

# Efficient stable simultaneous CW dual-wavelength diode-end-pumped Nd:YAG laser operating at 1.319 and 1.338 $\mu\text{m}$

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An efficient, stable diode-end-pumped simultaneous continuous-wave (CW) dual-wavelength laser operating at 1.319 and 1.338  $\mu\text{m}$  in a Nd:YAG crystal has been demonstrated. A total output power of 6.3 W is achieved at an absorbed pump power of 15 W, with a slope efficiency of 43.5%. The instability of output power is less than 1%. With a type II critical phase-matched KTP crystal inserted into the cavity as frequency doubler, a maximum output power of 200 mW in red region is acquired. In addition, a six-wavelength laser operation at 1.319  $\mu\text{m}$ , 1.338  $\mu\text{m}$ , 1.356  $\mu\text{m}$ , 659.5 nm, 669 nm, and 678 nm is observed. OCIS codes: 140.0140, 140.3480, 140.3580, 140.7300.

Efficient, simple, and compact laser sources of simultaneous emissions at multiple wavelengths have shown lots of application foregrounds in many fields, such as optical communication, photodynamic therapy (PDT), optical calculation, military interaction, environmental monitoring, laser remote sensing, laser radar, spectroanalysis, medical instrumentation, and scientific research on nonlinear optical mixers<sup>[1]</sup>. In addition, it can also be used as a pump source of Terahertz-wave generated by nonlinear optical difference frequency method<sup>[2]</sup>.

As is well known, rare-earth elements possess many energy levels. In a crystal, these energy levels will be split into a number of Stark sublevels due to the action of the crystal field. The transitions between the Stark sublevels of different manifolds can exhibit laser action with varying wavelengths. Owing to the differences of the stimulated-emission cross-section, fluorescence lifetime, fluorescence quantum efficiency as well as the operation condition of laser, a rare-earth laser oscillates generally at one wavelength. Under special conditions, the laser can oscillate at more than one wavelength.

Nd:YAG crystal is the most common laser gain medium for its excellent laser characteristics, physical, and chemical properties. Simultaneous continuous-wave (CW) or pulse multi-wavelength operation in Nd:YAG crystal based on traditional flash lamp pumping or diode pumping configuration has been reported<sup>[3–9]</sup>. Complex composite three-mirror or Y-shape resonator was involved in these reports, in order to acquire stable dual-wavelength laser operation.

In this paper, we report an efficient, stable simultaneous CW dual-wavelength diode-end-pumped Nd:YAG laser operation at 1.319 and 1.338  $\mu\text{m}$ , which is based on

a simple two-mirror configuration.

Nd:YAG crystal is a widely used laser crystal, whose optical properties have been investigated in detail. The stimulated-emission cross section and branching ratios at 1.319 and 1.338  $\mu\text{m}$  transitions are tabulated in Table 1<sup>[10]</sup>. Shen *et al.*<sup>[11]</sup> indicated that the ratio of the stimulated-emission cross section between the two transitions should not be too large for obtaining a CW dual-wavelength operation. The ratio of stimulated-emission cross section between 1.319 and 1.338  $\mu\text{m}$  transitions is nearly unit. In addition, their branching ratios are also nearly the same. Thus, according to Ref. [11], it is obvious that transitions at 1.319 and 1.338  $\mu\text{m}$  are very suitable for simultaneous CW operation.

In order to optimize dual-wavelength operation, the round-trip reflectivity value of each respective wavelength should be selected to approximately balance the gain curve for each of the two lasing wavelengths. That is to say lasers at these two wavelengths should have nearly the same threshold power. According to Refs. [11–13], the condition that both transitions possess the same threshold can be given by

$$\ln\left(\frac{1}{R_2}\right) = \left[ \frac{\eta_{Q,2}\sigma_2 \iiint s_2(r,z)r_p(r,z)dv}{\eta_{Q,1}\sigma_1 \iiint s_1(r,z)r_p(r,z)dv} \right] \times \left[ \ln\left(\frac{1}{R_1}\right) + L_1 \right] - L_2, \quad (1)$$

where  $L_i$  is the round-trip cavity excess loss at the corresponding transition wavelength,  $\eta_{Q,i}$  is the quantum efficiency for the corresponding transition,  $S_i(r,z)$  is the normalized cavity mode intensity distribution for the

**Table 1. Branching Ratios and Stimulated-Emission Cross Section at 1.319 and 1.338  $\mu\text{m}$  in Nd:YAG Crystal**

$\lambda$ ( $\mu\text{m}$ )	$\nu$ ( $\text{cm}^{-1}$ )	Transition	$\Delta\nu$ ( $\text{cm}^{-1}$ )	$\sigma$ ( $\times 10^{-20}$ $\text{cm}^2$ )	$\beta$
1.319	7581	$R_2 - X_1$	6	8.7	0.018
1.338	7471	$R_2 - X_3$	6	9.2	0.021

corresponding transition,  $r_p(r, z)$  is the normalized pump intensity distribution in the active medium.  $R_i$  is the reflectivity of output coupler at the corresponding transition wavelength, and the reflectivities of total reflected mirror for two wavelengths are supposed to be unit. Considering that the two lasing wavelengths in our experiments are very close, we do some assumptions as follows: the quantum efficiency, round-trip cavity loss, and normalized cavity mode intensity distribution are the same for the both lasing wavelengths. Thus, Eq. (1) can be simplified as

$$\ln\left(\frac{1}{R_2}\right) = \frac{\sigma_2}{\sigma_1} \times \left[ \ln\left(\frac{1}{R_1}\right) + L \right] - L. \quad (2)$$

With Eq. (2) and experiment parameters, the corresponding reflectivity value  $R_2$  at the lasing wavelength  $\lambda_2 = 1.338 \mu\text{m}$  is calculated as a function of the reflectivity value  $R_1$  at lasing wavelength  $\lambda_1 = 1.319 \mu\text{m}$ , as depicted in Fig. 1. The round-trip cavity loss  $L$  at both wavelengths is supposed to be 0.005. It is obvious from Fig. 1 that reflectivity at  $1.338 \mu\text{m}$  nearly linearly increases with that at  $1.319 \mu\text{m}$ , and they have nearly the same value. This makes coatings selection be much easier.

A simple plane-plane cavity configuration, as sketched in Fig. 2 has been investigated. A high-brightness high-power fiber-coupled diode laser emitting at 808 nm with a fiber core diameter of  $400 \mu\text{m}$  and a numerical aperture of 0.22 is employed. The multi-lens optical coupler has about 90% transmission at 808 nm, and can focus the pump radiation into gain medium with a spot size of about  $500 \mu\text{m}$  in diameter. The gain medium is a plano-parallel polished Nd:YAG rod ( $\Phi 4 \times 4 \text{ mm}$ ), with 1.1 at.-%  $\text{Nd}^{3+}$  doping level. The pumping facet of the Nd:YAG crystal is coated with high reflectivity (HR,  $R > 99.8\%$ ) coatings at both fundamental wavelengths (1.319 and  $1.338 \mu\text{m}$ ) and second harmonic generation (SHG) wavelengths (659.5 and 669 nm), high transmission (HT,  $T > 95\%$ ) coatings at 808 nm and  $1.06 \mu\text{m}$  ( $T > 90\%$ )

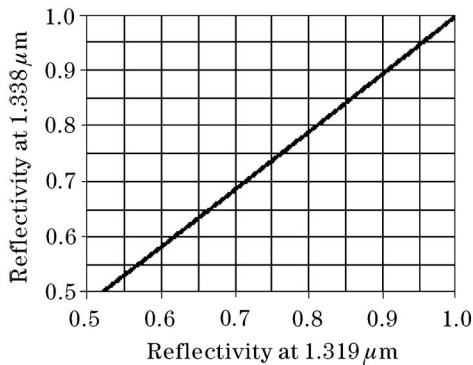


Fig. 1. The calculated corresponding reflectivities at both lasing wavelengths according to Eq. (2).

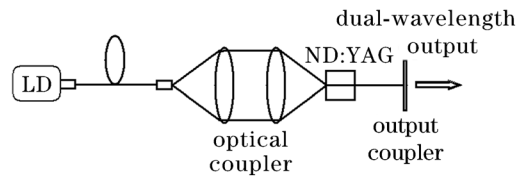


Fig. 2. Experimental setup of the simultaneous CW dual-wavelength laser.

to suppress the strong parasitical oscillation at this transition. Three flat output couplers (OCs) with partial reflection at both lasing wavelengths to provide an output and high transmission at  $1.06 \mu\text{m}$  ( $T > 90\%$ ) to suppress the strong  $1.06\text{-}\mu\text{m}$  transition are used in our experiment. Their reflectivities at both lasing wavelengths, which are measured by an Acton spectrometer (model SpectraPro-300i), and optimal reflectivities at  $1.338 \mu\text{m}$  with respect to the selected reflectivities at  $1.319 \mu\text{m}$  are tabulated in Table 2. It is shown that the reflectivities of our output couplers at  $1.338 \mu\text{m}$  are slightly deviated from the optimal values.

In order to obtain high output power, the cavity length is selected to be 10 mm for reducing the strong thermal effects under high pump power condition. Total output powers of 4.99, 6.3, and 5.76 W at both lasing wavelengths are obtained with  $\text{OC}_1$ ,  $\text{OC}_2$ , and  $\text{OC}_3$ , respectively. In the condition of two-mirror simultaneous CW dual-wavelength operation, significant fluctuation in output power of each lasing wavelength was observed by Chen<sup>[13]</sup>. However, in our experiment, nearly no output power fluctuation is observed with all these three output couplers, the instability of output power is less than 1% during half an hour. When  $\text{OC}_2$  is used as output coupler, the threshold of absorbed pump power is 0.62 W. At this time laser emissions at 1.319 and  $1.338 \mu\text{m}$  simultaneously begin to oscillate. And when the absorbed pump power is increased to 15 W, output power of 6.3 W at both lasing wavelengths is obtained, with a slope efficiency of 43.5%. The curve of output power versus absorbed pump power is shown in Fig. 3. The spectrum of this dual-wavelength laser at output power of 6.3 W is detected by an Agilent optical spectrum analyzer (model 86142B) and depicted in Fig. 4. For absence of effective filter mirror to separate any wavelength from the other, we can not exactly determine the proportion of 1.319 or  $1.338 \mu\text{m}$  in the total output power of 6.3 W and can not measure their beam qualities. We consider that the output power of  $1.319 \mu\text{m}$  should be about 5 W according to the corresponding spectrum intensity.

Laser emission at 1.319 and  $1.338 \mu\text{m}$  not only can be used as the pump source of terahertz-wave generator, but also can be used to obtain coherent red light through intracavity frequency-doubled method. By inserting a type II KTP crystal ( $3 \times 3 \times 10 \text{ mm}$ ),  $\theta = 59.8^\circ$ ,  $\phi = 0^\circ$ ) into the Nd:YAG laser cavity and replacing the  $\text{OC}_2$  with a

Table 2. Parameters of the Three Flat Output Couplers and the Corresponding Optimal Reflectivity at  $1.338 \mu\text{m}$

Output Coupler	Reflectivity at $1.319 \mu\text{m}$ (%)	Reflectivity at $1.338 \mu\text{m}$ (%)	Optimal Reflectivity at $1.338 \mu\text{m}$ (%)
$\text{OC}_1$	96.27	96.27	96.03
$\text{OC}_2$	94.40	93.09	94.06
$\text{OC}_3$	91.41	90.07	90.91

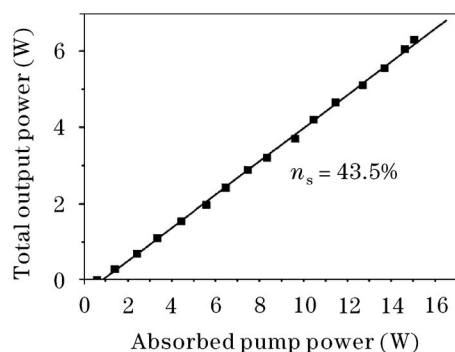


Fig. 3. Total output power of both wavelengths versus absorbed pump power.

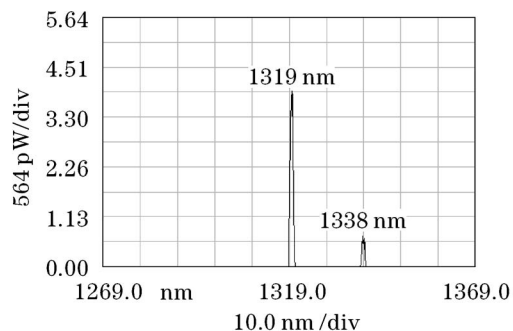


Fig. 4. Spectrum of simultaneous CW dual-wavelength laser operation at 1.319 and 1.338  $\mu\text{m}$ .

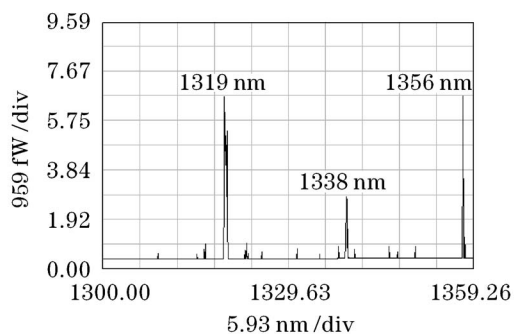


Fig. 5. Spectrum of fundamental wave.

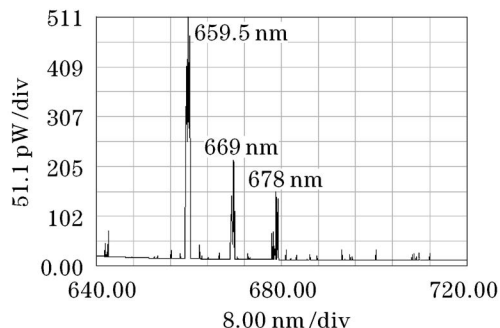


Fig. 6. Spectrum of red laser.

red laser output mirror which has HR coatings at near 1.319  $\mu\text{m}$  and HT coatings at near 660 nm, we obtain a red laser whose maximum output is 200 mW. And significant fluctuation in output power is observed. By examining the spectra of output red laser and fundamental wave, we find that the spectra are rather complicated.

Laser emissions not only at 1.319 and 1.338  $\mu\text{m}$  but also at 1.356  $\mu\text{m}$  are found in the fundamental wave. And the SHG waves of these wavelengths are also found. The corresponding intensities of these six wavelengths have significant fluctuation. The spectra of the fundamental wave and the red beam are shown in Figs. 5 and 6. It is well known that the procedure of intracavity frequency-doubling is equivalent to introduce a nonlinear loss into the cavity. This mechanism makes the competitive interaction between these wavelengths very seriously. We think that the seriously competitive interaction should be the main reason that caused the significant fluctuation of output power of red laser, though we also observe the so called "green problem"<sup>[14]</sup>.

In conclusion, we have demonstrated an efficient, stable diode-end-pumped simultaneous CW dual-wavelength Nd:YAG laser, which operates at 1.319 and 1.338  $\mu\text{m}$ . The total output power at both lasing wavelengths is 6.3 W with an absorbed pump power of 15 W, inducing to a slope efficient of 43.5%. The instability of the output power is less than 1% during half an hour, though a simple two-mirror resonator is involved. In addition, by inserting a type II critical phase-matched KTP crystal into the cavity as frequency doubler, six-wavelength operation is observed, which are fundamental waves of 1.319  $\mu\text{m}$ , 1.338  $\mu\text{m}$ , 1.356  $\mu\text{m}$  and SHG waves of 659.5 nm, 669 nm, 678 nm. The output power of the three-wavelength red laser is 200 mW and very unstable for seriously competitive interaction.

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