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Simultaneous dual-wavelength Q-switched Nd:YAG laser operating at 1.06 μm and 946 nm

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Abstract

Considering the reabsorption loss of the quasi-three level system and the unsaturable loss of the saturable absorber, we obtained the operating condition of a diode-pumped simultaneous dual-wavelength Q-switched Nd:YAG laser operating at 1.06 μm and 946 nm. The dual-wavelength pulsed laser was realized successfully through adaptive coating design of the cavity mirrors. As much as 1.6 W total average output power of the dual-wavelength at 1.06 μm and 946 nm was achieved at the incident pump power of 14.2 W with an optical conversion efficiency of 11.3%.

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Keywords: Diode-pumped laser; Dual-wavelength; Q-switched; Nd:YAG

The simultaneous dual-wavelength laser (SDWL), as a typical multi-wavelength laser, has attracted much attention for its wide application areas such as precision laser spectroscopy, lidar, nonlinear optical frequency conversion, laser noise, and so on. Over the last few years, a number of studies have been carried out on this topic [1–6]. However, among these lasers ever reported, only simultaneous continuous wave (CW) and Q-switched dual-wavelength generation at both around 1.0 μm ($^4F_{3/2}$–$^4I_{11/2}$) and 1.3 μm ($^4F_{3/2}$–$^4I_{13/2}$) have been reported, which are both the four-level system. Our group realized simultaneous dual-wavelength CW Nd:YAG laser operating at 1.06 μm and 946 nm in 2004 [7]. To the best of our knowledge, no research about simultaneous dual-wavelength pulsed operation at around 1.0 and 0.9 μm in Nd doped lasers has been reported. The laser at around 0.9 μm is difficult to realize owing to the reabsorption loss of the quasi-three level system and the small stimulated emission cross-section compared with that of the 1.0 μm laser. Therefore, it is more difficult to obtain simultaneous dual-wavelength operation that includes the 0.9 μm laser. In this paper, we successfully realized the simultaneous dual-wavelength Q-switched Nd:YAG laser operating at 1.06 μm and 946 nm for the first time through reasonable coating design of the cavity mirrors. A total average output power of 1.6 W of the dual-wavelength was obtained with an optical conversion efficiency of 11.3%.

According to the rate equation, the threshold condition is that roundtrip gain equals roundtrip loss. Considering the reabsorption loss and the unsaturable loss of the saturable absorber in the passive Q-switched quasi-three-level laser, the threshold condition for $^4F_{3/2}$–$^4I_{9/2}$ transition at 946 nm can be written as [8,9]

$$\int\int\int 2\sigma_1 l s_1(r,z)[\eta_p(f_a+f_b)P_{th}r_p(r,z)\tau/h\gamma_p - f_a N_0]\,dV = L_1 + \ln(1/r_1 r_1') + 2\ln(1/T_{01}) \quad (1)$$

where the subscript 1 is used to denote the qualities at 946 nm, σ_1 is the stimulated emission cross-section of

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946 nm, l is the length of the gain medium, $s_1(r, z)$ is the normalized cavity mode intensity distribution in the gain medium, η_b is the pump quantum efficiency, f_a is the fractional occupation of the lower laser level given by a Boltzmann distribution, f_b is the fraction of the upper manifold population in the upper laser level, P_{th} is the absorbed pump power at threshold, $r_p(r, z)$ is the normalized pump intensity distribution in the gain medium, τ is the upper manifold lifetime, $h\gamma_p$ is the pump photon energy, N_0 is the dopant concentration, V is the volume of the laser rod, L_1 is the roundtrip cavity excess losses, r_1r_1' is the product of the reflectivity of the cavity mirrors, T_{01} is the low-power transmittance of the saturable absorber. From Eq. (1), the absorbed pump power at threshold can be given by

$$P_{th1} = \frac{\pi h\gamma_p(w_{01}^2 + w_p^2)}{4\sigma_1\tau\eta_p(f_a + f_b)}[L_1 + \ln(1/r_1r_1') + 2\ln(1/T_{01}) + 2\sigma_1 l f_a N_0] \quad (2)$$

where w_p and w_{01} are the beam radii for the pump and laser cavity modes at the waist in the active medium.

Using the same method, the absorbed pump power at threshold for $^4F_{3/2}$–$^4I_{11/2}$ transition at 1.06 μm can be written as

$$P_{th2} = \frac{\pi h\gamma_p(w_{02}^2 + w_p^2)}{4\sigma_2\tau\eta_p f_c}[L_2 + \ln(1/r_2r_2') + 2\ln(1/T_{02})] \quad (3)$$

where the subscript 2 is used to denote the qualities at 1.06 μm, f_c is the fraction of the $^4F_{3/2}$ population that resides in the Stark component used as the upper laser level of 1.06 μm. The corresponding incident pump power is $P'_{th} = P_{th}/[1 - \exp(-\alpha l)]$, where α is the absorption coefficient of the gain medium. The operating condition of the dual-wavelength is that both transitions possess the same threshold, $P'_{th1} = P'_{th2}$, and can be given by

$$\ln\frac{1}{r_2r_2'} = \frac{w_{01}^2 + w_p^2}{w_{02}^2 + w_p^2}\frac{\sigma_2 f_c}{\sigma_1(f_a + f_b)}[L_1 + \ln(\frac{1}{r_1r_1'}) + 2\ln(1/T_{01}) + 2\sigma_1 l f_a N_0] - L_2 - 2\ln(1/T_{02}) \quad (4)$$

The basic parameters used in calculation were $w_p = 120$ μm, $w_{01} = 88$ μm, $w_{02} = 93$ μm, $\sigma_1 = 4\times10^{-20}$ cm^2, $\sigma_2 = 4.6\times10^{-19}$ cm^2, $f_a = 0.0074$, $f_b = 0.6$, $f_c = 0.4$, $L_1 = 0.05$, $T_{01} = 93.5\%$, $l = 3$ cm, $N_0 = 1.386\times10^{20}$ cm^{-3}, $L_2 = 0.04$, $T_{02} = 92.2\%$. Substituting the corresponding values into Eq. (4), we obtained the oscillation condition of simultaneous dual-wavelength: the relationship between r_2r_2' and r_1r_1'. According to the results shown in Fig. 1, if we assumed that the reflectivity for 946 nm radiation was 93%, the reflectivity for 1.06 μm radiation must be 15.8% to meet the oscillation condition of simultaneous dual-wavelength, which agreed well with the measured reflectivity of the cavity mirrors of 93% at 946 nm and 14% at 1.06 μm, respectively.

The experimental setup is shown in Fig. 2. We used a simple and compact linear cavity in length of 3.7 cm. The pump source was a 200 μm fiber-coupled diode laser with a numerical aperture of 0.22. The 808 nm pump light from a fiber was coupled into a diffusion-bonded Nd:YAG (3 mm YAG, 3 mm 1.0 at.% Nd:YAG, and 3 mm YAG). The composite laser rod minimized the heat effect effectively. The pump facet of the laser rod was coated for high transmission (HT) at 808 nm ($T = 88\%$), high reflection (HR) at 946 nm ($R = 99\%$), and partial reflection ($R = 40\%$) at 1.06 μm. The other side of the rod was coated with antireflection (AR) at 946 nm, 1.06 and 1.32 μm. The saturable absorber was a 2 mm-long co-doped Nd,Cr:YAG crystal with initial transmission of 93.5% at 946 nm and 92.2% at 1.06 μm. The laser rod and the saturable absorber were both cooled directly with flowing water ($T = 15.5$ °C). The output coupler was a concave mirror that had a curvature radius of 50 mm. It was HR at 946 nm ($R = 94\%$) and partial reflection ($R = 40\%$) at 1.06 μm. The two oscillation lasers could be separated when they passed through the prism. The 1.06 μm laser was detected by probe 1 directly. The 946 nm laser was detected by probe 2 when it was reflected by a mirror which was coated with HR at 946 nm.

The Q-switched pulse temporal behavior was recorded by a digital oscilloscope (Tektronix 500 MHz bandwidth and 500 MS/s) and a fast photodiode with a rising time of less than 1 ns. The two Q-switched laser wavelengths of 946 nm and 1.06 μm had the same repetition rate. The repetition rate as a function of the incident pump power is shown in Fig. 3. It shows the repetition rate of the Q-switched pulse increases almost linearly with the incident

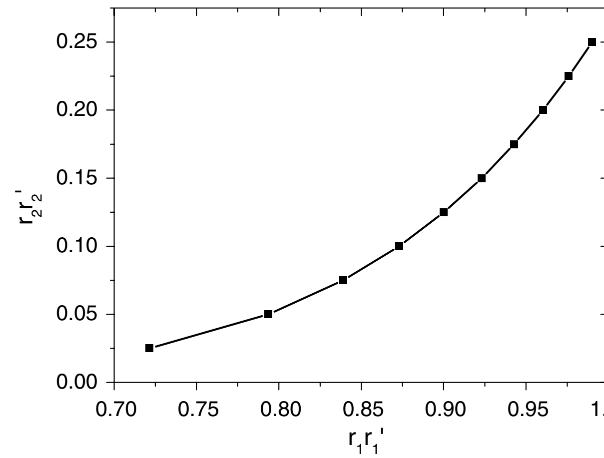

Fig. 1. The oscillation condition of simultaneous dual-wavelength: the relationship between r_2r_2' and r_1r_1'.

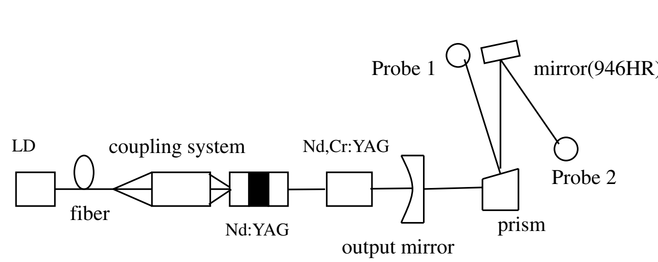

Fig. 2. Schematic of the simultaneous dual-wavelength Q-switched Nd:YAG laser.

pump power. With an incident pump power of 12.4 W, the Q-switched pulse repetition rate was 26 kHz. Further increased the incident pump power, the output of the pulse repetition rate consisted of a repetitive pulse set, in which a large pulse was followed by one or more smaller pulses. Fig. 4 showed the pulse widths of the two laser wavelengths versus the incident pump power. When the incident pump power was 12.4 W, the pulse widths were 24 ns of 1.06 μm laser and 25 ns of 946 nm laser, respectively. Further increased the incident pump power, the pulse widths of the two laser wavelengths became unstable. The average output powers at each laser wavelength and the total average output power of the two laser wavelengths versus the incident pump power are given in Fig. 5. When the incident pump power was increased to about 3.6 W, the dual-wavelength radiations were emitted. A total average output power of 1.6 W of the two wavelengths was achieved at the incident pump power of 14.2 W with an optical conversion efficiency of 11.3%. The upper laser levels of 946 nm and 1.06 μm belong to different sublevels of the $^4F_{3/2}$ level. The upper laser level populations of 946 nm and 1.06 μm are given by a Boltzmann distribution. It is probably because of their competitive interaction, a significant fluctuation in output power of 946 nm laser and 1.06 μm laser was observed in the simultaneous emission. We found that the relative output power of each wavelength was very sensitive to the alignment of the saturable absorber and the output mirror. It was mainly due to that the relative cavity loss was adjusted in the alignment procedure. We could obtain the relatively stable output of the two laser wavelengths through the alignment of the saturable absorber and the output mirror and the result is shown in Fig. 6. It is impossible to simultaneously achieve the maximum output powers for each wavelength by using of a two-mirror laser cavity. In order to further optimize the dual-wavelength laser operation, we could employ a three-mirror cavity which has different cavity lengths for different wavelength lasers. Chen reported that the stability of the output power at the two wavelengths could be enhanced by using of a three-mirror cavity [10]. This is also our next work.

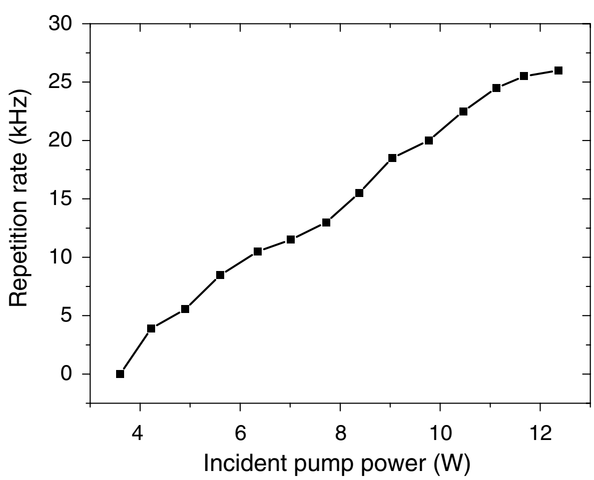

Fig. 3. The repetition rate of the Q-switched pulse as a function of the incident pump power.

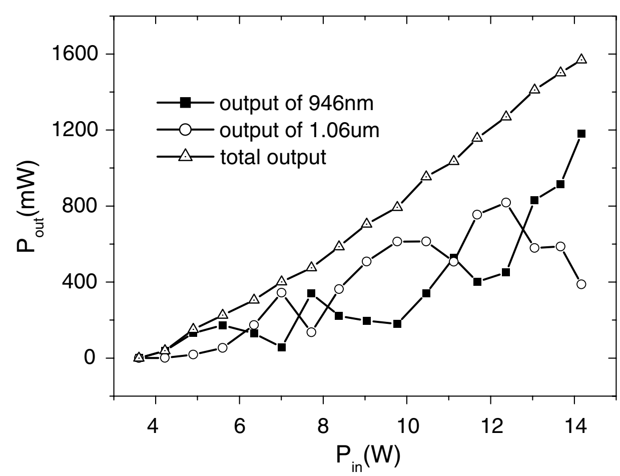

Fig. 5. The average output power as a function of the incident pump power.

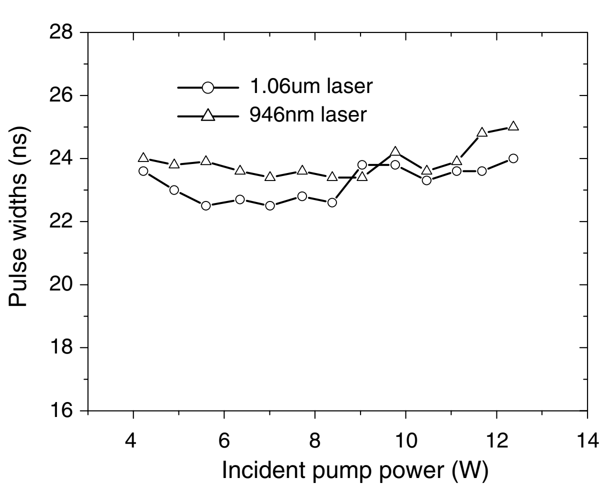

Fig. 4. The pulse widths of the two laser wavelengths versus the incident pump power.

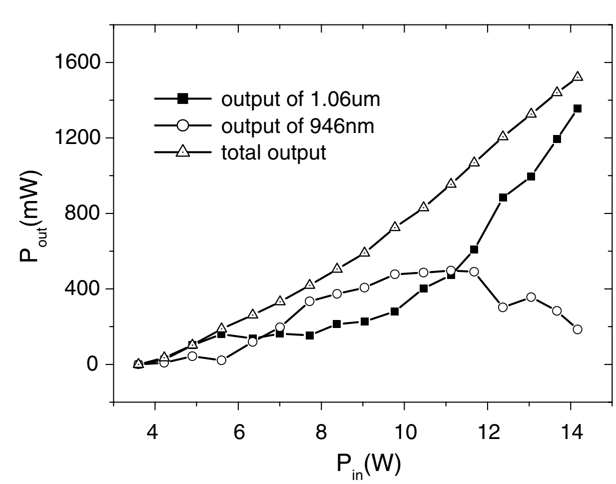

Fig. 6. The average output power as a function of the incident pump power after the alignment of the saturable absorber and the output mirror.

In conclusion, according to the operating condition of the simultaneous dual-wavelength, we have demonstrated a diode-pumped simultaneous dual-wavelength Q-switched Nd:YAG laser operating at 1.06 μm and 946 nm for the first time by appropriate coating design of the cavity mirrors. A total average output power of 1.6 W was achieved with an optical conversion efficiency of 11.3% at the incident pump power of 14.2 W. In order to further optimize the dual-wavelength laser operation, we could employ a three-mirror cavity. This is our next work.

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