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EDGE-PUMPED $Tm:Lu_2O_3$ DISK BROADBAND LASER AMPLIFIER DESIGN AT 1 kHz

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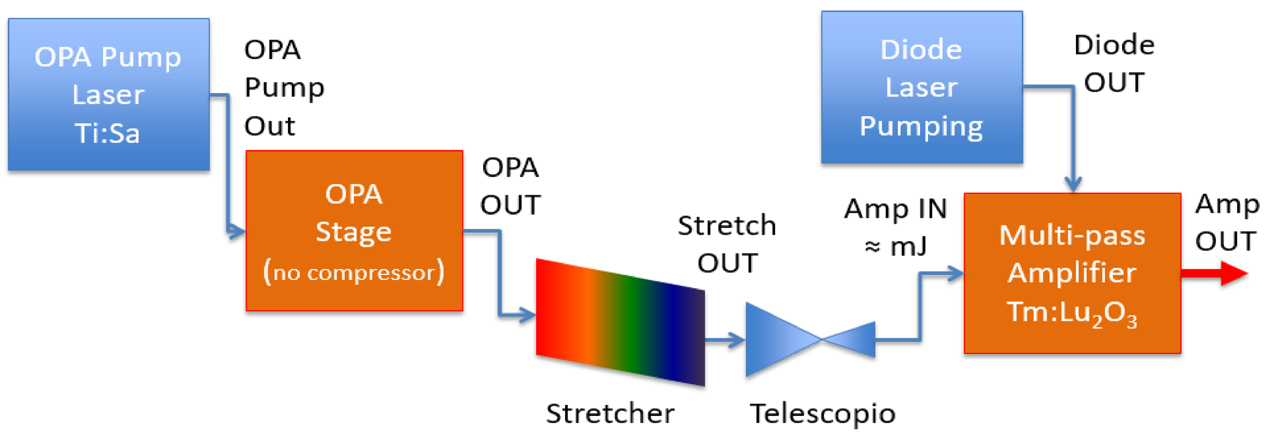
Introduction

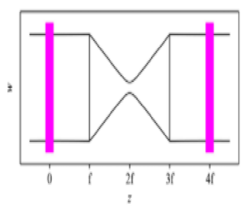
Intense ultrashort pulsed lasers are currently mainly based on Titanium-Sapphire (Ti:Sa) technology which, however, requires frequency-doubled Neodymium (Nd) lasers as optical pumping sources. The use of these ultrashort pulse lasers is currently limited in average power, not exceeding ~ 100 Watts. This limitation is essentially due to the optical pumping technology, based on flash lamps and this inherent high thermal load and low efficiency. Architectures based on Tm-doped gain media (Tm: YLF, Tm: YAG and $Tm:Lu_2O_3$) have recently been proposed for the potential advantages of energy efficiency and scalability at high average power and emission around 2 µm [2].

We report on the conceptual design of an amplification chain based on Tm-doped gain medium [1], for solid-state, ultra-short CPA laser pulses, aiming at high-efficiency, kHz repetition rate, high peak power and kW-scale average power, with emission wavelength around 2 µm. A multi-pass configuration is presented, with three stages, with 4% doped $Tm:Lu_2O_3$ ceramic thin discs, lateral (edge) [3] pumping (EPDL) scheme with an output energy of >500mJ from an input energy pulse of 1 mJ. The modelling of multipass extraction (at the 1kHz rep rate) and thermal load is also studied and discussed.

Overall architecture and amplifier(s) design

- 3 amplification stages, each based on 2 active media with a 4f multipass scheme. Active mirror configuration with CW lateral pumping (EPDL), with cooling on both front and rear sides.
- Selected doping: 4% atomic
- Pulse energy (each stage): 1mJ from front-end, >5 mJ seeding 1th amp, >60mJ from 2nd amp, >500mJ from 3rd amp





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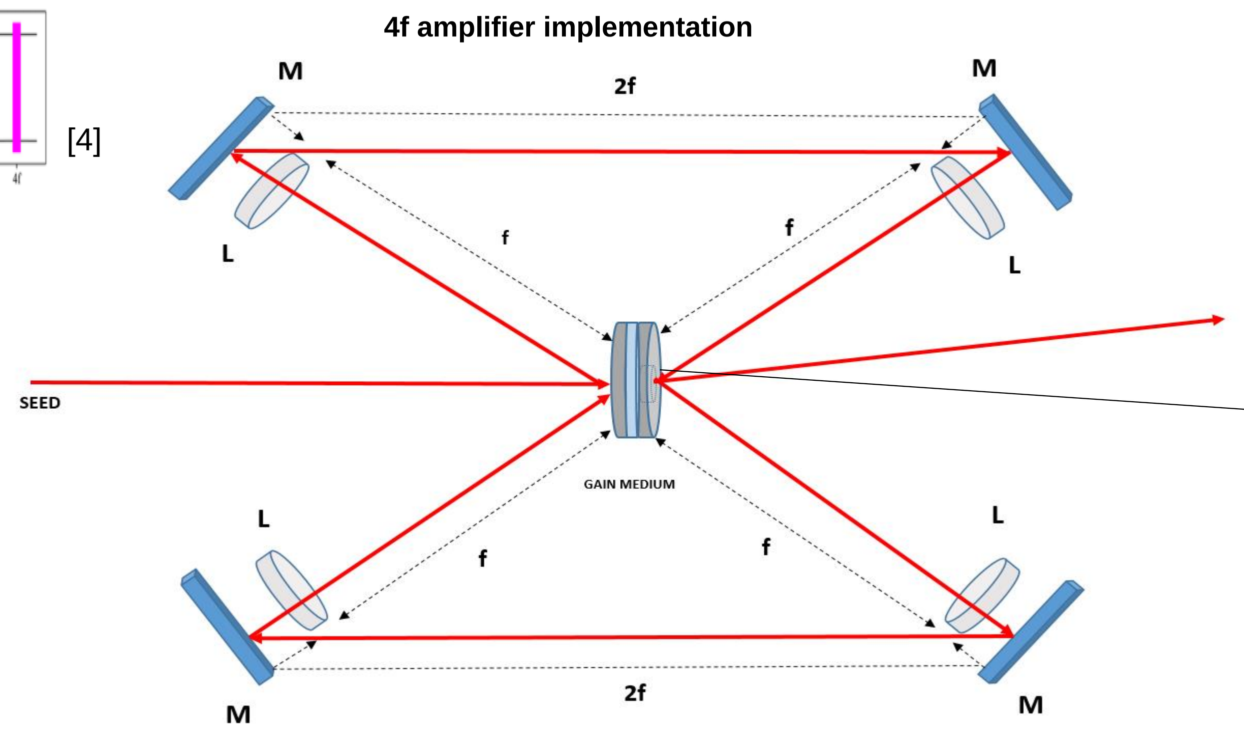
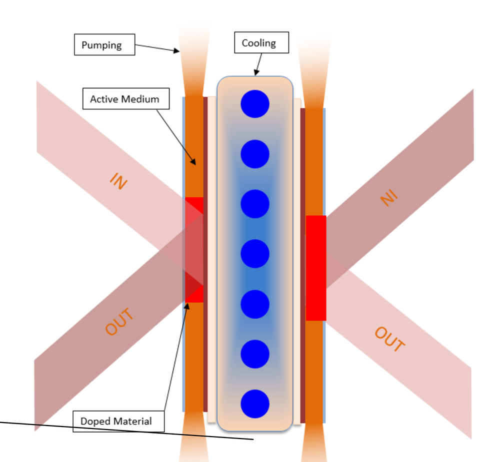
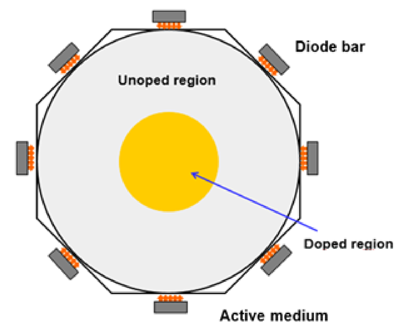
4f amplifier implementation



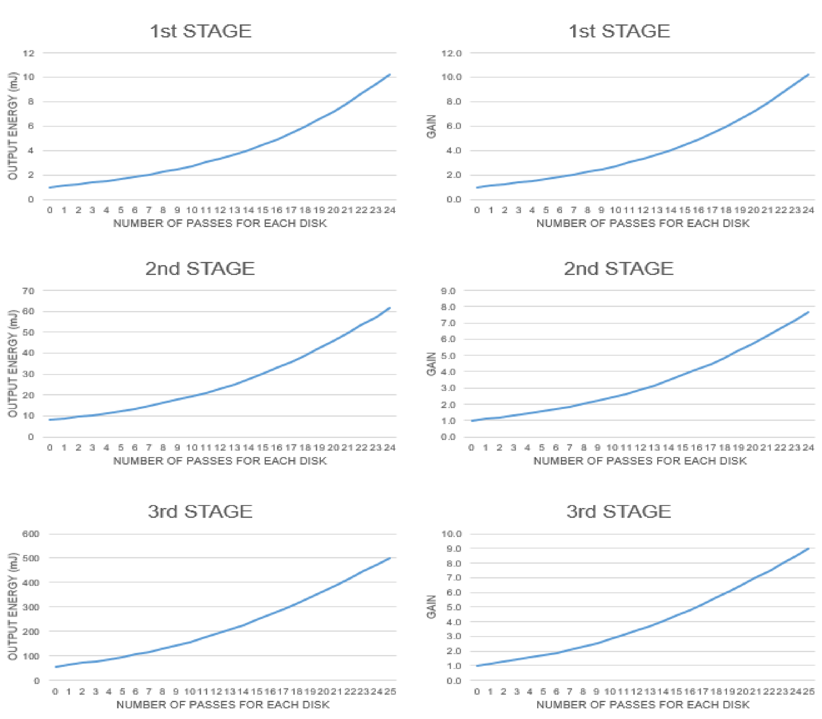
Detail of the gain media structure



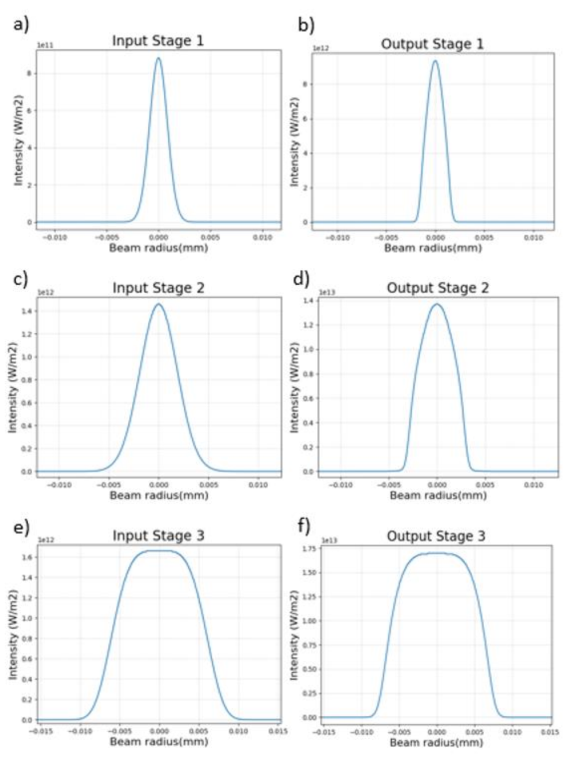
Basic pumping scheme (8-sided holder)



Output energy and gain vs number of passes

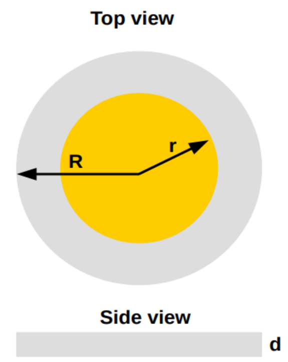


Input and output beam profile of each stage



Amplifier 1 (2X)	Amplifier 2 (2X)	Amplifier 3 (2X)
d= 3mm	d= 3mm	d= 3mm
R= 6mm	R= 6mm	R= 15mm
r= 2mm	r= 4mm	r= 8mm

Top view



STAGE	SEED DIAMETER (mm)	SEED PROFILE	PUMP DIAMETER (mm)	PUMP PROFILE	PUMP ENERGY DENSITY (J/m3)	TOTAL PUMP ENERGY (mJ)	INPUT ENERGY (mJ)	OUTPUT ENERGY (mJ)	NUMBER OF PASSES FOR EACH DISK	EXTRACTION EFFICIENCY
1st	2	GAUSSIAN	4	SUPERGAUSSIAN OF ORDER 5	3.05E+06	230	1	10	24	0.04
2nd	4.4	GAUSSIAN	7	SUPERGAUSSIAN OF ORDER 5	3.00E+06	700	8	61	24	0.09
3rd	12	SUPERGAUSSIAN OF ORDER 2	18	SUPERGAUSSIAN OF ORDER 5	3.00E+06	4600	56	510	25	0.11

Thermal Management

- FEM simulation model developed (using Mathematica) to study the heat distribution in the active medium
- Different longitudinal power distribution to optimize the heat dissipation were tested
- A maximum temperature of ~300° C (for the third stage) is expected.

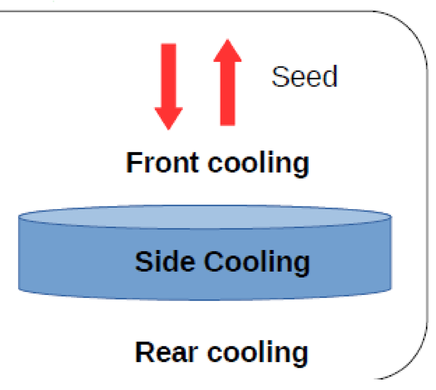
HEAT DISTRIBUTION MODEL

Heat Trasfer Equation (numerically solved):

$$\rho c_p \partial_t T(t,x) + \vec{\nabla}\cdot\left(-k(T(t,x))\vec{\nabla}T(t,x)\right) = Q(t,x)$$

Neumann contition on spatial boundaries:

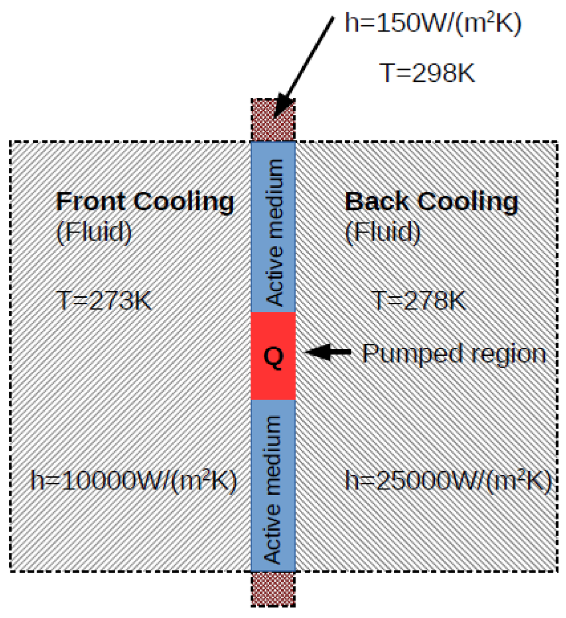
$$\frac{\partial T}{\partial n} = \frac{h}{k}\left(T_{amb} - T(t,x)\right)$$



Active medium parameters:

- Density: 9.33 g/cm³
- Specific heat capacity: c_p=0.24 J/gK
- Thermal conductivity: k=12.3 W/mK
- Intensity: ≈0.6 J/cm²

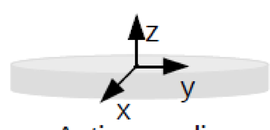
$$Q_{max} = \frac{E_p \cdot \nu_L \cdot \eta_h}{V_p}$$



LONGITUDINAL POWER DISTRIBUTION SIMULATIONS

For preliminary results an idealized SuperGaussian source Q(x,y,z) has been used. For a pumping frequency in the KHz range, the source model can be considered stationary.

$$Q = A(z)B(t)Q_0 e^{-\left(\frac{(x^2+y^2)}{r^2}\right)^{10}}$$



The functions A(z) and B(t) may taken into account the longitudinal power distribution and the duty cycle respectively. Different Longitudinal heat distribution models can be used to model different longitudinal doping profiles:

Linear:

$$A(z) = 1 + \frac{2\alpha}{d}z,\quad -1 \le \alpha \le 1,\quad -\frac{d}{2} \le z \le \frac{d}{2}$$

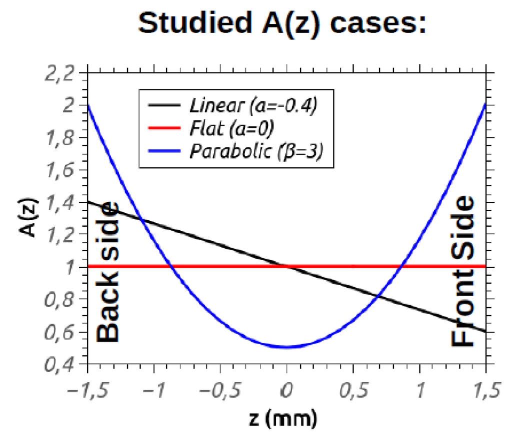
Parabolic:

$$A(z) = \frac{1+\beta\,|2z/d|^2}{1+\beta/3},\quad \beta \ge 0,\quad -\frac{d}{2} \le z \le \frac{d}{2}$$

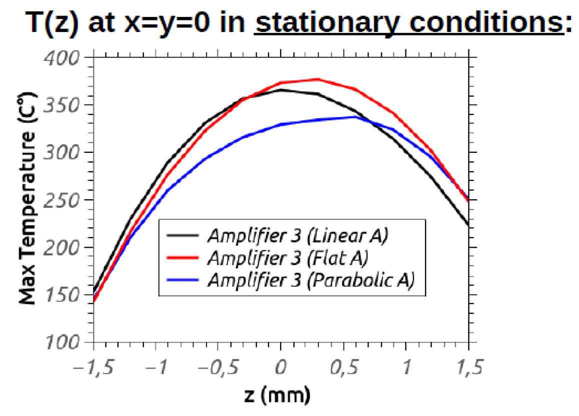
$$\frac{1}{d}\int_{-d/2}^{d/2} A(z)\,dz = 1$$

The total power is independent on A(z).

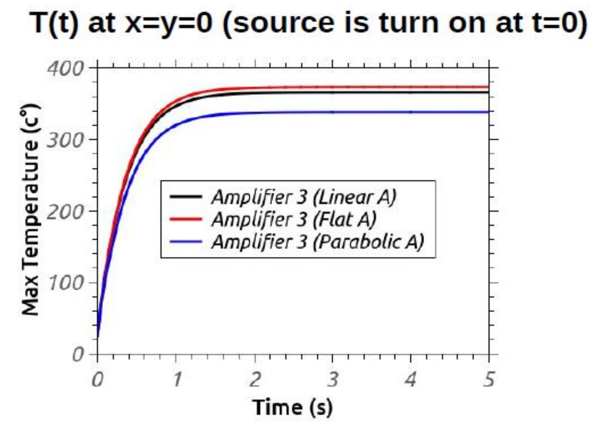
Studied A(z) cases:



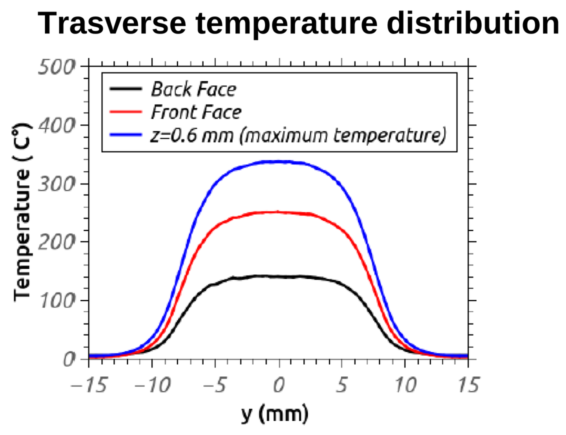
T(z) at x=y=0 in stationary conditions:



T(t) at x=y=0 (source is turn on at t=0)



Trasverse temperature distribution



With a parabolic heat distribution we decrease the density power on the inner disk regions, which are the most difficult to be cooled due the low thermal conductivity. In case of a single cooled face, however, it is convenient to adopt an exponential-like distribution.

Conclusions

- Conceptual design of a 500mJ, 1kHz amplification chain based on Tm:Lu2O3 carried out;
- Optical amplification simulations predict an extraction efficiency up to ~10% so far,
- Thermal management simulations show the need for longitudinal power distribution and both rear and front cooling to reduce maximum temperature/gradient.

References

[1] D.A.Copeland et al., "Wide-Bandwidth Tm-Based Amplifier for Laser Acceleration Driver", Proc. of SPIE Vol. 9729, 97290I, (2015)· doi: 10.1117/12.2220010
[2] E.V. Ivakin et al., "Laser ceramics Tm:Lu2O3. Thermal, thermo-optical, and spectroscopic properties", Optical Materials 35 499–503 (2013). doi:10.1016/j.optmat.2012.10.002
[3] J. Vetrovec, et al., "Wide-Bandwidth Ceramic Tm:Lu2O3 Amplifier", Proc. SPIE 9834, 983407 (2016); doi:10.1117/ 12.2224411
[4] Karsten Schuhmann,et al., "Multipass amplifiers with self-compensation of the thermal lens." Applied optics, Optical Society of America, 2018, 57 (35), pp.10323. ff10.1364/AO.57.010323ff. ffhal-01980145f

Acknowledgement

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