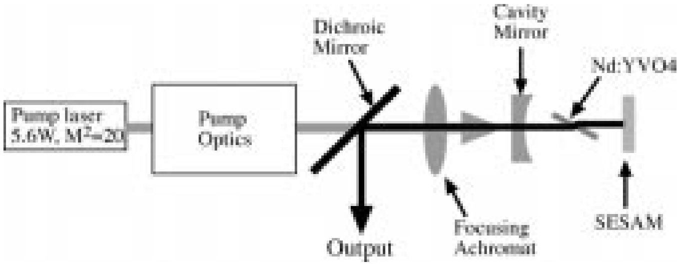
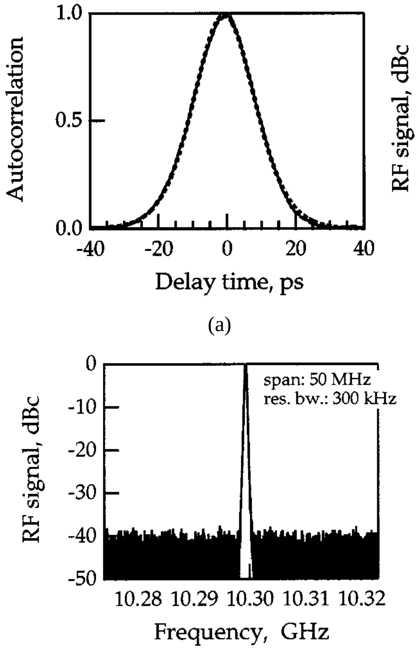


Fig. 1. Diode-pumped 10-GHz, 2-W Nd : YVO_4 setup.



(a)

(b)

Fig. 2. Autocorrelation (fully overlapping) with the (a) sech^2 fit and (b) RF spectrum of the 2-W 10-GHz laser.

To ensure efficient operation, the nonsaturable losses ΔR_{ns} of the SESAM had to be minimized. Furthermore, the saturation fluence as well as the modulation depth had to be kept small. We achieved this with a MOCVD-grown SESAM consisting of one 15-nm-thin $In_{0.25}Ga_{0.75}As$ quantum well embedded in 70-nm GaAs respectively AlAs spacer layers. To further reduce the nonsaturable losses, a dielectric top mirror with 70% reflectivity for the lasing wavelength of 1064 nm was deposited. The measured SESAM parameters are $F_{\mathrm{sat},\,A} \approx 100\ \mu\mathrm{J/cm}^2$, $\Delta R \approx$ 0.24%, and a recovery time of $\approx$100 ps. The estimated nonsaturable losses are <0.1%.

With 5.4 W of incident pump power at the crystal we achieved a mode-locked average output power of 2.1 W in a diffraction-limited beam. The lasing threshold was below 50-mW pump power. The optical-to-optical slope efficiency was 39% (electrical-to-optical efficiency: 13%) and showed no roll-off, even at maximum pump power. The measured autocorrelation is well fitted with a 13.7-ps sech^2 pulse. The resulting maximum peak power was 13 W. Fig. 2 shows the autocorrelation and the radio-frequency (RF) spectrum, indicating a clean mode-locked pulse train at 10.3 GHz. The measured QML threshold is around 1 W output power.

B. Miniature Nd : YVO_4 Lasers With Repetition Rates up to $\approx$157 GHz

This experiment was done to demonstrate the ultimate limit for the repetition rate of a mode-locked Nd : YVO_4 laser. As resonator setups with commercially available optics are too bulky

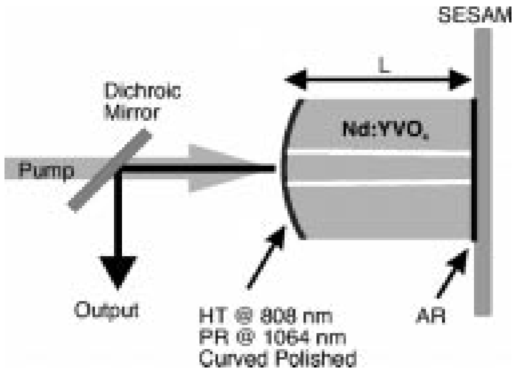


Fig. 3. Schematic miniature laser setup, as used for repetition rates >20 GHz. HT: high transmission. PR: partial reflection. Solid white lines indicate laser mode.

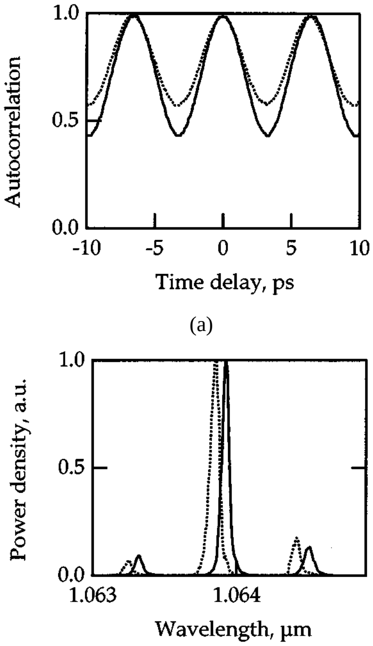
for this purpose, we used a quasimonolithic resonator design as shown in Fig. 3.

This type of resonator is made of a Nd : YVO$_4$ crystal which is polished with a certain radius of curvature on one side and flat on the other side. The curved side is coated as an output coupler with >95% transmission for the pump light. The flat side can be uncoated or antireflection coated for the laser wavelength. We used uniformly doped Nd : YVO$_4$ crystals for such resonators, although a composite structure with a doped and an undoped section, pumped through the undoped section, could be beneficial for multiwatt operation without thermal fracture. The repetition rate of the laser is mainly given then by the length of the solid medium and slightly reduced by the residual air gap between the crystal and SESAM. The pump beam and output beam are separated by a dichroic mirror. By using a specially designed output coupler SESAM [36], one could get rid of even the dichroic mirror, resulting in a very compact and rugged configuration.

This approach enabled us to demonstrate Nd:YVO$_4$ lasers with 29 GHz [37] and 59 GHz [33], and also with soliton pulses with up to a ≈77-GHz repetition rate [23]. Here, we show that modelocking is possible even at ≈157 GHz, although this repetition rate is already ≈60% of the FWHM gain bandwidth, so that a single longitudinal mode experiences most of the gain.

For nearly 160-GHz repetition rate, the 3% neodymium-doped crystal is only ≈440-μm long. The curved side has a 10-mm radius of curvature and is coated for 99.8% reflectivity at the laser wavelength (1064 nm) and high transmission (>98%) at the pump wavelength (808 nm). The other side is flat polished and antireflection coated for the lasing wavelength. In the modelocking experiments, we have used two different SESAMs. SESAM S1 is identical to the one described before. SESAM S2 is identical to S1, except with a 55% reflecting top mirror (instead of 70%), leading to a somewhat increased modulation depth, but also to increased losses (≈0.1%). The laser mode radius is ≈18 μm on the SESAM and in the gain medium. Note that the SESAM recovery between consecutive pulses is very incomplete, so that the effective reflectivity change is significantly smaller than the modulation depth measured at much lower repetition rates.

The slope efficiency of the laser is 21% with S1 and 9% with S2. For pump powers above 0.5 W, we observe a roll-off of the slope efficiency due to thermal effects. (Note that the high neodymium concentration reduces the efficiency of the material [24].) Therefore, the maximum achievable average output power for 0.5 W of pump power was 110 mW for SESAM S1 and 45 mW for S2.



(a)

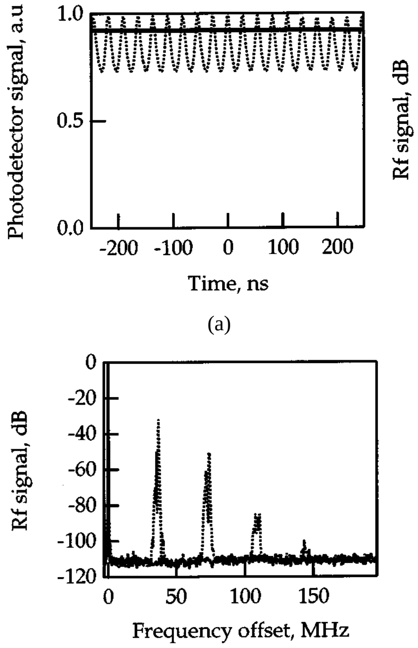
(b)

Fig. 4. (a) Autocorrelation trace of the ∼157-GHz pulse train. The pulses are about 6.4-ps apart. (b) Optical spectrum. Only three longitudinal modes are oscillating. Dotted lines: SESAM S1. Solid lines: SESAM S2.

Fig. 4 shows the autocorrelation (dotted line for SESAM S1, solid line for SESAM S2), including the cross-correlation with adjacent pulses for both SESAMs. The pulse-to-pulse spacing of ≈6.4 ps corresponds to a 157-GHz repetition rate. The autocorrelation of the shorter pulses (with SESAM S2) shows significant overlap of consecutive pulses. However, it is consistent with a train of hyperbolic secant pulses with 2.7-ps duration, so that the minimum power (between the pulses) is only 13% of the peak power, although the minimum autocorrelation signal is 46% of the maximum signal (see Fig. 4). SESAM S1 results in slightly longer pulses (and therefore bigger overlap), which is the result of the smaller modulation depth compared to S2. Fig. 4 shows the corresponding optical spectra for SESAM S1 (dotted line) and S2 (solid line), with the longitudinal modes resolved. In both cases, ≈80% of the power is in the central longitudinal mode.

Calculations show that the small power in the neighbored longitudinal modes is consistent with the pulse shape retrieved from the autocorrelation. This situation is very unusual for a mode-locked laser; nevertheless, the term “modelocking” is entirely appropriate here because a fixed phase relationship between the three longitudinal modes is essential for the generation of these pulses.

We could not take an RF spectrum as for the 157-GHz laser because the frequencies are too high. Q-switching instabilities could nevertheless be investigated. If the laser is somewhat misaligned, Q-switching instabilities, leading to an oscillation of



(a)

(b)

Fig. 5. Laser running in QML (dotted line) operation and CW mode-locked (solid line) operation. (a) Time domain, taken with a fast photodiode and a 400-MHz digital oscilloscope. *The oscillations represent bunches of pulses; individual pulses are not resolved.* (b) Corresponding RF spectrum. In clean CW mode-locked operation, the peaks disappear under the detection noise level. Data taken with SESAM S2.

the pulse energy, can be observed with a fast photodiode and an oscilloscope or a RF analyzer (Fig. 5). With proper laser alignment, they are firmly suppressed; a stable pulse train occurs on the oscilloscope, and the oscillation peaks observed on the RF analyzer disappear in the noise level, which is more than 60-dB lower. The data in Fig. 4 were taken in this situation.

Note that the intracavity dispersion is normal, so that the 157-GHz pulses are no solitons. Under these circumstances, the short pulse duration of 2.7 ps (for SESAM S2) first appears to be surprising, particularly because of the small modulation depth and only partial SESAM recovery between the pulses. However, note that spatial hole burning also must be expected to be rather strong in this laser, and this tends to support the neighbored longitudinal modes, thus decreasing the pulse duration [38], [39].

Because of the very small mode sizes (<20 μm radius) in the gain medium, the requirements for beam quality of potential diode pump lasers are quite high. Typical 2-W laser diodes at 808 nm operate with an M^2 of ≈ 20. Focused down to a spot radius of 20 μm, the confocal parameter would be as small as 0.13 mm. Because most of the pump light must be absorbed in order to achieve a high average intracavity power to suppress QML, the gain section should be at least 2 times the absorption length ($\sim$0.2 mm). Comparing that to the confocal parameter of a typical 2-W diode-pump, one could not focus properly to avoid the excitation of higher order modes with such pump lasers. Therefore, at the moment, a Ti : sapphire laser is the only choice for pumping such a laser, but one can expect that diode lasers with good beam quality and sufficient output power will soon become commercially available.

IV. CONCLUSIONS AND OUTLOOK

We have discussed in depth the design criteria for passively mode-locked ion-doped solid-state lasers with multigigahertz repetition rates. The main issue is the suppression of Q-switching instabilities. This is achieved with a combination of measures, notably the choice of $Nd:YVO_4$ as a very suitable gain medium for this purpose, the use of optimized laser cavities with very small mode areas, and the use of SESAMs with a small modulation depth. Based on the given design criteria, we have demonstrated lasers with extreme operation parameters. The first laser was optimized for high output power at a 10-GHz repetition rate with diode pumping. More than 2 W of average power has been achieved, despite design requirements which are somewhat in conflict with requirements for high-power operation. The second laser was pushed to an extremely high repetition rate of 157 GHz, reaching a new regime where consecutive pulses are getting so close that the pulse duration, which is limited by the gain bandwidth, set a limit on the repetition rate. In this unusual regime, $\approx$80% of the power is contained in a single longitudinal mode.

Compared to other high-repetition rate lasers, the output power of these $Nd:YVO_4$ lasers is very high. This has already enabled us to pump a 10-GHz parametric oscillator [34], and applications in combination with other nonlinear processes have also become possible. In particular, continuum generation [40] should be feasible at a multigigahertz repetition rate.

For output wavelengths other than $\approx$1 μm, particularly for the telecom band around 1.5 and 1.3 μm, the available gain media are less ideal for high repetition rates compared to $Nd:YVO_4$. Nevertheless, the discussed design aspects are similar, and we could recently demonstrate a 10-GHz passively mode-locked Er : Yb:glass laser at 1.5 μm [22]. Other interesting candidates are $Nd:YVO_4$ and Nd : YLF with emission at 1342 and 1313 nm, respectively.

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