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Simultaneous three-wavelength continuous wave laser at 946 nm, 1319 nm and 1064 nm in Nd:YAG

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ABSTRACT

A continuous-wave (cw) diode-end-pumped Nd:YAG laser that generates simultaneous laser at the wavelengths 946 nm, 1319 nm and 1064 nm is demonstrated. The optimum oscillation condition for the simultaneous three-wavelength operation has been derived. Using the separation of the three output couplers, we obtained the maximum output powers of 0.24 W at 946 nm, 1.07 W at 1319 nm and 1.88 W at 1064 nm at the absorbed pump power of 11.2 W. A total output power of 3.19 W for the three-wavelength was achieved at the absorbed pump power of 11.2 W with optical conversion efficiency of 28.5%.

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1. Introduction

Simultaneous emission at multiple wavelengths has been of interest for the practical applications, such as medical instrumentation, research on nonlinear optical mixers, environmental monitoring, laser radar, spectral analysis and THz research, etc. Nd^{3+}-ion-doped laser is the most important source because of its high gain and good thermal and mechanical properties. As we know, there exist three transitions: $^4F_{3/2}$–$^4I_{9/2}$, $^4F_{3/2}$–$^4I_{11/2}$, and $^4F_{3/2}$–$^4I_{13/2}$, in Nd^{3+} ion, leading to potential laser radiations around 0.9, 1.06 and 1.3 μm, respectively. These Nd-doped lasers, generated by two different transitions from $^4F_{3/2}$–$^4I_{9/2}$, $^4F_{3/2}$–$^4I_{11/2}$ and $^4F_{3/2}$–$^4I_{13/2}$ in Nd^{3+}-doped crystals, have been reported. For example, several groups have reported dual-wavelength generation by using different Nd^{3+}-doped media such as Nd:YAG [1–5], Nd:YLF [6], Nd:YVO_4 [7–11], Nd:$GdVO_4$ [12–16], Nd:$LuVO_4$ [17], and Nd:YAP [18,19]. Nadtocheev et al. [20] reported a simultaneous cw dual-wavelength laser operating at 1319 and 1338 nm and a three-wavelength laser operation at 1319, 1335, and 1338 nm. Danailov et al. [21] demonstrated a simultaneous four-wavelength Nd:YAG laser at 1052, 1061, 1064, and 1074 nm. Zou et al. reported an efficient, stable diode-end-pumped simultaneous cw dual-wavelength Nd:YAG laser operating at 1319 and 1338 nm. In addition, a three-wavelength laser operation at 1319, 1338, and 1356 nm was observed [22]. To the best of our knowledge, no research about pulsed or cw simultaneous three-wavelength operation at 0.9 μm ($^4F_{3/2}$–$^4I_{9/2}$), 1.3 μm ($^4F_{3/2}$–$^4I_{13/2}$), and 1.06 μm ($^4F_{3/2}$–$^4I_{11/2}$) in Nd^{3+}-doped lasers has been reported. However, three-wavelength operation with the same laser medium is rather difficult at these particular wavelengths because of strong gain competition among the three transitions. Moreover, the emission cross-section of 0.9 μm is quite smaller than those of 1.06 and 1.3 μm and the laser at 0.9 μm is a quasi-three-level system, which results in a considerable re-absorption loss due to thermal population at the lower level.

In this work, we will present our recent results of exploring a three-wavelength Nd:YAG laser. Using the separation of the three output couplers, we obtained the maximum output powers of 0.24 W at 946 nm, 1.07 W at 1319 nm and 1.88 W at 1064 nm. To our knowledge, this is the first work of realizing simultaneous three-wavelength Nd:YAG laser operation at 946 nm, 1319 nm and 1064 nm.

2. Theoretical analysis

To optimize three-wavelength lasing operation, the reflectivity value of each wavelength at the output coupler should be set to approximately balance the gain curves for each of the three output wavelengths. Let σ_i (i=1,2,3) and R_i (i=1,2,3) be, respectively, the stimulated-emission cross section and the reflectivity of the output coupler. The subscripts 1, 2 and 3 are used to denote these qualities at λ_1=946 nm, λ_2=1319 nm and λ_3=1064 nm respectively. For a diode-end-pumped solid-state laser, the threshold condition for $^4F_{3/2}$–$^4I_{9/2}$ transition at 946 nm (for quasi-three-level system) derived from the rate equation can

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be written as [23]

$$P_{th,1}=\frac{\ln(1/R_1)+L_1+2\sigma_1 lf_a N_0}{2l\eta_p f_b}\frac{h\nu_p}{\sigma_1\tau_1}\frac{1}{\iiint s_i(r,z)r_p(r,z)d\upsilon} \quad (1)$$

and the threshold conditions for $^4F_{3/2}$–$^4I_{11/2}$ and $^4F_{3/2}$–$^4I_{13/2}$ transitions (for four-level system) can be written as

$$P_{th,i}=\frac{\ln(1/R_i)+L_i}{2l\eta_p f_i}\frac{h\nu_p}{\sigma_i\tau_i}\frac{1}{\iiint s_i(r,z)r_p(r,z)d\upsilon} \quad (2)$$

$i=2,3$

where l is the length of the active medium, L_i $(i=1,2,3)$ are resonator round-trip residual losses at the corresponding transition wavelength, τ_i $(i=1,2,3)$ is the fluorescence lifetime at the upper level, f_a is the fraction of the $^4F_{3/2}$ population that resides in the Stark component used as the lower laser level of 946 nm, f_b and f_c are the fractions of the $^4F_{3/2}$ population that resides in the Stark component used as the upper laser levels (11423 cm^{-1} and 11507 cm^{-1}), respectively, η_p is the quantum efficiency for the corresponding transition, $h\nu_p$ is the pump photon energy, $s_i(r,z)$ is the normalized cavity mode intensity distribution for the corresponding transition, and $r_p(r,z)$ is the normalized pump intensity distribution in the active medium. The condition that three transitions possess the same threshold, $P_{thi}=P_{th1}(i=2,3)$, can be given by

$$\ln\left(\frac{1}{R_i}\right)+L_i=\beta_i\left[2\sigma_1 lf_a N_0+\ln\left(\frac{1}{R_1}\right)+L_1\right] \quad (3)$$

where

$$\beta_i=\frac{\sigma_i f_c}{\sigma_1 f_b}\frac{\int_0^l e^{-\alpha z}(1-e^{-2q_i^2})/\omega_p^2(z)dz}{\int_0^l e^{-\alpha z}(1-e^{-2q_i^2k_i^2})/\omega_p^2(z)dz} \quad (4)$$

$i=2,3$

where $\omega_p(z)$ is the pump size in the active medium, $q_i=\omega_{po}/\omega_{0i}$ $(i=2,3)$ and $k_i=\omega_{0i}/\omega_{01}$ $(i=2,3)$ are the beam size ratios (the parameters β and k have been defined in [15] and [24]), ω_{po} and ω_{0i} $(i=1,2,3)$ are the beam radii for the pump and laser cavity modes at the waist in the active medium. With the usual M^2 propagation law, the pump beam is given by

$$\omega_p^2(z)=\omega_{po}^2\left\{1+\left[\frac{\lambda_p M_p^2}{n\pi\omega_{po}^2}(z-z_0)\right]^2\right\} \quad (5)$$

where λ_p is the pump wavelength, M_p^2 is the pump beam quality factor, z_0 is focal plane of the pump beam in the active medium, and n is the refractive index of the active medium. With Eq. (4) and the parameters in the experiment, the corresponding values of β_i $(i=2,3)$ were calculated as a function of the beam size ratio k_i $(i=2,3)$ as shown in Fig. 1. The basic parameters used in calculation are $\omega_P=0.2$ mm, ω_{03} $=0.2$ mm, $\omega_{02}=0.15$ mm, $L_1=0.005$, $L_2=L_3=001$, $\sigma_1=4\times10^{-20}$ cm^2, $\sigma_2=9.2\times10^{-20}$ cm^2, $\sigma_3=4.6\times10^{-19}$ cm^2 $f_a=0.0074$, $f_b=0.6$, $f_c=0.4$, $\alpha=15.8$ cm^{-1}, $n=1.82$, $M_p^2=310$. The values of L_i $(i=1,2,3)$ were measured by the Findlay–Clay method [25].

Fig. 1 shows that the values of β_3 and β_2 are nearly independent of the values of $k_3(k_3>1.3)$ and $k_2(k_2>1)$, respectively. In the experiment we selected an appropriate size of $\omega_{01}(\omega_{01}=0.15$ mm), so the relationship between R_i $(i=2,3)$ and R_1 in Eq. (3) is independent of the values of q_i $(i=2,3)$ and k_i $(i=2,3)$. With Eq. (3) and the parameters in the experiment, the corresponding reflectivities R_i $(i=2,3)$ were calculated as a function of the reflectivity R_1 as shown in Fig. 2. According to the results shown in Fig. 3, if we assumed that the reflectivity R_1 was 99%, the reflectivities R_2 and R_3 must be 90.7% and 51.8% respectively to satisfy the simultaneous three-wavelength oscillation condition in Nd:YAG laser, which agreed well with the measured reflectivities of the output mirrors of 99.2%, 91.7% and 52.8% at 946 nm, 1319 nm and 1064 nm respectively. The cavity lengths for 946 nm, 1319 nm and 1064 nm oscillations were 61 mm, 55 mm and 100 mm, respectively. The cavity length chosen here resulted in the mode ratios of k_i $(i=2,3)$ greater than unity and enhanced the output stability in the three-wavelength operation.

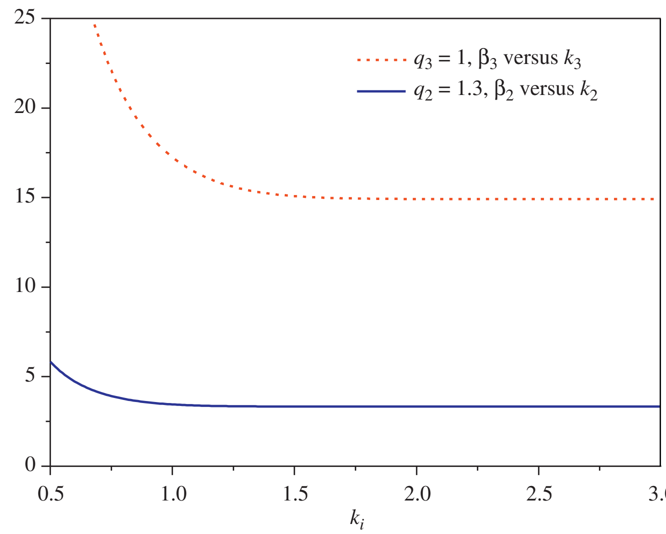

Fig. 1. Values of β_i $(i=2,3)$ as a function of the beam size rates k_i $(i=2,3)$.

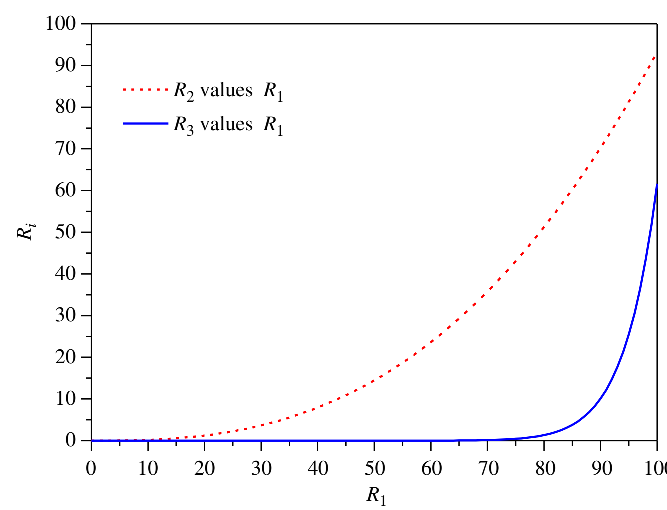

Fig. 2. Corresponding reflectivity values R_3 and R_2 as a function of the values R_1.

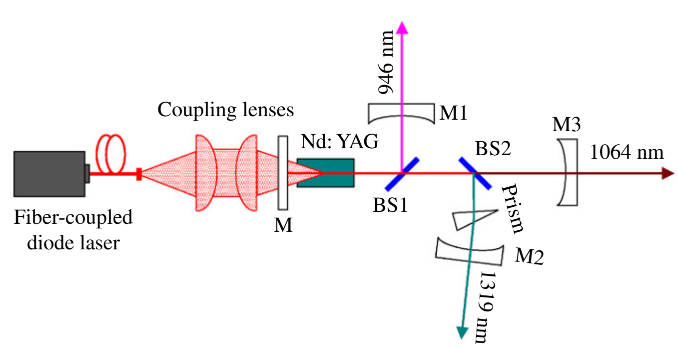

Fig. 3. Schematic setup of the laser configuration used for single wavelength or simultaneous three-wavelength emission.

3. Experimental setup

The experimental setup used is described in Fig. 3. In previous papers, similar T-type or N-type resonator configuration was used by other authors to obtain simultaneous laser emission at 1.06 and 1.3 μm from Nd:YAG and Nd-vanadate lasers [26–28]. The optical pumping was done by using fiber-coupled (diameter of 400 μm and numerical aperture NA=0.22) diode lasers from Coherent Co., USA. The 808 nm emitting diode outputted 12 W of pump power with an emission bandwidth of 2.5 nm (FWHM definition). The coupling optics consists of two identical plano-convex lenses with focal lengths of 15 mm used to re-image the pump beam into the laser crystal at a ratio of 1:1. The coupling efficiency is 95%. A 1.0 at% Nd^{3+} doped Nd:YAG crystal with a dimension of 3 mm in length and 4 mm in diameter was used as the laser rod. It was wrapped with indium foil and mounted at a thermal electronic cooled (TEC) copper block, and the temperature was maintained at 20 °C. The whole cavity was also cooled by TEC. Both sides of the laser crystal were coated for high transmission (HT) at 946, 1319 and 1064 nm. The first beam splitter (BS1) is HT coated for 1319 and 1064 nm and HR at 946 nm. The second beam splitter (BS2) is HT coated for 1064 nm and HR at 1319 nm. The input mirror, M, was HT coated at the pump wavelength and highly reflective (HR) at 946, 1319 and 1064 nm. The concave mirror, M1, with a radius of curvature −500 mm was used as the output coupler for 946 nm resonant. The concave mirror, M2, with a radius of curvature −350 mm was used as the output coupler for 1319 nm resonant. In order to achieve the 1319 nm single wavelength laser operation, a prism was inserted in the 1319 nm cavity to avoid emission at 1338 nm in the Nd:YAG crystal. Because the stimulated emission cross sections of 1319 nm and 1338 nm are 9.2×10^{-20} cm^2 and 9×10^{-20} cm^2, respectively [29], very close to each other. The concave mirror, M3, with a radius of curvature -700 mm was used as the output coupler for 1064 nm resonant.

4. Results and discussion

The experiments on single wavelength operation were performed first. The laser performance is presented in Fig. 4. The maximum cw output power at 946 nm was 1.67 W, corresponding to a slope efficiency η_{sa} of 23.6% with respect to the absorbed pump power. The optical-to-optical efficiency η_{oa} with respect to the absorbed pump power was 14.9% and the absorbed pump power at threshold P_{tha} was about 4.1 W; the absorption efficiency η_a of the pump power in the Nd:YAG crystal was nearly 98%. The output mirror M1 has a transmission of 2.8% at 946 nm. When the output mirror M2 with a transmission of 4.6% at 1319 nm was used, the laser emitted maximum 3.38 W output power at this wavelength, whereas the threshold was P_{tha}=2.5 W. Optical efficiency η_{oa} and slope efficiency η_{sa} were 30.2% and 39.1%, respectively. The laser yielded 5.92 W at 1064 nm with optical efficiency η_{oa}=52.9%, slope efficiency η_{sa}=58.9% and pump power at threshold P_{tha}=1.4 W. The output mirror M3 had a transmission of 10.3% at 1064 nm.

When the absorbed pump power was increased to about 3.2 W, the three-wavelength radiation was emitted. The output powers at each lasing wavelength versus absorbed power are given in Fig. 5. It can be seen that the output power of 1319 nm first increases linearly with the absorbed pump power, reaches its power of 0.81 W at the absorbed pump power of 8.5 W, and then rises monotonically. It was observed that the output power of 1064 nm increases quadratically as the absorbed pump power increases, reaches its power of 1.88 W at the absorbed pump power of 11.2 W. On the other hand, as the absorbed pump power was increased, the 946 nm transitions was not suppressed completely by the 1064 nm and 1319 nm transitions, but the three wavelengths competed with each other. As the absorbed pump power increased, the 946 nm output increase more slowly than 1319 nm and 1064 nm. And it was found that the output power at 946 nm was much lower than those at 1319 nm and 1064 nm due to the high reflectivity coating for the output coupler at 946 nm. At an absorbed pump power of 11.2 W, the maximum output power obtained at 946 nm is 0.24 W. The output power proportion of 946 nm, 1319 nm and 1064 nm was 1:4.5:7.8. A total output power of 3.19 W for the three-wavelength was achieved at the absorbed pump power of 11.2 W with optical conversion efficiency of 28.5%.

The stability testing is carried out by monitoring the output powers of each wavelength with a Field-Master-GS powermeter at 10 Hz. The fluctuations for 946 nm, 1319 nm and 1064 nm lights at the pump power of 11.2 W are about 2.6%, 1.8% and 2.1% in 4 h, respectively. We found that the fluctuations in the output powers of each wavelength were substantially stable. We used the algorithms of the knife-edge technique 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,

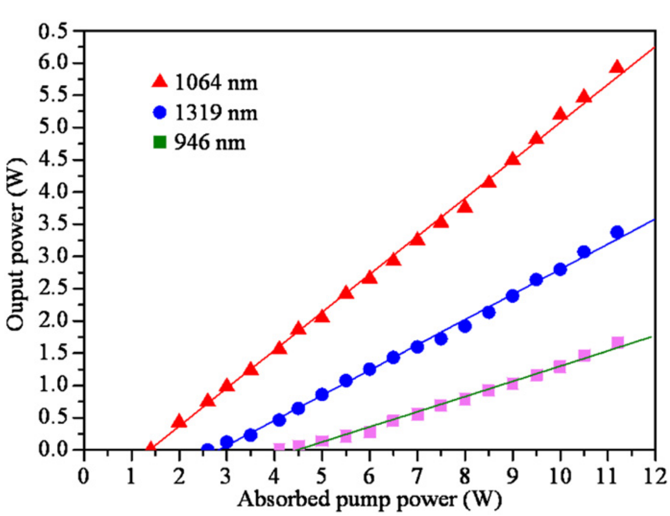

Fig. 4. Output power versus pump power for cw single wavelength operation at 946, 1319 and 1064 nm.

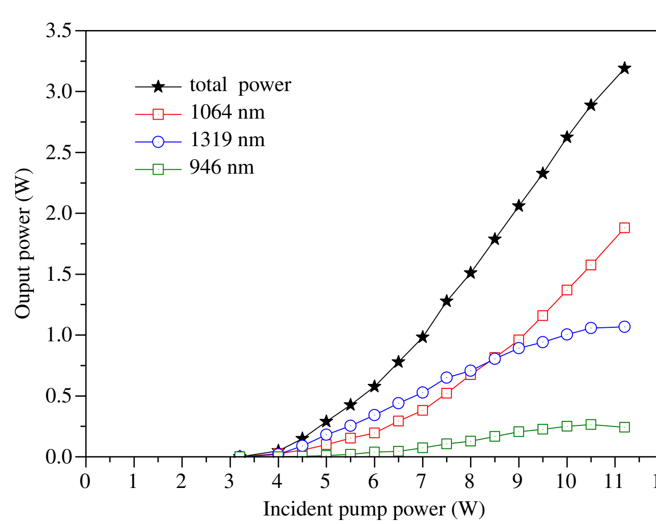

Fig. 5. Output powers versus the absorbed pump power for three-wavelength operation.

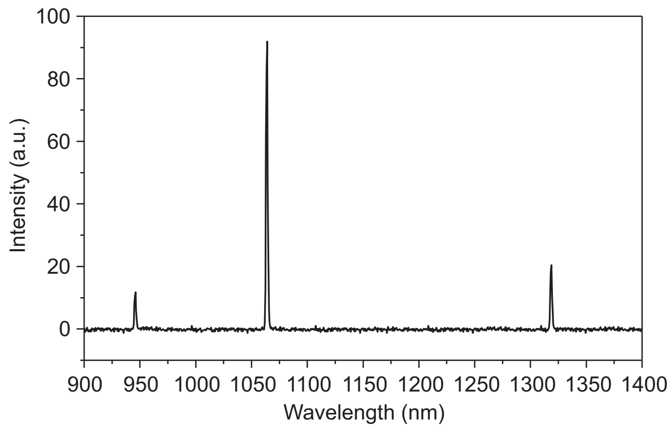

Fig. 6. Optical spectrum of three-wavelength operation at a pump power of 11.2 W.

respectively. The M^2 values for 946 nm, 1319 nm and 946 nm lights at the pump power of 11.2 W were found to be around 1.24, 1.21 and 1.12, respectively. Fig. 6 shows the measured optical spectrum for the simultaneous three-wavelength laser at the pump power of 11.2 W. The central wavelengths are 946 nm, 1319 nm and 1064 nm, with the spectral line widths of 1.4 nm, 1.6 nm and 1.5 nm, respectively.

5. Conclusion

In summary, the operating condition of cw simultaneous three-wavelength laser in Nd:YAG crystal was studied, and the simultaneous cw emission of three-wavelength, 946 nm, 1319 nm and 1064 nm, from a diode-end-pumped Nd:YAG laser has been achieved experimentally. A total output power of 3.19 W was yielded with optical conversion efficiency of 28.5% at the absorbed pump power of 11.2 W. Experimental results show that the stable output powers at the three-wavelength could be obtained by the use of the separation of the output couplers. To our knowledge, this is the first time that such a cw simultaneous three-wavelength operation is reported for a diode-pumped Nd:YAG laser.

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