Q-switched resonantly diode-pumped Er:YAG laser

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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 >3.5 W in the TEM_{00} mode was demonstrated. More than 11 mJ of output pulse energy in the TEM_{00} mode has been achieved for Q-switched operation at 20Hz repetition rate. M^2 of the output beam was better than 1.5 over the entire range of output pulse energies. We achieved an output peak power of ~400 kW.

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 initiated a new wave of 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 the 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. A schematic of the CW and quasi-CW pumped Er^{3+}:YAG laser setup is shown in Fig. 1. Figure 1a demonstrates pump ray-tracing results in one plane. Figure 1b demonstrates pump ray-tracing results in the perpendicular plane. The laser cavity comprised two flat mirrors M1 (>99.8% at 1645nm) and M2 (output coupler), and the total cavity length was 160 mm. Mirror M1 was a dichroic mirror. An acousto-optic modulator (AOM) was used for Q-switched operation. Output couplers with reflectivities of 93% and 85% were used for these experiments. Our pump source was built by spatially combining twelve individual emitters.

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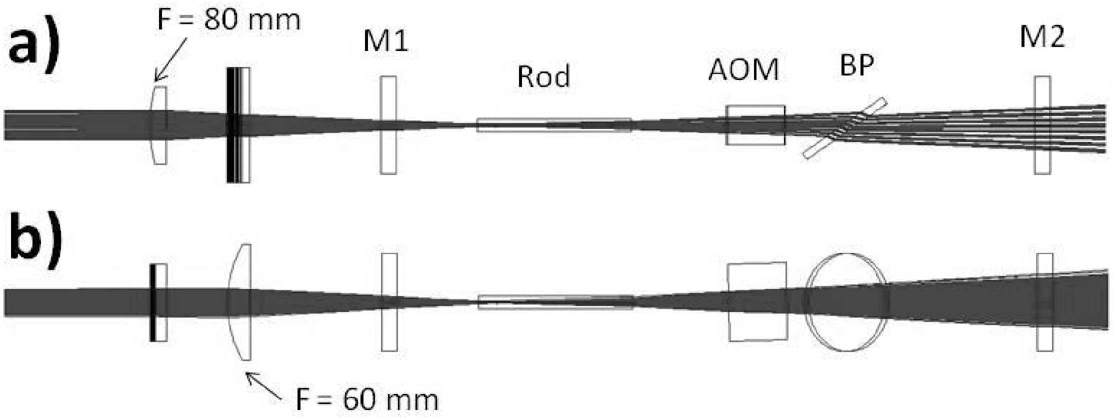

Fig. 1. Schematic view of the Er:YAG SSL. (a) pump ray-tracing in the plane of setup; (b) pump ray-tracing in the plane perpendicular to the setup.

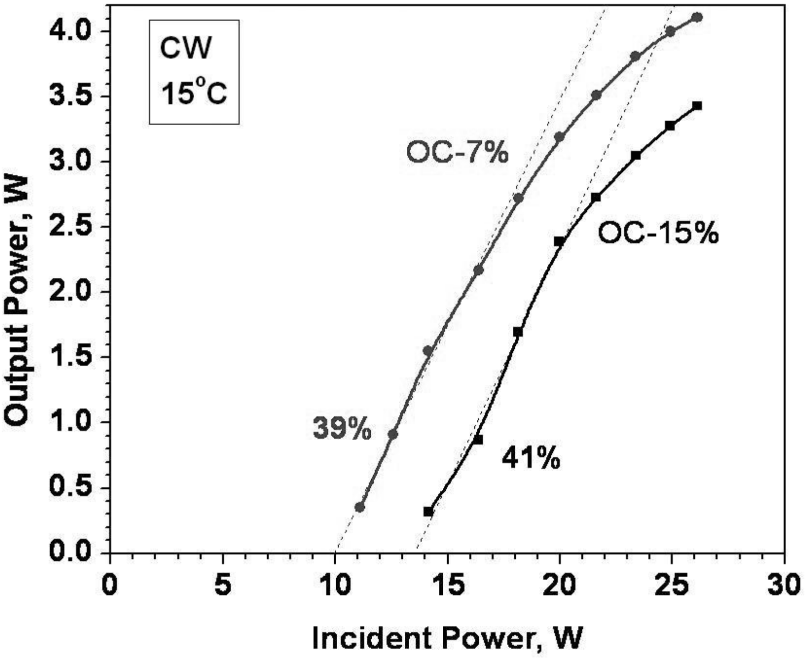

Fig. 2. Dependence of output power on incident power for SSL at CW operation for two output couplers (T=7% and T=15%).

Pump power was >30W in CW operation and >40W in quasi-CW operation. The size of the pump beam was less than 10 mm x 7 mm with a divergence of 4 mrad x 3 mrad. Two cylindrical lenses with focal lengths of 80 mm and 60 mm were used to launch pump radiation into the rod through the dichroic mirror M1. 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 - 0.81 mm. The calculation was made by using the ABCD-matrix method while taking in account the thermo-lensing effect. Therefore, the overlap between the pump and laser modes can be estimated to be 0.5 - 0.65. High spectral brightness of the pump source 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.

The use of 1470 nm pump sources results in higher quantum defect compared to 1532 nm pump sources. However, 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 1470nm 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.

3. RESULTS AND DISCUSSION

Initially, we characterized the performance of the SSL in CW operation with all optical elements shown on Fig. 1. Results for two output couplers (T=7% and T=15%) are shown on Fig. 2. We observed an equivalent slope efficiency of 39 – 41% up to 2.5 W of output power for both output couplers. The CW SSL exhibits more than 3.5 W output power in TEM_{00} mode. Divergence of the output beam (1/e^2 level, half-angle) versus the output power for the SSL laser with the T=15% output coupler is demonstrated in Fig. 3.

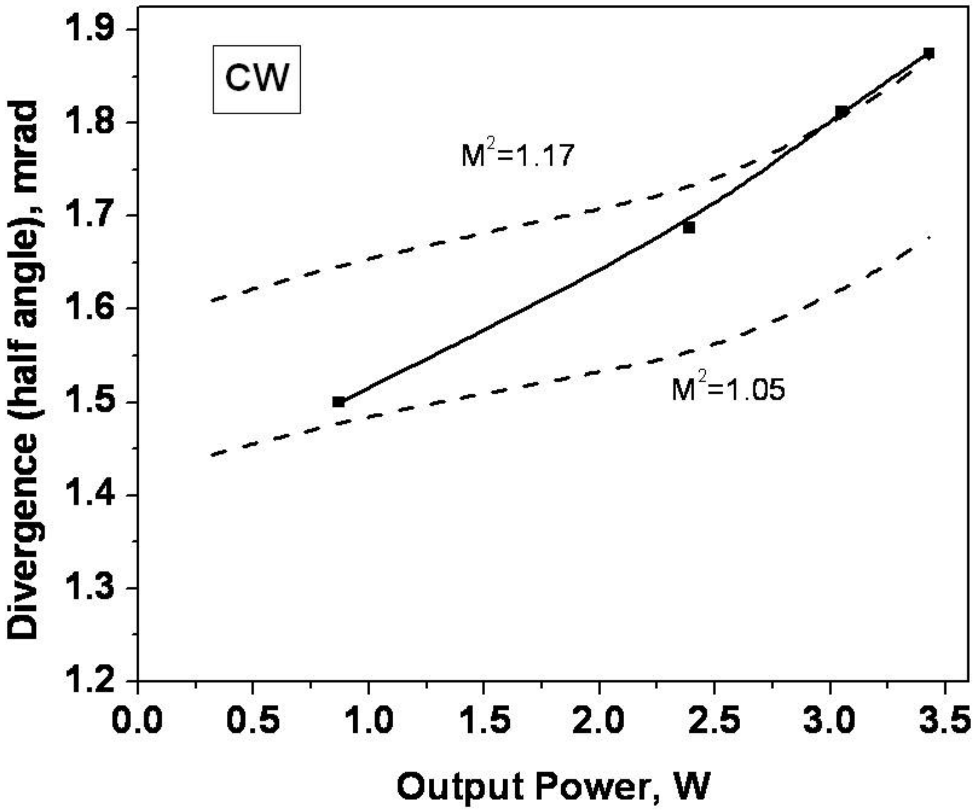

Fig. 3. Dependences of output beam divergence (1/e^2 level, half-angle) on output power for CW SSL laser with output coupler T=15%. The solid curve illustrates experimental data, and dashed curves show calculated results for $M^2 = 1.05$ and $M^2 = 1.17$

We used the Rayleigh method to measure the M^2 parameter, which was found to be ~1.17 at 3.5 W. This value was in good agreement with the calculated laser mode in the cavity found using the ABCD-matrix method while taking account of thermo-lensing in the rod. Calculated dependences of divergence versus output power for output beams with M^2 of 1.05 and 1.17 are shown on Fig. 3 (dashed curves). As seen from Fig. 2, degradation of CW SSL performance is observed for incident power levels >20 W. This degradation can be attributed to two factors. First, the thermo-lensing effect leads to a decrease in the overlap between laser and pumping modes. Second, the increase of the temperature of the rod causes an increase in the population of the laser terminal level.

An output coupler with T=15% was used in Q-switched operation to avoid damaging optical components inside the cavity. Such factors as optical losses, overlapping between laser and pumping modes, and the temperature of the active medium—which determine performance of the SSL in CW operation—also impact the performance of Q-switched operation. However, an additional important parameter plays a significant role in Q-switched operation: the accumulation time (t_a), or time between output pulses with CW pumping.

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

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

where t_a is the accumulation time and t_s is the storage time (i.e., lifetime of the laser upper level). Storage time at very low excitation levels is about 6 – 8 ms for Er:YAG and is several times smaller at excitation levels required for laser operation because of the impact of processes such as up-conversion and amplified stimulated emission. Direct estimation of the storage time can be made from the dependence of the output energy on accumulation time. Experimental dependences of pulse energy on accumulation time for our SSL at two different levels of incident power are shown in Fig. 4. Both dependences had similar behavior, with an increase of output pulse energy up to ~5 ms and a slight decline after ~7 ms.

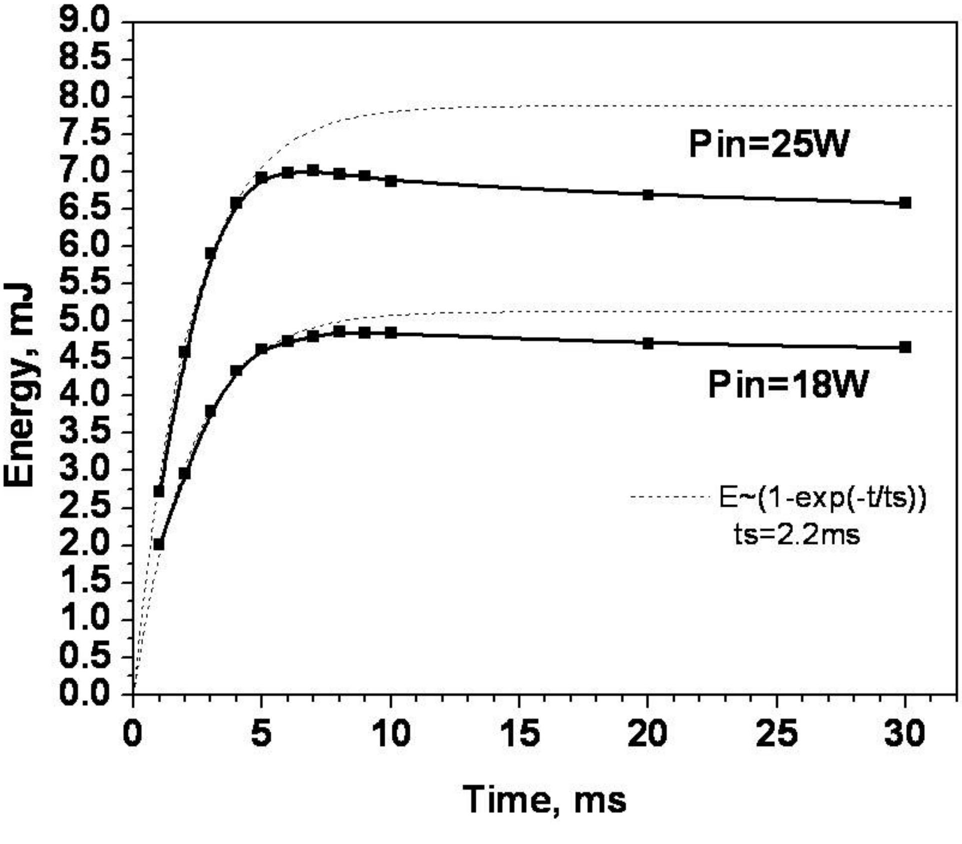

Fig. 4. The dependence of Q-switched SSL output pulse energy with CW pumping versus accumulation time for two incident powers: 18W and 25W. Solid curves illustrate experimental data, and dashed curves indicate fitting by $E = A\times(1-\exp(-t/t_s))$.

The fitting of experimental curves was obtained using Eq. (1) in the limit of small accumulation times, where the thermal impact on performance of Q-switched SSLs is close to that of CW SSLs. The storage time, estimated from these fittings 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. Also, we can conclude that the optimal accumulation time for reaching the highest pulse energy is ~5 ms.

The dependence of output pulse energy on incident power for a SSL in Q-switched mode with 5 ms accumulation time is shown in Fig. 5. A maximum output energy of >7 mJ was reached at an incident power of 26 W. The pulse width at 7 mJ was ~35 ns; see insert of Fig. 7 for the pulse shape. Therefore, the peak output power was ~200 kW. We observed a degradation in performance beyond an incident power of ~18W. This finding is in agreement with our observation for CW operation, where a drop in slope efficiency occurred for incident power beyond ~20W, or ~20 W - 2.5 W = 17.5 W power dissipated in the active medium. Therefore, thermal effects have a strong impact on the performance of the Q-switched SSL for incident powers larger than 18 W.

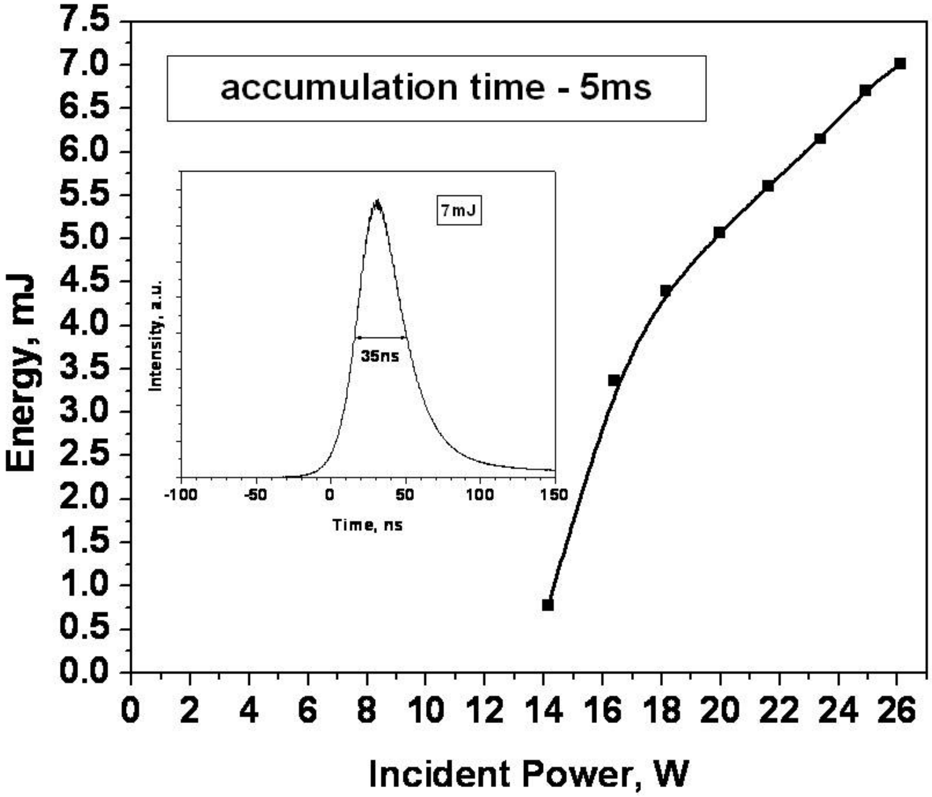

Fig. 5. Output pulse energy versus incident power at CW pumping and accumulation time 5 ms. Insert: pulse shape at 7 mJ.

The dependence of divergence (1/e^2 level, half-angle) on output pulse energy is demonstrated in Fig. 6. The divergence was higher than we observed in CW mode. The output beam had a divergence of ~2.5 mrad (compare to 1.87 at the same incident power in CW) at 7 mJ caused by the higher M^2 parameter in Q-switched mode. Therefore, the measured M^2 parameter at 7 mJ and 26 W incident power was 1.5 instead of 1.17 at the same level of incident power.

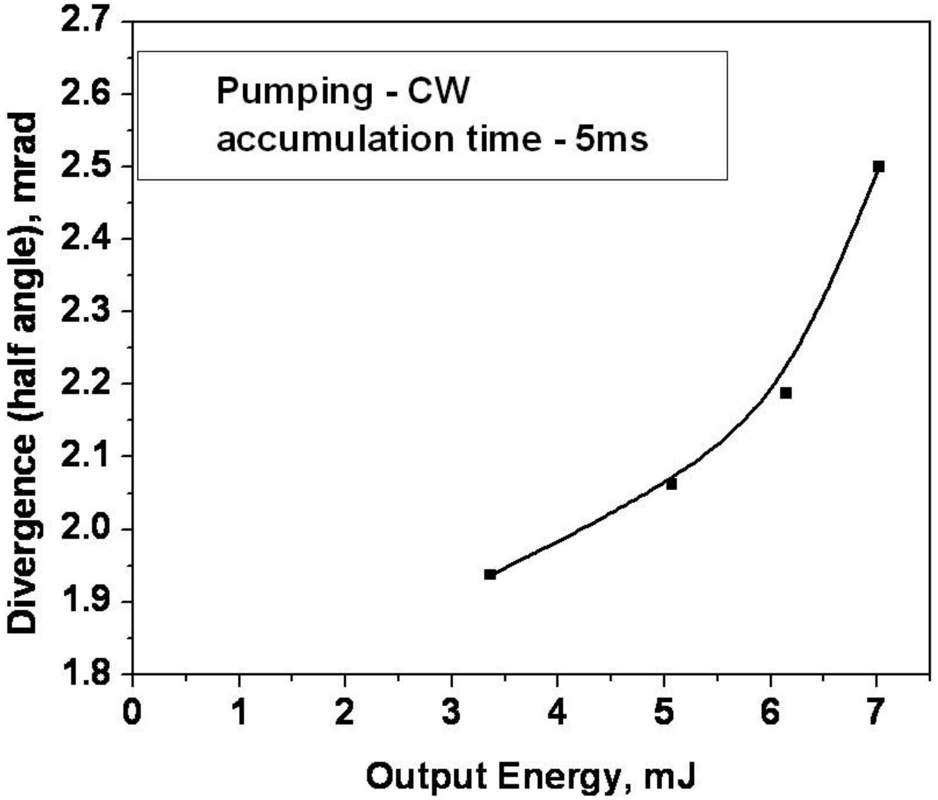

Fig. 6. Divergence (1/e^2 level, half angle) versus output energy with CW pumping and an accumulation time of 5 ms.

The same setup was used for Q-switched operation 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. The average power consumption of the system can be significantly lower than that for CW operation and enables an affordable, portable, battery-based solution.

As we demonstrated earlier, the accumulation time for high energy pulse operation has to be <5 ms. A 10 – 20Hz repetition rate is used in many types of rangefinders. Therefore, we selected 5ms/20Hz quasi-CW pumping for our experiments. The dependence of output pulse energy on incident energy at 5ms/20Hz quasi-CW pumping is shown on Fig. 7. As can be seen, the dependence is practically linear up to 8.5 mJ, and the observed slope efficiency is about 39% in this range. The slight decrease of slope efficiency observed after 8.5 mJ is caused by thermo-lensing effects. The maximum output pulse energy was >11 mJ at 175 mJ incident energy. Therefore, we obtained 11mJ/20Hz operation at ~3.5 W average pump power.

The pulse shape at 10.5 mJ output energy is demonstrated in the insert of Fig. 7, 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 ~2.5 mrad, and the M^2 parameter was ~1.5.

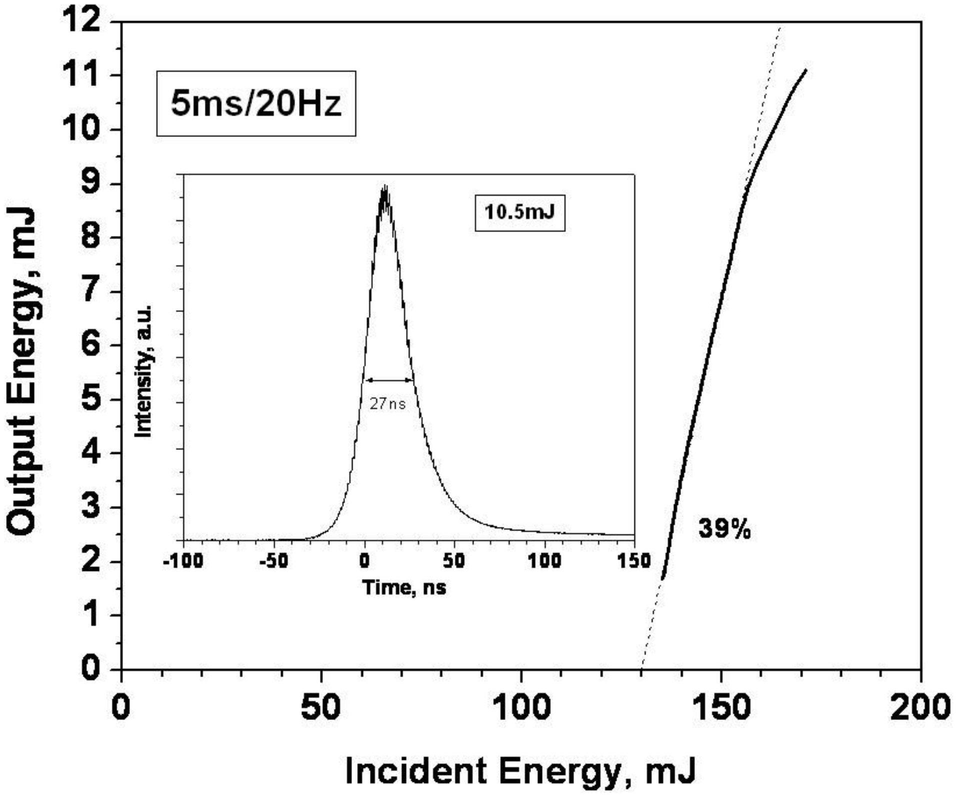

Fig. 7. Output pulse energy versus incident power with quasi-CW pumping 5ms/20Hz. Insert: pulse shape at 10.5 mJ.

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 a slope efficiency of 39 – 41% was demonstrated, and an output power of >3.5W in the TEM_{00} mode has been achieved. The output beam had an M^2 parameter better than 1.17 over the entire range of output powers used. Additionally, the optimal accumulation time for high output energy in Q-switched mode was investigated for our Er:YAG SSL. More than 11 mJ of output pulse energy in the TEM_{00} mode was demonstrated in Q-switched mode at 20Hz repetition rate. 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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