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A high-power harmonically self-mode-locked Nd:YVO$_4$ 1.34-μm laser with repetition rate up to 32.1 GHz

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Abstract
We develop a practical method to achieve harmonically self-mode-locked operation in a Nd:YVO$_4$ 1.34-μm laser for the generation of high-repetition-rate pulse trains. We exploit a gain medium with partial-reflection coating at the lasing wavelength to introduce effective mode selection. We numerically demonstrate that the coated gain medium can effectively modify the mode spacing of the laser cavity to be the harmonics of the free spectral range of the gain medium when the optical cavity length is adjusted to be commensurate with the optical length of the gain medium. We further employ a coated Nd:YVO$_4$ crystal to realize harmonically mode-locked operation with a highest repetition rate of up to 32.1 GHz. At a pump power of 11.5 W, the average output power of 2.3 W is generated with a pulse duration as short as 5.7 ps. The locking range for the cavity length is also experimentally explored.

Keywords: harmonic mode locking, GHz repetition rate, mode selection

(Some figures may appear in colour only in the online journal)

1. Introduction

Light sources with wavelengths near 1.3 μm have many potential applications, such as telecommunication, fiber sensing, ranging, and data storage. Due to their potential, numerous Nd-doped crystals have been developed for the generation of 1.3-μm lasers at cw or pulsed operation [1–5]. Nd-doped yttrium vanadate (Nd:YVO$_4$) has been identified as an excellent laser host material for all-solid-state lasers. Recently, it has been demonstrated that the large third-order nonlinearity of Nd:YVO$_4$ crystals can be used to achieve efficient self-mode-locked operation at frequencies of several gigahertz (GHz) [6]. The physical mechanism for the self-mode-locking is attributed to the combined effects of Kerr lensing and thermal lensing [7–9].

Nowadays, laser sources with pulse repetition rates higher than 10 GHz are the key components in a great variety of applications such as large-mode-spacing supercontinuum generation [10], high capacity optical networks [11], optical clocking [12], wireless communication [13], telecommunication [14], and quantum communication [15]. To generate $>$10 GHz mode-locked pulse trains, the cavity lengths generally need to be shorter than 15 mm. Solid-state lasers with such short cavity lengths, however, are difficult to achieve with high-power operation. Harmonic mode-locking is a useful method to achieve high repetition rates at harmonic multiples of the fundamental mode spacing. Harmonically mode-locked operation has been studied in diverse lasers, such as fiber lasers [16, 17], vertical-external-cavity surface-emitting lasers [18, 19], and Nd:YLF lasers [20]. Nevertheless, there are no reports to date addressing the realization of harmonic mode-locking in Nd:YVO$_4$ 1.34-μm lasers. It would be very useful to develop a practical method to achieve harmonically self-mode-locked operation in Nd:YVO$_4$ 1.34-μm lasers.

The aim of this work is to develop a practical approach to achieve harmonically self-mode-locked operation in a

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Nd:YVO4 1.34-μm laser. We exploit a specially coated gain medium with an appropriate tilt angle to introduce effective spectrum modulation for mode selection. We numerically show that Fabry–Perot filtering of the coated gain medium in combination with a cavity length satisfying the commensurate condition $L_c^*/L_g^* = q/p$ can lead to the overall mode spacing being equal to the pth harmonics of the free spectral range of the gain medium, Δf_g, where L_c^* and L_g^* are the optical cavity length and the optical crystal length, respectively. We further employ a coated Nd:YVO4 crystal with $\Delta f_g = 10.7$ GHz in a concave–plano cavity to demonstrate harmonically mode-locked operation with a highest repetition rate of up to 32.1 GHz. At a pump power of 11.5 W, we obtain an average output power of 2.3 W, corresponding to an optical conversion efficiency of 19.6%. The pulse duration at 32.1 GHz is found to be as short as 5.7 ps.

2. Analysis

For a typical solid-state laser cavity as shown in figure 1(a), the mode spacing of the longitudinal mode is given by $\Delta f_c = c/(2L_c^*)$, where $L_c^* = L_c + (n_r - 1)L_g \cos\theta$, L_c is the geometric length of the cavity, L_g is the geometric length of the gain medium, θ is the internal angle between the laser beam and the normal axis through the gain medium, and n_r is the refractive index of the gain medium. Provided that the lasing longitudinal modes are phase locked in the cavity, the frequency distribution can be ideally expressed as

$$I(f) = \sum_{m=-M}^{M} a_m\, \delta(f - f_o - m\,\Delta f_c), \tag{1}$$

where a_m is the weighting coefficient and f_o is the central frequency. To include the effective line width, the δ-function in equation (1) is explicitly replaced with a series of Lorentzian functions,

$$I(f) = \frac{1}{\pi} \sum_{m=-M}^{M} \frac{a_m\, \Gamma_c\, \Delta f_c^2}{[(f - f_o) - m\,\Delta f_c]^2 + (\Gamma_c\, \Delta f_c)^2}, \tag{2}$$

where Γ_c is the effective linewidth of the cavity mode.

Provided that both end surfaces of the gain medium are coated to have a reflectance R to introduce a Fabry–Perot modulation effect, the frequency distribution of the laser emission is modulated with an effective transmission function:

$$I(f) = \left[\frac{1}{\pi} \sum_{m=-M}^{M} \frac{a_m\, \Gamma_c\, \Delta f_c^2}{[(f - f_o) - m\,\Delta f_c]^2 + (\Gamma_c\, \Delta f_c)^2}\right] \times \left[\sum_{n} \frac{\Gamma_g\, \Delta f_g^2}{(f - n\,\Delta f_g)^2 + (\Gamma_g\, \Delta f_g)^2}\right], \tag{3}$$

where $\Delta f_g = c/(2L_g^*)$ is the free spectral range of the gain medium, $L_g^* = n_r\, L_g \cos\theta$, and Γ_g is given by $(1/2\pi)\ln(1/R)$. The value of θ can be directly associated with the tilt angle of the gain medium. Although $\theta = 0$ can minimize the cavity losses to reach the maximum output power, this value cannot be used to obtain effective loss modulation for mode selection. On the other hand, if the tilt angle θ is too large, the cavity losses may rapidly increase to reduce the output power significantly. Practically, the appropriate range for the tilt angle θ is approximately 0.8–1.6 degrees. Figure 1(b) depicts the numerical results for the frequency spectrum as a function of the ratio L_c^*/L_g^* in the range 2.0–3.0. The values for the parameters are $a_m = 1$, $\Gamma_c = 0.03$, $\Gamma_g = 0.1$, and $\theta = 1.0°$. It can be seen that when the cavity length leads to a ratio $L_c^*/L_g^* = \Delta f_g/\Delta f_c$ close to a simple fraction q/p, the frequency spectrum can form a structure with an effective mode spacing of $p\,\Delta f_g = q\,\Delta f_c$. In other words, the Fabry–Perot filtering of the coated gain medium in combination with the cavity length satisfying $L_c^*/L_g^* = q/p$ can lead to the effective mode spacing being equal to the pth harmonics of the free spectral range of the gain medium, Δf_g, and simultaneously equal to the qth harmonics of the cavity mode spacing, Δf_c.

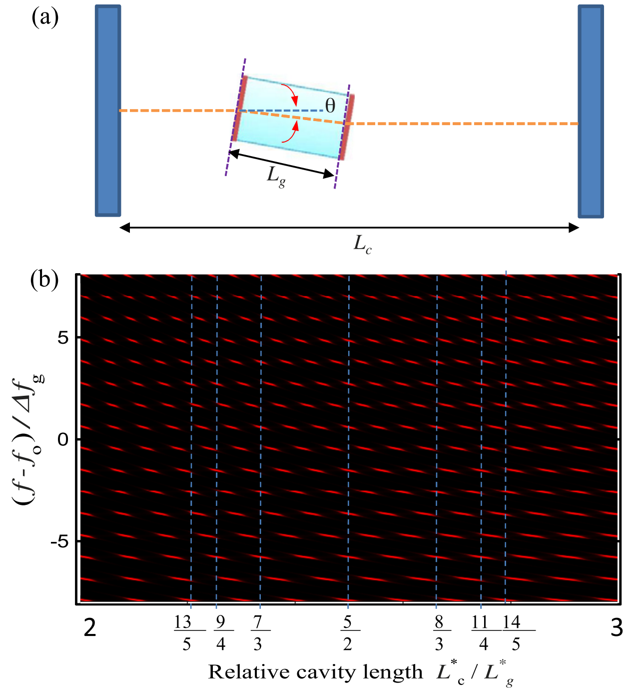

Figure 1. (a) Schematic diagram of the cavity setup for harmonically self-mode-locked operation. (b) Numerical results for the frequency spectrum as a function of the ratio L_c^*/L_g^* in the range 2.0–3.0.

3. Experiment

To realize harmonic mode-locking, the gain medium was coated to have a reflectance of approximately $R = 10\%$ on both end surfaces at 1.34 μm. The resonator was a concave–plano cavity. The gain medium was an a-cut 0.5 at.% Nd:YVO4crystal with dimensions of $3 \times 3 \times 6.4$ mm^3. With a refractive index of 2.187, the optical length L_g^* can be found to be approximately 14 mm, corresponding to a free spectral range of $\Delta f_g = 10.7$ GHz. In addition to the partial reflection at 1.34 μm, both end surfaces of the Nd:YVO4 crystal were coated for high transmission ($T > 97\%$) at the wavelength of 808 nm for the pump light. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The water temperature was maintained at 16 °C to ensure stable laser output. The input mirror was a 500-mm radius-of-curvature concave mirror with antireflection coating at 808 and 1064 nm on the entrance face and with high reflection coating at 1342 nm (>99.8%) and high transmission coating at 808 and 1064 nm on the concave side. A wedged flat mirror with 7% transmission at 1342 nm and high transmission at 1064 nm was used as an output coupler. The pump source was a 16-W, 808-nm fiber-coupled laser diode with a core diameter of 400 μm and a numerical aperture of 0.22. A focusing lens with 25-mm focal length and 90% coupling efficiency was used to reimage the pump beam into the laser crystal. The average pump diameter was approximately 200 μm. The separation between the laser crystal and the input mirror was fixed to be approximately 3 mm. The cavity length L_c^* could be precisely controlled in the range of 28–70 mm. The temporal behavior of the laser output was analyzed by exploiting the first- and second-order autocorrelations. The first-order autocorrelation trace was performed with a Michelson interferometer (Advantest, Q8347) with a resolution of 0.003 nm that was also able to perform optical spectral analysis by Fourier transforming the first-order field autocorrelation. The second-order autocorrelation trace was obtained with a commercial autocorrelator (APE Pulse Check, Angewandte Physik and Elektronik GmbH).

To begin with, the cavity length L_c^* was set to be near 28 mm to satisfy $L_c^*/L_g^* = 2$, corresponding to a mode spacing of 5.35 GHz. The gain medium was aligned to be $\theta \approx 0$ to obtain the maximum output power. Figure 2 depicts the average output power versus the pump power in maximum output power operation. At an incident pump power of 11.5 W, the average output power was 3.1 W and the slope efficiency was approximately 28.3%. Under the condition $\theta \approx 0$, the temporal behavior of the laser output displays irregular pulse trains. To obtain regular mode-locked pulse trains, the gain medium needed to be slightly tilted. We set the angle to be approximately $\theta = 1.0°$ and finely tuned the cavity length to optimize the mode-locked operation by monitoring the autocorrelation trace. When optimum mode-locked operation was achieved, the average output power was found to be approximately 2.3 W at a pump power of 11.5 W. In other words, the average output power in mode-locked operation is approximately 75% of the maximum average output power in free running. Figure 3(a) shows the experimental first-order autocorrelation trace of mode-locking at an average output power of 2.3 W. The pulse repetition rate was measured to be 10.7 GHz, which is two times the cavity mode spacing and just corresponds to the free spectral range of the optical crystal length. As shown in figure 3(b), the optical spectrum was found to be centered at 1342.16 nm with a full-width at half-maximum (FWHM) of 0.268 nm. The longitudinal mode spacing of 0.06 nm agrees with the pulse repetition rate of 10.7 GHz. Figure 3(c) depicts the FWHM width of the central peak of the second-order autocorrelation trace. Assuming the temporal intensity to be a Gaussian profile, the pulse duration can be derived as 10.1 ps. Therefore, the time–bandwidth product of the mode-locked pulse is found to be 0.45, which is very close to the Fourier-limited value of 0.44.

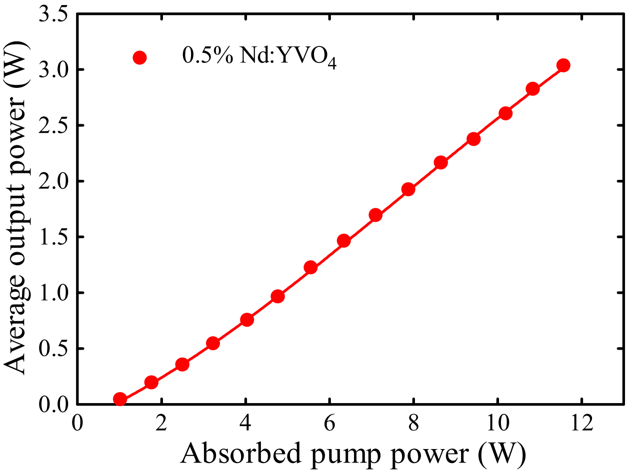

Figure 2. Average output power versus pump power in maximum output power operation under the condition $\theta = 0$.

By scanning the cavity length, we experimentally confirmed that when the cavity length was adjusted to be near the region of $L_c^*/L_g^* = q/p$, the laser output could turn into harmonically self-mode-locked operation. Figures 4(a)–(c) are the same plots as shown in figures 3(a)–(c) for experimental data obtained with the cavity length near $L_c^*/L_g^* = 5/2$ at a pump power of 11.5 W. The average output power approximately remained at 2.3 W. It can be seen that the mode-locked behavior just corresponds to the second harmonic of the free spectral range Δf_g and simultaneously corresponds

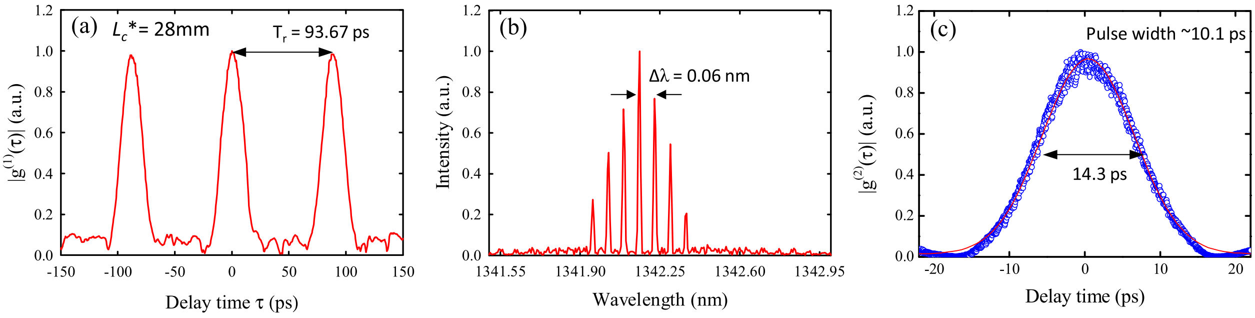

Figure 3. Experimental results obtained with $L_c^*/L_g^* = 2$ at a pump power of 11.5 W: (a) trace of the first-order autocorrelation; (b) optical spectrum; (c) trace of the second-order autocorrelation.

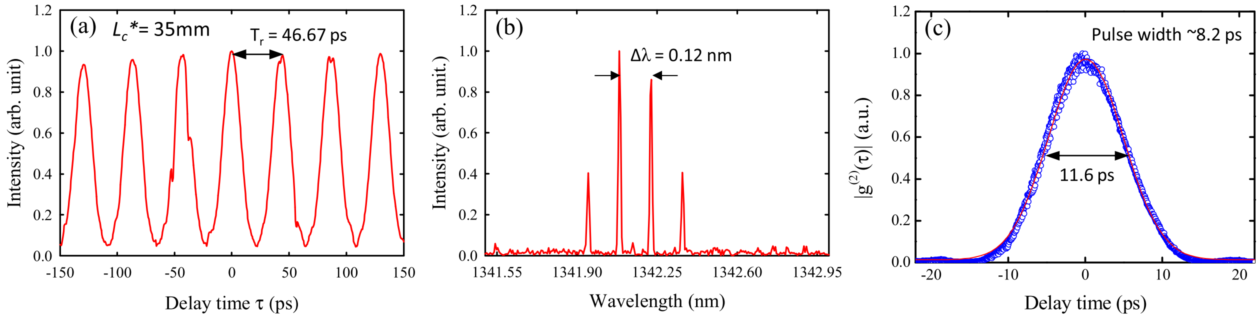

Figure 4. The same as figure 3 for the case of $L_c^*/L_g^* = 5/2$ at a pump power of 11.5 W.

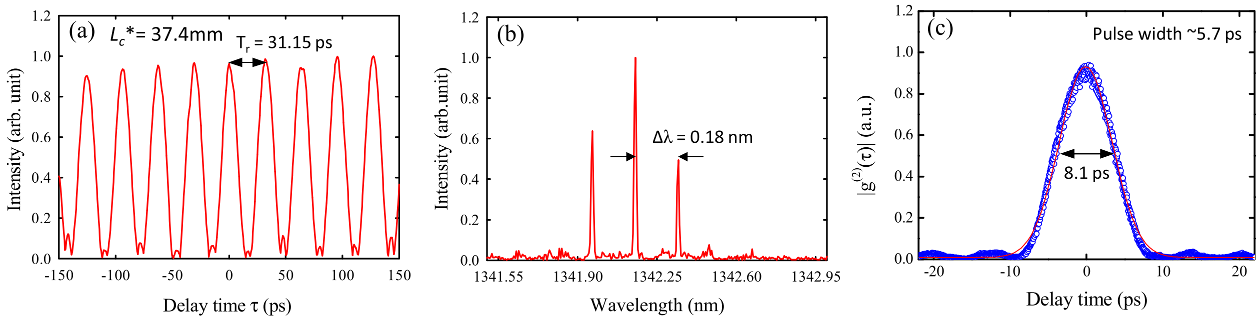

Figure 5. The same as figure 3 for the case of $L_c^*/L_g^* = 8/3$ at a pump power of 11.5 W.

to the fifth harmonic of the cavity mode spacing Δf_c. As shown in figure 4(c), the pulse duration is approximately 8.2 ps. Figures 5(a)–(c) are the same plots as shown in figures 3(a)–(c) for experimental data obtained with the cavity length near $L_c^*/L_g^* = 8/3$ at a pump power of 11.5 W. The average output power was also unchanged. The experimental results clearly reveal that the mode-locked performance corresponds to the third harmonic of the free spectral range Δf_g and simultaneously corresponds to the eighth harmonic of the cavity mode spacing Δf_c. The pulse duration can be seen to be as short as 5.7 ps.

Figure 6 shows the observed repetition rate in harmonically mode-locked operation for the cavity length in the range between $L_c^*/L_g^* = 2$ and $L_c^*/L_g^* = 5$. It can be seen that the repetition rate can be locked in the region of $f_{\text{rep}} = p\,\Delta f_g$ with $p = 1$, 2, and 3. The gain bandwidth of the laser crystal limit hindered the repetition rate $f_{\text{rep}} = p\,\Delta\, f_g$ with p greater than 4. We also found that the locking range for the cavity length could be empirically expressed as $L_c^* = (q \pm \nu)L_g^*/p$ with $\nu = 0.16$. In other words, the locking range for the cavity length is proportional to the crystal length and inversely proportional to the integer p. When the cavity length is out of the locking range, the laser output generally displays the feature of multi-pulse mode-locking. The locking range is an interesting phenomenon and further investigation is underway.

4. Conclusions

In summary, we have successfully generated high-power and high-repetition-rate Nd:YVO$_4$ 1.34-μm lasers by developing a method to achieve harmonically self-mode-locked operation. It was numerically revealed that when the optical cavity length is adjusted to be commensurate with the optical length of the gain medium, the gain medium with partial-reflection coating at the lasing wavelength can effectively modify the mode spacing of the laser cavity to be the harmonics of the free spectral range of the gain medium, Δf_g. We further exploited a coated Nd:YVO$_4$ crystal to realize harmonically mode-locked operation. The experimental results revealed that the repetition rate could be locked in the region of $f_{\text{rep}} = p \times 10.7$ GHz with the index

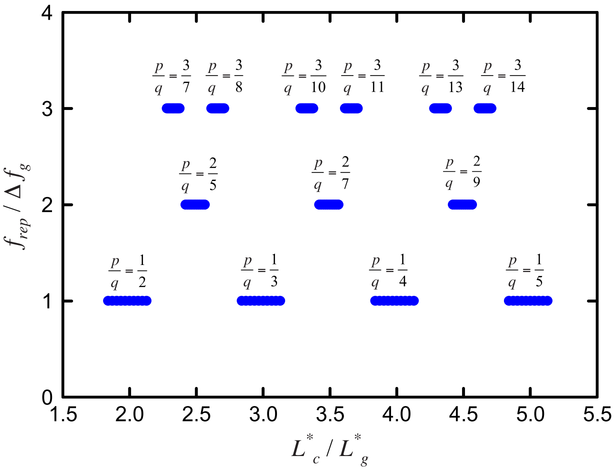

Figure 6. The observed repetition rate in harmonically mode-locked operation for the cavity length in the range between $L_c^*/L_g^* = 2$ and $L_c^*/L_g^* = 5$.

$p = 1, 2$, and 3. At a pump power of 11.5 W, the overall average output power was up to 2.3 W with the pulse duration as short as 5.7 ps. We also experimentally explored the locking range for the cavity length and found that it is proportional to the crystal length and inversely proportional to the index p.

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