High power diode-pumped Nd:YLF amplifier development

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Introduction

Currently three diode pumped Nd:YLF amplifiers based on a similar pump module geometry are under construction in the Laser R&D group. One is operated in pulsed mode as an OPCPA pump; the other two in quasi steady state mode are built for a photo-injector at CERN in the framework of the large European CARE project.

Photo-injector laser for CARE. This laser is designed to deliver microsecond long train of mode-locked pulses onto the photocathode of a photo-injector gun to produce electron bunches. Using a laser based photo-injector gives the flexibility to generate arbitrary electron bunch structures and high brightness, but very high stability is required.

The laser system is designed to produce 1.5 μs pulse trains (macropulses) of ~2300 micropulses, which correspond to a 1.5 GHz mode-locked repetition rate to match the 30 GHz RF of the accelerator. The system runs at up to 50Hz macropulse repetition rate, delivering 15 kW pulse train mean power in the IR. This light is then converted into the UV. The system requirements are shown in Table 1.

Electron charge/bunch	2.33 nC
Number of pulses	2332
Micro-pulse rep rate	1.5 GHz
Pulse train length	1.548 μs
Wavelength	262 nm
Energy at cathode	370 nJ/micropulse
Pulse duration	10 ps
Repetition rate	50 Hz
Energy stability	<0.1%

Table 1. System requirement for CARE Photo-injector laser.

Pump laser for 5fs OPCPA system. A high pulse energy and high average power pulsed laser is being developed for pumping our few-cycle OPCPA system, currently under development for attosecond applications in a multi collaborative program. This pump laser is designed to produce pulse energies up to ~200mJ with pulse durations of ~40ps, operated at high repetition rates up to 1 kHz which is desired for optimum signal-to-noise ratio in the high order harmonic generation experiments.

System description

Seed source for OPCPA pump. A commercial (HighQLaser GmbH) Nd:YLF passively mode-locked oscillator and a regenerative amplifier delivers 40ps long, 1mJ pulses at repetition rate up to 1 kHz.

Seed source for CARE. From the same supplier, a Nd:YLF passively mode-locked oscillator and cw preamplifier system has been purchased, producing 6 ps pulses at a 1.5 GHz repetition rate at 1047 nm with an average power 320 mW after the oscillator and 10W after the preamplifier. Both lasers can be synchronised to an external reference source with a time jitter <1ps.

Laser head design. All amplifiers are based on five fold geometry side pumped Nd:YLF rods. The laser heads mechanics have been designed and manufactured at RAL. To improve the previous assembly and achieve homogeneous pumping along the length of the rod, the current design is based on long vertical stacks of diode bars, which match the length of the Nd:YLF rods. The fast axis divergence of 40^{o} assures the filling of the rod along the optical axis while the 10^{o} slow axis divergence is corrected by long cylindrical lenses to match the cross-section of the rod. The glass tube, which contains the coolant for the laser rod is partially aluminium coated on the outside to couple transmitted light back into the rod. The expected overall coupling and absorption efficiency in the rod is ~70%.

The rod mounting system allows easy rotation of the naturally birefringent rods to suit the input polarization and interchange of the rods.

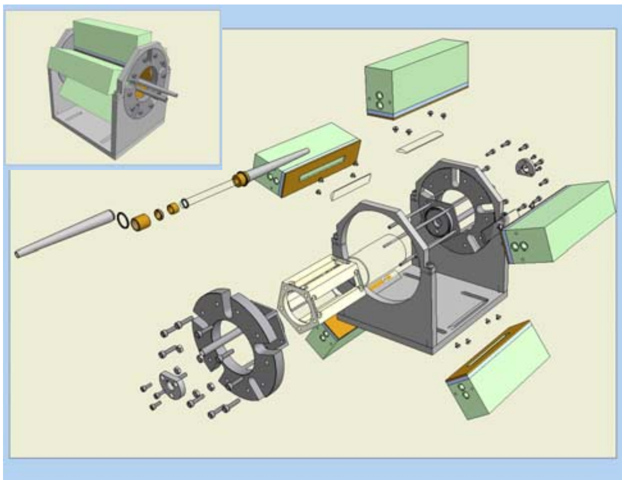

Figure 1. Amplifier head assembly.

	Amplifier for OPCPA pump	1st amplifier for CARE	2nd amplifier for CARE
Length of the rod	10cm	8 cm	12 cm
Diameter of the rod	5 – 6 mm	7 mm	10 mm
Effective pump length	9 cm	7 cm	11 cm
Total peak pumping power	5 kW	18 kW	25 kW
Repetition rate	1-1000Hz	1-50 Hz	1-50 Hz
Max. duty cycle	25%	2.5%	2%
Max. average pumping power	1.25 kW	450 W	500 W
Cooling requirement	30 l/min	45 l/min	66 l/min
Number of passes	4	3	3
Expected saturated gain	300	300	5

Table 2. Amplifier head parameters.

Amplifier design

Amplifier for OPCPA pump. The analysis is given for a pulsed Nd:YLF amplifier operated at a repetition rate up to 1kHz, for ps laser pulse amplification. Details of pump head geometry and the specifications of pump diode arrays are described above, and listed in Table 2. Three different diameter rods from 5mm to 6mm are under investigation for optimum laser performance. A comprehensive simulation study has been carried out based on a simplified rate equation model to establish optimum operation modes and conditions for stable and reliable laser performance.

Nd:YLF has two levels very close to each other in the upper laser state, namely R2 corresponding to π-pol laser emission at 1047nm and R1 σ-pol radiation at 1053nm. At thermal equilibrium, the relative population fractions at R2 and R1 are 40% and 60%, respectively. Depopulating one level should be followed by population redistribution between these two levels to resume the equilibrium fraction ratio of 40/60. Rigorous evaluation of redistribution effect on the laser performance requires incorporating the dynamics of population redistribution with the laser rate equations. For fast pulse amplification in Nd:YLF, the finite life time of the lower laser level, which is ~21.6ns, needs to be taken into account, and may have a significant effect on laser performance. At thermal equilibrium, the relative population fraction at the lower laser level is ~21% of the lower laser state manifold. Accumulated population at the lower laser level during pulse amplification is redistributed in the manifold and then decays to the ground state through slow relaxation processes compared with the pulse length. Since there is a lack of exact information on population redistribution times in both upper and lower laser states, and also for simplicity of calculation, two extreme situations are considered, 'long pulse assumption' where the laser pulse length is much longer than redistribution time, and 'short pulse assumption' where the laser pulse is much shorter than the redistribution time. In the first situation, the total stored energy in the upper laser state is used for laser amplification while only population on R2 makes contribution to amplification in the latter.

Assuming the laser beam is spatially and temporally uniform through the Nd:YLF rod, the gain coefficient α in a small length element Δl may be given by

$$\alpha = N\sigma = \frac{0.4E_{ST}}{(1-f_l)F_{SAT}} \qquad (1)$$

and the small signal gain is governed by

$$G_0 = \exp(\alpha\Delta l) \qquad (2)$$

where N is the upper level population, σ the stimulated emission cross section, E_{ST} the total stored energy density, f_l the relative population fraction at the lower laser level and F_{SAT} the saturation fluence. σ and F_{SAT} refer to level R2 alone. The upper level depopulation due to laser amplification may be given by

$$\Delta\alpha = -\frac{p}{(1-f_l)F_{SAT}}\frac{d}{dl}\Delta F_L \qquad (3)$$

where F_L is the laser pulse fluence, and p the case coefficient of 0.4/1 corresponding to long/short pulse, respectively. For small enough Δl, the laser amplification may be approximated to zero order by

$$\frac{d}{dl}(\Delta F_L) = \alpha\Delta F_L \qquad (4)$$

Substituting (4) into (3) and assuming uniform distribution of α in a small Δl, we have

$$\alpha_i = \alpha_{i-1}\exp(-pk_i) \qquad (5)$$

$$k_i = k_{i-1} + \alpha_{i-1}\frac{\Delta l}{p}\left(1-\exp(-pk_{i-1})\right) \qquad (6)$$

where k_i is defined as $\frac{F_L}{(1-f_l)F_{SAT}}$ and α_i is the gain coefficient in the i[th] element.

The pump rate into the upper laser state is given by

$$P = \frac{\eta_a\eta_c\eta_q P_d}{ALF_{SAT}} \qquad (7)$$

while the initial α is determined by

$$\alpha_0 = p\tau\left(1-\exp\left(-\frac{T_0}{\tau}\right)\right) + \alpha_r \qquad (8)$$

where η_a is absorption efficiency, η_c the coupling efficiency of the cavity, η_q the quantum defect between the pump and laser emission, A the cross section of the rod, L the length of the rod, τ the lifetime of upper laser level, P_d the total peak pump power of diodes, T_0 the pump duration and α_r the residual gain from the previous pulse. To evaluate the beam quality, the B-integral is also calculated.

Figure 2 shows typical output pulse energies for 'long pulse assumption' as a function of input seed pulse energy in a 4-pass amplifier with a 5.5mm rod for different pumping powers at 1 kHz with 25% duty cycle. Stable and reliable operation modes may be established in the area defined by the intersection of the thermal limit curve and the B-integral limit curve. The optimum output pulse energy may be obtained towards lower input pulse energy. Furthermore, the thermal deposition power at the maximum available output pulse energy for rods of three different diameters is depicted in Figure 3 as a function of repetition rate, which is limited by both rod fracture threshold and B-integral limit. As can be seen, the maximum pulse energy of ~200mJ in the IR may be obtained at up to 1 kHz for 5.5mm rod, and hence 80 ~ 100mJ in the green may be envisaged for OPCPA pumping using a frequency doubling crystal of BBO.

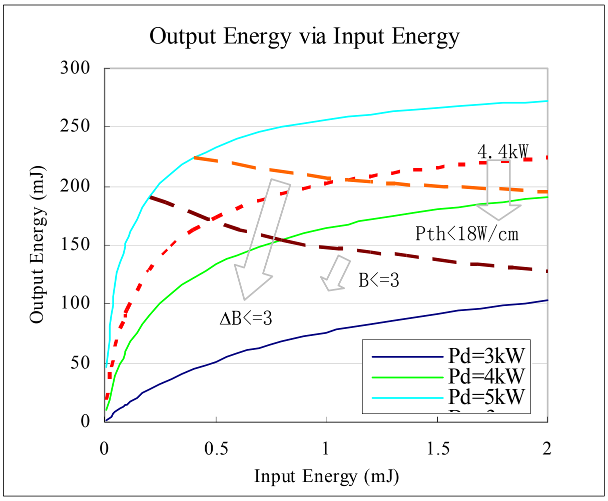

Figure 2. Stable and Reliable Operational Area.

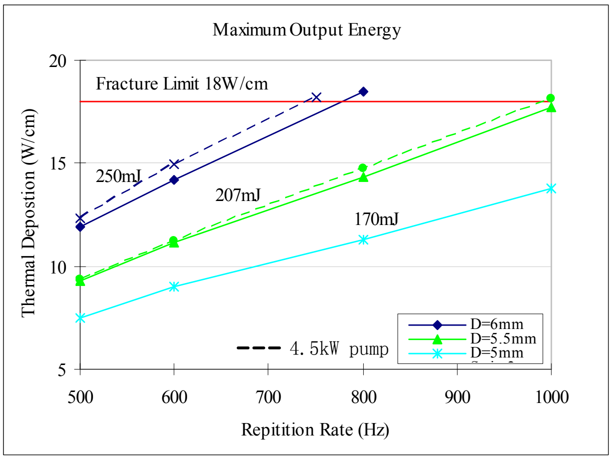

Figure 3. Maximum Output Energy.

Amplifiers for CARE. The amplifier design is based on a quasi steady-state operation, because of the high stability required[1]. Detailed model is discussed in [2]. Figure 4 shows the calculated gain in the two amplifiers as a function of pumping duration.

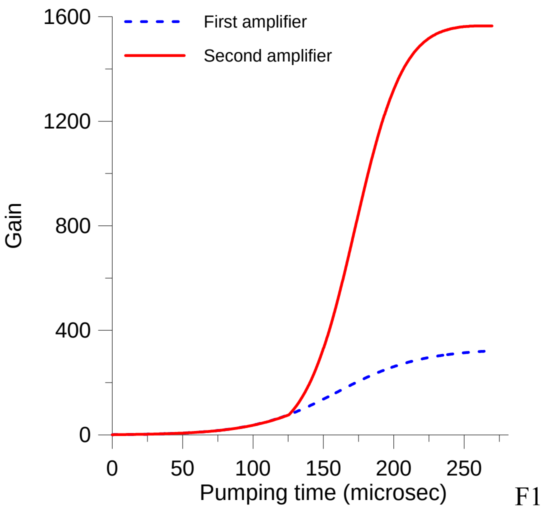

Figure 4. Calculated gain in the two amplifiers. The second is switched on 125 µs later.

It can be seen that the steady-state is reached after 250 µs.

Amplifier performance

We have carried out preliminary experimental investigations of ps pulse amplification in Nd:YLF using a previously developed amplifier with a 5mm diameter rod, designed to be operated in a quasi steady state mode. Details of this amplifier were recently reported by Ian Ross *et al.*,[3]. The seed laser pulse was provided by a commercially available system, HighQ IC-1000, delivering maximum pulse energy of 1mJ with ~40 ps pulse duration operated at a repetition rate up to 1 kHz. The power amplifier was operated at a repetition rate of ~10Hz, and synchronized to the seed laser pulse with an appropriate delay provided by Stanford pulse generator.

The laser output energy of the focused beam in a 2-pass amplifier was measured by Thermopile power meter along with a CCD camera for monitoring the beam profile. A maximum saturated output pulse fluence of 2.6J/cm^2 was obtained for 500µs pumping durations. Typical measured and calculated output energy fluences and gains at pump duration of 450µs are shown in Figure 5 as a function of input pulse energy. As seen, the calculated results, assuming fast redistribution times for both upper and lower levels, are in reasonably good agreement with experimental ones. In addition, uniform beam laser performance has also been demonstrated in a 4-pass amplifier, and non-optimized output pulse energy up to 75mJ was obtained.

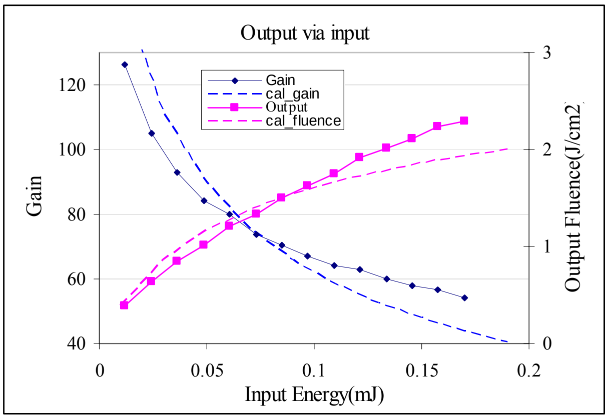

Figure 5. Measured and calculated gain and output energy fluence as the function of input energy in a 2-pass amplifier.

Conclusions

High power diode pumped Nd:YLF amplifiers in both pulsed and quasi steady state mode, based on a common concept of pump head geometry, have been designed and developed. Preliminary experimental results are very promising for meeting ultimate requirements. Calculations based on a simplified model show good agreement with experimental results, indicating a good guideline for further development and optimization of laser performance.

The CARE amplifier assembly will start autumn of 2005 and the delivery of the system to CERN with harmonic generation stages is planned for summer 2006.

References

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