High-efficiency, room-temperature nanosecond Yb:YAG laser

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Abstract: Yb^{3+}-doped gain media offer favorable properties for diode-pumped laser amplifiers for high-energy ns-pulses. To reach high optical-to-optical conversion efficiencies at room temperature however, very high and often impractical fluences are required both for pumping and extraction. Low temperature operation offers a solution, but the required cryogenic cooling systems add considerable complexity, bulkiness and cost. Multi-passing both pump and extraction beams through the gain medium is an alternative approach to overcome efficiency limitations at room temperature. In this article we present numerical and experimental results to this effect. We demonstrated ns-pulse output from a diode-pumped Yb:YAG amplifier at an energy of 566 mJ and an optical-to-optical efficiency of 20 %, which is almost a doubling of the efficiency achieved with ns-lasers employing Yb^{3+}-doped gain media at this energy level.

OCIS codes: (140.3280) Laser amplifiers; (140.3615) Lasers, ytterbium; (140.3480) Lasers, diode-pumped.

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1. Introduction

High energy ns lasers are predominately used for laser plasma research, both for direct applications such as laser fusion and for pumping high-energy sources of ultra short pulses such as Ti:sapphire or optical parametric amplifiers. So far, flashlamp pumped Nd:Glass amplifiers have been the mainstay of high energy ns pulse generation. However, these systems can only be operated at very low repetition rates and also suffer from very low energy conversion efficiency. These points need to be addressed to enable both further advances in laser plasma research and envisioned real-world applications such as laser fusion energy and laser driven particle accelerators. Diode pumped solid state lasers offer a route toward ns sources of high energy, efficiency and repetition rate.

Due to their low quantum defect, long fluorescence lifetime and the absence of excited state absorption and quenching effects, Yb^{3+}-doped media offer favorable properties for high energy pulsed laser amplifiers. However, due to the quasi three-level nature of Yb^{3+} at room temperature, high pump fluences are required to overcome the reabsorption losses and to reach a high storage efficiency, defined as extractable fluence divided by pump fluence. The realization of a high pump fluence is challenging in itself, but reaching a high optical-to-optical efficiency then also necessitates a high extraction fluence.

For a large variety of Yb-doped laser materials, the minimum required pump fluence for bleaching out the reabsorption at the lasing wavelength lies at around $1-10\,\mathrm{J\,cm^{-2}}$. This is in the same range as the damage threshold for ns pulses, so efficient operation, which requires pumping at several times the bleaching fluence, becomes very difficult due to optical damage. The reason why reabsorption is such a great concern is that the high energy systems under consideration here will operate at few 10s of Hz at best, so the population of exited atoms that needs to be build up to overcome reabsorption will decay completely until the next shot. This is not the case in cw and high repetition rate systems (repetition period $\ll$ fluorescence lifetime). High energy, low repetition rate amplifiers also suffer more strongly from spontaneous emission losses during the pump pulse, which is why they will never reach the extraordinary slope efficiencies that have been demonstrated for Yb-based cw thin-disk and fibre lasers [1, 2].

Highest pulse energies in excess of 60 J obtained with diode-pumping have been demonstrated using Yb-doped S-FAP (saturation fluence $F_{sat} = 3.2\,\mathrm{J\,cm^{-2}}$) at an optical-to-optical conversion efficiency η_{o-o} of 12 % [3]. Recently, Joule-level nanosecond pulses were generated employing Yb:YAG ($F_{sat} = 9.6\,\mathrm{J\,cm^{-2}}$) at an efficiency η_{o-o} of 9 % [4], whereas with the low gain material Yb:CaF_2 ($F_{sat} = 80\,\mathrm{J\,cm^{-2}}$) an efficiency of 4 % [5] was achieved. In contrary, efficiencies of 20 % and higher have been demonstrated with diode-pumped systems based on Nd^{3+} such as Nd:glass ($F_{sat} = 6\,\mathrm{J\,cm^{-2}}$) [6].

However, due to the fluorescence lifetime of a few 100 μs (compared to 1 ms or higher in case of most Yb-doped media) and the peak absorption wavelength around 808 nm (higher quantum defect than pumping Yb^{3+} around 940 nm or even 975 nm) Nd-doped materials are less attractive in terms of pumping high-energy lasers with laser diodes. The lower quantum defect of Yb^{3+} leads to less heat deposition and would therefore allow to operate the laser at higher repetition rates, whereas the longer fluorescence life time increases the stored energy per volume

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and allows to generate more pulse energy per diode peak power.
The practical results listed above may be an indication that the reabsorption losses of Yb-doped laser materials are mainly responsible for the low efficiencies obtained rather than a high saturation fluence of a specific laser material, which can be compensated by a multi-pass amplifier design [7]. One possibility to overcome reabsorption is cryogenic cooling of the Yb-doped laser materials [8] in order to deplete the thermally populated lower laser level and therefore reduce the minimum pump fluence. Recently, an efficiency η_{o-o} of 30 % at 200 mJ output energy was demonstrated with a cryo-cooled Yb:YAG amplifier [9]. An additional advantage of cryo-cooling is the fact that the thermal properties of most gain media such as their thermal conductivity and thermo-optical coefficient improve at low temperatures.
However, cryo-cooling adds significant cost, complexity and bulkiness to a laser system. Also, the energy required by the cryo-cooler impacts on the overall system efficiency and could more than offset the efficiency gains in the laser amplifier. In this paper, we present simulations and their experimental proof of an alternative approach called regenerative or multi-pass pumping, enabling high efficiency at room temperature using only moderate pump and extraction fluence levels. Multi-pass pumping is well known in thin disk lasers [1, 10]. The benefit is that the pump light can be efficiently absorbed in an optically thin medium. In thin disk lasers, the low optical thickness results from a low geometrical thickness, which is mainly motivated by thermal management considerations. In a high energy amplifier on the other hand a low optical thickness is required to achieve a high population inversion at a low pump fluence. Provided that thermal management issues are solved otherwise, regenerative pumping can hence also be applied to a low-aspect ratio amplifier medium, as the high aspect ratio of thin disk amplifiers promotes amplified spontaneous emission (ASE) losses and in the extreme case parasitic lasing [7, 11]. Based on regenerative pumping we demonstrated a joule-level bulk Yb:YAG nanosecond laser reaching an optical-to-optical conversion efficiency of 20 %.

2. Theoretical considerations

Due to the quasi-three level system of Yb^{3+}, a minimum fraction of excited Yb-ions $\beta_{min} = \sigma_a/(\sigma_a+\sigma_e)$ is required to bleach out the reabsorption at the laser wavelength. The fraction of excited Yb-ions is given by $\beta = N/N_{dop}$, where σ_a is the absorption cross section, σ_e the emission cross section at the lasing wavelength λ_l, N the density of excited and N_{dop} the total density of Yb-ions. In general, the gain saturation fluence $F_{sat} = hc\cdot(\lambda_l\,\sigma_e)^{-1}$ is a measure at which laser pulse fluence the gain will be saturated, where h is Planck's constant and c the vacuum speed of light. In the case of Yb^{3+}, the effective gain cross section is given by

$$\sigma_g = \beta\,\sigma_e - (1-\beta)\,\sigma_a = \sigma_e \cdot \frac{\beta-\beta_{min}}{1-\beta_{min}} \tag{1}$$

resulting in a reduced saturation fluence $F^*_{sat} = F_{sat}\cdot(1-\beta_{min})$. It was previously shown that in a multi-pass amplifier with m passes, also in the case of gain saturation, the effective gain saturation fluence is reduced by a factor m [7]:

$$\tilde{F}^*_{sat} = F_{sat}\cdot(1-\beta_{min})/m. \tag{2}$$

The multi-pass approach therefore is a good method to overcome problems associated with high gain saturation fluences (mainly optical damage) and it can also be adapted to the pump process in order to reduce reabsorption losses.
In real four-level systems reabsorption does not occur and the optical thickness of the gain medium can be maximized in order to reach a high degree of pump absorption. In quasi-three-level system however, the losses associated with reabsorption grow with increasing optical

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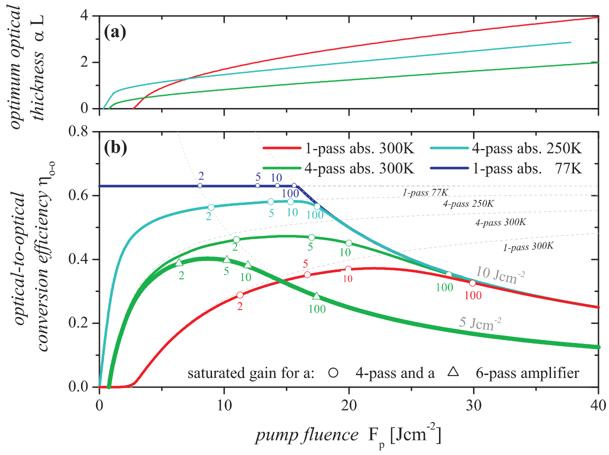

Fig. 1. Simulation results: (a) optical thickness for maximum storage efficiency as function of pump fluence. (b) storage efficiency η_{st} (dashed lines: extractable fluence divided by pump fluence) and efficiency limit due to laser induced damage (dotted lines) vs. pump fluence for Yb:YAG at a pump pulse duration of 0.8 ms; The optical-to-optical conversion efficiency η_{o-o} including the extraction efficiency of a short pulse laser amplifier (symbols mark the saturated gain at four and six pass amplification) follows the solid (colored) lines. The thick green curve (damage fluence: $F_D = 5\,\mathrm{Jcm}^{-2}$) is comparable to the experimental proof in section 3.

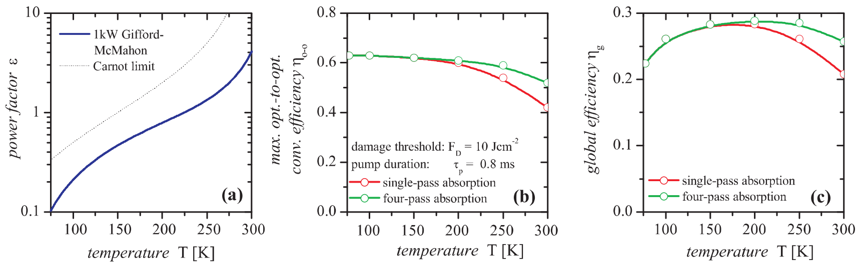

Fig. 2. Simulation results: (a) power factor of a typical He-gas cooler and the Carnot limit. (b) calculated maximum efficiency η_{o-o} of a 4-pass Yb:YAG amplifier at $F_D = 10\,\mathrm{Jcm}^{-2}$ and $\tau_p = 0.8$ ms, and (c) its global efficiency η_g over the operating temperature.

thickness and hence an optimum, where the combined reabsorption and pump transmission losses are minimal, needs to be found. The model introduced in the following will illustrate the sensitivity of the global efficiency (defined below) upon various factors such as optical thickness, pump fluence and operating temperature. In the model, transversely uniform and collinear pump and extraction beams are assumed and pump pulses with rectangular shape in time. The pump process prior to pulse amplification is described by

$$\frac{\partial \beta}{\partial t} = R \cdot \left(1 - \frac{\beta}{\beta_{max}}\right) - \frac{\beta}{\tau_f} \quad \text{and} \quad \frac{\partial R}{\partial z} = -\alpha' \cdot \left(1 - \frac{\beta}{\beta_{max}}\right) \cdot R. \tag{3}$$

Here $\alpha' = \sigma_a' N_{dop}$ denotes the absorption coefficient, σ_a' and σ_e' the absorption and emission cross sections at the pump wavelength λ_p, τ_f the fluorescence lifetime, $R = I_p \cdot (I_{sat}\,\tau_f)^{-1}$ the pump rate, I_p, $I_{sat} = hc \cdot (\lambda_p\,\sigma_a'\,\tau_f)^{-1}$ the pump saturation intensity, and β_{max} the maximum fraction of excited ions $\beta_{max} = \sigma_a'/(\sigma_a' + \sigma_e')$. With the resulting $\beta(z)$, the pump duration τ_p,

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the length of the homogeneously doped gain medium L, the pump fluence $F_p = I_p\,\tau_p$, and the maximum extractable fluence F_{st}, the storage efficiency (extractable fluence divided by pump fluence) including fluorescence, transmission and reabsorption losses at longitudinal pumping is given by

$$\eta_{st} = \frac{h\,c\,N_{dop}}{\lambda_l\,I_p\,\tau_p}\int_0^L (\beta(z) - \beta_{min})\,dz. \tag{4}$$

In the case of absorption saturation Eq. (3) must be treated numerically. For regenerative pumping $\partial R/\partial z$ is solved individually for each pump pass. Due to their dependence on the aspect ratio (width/diameter of the gain medium divided by L) [11], losses caused by ASE and parasitic lasing are not included in the model and need to be calculated separately.

Figure 1(a) shows the optimum optical thickness of Yb:YAG for single and multi-pass pumping. Due to a significant increase in the excitation level β, regenerative pumping improves the storage efficiency especially at low pump fluences, as illustrated in Fig. 1(b). Furthermore, the maximum efficiency η_{o-o} as a product of the storage and the extraction efficiency is plotted as function of pump fluence. The energy extracted depends on the amplifier gain and the number of passes, and it is limited by the damage threshold of the optical components.

Considering the global efficiency of a diode-pumped laser system, the power consumption of both the optical part such as the pump source and the laser head as well as the their cooling systems have to be taken into account. The latter becomes a dominating issue when operating at cryogenic temperatures. This is because the coefficient of performance ε_c (heat removed divided by energy required) of cooling systems becomes increasingly small at low temperatures. It is limited to the Carnot efficiency but in practice is often only a fraction of that. With η_{e-o} being the conversion efficiency of electrical energy into (useful) pump light (assumed to be 40 %), η_{o-o} the optical-to-optical conversion efficiency of the laser amplifier, ε_c the coefficient of power of the laser head cooling system and q the heat deposited into the gain medium expressed as fraction of the pump power, the global efficiency is defined by

$$\frac{1}{\eta_g} = \frac{1}{\eta_{o-o}} \cdot \left[\frac{1}{\eta_{e-o}} + \frac{q}{\varepsilon_c}\right]. \tag{5}$$

Figure 2(a) shows $\varepsilon_c(T)$ of a typical He-gas cooler based on the Gifford-McMahon or the Sterling process as a function of the temperature, reaching 10% at LN temperature [12]. Also shown as function of temperature are the Carnot efficiency (theoretical limit, see (see Fig. 2(a)), the maximum efficiency η_{o-o} of a Yb:YAG laser amplifier (see Fig. 2(b)), and its maximum global efficiency (see Fig. 2(c)) [8]. For these calculations the minimum heat fraction of $q = 0.09$ due to the quantum defect was assumed. Furthermore, the amplifier extraction efficiency was calculated for a 4-pass Yb:YAG amplifier operated at an output fluence of 10 Jcm^{-2} which is a typical damage threshold of commercially available optical coatings at nanosecond pulses. As illustrated in Fig. 2(c), regenerative pumping leads to a higher global efficiency and the optimum efficiency is reached at a higher temperature.

3. Experimental results

Figure 3(a) shows the layout of the diode-pumped Yb:YAG multi-pass amplifier seeded by a nanosecond master oscillator power amplifier (MOPA). Pulses as short as 6 ns were generated in a Q-switched oscillator running at 1030 nm. They were amplified to about 100 mJ in an Yb:YAG booster with a total gain of 10^3 [4]. The output beam profile is shown in Fig. 3(b).

The gain medium of the subsequent multi-pass amplifier was pumped by a stack of 25 fast axis collimated diode-laser bars (Jenoptik Laserdiode GmbH, Germany) with a peak output power of 4 kW and a center wavelength of 940 nm. The four-pass pumping scheme after re-collimation and focussing consists of a roof mirror, a turning mirror, a plane reflecting mirror,

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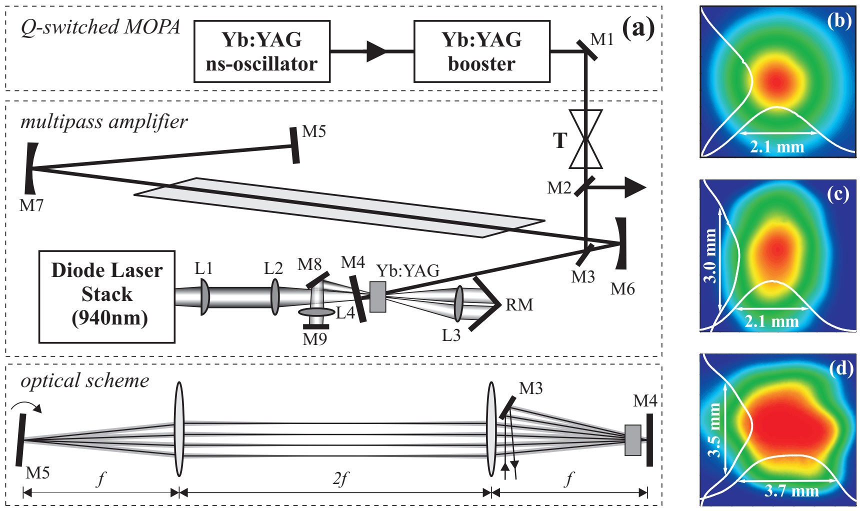

Fig. 3. (a) Experimental setup: Multipass Yb:YAG amplifier, seeded by a Q-switched nanosecond MOPA based on Yb:YAG; T, spherical lens telescope (magnification: 2); M1-M3, dielectric flat turning mirrors (HR 45° 1010-1060 nm), diameter: 25 mm; M4, dichroic flat mirror (HR 1020-1060 nm, AR 930-950 nm), diameter: 50 mm; M5, dielectric flat mirror (HR 0° 1010-1060 nm), diameter: 25 mm, M6, M7, dielectric concave mirrors (HR 0° 1010-1060 nm), radius of curvature: 750 mm, diameter: 50 mm; M8, dielectric flat turning mirror (HR 45° 1010-1060 nm), width × height: 35 × 50 mm; M9, dielectric broadband flat mirror, diameter: 50 mm; RM, roof mirror comprising of 2 M8 mirrors; L1, toric lens (fast axis: $f_{FA} = 800$ mm; slow axis: $f_{SA} = 115$ mm); L2, spherical lens ($f = 150$ mm); L3, L4, spherical lenses ($f = 100$ mm); Beam profiles: (b) seed, (c) amplified output after 6 passes, (d) pump profile. Beam diameters at full width half maximum (FWHM) are given.

and two spherical lenses placed at a distance from the gain medium equal to their focal length. Single-crystalline Yb:YAG (FEE GmbH, Germany) doped at 1.4% was used as the amplifying medium. In order to prevent strong thermal lens aberrations within the transversally conduction-cooled gain medium (width × height = 16 × 16 mm^2) the repetition rate was limited to 1 Hz at a pump duration of 0.8 ms and a pump peak-power of 3 kW.

A plane dichroic mirror (M4) directly behind the Yb:YAG crystal acted as wavelength coupler.

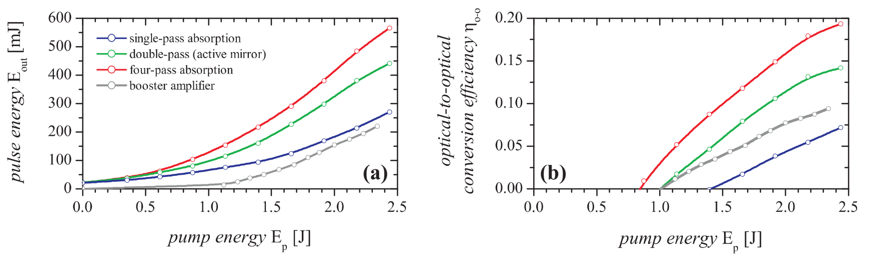

Fig. 4. Experimental results: (a) Output pulse energy of both the booster [4] and the main Yb:YAG amplifier and (b) their optical-to-optical efficiencies. With the main amplifier the influence of single- and multi-pass pumping was investigated (seed pulse energy: 95 mJ).

Angular multiplexing along the vertical axis allowed a six-pass amplification of the seed-pulses within a relay imaging cavity (see optical scheme in Fig. 3(a)). Here, the incoming and the out-

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going beams were vertically separated at the high-reflection (HR)-coated mirrors M2 and M3. A vacuum tube with Brewster windows was placed at the focal region between M6 and M7 in order to prevent air breakdown. The output profile (see Fig. 3(c)) is distorted due to the shape of the pump profile (see Fig. 3(d)) and mainly due to the astigmatism induced by the tilted cavity setup. The astigmatism however can be compensated after amplification.
Although the optical thickness of the gain medium (here $\alpha'\,\mathrm{L} = 0.8$) reached its optimum for each configuration at a different pump energy, the reduction of the minimum required pump fluence and hence the increase in efficiency (η_{o-o}) at multi-pass pumping become obvious by the experiment shown in Fig. 4. In comparison, values achieved with the Yb:YAG booster amplifier ($\alpha'\,\mathrm{L} = 2.2$) which was optimized only for single-pass pumping are plotted. With regard to the simulation results shown in Fig. 1 both the saturated gain and the efficiency η_{o-o} are reduced due to resonator losses in practice. In our specific case the efficiency η_{o-o} drops even further due to observed optical damage of the crystal anti-reflection (AR) coating at about $5\,\mathrm{J\,cm^{-2}}$ (above 600 mJ) instead of $10\,\mathrm{J\,cm^{-2}}$ and the overlap between pump and seed beams at Gaussian instead of flat-top shaped profiles.

4. Conclusion

The reduction of reabsorption losses in high-energy Yb-based nanosecond laser amplifiers is key to maximizing their optical-to-optical conversion efficiency. Regenerative pumping is a promising alternative to cryogenic cooling for reducing these reabsorption losses. In this paper, we have demonstrated ns pulse amplification in Yb:YAG up to an energy of 566 mJ at an optical-to-optical conversion efficiency of 20% using a four-pass pump configuration. With reference to the presented simulation results a boost of efficiency is expected when performing a further setup optimization in our case, which means advanced crystal coating and beam shaping for instance.
Due to thermal lens issues the repetition rate was limited to 1 Hz. However, there is a large potential to improve the thermal management, for instance by using longitudinal instead of transverse cooling. A multiple thin disk design, for example, which is comparable to a distributed bulk material, will enable both scaling of the pulse energy and average power. In conclusion, we propose a combination of both cooling at moderate temperatures between 200 and 300 K and regenerative pumping to achieve the optimum operation of high-energy diode-pumped lasers based on Yb-doped materials.

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