Qualifying Exam

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July 10th, 2009

Papers

1. Christoph Wandt, et al, "**Generation of 220 mJ nanosecond pulses at a 10 Hz repetition rate with excellent beam quality in a diode-pumped Yb:YAG MOPA system,"** Optics Letters 33, 1111-1113 (2008).

2. Stuart Pearce, et al, **“Efficient generation of 200 mJ nanosecond pulses at 100 Hz repetition rate from a cryogenic cooled Yb:YAG MOPA system,”** Optics Communications 282, No. 11, 2199-2203 (2009).

3. D. Albach, et al, **"Influence of ASE on the gain distribution in large size, high gain Yb3+:YAG slabs,"** Optics Express 17, 3792-3801 (2009).

Outline

- Introduction
  - Diode Pumped Solids State Lasers (DPSSL)
  - Yb:YAG
  - Limitations of High Energy Laser Systems
- Laser Systems:
  - Paper 1: **“Generation of 220 mJ nanosecond pulses at a 10 Hz repetition rate with excellent beam quality in a diode-pumped Yb:YAG MOPA system”**
  - Paper 2: **“Efficient generation of 200 mJ nanosecond pulses at 100 Hz repetition rate from a cryogenic cooled Yb:YAG MOPA system”**
  - Comparison of Systems
- Paper 3: **"Influence of ASE on the gain distribution in large size, high gain Yb3+:YAG slabs"**

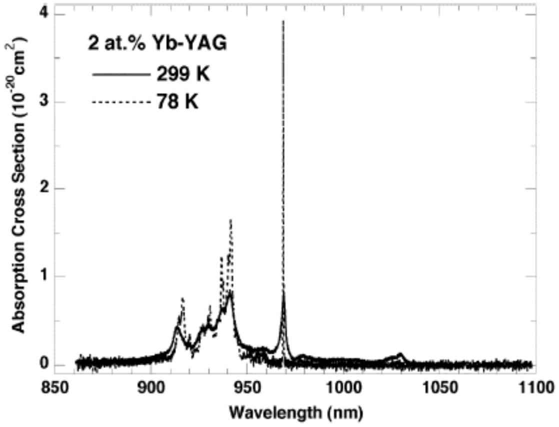
- Questions

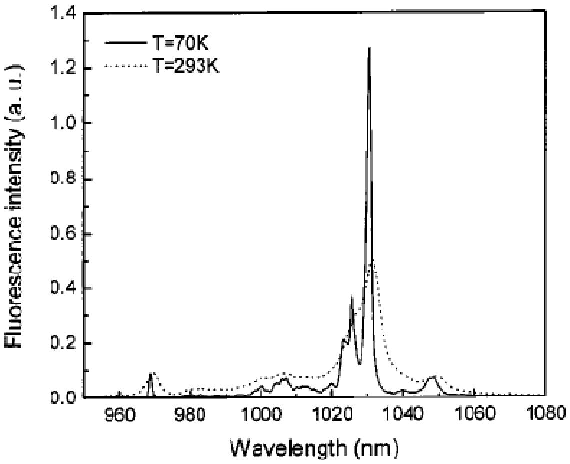
Diode Pumped Solid State Lasers

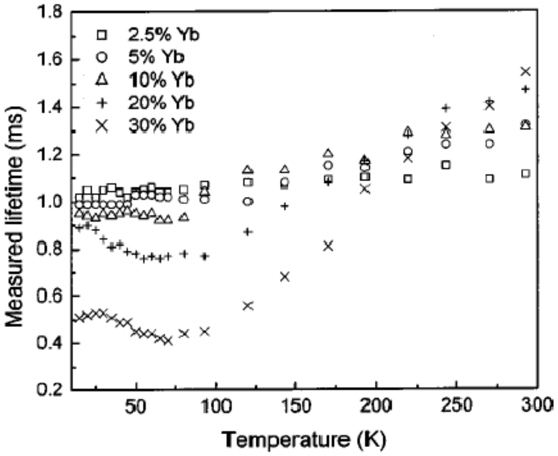
Advantages:

- Extremely compact
  - Delivers kilowatts in a few cc's
- Narrow bandwidth
  - Capable of efficiently pumping a single transition
- Very efficient (electrical efficiency >50%)
  - Greatly simplifies cooling for high average power
- Reasonable beam quality
  - Capable of end-pumping solid state lasers

Yb:YAG







Absorption spectrum is ideal for pumping with 940 nm laser diodes.

Emission cross section peaks at 1030 nm, $\eta_{quantum}$ = 90%.

Long upper level lifetime, τ = 1 ms, is favorable for diode pumping.

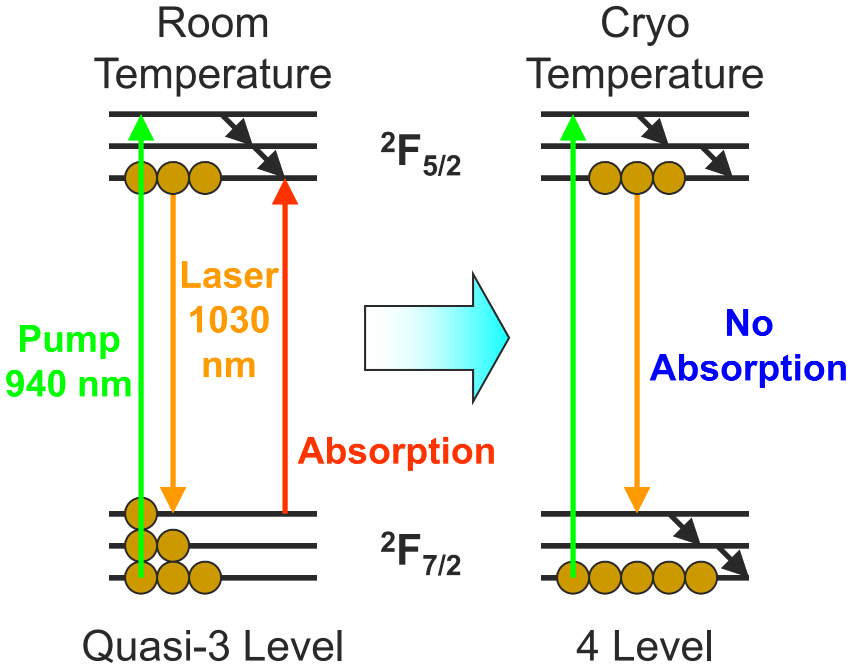
Ripin, D.J et al. "300-W cryogenically cooled Yb:YAG laser," Quantum Electronics, IEEE Journal of , vol.41, no.10, pp. 1274-1277, Oct. (2005)

J. Dong, M. Bass, Y. Mao, P. Deng, and F. Gan, "Dependence of the Yb3+ emission cross section and lifetime on temperature and concentration in yttrium aluminum garnet," J. Opt. Soc. Am. B 20, 1975-1979 (2003).

Cryogenic Yb:YAG

Comparison between Yb:YAG at room temperature and LN_2 temperature

	300ºK	77ºK	
κ (W/mºK)	10	90	x9
dn/dT (10^{-6} ºK)	9	1.2	x1/7
α (10^{-6}/ºK)	7	1.6	x1/4
F_{sat} (J/cm^2)	10	1.5	x1/7



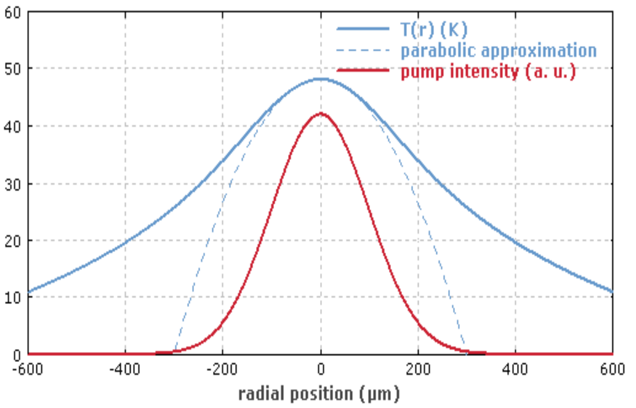
- A number of material properties are improved when cooled to cryogenic temperatures.

G. A Slack and D. W. Oliver; Phys. Rev. B4; 592-609 (1971)

R. Wynne, J. L. Daneu and T. Y. Fan; Appl. Opt. 38, 3282-3284 (1999)

Limitations of high energy laser systems

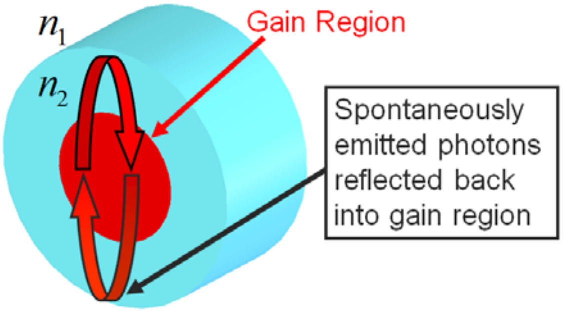
- Thermal Effects
  - Thermal lensing



  - Thermal depolariziton

http://www.rp-photonics.com/thermal_lensing.html

- Amplified Spontaneous Emission



Spontaneously emitted photons reflected back into gain region

- Nonlinear Effects
  - In most materials the refractive index increases with increasing intensity
  - Self-focusing can occur.

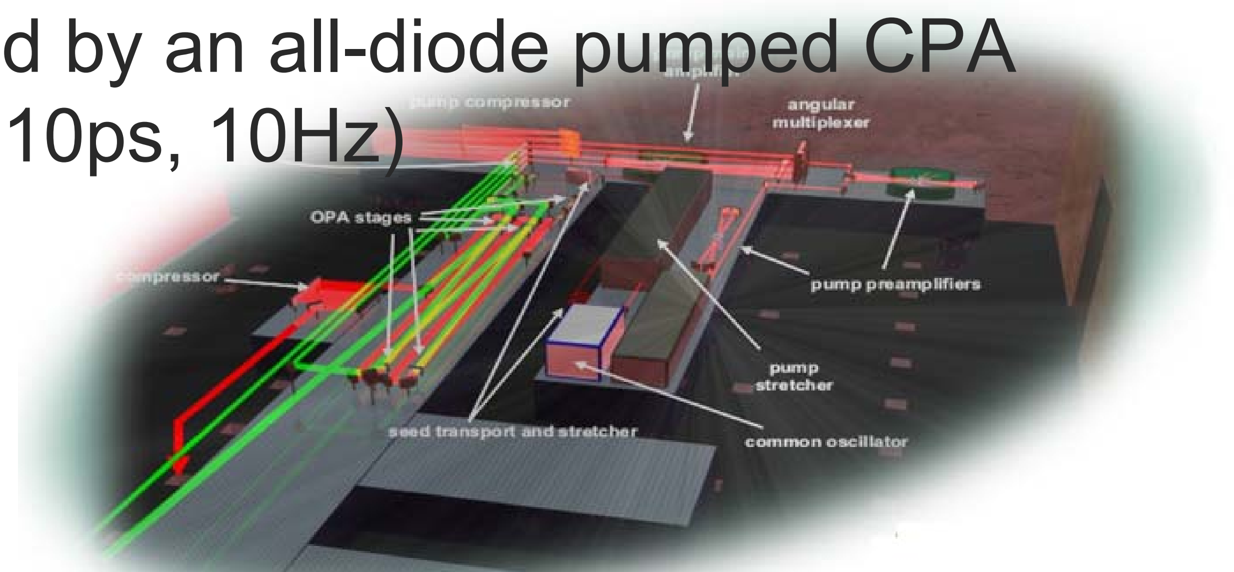
$$B = \frac{2\pi}{\lambda} \int n_2 I(z)\, dz$$

Paper 1

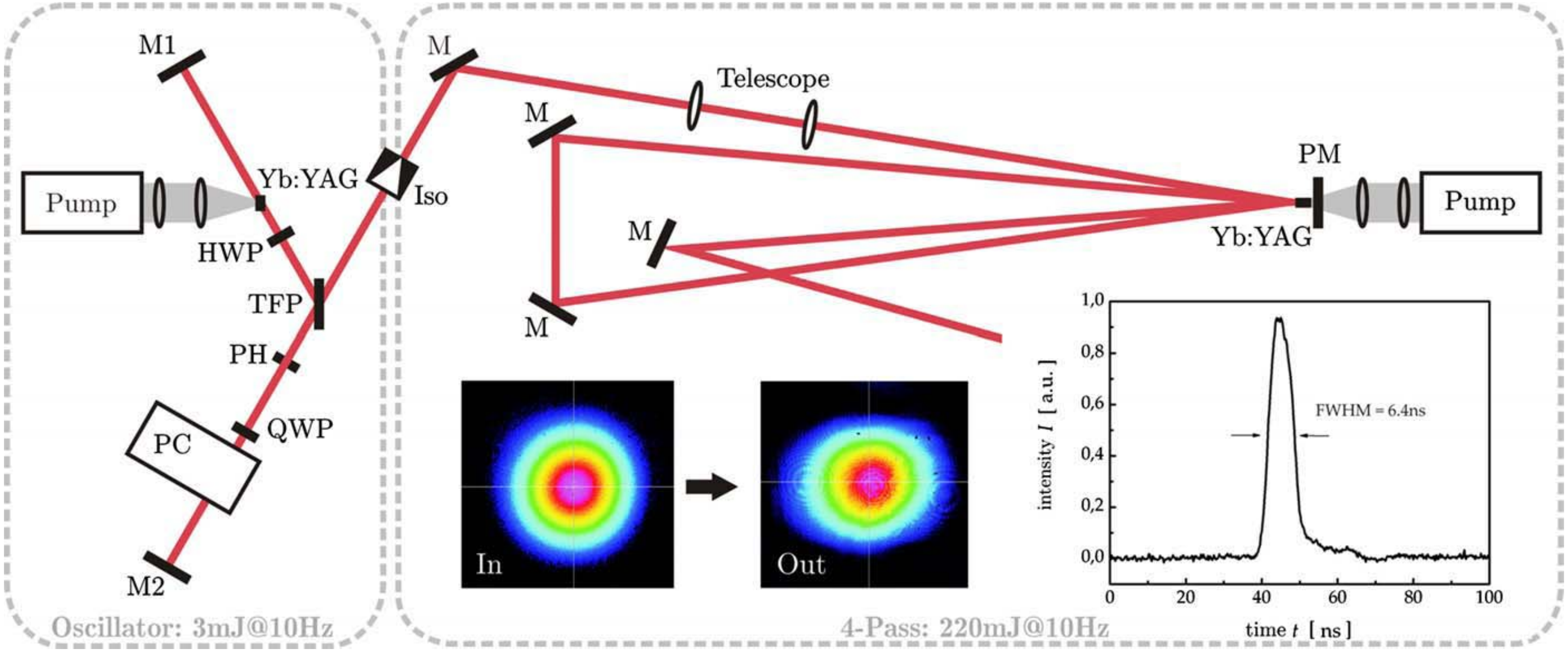
Christoph Wandt, et al, "**Generation of 220 mJ nanosecond pulses at a 10 Hz repetition rate with excellent beam quality in a diode-pumped Yb:YAG MOPA system,"** Optics Letters 33, 1111-1113 (2008).

Motivation

- Petawatt Field Synthesizer
  - Designed to generate multiJoule, few-cycle pulses at high repetition rates (>3J, <5 fs, 10 Hz) .
- Based on Optical Parametric Chirped Pulse Amplification (OPCPA).
- OPCPA pumped by an all-diode pumped CPA system (50J, 1-10ps, 10Hz)

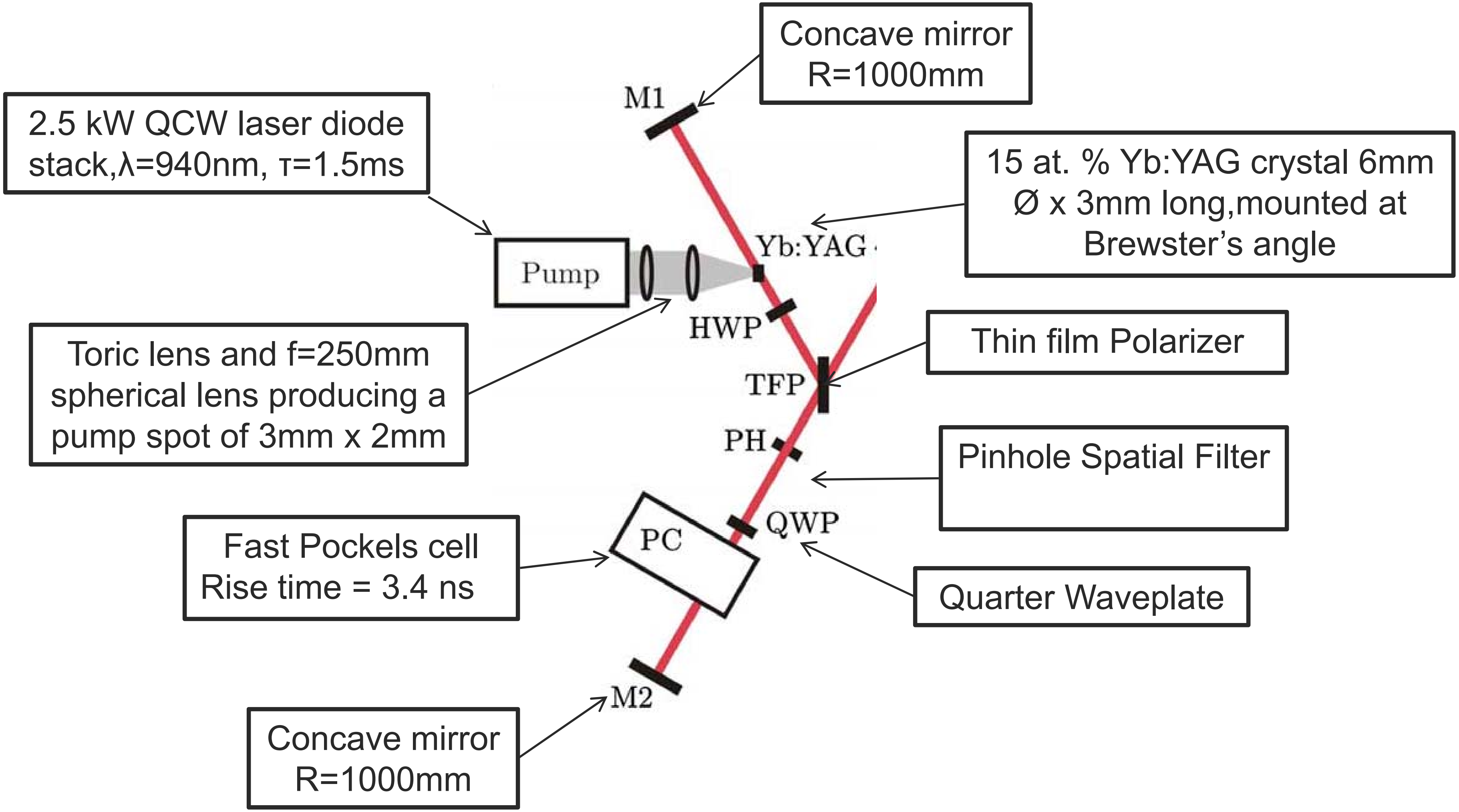


Laser System



- Very simple amplification scheme.
  - Q-switch oscillator delivering 3mJ pulses seeds a 4-pass amplifier to achieve 220 mJ.
  - Operated at room temperature.

Oscillator cavity



Concave mirror
R=1000mm

2.5 kW QCW laser diode
stack,λ=940nm, τ=1.5ms

15 at. % Yb:YAG crystal 6mm
Ø x 3mm long,mounted at
Brewster's angle

Toric lens and f=250mm
spherical lens producing a
pump spot of 3mm x 2mm

Thin film Polarizer

Pinhole Spatial Filter

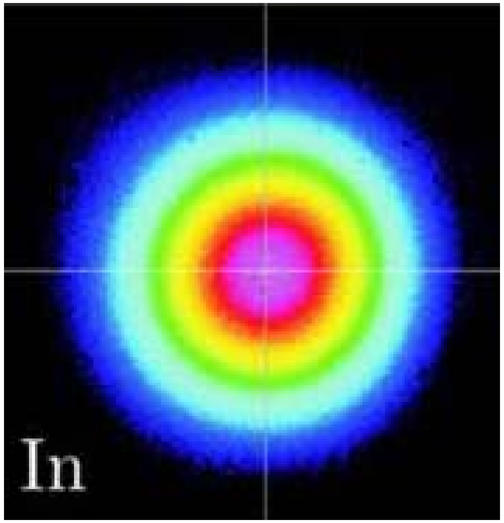
Fast Pockels cell
Rise time = 3.4 ns

Quarter Waveplate

Concave mirror
R=1000mm

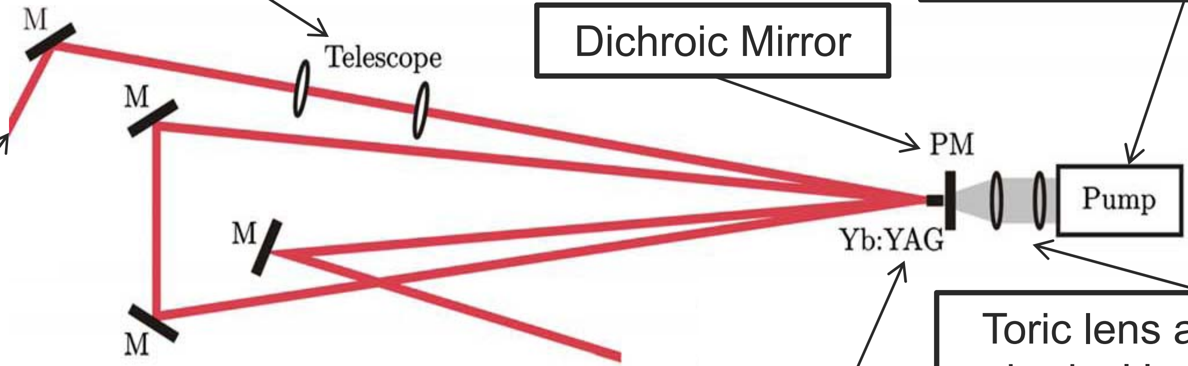
Oscillator Results

- 3 mJ, 6.4 ns FWHM pulses were obtained with a pump energy of 1 J in 1.5 ms.
- Thermal lensing was significant, $f_{thermal}$ = 200-500 mm, and had to be accounted for in cavity design.
- Excellent beam quality, $M^2 = 1.2$.



- Maximum energy was limited by damage to the thin film polarizer.

Amplifier layout



Telescope for collimation and mode-matching

2.5 kW QCW laser diode stack ,λ=940nm, τ=1.5ms

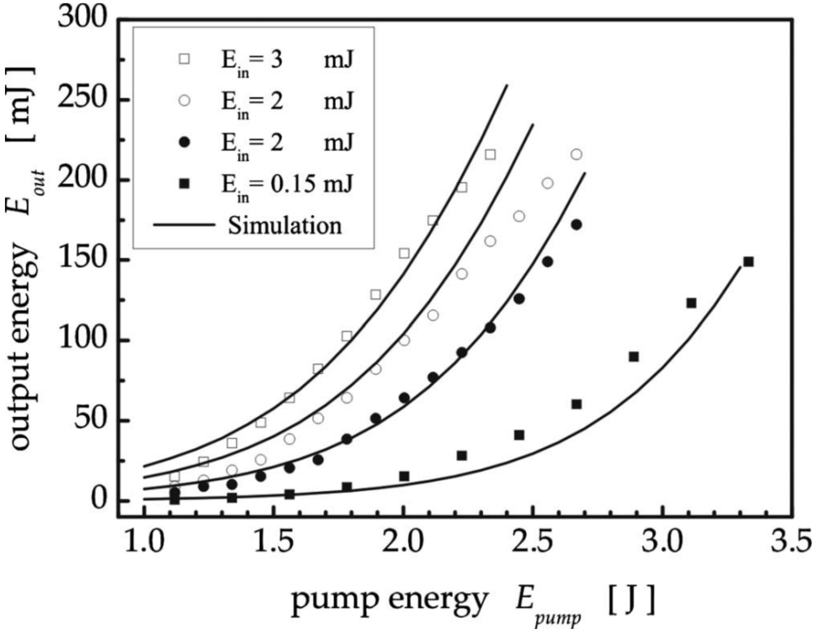
Dichroic Mirror

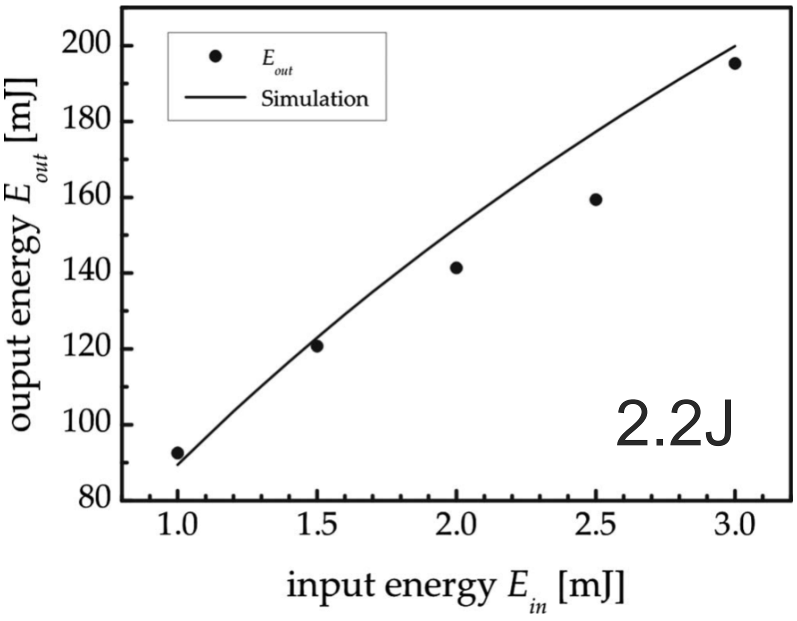
3 mJ from Oscillator

Toric lens and f=250mm spherical lens producing a pump spot of 3mm x 2mm

3 at. % Yb:YAG crystal 6mm Ø x 8mm long, AR coated

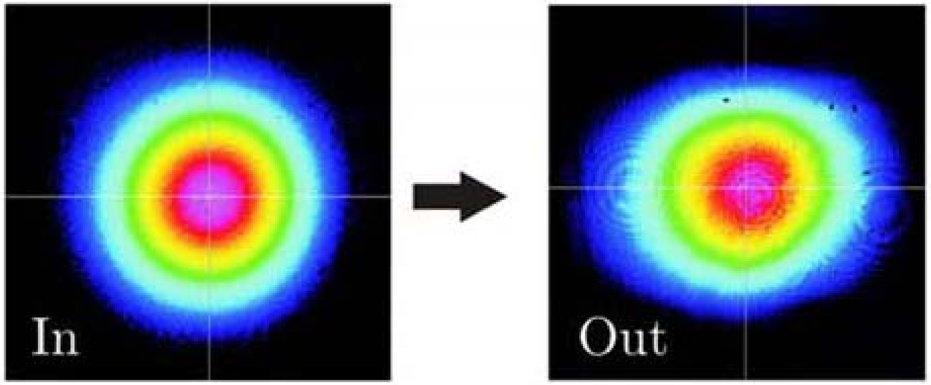
Results





- 220 mJ pulses were demonstrated, limited by damage to the final mirror.
- 700 mJ max output was observed in QCW mode.
- Amplifier was not operated in saturation.

Results



- “Good” beam quality is preserved
  - No M^2 measurement after amplification is reported.
  - Thermal distortions of the beam profile are also not discussed.

Summary

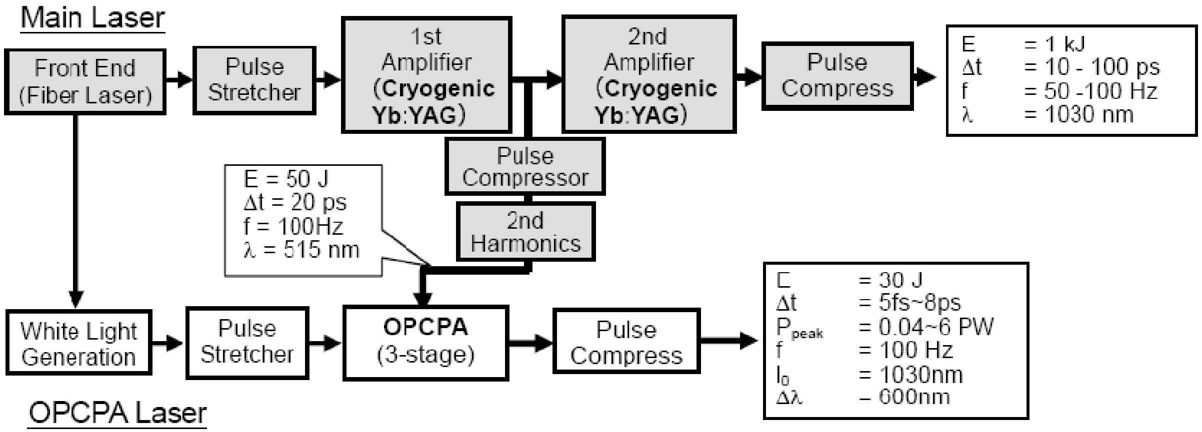
- 220 mJ, 6.4 ns pulses at 10 Hz were obtained from an all diode-pumped, very compact laser system.
- Optical to optical efficiency was low: ~10% for amplifier, 0.3% for oscillator.
- Direct operation in CPA may be difficult due to damage threshold issues.
- Beam quality appears to be ok, but there are no measurements and the discussion of thermal distortions is lacking.
- Limitation in repetition rate is blamed on driver electronics but is probably more likely to be limited by thermal lensing.

Paper 2

- Stuart Pearce, et al, **“Efficient generation of 200 mJ nanosecond pulses at 100 Hz repetition rate from a cryogenic cooled Yb:YAG MOPA system,”** Optics Communications 282, No. 11, 2199-2203 (2009).

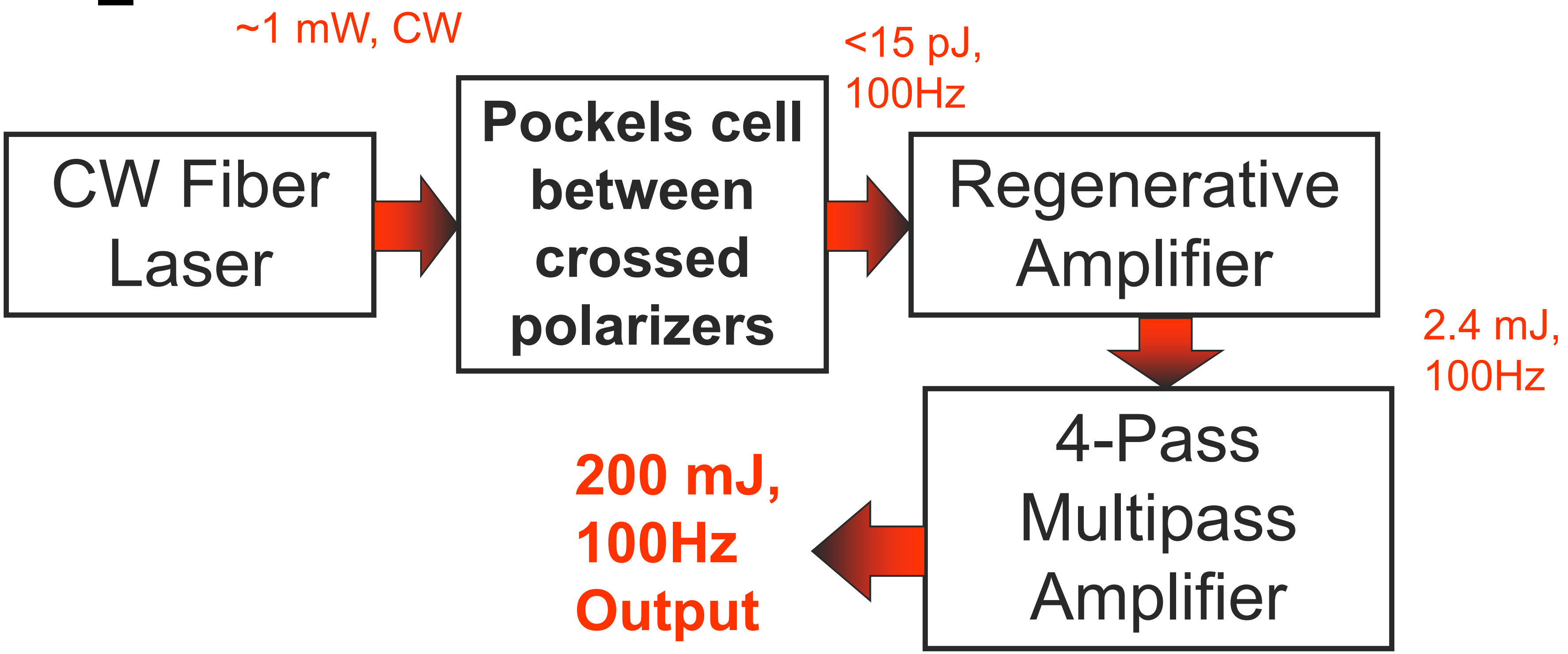
Motivation

- GENBU laser
  - Diode-pumped Yb:YAG System: **1kJ, 10 ps, 100 Hz**
  - Yb:YAG pumped OPCPA: **30 J, 5 fs, 100Hz, 6 PW**
- Utilize **cryogenically-cooled** Yb:YAG
- All diode-pumped 200 mJ, 10 ns, 100 Hz laser developed to test feasibility of cryo-cooled Yb:YAG



www.ile.osaka-u.ac.jp/zone1/public/publication/apr/.../6/6.25.pdf

Laser System Layout



~1 mW, CW

CW Fiber Laser

Pockels cell between crossed polarizers

<15 pJ, 100Hz

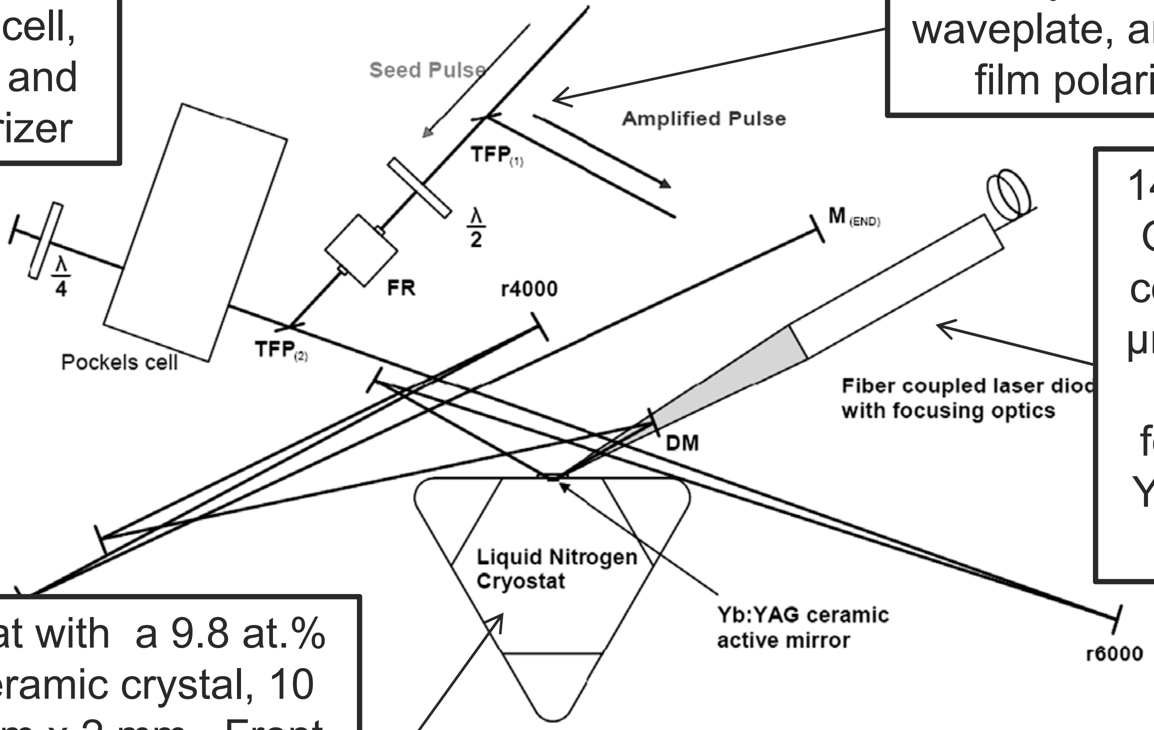
Regenerative Amplifier

2.4 mJ, 100Hz

4-Pass Multipass Amplifier

200 mJ, 100Hz Output

Regenerative Amplifier



Fast Pockels cell, ¼ waveplate, and thin film polarizer

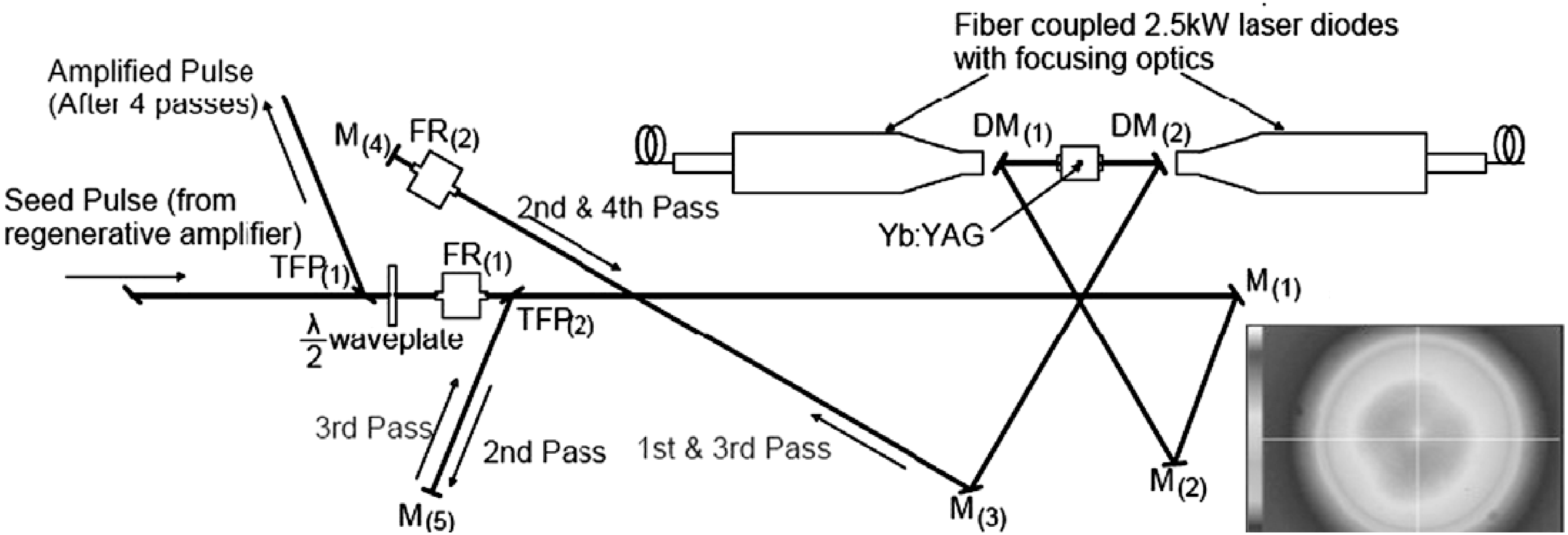
Faraday Rotator, ½ waveplate, and thin film polarizer

140 W peak power QCW laser diode coupled into a 600 µm core fiber. The pump light was focused on to the Yb:YAG through a dichroic mirror.

LN2 cryostat with a 9.8 at.% Yb:YAG ceramic crystal, 10 mm x 10 mm x 2 mm. Front surface is uncoated, back surface coated HR for 940 nm and 1030 nm. The laser beam had a 1/e^2 spot size of 1.8mm on the crystal.

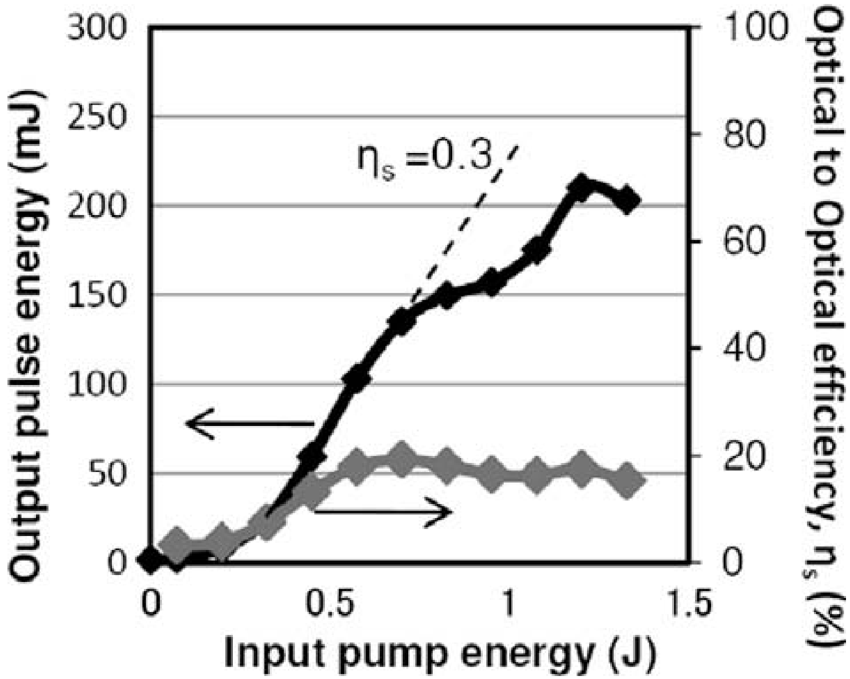
- Sub-15pJ seed pulses were amplified to 4.6 mJ at 100 Hz in about 30 roundtrips.

Multipass Amplifier



- 12mm diameter by 6.6 mm long 5.5 at.%Yb:YAG rod with a pump spot size of 4mm.
- Pumped by two 2.5 kW peak power fiber-coupled laser diodes stacks with pulse durations between 50µs – 2ms.

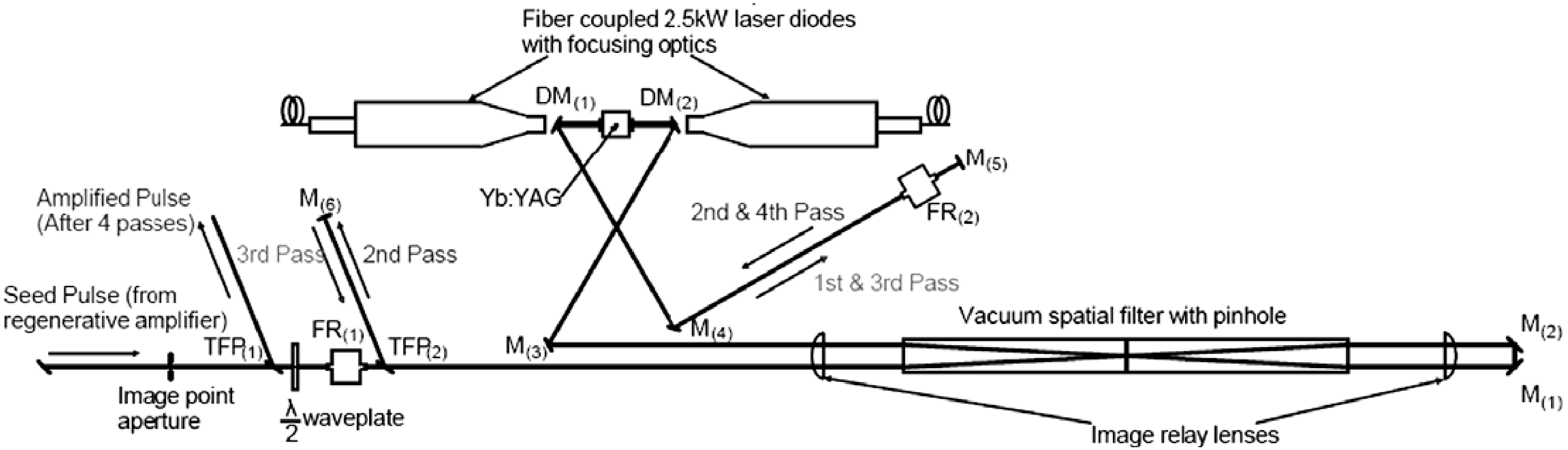
Results



700 µs pump pulse duration

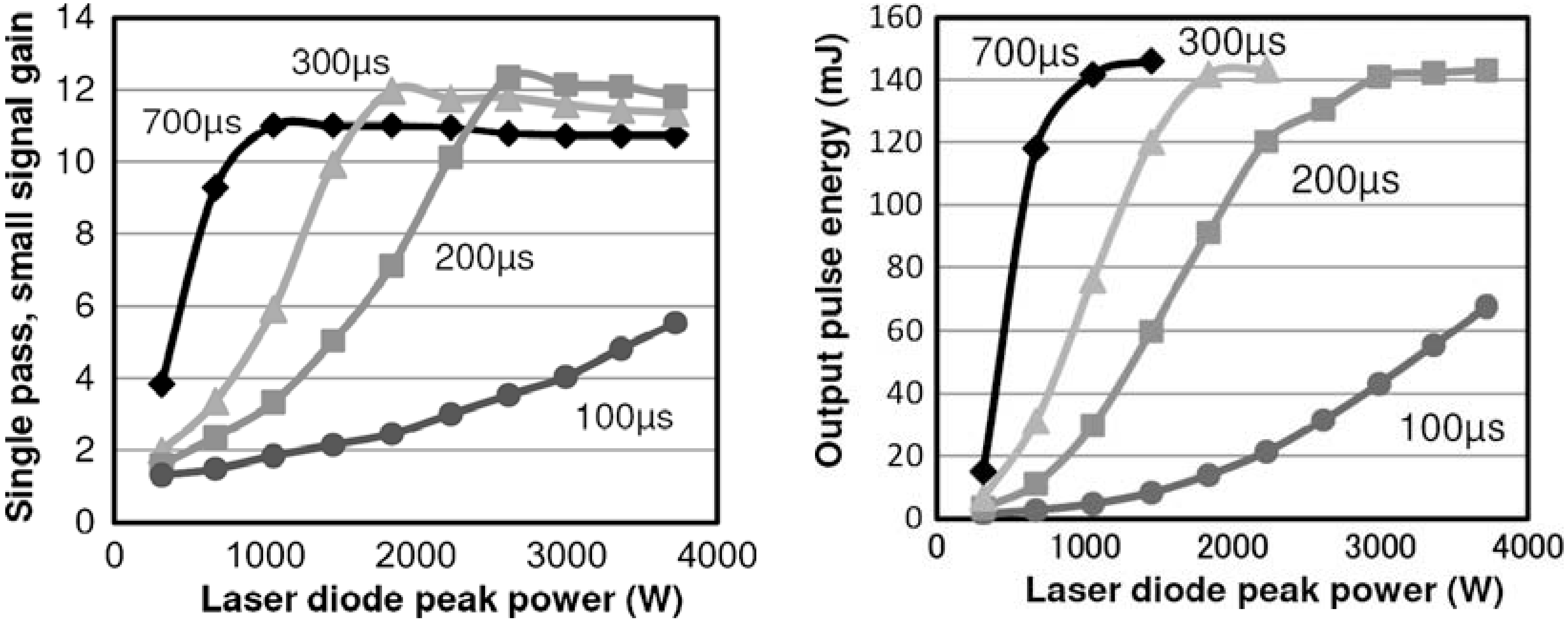
- 214 mJ pulses at 100 Hz repetition rate were achieved.
- Slope efficiency of 30% and optical-optical efficiency of 19% were observed.
- After 0.7J of input pump energy very interesting behavior is observed:
  - Initial saturation is attributed to amplified spontaneous emission
  - Further increase in output energy is reported to be due to thermal lensing improving mode-matching
  - At the highest pump energies, thermal lensing reduces mode-matching

Multipass Amplifier 2



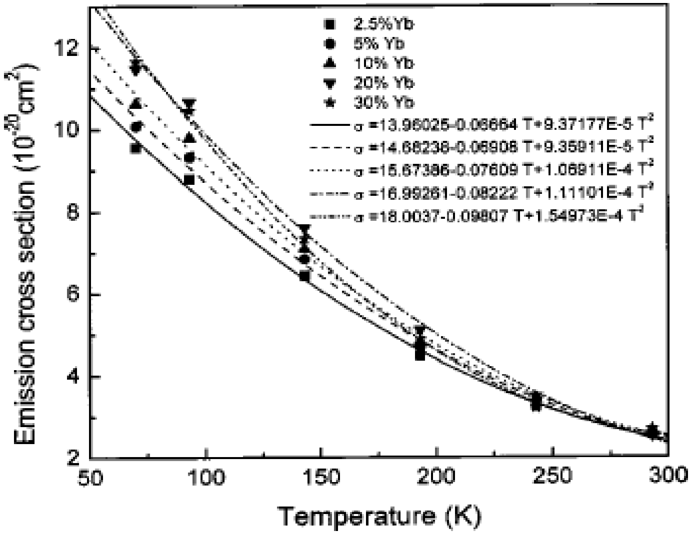
- Added a vacuum spatial filter and relay imaging telescopes before the first and third passes to improve mode-matching and beam quality.
- Repetition rate was reduced to 10 Hz to decrease thermal lensing effects.

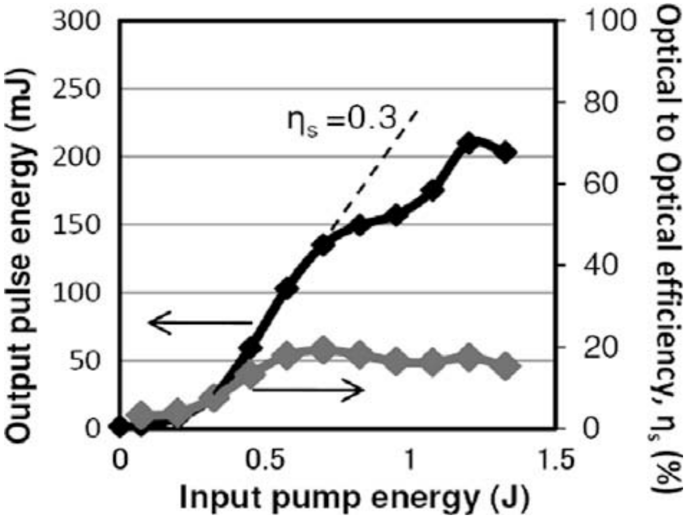
Results with imaging and filtering at 10 Hz



- Small signal gain measurements show significant ASE and parasitic lasing losses, but also possible thermal effects.
- Maximum pulse energy is reduced to ~150 mJ
- Higher efficiencies were obtained: $\eta_{o\text{-}o}$=30% and η_s=44%

Gain Cross Section vs. Temp

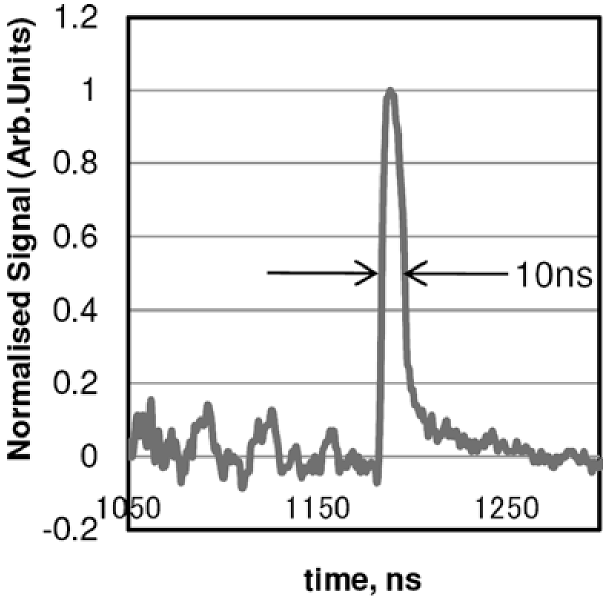


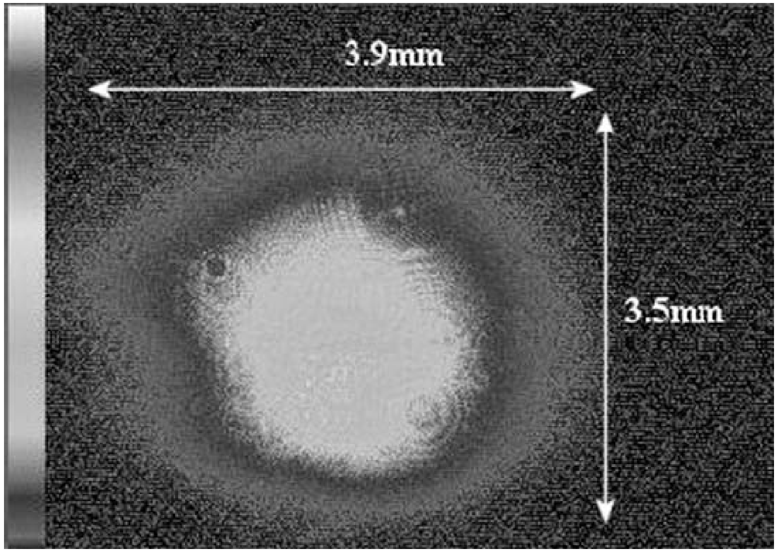


- Near liquid nitrogen temperature the stimulated emission cross section of Yb:YAG changes relatively quickly.
- In a multipass amplifier a small change in temperature can have a large effect on the gain.
- Lower gain also lessens the effects of ASE and increases the maximum possible stored energy.
- A measurement of the small signal gain vs. repetition rate would clarify this.

J. Dong, M. Bass, Y. Mao, P. Deng, and F. Gan, "Dependence of the Yb3+ emission cross section and lifetime on temperature and concentration in yttrium aluminum garnet," J. Opt. Soc. Am. B 20, 1975-1979 (2003).

10 Hz Results Cont.





- Noisy temporal pulse profile shows 10 ns FWHM width but doesn’t provide contrast to ASE info.
- Near-field mode quality of 10 Hz beam appears fairly nice, but no measurements of its ability to propagate nicely were presented.

Conclusions

- 214mJ, 10 ns pulses were generated at 100 Hz from an all diode-pumped laser system based on cryo-cooled Yb:YAG.
- The main amplifier had a fairly high efficiency: ($\eta_{o\text{-}o}$=30%).
- The choice to implement relay imaging at 10 Hz, but not at 100 Hz is puzzling.
- ASE and parasitic lasing were clearly limiting factors, but the importance of heating was not treated properly in the analysis.
- A simple measurement of the single-pass gain vs. repetition rate would clarify the results.

Comparison of 200 mJ Systems

Room temperature system:

- 10 Hz repetition rate.
- Not saturated, significantly more energy is stored than is extracted.
- 10% optical-optical efficiency.
- Significant thermal lensing observed, limiting maximum extractable energy

Cryo temperature system:

- 100 Hz repetition rate
- Operated in saturation, stored energy limited by larger amounts of amplified spontaneous emission and parasitic lasing.
- 30% optical-optical efficiency.

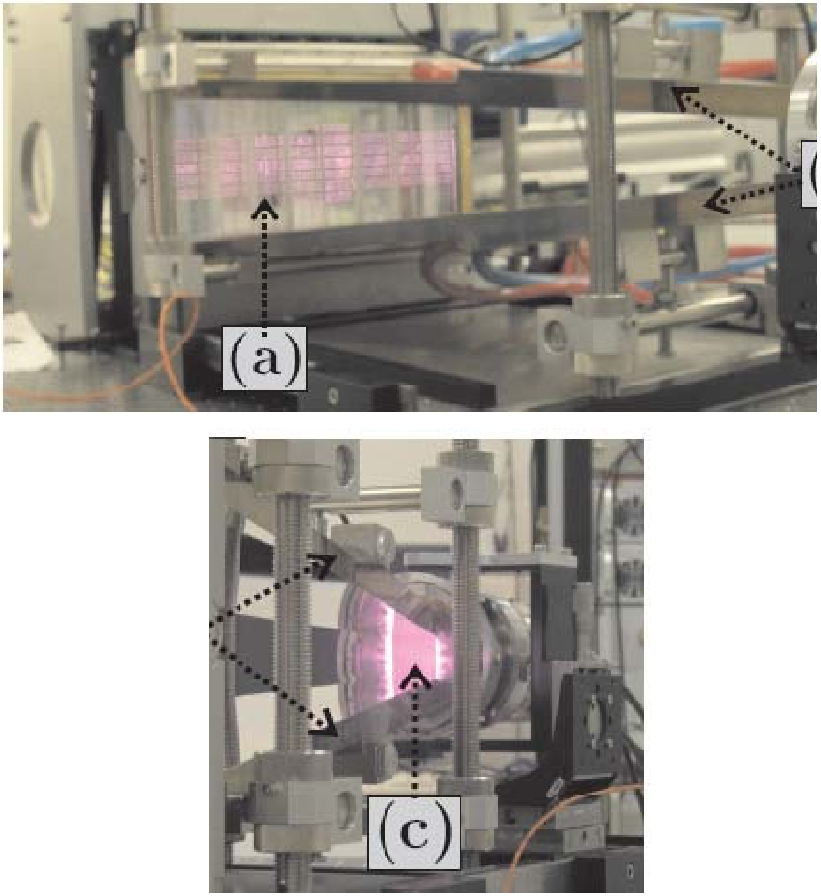
- **Similar systems had different limiting factors due to the differences Yb:YAG displays at room and cryo temperatures.**

Paper 3

- D. Albach, et al, **"Influence of ASE on the gain distribution in large size, high gain Yb3+:YAG slabs,"** Optics Express 17, 3792-3801 (2009).

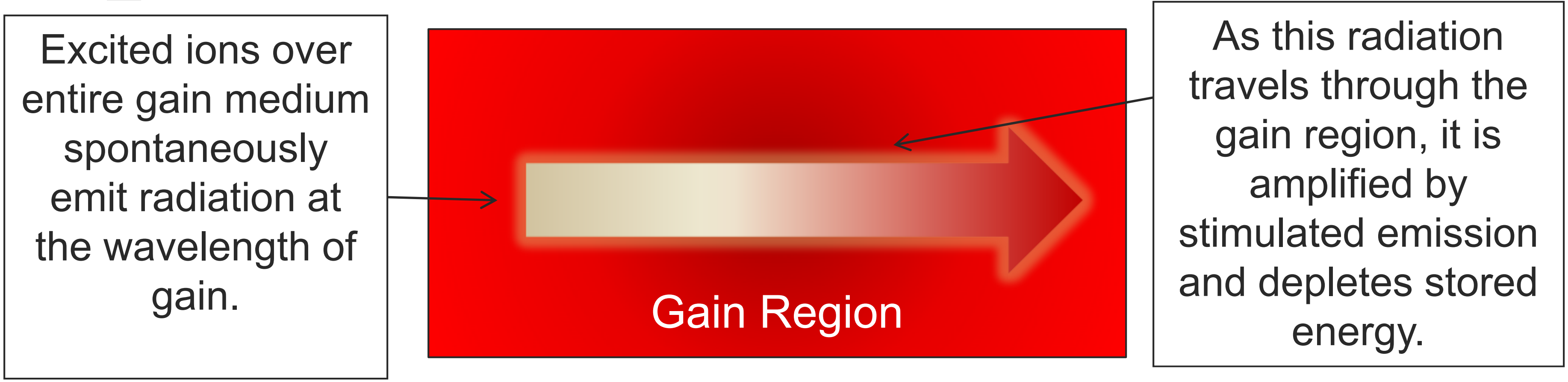
Motivation

- LUCIA laser
  - 100 J, 10 Hz, all diode-pumped.
  - Again, will be used for pumping an OPCPA ultrafast system.
- Large gain regions required in high energy lasers lead to very large Gain x Length products.
- Large GLs lead to amplification of spontaneous emission and parasitic lasing
- Severely limits laser energy storage.



Yb:YAG slab pumped by 88 Laser Diode Stacks, 264 kW in final configuration.

Motivation - ASE



Excited ions over entire gain medium spontaneously emit radiation at the wavelength of gain.

As this radiation travels through the gain region, it is amplified by stimulated emission and depletes stored energy.

- This paper describes the development of a computer model to simulate the effects of ASE in large Yb:YAG slabs.
- Model is benchmarked by temporally and spatially resolved measurements of the small signal gain
- Used to determine the optimal Yb^{+3} density and slab thickness

ASE Equations

Rate equation for the density of ions on the upper laser level:

$$\frac{dn}{dt} = \frac{dn}{dt}\Big|_{pump} - \frac{dn}{dt}\Big|_{SE} \times \boxed{M_{ASE}}$$

where: $\frac{dn}{dt}pump = \frac{P/V}{h\nu}$, $\frac{dn}{dt}SE = \frac{n}{\tau}$

$$M_{ASE}(\vec{r}_0) = 1 + \tau_{rad}(\vec{r}_0)\int_\lambda \Big[\underbrace{\sigma_a(\lambda,\vec{r}_0)\left(1 - \frac{n_{tot}(\vec{r}_0)}{n(\vec{r}_0)}\right)}_{\text{Absorption}} \underbrace{+\,\sigma_e(\lambda,\vec{r}_0)\Big]}_{\text{Stimulated Emission}} \underbrace{\Phi_{ASE}(\lambda,\vec{r}_0)\,d\lambda}_{\text{ASE Flux}}$$

$$\Phi_{ASE}(\lambda,\vec{r}_0) = \underbrace{\frac{1}{4\pi}\int_V \frac{1}{|\rho(\vec{r},\vec{r}_0)|^2}}_{\text{Fraction of solid angle incident at } r_o.} \underbrace{\frac{n(\vec{r})}{\tau_{rad}(\vec{r})}}_{\text{Photons emitted from r per unit time per volume}} \underbrace{g(\lambda)\,G_{\vec{r}\to\vec{r}_0}\,dV}_{\text{Gain between r and } r_o}$$

ASE Equations

Assuming the monochromatic case and constant lifetime:

$$M_{ASE}(\vec{r}_0) = 1 + \frac{1}{4\pi}\left[\sigma_a\left(1 - \frac{n_{tot}(\vec{r}_0)}{n(\vec{r}_0)}\right) + \sigma_e\right]\int_V \frac{n(\vec{r})}{|\rho(\vec{r},\vec{r}_0)|^2}\, G_{\vec{r}\to\vec{r}_0}\, dV$$

$$\frac{dn}{dt} = \frac{P/V}{h\nu} - \frac{n}{\tau} \times M_{ASE}$$

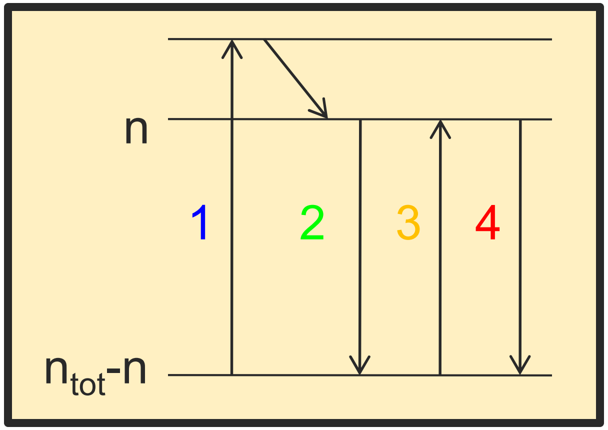
The M_{ASE} factor can be interpreted as a local reduction of the upper level lifetime.

Rewriting by distributing terms:

$$\frac{dn}{dt} = \frac{P/V}{h\nu} - \frac{n}{\tau} + \Phi_{ASE}\left[\sigma_a\left(n_{tot} - n\right) - \sigma_e n\right]$$

1 2 3 4

This analysis assumes a 3-level system which is not the case of Yb:YAG, but is ok as long as σ_a includes the Boltzmann factor.



ASE Equations

- If ASE becomes so strong that it compensates the pump, we can derive a maximum population inversion $n_{\max}$:

$$0=\frac{P/V}{h\nu}-\frac{n_{\max}}{\tau}\times M_{ASE}=\frac{I_P}{h\nu_P}\sigma_P(n_{tot}-n_{\max})-\frac{n_{\max}}{\tau}\times M_{ASE}$$

$$n_{max}\approx\frac{I_P\,n_{tot}}{I_{satp}M_{ASE}+I_P}$$ Where: $$I_p=PumpIntensity,I_{satp}=\frac{h\nu_{pump}}{\tau\sigma_p}$$

- To quickly check if ASE is important one can:
- 1. Calculate n neglecting ASE.
- 2. Using this n estimate $M_{ASE.}$
- 3. Then compare n_{max} and n. If n_{max} is comparable or smaller than n, ASE cannot be neglected.

ASE in Papers 1 and 2

1. Calculate n neglecting ASE.
2. Using this n estimate M_{ASE}.
3. Then compare n_{max} and n. If n_{max} is comparable or smaller than n, ASE cannot be neglected.

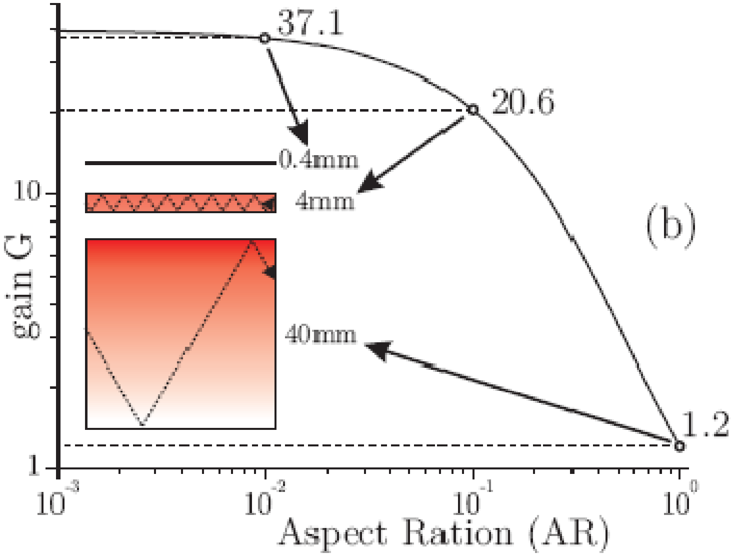
	Room Temperature System	**Cryo Temperature System**
σ_e	2.46e-20 cm^2	1.1e-19 cm^2
σ_a	1.35e-21 cm^2	0
σ_p	8e-21 cm2	1.6e-20 cm^2
I_p	26 kW/cm^2	20 kW/cm^2
n (neglecting ASE)	**1.1e20 cm^{-3}**	**7.2e19 cm^{-3}**
M_{ASE}	**1.57**	**18.6**
n_{max}	**1.54e20 cm^{-3}**	**5.1e19 cm^{-3}**

- ASE is much more significant in Cryo-cooled system.

Model

- Developed a 3-D computer model implementing a Monte-Carlo strategy to estimate the stored energy density.
- In a series of time steps during the pump, the code estimates M_{ASE} using the equation presented earlier, and then calculates the excited state population density at each point in the gain medium.
- The model neglects reflections from the crystal surfaces, which can be significant.

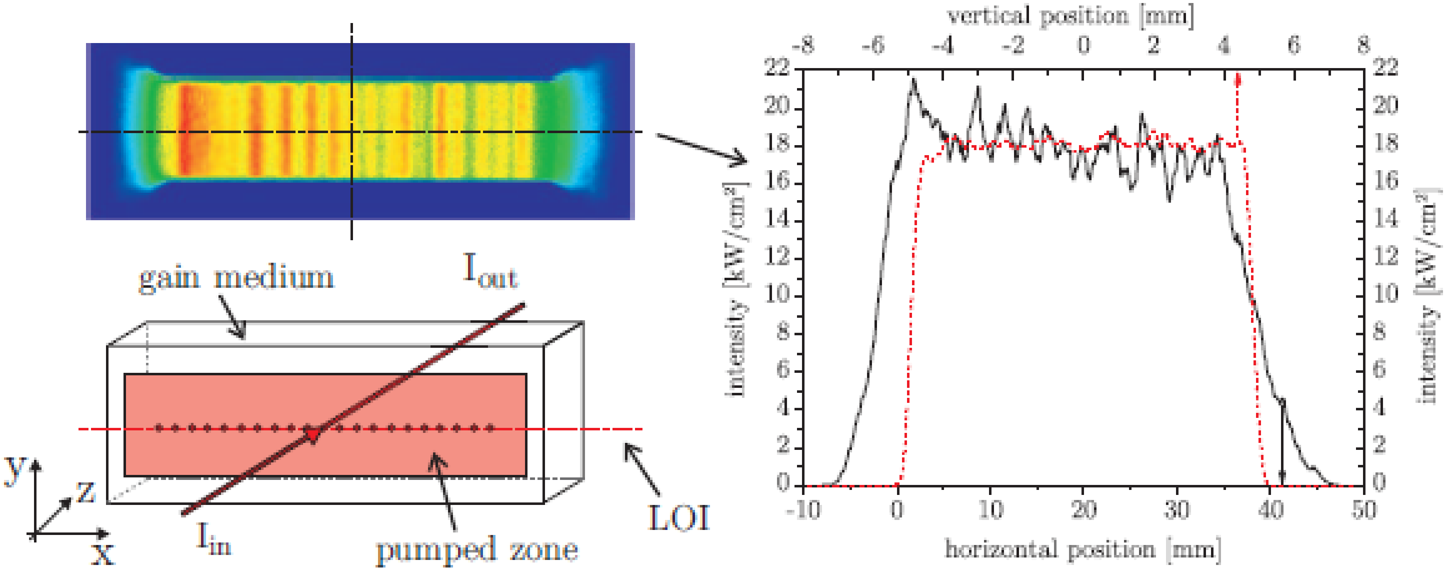
Multiple Reflections



10 kW/cm2,
1% Yb:YAG,
Gain along TIR
Ray

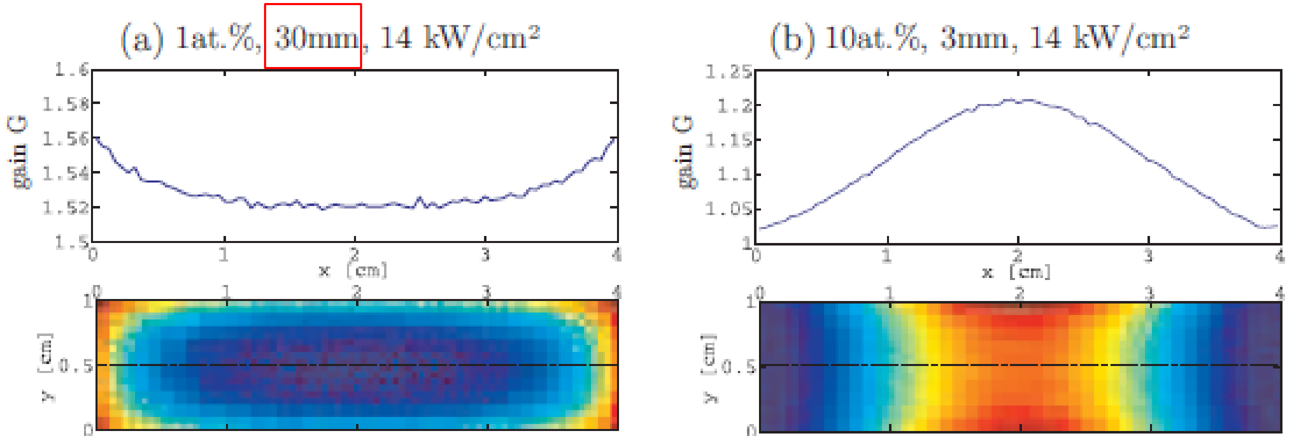
- Total internal reflections rapidly increase ASE.
- Thinner crystals with small aspect ratios are much more susceptible to feedback than longer crystals.

Geometry



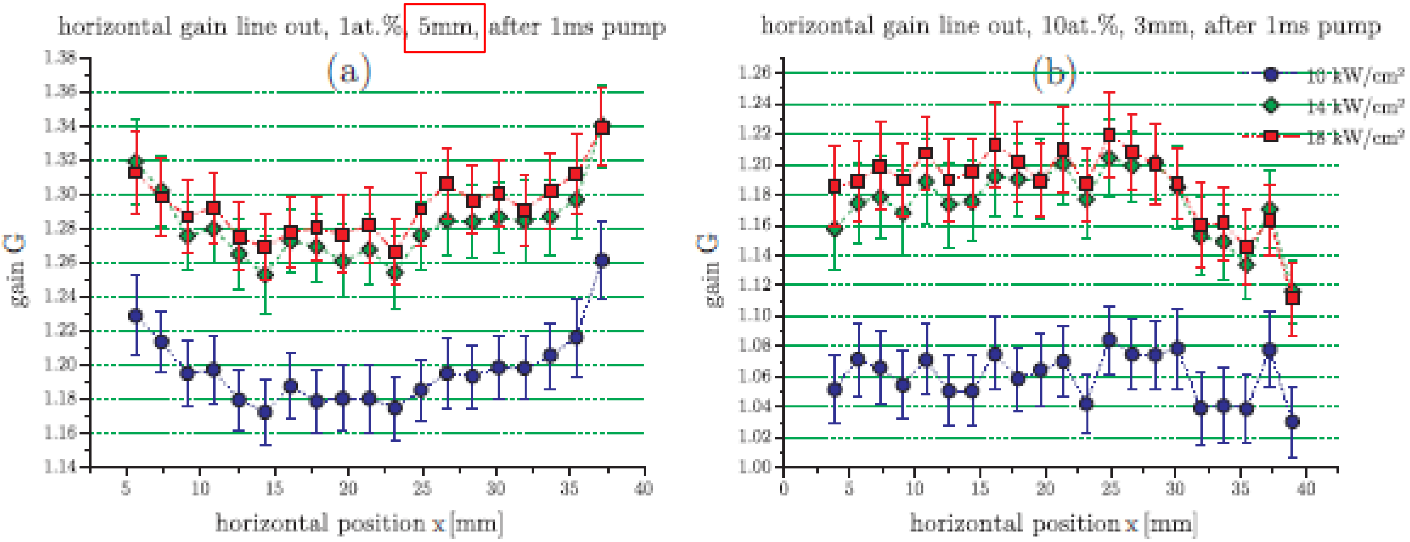
- Gain region is 40 mm x 10 mm with thicknesses ranging 1-6mm.
- Material is Yb:YAG with doping densities between 1 and 10 %-at.
- The slab is pumped uniformly and at normal incidence from the broad face, gain is measured at an angle of 24° AOI.
- The 4 small faces of the crystals were not polished to reduce feedback of ASE back into the gain region.

Model Results vs. Experiment



(a) 1at.%, 30mm, 14 kW/cm²

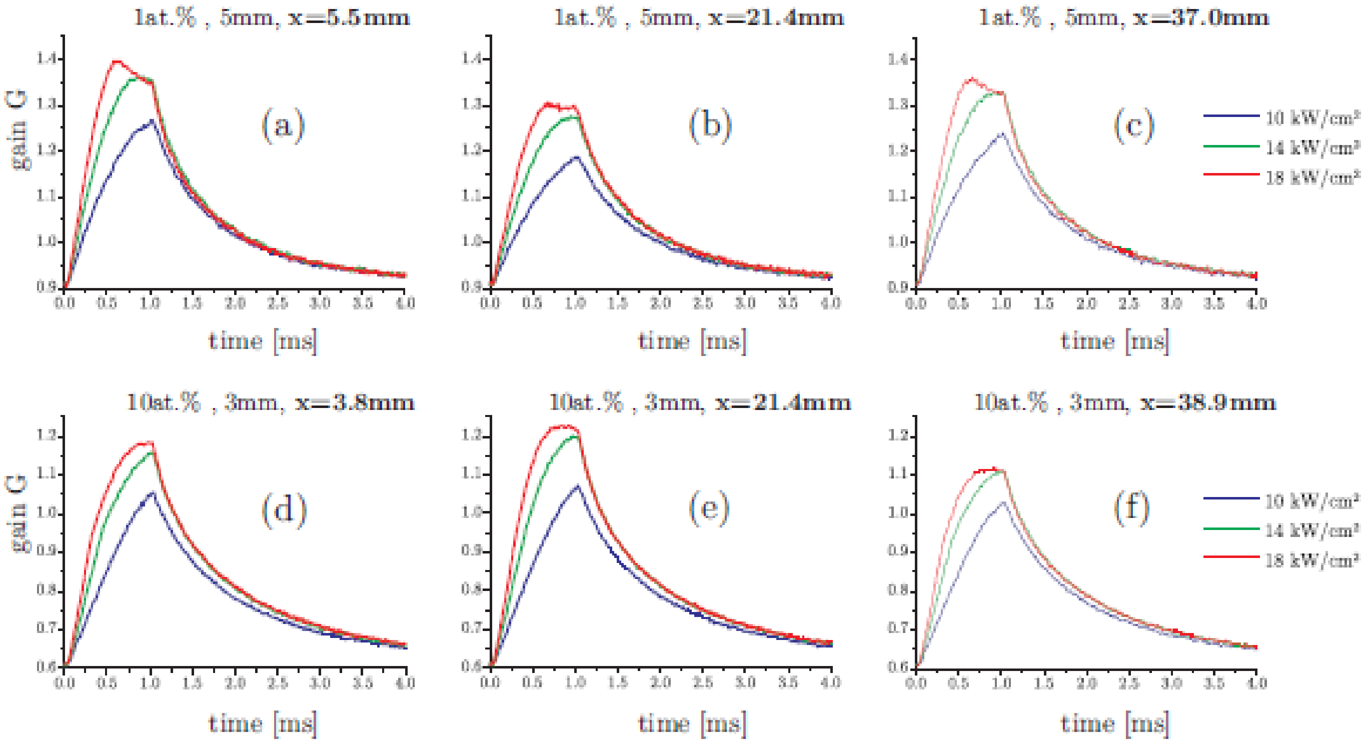
(b) 10at.%, 3mm, 14 kW/cm²



horizontal gain line out, 1at.%, 5mm, after 1ms pump

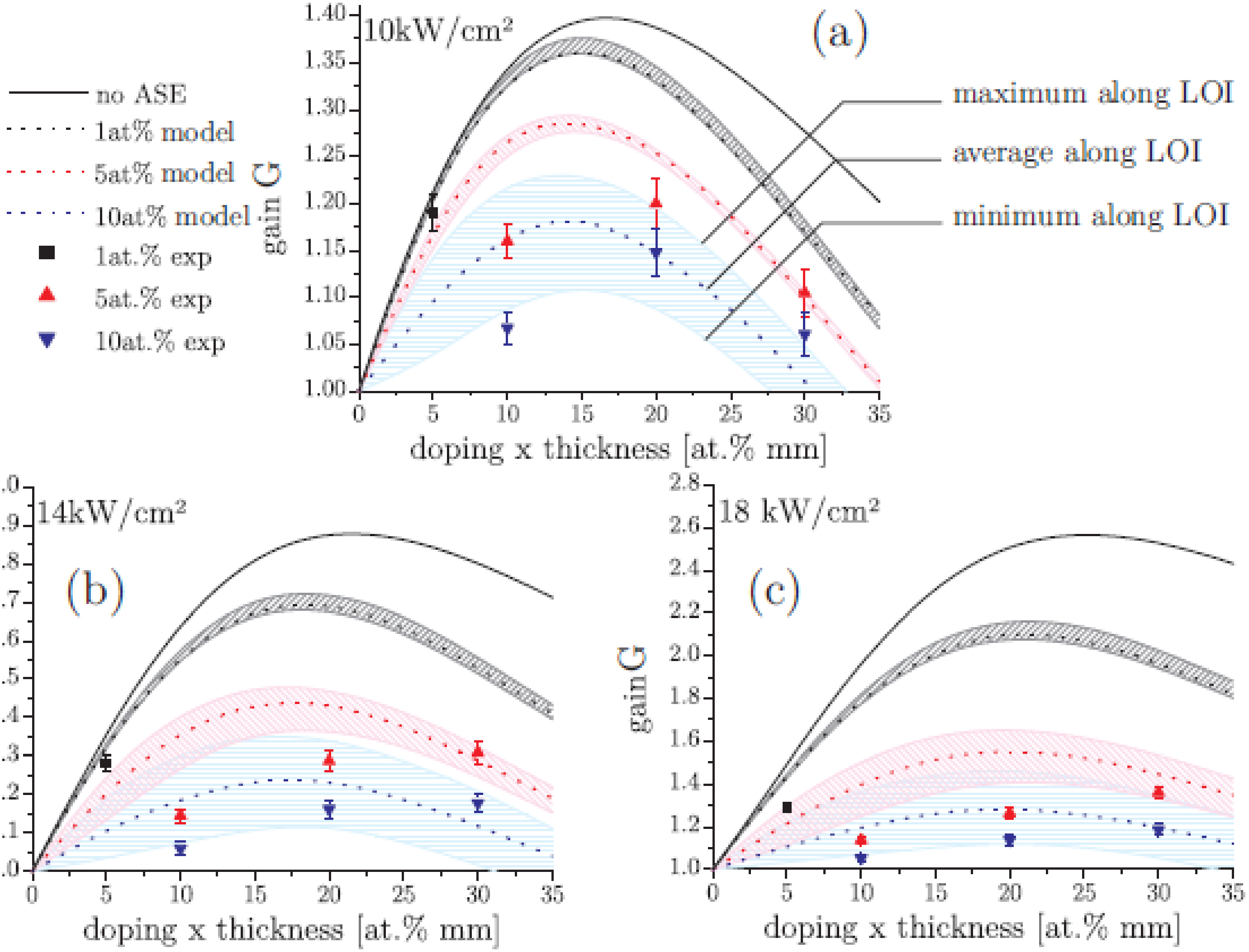
horizontal gain line out, 10at.%, 3mm, after 1ms pump

Temporal Evolution of the Gain (Measured)



- Higher doping required higher pumping to bleach absorption.
- ASE effects are also clearly observed in temporal gain profiles.

Optimum Crystal Specifications



Conclusions

- A relatively straight-forward model of ASE was developed.
- The model results showed modest agreement with experimentally measured values.
- The most serious flaw in the ASE model is neglecting reflections off the surfaces of the crystal.
- The authors demonstrated that longer, lower doped crystals are less susceptible to ASE, however this is not a new result and has been previously recognized. Longer crystals are much more difficult to cool, and can lead to thermal problems.
- The authors also recognize, but made no simulations or measurements, that a crystal with variable doping in the direction of the pump could allow for shorter crystals with lowered ASE.

Acknowledgements

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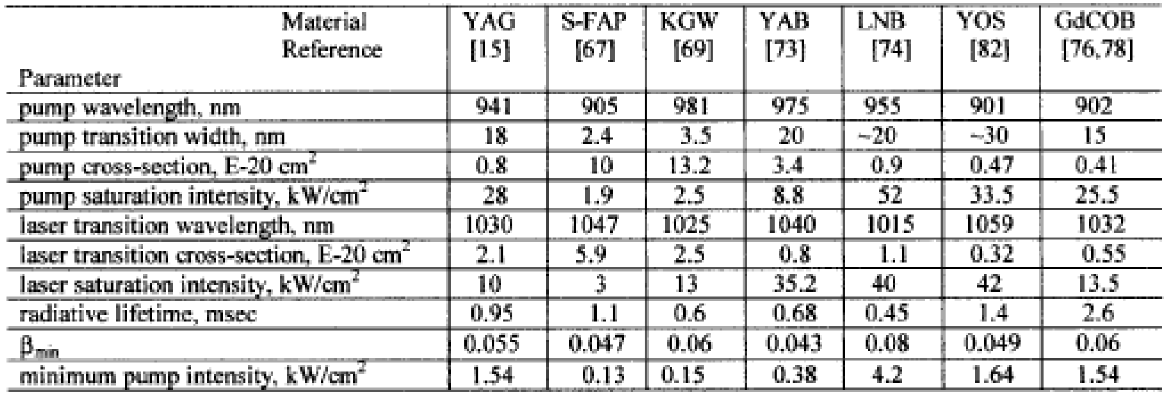
- Federico Furch, Alden Curtis, Mike Grisham, Dale Martz.
- Sean Meehan and Keith Wernsing.
- Committee members: Jorge Rocca, Mario Marconi, Carmen Menoni, David Krueger
- Everyone else at ERC

Questions?

Other YAG Properties

TABLE IV
LASER SPECTROSCOPIC PARAMETERS FOR SEVERAL YTTERBIUM-DOPED CRYSTALS



Material Reference Parameter	YAG [15]	S-FAP [67]	KGW [69]	YAB [73]	LNB [74]	YOS [82]	GdCOB [76,78]
pump wavelength, nm	941	905	981	975	955	901	902
pump transition width, nm	18	2.4	3.5	20	~20	~30	15
pump cross-section, E-20 cm^2	0.8	10	13.2	3.4	0.9	0.47	0.41
pump saturation intensity, kW/cm^2	28	1.9	2.5	8.8	52	33.5	25.5
laser transition wavelength, nm	1030	1047	1025	1040	1015	1059	1032
laser transition cross-section, E-20 cm^2	2.1	5.9	2.5	0.8	1.1	0.32	0.55
laser saturation intensity, kW/cm^2	10	3	13	35.2	40	42	13.5
radiative lifetime, msec	0.95	1.1	0.6	0.68	0.45	1.4	2.6
β_{min}	0.055	0.047	0.06	0.043	0.08	0.049	0.06
minimum pump intensity, kW/cm^2	1.54	0.13	0.15	0.38	4.2	1.64	1.54

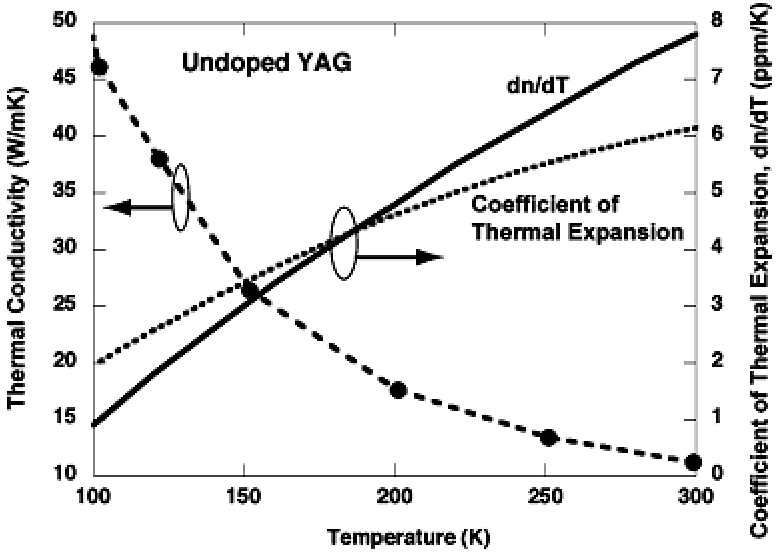
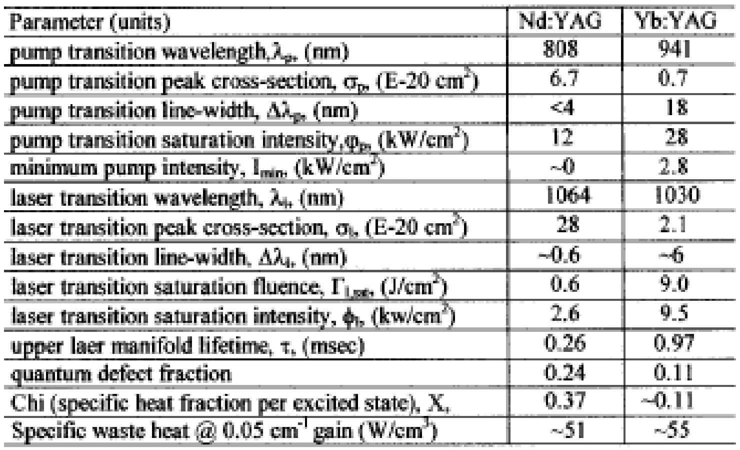
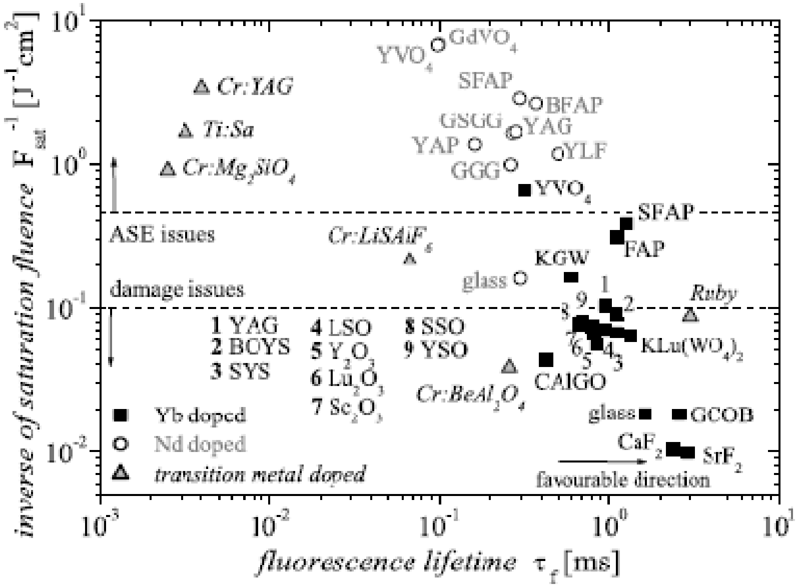


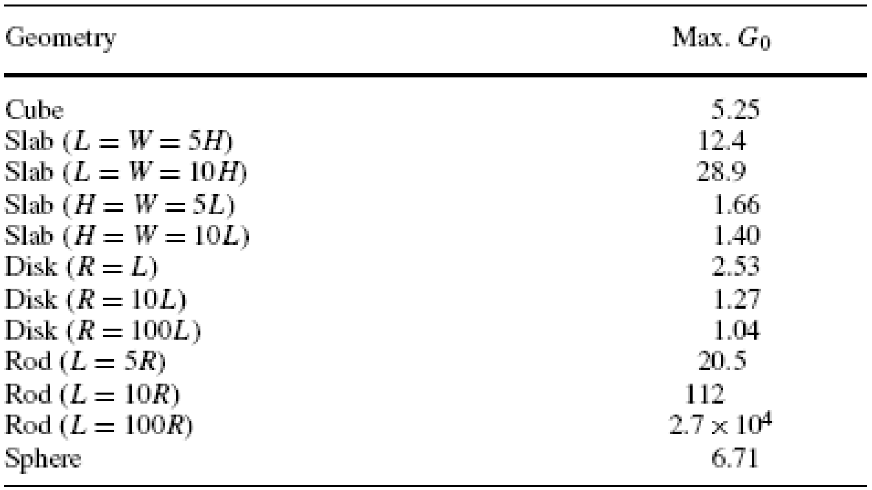
TABLE I
SPECTROSCOPIC LASER PARAMETER VALUES FOR Nd : YAG AND Yb : YAG



Parameter (units)	Nd:YAG	Yb:YAG
pump transition wavelength, λ_p, (nm)	808	941
pump transition peak cross-section, σ_p, (E-20 cm^2)	6.7	0.7
pump transition line-width, $\Delta\lambda_p$, (nm)	<4	18
pump transition saturation intensity, φ_p, (kW/cm^2)	12	28
minimum pump intensity, I_{min}, (kW/cm^2)	~0	2.8
laser transition wavelength, λ_l, (nm)	1064	1030
laser transition peak cross-section, σ_l, (E-20 cm^2)	28	2.1
laser transition line-width, $\Delta\lambda_l$, (nm)	~0.6	~6
laser transition saturation fluence, $\Gamma_{l,sat}$, (J/cm^2)	0.6	9.0
laser transition saturation intensity, ϕ_l, (kw/cm^2)	2.6	9.5
upper laer manifold lifetime, τ, (msec)	0.26	0.97
quantum defect fraction	0.24	0.11
Chi (specific heat fraction per excited state), X,	0.37	~0.11
Specific waste heat @ 0.05 cm^{-1} gain (W/cm^3)	~51	~55

Lifetime, Fsat, ASE

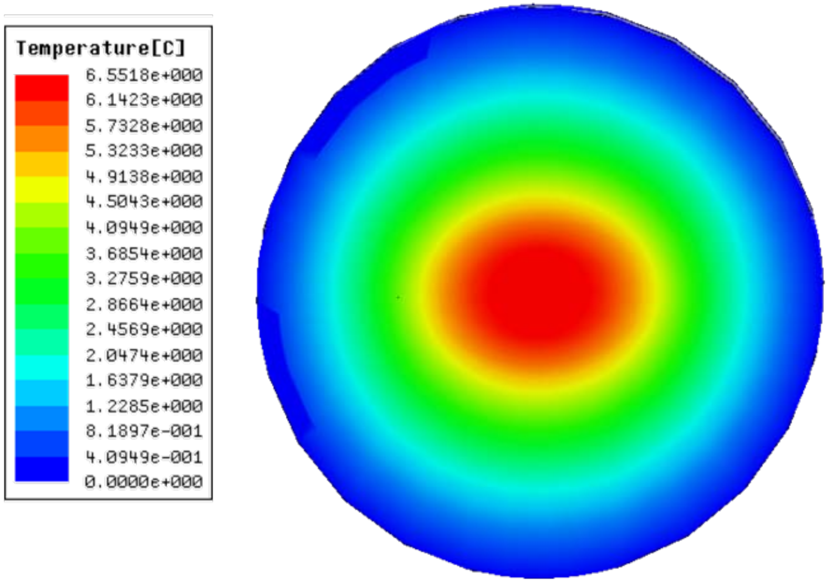




Geometry	Max. G_0
Cube	5.25
Slab ($L = W = 5H$)	12.4
Slab ($L = W = 10H$)	28.9
Slab ($H = W = 5L$)	1.66
Slab ($H = W = 10L$)	1.40
Disk ($R = L$)	2.53
Disk ($R = 10L$)	1.27
Disk ($R = 100L$)	1.04
Rod ($L = 5R$)	20.5
Rod ($L = 10R$)	112
Rod ($L = 100R$)	2.7×10^4
Sphere	6.71

Siebold, M.; Hein, J.; Hornung, M.; Podleska, S.; Kaluza, M. C.; Bock, S.; Sauerbrey, R. *“Diode-pumped lasers for ultra-high peak power” Applied Physics B, Volume 90, Issue 3-4, pp. 431-437 (2008)*

Oscillator Heating



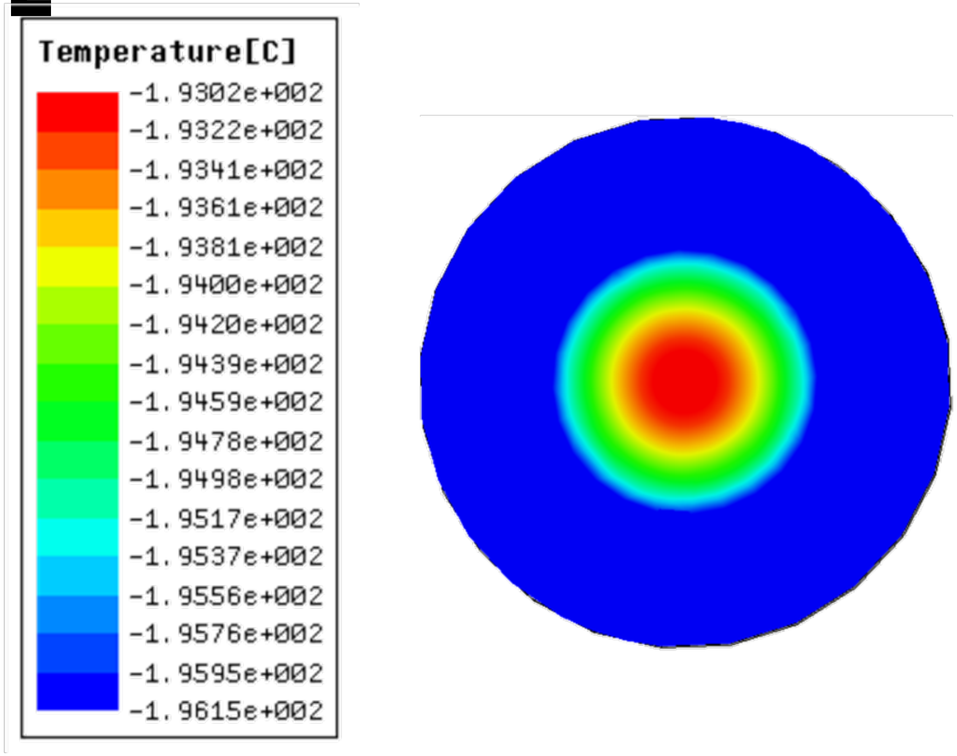
$$f = \frac{\pi K w_p^2}{P(dn/dt)}\left(\frac{1}{1-\exp(-\alpha l)}\right)$$

For Gaussian with 1/e2 radius wp. Koechner, Solid-State Laser Engineering, 2206

f=3.5m

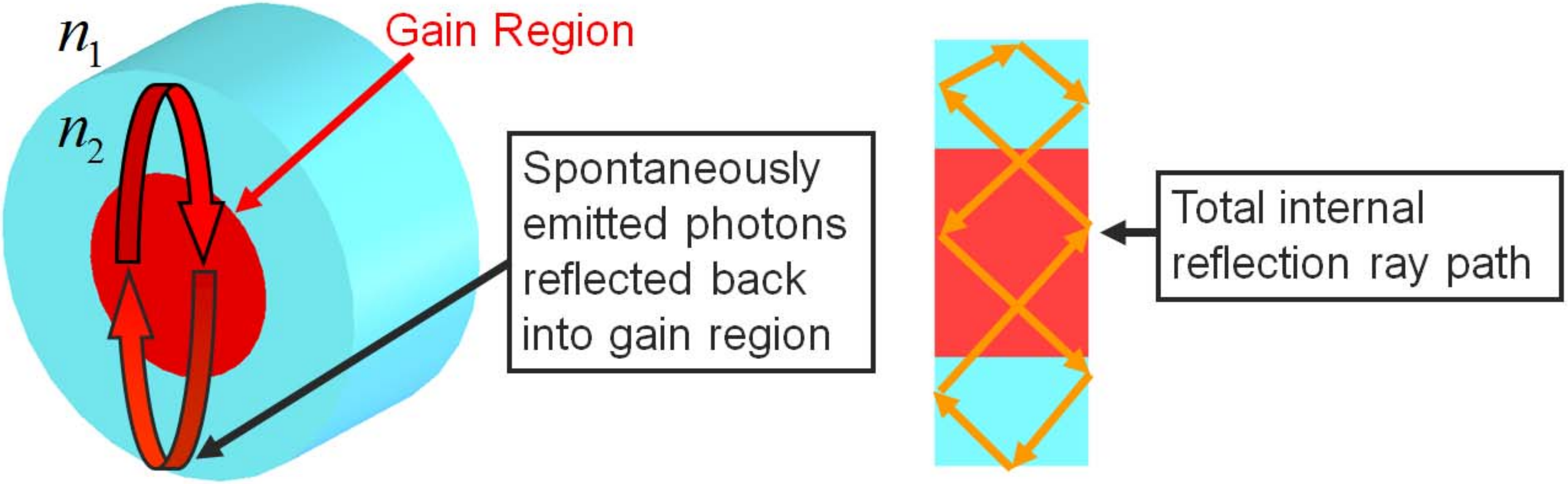
- Assuming flat-top profile, ΔT=3deg.
- f=5m

Cryo-amplifier Temperature



- Cryo-amplifier Yb:YAG has 3-4 deg change in temperature across crystal.
- Probably higher due to mount.

Parasitic Lasing



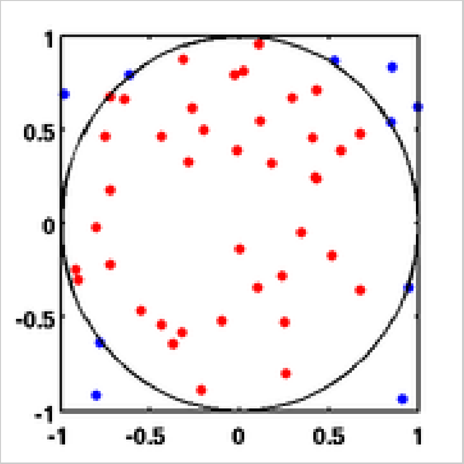
Spontaneously emitted photons reflected back into gain region

Total internal reflection ray path

- Photons fed back into the gain region are amplified reducing the stored energy and the gain.
- For high gain lasers with high feedback, parasitic lasing occurs and is a limiting factor.

Monte Carlo Integration

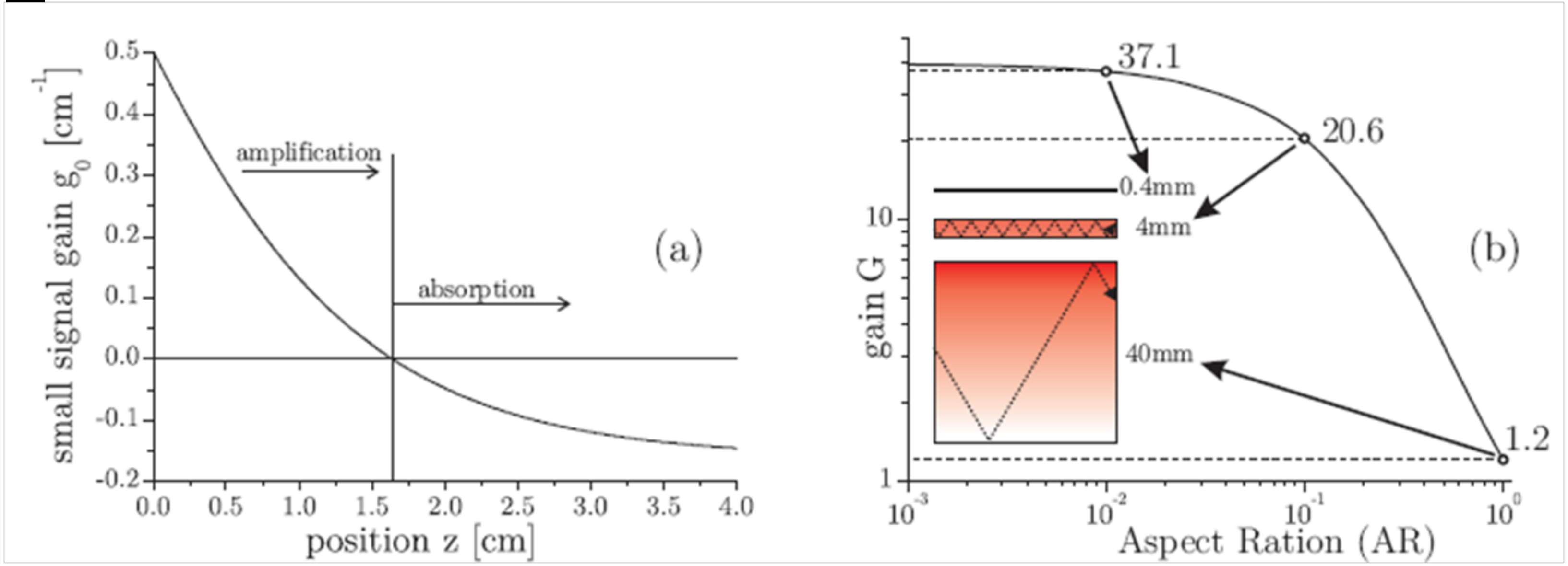
In mathematics, **Monte Carlo integration** is numerical integration using random numbers. That is, Monte Carlo integration methods are algorithms for the approximate evaluation of definite integrals, usually multidimensional ones. The usual algorithms evaluate the integrand at a regular grid. Monte Carlo methods, however, randomly choose the points at which the integrand is evaluated. Informally, to estimate the area of a domain D, first pick a simple domain d whose area is easily calculated and which contains D. Now pick a sequence of random points that fall within d. Some fraction of these points will also fall within D. The area of D is then estimated as this fraction multiplied by the area of d.



An illustration of Monte Carlo integration. In this example, the domain D is the inner circle and the domain d is the square. Because the square's area can be easily calculated, the area of the circle can be estimated by the ratio (0.8) of the points inside the circle (40) to the total number of points (50), yielding an approximation for $\pi/4 \approx 0.785$

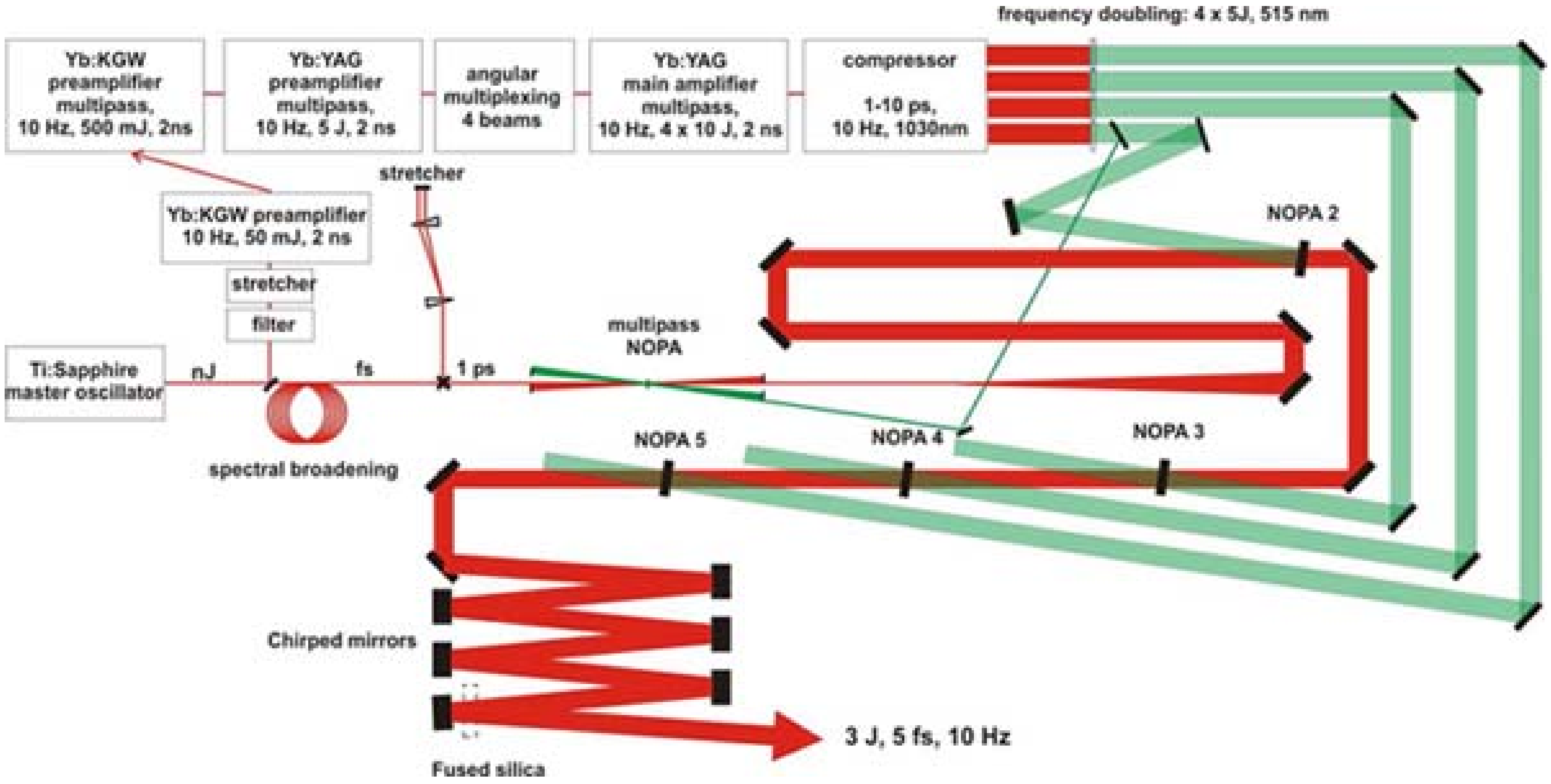
http://en.wikipedia.org/wiki/Monte_Carlo_integration

Gain vs. Absorption



- For low power, single-sided pumping of long crystals, the back side absorbs, while the front side amplifies.

PFS



http://www.attoworld.de/research/PFS_1.html