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Experimental investigation of a diode-pumped powerful continuous-wave dual-wavelength Nd:YAG laser at 946 and 938.6 nm

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Abstract
In this paper, a diode-pumped high-power continuous-wave (cw) dual-wavelength Nd:YAG laser at 946 and 938.6 nm is reported. By using an end-pumped structure, comparative experiments indicate that a 5 mm-length Nd:YAG crystal with a Nd^{3+}-doping concentration of 0.3 at.% is favorable for high-power laser operation, and the optimal transmissivity of the output coupler is 9%. As a result, a maximum output power of 17.2 W for a dual-wavelength laser at 946 and 938.6 nm is obtained at an incident pump power of 75.9 W, corresponding to a slope efficiency of 26.5%. To the best of our knowledge, this is the highest output power of a quasi-three-level dual-wavelength laser using a conventional Nd:YAG crystal achieved to date. By using a traveling knife-edge method, the beam quality factor and far-field divergence angle at 17 W power level are estimated to be 4.0 and 6.13 mrad, respectively.

(Some figures may appear in colour only in the online journal)

1. Introduction

High-power Nd^{3+}-doped quasi-three-level lasers around 900 nm are attractive sources for the generation of blue lasers by frequency doubling technology. Blue lasers have many important applications ranging from high-density optical data storage, biological and medical diagnostics, color displays, to underwater imaging or underwater communication. Additionally, powerful laser emission around 940 nm with good beam quality can be also used as a pump source for Yb-doped materials and for remote sensing of water-vapor concentration. Many Nd^{3+}-doped laser media have been used for high-power quasi-three-level laser operation, such as a 946 nm Nd:YAG laser, a 914 nm $Nd:YVO_4$ laser, a 912 nm $Nd:GdVO_4$ laser, a 916 nm $Nd:LuVO_4$ laser, a Nd^{3+}-doped fiber laser, and so on [1–12]. Nd:YAG is mostly used for its merits of higher thermal conductivity, better crystal quality and longer lifetime of the upper laser level. In 1987, the first 946 nm Nd:YAG laser was demonstrated by Fan and Byer [1]. Since then, much more attention has been paid to the development of a high-power continuous-wave (cw) 946 nm laser. In 2000, Zeller reported an output power of 5.35 W for a cw 946 nm Nd:YAG laser with a slope efficiency of 40.2% [2]. Zhou *et al* demonstrated 8.3 W cw 946 nm laser output using a conventional Nd:YAG rod in 2005, and presented 15.2 W laser power at 946 nm with a diffusion bonded rod in 2006 [4, 5]. For dual-wavelength quasi-three-level laser output, Wang *et al* reported a total output power of 527 mW for a 946 nm and 938.5 nm laser by using a conventional Nd:YAG crystal. By employing a

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thin-disk geometry, the power was increased to 25.4 W by Gao *et al*, but the pump power was up to 137 W [13, 14]. To realize a high-power quasi-three-level laser output efficiently, four-level lasers with larger stimulated cross-sections should be suppressed, and the unfavorable effects need be overcome, such as the thermal-lensing effect, the reabsorption effect, upconversion and the amplified spontaneous emission (ASE) effect, and so on.

In this paper, a powerful diode-pumped dual-wavelength laser at 946 and 938.5 nm is obtained by using a conventional Nd:YAG crystal. Through experimental optimization of the laser medium and cavity parameters, the maximum output power of the 17.2 W cw laser is achieved at an incident pump power of 75.9 W, with a corresponding slope efficiency of 26.5%. To the best of our knowledge, this is the highest output power of a diode-pumped dual-wavelength laser at 946 and 938.5 nm by using a conventional Nd:YAG crystal. The beam quality factor and far-field divergence angle at 17 W power level are estimated to be 4.0 and 6.13 mrad, respectively.

2. Theoretical analysis

The energy levels and laser emission for Nd^{3+} in the laser medium of Nd:YAG are shown in figure 1. The lower levels of the 946 and 938.6 nm laser transitions are the upper 853 cm^{-1} crystal-field components of the $^4I_{9/2}$ ground-state manifold, and their upper laser levels are the different stark-splitting levels of the $^4F_{3/2}$, so the 946 and 938.6 nm laser oscillations are quasi-three-level laser operations. As we know, it is a challenge to achieve high-power Nd^{3+}-doped quasi-three-level laser output. Firstly, the stimulated-emission cross-section is much smaller than that of the four-level laser transitions at 1064 or 1340 nm. Secondly, the thermal-lensing effect, upconversion, amplified spontaneous emission (ASE) effect as well as the reabsorption loss will influence the laser performance seriously. To realize quasi-three-level laser output, oscillation of four-level lasers with larger stimulated-emission cross-sections should be restrained. Usually the lasing threshold of a four-level laser is increased by coating antireflective films on the cavity mirrors to increase the transmissivity at 1064 and 1340 nm.

The lasing thresholds of quasi-three-level and four-level lasers are given by [10, 15, 16]

$$P_{\mathrm{th}}\ 946\ \mathrm{nm} = \frac{\pi h\nu_{\mathrm{p}}\omega_L^2(L+T)(1+a^2)(1+B)}{4\sigma_{946\ \mathrm{nm}}\tau\eta_\alpha(f_1+f_2)} \quad (1)$$

$$P_{\mathrm{th}}1064\ \mathrm{nm}/1340\ \mathrm{nm} = \frac{\pi h\nu_{\mathrm{p}}}{4\sigma_{1064\ \mathrm{nm}/1340\ \mathrm{nm}}\tau\eta_\alpha}(\omega_{\mathrm{P}}^2+\omega_L^2) \times \left\{L+\sum_{i=1}^{n}\ln[1/(1-T_i)]\right\} \quad (2)$$

where ν_{P} is the pump frequency and h is Planck's constant. τ is the lifetime of the upper laser level. ω_{p} and ω_L are the pump beam waist and the oscillating beam waist, respectively, and a is the ratio between ω_{P} and ω_L. f_1 and f_2 are the fractions of the population density in the upper and lower laser levels, respectively. B is the ratio of reabsorption loss to cavity loss. $\eta_\alpha = 1-\exp(-\alpha l)$ is the fraction of absorbed pump power by the laser crystal with a length of l and absorption coefficient α. $\sigma_{946\ \mathrm{nm}}$, $\sigma_{1064\ \mathrm{nm}}$ and $\sigma_{1340\ \mathrm{nm}}$ are the stimulated cross-sections of 946 nm, 1064 nm and 1340 nm lasers, respectively. L is the intracavity round-trip dissipative optical loss and T is the transmissivity of the output coupling mirror. In addition, n is the number of cavity mirrors with antireflective coating at 1064 or 1340 nm.

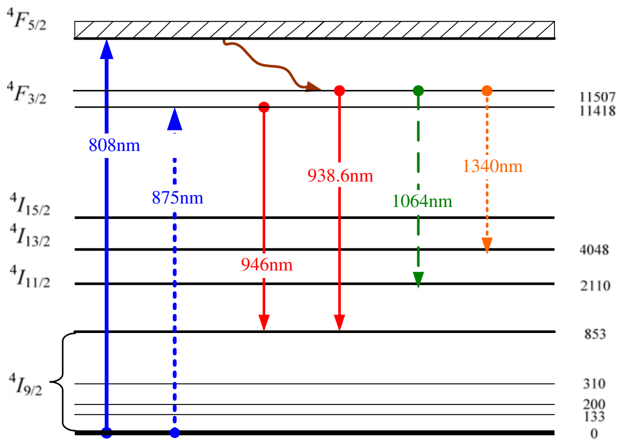

Figure 1. Energy levels and laser emission for Nd^{3+} in the laser medium of Nd:YAG.

Table 1. The main parameters for the calculation.

Parameter	Value	Parameter	Value
f_1	0.51	ω_{p}	200 μm
f_2	0.04	ω_L	200 μm
τ	230 μs	$\sigma_{946\ \mathrm{nm}}$	3.7×10^{-20} cm^2
λ_{p}	808 nm	$\sigma_{1064\ \mathrm{nm}}$	2.8×10^{-19} cm^2
α	1.83 cm^{-1}	$\sigma_{1340\ \mathrm{nm}}$	1.8×10^{-19} cm^2
η_α	0.6	L	0.02
l	5 mm	T	9%

According to the main parameters listed in table 1, the lasing threshold of the 946 nm laser is calculated to be 12.1 W when a and B are equal to 1. The threshold power of a four-level laser versus the transmissivity of the cavity mirrors is shown in figure 2. It can be seen that the cavity mirrors should be antireflective coated at 1064 or 1340 nm to suppress the four-level laser oscillation, and the required transmissivity at 1030 nm is lower than that at 1064 nm due to its relative smaller gain. In addition, the transmissivity of the cavity mirrors can be reduced with increase of n.

3. Experimental setup

Figure 3 shows the experimental setup of the diode-end-pumped cw Nd:YAG laser. A fiber-coupled LD (HLU110F400, LIMO Inc., Germany) serves as the pump source, which provides up to 110 W high brightness pump power from a fiber with a core diameter of 400 μm and a numerical aperture of 0.22. The pump beam is coupled into the gain medium by a coupling optical system, which consists

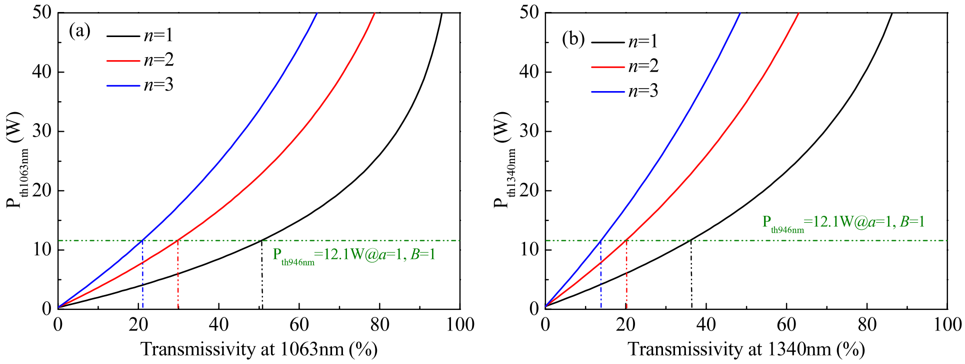

Figure 2. Threshold power of four-level lasers versus transmissivity (a) 1064 nm (b) 1340 nm.

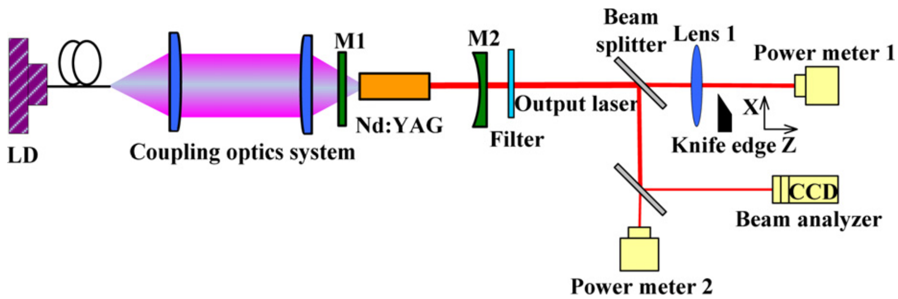

Figure 3. Experimental setup of a diode-end-pumped cw Nd:YAG laser.

of two identical plano-convex lenses with focal lengths of 21.3 mm. The pump beam is re-imaged into the laser crystals at a ratio of 1:1, and the coupling efficiency is 95%. *a*-cut plane-parallel polished conventional Nd:YAG rods are used as the gain media. These rods are wrapped with 0.05 mm thick indium foil, mounted in a copper micro-channel heat sink and maintained at 10 °C by water cooling; the low operating temperature depopulates the higher lying Stark levels of the Nd^{3+}-ions in the ground state. To prevent the more efficient four-level transitions at 1064 and 1340 nm, both sides of the laser crystals are not only coated for high transmission (HT) at 946 nm ($T > 99.8\%$) and 808 nm ($T > 99\%$), but also have antireflection coating (AR) at 1064 ($R < 2\%$) and 1340 nm ($R < 10\%$). The experiments are carried out with simple linear cavities with a cavity length of 25 mm, in which, due to the short length of the cavity, the influence of the thermal-lensing effect can be reduced. The plane input mirror M1 has AR coating at 808 nm and high-reflection (HR) coating at 946 nm ($R > 99.8\%$), M2 is highly transmitting at 1064 and 1340 nm, and is partially transmitting at 946 nm as an output mirror. The output power is recorded by laser power meters (PM30, Coherent Inc., America) and the laser intensity distribution is displayed by a laser beam analyzer (LBA-712PC-D, Spiricon Inc., America).

4. Experimental results and discussion

For the sake of improving the output power and efficiency of the quasi-three-level laser transition, the Nd^{3+}-doped concentration and length of the Nd:YAG crystals should be optimized. In the experiments, 0.3, 0.5 and 1.0 at.% doped-level Nd:YAG rods with lengths of 5 and 4 mm are used. In a plane-concave cavity with an output coupling mirror of T (transmissivity) $= 9\%$ at 946 nm and r (radius of curvature) $= 200$ mm, the laser performance of the three kinds of Nd:YAG rod is tested, and the results are shown in figure 4. For the 4 mm 1.0 at.% laser rod, the lasing threshold is the lowest for high absorption efficiency of the pump laser. The laser output power is highest at the beginning stage, but it is inclined to saturate at a pump power of 20 W. With the pump power increasing, the laser output power for the 4 mm 0.5 at.% rod exceeds that of the other two kinds of rod, and an 11.6 W laser can be achieved at an incident pump power of 47 W. Furthermore, a slope efficiency of 29.1% is estimated in the linear increasing region, which is also higher than those of the other two kinds of rod. However, the output laser is also saturated when the pump power exceeds 45 W, and the rod may rupture because the majority of the pump light is absorbed locally. The inhomogeneous absorption will limit the scaling of the pump power in the end-pumped structure. For the 5 mm 0.3 at.% crystal, although the output power is a little lower, it is not saturated when the pump power is up to 50 W, which indicates that it is favorable for high-power laser operation.

Further tests are conducted to estimate the best output coupling mirror for high-power laser operation. In the experiments, three kinds of concave mirror ($T = 9\%, r = 200$ mm; $T = 10.5\%, r = 200$ mm and $T = 12.6\%, r = 200$ mm) and one kind of plano mirror ($T = 9\%$) are used,

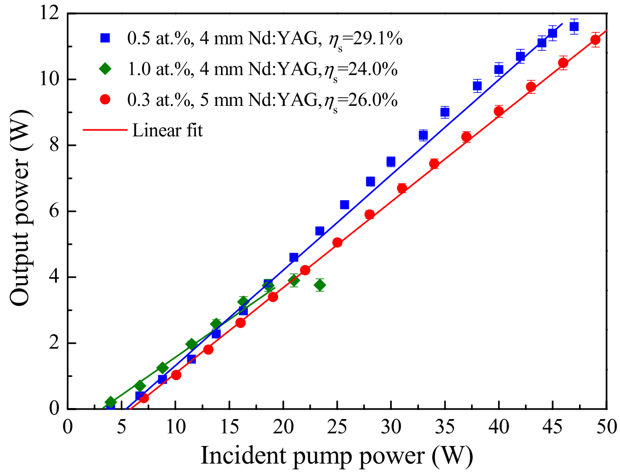

Figure 4. Output power versus incident pump power using different Nd:YAG crystals.

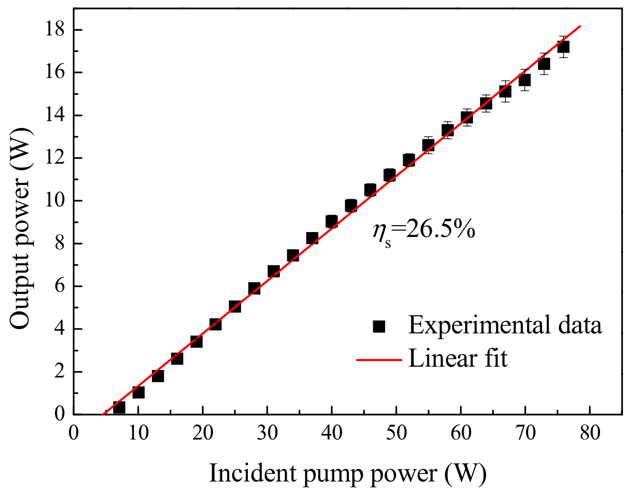

Figure 6. High-power 946 nm laser performance.

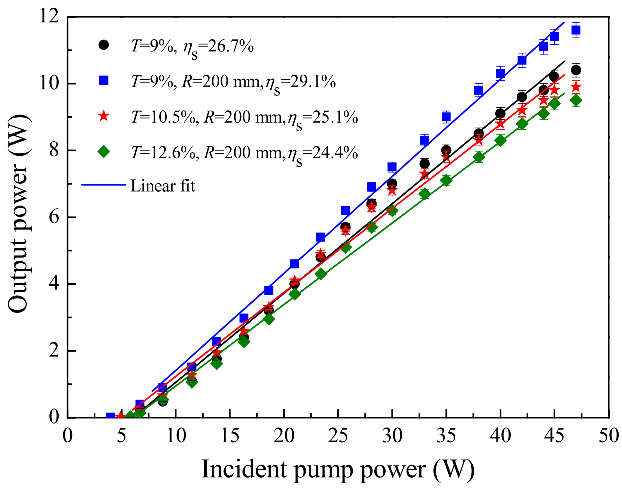

Figure 5. Output performance of the 946 nm laser using different output couplers.

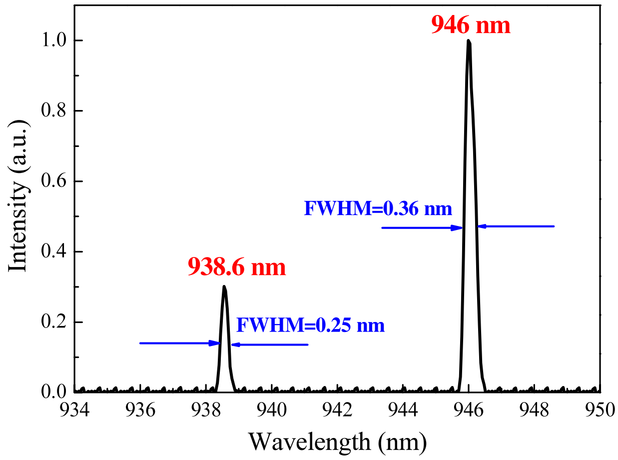

Figure 7. Output spectrum of the dual-wavelength Nd:YAG laser.

and the output laser performance is shown in figure 5. For the $T = 9\%$, $r = 200$ mm output mirror, the lasing threshold is the lowest, and the laser output power is the highest at the same pump power. Using the other three kinds of mirror, maximum output powers of 11.6 W ($T = 9\%$), 9.9 W ($T = 10.5\%$, $r = 200$ mm), and 9.5 W ($T = 12.6\%$, $r = 200$ mm) are obtained at an incident pump power of 47 W, corresponding to slope efficiencies of 26.7%, 25.1% and 24.4%.

Using the 5 mm-length 0.3 at.% Nd:YAG crystal and the $T = 9\%$, $r = 200$ mm output coupler, high-power cw quasi-three-level Nd:YAG laser operation is realized. Figure 6 shows that the laser operates like a four-level laser system and the output power increases linearly and efficiently. The maximum power of the 17.2 W laser is achieved at an incident pump power of 75.9 W, with a corresponding slope efficiency of 26.5%. In the spectrum of the laser emission shown in figure 7, laser oscillation is observed at two wavelengths of 946 and 938.6 nm, and the full wave at half maximum (FWHM) values are 0.36 nm and 0.25 nm, respectively. Additionally, the wavelength of 946 nm has a lower threshold and its intensity is always higher than that of the 938.6 nm emission.

A typical beam profile of the output laser at a power level of 17.0 W was measured with a laser beam analyzer (LBA-712PC-D, Spiricon Inc.) at about 30 mm distance from the output coupling mirror. 2D and 3D far-field intensity distributions for the laser beam are shown in figure 8. The beam radius was also measured by a traveling 90/10 knife-edge method. Figure 9 shows the measured beam radius at different distances from the lens. By fitting the standard Gaussian beam expression to these data, the beam quality and the far-field divergence angle are estimated to be $M^2 = 4.0$ and 6.13 mrad, respectively.

5. Conclusion

In summary, a high-power cw dual-wavelength Nd:YAG laser at 946 and 938.6 nm is demonstrated. By using a 5 mm-length conventional Nd:YAG crystal with a Nd^{3+}-doping concentration of 0.3 at.% and a concave output coupler with

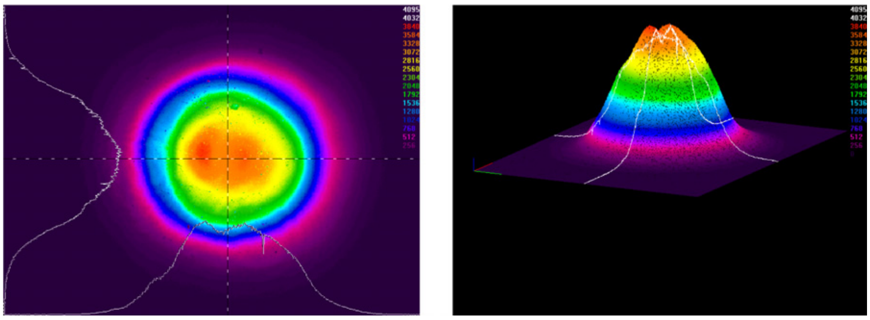

Figure 8. Profile of the high-power laser beam.

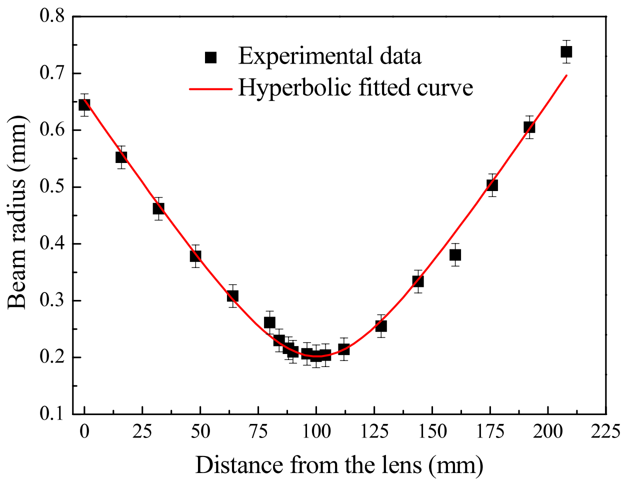

Figure 9. Beam quality and far-field divergence angle tests using the knife-edge method.

a transmissivity of 9%, an up to 17.2 W dual-wavelength laser at 946 and 938.6 nm is obtained at an incident pump power of 75.9 W, with a corresponding slope efficiency of 26.5%. To the best of our knowledge, this is the highest output power of a diode-pumped dual-wavelength quasi-three-level laser achieved by using a conventional Nd:YAG crystal. By using a traveling knife-edge method, the beam quality factor and far-field divergence angle at an output power of 17 W are estimated to be 4.0 and 6.13 mrad, respectively.

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