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Oscillation conditions of cw simultaneous dual-wavelength Nd:YAG laser for transitions $^4F_{3/2}-^4I_{9/2}$ and $^4F_{3/2}-^4I_{11/2}$*

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The operating condition of a cw simultaneous dual-wavelength Nd:YAG laser for both $^4F_{3/2}-^4I_{9/2}$ (quasi-three-level system) and $^4F_{3/2}-^4I_{11/2}$ (four-level system) transitions is studied. According to this condition, the cw simultaneous dual-wavelength at 1.06μm and 946 nm in Nd:YAG crystal has been realized experimentally through an adaptive coating design of the cavity mirrors. A total power output of 2.5W of the dual-wavelength at 946nm and 1.06μm has been achieved with an optical conversion efficiency 14.3%. The experimental results are in good agreement with the theoretical analysis.

Keywords: dual-wavelength, Nd:YAG laser, diode-pumped laser
PACC: 4215E, 4255B, 4260B, 4260D

1. Introduction

Much attention has been paid to a laser that can generate coherent radiation at two different wavelengths simultaneously due to its various applications such as precision laser spectroscopy, lidar, nonlinear optical frequency conversion, and laser multi-stage ionization of atoms and molecules.[1−3] As is well known, rare earth elements possess many energy levels, which will be split into a number of Stark sublevels due to the action of crystal field. The transitions between the Stark sublevels of different manifolds can radiate lights at various frequencies. Generally, only one oscillation can operate in the same crystal because of different stimulated emission cross-sections, fluorescent lifetime, and fluorescent quantum efficiency. But under special conditions, more than one wavelength can be achieved simultaneously. This kind of laser has been reported in Nd-doped laser, and the oscillation conditions of simultaneous multiple wavelength laser action have also been studied. However, all of these lasers operate at two different four-level-system transitions: $^4F_{3/2}-^4I_{11/2}$ and $^4F_{3/2}-^4I_{13/2}$.[4−8] Up to now, no research into the dual-wavelength operation at transitions $^4F_{3/2}-^4I_{9/2}$ and $^4F_{3/2}-^4I_{11/2}$ in quasi-three-level and four-level systems has been reported. This is because in the quasi-three-level system the transition $^4F_{3/2}-^4I_{9/2}$ suffers from a considerable re-absorption loss due to thermal population at a lower level.[9−11] However, in the four-level system, the re-absorption loss at transitions $^4F_{3/2}-^4I_{11/2}$ and $^4F_{3/2}-^4I_{13/2}$ is traditionally neglected. In addition, the emission cross-section of transition $^4F_{3/2}-^4I_{9/2}$ is much smaller than those of transitions $^4F_{3/2}-^4I_{11/2}$ and $^4F_{3/2}-^4I_{13/2}$. Therefore, it is more difficult to perform simultaneous dual-wavelength operation at transition $^4F_{3/2}-^4I_{9/2}$ and either of the other two transitions.

In this paper, the theory of a dual-wavelength laser operating simultaneously in the quasi-three-level system and the four-level system of the Nd:YAG crystal, based on rate equations, is put forward for the first time. According to the analysed results, the cw simultaneous dual-wavelength Nd:YAG laser at 946nm and

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1.06μm is obtained experimentally for the first time. A total power output of 2.5W is achieved.

2. Theoretical analysis

In order to optimize dual-wavelength lasing operation, the reflectivity values for each wavelength at the cavity mirror should be designed according to the stimulated emission cross-section. In this paper, we use the rate equation approach to derive the operating condition of the dual-wavelength emission. The diagram of the energy levels in the dual-wavelength of Nd:YAG laser with the laser transitions is given in Fig.1. The subscripts 1 and 2 respectively denote the qualities at dual-wavelength of 946nm ($^4F_{3/2}$–$^4I_{9/2}$) and 1.06μm ($^4F_{3/2}$–$^4I_{11/2}$) such as the stimulated-emission cross-section, the cavity losses and the reflectivity of the output mirror. Firstly, the threshold

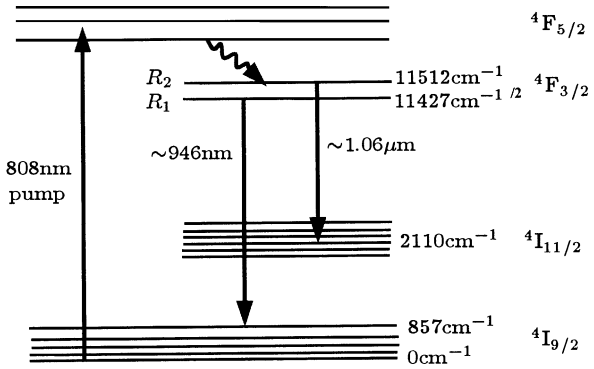


Fig.1. Diagram of the energy levels in the dual-wavelength Nd:YAG laser with the laser transitions.

condition of the quasi-three-level laser at 946nm ($^4F_{3/2}$–$^4I_{9/2}$) is studied. The upper laser level population N_b in a steady state at or below a threshold is given by the rate equation[10]

$$\frac{dN_b(r,z)}{dt} = -\frac{N_b(r,z)}{\tau} + Rf_b r_p(r,z) = 0, \qquad (1)$$

where N_b is the upper laser level (11427cm^{-1}) population, τ is the lifetime of the upper laser manifold, f_b is a fraction of the $^4F_{3/2}$ population that resides in the Stark component used as an upper laser level, R is the total pump rate given by $R = \eta_p P_a/h\nu_p$, where η_p is the pump quantum efficiency, P_a is the absorbed pump power, and $h\nu_p$ is the pump photon energy, $r_p(r,z)$ is the normalized pump intensity distribution in the gain medium. If we assume a circular Gaussian beam for the pump, $r_p(r,z)$ is given by[9–11]

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

where ω_p is the radius of the pump beam, α is the absorption coefficient at the pump wavelength, l is the length of gain medium.

The threshold condition is that the round-trip gain $2\sigma_1\Delta N_1(r,z)l$ is equal to the round-trip cavity loss δ_1, where $\delta_1 = \ln(1/r_1r_1') + 2L\delta_{in1}$ (L is the cavity length, δ_{in1} is the coefficient of the internal loss at 946 nm, r_1r_1' is the product of the reflectivity of the cavity mirrors at 946nm), σ_1 is the stimulated cross-section, ΔN_1 is the population inversion density, which is given by

$$\Delta N_1 = N_b - N_a, \qquad (3)$$

where N_a is the population of the lower level (857cm^{-1}) and equal to f_aN_0, N_0 is the dopant concentration and f_a is a fraction of the $^4I_{9/2}$ population that resides in the Stark component used as a lower laser level. The depletion of the lower manifold population is ignored. This approximation is reasonable because the lower laser level has a small population compared with the total dopant concentration, and the upper state population required to reach the threshold is also small. If the spatial distribution of the pump and laser cavity mode is taken into account, then the threshold condition is given by

$$\iiint 2\sigma_1 l s_1(r,z)[\eta_p f_b P_{th} r_p(r,z)\tau/h\nu_p - f_aN_0]dV = \delta_1, \qquad (4)$$

where V is the volume of the laser rod, $s_1(r,z)$ is the spatial distribution of the laser photons at 946nm, and normalized such that

$$\iiint s_1(r,z)dV = 1. \qquad (5)$$

If we assume a circularly symmetric Gaussian beam for the laser mode, then

$$s_1(r,z) = \frac{2}{\pi\omega_{01}^2 l}\exp\left(\frac{-2r^2}{\omega_{01}^2}\right), \qquad (6)$$

where ω_{01} is the beam radius of the laser cavity mode at 946nm.

Combining Eqs.(2) and (6) with Eq.(4) and integrating the resultant, the threshold condition can be rewritten as

$$P_{th1} = \frac{\delta_1 + 2\sigma l f_a N_0}{2L\eta_p f_b}\cdot\frac{h\nu_p}{\sigma_1\tau}\cdot\frac{1}{\iiint s_1(r,z)r_p(r,z)dV} = \frac{\delta_1 + 2\sigma_1 l f_a N_0}{4\eta_p f_b}\cdot\frac{\pi h\nu_p}{\sigma_1\tau}(\omega_{01}^2+\omega_p^2). \qquad (7)$$

For a four-level laser, the rate equation at the threshold for transition $^4F_{3/2}$–$^4I_{11/2}$ ($\sim$1.06μm) can be written as

$$\frac{dN_c(r,z)}{dt} = 0 = -\frac{N_c(r,z)}{\tau} + Rf_c r_p(r,z), \quad (8)$$

where N_c is the upper laser level (11512cm^{-1}) population. For the four-level system, the population of the lower laser level (2110cm^{-1}) can be assumed to be zero. Therefore, the population inversion density ΔN_2 is equal to N_c; f_c is a fraction of the $^4F_{3/2}$ population that resides in the Stark component used as the upper laser level. According to similar theory to that discussed above, the threshold condition for the four-level laser is given by

$$\iiint 2\sigma_2 l s_2(r,z)[\eta_p f_c P_{th2} r_p(r,z)\tau/h\nu_p]dV = \delta_2, \quad (9)$$

where $s_2(r,z)$ is the spatial distribution of the laser photons for the $^4F_{3/2}$–$^4I_{11/2}$ transition, which is also normalized. After integrating Eq.(9), the threshold condition can be rewritten as

$$P_{th2} = \frac{\delta_2}{2l\eta_p f_c} \cdot \frac{h\nu_p}{\sigma_2\tau} \cdot \frac{1}{\iiint s_2(r,z) r_p(r,z) dV}$$
$$= \frac{\delta_2}{4\eta_p f_c} \cdot \frac{\pi h\nu_p}{\sigma_2\tau}(\omega_{02}^2 + \omega_p^2). \quad (10)$$

The operating condition of the dual-wavelength is that both transitions possess the same threshold, $P_{th1} = P_{th2}$, and can be given by

$$\ln\left(\frac{1}{r_2 r_2'}\right) = \frac{f_c}{f_b}\frac{\sigma_2}{\sigma_1}\frac{\omega_{01}^2 + \omega_p^2}{\omega_{02}^2 + \omega_p^2}(2\sigma_1 l f_a N_0 + \ln\left(\frac{1}{r_1 r_1'}\right) + 2L\delta_{in1}) - 2L\delta_{in2}. \quad (11)$$

According to Eq.(11), with different reflectivity values of output mirror for the radiation at the $^4F_{3/2}$–$^4I_{11/2}$ transition ($\sim$1.06μm), we calculate the corresponding reflectivity values for the radiation at the $^4F_{3/2}$–$^4I_{9/2}$ transition ($\sim$946nm). The results are shown in Fig.2. The basic parameters used in the calculation are $f_a = 0.0074$, $f_b = 0.6$, $f_c = 0.4$, $\omega_p = 300\mu$m, $l = 3$mm, $N_0 = 1.386 \times 10^{20}$cm^{-3}, $\sigma_1 = 4\times10^{-20}$cm^2,[11] $\sigma_2 = 4.6\times10^{-19}$cm^2, $\omega_{01} = 122.4\mu$m, $\omega_{02} = 129.5\mu$m, $\delta_{in1} = 0.004$ cm^{-1}, $\delta_{in2} = 0.007$ cm^{-1}. The values of δ_{in1} and δ_{in2} can be measured by the Findlay–Clay method.[12] We assume that the pump quantum efficiency of converting the optical power absorbed by the crystal to the power of fluorescence is the same for all of the operated wavelengths in crystal. According to the results shown in Fig.2, when the reflectivity values of output mirror at the $^4F_{3/2}$–$^4I_{9/2}$ transition lie in the range of 70%–99%, the reflectivity of output mirror at the $^4F_{3/2}$–$^4I_{11/2}$ transition must be in the range of 3.6%–58% for Nd:YAG crystal. We find that it is almost impossible to achieve the simultaneous dual-wavelength operation on the transitions $^4F_{3/2}$–$^4I_{9/2}$ and $^4F_{3/2}$–$^4I_{11/2}$ in Nd:YVO_4 crystal. As the crystal field for splitting the energy level of 433cm^{-1} in Nd:YVO_4 is about two times smaller than in Nd:YAG (857cm^{-1}), the Boltzmann factor f_a of the lower laser level is about 5% at a room temperature compared with 0.74% for Nd:YAG. In addition, the ratio of emission cross-section σ_2/σ_1 is much larger in Nd:YVO_4 than in Nd:YAG.

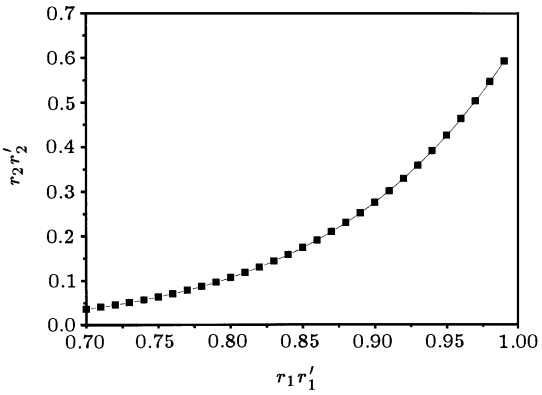


Fig.2. Corresponding reflectivity values at the lasing wavelength λ_2 =1.06μm, r_2r_2', as a function of the values r_1r_1' at λ_1 =946nm.

3. Experiment and results

If we assume that the reflectivity for 946nm radiation is 99%, the reflectivity for 1.06μm radiation must be 59% in order to satisfy the oscillation condition in Nd:YAG laser at both 1.06μm and 946nm, which is in agreement with the measured reflectivity (rr') of the cavity mirrors: 98% at 946nm and 62% at 1.06μm.

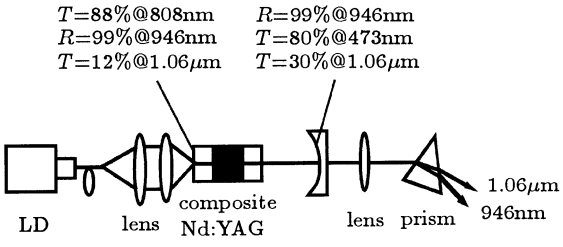


Fig.3. Experimental setup of the cw simultaneous dual-wavelength generation at 1.06μm and 946nm in Nd:YAG.

The experimental setup is shown in Fig.3. A composite laser rod is used as a gain medium. This rod is

composed of one 1.0at.% Nd:YAG crystal rod and two undoped YAG crystal rods. The three rods are all the same in size: 3mm in radius and 3mm in length. The two undoped YAG rods are diffusion-bonded to both ends of the doped Nd:YAG rod, resulting in a composite laser rod. Both end plates of the composite rod are polished (as will be mentioned below) and kept parallel to each other. The composite laser rod works in such a way that the thermal effects through the two undoped end caps can be decreased.[13] Because the undoped region is transparent to the pump radiation, the diffusion bond can make the generated heat flow from the doped to the undoped regions. Therefore, the temperature can be greatly decreased in the gain medium, which is essential for this quasi-three-level laser at 946nm. The diameter of the crystal is chosen to be 3mm so as to achieve the efficient heat transfer. The pumping facet of the laser crystal is coated to be of high reflectivity (HR) at 946nm (R=99.8%) and high transmission (HT) at 808nm (T=88%). And it is also specially coated to be of partial transmission (T=12%) at 1.06μm, which is different from the high transmission ($T > 80\%$) designed for a single wavelength operation at 946nm.[14] Therefore, the pumping facet of the laser rod acts as one of the resonator mirrors. Another end plate of the undoped YAG crystal of the composite laser rod is AR coated at 946nm, 1.06μm and 1.32μm. In order to remove the heat generated under high pump powers from the crystal effectively, the laser crystal is cooled directly with running water (T=14°C). The pump source is a fibre-coupled diode laser operating at 808 nm with a maximum power output of 20W. The diameter of the fibre core is 400μm with a numerical aperture of 0.22. The pump light is focused onto the laser rod with two achromatic lenses. The pump spot size in the gain medium is around 300μm. The output coupler is a concave mirror with a curvature radius of 100mm. To obtain fundamental dual-wavelength emission at both 946nm and 1.06μm in cw operation, it is coated to be of HR at 946nm (R=99%) and partial transmission at 1.06μm (T=30%). The cavity length is set to be 48mm.

The spectra at 946nm and 1.06μm were detected by using the optical spectrum analyser sensitive only to the IR region (above 850nm). The result is shown in Fig.4. During the experiment, we find that the relative power output of each wavelength is very sensitive to the alignment of the output mirror. This is mainly due to the fact that the relative cavity losses are adjusted in the alignment procedure. It is impossible for these two wavelengths to achieve the maximum power output at the same time. So the alignment criterion is based on the minimum threshold for the dual-wavelength generation. When the incident pump power is increased to 3.6W, the dual-wavelength radiation is emitted. A total power output of 2.5W for the dual-wavelength is achieved at an incident pump power of 17.5W with an optical conversion efficiency of 14.3 %. The output ratio of the two wavelengths at 1.06μm and 946nm is 28.6:1. If we want to achieve a higher power output at 946nm, the transmission at this transition should be enhanced according to the operating condition given by Eq.(11). For example, if the reflectivity ($r_1 r_1'$) at 946nm is assumed to be 96%, the reflectivity ($r_2 r_2'$) at 1.06μm should be set to be about 46%.

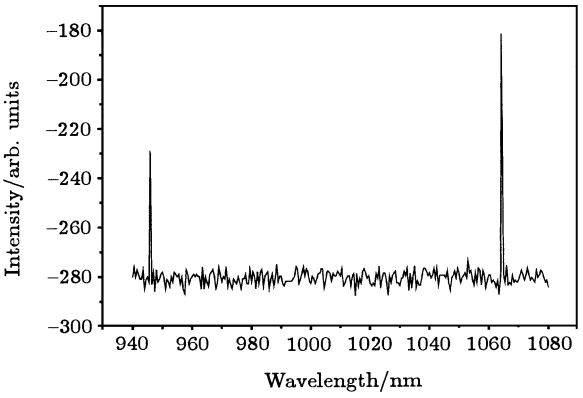


Fig.4. Spectrum of generation at 946nm and 1.06μm.

4. Conclusion

In conclusion, the operating condition of a cw simultaneous dual-wavelength Nd:YAG laser has been studied at transitions $^4F_{3/2}-^4I_{11/2}$ and $^4F_{3/2}-^4I_{9/2}$. Simultaneous cw emission of two wavelengths, λ_1=946nm andλ_2=1.06μm, from a diode-end-pumped Nd:YAG laser has been achieved experimentally for the first time. A total power output of 2.5W has been yielded with an optical–optical efficiency of 14.3% at an incident pump power of 17.5W. As is known, the pulsed simultaneous dual-wavelength operation at 1.06μm and 1.32μm from Nd:YAG laser has been reported by other researchers,[14] and we can now conclude that the simultaneous three fundamental wavelengths of 1.32μm, 1.06μm and 946nm may be realized on condition that a suitable coating for the cavity mirrors is designed.

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