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Dual-wavelength CW diode-end-pumped a-cut Nd:YVO_4 laser at 1064.5 and 1085.5 nm

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Abstract A simple and compact dual-wavelength continuous wave (CW) laser-diode end-pumped laser operating simultaneously at 1,064.5 and 1,085.5 nm in a single a-cut Nd:YVO_4 has been demonstrated. We have used two Nd:YVO_4 crystals with different Nd^{+3} concentrations and lengths; 0.1 %-14 mm and 0.25 %-12 mm. The maximum total output power of 5 and 6.18 W, including 1,064.5 and 1,085.5 nm, is achieved at the incident pump power of 22 and 18 W, with a slope efficiency 23.3 and 32.9 %, respectively, for the crystals of 0.1 %-14 mm and 0.25 %-12 mm. The calculations show both wavelengths lasing at 1,064.5 and 1,085.5 nm can possess the same threshold when reflectivity of the output coupler at 1,064.5 nm is less than 87.5 % and, at this condition, the reflectivity of the output coupler at 1,085.5 nm increases nearly linearly with that of 1,064.5 nm.

1 Introduction

Simple, compact, and efficient simultaneous dual-wavelength lasers are attractive for a wide range of different scientific and technical applications such as biomedicine, lidar, differential analysis, nonlinear frequency conversion, and especially THz frequency generation [1–5]. The major approach of dual- or multi-wavelength operation is based on balancing the gain and loss at the wavelength by utilizing a dispersion element, such as a prism [6, 7], a diffraction grating [8, 9], precise coating [10, 11], or etalon [12, 13] inside the cavity.

By the time now, continuous-wave multi-wavelength laser for different transitions of Nd^{3+} have been reported for some crystals such as Nd:YAG, Nd:YLF, Nd:YVO_4, (Er, Nd):YAG, (Ho, Nd):YAG, Nd:GdVO4, Nd:LYSO, Nd:YAP, Nd:YAB, Nd:Mgo:$LiNbO_3$, Nd:GSAG, Nd:$LuVO_4$ and Nd:$YAIO_3$ (see for example; [10–25]). Among this family, Nd:YVO_4 is commonly used as gain medium in commercial laser products with high efficiency and good beam quality mainly because of the favorable features such as a broad absorption band with higher absorption coefficient, higher stimulated emission cross-section, higher allowable doping level and good thermal and mechanical properties. In most cases, an Nd:YVO_4 laser operates at one particular wavelength around 0.9, 1.06, and 1.3 μm, corresponding to the transitions of ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$, ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$, or ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$, respectively, with comparatively large stimulated emission cross-sections. Each of them splits into closely packed Stark levels, especially transition of ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$, which permits multi-wavelength operation from the inter-manifold transitions. We may note that the dual-wavelength operation on only one transition of ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$, ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$, or ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ has potential for coherent THz radiation generation. Coherent THz waves, the electromagnetic radiation in the 0.1–10 THz, are attractive for THz radar, spectral identification of materials, imaging, and sensing [26–28].

Recently we have reported a tunable single and multi-wavelength continuous-wave c-cut Nd:YVO_4 laser [13]. As shown in Fig. 1, c-cut Nd:YVO_4 has a unique advantage that the cross-section of 1,067 nm is about 1.5–2 times of

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1,085.5 and 1,088 nm; which makes it suitable for tunable multiwavelength operation at transitions of $^4F_{3/2} \rightarrow {}^4I_{11/2}$ in a single crystal [29]. However, poor thermal properties and small saturation fluence of c-cut $Nd:YVO_4$ at room temperature make it unsuitable for high-power operation. An a-cut $Nd:YVO_4$ crystal has advantages of four times higher emission cross-section and better thermal and mechanical properties than that of c-cut crystal.

Some of the multiwavelength lasers reported over the past years on transitions of $^4F_{3/2} \rightarrow {}^4I_{11/2}$ are listed in Table 1. It is evident that most of the multiwavelength $Nd:YVO_4$ lasers are limited to emission around the main oscillation of 1,064 nm. It is because, the much higher emission cross-section at 1,064 nm in an a-cut $Nd:YVO_4$ crystal suppresses the oscillation of the other transitions and makes it difficult to perform multiwavelength emission on other transitions. In this paper, we report, for the first time to the best of our knowledge, simultaneous dual-wavelength operation at 1,064.5 and 1,085.5 nm, originate from $^4F_{3/2}$ level and terminating at the $^4I_{11/2}$ level, by proper cavity design in a single a-cut $Nd:YVO_4$. We have utilized two $Nd:YVO_4$ crystals with different Nd^{+3} concentration and length; 0.1 %-14 mm and 0.25 %-12 mm. The maximum total output power 5 and 6.18 W was achieved at the incident pump power 22 and 18 W, corresponding to the total optical-to-optical efficiency 22.7 and 34.3 %, respectively, for the crystals of 0.1 %-14 mm and 0.25 %-12 mm.

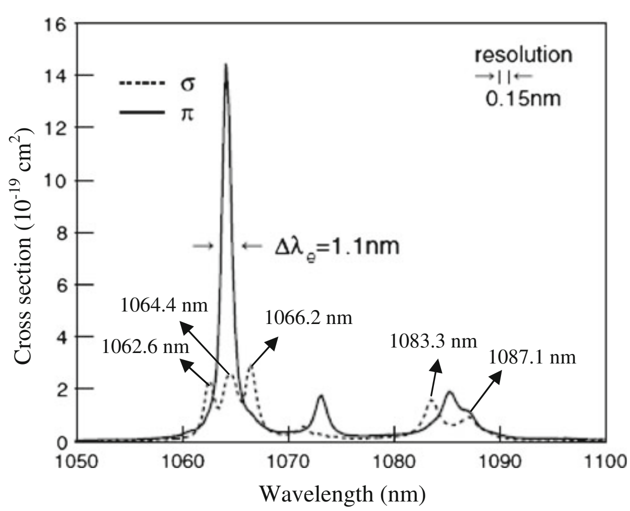

Fig. 1 Stimulated emission cross-section for the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of $Nd:YVO_4$ [29]

2 Experimental setup

The experimental arrangement is schematically shown in Fig. 2. The laser crystal is an a-cut, 0.25 (or 0.1) at % Nd^{3+} doped $Nd:YVO_4$ crystal with a length of 12 mm (or 14 mm) and an aperture of 3 × 3 mm^2. The pump source is a fiber-coupled laser diode at 808 nm with a core diameter of 800 µm and a numerical aperture of 0.22. The pump radiation was coupled into the laser crystal by an optical focusing system with a 35-mm focal length and 97.6 % transfer efficiency. The input concave mirror M_1, having a radius of curvature of 250 mm, was coated with anti-reflection (AR) dielectric layers at 808 nm ($T > 99.5$ %) and high-reflection (HR) dielectric layers

Table 1 Some simultaneous multiwavelength oscillation at transitions from $^4F_{3/2} \rightarrow {}^4I_{11/2}$

Laser material	Wavelengths (nm)	Total optical efficiency	Regime	References
Yb:GYSO	1,041–1,043, 1,048–1,052, 1,056–1,063 and 1,080–1,089	–	CW-Tunable	[7]
Nd:YAG	1,116 and 1,123	9.2	CW	[12]
$Nd:YVO_4$	1,066.5–1,066.8, 1,083.1–1,084.6, and 1,087.2–1,088.2	–	CW-Tunable	[13]
Nd:YAG	1,052, 1,061, 1,064, and 1,074		Pulsed	[17]
Nd: YVO_4 and $Nd:GdVO_4$	1,062.8 and 1,064.1	31 % CW and 13 % @ 5 kHz	CW and Q-switched	[18]
Nd:LSO	1,075 and 1,079	–	CW and Q-switched	[19]
$Nd:GdVO_4$	1,065 nm and 1,063	14.6 %	CW	[20]
Nd:LYSO	1,075 and 1,079	27.7 %	CW	[21]
Nd:YAG	1,061.5 and 1,064.17		CW	[22]
$Nd:LuVO_4$	1,085.7 and 1,088.5	17.5 %	CW	[23]
Nd:YAG	1,074 and 1,112	23.6 %	CW	[24]
Yb:YAG ceramic	1,033.6 and 1,047.6	–	Mode-locked	[25]

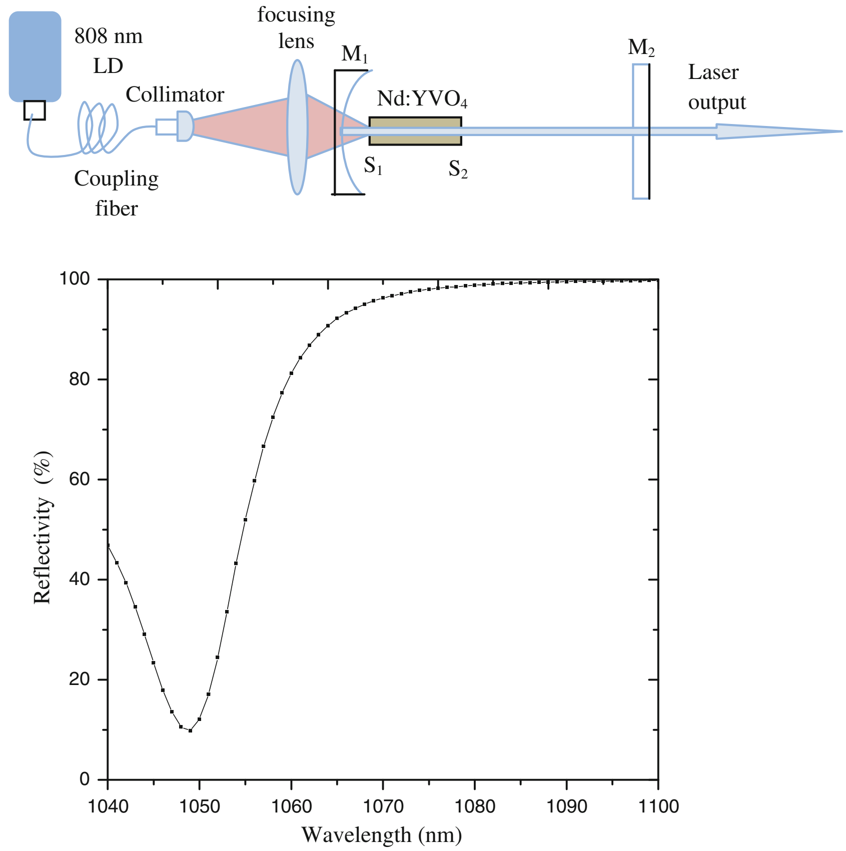

Fig. 2 Schematic diagram of experimental setup of dual-wavelength Nd:YVO_4 laser. *Bottom* measured reflectivity spectrum of the output coupler

between 1,000 and 1,200 nm ($R > 99.9$). The M_2 mirror is a flat mirror with reflectance of 99.4 and 90.76 % at 1,086 and 1,064 nm, respectively. The pumping side (S_1) of the laser crystal has high-transmission coating at 808 nm ($T > 99.5$ %) and both sides were AR-coated at 1,064 and 1,086 nm ($R < 0.5$ %). The laser crystal was wrapped in an indium foil with 0.2 mm thickness and was placed in a copper holder cooled to 20 °C favorable for maintaining the thermal stability of the laser. The geometry length of the cavity was 75 mm.

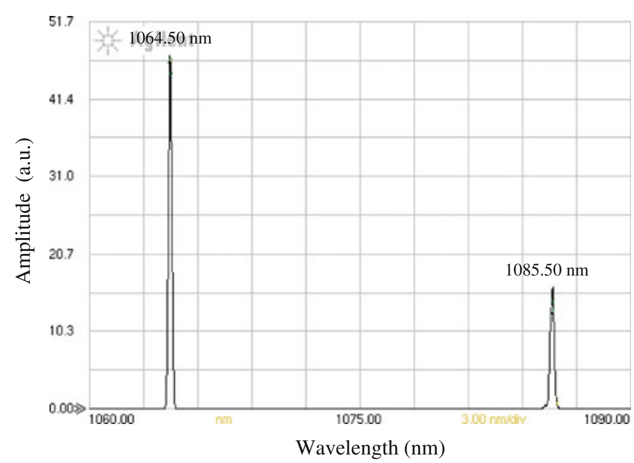

Fig. 3 Spectrum of dual-wavelength operation of the laser at 1,064.5 and 1,085.5 nm at 10-W incident pump power

3 Results and discussion

The alignment for the laser cavity and the pump beam was carefully adjusted to obtain a higher laser output in the CW regime with TEM_{00} mode. The emission spectrum of the laser is shown in Fig. 3 at an incident pump power of 10 W. It is clearly seen that only 1,064.5 and 1,085.5 nm emissions were detected in the range 1,060–1,090 nm. Figure 4 shows the average output spectrum at 1,064.5 and 1,085.5 nm with the spectral bandwidth (FWHM) of ~0.08 nm, which was measured over 50 pulses.

We also measured the output power as a function of the incident pump power for different gain mediums with properties of 0.1 %-14 mm and 0.25 %-12 mm. Fig. 5 shows the measured total output power at dual-wavelength versus pump power. It can be seen from Fig. 5, the output power increases linearly with the pump power at first, and then decreases because of thermal effects. In order to reduce the influence of thermal effects, the length of the cavity should be reduced as possible. We can also see that the thermal effects in the laser crystal of 0.1 %-14 mm (longer crystal with lower doping level) are weaker than that of 0.25 %-12 mm, which are in good agreement with

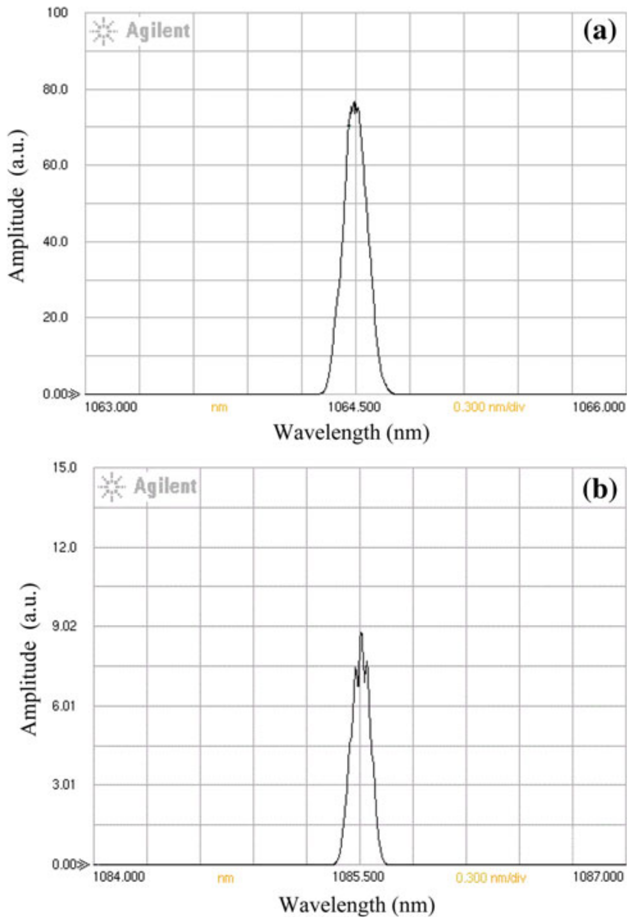

Fig. 4 Spectrum of the laser at 1,064.5 and 1,085.5 nm with the spectral bandwidth (FWHM) of ~0.08 nm at 10-W incident pump power. It was measured over 50 pulses

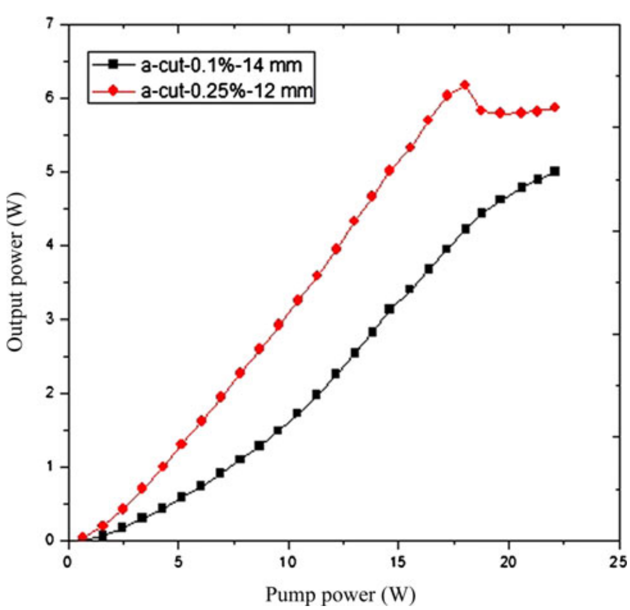

Fig. 5 Total output power as a function of input power for crystals with different doping level and length; 0.1 %-14 mm and 0.25 %-12 mm

the theoretical results pointed out in [30]. By increasing the pump power and analyzing the emission spectrum of the laser, the threshold oscillation of 1,064.5 and 1,085.5 nm was obtained at about 0.67 and 1.15 W, respectively, for the crystal with 0.25 % Nd^{+3} concentration and 12 mm length. The maximum output power of 5 and 6.18 W is achieved at the incident pump power of 22 and 18 W, corresponding to the optical conversion efficiency of 22.7 and 34.4 %, and the slope efficiency of 23.3 and 32.9 %, respectively, for the crystals of 0.1 %-14 mm and 0.25 %-12 mm. It should be pointed out that in the present configuration the gain competition between ~1,073 nm and other transitions suppresses the oscillation of 1,073 nm.

In order to explain the oscillation 1,085.5 nm, it is best to begin with some theory regarding dual-wavelength lasing for a single ion system operating on the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. This transition operates as a four-level laser. For a four-level laser, the single-pass gain can be written as [30]:

$$g_i = \frac{2\sigma_{e,i}\tau_{f,i}}{\pi h v_i V_{\mathrm{eff},i}}\eta_{p,i}P_{\mathrm{in}} \quad i = 1, 2 \tag{1}$$

where τ_f is the lifetime of the upper laser level, σ_e is the emission cross-section, P_{in} is the incident pump power, and $\eta_{p,i} = \eta_t\eta_a(v_i/v_p)$ is the pumping efficiency, where η_t is the optical transfer efficiency, and η_a is the absorption efficiency, v_i is the laser photon frequency, v_p is the pump photon frequency, and V_{eff} is the mode volume efficiency between the pump and the laser modes as given by:

$$V_{\mathrm{eff},i} = \left[\iiint s_i(x,y,z) r_p(x,y,z)\mathrm{d}V\right]^{-1} \tag{2}$$

where s_i is the normalized cavity mode intensity distribution and r_p is the normalized pump intensity distribution in the active medium. The subscripts 1 and 2 denote the gain at $\lambda_1 = 1{,}064.5$ nm and $\lambda_2 = 1{,}085.5$ nm, respectively. The 1,064.5 and 1,085.5 nm lines of $Nd{:}YVO_4$ crystal are both from the transition $^4F_{3/2} \rightarrow {}^4I_{11/2}$ but corresponding to different Stark energy levels. Accurately, the 1,064.5 nm radiation comes from $R_2 \rightarrow Y_2$ transition and 1,085.5 nm radiation from $R_1 \rightarrow Y_5$, as shown in Fig. 6.

Assuming a Gaussian mode with negligible diffraction in the gain medium for cavity and pump modes, by eliminating V_{eff}, Eq. (1) can be rewritten as [31]:

$$g_i = \frac{2\sigma_{e,i}\tau_{f,i}}{\pi h v_i\left(w_{l0,i}^2 + w_p^2\right)l}\eta_{p,i}P_{\mathrm{in}} \quad \text{where } i = 1, 2 \tag{3}$$

where $w_{l0,i}$ and w_p are beam radii for laser and pump modes at the waist in the active medium, respectively, and l is the gain medium length. Since the two lasing wavelengths oscillate in the same cavity and have the same upper level, therefore, Eq. (3) can be expressed as:

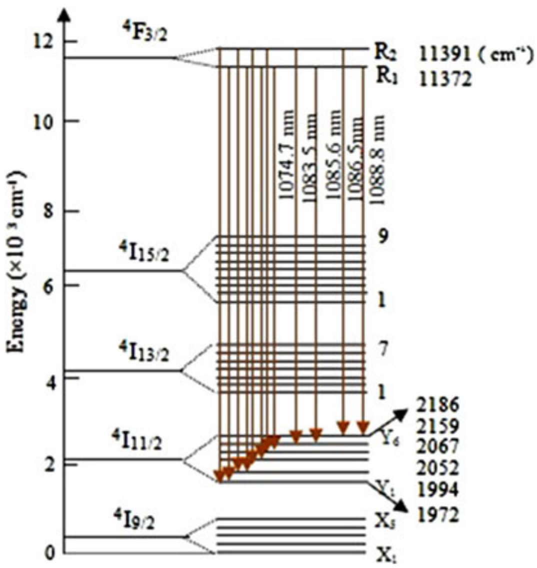

Fig. 6 The laser energy levels and transitions from $^4F_{3/2}$ to $^4I_{11/2}$ of Nd:YVO$_4$ [32]

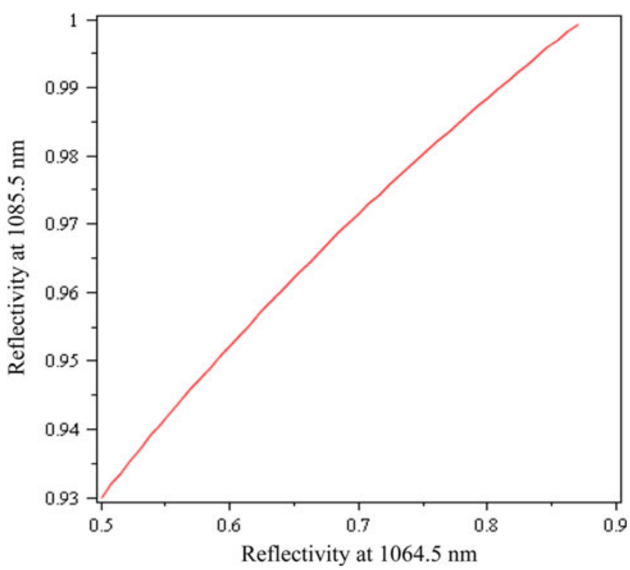

Fig. 7 The corresponding reflectivity at lasing wavelength $\lambda_2 = 1{,}085.5$ nm as a function of reflectivity at $\lambda_1 = 1{,}064.5$ nm according to Eq. (7)

$$g_i = \frac{2\sigma_{e,i}\tau_f}{\pi h v_i \left(w_{l0}^2 + w_p^2\right) l}\eta_t\eta_a\eta_{q,i}P_{\text{in}} \quad i = 1, 2 \tag{4}$$

where $\eta_q = v/v_p$ is the quantum efficiency. For a given gain g_i and total cavity round-trip loss $\delta_i = L_i - \ln(R_i)$, the threshold condition of oscillation is given by:

$$\exp(2g_i l - \delta_i) = 1 \tag{5a}$$

or

$$R_i \exp(2g_i l - L_i) = 1 \tag{5b}$$

where R_i is the reflectivity of the output coupler at λ_i and L_i is the round-trip cavity internal loss. For the a-cut Nd:YVO$_4$, $\sigma_{e,1} = 13.4 \times 10^{-19}$ cm^2, $\sigma_{e,2} = 1.74 \times 10^{-19}$ cm^2 [29], $L_i = 0.02$ is measured using the Findlay–Clay method [33]. $\eta_{q,1} = 75.9$ % and $\eta_{q,2} = 74.5$ % for pumping at 808 nm.

Taking into consideration the above data, we can obtain:

$$P_{\text{th},2} = 1.7P_{th,1} \tag{6}$$

The measured pump thresholds of 0.67 and 1.15 W for 1,064.5 and 1,085.5 nm, respectively, show a good agreement with the theoretical Eq. (6).

From Eqs. (4) and (5), the condition that both transitions possess the same threshold can be given by:

$$\ln\left(\frac{1}{R_2}\right) = \frac{\sigma_{e,2}}{\sigma_{e,1}} \times \left[\ln\left(\frac{1}{R_1}\right) + L_1\right] - L_1. \tag{7}$$

With Eq. (7) and experiment parameters, the reflectivity of the output coupler at λ_2 is plotted as a function of reflectivity at λ_1. It is obvious from Fig. 7 that both wavelength lasing at 1,064.5 and 1,085.5 nm can possess the same threshold when R_1 is less than 87.5 % and reflectivity at 1,085.5 nm increases nearly linearly with that of 1,064.5 nm.

4 Conclusions

In summary, we experimentally demonstrated a compact, simple CW dual-wavelength simultaneous oscillation Nd:YVO$_4$ laser at 1,064.5 and 1,085.5 nm by proper cavity design using crystals with different doping levels and lengths; 0.1 %-14 mm and 0.25 %-12 mm. A total maximum output power of 5 and 6.18 W is achieved at the incident pump power of 22 and 18 W, with slope efficiency of 23.3 and 32.9 %, respectively, for the crystals of 0.1 %-14 mm and 0.25 %-12 mm. Our investigation shows both wavelengths lasing at 1,064.5 and 1,085.5 nm can possess the same threshold when reflectivity of output coupler at 1,064.5 nm is less than 87.5 % and, at this condition, the reflectivity of the output coupler at 1,085.5 nm increases nearly linearly with that of 1,064.5 nm. The difference frequency interactions among these wavelengths may be used to generate radiation at 5.5 THz by using an appropriate nonlinear crystal.

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