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Efficiency and Threshold Analysis of Resonantly Diode-Laser-Pumped 1.6-μm Er:YAG Laser

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Abstract: Resonant diode pumping of the 1.6-μm Er^{3+}(1%):YAG laser is reported with the absorbed photon conversion efficiency of 26%. Fluorescence study indicates that upconversion is a dominant mechanism affecting the solid-state laser threshold.

OCIS codes: (140.3480) lasers, diode-pumped; (140.3500) lasers, erbium; (140.3580) lasers, solid-state

1. Introduction

Yb:YAG solid state lasers (SSL) resonantly pumped by GaAs-diode lasers and operating in quasi-three level scheme demonstrate superior performance among solid state sources of coherent radiation [1]. Resonance pumping approach can be used also for Er:YAG SSL operating in the eye-safe 1.6-μm spectral range. Recently 54% optical-to-optical slope efficiency has been obtained for 1.6-μm Er:YAG SSL resonantly pumped with 1532 nm fiber laser [2].

Reported in this paper are the results of the direct resonant pumping of the 1.6-μm Er^{3+}-doped bulk SSL with 1470 nm InGaAsP/InP diode laser. To facilitate the first steps in this new development the high-brightness CW single-mode InP-based diode laser was used for pumping. This diode laser was fabricated from 1470-nm Quantum Well Separated Confinement laser structure and packaged in standard telecom 12-pin butterfly module with polarization maintaining fiber output as described earlier [3].

Absorption and emission peaks in Er^{3+}YAG crystals in the spectral range of 1450-1660-nm are due to the transitions between the $^4I_{13/2}$ and $^4I_{15/2}$ Stark-split manifolds forming in Er^{3+}:YAG a quasi-three level system (Fig.1). Four upper states out of the eight Stark components of the ground $^4I_{15/2}$ manifold serve as the terminal states for Er^{3+} laser transitions with the wavelengths ranging from 1617 to 1660 nm [4].

2. DPSSL layout, measurement results and discussion

In the experiments described here, a 4.8-mm-long, 5-mm-dia., Er^{3+}(1%):YAG laser rod was single-end pumped in a folded polarization-coupled cavity as shown in Fig. 2. A Polarizing Beamsplitter (PBS) was utilized to separate pumping and lasing radiation paths. A lens L1 and a highly reflective plano-concave mirror M1 (Fig. 2) provide appropriate pumping and laser mode geometric overlap with beam waist radius of about 30 μm in the rod center. Four different flat output couplers (OC) M_2 with transparencies of 0.24%, 3.3%, 9.4% and 13.9% were used to provide variable outcoupling. In addition to the measurement of DPSSL output power the intensities of the infrared fluorescence lines and green upconversion-excited fluorescence have been recorded in these experiments. The infrared fluorescence consists of three components with respective spectral positions of 1646 nm, 1617 nm and 1530 nm. In order to separate these components and measure their respective intensities the overall Er:YAG emission was spectrally decomposed by the 600 groove/mm diffraction grating and measured by an InGaAs photodetector. A Si-photodiode was used for green fluorescence measurement. The intensities of fluorescence spectral components have been recorded with and without output couplers. DPSSL operates in single 1617 nm line with 9.4% and 13.9% OC while at T=3.3% and T=0.23% the spectrum consists of two lines at 1617 nm and 1646 nm.

To record fluorescence intensities and lasing output power as a function of the power absorbed in the YAG rod two photodiodes (PD_i) and a tilted glass plate (P), shown in Fig. 2, provided reference signals proportional to the incident and unabsorbed pump powers. This component of data acquisition system was calibrated by the signals taken with no rod in the cavity.

The DPSSL output power characteristics measured with different output couplers are shown in Fig. 3. The data were taken at rod temperatures of 20 ^{0}C (dashed curves) and 0 ^{0}C (solid curves). Drastic increase of the threshold pump power with increasing OC transmission (T) loss prevents SSL from lasing at 20 ^{0}C when T=13.9%. The lasing with 13.9% OC has been achieved only with the rod temperature reduction down to 0^0 C. The slope of P_{out} vs P_{abs} is the optical-to-optical efficiency (η_{opt}), which, in particular, incorporates a ($\lambda_{laser} / \lambda_{pump}$) factor (in our case this

factor is about 0.9). We corrected the values of η_{opt} by this factor and used the absorbed photon conversion efficiency (η) instead of η_{opt} to do the Caird's analysis [5].

Despite of the limited range of the available pump power above the threshold we estimated the absorbed photon conversion efficiency (η) as 26%±3% for the 13.9% OC (Fig. 3). Corresponding values of η for T=3.3% and 9.4% were 9% and 20%. These data have been used to perform the Caird's loss and pumping efficiency analysis [5]. By plotting data in the form of

$$\frac{1}{\eta} = \frac{1}{\eta_p}\left[1 + \frac{L}{T}\right] \quad ,$$

where T is the outcoupling loss, η - photon-to-absorbed-photon efficiency, pumping efficiency of η_p = 0.37 and intracavity losses of L = 9.2% were inferred (Fig. 4). Using our DPSSL as a probe source the double-path absorption loss in a PBS at λ=1617 nm was found to be about 8% (in a lasing path, see Fig. 2) – most likely because anti-reflective coatings in PBS were designed by manufacturer for 1550 nm. It is anticipated that by minimizing intracavity losses the total L-value can be reduced by an order of magnitude so that $\eta \longrightarrow \eta_p$.

Obtained low value of η_p is clearly associated with imperfect pump and cavity physical active mode matching in this first experiment and fluoresce intensity data (Fig. 5) confirm this assumption. Indeed, 1530 nm and green fluorescence intensities continue to grow at pump powers exceeding the laser threshold. In future experiments we anticipate to considerably improve pump and cavity physical active mode matching to achieve $\eta_p \cong 1$.

Data in Fig. 5, collected within 4 orders of magnitude of pump power, indicate the sublinear behavior of the 1617 nm and 1530 nm fluorescence intensities (F) with absorbed power (P_p) increase (curves 1 and 2). While at very low pump levels F is proportional to P_p , at pumping levels closer to the laser threshold fluorescence intensities F, are clearly proportional to $(P_p)^{1/2}$. This indicates that the two-ion upconversion process is the dominant factor driving the effective lifetime of the excited ions in $^4I_{13/2}$ states. Considering that F is proportional to the excited Er3+ ion population in these states and ignoring the depopulation of $^4I_{15/2}$ the system can be treated so that the gain is simply proportional to F. Fig. 6 indicates that with these assumptions one can explain the fast laser threshold increase with increasing output coupler transparency. ΔF values plotted in Fig. 6 were estimated as $\Delta F = F - F_0$ where F_0 is the 1617 nm line intensity at the inversion threshold P_I=25 mW. F and F_0 are fluorescence intensity values measured without the OC. The right axis in Fig. 6 indicates the threshold gain values calculated from ln [(1-T)(1-L)], where T and L are output and intracavity losses, correspondingly. Solid line 2 in Fig. 6 shows the extrapolation (ΔF_t) for linear increase of F with pump power. The differences between positions of experimental points for threshold relative to line 2 are indicative of the threshold increase caused by the upconversion losses. As seen from Fig. 6, more than three-fold increase due to the up-conversion was observed for the T=13.9%. This result is in agreement with data obtained from the fluorescence dynamic study in Er^{3+}(1%):YAG [6].

3. Conclusions

We reported resonant diode pumping of the 1.6-μm Er^{3+}-doped bulk solid-state laser. Using 1470 nm single mode pumping diode laser module, the absorbed photon conversion efficiency of 26% has been achieved in these first experiments. Analysis of the DPSSL output characteristics indicates that obtained slope efficiency can be doubled through the intracavity loss reduction and pumping efficiency improvement.

Measurements of infrared and green fluorescence intensities versus absorbed pump power clearly indicate that at the excitation levels close to the threshold the upconversion becomes the dominant mechanism limiting the effective lifetime of excited $^4I_{13/2}$ states. It results in super linear increase of the pumping threshold with increasing outcoupling losses. Upconversion impact data are essential for follow-on low-threshold and more efficient resonantly-pumped 1.6-μm Er^{3+}:YAG DPSSL design.

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4. References

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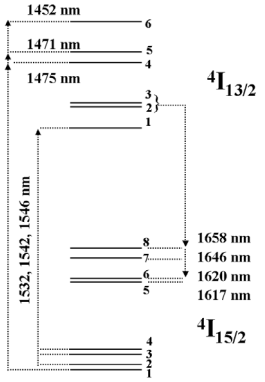

Fig.1. Er^{+3}:YAG absorptive and radiative transitions in the 1.45-1.66 μm spectral range.

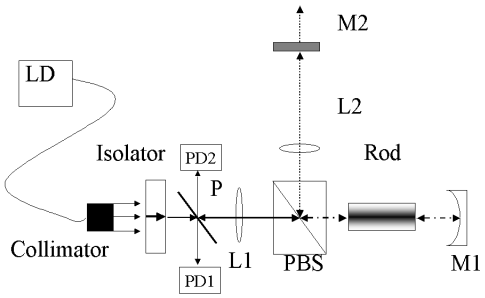

Fig. 2. Resonantly-pumped Er^{+3}:YAG DPSSL - optical layout.

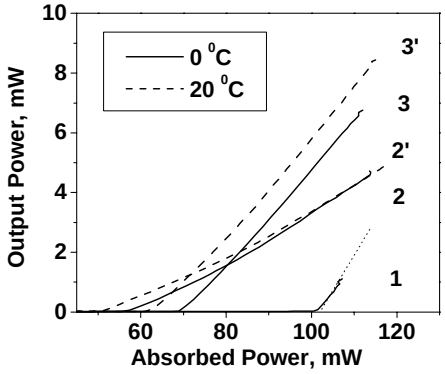

Fig. 3. Output power as a function of absorbed power for 1470-nm pumped Er^{+3}:YAG DPSSL with different output couplers: 1 - T=3.3%, 2 – T=9.4%, 3 – T=13.9%. Curves 1, 2 and 3 were measured at rod temperature 0°C and dashed curves 2′, and 3′ at 20°C.

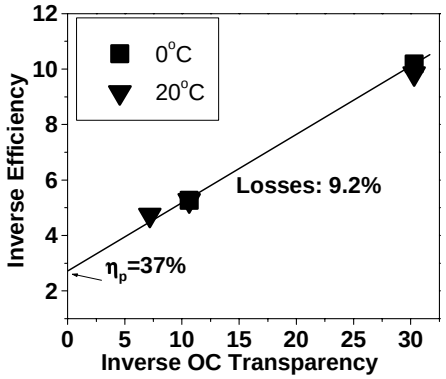

Fig. 4. Inverse absorbed photon conversion efficiency (1/η) vs. inverse output coupler transmission at T=0°C and T=20°C.

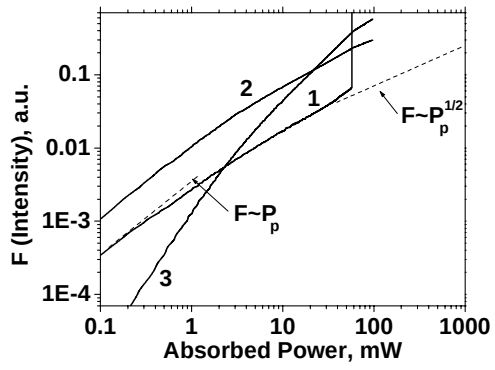

Fig. 5 Fluorescence intensities as a function of the absorbed power measured with 3.4% output coupler. 1 and 2 are for 1617 nm and 1530 nm lines, correspondingly. (3) –green fluorescence. Lasing threshold is seen at 50 mW of absorbed power.

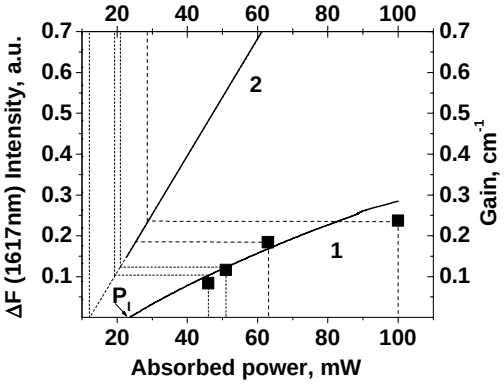

Fig 6. Curves 1 and 2 (left scale) show the increase of the 1617 nm fluorescence intensities at powers above the inversion threshold. 1-ΔF from experimental data measured without output coupler, 2-ΔF_t calculated from the extrapolation of the linear portion of dependence F =f(P_p) at low excitation level. Solid squares display the threshold gain (right scale) at different output couplers.