1645 nm Q-switched Er:YAG laser with in-band diode pumping

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ABSTRACT

In this work, resonant diode pumping has been demonstrated for Q-switched and CW Er:YAG solid state lasers (SSLs) at eye-safe wavelengths. Resonant pumping was realized by using high spectral brightness 1470 nm laser diodes. An efficient 1645 nm CW laser with output power >5 W in the TEM_{00} mode was demonstrated. Total optical-to-optical efficiency was >19%. More than 11 mJ of output pulse energy and an output peak power of ~400 kW have been achieved in the TEM_{00} mode for Q-switched operation.

Keywords: Er:YAG, diode-pumped, Q-switched lasers, solid-state lasers.

1. INTRODUCTION

Growing interest in high pulse energy and high peak power lasers in the eye-safe spectral domain has instigated new activity in developing solid-state lasers (SSLs) based on Er^{3+}-doped materials. The resonant pumping of SSLs allows for shifting a significant portion of the system thermal load from the gain medium to the pump diodes, thus greatly reducing gain medium thermal distortions deleterious to SSL power scaling with high beam quality. Er^{3+}:YAG has good mechanical, thermal, and thermo-optic properties and is one of the most attractive active materials for developing ~1.6-μm eye-safe SSLs. 1470 nm and 1530 nm resonant pumping bands provide a low quantum defect for these 1645 nm SSLs. However, their absorption lines have a narrow spectral width, which requires a pumping source with high spectral brightness.

Significant recent progress has been made in the development of resonantly-pumped CW Er:YAG SSLs with Er-fiber laser pumping as well as direct diode pumping [1-5]. However, most investigations of Q-switched Er:YAG SSLs have been connected with hybrid lasers, where a fiber laser was utilized as the pumping source [6-7]. In contrast, our efforts have been focused on the development of efficient high peak power Q-switched SSLs with direct laser diode pumping.

2. EXPERIMENT

A 40 mm 0.5% Er:YAG rod was used in our experiments, with the low doping level chosen to minimize Er^{3+} upconversion losses [8]. The rod was mounted to a TEC-cooled copper heatsink, and all measurements were conducted with a heatsink temperature of 15°C. The two sides of the rod were polished and had antireflective coatings ($R < 0.2\%$ at 1645 nm and $R < 1\%$ at 1470 nm).

We used an end pumping geometry for the SSL. The laser cavity comprised two mirrors: a dichroic mirror (>99.8% at 1645nm and <5% at 1470nm) and an output coupler mirror with $T = 25\%$. The total cavity length was 160 mm. An acousto-optic modulator (AOM) was used for Q-switched operation.

Our 1470 nm in-band pump source was built by spatially combining ten individual emitters. Pump power was >30 W in CW operation and >40 W in quasi-CW operation (Fig. 1). The size of the pump beam was less than 10 mm x 7 mm with a divergence of 4 mrad x 3 mrad.

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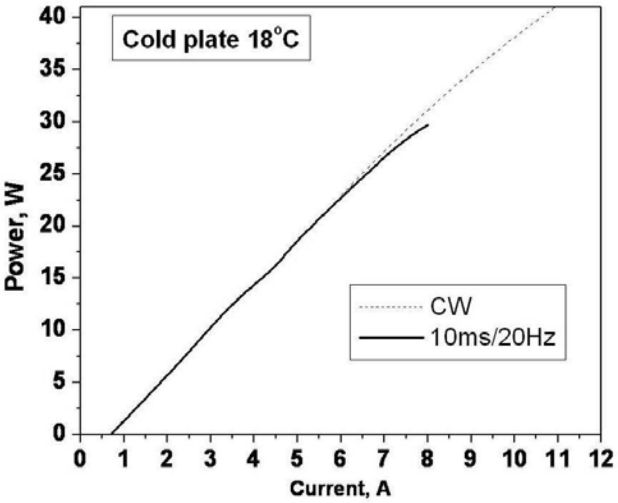

Fig. 1. Dependence of output power on current of 1470 nm pumping source

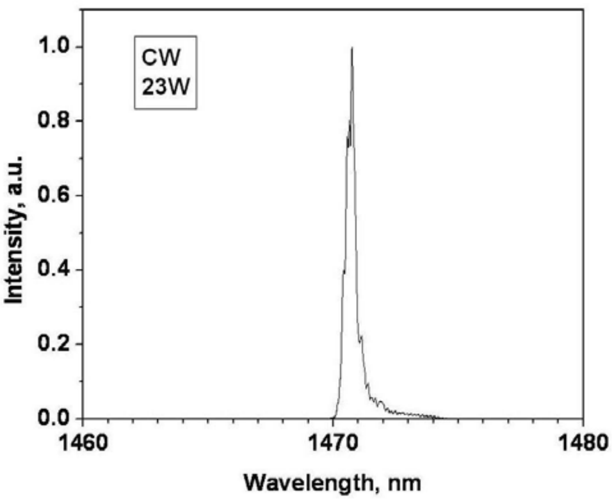

Fig. 2. Spectrum of pumping source at 23 W of output power.

Two cylindrical lenses were used to launch pump radiation into the rod through the dichroic mirror. This optical solution provided a pump beam waist with a diameter of less than 1 mm at a 25 mm distance inside the rod. The calculated mode size in the rod was 0.7 - 0.9 mm. The calculation was made by using the ABCD-matrix method while taking into account the thermo-lensing effect. Therefore, the overlap between the pump and laser modes can be estimated to be 0.5 - 0.8.

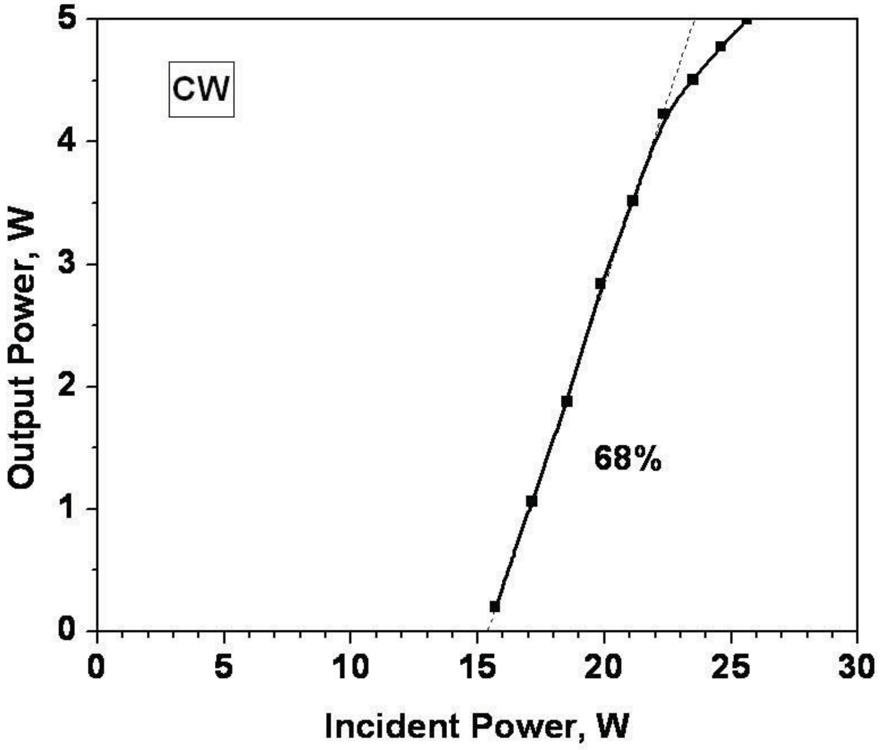

Fig. 3. Dependence of output power on incident power for SSL in CW operation.

High spectral brightness of the pump source (Fig. 2) was obtained by utilizing volumetric Bragg gratings [9]. The resulting spectral width was less than 0.5 nm, and the spectral position was about 1470 nm for this source. Although the use of 1470 nm pump sources results in higher a quantum defect compared to 1532 nm pump sources, the shorter wavelength 1470 nm pump has several advantages in practical applications. First, producing dichroic mirrors for high energy operation at this wavelength is significant easier. Second, the 1470 nm absorption line is wider than the 1532 nm line, thus allowing for spectral stabilization elements with relaxed requirements for spectral position precision and spectral width.

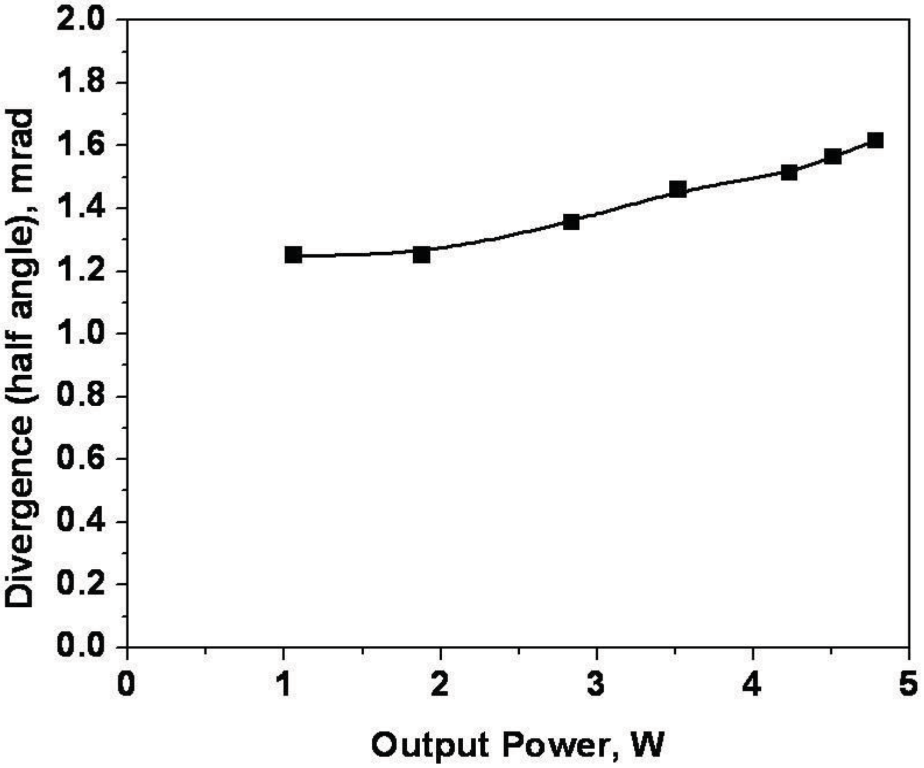

Fig. 4. Dependence of output beam divergence (1/e^2 level, half-angle) on output power for CW SSL laser.

3. RESULTS AND DISCUSSION

The SSL developed in this study exhibited good performance in TEM$_{00}$ mode CW operation even with the inclusion of the acousto-optic modulator. The dependence of output power on incident power for an output coupler transmission of T = 25% is shown in Fig. 3. It should be noted that this output coupler transmission is not optimal for CW operation, but a high transmission value is important for Q-switched operation to decrease the risk of optical component due to excessively high energy density inside the cavity.

The SSL demonstrated an optical-to-optical slope efficiency >68% up to an output power level of 4 W. The total optical-to-optical efficiency (taking threshold power into account) was >19% at an output power of ~5 W. Divergence of the output beam (1/e^2 level, half-angle) versus the output power for the CW SSL laser is demonstrated in Fig. 4. The dependence of the divergence on output power is fairly flat, and divergence is <1.6 mrad at all power levels. We used the Rayleigh method to measure the M^2 parameter, which was found to be <1.1 at 4.0 W. This value is in good agreement with the calculated laser mode in the cavity found while taking account of thermo-lensing in the rod.

Good performance of the SSL in CW operation is generally correlated with the potential for good results in Q-switched regime.

The pulse energy E_{pulse} in Q-switched operation can be approximated by the equation

$$E_{pulse} \sim (1-\exp(-t_a/t_s)) \qquad (1)$$

where t_a is the accumulation time and t_s is the storage time (i.e., the lifetime of the laser upper level). Storage time t_s at very low excitation levels is about 6 – 8 ms for Er:YAG, and t_s is several times smaller at excitation levels required for laser operation because of processes such as up-conversion and amplified stimulated emission. The storage time, estimated in previous investigations [7, 10] to be ~2.2 ms, is indeed several times less than the lifetime of the upper laser level at low excitations. This means that the most efficient operation (where average power in Q-switch mode is close to CW mode) can be reached with an accumulation time less than 2 ms. Additionally, we have concluded previously [10] that the optimal accumulation time for reaching the highest pulse energy is ~5 ms.

Initial tests of Q-switched operation of the SSL were conducted with quasi-CW pumping. This type of pumping has several advantages if high pulse repetition rate is not needed for the application being considered. First, it does not create a high heat load for the pumping source and active medium. Second, the average power consumption of the system can be significantly lower than that for CW operation and enables an affordable, portable, battery-powered solution.

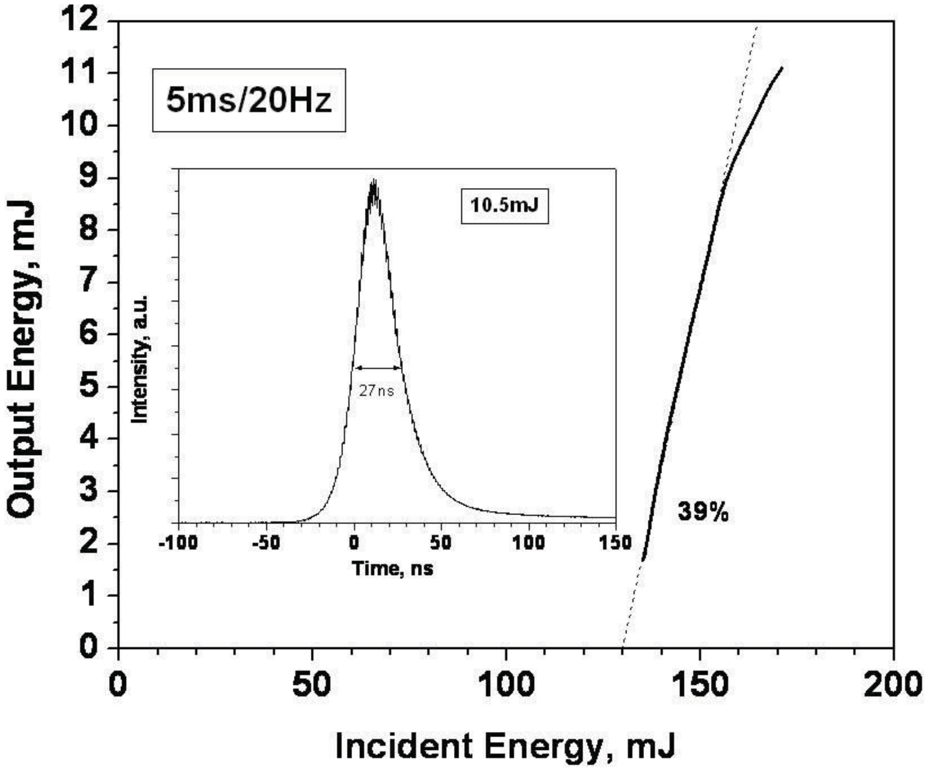

Fig. 5. Output pulse energy versus incident energy with quasi-CW pumping at 5 ms/20 Hz. Insert: pulse shape at 10.5 mJ.

An accumulation time of 5 ms was selected for high energy pulse operation. A 10 – 20 Hz repetition rate is typical of many range-finder sources, so we selected 5 ms/20 Hz quasi-CW pumping for our experiments. The dependence of output pulse energy on incident energy with 5 ms/20 Hz quasi-CW pumping is shown in Fig. 5. The dependence is essentially linear up to 8.5 mJ output, and the observed optical-to-optical slope efficiency is about 39% in this linear range. The slight decrease of slope efficiency observed after 8.5 mJ is caused by thermal effects. The maximum output pulse energy was >11 mJ at 175 mJ incident energy. Therefore, we obtained 11 mJ/20 Hz operation at ~3.5 W average pump power.

The pulse shape at 10.5 mJ output energy is demonstrated in the insert of Fig. 5, which exhibits a pulse width of about 27 ns. Therefore, the peak power was ~400 kW. The measured divergence (1/e^2 level, half-angle) at 11 mJ was <2.2 mrad, and the M^2 parameter was <1.5.

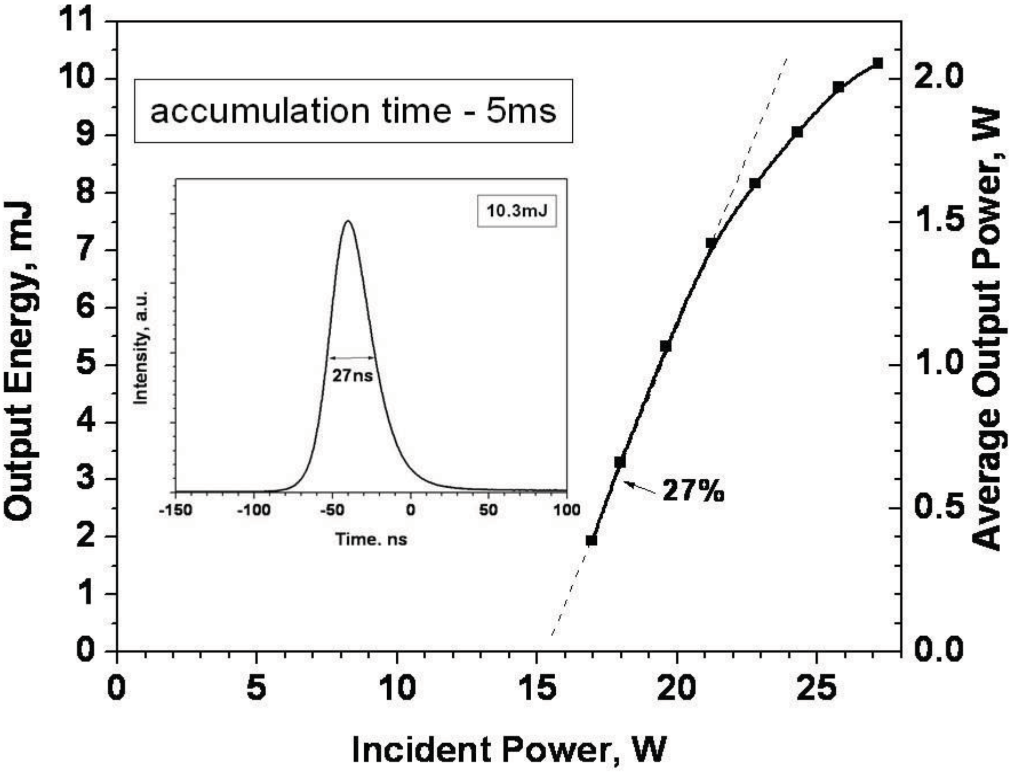

Fig. 6. Output pulse energy versus incident power with CW pumping and an accumulation time of 5 ms. Insert: pulse shape at 10.3 mJ.

In addition to quasi-CW pumpting, the Q-switched SSL was also tested with CW pumping. We used the same 5 ms accumulation time as for the quasi-CW pumping case. Results are shown in Fig. 6. Despite a much higher thermal load, the performance of the Q-switched SSL with CW pumping was close to that observed with quasi-CW pumping. The maximum output pulse energy was >10.5 mJ, which corresponds >390 kW of peak power with a pulse width <27 ns (see insert in Fig. 6). The divergence dependence on output energy had a behavior similar to that shown in Fig. 4 but was somewhat higher by ~0.5 mrad. Therefore, M^2 can be estimated to be <1.5. The dependence of average output power versus incident power was similar to what we observed for CW SSL operation, but optical-to-optical efficiency was ~2.5 times lower. Although a lower slope efficiency induces this decrease for CW pumping total, the optical-to-optical efficiency is still reasonably high, with a value of ~7.6% at pulse energies >10 mJ.

Lower performance in comparison with quasi-CW SSL was expected because the effective storage time for 0.5% Er:YAG media is ~2 – 3 ms. The dependences of output pulse energy and average power on accumulation time shown in Fig. 7 support this estimation of effective storage time. Average power increases with decreasing accumulation time, and average power at a 1 ms accumulation time is only 1.4 times less than the power observed with CW operation. Fitting of the dependence of output pulse energy on accumulation time by Eq. (1) for values up to 5 ms gives a storage time of ~2.9 ms.

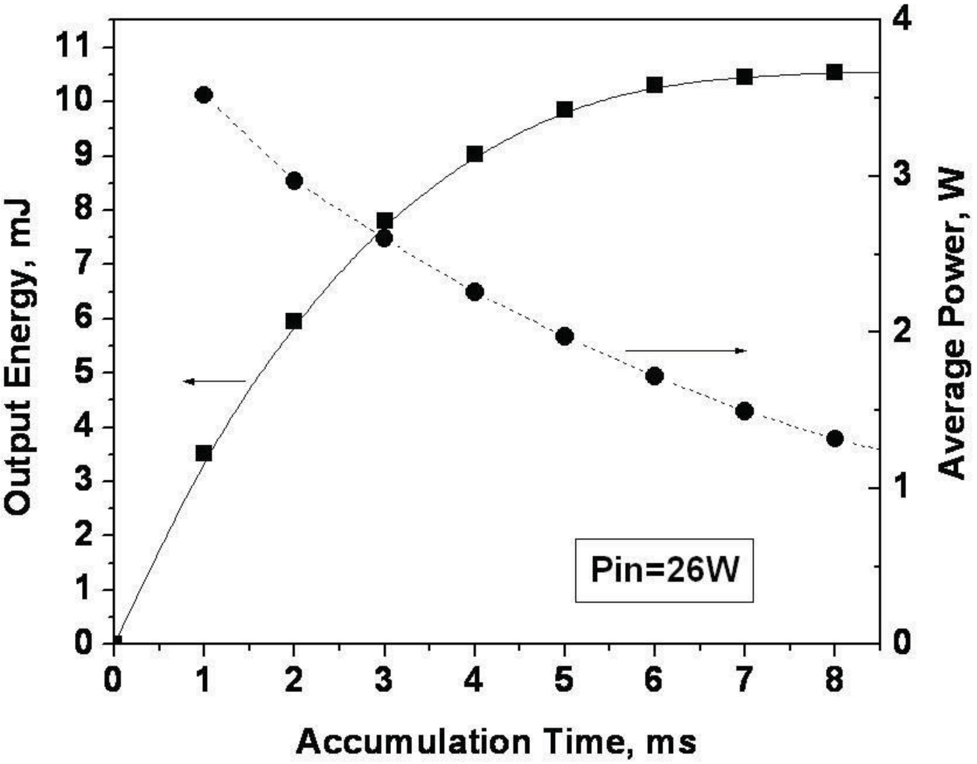

Fig. 7. Output energy and average power of Q-switched SSL at 26 W CW pumping versus accumulation time.

4. CONCLUSION

In this work, resonant diode pumping has been demonstrated for Q-switched and CW Er: YAG solid state lasers emitting at an eye-safe wavelength. Resonant pumping was realized by using high spectral brightness 1470 nm laser diodes. 1645 nm CW laser output with an optical-to-optical efficiency of ~68% was demonstrated, and an output power of >5 W in the TEM_{00} mode has been achieved. The output beam had an M^2 parameter better than 1.1 over the entire range of output powers used. More than 11 mJ of output pulse energy in the TEM_{00} mode was demonstrated for Q-switched operation with quasi-CW 20 Hz repetition rate pumping, and under comparable conditions, 10.5 mJ pulse energy was obtained with CW pumping. M^2 of the output beam was better than 1.5 over the entire range of output pulse energies, and an output peak power of ~400 kW was reached.

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