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cw dual-wavelength operation of a diode-end-pumped Nd:YVO$_4$ laser

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Abstract. A dual-wavelength continuous wave (cw) diode-end-pumped Nd:YVO$_4$ laser that generates simultaneous laser action at the wavelengths 1064 nm and 1342 nm is demonstrated. The optimum oscillation condition for the simultaneous dual-wavelength operation in a diode-end-pumped solid-state laser has been derived. The relationship between the laser cavity and the output stability is also studied. Experimental results show that the stability of the output power at the two wavelengths could be enhanced by use of a three-mirror cavity.

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Simultaneous emission at multiple wavelengths has been of interest for the practical application of these lasers such as medical instrumentation and research on nonlinear optical mixers. Pulsed operation has been reported in a Nd:YAG laser [1], in a Nd:YLF laser [2], in (Er, Nd):YAG laser [3], and in (Ho, Nd):YAG laser [4]. cw operation has been reported in a Nd:YAG laser [5] and in a Nd:YAP laser [6]. All of these lasers are operated in the lamp-pumped configuration. Shen et al. [6] analyze the possibility of simultaneous dual-wavelength lasers in Nd:YAG, Nd:YLF, Nd:BEL, and Nd:YAP crystals at the transitions from $^4F_{3/2} - {}^4I_{11/2}$ and $^4F_{3/2} - {}^4I_{13/2}$ and recognize that dual-wavelength operation of Nd host crystals is easier to accomplish with pulse operation and difficult to obtain with cw operation. Their analysis [6] shows that the ratio of the stimulated-emission cross section between $^4F_{3/2} - {}^4I_{11/2}$ and $^4F_{3/2} - {}^4I_{13/2}$ transitions can not be too large for obtaining a cw dual-wavelength operation. This is why in [6] cw dual-wavelength operation is only possible with Nd:YAP and is hardly obtainable with the other Nd-doped crystals studied.

Diode-pumped solid-state lasers have been shown to be efficient, compact, and reliable all-solid-state optical sources. The Nd:YVO$_4$ crystal has been identified as one of the promising materials for diode-pumped solid-state lasers because of its high absorption over a wide pumping wavelength bandwidth and its large stimulated-emission cross section at both 1064 nm and 1342 nm. For Nd:YAG crystal, the ratio of the stimulated-emission cross section between $^4F_{3/2} - {}^4I_{11/2}$ and $^4F_{3/2} - {}^4I_{13/2}$ transitions is around 5–5.1 [7], whereas this ratio for Nd:YVO$_4$ crystal is about 3.3. Therefore, the Nd:YVO$_4$ crystal may be a good candidate for dual-wavelength operation at $^4F_{3/2} - {}^4I_{11/2}$ and $^4F_{3/2} - {}^4I_{13/2}$ transitions. In this work, simultaneous cw emission of two wavelengths, $\lambda_1 = 1342$ nm and $\lambda_2 = 1064$ nm, from a diode-end-pumped Nd:YVO$_4$ laser was investigated and achieved experimentally.

1 Analysis

To optimize dual-wavelength lasing operation, the reflectivity values of each respective wavelength at the output coupler should be set to approximately balance the gain curves for each of the two output wavelengths. Let σ and R be, respectively, the stimulated-emission cross section and the reflectivity of the output coupler with the subscripts 1 and 2 used to denote these qualities at $\lambda_1 = 1342$ nm and $\lambda_2 = 1064$ nm. For a diode-end-pumped solid-state laser, the threshold condition for each transition can be written as [8]

$$P_{\mathrm{th},i} = \frac{\ln(1/R_i) + L_i}{2l\eta_{\mathrm{Q},i}} \frac{h\upsilon_{\mathrm{p}}}{\sigma_i \tau_i} \frac{1}{\int\int\int s_i(r,z) r_{\mathrm{p}}(r,z)\,\mathrm{d}v}\,, \quad i = 1, 2\,, \tag{1}$$

where l is the length of the active medium, L_i is the roundtrip cavity excess losses at the corresponding transition wavelength, τ_i is the fluorescence lifetime at the upper level, $\eta_{\mathrm{Q},i}$ is the quantum efficiency for the corresponding transition, $s_i(r,z)$ is the normalized cavity mode intensity distribution for the corresponding transition, and $r_{\mathrm{p}}(r,z)$ is the normalized pump intensity distribution in the active medium.

From (1), the condition that both transitions possess the same threshold can be give by

$$\ln\left(\frac{1}{R_2}\right) = \left[\frac{\eta_{Q,2}\sigma_2 \int\int\int s_2(r,z) r_p(r,z)\,\mathrm{d}v}{\eta_{Q,1}\sigma_1 \int\int\int s_1(r,z) r_p(r,z)\,\mathrm{d}v}\right] \times \left[\ln\left(\frac{1}{R_1}\right) + L_1\right] - L_2\,. \qquad (2)$$

Here we used the fact that the fluorescence lifetimes for the each lasing wavelength are equal because of the transitions originating from the same upper laser level. The beam profile of a fiber-coupled laser diode, $r_p(r, z)$, can be approximately described as a top-hat distribution:

$$r_p(r,z) = \frac{\alpha \mathrm{e}^{-\alpha z}}{\pi\omega_p^2(z)[1-\mathrm{e}^{-\alpha l}]}\Theta\left(\omega_p^2(z) - r^2\right)\,, \qquad (3)$$

where $\omega_p(z)$ is the pump size in the active medium, and $\Theta(\,)$ is the Heaviside step function. With the usual M^2 propagation law, the pump beam is given by

$$\omega_p^2(z) = \omega_{po}^2\left\{1 + \left[\frac{\lambda_p M_p^2}{n\pi\omega_{po}^2}(z - z_o)\right]^2\right\}\,, \qquad (4)$$

where ω_{po} is the radius at the waist, λ_p is the pump wavelength, M_p^2 is the pump beam quality factor, and z_o is focal plane of the pump beam in the active medium. For a single transverse mode TEM_{00}, $s_i(r, z)$ can be given by

$$s_i(r,z) = \frac{2}{\pi\omega_i^2 l}\exp\left(-\frac{2r^2}{\omega_i^2}\right)\,, \qquad (5)$$

where ω_i is the beam size in the gain medium. Here a constant beam size was used because the variation of the beam size in the gain medium is rather small. Assuming the quantum efficiency being the same for the both lasing wavelength and substituting (3) and (5) into (2), we obtain

$$\ln\left(\frac{1}{R_2}\right) = \left[\frac{\sigma_2 \int_0^l \mathrm{e}^{-\alpha z}\left(1-\mathrm{e}^{-2\omega_p^2(z)/\omega_2^2}\right)/\omega_p^2(z)\,\mathrm{d}z}{\sigma_1 \int_0^l \mathrm{e}^{-\alpha z}\left(1-\mathrm{e}^{-2\omega_p^2(z)/\omega_1^2}\right)/\omega_p^2(z)\,\mathrm{d}z}\right] \times \left[\ln\left(\frac{1}{R_1}\right) + L_1\right] - L_2\,. \qquad (6)$$

With (6) and the parameters in the experiment, the corresponding reflectivity values at the lasing wavelength $\lambda_2 = 1064\,\mathrm{nm}$, R_2, was calculated as a function of the beam size ratio, ω_2/ω_1, for several reflectivity values of output coupler at the lasing wavelength $\lambda_1 = 1342\,\mathrm{nm}$, R_1, as shown in Fig. 1. The basic parameters used in calculation are $\omega_{po} = 0.25\,\mathrm{mm}$, $\omega_1 = 0.26\,\mathrm{mm}$, $L_1 = 0.005$, $L_2 = 0.006$, $M_p^2 \approx 310$, $n = 2.165$, $l = 6\,\mathrm{mm}$, $\alpha = 10\,\mathrm{cm}^{-1}$, $\sigma_1 = 7.6 \times 10^{-19}\,\mathrm{cm}^2$ [9], and $\sigma_2 = 25 \times 10^{-19}\,\mathrm{cm}^2$ [10]. The values of L_i were measured by the Findlay–Clay method [11]. Figure 1 shows that R_2 is nearly independent of the ratio ω_2/ω_1 for a given R_1 as $\omega_2/\omega_1 > 1$. To obtain the operation with a low threshold, the reflectivity of the output coupler at 1342 nm was coated to be 98% in experiment.

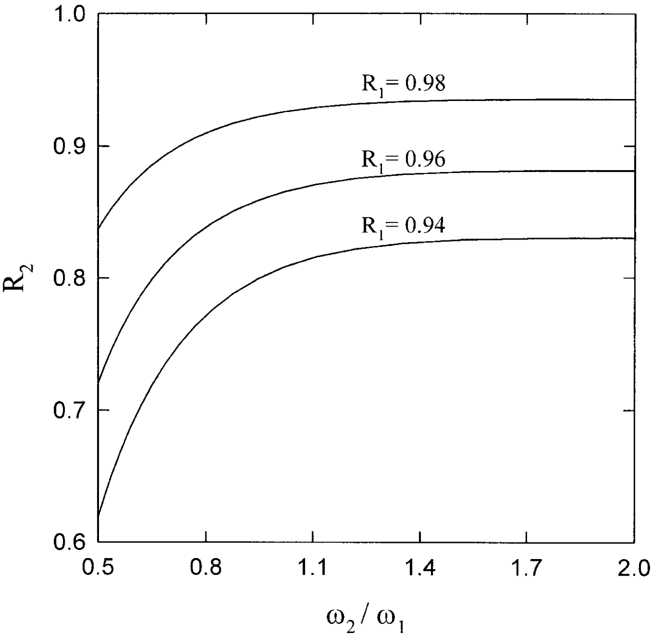

Fig. 1. A plot of the corresponding reflectivity values at the lasing wavelength $\lambda_2 = 1064\,\mathrm{nm}$, R_2, as a function of the beam size ratio, ω_2/ω_1, for several reflectivity values of output coupler at the lasing wavelength $\lambda_1 = 1342\,\mathrm{nm}$, R_1

2 Experiment and discussion

Two types of cavity configuration, as sketched in Figs. 2a and 2b, have been investigated. The length of Nd:YVO$_4$ crystal was 6 mm with 0.5 at. % Nd^{3+} concentrations. The pump source was a 15-W fiber-coupled laser diode with a core diameter of 1.15 mm and a numerical aperture of 0.12. The fiber output was focused into the crystal and the pump spot

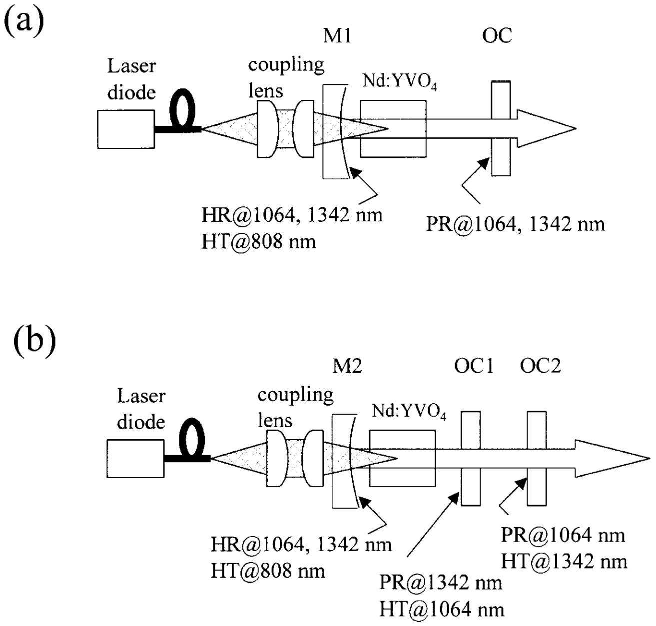

Fig. 2. Schematic of the diode-end-pumped Nd:YVO$_4$ laser cavity for simultaneous oscillation at 1064 and 1342 nm

size was around 0.25 mm. The first laser cavity was a two-mirror resonator formed by an input mirror and an output coupler, as shown in Fig. 2a. The input mirror M1 was a 1-m radius-of curvature concave mirror with antireflection coating at the pump wavelength on the entrance face ($R < 0.2\%$) and with high-reflection coating at both lasing wavelengths ($R > 99.9\%$) high-transmission coating at the pump wavelength on the second surface ($T > 95\%$). The output coupler OC was a flat mirror with partial reflection at both lasing wavelengths to provide an output. The cavity length was set to be 9 cm for appropriate mode-size matching. With this cavity length, the mode size at the input mirror was around 0.26 mm. The second laser cavity was a three-mirror resonator that consisted of the input mirror M2 and two flat output couplers OC1 and OC2, as shown in Fig. 2b. The input mirror M2 is the same as M1 of the laser cavity shown in Fig. 2a. One side of the output coupler OC1 was coated to be partially reflecting at the λ_1 wavelength and highly transmitting at the λ_2 wavelength ($T > 95\%$). The remaining side of the OC1 was antireflective at both lasing wavelengths ($R < 0.2\%$). On the other hand, one side of the output coupler OC2 was coated to be partially reflecting at the λ_2 wavelength and highly transmitting at the λ_1 wavelength ($T > 95\%$). The remaining side of the OC1 was antireflective at both lasing wavelengths ($R < 0.2\%$). The cavity length for λ_1 oscillation was 3 cm and the total cavity length was 9 cm. The cavity length chosen here resulted in the mode ratio of ω_2/ω_1 greater than unity and enhanced the output stability in the dual-wavelength operation.

For the two-mirror laser cavity shown in Fig. 2a, the ratio ω_2/ω_1 is equal to $\sqrt{\lambda_2/\lambda_1} = 0.89$. With $\omega_2/\omega_1 = 0.89$ and $R_1 = 0.98$ and from Fig. 1, the corresponding reflectivity R_2 was found to be around 91.5%. Practically, it is very difficult to control the reflectivity values of the output coupler at precise values for both wavelengths at 1064 and 1342 nm. In experiment an output coupler with the reflectivity values of 92% and 98% for 1064 nm and 1342 nm, respectively, was used to achieve simultaneous dual-wavelength lasing. We found that the relative output powers of each wavelength were very sensitive to the alignment of the output coupler. The alignment sensitivity the relative output power may be due to the fact that the relative cavity losses L_i were adjusted in the alignment procedure. It is impossible to simultaneously achieve the maximum output powers for each wavelength by use of two-mirror laser cavity. Therefore, the alignment criterion is based on the minimum threshold for the dual-wavelength operation. The output powers at each lasing wavelength versus input power are given in Fig. 3. A significant fluctuation in output power of each lasing wavelength was observed in the simultaneous emission because of their competitive interaction. The simultaneous emission of 1064-nm and 1342-nm lights was in the dominant TEM_{00} mode. The error bars indicate the output power fluctuation. It can be found that as the pump power increased the output powers at 1064 nm and 1342 nm rose monotonically whereas, from a certain value of pump power, the output power at 1064 nm decreased until the lasing at this wavelength was completely suppressed. We believe that the gain competition between 1064-nm and 1342-nm lights results in the output-power decrease of 1064-nm light above 6 W of pump power.

For the present three-mirror cavity, the value of the ratio ω_2/ω_1 was around 1.2. With $\omega_2/\omega_1 = 1.2$ and $R_1 = 0.98$ and from Fig. 1, the corresponding reflectivity R_2 was found to be around 93.5%. In experiment an output coupler with the reflectivity of 98% for 1342 nm and an output coupler with the reflectivity of 93% for 1064 nm were used to achieve simultaneous dual-wavelength lasing in the three-mirror cavity. The dual-wavelength system was initially optimized at 1342 nm without the output coupler OC2 shown in Fig. 2b. By introducing OC2 into the laser cavity, simultaneous cw lasing was achieved at 1342 nm and 1064 nm. The output powers at each lasing wavelength versus input power are given in Fig. 4. It can be seen that the output powers of both

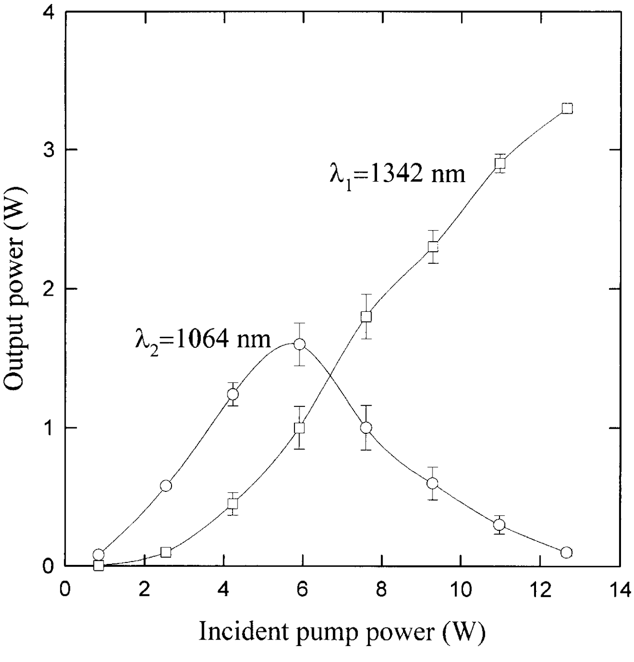

Fig. 3. Dependence of the relative output powers at 1064 and 1342 nm on the incident pump power with the two-mirror laser cavity

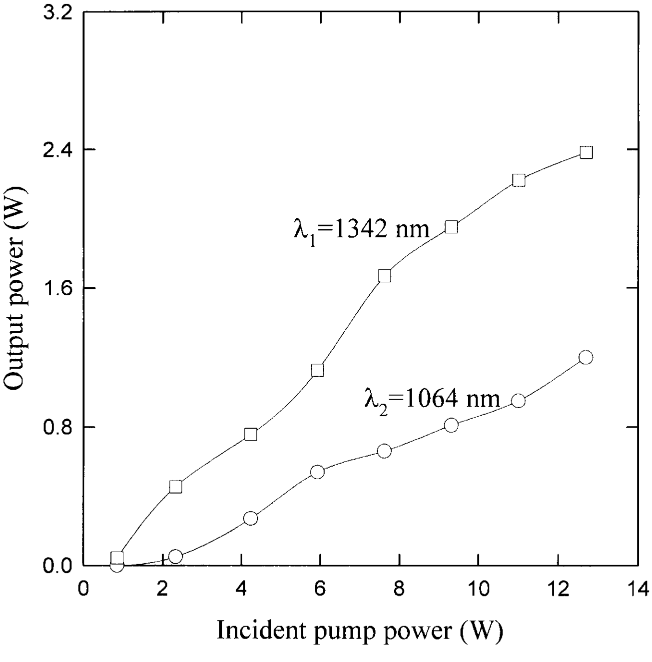

Fig. 4. Dependence of the relative output powers at 1064 and 1342 nm on the incident pump power with the three-mirror laser cavity

wavelengths monotonically increased as the pump power increased. We also found that the fluctuations in the output powers of each wavelength were substantially reduced. The reduction of the competitive interaction between two wavelengths is partly due to the separation of the output couplers for each wavelength. The other reason for stable operation arises from the condition of the ratio $\omega_2/\omega_1 > 1$. For a fixed total cavity length, adjusting the position of the output coupler OC1 can vary the ratio ω_2/ω_1. Experimental results show that the competitive interaction between two wavelengths depends on the ratio ω_2/ω_1 and the output power can be more stable as the ratio ω_2/ω_1 is slightly greater than unity. In addition, the ratio of the output power for both wavelengths can easily be changed by only altering the reflectivity value of the output coupler for 1064 nm, as shown in Fig. 5 for the incident pump power of 12.4 W.

Finally, we used the algorithms of the knife-edge technique [12] to determine the beam width for various positions of the laser beam along the optical axis in the focused beam-waist region and in the far field, respectively. The values of the M^2 factor were determined via a hyperbolic fit to the experimental data. The M^2 values for 1064-nm and 1342-nm lights in the three-mirror cavity at the pump power of 12.4 W were found to be around 1.1 and 1.3, respectively. The slightly worse beam quality in 1342 nm was due to the mode-size mismatching. However, the M^2 values in the two-mirror cavity were difficult to determine because of the large fluctuation in output power.

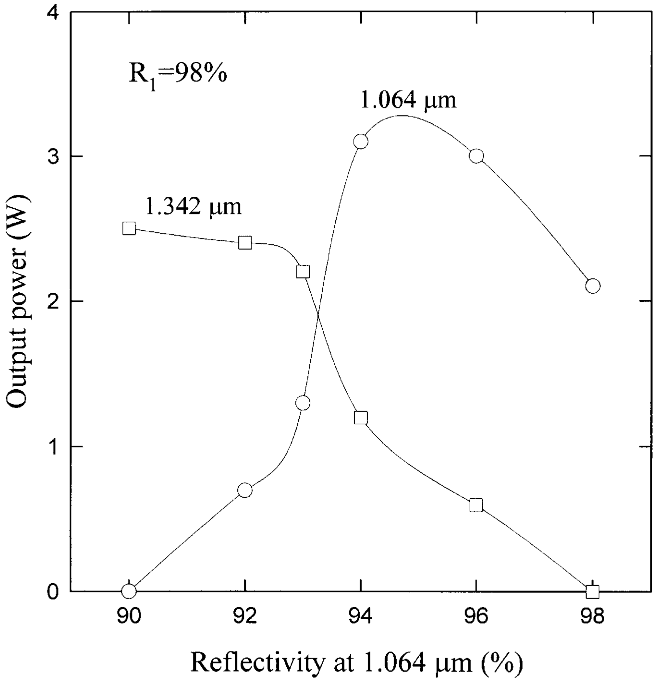

Fig. 5. Dependence of the relative output powers at 1064 and 1342 nm on the reflectivity value of the output coupler for 1064 nm for a fixed $R_1 = 0.98$ with the three-mirror laser cavity at the pump power of 12.4 W

3 Conclusion

The use of diode-end-pumped Nd:YVO$_4$ crystal to achieve the dual-wavelength cw solid-state laser at 1064 and 1342 nm has been demonstrated for the first time. The analysis has been performed to show how the reflectivity values of each respective wavelength at the output coupler should be set to optimize dual-wavelength lasing operation in diode-end-pumped lasers. Both two-mirror and three-mirror laser cavities are used to achieve simultaneous emission of two wavelengths. The experimental results verify that the stability of the output power at the two wavelengths can be improved by use of the three-mirror cavity with the ratio $\omega_2/\omega_1 > 1$.

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