Diode-pumped passively mode-locked multiwatt $Nd:GdVO_4$ laser with a saturable Bragg reflector

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We report a first demonstration, to our knowledge, of a cw passively mode-locked $Nd:GdVO_4$ laser (λ = 1063 nm). A relaxed saturable Bragg reflector was used. The laser generates pulses of 9.2 ps at a repetition rate of 119 MHz. As much as 5.4 W of average power was realized with a slope efficiency of 25.7%. © 2003 Optical Society of America

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1. Introduction

Compact diode-pumped mode-locked solid-state lasers with high average power and good beam quality are essential for a wide variety of fundamental and industrial applications.[1–3] For high-peak-power applications, passively mode-locked lasers are generally more desirable than active ones because of their simpler cavity setup and shorter pulse width. Owing to the successful development of semiconductor saturable absorber mirrors (SESAMs)[4] and saturable Bragg reflectors (SBRs),[5,6] self-starting passive mode locking of a variety of diode-pumped solid-state lasers have been demonstrated.[7] The advantages of these semiconductor-based saturable absorbers are their low saturation energies, their compact design, and the possibility of engineering the absorber for particular laser systems, e.g., dispersion compensation.[8] Pulses as short as 2 cycles have been generated from a Ti:sapphire laser with a SESAM.[9] Saturation fluence as low as $<10\ \mu J/cm^2$ was realized in a SBR with triple-strained quantum wells,[7] making this device particularly attractive for low-energy diode-pumped solid-state lasers. In the picosecond regime, various lasers with neodymium- (Nd-) doped laser crystals, e.g. Nd:YAG,[10] $Nd:YVO_4$,[11,12] Nd:YLF,[13] and $Nd:KGd(WO_4)_2$[14] have been mode locked successfully by use of either SESAMs or SBRs. Recently gadolinium vanadate doped with Nd, or $Nd:GdVO_4$, has been recognized as a promising laser medium.[15,16] $Nd:GdVO_4$, is similar to $Nd:YVO_4$ in many aspects, such as belonging to the same space group and having a higher absorption coefficient for diode pumping and a larger emission cross section (seven-times-higher absorption cross section at 808 nm and a three-times-larger emission cross section at 1.06 μm than does Nd:YAG).[17,18] On the other hand, $Nd:GdVO_4$ exhibits some desirable features over $Nd:YVO_4$, such as a wider bandwidth (1.3 nm versus 0.8 nm) and much higher thermal conductivity along the <110> direction.[18] Furthermore the specific heat of $Nd:GdVO_4$ is larger than that of $Nd:YVO_4$. Because the specific heat is an important factor that influences the damage threshold of a laser crystal, $Nd:GdVO_4$ might be a promising alternative to $Nd:YVO_4$ in high-power pulsed laser systems. Both continuous-wave (cw) and *Q*-switched diode-pumped $Nd:GdVO_4$ lasers have been reported.[19,20] Wang *et al.* have compared the performances of diode-pumped $Nd:GdVO_4$ and $Nd:YVO_4$ lasers.[20] The cw $Nd:GdVO_4$ lasers at 1.06 and 1.34 μm and intracavity frequency-doubled $Nd:GdVO_4$ lasers with KTP and LiB_3O_5 outperform the $Nd:YVO_4$ lasers in terms of either slope efficiency or optical conversion efficiency.[11,15] Further, the wider bandwidth of $Nd:GdVO_4$ promises subpicosecond pulses in mode-locked operation. In this paper we report what is to our knowledge the first cw diode-pumped passively mode-locked $Nd:GdVO_4$ laser with a SBR. We successfully generated a 9.2-ps pulse train at 119 MHz.

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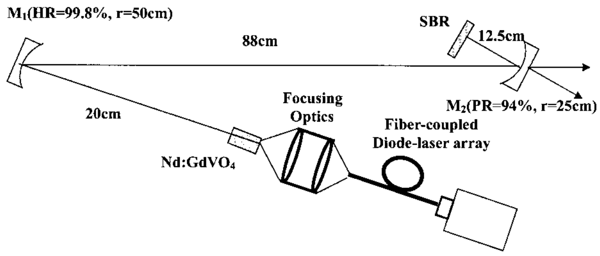


Fig. 1. Cavity configuration of the diode-pumped $Nd:GdVO_4$ laser. M_1 and M_2, mirrors; HR, high reflection; PR, partially reflective.

The laser output power was 5.4 W with a slope efficiency of 25.7%.

2. Experimental Setup

A schematic of the laser configuration is shown in Fig. 1. The diode-laser pump source (Coherent FAP-81-25c-800-B) is rated at a maximum power of 25 W into a bandwidth of 3 nm (FWHM) around $\lambda p = 808$ nm at 25 °C. A fiber bundle with a diameter of 0.8 mm and a numerical aperture of 0.2 and coupling optics were used to focus the pump beam into the laser crystal. The spot size of the pump beam on the laser crystal facet was approximately 640 μm. The a-cut 3 mm × 3 mm × 4 mm $Nd:GdVO_4$ crystal, doped at 1.3%, was coated for high reflection (HR, R· 99.8%) at 1063 nm and antireflection at 808 nm on the end face perpendicular to the laser beam axis. The front surface of the crystal was antireflection coated at 1063 nm to avoid a potential etalon effect. The laser crystal was wrapped with indium foil and then mounted in a water-cooled copper block. The water temperature was maintained at 20 °C. The cavity is a simple Z-folded resonator with one highly reflective ($R > 99.8\%$ at 1063 nm) mirror M_1, one partially reflective mirror M_2 ($R \cdot 94\%$ at 1063 nm), and a SBR. The radii of curvature of M_1 and M_2 are 50 and 25 cm, respectively, and the two mirrors are separated by 88 cm; the total cavity length is approximately 1.2 m. The laser cavity mode is focused more tightly on the SBR than on the laser rod, with a mode diameter approximately two times smaller than one on the laser rod. The absorber saturation pulse energy was estimated to be approximately 40 $\mu J/cm^2$, which is sufficiently small relative to the gain saturation fluence to ensure fast absorption saturation pulse shaping. The SBR was mounted on a copper heat sink, without cooling water or temperature regulation. It consisted of a distributed Bragg reflector with 35 pairs of high–low $\lambda/4$ Bragg layers of GaAs/AlAs grown by molecular beam epitaxy. An additional $\lambda/4$ layer of AlAs was grown on the top of the distributed Bragg reflector mirror, and a strained quantum well ($In_{0.3}Ga_{0.7}As/GaAs$) was inserted as the saturable absorber. For matching the wavelength of the laser, the SBR was designed with the photoluminescence peak wavelength of the absorber and the high reflectivity ($R > 99.5\%$) of the distributed Bragg reflector, both around 1.1 μm. The modulation depth, nonsaturable losses, saturation fluence, and absorption recovery time of the SBR are 1.0%, 0.2%, 40 $\mu J/cm^2$, and ~20 ps, respectively. The same SBR was previously employed successfully for passive mode locking of a diode-pumped cw $Nd:YVO_4$ solid-state laser.[12]

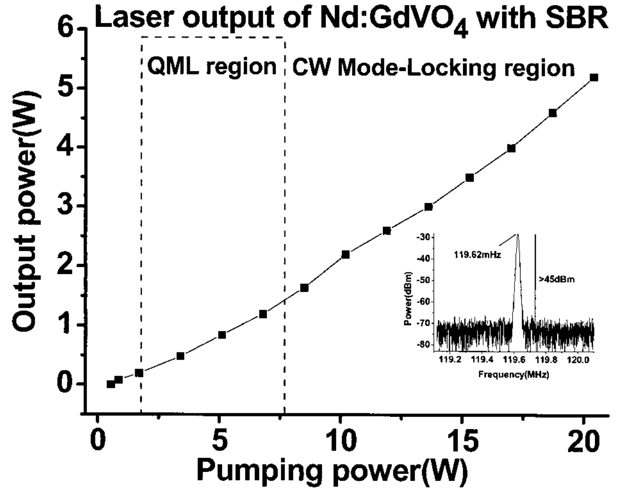


Fig. 2. Dependence of the laser output power on absorbed pump power; inset shows the rf spectrum of the cw mode-locking operation. QML, Q-switched mode locking.

3. Results and Discussions

In Fig. 2 the laser output power is plotted as a function of pumping power. The reported power is the sum of two output beams from the output coupler M_2. No saturation in the laser power output was observed with our full diode-laser output, which clearly shows superior thermal properties of the material.[19,20] We noted that the same laser output power can also be obtained when the SBR was replaced with a high-reflective mirror. This observation indicates a low unsaturable loss of our SBR. This plot reveals that the cw threshold pumping power of the laser was as low as 540 mW. As the pumping power was increased to 20.4 W, the output power of the laser can reach 5.4 W with a conversion efficiency of 26.3%. Both results are essentially similar to that of a $Nd:YVO_4$ laser mode locked by the same SBR and the same pump power reported by Chen *et al.*[12] Chen *et al.* achieved an average power of 23.5 W with 9-mm-long $Nd:YVO_4$ laser crystal pumped at 50 W. Their laser pulse width was 21 ps. Because of the higher thermal tolerance of $Nd:GdVO_4$, we expect similar or better performance if a high-power diode laser and a longer rod length become available.

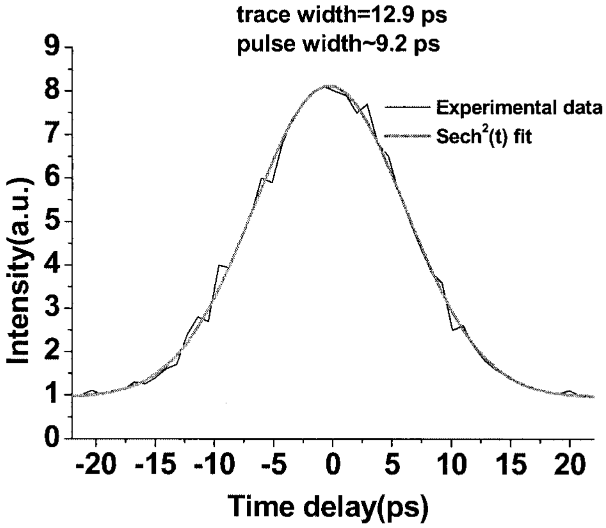
The laser also exhibits a clear regime of a Q-switched mode-locking state at a pump power range of $1.7\ W \leq P_{pump} \leq 7.65\ W$. We employed a rf spectrum analyzer (HP52601) to analyze the rf power spectrum. Relaxation oscillation at 110 kHz was observed in the Q-switched mode-locking region. At higher pumping power, a stable cw mode-locking state was achieved. The inset in Fig. 2 shows that the rf spectrum of the mode-locked pulse trains with a repetition rate of around 119.6 MHz. A side-mode suppression as large as −45 dBm was achieved, indicating a fairly stable cw mode-locking operation of our laser.

According to Refs. 21 and 22, the minimum intracavity pulse fluence $F_{P,c}$ for stable cw mode locking can be obtained by

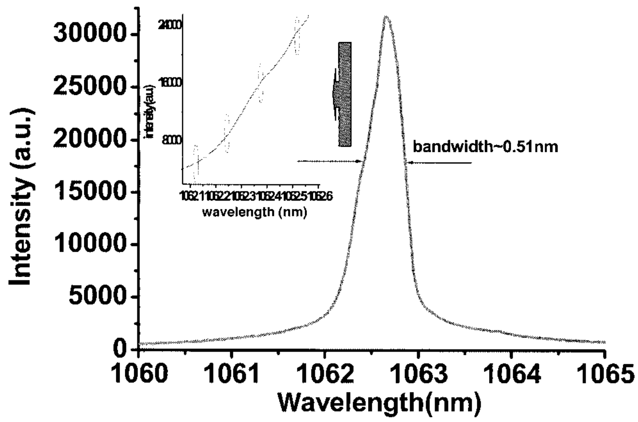
$$F > F_{P,c} = (F_{\mathrm{sat},L}\, F_{\mathrm{sat},A}\, R)^{1/2}, \qquad (1)$$

where $F_{\mathrm{sat,L}} = h\nu/\sigma m$ denotes the saturation fluence of the gain medium with a lasing frequency ν, σ is the stimulated emission cross section, and $m = 2$ is used to reflect an average over the standing wave in a linear cavity; $F_{sat,A}$ denotes the saturation fluence of the saturable absorber with a modulation depth of R. For Nd:$GdVO_4$, the gain saturation fluence is estimated to be $F_{sat,L} = 0.375$ J/cm^2. The spot size on the saturable absorber was ~120 μm, the saturation fluence of the absorber is then found to be $F_{sat,A} \sim 40$ μJ/cm^2, and the modulation depth of the saturable absorber is ~1%. Therefore the estimated minimum intracavity pulse energy for stable cw mode locking is $E \approx 12$ nJ. At a pump power of 8 W, we estimate that $E \sim 100$ nJ, which can be increased to 300 nJ when the pump power is higher than 19 W in our setup. Inequality (1) is therefore well fulfilled. The transition from Q-switched mode locking to stable cw mode locking is typical for passively mode-locked solid-state lasers. A similar trend was also observed by Chen's group.[12]

The output pulses were further characterized with an autocorrelator by use of KTP as the frequency-doubling crystal. The FWHM of the autocorrelation trace [see Fig. 3(a)] was measured to be 12.9 ps. Assuming a hyperbolic secant pulse profile, we estimate the pulse duration to be approximately 9.2 ps. The measured optical spectrum of the mode-locking laser is presented in Fig. 3(b). The spectrum is centered at 1062.7 nm with a FWHM bandwidth of 0.51 nm with a slight asymmetric spectral distribution. The spectral feature also shows longitudinal mode spacing with an effective optical length of 0.86 cm [see inset of Fig. 3(b)]. By considering the index of refraction of the $GdVO_4$ crystal, we found the resulting geometrical length of 4 mm to be fairly close to the laser crystal length. This indicates that the etalon effect from the two end surfaces of the crystal is not completely eliminated. It has been known that an intracavity etalon effect plays a significant role in the mode-locking pulse-shaping process and could lead to a asymmetric spectral profile. The resulting time–bandwidth product of the laser pulses is 1.24, indicating the presence of strong phase-modulation effects. Because the only transmissive element in our laser cavity is the gain medium, we therefore attribute the resulting non-transform-limited time–bandwidth product to originate from the dispersive effect of the laser rod. When compared with the result of 21-ps pulse duration from a 9-mm-long Nd:YVO_4 gain rod,[12] the shorter pulse width of 9.2 ps obtained in this study is a factor of 2.3 lower, which agrees well with the fact of a lower dispersion with a shorter rod length. With intracavity dispersion compensation, such as the use of Gires–Tournois interferometer mirrors for dispersion compensation,[23] a transform-limited pulse width as short as 0.9 ps should be possible if the entire gain bandwidth can be utilized.



(a)



(b)

Fig. 3. (a) Envelope of collinear interferometric autocorrelation trace of the mode-locked laser pulses; (b) Corresponding optical spectrum of the laser; inset is the magnification of part of the spectrum, showing minor peaks due to the etalon effect.

4. Summary

In summary, we report a first demonstration of a continuous-wave passively mode-locked Nd:$GdVO_4$ laser at $\lambda = 1062.7$ nm. A strain-relaxed saturable Bragg reflector was used in the laser to generate pulses of 9.2 ps at a repetition rate of 119 MHz. As much as 5.4 W of average power was realized with a slope efficiency of 25.7%. Because of the excellent thermal properties and broad bandwidth (compared with Nd:YVO_4), the mode-locked Nd:$GdVO_4$ laser could be an interesting alternative to Nd:YVO_4 for the generation of high-power picosecond-to-subpicosecond pulses and applications.

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