

Study on CW Nd:YAG infrared laser at 1319 nm

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Received May 28, 2003

A continuous wave (CW) Nd:YAG infrared laser at 1319 nm is reported in this paper. The energy level of 1319-nm wave was analyzed. The repression of 1064-nm lasing and enhancement of 1319-nm output power were discussed. Mirror coating and cavity structure were studied and a maximum CW output power of 43 W at 1319 nm was achieved in experiments.

OCIS codes: 140.3580, 140.3070.

A continuous wave (CW) Nd:YAG infrared laser at 1319 nm is reported in this paper. It can also be used to output high power red light of 660 nm by frequency doubling which can be used for the pumping source of OPA and fiber Raman amplifier. In addition, it is useful in medical treatments. In this paper, the transition energy states of 1319-nm infrared laser are analyzed and rate equations model is set up. The repression of 1064-nm laser oscillation and enhancement of 1319-nm laser output power are discussed in detail. Mirrors coatings and cavity structure were determined in our study. Finally, a maximum CW 1319-nm infrared laser output power of 43 W was achieved in our experiments.

Experiments were performed with a $\phi 6 \times 110$ mm² Nd:YAG laser rod. The Nd:YAG crystal has high thermal conductivity and high anti-destructive threshold, so it has good conduct heat and thus small thermal distortion. It can be used in CW and quasi-CW laser operation. Nd:YAG laser crystal is a four-level laser system with emitting wavelengths of 950, 1064 and 1319 nm.

Figure 1 is part of energy level diagram of Nd:YAG crystal. In the figure, ⁴I_{9/2} is the ground state, ⁴F_{7/2}, ⁴S_{3/2}, ⁴F_{5/2} and ²H_{9/2} are pump upper levels. ⁴I_{13/2} and ⁴I_{11/2} are laser lower levels. The center wavelengths of absorption peaks of ground-state Nd³⁺ ions are at 810 and 750 nm with a band width of 30 nm. Nd³⁺ ions are excited to pump upper level ⁴F_{7/2}, ⁴S_{3/2}, ⁴F_{5/2} and ²H_{9/2} by absorbing the energy of pump photons. Then almost all of them decay quickly to the metastable energy level ⁴F_{3/2}, which is laser upper level through

radiationless transition where they have a life time of 0.23 ms. Subsequently Nd³⁺ ions decay to three lower levels ⁴I_{11/2}, ⁴I_{13/2} and ⁴I_{9/2}. The maximal probability occurs in the ⁴F_{3/2} → ⁴I_{11/2} transition with the emitting wavelength of 1064 nm. The transition from ⁴F_{3/2} to ⁴I_{9/2} has a lower probability at 946 nm and minimum probability happens at the transition to ⁴I_{9/2} at 1319 nm. Because the laser lower level ⁴I_{11/2} is above the ground state resulting in scarce population, a small quantity of energy is enough to realize 1064 nm laser oscillation. The transition process from ⁴F_{3/2} to ⁴I_{11/2} is simultaneously weakened so that 1319-nm radiation is hard to build up. So some measures should be taken to repress 1064-nm lasing.

The rate equations for 1319-nm multimode laser were set up through above analysis. When the loss of various modes is assumed equal for the multi-modes oscillation and rectangular lineshape function is substituted for actual lineshape function, we got the simplified four-level multimode rate equations as follows

$$\left. \begin{aligned} \frac{dN}{dt} &= \left(n_2 - \frac{f_2}{f_1} n_1' - \frac{f_2}{f_1''} n_1'' \right) \sigma_{21} v N - \frac{N}{\tau_R} \\ \frac{dn_2'}{dt} + \frac{dn_2''}{dt} &= n_0 W'_{03} + n_0 W''_{03} - \frac{n_2' S_{32}}{\eta_1} - \frac{n_2'' S_{32}}{\eta_1} \\ \frac{dn_2}{dt} &= n_3' S'_{32} + n_3'' S''_{32} - \left(n_2 - \frac{f_2}{f_1} n_1' - \frac{f_2}{f_1''} n_1'' \right) \\ &\quad \times \sigma_{21} v N - \frac{n_2 A'_{21}}{\eta_2'} - \frac{n_2 A''_{21}}{\eta_2''} \\ \frac{dn_0}{dt} &= n_1' S'_{10} + n_1'' S''_{10} - n_0 W'_{03} - n_0 W''_{03} \end{aligned} \right\} \quad (1)$$

In the equations, n_0 , n_1' , n_1'' , n_2 , n_3' and n_3'' are population densities of corresponding energy levels; N is the sum of photon densities of various modes; f_1' , f_1'' and f_2 are statistical weights of energy level; σ_{21} is emission cross section at center frequency; v is light velocity in the medium; τ_R is photon lifetime of mode l .

We simply marked each energy level with E_0 , E_2 , E_3' , E_3'' , E_1' , E_1'' in Fig. 1. W'_{03} and W''_{03} are transition probabilities of stimulated absorption. S'_{32} , S''_{32} , S'_{21} , S''_{21} and S'_{10} , S''_{10} are radiationless transition probabilities. W'_{21} is transition probability of stimulated emission and it is expressed as

$$W'_{21} = \frac{A'_{21}}{n_\nu \Delta\nu} N_l. \quad (2)$$

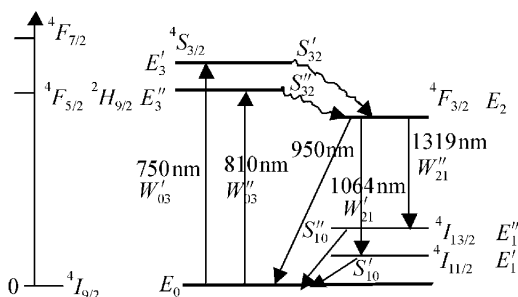


Fig. 1. Part of energy levels diagram in Nd:YAG crystal.

In the expression, A'_{21} is transition probability of spontaneous emission. N_l is photon density of mode l . n_ν is mode density at frequency ν . $\Delta\nu$ is spectral line width. W''_{21} is also transition probability of stimulated emission and the formula is

$$W''_{21} = \frac{A''_{21}}{n_\nu \Delta\nu} N_l, \tag{3}$$

A''_{21} are transition probability of spontaneous emission. η'_1, η''_1 are quantum efficiency of non-radiative transition. η'_2, η''_2 are fluorescence efficiency of energy level transition.

In the whole energy level system, n_w , part of population carried to pump upper level E'_3, E''_3 , transfers to laser upper level E_2 through radiationless transition (thermal relaxation). And n_F , part of population at laser upper level, decays to laser lower level E'_1 and E''_1 , respectively. The former corresponds to n_{F1} emitting photons of 1064 nm and the later corresponds to n_{F2} emitting 1319-nm photons. These two radiations originate from n_F , so

$$n_F = n_{F1} + n_{F2}. \tag{4}$$

For a certain system n_F is determinate. Hence the stronger the emission process of 1064-nm photons is or the larger n_{F1} is, the weaker the emission process of 1319-nm photons is. For Nd:YAG laser crystal, the state of inverted population is liable to form between E_2 and E'_1 , that is, the process of emitting 1064-nm photons is vibrant, which is its inherent nature. Consequently, 1064-nm wave oscillation dominates in the gain medium and impairs the transition of emitting 1319-nm photons directly. Thus, it is crucial to repress the 1064-nm radiation in order to increase output power of 1319-nm laser.

Combining Eqs. (1), (2) and (3), we know that depressing the re-excitation of 1064-nm photons can reduce transition of population on E_2 level to laser lower level E'_1 . Thus by repressing 1064-nm oscillation, we can achieve the generation of 1319-nm infrared laser.

Another measure we have taken is to optimize the cavity design of 1319-nm infrared laser configuration shown in Fig. 2 schematically. For lower order mixing mode, we can approximately estimate that its beam radius is k times that of the TEM₀₀ mode. k is the coefficient of mixing mode, $k = \omega_{mn,0}/\omega_{00,0} = \omega_{mn,z}/\omega_{00,z}$. The Nd:YAG crystal has a thermal focus f_1 because of the thermal lens effects. Thus, there are the following relations

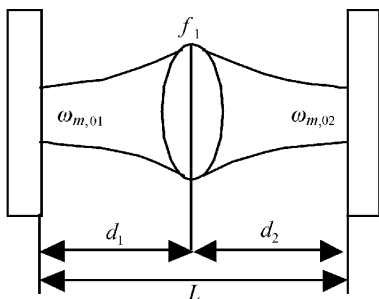


Fig. 2. Schematic of laser cavity.

$$\left. \begin{aligned} d_2 &= \frac{f_1 \left(\frac{\pi \omega_{m,01}^2}{\lambda k^2} \right)^2 + f_1 d_1^2 - f_1^2 d_1}{f_1 - 2d_1 f_1 + d_1^2 + \left(\frac{\pi \omega_{m,01}^2}{\lambda k^2} \right)} \\ \omega_{m,02} &= \frac{\omega_{m,01}}{\sqrt{\left(1 - \frac{d_1}{f_1}\right)^2 + \left(\frac{\pi \omega_{m,01}^2}{\lambda f_1 k^2}\right)^2}} \end{aligned} \right\} \tag{5}$$

$\omega_{m,01}$ and $\omega_{m,02}$ are the multimode spot radius on the two mirrors. L is the cavity length (it should be the difference between the real cavity length and the length of crystal YAG). d_1 and d_2 are distances from crystal end faces to corresponding mirrors. The cavity is supposed to be symmetrical, so d_1 and d_2 are equal to $L/2$. From the beam self-consistency in the resonant cavity, we get $\omega_{m,01} = \omega_{m,02} = \omega_{m,0}$. θ is a far field divergence angle. Thus we can obtain

$$\left. \begin{aligned} \left(1 - \frac{d_1}{f_1}\right)^2 + \left(\frac{\pi \omega_{m,0}}{\lambda f_1 k^2}\right)^2 &= 1, \\ \frac{\omega_{m,0}}{k} &= \sqrt{\frac{\lambda^2}{\pi^2} L \left(f_1 - \frac{L}{4}\right)}, \\ \theta &= \frac{\omega_{m,0}}{f_1 \sqrt{L \left(1 - \frac{d_1^2}{f_1^2}\right)^2}} = \frac{\omega_{m,0}}{\sqrt{(2f_1 - d_1)d_1}}. \end{aligned} \right\} \tag{6}$$

For a certain intensity of pump power, f_1 is a constant. In order to get bigger mode volume, $\omega_{m,0}/k$ should have a maximum value when an optimum length of cavity is obtained. Thereby an operation close to the fundamental mode state can be reached. Due to different system parameters we adopt, the optimum cavity length range from 380 to 470 mm unequally. We can improve output power by shortening length of cavity and properly keeping the main elements unchangeable at the same time. Taking into account of bigger mode volume and better beam quality we choose a flat-parallel cavity configuration.

Figure 3 is the schematic of the setup of 1319-nm laser. The filter has 99% transmissivity at 1319 nm and 99.7% reflectivity at 1064 nm. And in the experiments, output power declined by 0.4 W when the filter was in use, which approved that 1319-nm laser dominated in the output so that 1064-nm component could be ignored.

As described above, 1064-nm wave resonance should be constrained and the intracavity loss of 1319-nm wave should be diminished. So both facets of the Nd:YAG rod are anti-reflective (AR) coated at 1064 and 1319 nm. The high reflector is also AR coated at 1064 nm and has a high reflectivity (HR) at 1319 nm. Furthermore, the output coupler has a high transmissivity at 1064 nm and a partial transmissivity at 1319 nm. All the coatings should make 1064-nm photons leak out of the cavity efficiently and realize 1319-nm laser oscillation.

The condense cavity is gilded and consists of two-flashlights. A 580C model two-flashlight-pumped CW laser power supply developed by ourselves is applied, which has a normal current of 26 A, a normal voltage

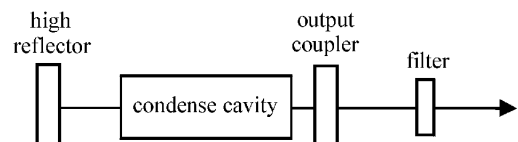


Fig. 3. Experimental setup of 1319-nm Nd:YAG laser.

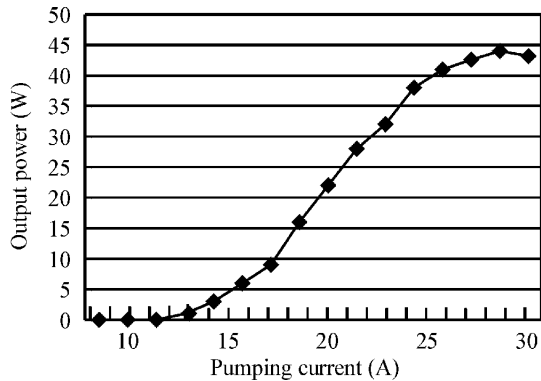


Fig. 4. Output power versus pumping current at 1319 nm.

of 240 V and a maximal current of 30 A. To advance output power effectively, we changed the longitudinal joint method of electrodes to a lateral one in order to shorten the length of condense cavity. Regarding cooling of the condense cavity and YAG crystal, a special cooler of 5-kW power is used.

Figure 4 shows the curve of output power versus pumping current. From the figure, we can see that power output emerged when pumping current risen to 12.5 A. And a power of 43 W was achieved in the case of 26 A.

In the experiments, we also tried to use a output coupler without AR coating at 1064 nm. 1319-nm laser output power was low at that time, which consists with the forementioned analysis. So quality and parameters of coatings have significant influence on 1319-nm laser output. But transmissivity of output coupler (T) should not be excessively high for 1319-nm oscillation. The moderate value is between 3–7 percent based our experimental measurement. If T is too high, 1319-nm photons leak out of the cavity too much to oscillate. On the other hand, when T is too low, output power is also low because of a little amount of output laser. The output power begins to fall after the current exceeds 28.5 A on account of thermal effect of laser rod.

How cavity length influences output power is illustrated in Fig. 5. As shown, output power drops with the elongation of cavity length. For mixing-mode output of high power, f_1 is usually greater than d_1 . The experiment indicates that under the circumstances of allowable structure, we can elevate output power by shortening cavity length.

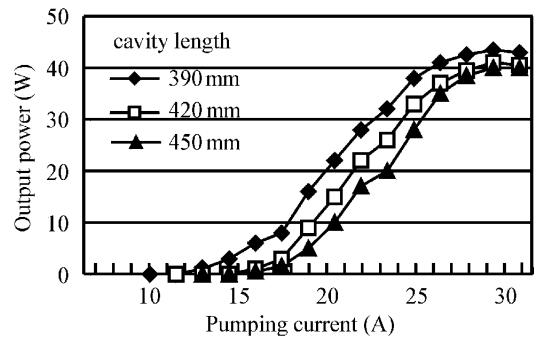


Fig. 5. Output power versus pumping current for different cavity lengths.

In summary, investigation of 1319-nm CW laser successfully accomplished. To repress the generation of 1064-nm laser, it is essential to enhance output power of 1319-nm laser. The coating parameters and cavity structure are specified through our study. And 1064 nm laser oscillation is effectively suppressed. Shortening the length of cavity appropriately can increase the laser output power. CW laser output power of 43 W at 1319 nm was achieved and the operation was steady.

This work was supported by the State Key Laboratory of Laser Technology of China (No. 20010104). T. Wang's e-mail address is wta@eyou.com.

References

1. J. Q. Yao, *Nonlinear Optical Frequency Transformation and Laser Tuning Technology* (in Chinese) (Science in China Press, Beijing, 1995) p. 109.
2. B. K. Zhou, Y. Z. Gao, C. R. Chen, and J. H. Chen, *Laser Elements* (in Chinese) (National Defence Industry Press, Beijing, 2000) p. 123.
3. T. Wang, J. Q. Yao, X. F. Li, Z. Y. Wang, J. Chen, B. G. Zhang, and P. Wang, *Laser Journal* (in Chinese) **23**, 10 (2002).
4. J. Q. Yao, Y. Z. Yu, P. Wang, T. Wang, B. G. Zhang, X. Ding, J. Chen, H. J. Peng, and H. S. Kwok, *Chin. Phys. Lett.* **9**, 1214 (2001).
5. T. Wang, J. Q. Yao, X. F. Li, L. Guo, J. Chen, Y. Z. Yu, Z. Y. Wang, and P. Wang, *J. Optoelectronics-Laser* (in Chinese) **13**, 575 (2002).