Generation of high power laser at 1314 nm from a diode-side-pumped Nd:YLF module

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We demonstrate a high power continuous-wave (CW) and acoustic-optically (AO) Q-switched 1314-nm laser with a diode-side-pumped Nd:YLF module. A maximum CW output power of 21.6 W is obtained with a diode pump power of 180 W, corresponding to an optical-to-optical conversion efficiency of 12.0% and a slope efficiency of 16.1%. In the Q-switching operation, a highest pulse energy of 3.8 mJ is obtained at a pulse repetition rate of 1 kHz. The shortest pulse width and maximum single peak power are 101.9 ns and 37.3 kW, respectively.

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High power 1.3-μm lasers are relatively safe to eyes and can transmit with the low dispersionand low-loss in silica fiber. Therefore, they have a wide range of applications, such as sensing, timing systems, communications, and monitoring techniques. Besides, they can also be used for the pump source of Raman lasers[1] and to generate red lasers by second harmonic generation process. As is well known, the transition between the levels of $^4F_{3/2}$ and $^4I_{13/2}$ in Nd^{3+} ions contribute to the generation of 1.3-μm lasers radiation[2−6].

Nd:YLF crystal is a natural birefringence material, capable of producing linearly polarized output with virtually no depolarization loss. It shows good qualities as a host material due to its superior thermo-optical characteristics, which is infavour of generating high quality output beam. Besides, compared with the fluorescence lifetime of the common Nd:YAG and Nd:YVO$_4$ crystals, the Nd:YLF crystal has longer fluorescence lifetime and thus the greater energy storage capability is expected[7,8]. Botha *et al.*[6] have experimentally demonstrated a 10-W 1314-nm diode-end-pumped Nd:YLF laser with a maximum pulse energy of 825 μJ. So Nd:YLF crystal is an attractive host material for Q-switched operation and laser amplifier applications. Some thermal and optical parameters of various Nd^{3+}-doped crystals are summed in Table 1[6,9−11], from which we can see that, the main 1.3-μm emission lines of Nd:YLF are located at 1321 nm for π-polarization and 1314 nm for σ-polarization. Moreover, due to the high thermal conductivity and low thermo-optical coefficient for σ-polarization laser operation, weak thermal lensing effect is observed under lasing operation. In addition, for the Nd:YLF crystal, the refractive index decreases with the increase of temperature, which leads to a negative thermal lensing effect and can be partly compensated by a positive lens due to expansion of the material. Therefore, high energy 1.3-μm Nd:YLF Q-switched laser operating at the σ-polarization has attracted a lot.

In this letter, we demonstrate a high-power diode-side-pumped a-cut Nd:YLF lasers operating at 1314 nm in both continuous-wave (CW) and acoustic-optically (AO) Q-switching regimes. A 21.6-W CW output power is obtained with an optical conversion efficiency of 12.0% and a slope efficiency of 16.1%. For AO Q-switching operation, the obtained highest pulse energy and shortest pulse width are 3.8 mJ and 101.9 ns, respectively. The results verify that the diode-side pumped Nd:YLF module is an advantageous method to obtain high power and high energy 1.3-μm laser output.

Table 1. Optical Parameters and Thermal Conductivities of Various Nd^{3+}-doped Crystals at 1.3 μm

Crystal	Nd:YLF$^{a)}$	Nd:YAG$^{b)}$	Nd:YVO$_4$$^{c)}$	Nd:YAP$^{d)}$
Wavelength (nm)	1321 (π) 1314(σ)	1338/1319	1342	1341
Stimulated Emission Cross Section (10^{-19}cm^2)	0.2−0.25	1.0/0.95$^{c)}$	6	2.2
Fluorescence Lifetime (μs)	480	230	100	180
Thermal Conductivity (Wm^{-1}K^{-1}@300 K)	5.8 (π) 7.2 (σ)	12	5.2	11
dN/dT(10^{-6} K^{-1}@300 K)	−4.3 (π) -2.0 (σ)	8.3	8.5 (π) 2.9 (σ)	9.7 (π)14.5 (σ)
Expansion Coeff. (10^{-6} K^{-1}@300 K)	8 (π) 13 (σ)	5.8	4.43 (π) 11.37(σ)	9.5 (π) 10.8 (σ)

$^{a),b),c),d)}$Taken from Refs. [6,9-11], respectively.

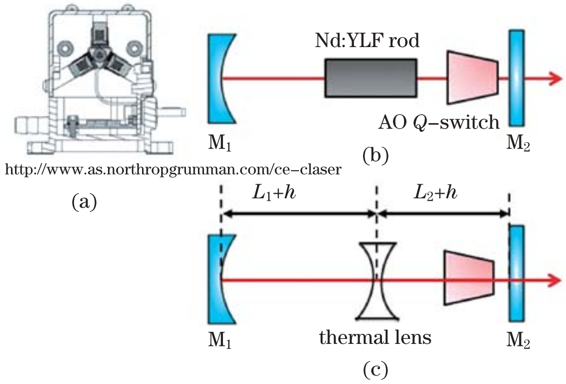

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Fig. 1. (Color online) (a) Scheme of diode-side-pumped Nd:YLF rod system; (b) experimental arrangement of the diode-side-pumped Nd:YLF laser; (c) equivalent laser resonator. M_1, M_2: laser mirrors; h: the distance between the rod end and the principle axis, where $h = L/2n_0$ (L is the length of the rod, and n_0 is the refractive index of Nd:YLF crystal).

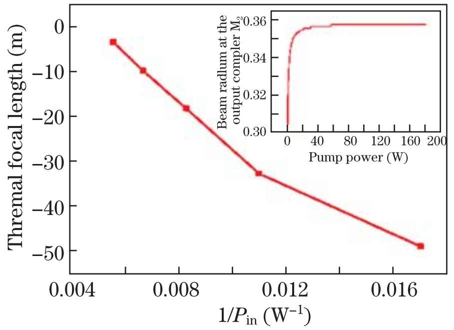

Fig. 2. (Color online) Relationship between thermal focal length and pump power. The inset shows the relationship between the beam radius on the output coupler and the pump power.

The experimental arrangement is shown schematically in Fig. 1. Longitudinal pumping geometries can provide optimal mode matching, which leads to high efficiency and high beam quality. But it restricts the pump power due to the risk of thermal fracture (the tensile strength for Nd:YLF is as low as 33 MPa[12]). Therefore, we used a side-pumping configuration for scaling the output power. As is shown in Fig. 1, a 63-mm-long a-cut Nd:YLFrod with 3 mm in diameter was side-pumped by nine diode arrays, which emitted an available maximum output power of approximately 180 W at 796 nm. The transfer coupling efficiency of the total pump system was about 90%. The pump chamber with diffuse reflector was used to improve the pumping uniformity. The Nd:YLF rod was placed in a flow tube with direct water cooling at temperature of 18 °C. M_1 was a concave mirror with radius of 800 mm and high reflectivity coated at 1.31 μm (HR@1.31 μm R >99.9%) on the inside surface. M_2 was a flat mirror with transmissions of 3%, 8%, and 15% at 1.31 μm, functioning as the output couplers. Moreover, all the mirrors used were high-transmission (HT) coated (T >95%@1.05 μm) to suppress the oscillation of 1.05 μm in the resonator. The AO Q-switch (NEOS) was antireflection coated at 1.31 μm on both crystal surfaces and driven by a radio freuency power of 50 W at a center frequency of 27 MHz. The laser pulse signal is recorded by a Tektronix DPO7104 digital oscilloscope (1-GHz bandwidth, 5-Gs/s sampling rate) and a photo-detector (1623, New Focus, USA). The average output power was measured by a laser power meter (Field-max II, Coherent, USA).

Due to the larger quantum defect as well as the stronger excited state absorption, the thermal lens effect of the diode-pumped Nd-doped lasers at 1.3 μm is stronger than that at 1.05 μm. Using the method mentioned in Ref. [13], we firstly measured the thermal focal length of the 1.3-μm Nd:YLF laser with the polarization of 632.8-nm He-Ne probe light along the a-axis of Nd:YLF crystal. The results are shown in Fig. 2, where the thermal focal length was minus for the negative dn/dT of Nd:YLF crystal. The relationship between thermal focal length and pump power was fitted to be $f_{\rm th}$=16.24−3977.47/$P_{\rm in}$. We used the ABCD ray transfer matrix to investigate beam radius at the position of M_2 with cavity length of 170 mm (L_1 = 70 mm and L_2 = 50 mm). In the numerical model, the Nd:YLF rod was treated as a thin lens sandwiched between two free-spaces that were fixed in Refs. [14,15]. According to the measured thermal lensing focal length, the variation of the beam radius on the output coupler versus the pump power for the cavity was explored as shown in the inset figure in Fig. 2. As can be seen, the beam radius on the output coupler M_2 was insensitive to the thermal lens effect at the pump powers ranging from 10 to 180 W.

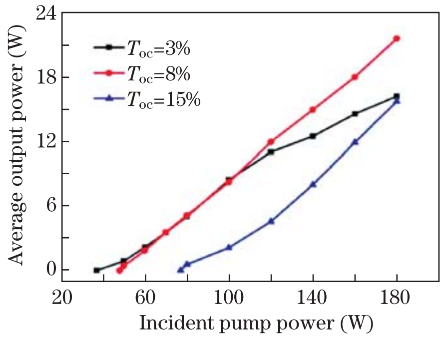

Fig. 3. (Color online) Relationship between the CW output power and the incident pump power for different output couplers used.

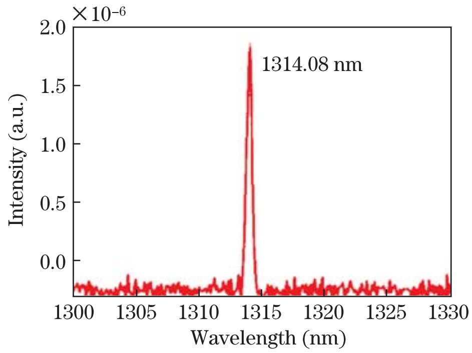

Fig. 4. (Color online) Laser output wavelength of a-cut Nd:YLF laser in our experiment.

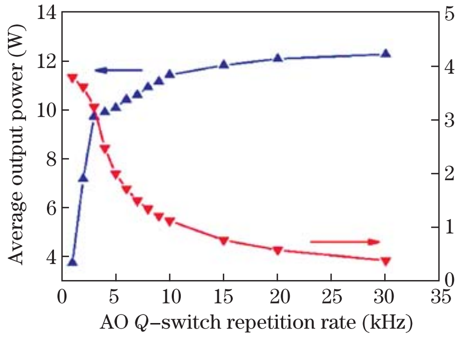

Fig. 5. (Color online) Average output and single pulse energy versus the repetition rate in the range of 1-30 kHz.

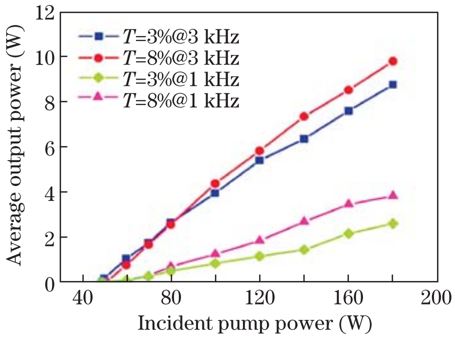

Fig. 6. (Color online) Relationship between the average output power and pump power at the repetition rate of 1 and 3 kHz.

The relationship between the CW output power and the pump power is shown in Fig. 3. The pump thresholds were 37.2, 48.5, and 77 W, respectively, for output couplers of T=3%, 8%, and 15%. By fitting the formula $-\ln(R)= 2KP_{\rm th} - L$, where R is the reflectivity of the output coupler, $P_{\rm th}$ is the pump threshold, L is the roundtrip optical loss of the resonator, and K is the constant[16], a roundtrip intrinsic loss of about 0.084 was obtained. The highest output power of 21.6 W was obtained with the output coupler of T=8%, corresponding to the optical-to-optical conversion efficiency and slop efficiency of 12.0% and 16.1%, respectively. The CW output power increased almost linearly with the augment of the pump power, and no saturation appeared. However, when T=3% output coupler was used, the output power presented saturation trend due to the high intra-cavity power intensity under the high pump power. The laser output wavelength was measured and shown in Fig. 4. The measured spectrum indicates that the output laser was purely σ polarization at 1314 nm, which was similar to Ref. [6]. We attribute this to the dominant gain of the σ polarization than π polarization laser, as well as the much stronger negative thermal lens associated with π polarization, which might make the oscillator being unstable.

In the Q-switched regime, the output power and pulse width at different repletion rates were measured with the output coupler of T=8% under the maximum pump power of 180 W, and the results are shown in Fig. 5. The average output power increased with the augment of the repetition rates. The variation trend was abrupt (from 1 to 3 kHz) and then became slow (from 4 to 30 kHz). The maximum output power was 12.3 W at the repetition rate of 30 kHz and decreased to 3.8 W at 1 kHz. Obviously, the single pulse energy underwent a reverse trend. The highest single pulse energy was determined to be 3.8 mJ.

With the output couplers of T=3% and 8%, the average output powers at the repetition rates of 1 and 3 kHz were measured and shown in Fig. 6, respectively. At the two different repetition rates, the pump power thresholds of Q-switched lasers were about 49.2 W for T=3% and 51 W for T=8%, which were independent on the repetition rates. The maximum average output power of 9.75 W was obtained with T=8% under the pump power of 180 W, corresponding to an optical conversion efficiency of 5.42% and a slop efficiency of 7.65%.

Figure 7 shows the laser pulse width and the pulse peak power characteristics at different repetition rates under the maximum pump power. With the augment of the repetition rate, the pulse width became longer and the pulse peak power decreased. At the repetition rate of 1 kHz, the shortest pulse width of 101.9 ns and maximum pulse peak power of 37.3 kW were obtained. Figure 8 shows the temporal profile of the shortest pulse. The beam quality factor M^2 was measured to be 17.8 by using the knife-edge method. In the Q-switching regime, the laser output wavelength was measured, to be also 1 314 nm.

In conclusion, a diode side-pumped CW and AO Q-switched Nd:YLF laser operating at 1314 nm is reported. In the CW regime, the maximum output power reaches 21.6 W with an optical conversion efficiency of 12% and a slope efficiency of 16.1%. In active Q-switching regime, the maximum output power of 9.75 W is obtained at the repetition rate of 3 kHz. The

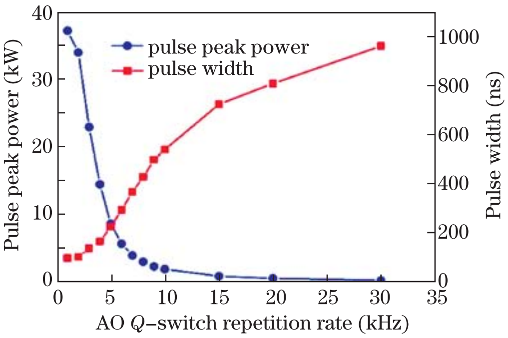

Fig. 7. (Color online) Average output pulse peak powers and pulse width versus the repetition rates in the range of 1−30 kHz.

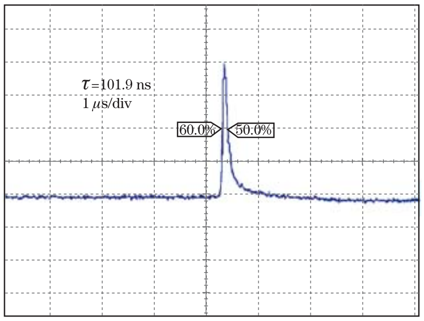

Fig. 8. (Color online) Profile of the shortest laser pulse.

highest single pulse energy of 3.8 mJ is obtained with the output coupler of T=8% at the repetition rate of 1 kHz, corresponding to the shortest pulse width of 101.9 ns and the largest pulse peak power of 37.3 kW. The results further verify that Nd:YLF crystal is one of the promising laser media around 1.3 μm and the diode-side pumped Nd:YLF laser is an advantageous method to obtained high-power 1.3-μm radiations.

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