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Effects of spatial hole burning in 888 nm pumped, passively mode-locked high-power Nd:YVO_4 lasers

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Abstract We report on an experimental study of 888 nm pumped, passively mode-locked, high-power Nd:YVO_4 lasers with an enhanced cavity design, involving spatial hole burning (SHB) in the active medium. We observed a significant pulse shortening due to the concept of "Gain-at-the end," despite using long gain length up to 30 mm. A 31.6 W average output power TEM_{00} Nd:YVO_4 oscillator, providing 16.2 ps pulses at an repetition rate of 96 MHz is presented. The pulse duration turns out to be primarily a function of the effective gain length, which can be explained by means of SHB. A further pulse shortening with decreasing gain length down to 9.5 ps at 11.1 W average output power is demonstrated.

1 Introduction

Solid-state lasers, providing ps pulses with high average output power are essential for a wide variety of fundamental and industrial applications, particularly those involving nonlinear frequency conversion where high peak powers in the multi-kW regime are desired. The complexity of ps-laser sources can strongly be reduced if such performance is directly obtained from a diode-pumped, passively mode-locked laser oscillator without the need for additional amplifier stages. Achieving this requires a laser material capable of sustaining high pump power while exhibiting a high gain and limited thermal lensing. Neodymium-doped orthovanadate is the material of choice for realizing compact, high optical efficiency, and also high-repetition-rate picosecond pulse sources thanks to its large stimulated emission cross section. In recent years, we have demonstrated a technique for end-pumping Nd:YVO_4 at 888 nm with high optical power [1]. A 888 nm pumped Nd:YVO_4 oscillator providing 54 W of average output power at a repetition rate of 110 MHz with 33 ps pulse duration without spatial hole burning (SHB) has been presented [2]. Thanks to the benefits of the pumping scheme, a diffraction limited beam quality and an optical efficiency of 52% has been achieved. However, the obtained pulse duration is about 2–3 times longer than usually provided by Nd:YVO_4 oscillators, conventionally pumped at 808 nm [3, 4]. The reason for this is the increased effect of gain narrowing as a consequence of large output coupling losses in a range between 30% to 50%, necessary to achieve maximum output power extraction. Different approaches are possible to counteract the spectral filtering of the pulse spectrum by the finite gain bandwidth. A properly designed etalon inside the cavity, whose transmission minimum coincides with the maximum of the gain curve could more strongly reduce the gain per round trip around the center than at the wings of the emission line. Therefore, the effective gain bandwidth increases and shorter pulses could be achieved [5]. A more common way is to create spatial hole burning in the active medium in mode-locked operation by simply positioning the gain medium at one of the resonators end mirrors ("Gain-at-the-End" (GE)). The induced gain grating in the active medium also leads to a strong flattening and effectively broadening of the spectral gain, which has been extensively investigated in experimental and theoretical studies [6–9].

In this paper, we present a detailed experimental investigation of pulse shortening due to SHB in 888 nm pumped, passively mode-locked high power Nd:YVO_4 lasers. The results clearly verify, that the influence of SHB is strongly af-

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fected by the effective length of the pumped gain volume as will be explained in the following section.

2 SHB in mode-locked operation

Although a comprehensive theoretical investigation of the dynamics of end pumped solid-state lasers with SHB has been presented [8], it is worth to sketch out a short description of SHB in mode-locked operation that emphasizes the special feature of end pumping Vanadate at 888 nm.

SHB results in a strong feedback between the pulse spectral shape and the saturated spectral gain $G(\nu)$, which complicates a general description of mode-locking, that also accounts for nonstationary effects such as pulse build up or Q-switch mode-locking. Following the model demonstrated in [9], we restrict ourselves to the steady state by simply assuming a given spectral shape of the mode-locked pulse. Furthermore, because of the long fluorescence lifetime τ_f of $Nd{:}YVO_4$ of approximately 100 µs, which is much longer than the pulse round-trip time, a dynamic, fast pulse-induced gain saturation can be neglected. The spatial population inversion is rather saturated by the time averaged intensity distribution inside the gain medium. If we assume for reason of simplicity a Gaussian spectral shape, the time averaged intracavity intensity $\langle I(z)\rangle$ in a distance z from one of the end mirrors, which is positioned at $z = 0$, can be analytically calculated [9]:

$$\langle I(z)\rangle = 2 \cdot \frac{P}{A} \cdot \left(1 - e^{-\left(\frac{\pi n_m z \Delta\nu}{c\sqrt{\ln 2}}\right)^2} \cdot \cos\left(\frac{4\pi n_m \nu_0 z}{c}\right)\right), \quad (1)$$

where $\Delta\nu$ denotes the FWHM bandwidth, ν_0 the center frequency of the mode-locked lasing spectrum, P the intracavity optical power in one direction, A the effective mode area, which is assumed to be constant over a length of the gain medium and n_m the refractive index of the intracavity medium. As can be seen from (1) and also from Fig. 1a, the average intensity profile close to the end mirror is a standing wave pattern whose period is given by the center wavelength of the lasing spectrum. With increasing distance z, the oscillations loose contrast until they finally vanish. In time domain, this can be explained by a traveling pulse, who overlaps with itself due to reflection at the end mirror, thus creating a interference pattern whose time averaged spatial intensity profile is described by (1). At a distance Δz, the amplitude of the rapid oscillations drops to $1/e^2$ of the initial value. According to (1), Δz is given by

$$\Delta z = \frac{c \cdot \sqrt{2\ln 2}}{\pi \cdot \Delta\nu \cdot n_m}. \quad (2)$$

If the gain medium is positioned at a distance z larger than the minimum value Δz, as depicted in Fig. 1a, the laser

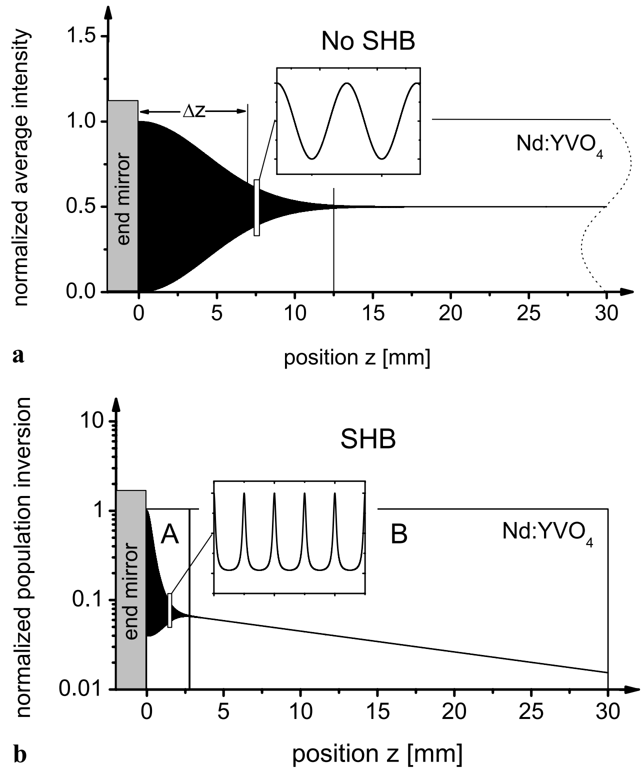

Fig. 1 Schematic description of SHB in mode-locked operation: (**a**) normalized average intensity along the cavity z-axis, assuming a 12 GHz (FWHM) Gaussian spectrum; (**b**) normalized population inversion in a 888 nm end pumped 30 mm long, 0.5 atomic percent (at.%) doped $Nd{:}YVO_4$ crystal, assuming a 28.6 GHz Gaussian spectrum and $P/AI_{sat} = 6$

radiation cannot cause spatial inhomogeneities of the population inversion along the z direction in the gain medium. No SHB occurs and the pulse duration and the pulse bandwidth is in general not affected by the exact z position of the gain inside the cavity. In this regime, the pulse duration of ps lasers is mainly determined by the value of the saturated net gain (=gain per round trip) and the properties of the saturable absorber, such as modulation depth and response time [10]. This situation becomes different if the gain/mirror separation goes below the critical value Δz. In this case, the highly modulated intensity pattern coincides with the gain medium, thus generating SHB, as depicted in Fig. 1b. The spectral gain $G(\nu)$ of a longitudinal mode with frequency ν is given by the spatial overlap of its own standing wave pattern with the spatial population inversion:

$$G(\nu) \sim \int_0^L n(z) \cdot \sigma(\nu) \cdot \sin^2\left(\frac{2\pi n_A \nu}{c} \cdot z\right) dz, \quad (3)$$

where $n(z)$ is the population inversion density along the z axis, $\sigma(\nu)$ the frequency dependent stimulated emission cross section and n_A the refractive index of the gain medium. Because the antinodes of the center frequency perfectly match the higher saturated regions of the gain grating, and frequencies far of the center of the emission line experience lower saturated regions, the spectral gain is flattened and effectively broadened.

If the gain length is much longer than the spatial width of the gain grating, as it is the case for 888 nm pumping of Nd:YVO_4, the gain medium and also the integration (3) can theoretically be divided into two spatial parts, both separately contributing to the exact shape of the spectral gain $G(v)$: A rear part, not suffering from SHB, that favors a Lorentzian spectral gain shape and a leading one, where the natural favoritism of the center frequency is suppressed. This is shown in Fig. 1b, where we calculated the spatial population inversion simply from the local average intensity (1), taking into account the spatial distribution of the 888 nm pump intensity, but neglecting the finite gain bandwidth by using the saturation intensity $I_{\text{sat}} = h\nu_0/\sigma(\nu_0)\tau_f$ at the center frequency ν_0 of the emission line, which is a good approximation if the lasing bandwidth is much smaller than the gain bandwidth. For this calculation, the spatial distribution of the 888 nm pump beam's intensity inside the 0.5 atomic percent (at.%) neodymium-doped orthovanadate crystal was assumed to follow a pure exponential decay with an absorption coefficient of 0.53 cm^{-1}. Particularly, end pumping Nd:YVO_4 at 888 nm features a very weak and isotropic absorption of the pump radiation, which optimizes absorption uniformity and minimizes crystal stress. For example, only 80% of pump power is absorbed in single pass through a 30 mm long, 0.5 at.% doped Nd:YVO_4 crystal. Although this is advantageous for high power operation, the impact of SHB on pulse shortening in a GE cavity is significantly reduced, because the homogenous rear part of the gain medium without SHB strongly participates in the overall gain. If the contribution of the rear part would be significantly reduced, the impact of SHB on the effective broadening of the spectral gain $G(v)$ is increased, thus providing shorter pulses. Because the 888 nm radiation is not completely absorbed in single pass, this can be achieved by simply shorten the laser crystals length. An influence of the gain length on the average mode spacing of the cw-running modes in GE-cavities was already observed in [7, 8], but no further information was given about the influence on the spectral lasing bandwidth, especially in mode-locked operation. Certainly, by simply using shorter crystals, a greater part of the 888 nm pump power is lost and efficiency decreases. Furthermore, the optical power is spread over a smaller volume, thus lowering the maximum possible absorbed pump power because of a stronger tendency for thermal lensing induced beam quality deterioration. Nevertheless, even in shorter crystals the laser performance still benefits from the 888 nm pumping scheme due to a very smooth, polarization insensitive absorption and a low quantum defect.

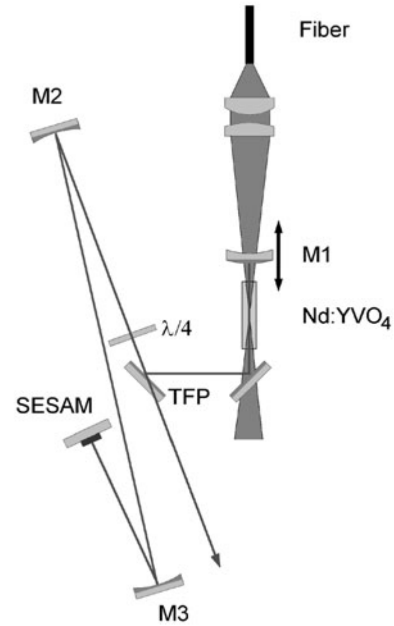

Fig. 2 Basic laser cavity design. The radii of mirror curvature and mirror spacings in each setup vary with crystal length and absorbed pump power

3 Experimental setup

Figure 2 represents schematically the experimental resonator setups. Although the particular resonators with different Nd:YVO_4 crystal length were individually optimized, because thermal lensing varies with crystal length and the amount of absorbed pump power, the basic setup is identical to Fig. 2. The 888 nm pump light is focused on a 1.5 mm diameter pump spot in the center of the crystal, providing an almost collimated pump volume in the crystals. The convex pump mirror M1 ("zero lens") near to the crystals endface partially compensates for the spherical part of the thermal lens, thus shifting the resonators stability range to higher pump power. Furthermore, the end mirror M1 was mounted on a mechanical translation stage that allows for an adjustable distance between the crystals endface and M1 in a range between 0 mm to 15 mm. In all cases, a maximum mirror endface separation distance of 15 mm was sufficient to avoid SHB in the gain medium, because the spectral bandwidth of our mode-locked lasers in a pure Gain-in-the-middle (GM) configuration does not go below 11 GHz at optimum output coupling. Therefore, pulse shortening due to SHB for a given Nd:YVO_4 length can be quantified in a single setup, because SHB can be continuously switched on and off via the variable mirror/endface spacing. The lasermode is focused onto the semiconductor saturable absorber mirror (SESAM) by a intracavity telescope, formed by Mirror M2 and M3. Each setup was first optimized in cw-operation, where the SESAM was replaced by a plane, high reflecting mirror. Depending on the intracavity power

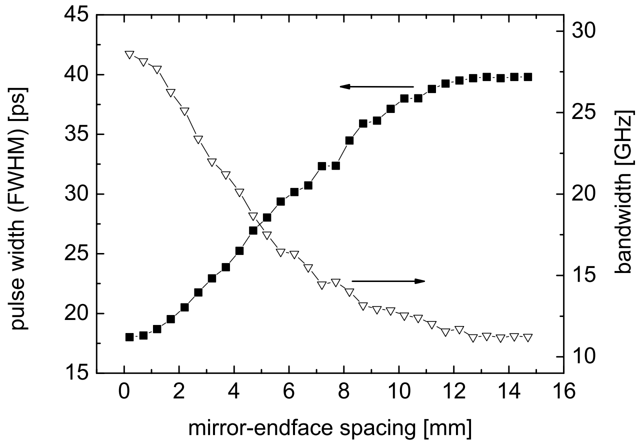

Fig. 3 Mode-locked pulse width and spectral bandwidth as a function of the end mirror/crystal spacing. The pulse widths are calculated from the autocorrelation trace's sech^2 fit FWHM

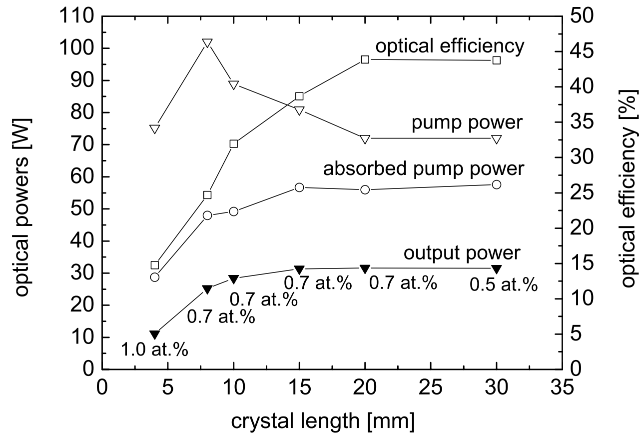

Fig. 4 Optical pump power, absorbed pump power, output power at optimum output coupling and the associated optical efficiency of the mode-locked lasers with different Nd:YVO_4 crystal length and Nd-doping concentrations

at optimum output coupling, the mode size on this end mirror was adjusted to ensure approximately the same pulse fluence of (1.15 ± 0.07) mJ/cm^2 on the SESAM in mode-locked operation in each setup. The SESAM consists of an antireflection-coated, annealed InGaAs single quantum well, embedded in a $\lambda/2$ GaAs layer over an AlAs/GaAs distributed Bragg reflector mirror. Furthermore, the cavity length in each setup is almost constant, resulting in a pulse repetition rate of (96 ± 0.5) MHz. A variable output coupling was realized using a thin-film polarizer and quarter-wave plate combination. Pulse durations in mode-locked operation were calculated from the autocorrelation trace's sech^2 pulse fit FWHM, measured with a 150 ps delay autocorrelator. The optical spectrum was measured using a plano-mirror scanning Fabry–Pérot interferometer, depending on the pulse bandwidth with a 75 GHz or 150 GHz free spectral range.

4 Experimental results

We first consider the results obtained for the 30 mm, 0.5 at.% doped vanadate crystal, the longest crystal in our study. For a large mirror/crystal spacing, no significant SHB occurs in the gain medium in mode-locked operation, and the pulse duration becomes independent from the exact position of the gain medium, as can be seen from Fig. 3. In this regime, we observed a pulse duration of 39.5 ps and a spectral width of 11.6 GHz at an output coupling transmission of 35%, corresponding to a time bandwidth product of 0.46, which is 1.46 times of the Fourier limit for a sech^2 pulse. For lower distances, the pulse overlaps with itself due to reflection at the end mirror within the gain region, therefore, generating SHB. With decreasing mirror/endface spacing, we observed a significant pulse shortening associated with a broadening of the mode-locked spectrum. For a vanishing mirror spacing, a minimum pulse duration of 18.0 ps and a maximum bandwidth of 28.6 GHz was measured, corresponding to time-bandwidth product of 0.51. As already observed and explained in [7, 8], a slight increase of the time-bandwidth product in the presence of SHB is due to the flattened spectral gain, which results in a deviation of the spectral and temporal pulse shape from the well-known sech^2 pulse shape solution in the case of passive mode-locking. No significant change of beam quality ($M^2 < 1.1$, knife-edge), average output power or mode size at the SESAM was detected due to the change of the mirror/endface separation distance.

The experiments clearly verify, that the pulse duration can be shortened by approximately a factor of 2 due to the concept of GE for our setup. However, the pulse duration is still longer as usually provided by mode-locked Nd:YVO_4 GE-oscillators based on the conventional 808 nm pump technique [3, 4]. As already discussed in the previous subsection, the reason for this much longer pulses origins from the very long absorption length at 888 nm that significantly reduces the spatial overlap between the SHB induced gain grating and the whole gain length. Using (2), we estimate this spatial ratio of gain grating to crystal length to be only 6% in the case of 888 nm pumping, assuming a measured bandwidth of 28.6 GHz and a refraction index of $n_m = 2.16$ for Nd:YVO_4. A further pulse shortening due to SHB requires to increase this spatial ratio, which can be achieved by simply shortening the Nd:YVO_4 crystal length.

As the crystal length decreases, an increasing part of optical power is lost, because the single pass absorption at 888 nm drops down from 80% for 30 mm (0.5 at.% doped) to 38% for a 4 mm long (1.0 at.% doped) crystal (Fig. 4). We tried to compensate for the loss in absorbed pump power by increasing the overall pump power, but this was limited by beam quality deterioration especially for the shorter crystals.

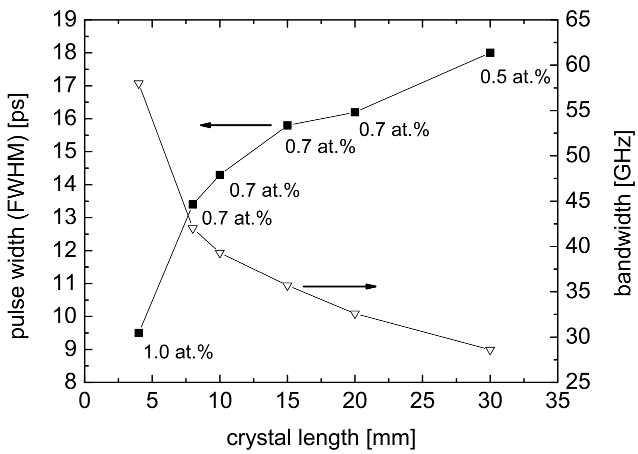

Fig. 5 Pulse width and spectral bandwidth of the mode-locked lasers with different Nd:YVO crystal length and Nd-doping concentrations. All values correspond to a minimum end mirror/crystal spacing <200 μm

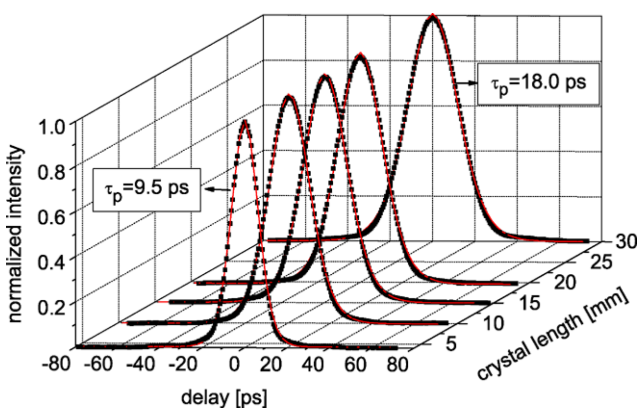

Fig. 6 Measured autocorrelation traces (*dots*) and their sech^2 fits (*red lines*) for the mode-locked lasers with different Nd:YVO$_4$ crystal length. All autocorrelations correspond to a minimum end mirror/crystal spacing <200 μm

Whereas the 30 mm long crystal has proven to withstand absorbed pump powers above 100 W at 888 nm providing a diffraction limited beam quality [1], the pump powers shown in Fig. 4 for the shorter crystals (15 mm to 4 mm) are the upper limits of pump power, still ensuring a beam quality factor $M^2 < 1.1$ (knife edge). For higher optical powers, a significant beam quality deterioration was observed, which could not be further improved by optimizing the overlap between pump- and laser mode. Therefore, with decreasing crystal length, the absorbed pump power drops from 57.6 W for the longest crystals to 28.7 W for the 4 mm, 1.0 at.% doped crystal, corresponding to a decrease in average output power from 31.5 W to 11.1 W at optimum output coupling.

However, as can be seen from Figs. 5 and 6, the pulse duration drops continuously from 18.0 ps for the 30 mm to 9.5 ps for the 4 mm long Vanadate crystal, while the spectral bandwidth increases from 28.6 GHz to 58.0 GHz. Estimating the spatial extension of the gain grating inside the gain medium (2), reveals a significant increase of the spatial ratio of gain grating to the overall crystal length from 6% for the 30 mm, to 23% for the 4 mm crystal, as shown in Table 1. It is worth to note that the decrease in pulse duration is neither caused by the lower amount of absorbed pump power nor by the lower output coupling for the shorter crystals but primarily by the stronger contribution of SHB. This was experimentally verified by realizing mode-locked oscillators using the longer crystals, but scaling down the absorbed pump power to a value comparable to the oscillator using the 4 mm crystal. As can be seen from Fig. 7, mode-locked lasers using the 10 mm, crystal for example provided always the same pulse duration of approximately 14 ps, although the optical pump power differs more than about 40 W. Furthermore, we observed a very strong stabilization of pulse duration and spectral bandwidth against changes in cavity losses as shown in Fig. 8. Whereas the pulse duration significantly decreases from 36.6 ps to 28.6 ps while reducing output coupling transmission from 41% to 22% without SHB, the pulse duration seems to be completely fixed in the presence of SHB (Fig. 8). As we believe, this can be explained as follows: In the traditional picture of mode-locking, the stationary pulse duration is the result of a bal-

Table 1 Spatial ratio $\Delta z/L$ of gain grating to overall crystal length, calculated from the measured spectral bandwidth $\Delta\nu$ according to (2)

Crystal length L [mm]	$\Delta\nu$ [GHz]	$\frac{\Delta z}{L} = \frac{c\cdot\sqrt{2ln2}}{\pi\cdot\Delta\nu\cdot n_m}$
30	28.6	0.06
20	32.6	0.08
15	35.7	0.10
10	39.3	0.13
8	42.0	0.16
4	58.0	0.23

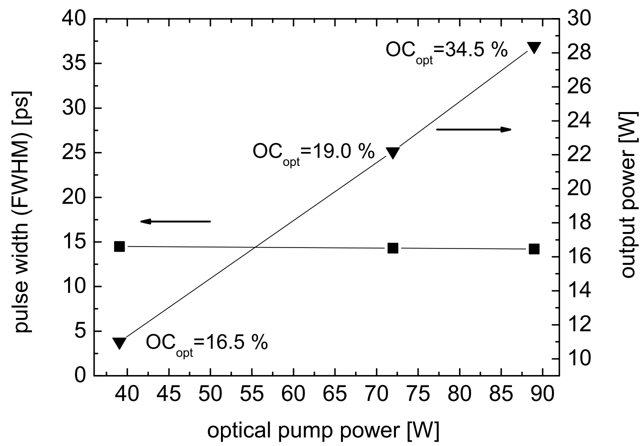

Fig. 7 Pulse duration and output power at optimum output coupling provided by mode-locked oscillators, using the 10 mm, 0.7 at.% doped Nd:YVO$_4$ crystal pumped at different optical powers

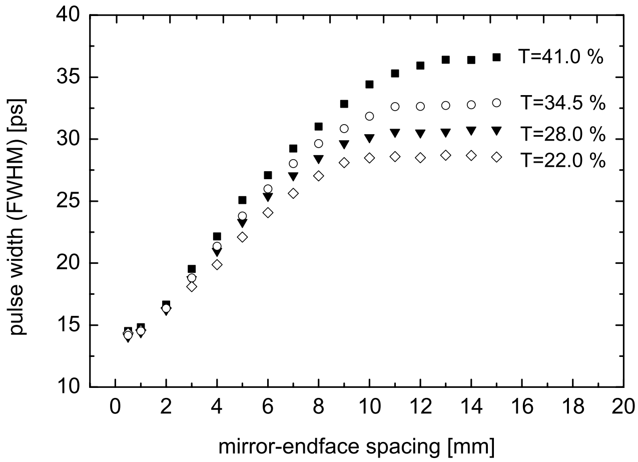

Fig. 8 Pulse duration as a function of the end mirror/crystal spacing for different output coupling transmissions, provided by the mode-locked laser using a 10 mm long, 0.7 at.% doped Nd:YVO_4 crystal and a optical pump power of 89 W

ance between the spectral filtering of the gain medium and pulse shaping due to the saturable absorber that has to force energy from the center modes into modes farther from the emission line. Because gain narrowing depends on the magnitude of the saturated gain, pulse duration appears to be a function of cavity losses. This process becomes less crucial in a GE cavity, because gain dispersion is strongly compensated and, therefore, pulse bandwidth is mainly determined by the flattening of the spectral gain and less by its absolute value. This is also in well agreement with experimental observations [7], that the pulse duration in a GE cavity can neither depend strongly on the type of mode-locker (active or passive) or on the saturable absorber modulation depth. Therefore, SHB not only supports shorter pulses but also stabilizes mode-locking against cavity losses or changes of the saturable absorber characteristics.

As both the 20 mm, 0.7 at.% and the 30 mm, 0.5 at.% doped Nd:YVO_4 crystals absorb approximately 80% of pump light in single pass, a maximum absorption efficiency of 95% can be achieved in double pass. This maximizes the overall optical efficiency as well as spatial absorption uniformity, thus reducing crystal stress, which is advantageous especially for high optical pump powers exceeding 100 W [1]. We additionally refocused the unabsorbed pump light by a lens-mirror combination into the center of the crystal in both setups. Because the optical pump power was adjusted to keep the amount of absorbed power fixed at 58 W, as in the single pass configuration (Fig. 4), thermal lensing and average output power remains unchanged, but optical efficiency increases to 50% for both crystals. Nevertheless, the double pass pump configuration causes a spatial redistribution of the absorbed pump intensity which slightly more emphasizes the gain contribution of the rear part of the laser crystal compared to the single pass configuration. In accordance to the model discussed in Sect. 2, this results in somewhat longer pulse durations of 17.6 ps for the 20 mm and 19.1 ps for the 30 mm long Nd:YVO_4 crystal.

5 Conclusion

We presented a detailed experimental investigation of pulse shortening and spectral broadening due to SHB in 888 nm end pumped, passively mode-locked Nd:YVO_4-lasers. We have demonstrated that the increased effect of gain narrowing, which unavoidably occurs in high power ps-lasers due to the large output coupling can be significantly compensated by SHB in a GE cavity, even if the gain is spread over long crystal length up to 30 mm, as it is the case for 888 nm pumping. A strong pulse shortening due to SHB by more than a factor of 2 was observed in our setup, resulting in a minimum pulse duration of 16.2 ps at a repetition rate of 96.2 MHz and an average output power of 31.6 W. Nevertheless, the maximum pulse bandwidth supported by SHB in 888 nm pumped Vanadate lasers is significantly lower compared to the pumping at Vanadate's absorption maximum. This is due to the much longer gain length, which reduces the spatial overlap between the gain grating and the overall gain length. We have shown that the impact of SHB on the flattening and broadening of the spectral gain can be increased, by reducing the length of the gain medium. Therefore, a further pulse shortening down to 9.5 ps was achieved, which was accompanied with a decrease in optical efficiency and maximum output power. This compromise between pulse duration and high power operation can be overcome, if the mode-locking mechanism itself is capable of generating much shorter pulses, without the assistance of SHB.

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