Recent Progress of Ceramic Laser for Ultrashort Pulse Lasers

1. High power pumping source
2. High efficiency 50fs pulse generation

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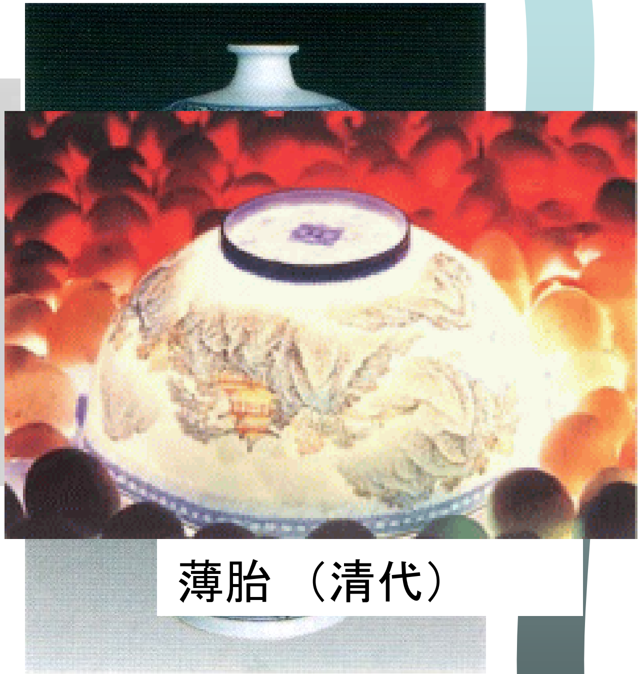
Historical Background of Ceramics

-Origin of "Ceramics" : Greek "Keramos"
- Clay sintering

景德鎮　Jingdezhen
"Ceramics Metropolis"

9000 years ago
4000-3300 BC
<900ºC
Low quality clay
Inhomogeneous



Traditional Ceramics
1300 – 1500 ºC
High quality clay
Special harmony

Modern Ceramics
Late 20 century
Synthesized particles
Homogeneous

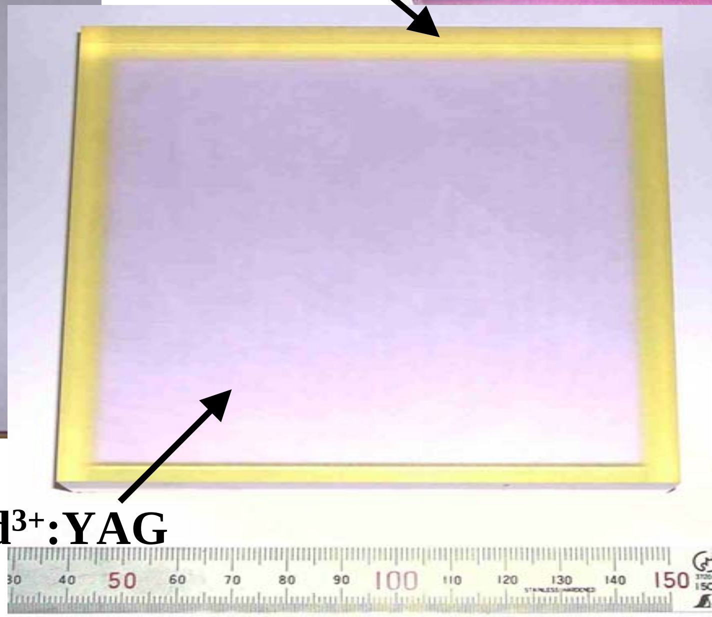
Translucent Ceramics → Transparent Ceramics

Ceramic lasers: scalable, spectral control

For IFE driver, industrial femto-second laser

Large size Nd:YAG disk

Sm^{3+}:YAG

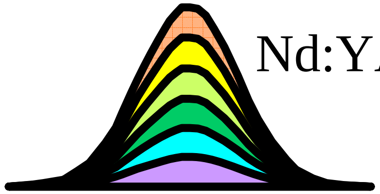


Nd^{3+}:YAG

Nd:YAG slab and rod

Konoshima chemical, ILS/UEC

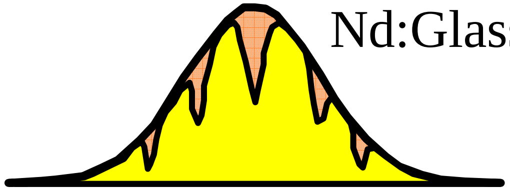
Crystal or Glass or Ceramics?



Nd:YAG

Homogeneous line

Ceramic laser: Glass-like fabricated crystal

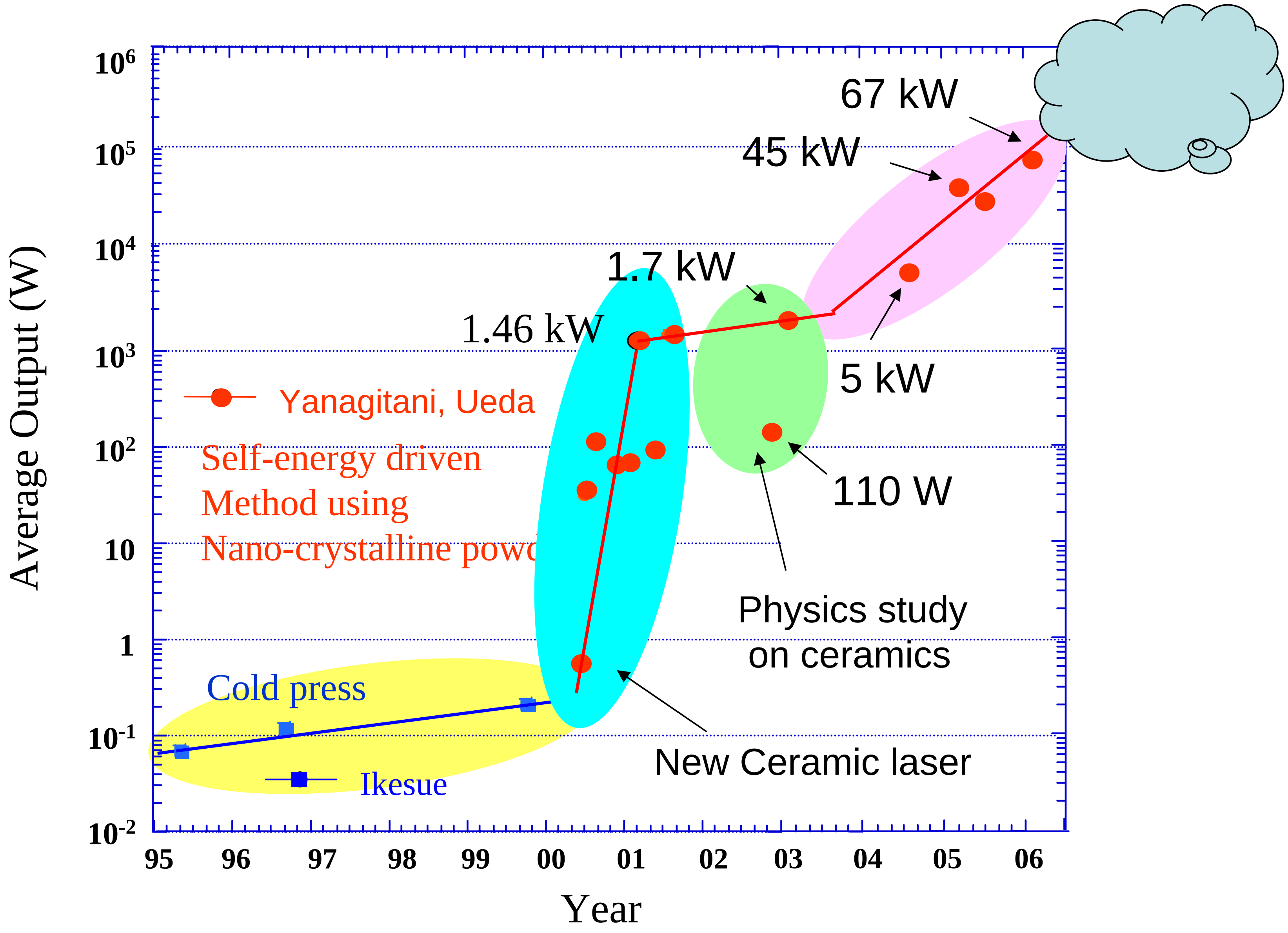


Nd:Glass

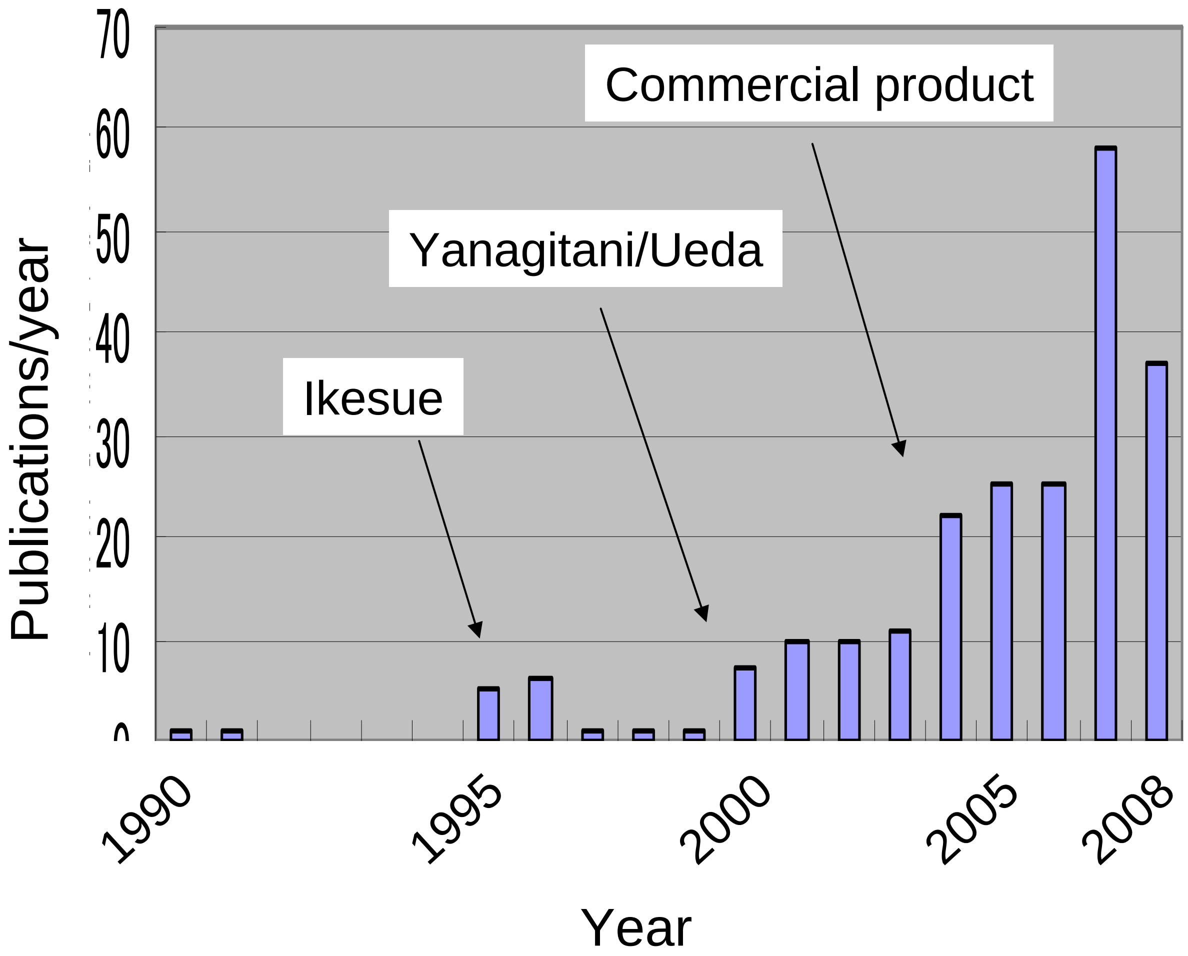
Inhomogeneous line

	Nd:YAG crystal		*Nd:YAG ceramics*		*Nd:phosphate glass*	
σ (cm^2)	○	30×10^{-20}	○	30×10^{-20}	×	4×10^{-20}
τ (μs)	○	260	○	260	○	300
στ product (cm^2s)	○	7.8×10^{-23}	○	7.8×10^{-23}	×	1.2×10^{-23}
K (W/m K)	○	12-13	○	12-13	×	0.78
α (1/K)	○	7.8×10^{-6}	○	7.8×10^{-6}	×	7.6×10^{-6}
Fracture limit (MPa)	○	1.8	◎	5.2	×	
Thermal shock (W/m)	○	790	◎	(2400)	×	140
Scalability (40 cm x 1 m)	×	No	○	OK	◎	Easy
Mass production	×	No	○	Possible	◎	Easy
Possible cost	×	High	○	Medium	◎	Low

Recent Progress of Ceramic Lasers



Publication on Ceramic Lasers



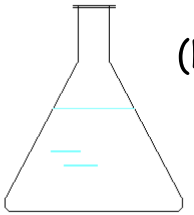
Synthesis of Transparent YAG Ceramics

Non-Reactive sintering

Precipitation/ Calcination route

(Dr. Ueda's group, Konoshima Chem. Co.)

Y^{3+}, Al^{3+}, Nd^{3+} salts in aqueous solution



$(NH_4)HCO_3$

$(NH_4)_2SO_4$ + Colloidal SiO_2

Monodisperse YAG precursor nanoparticles

Separation
Washing
Drying
Calcination at 1200°C

Nd^{3+} :YAG powder

Wet ball milling
Binder
Molding
Vacuum sintering at 1750°C, 10^{-6} torr during 10 h

Transparent Nd^{3+} :YAG ceramic

Reactive sintering

Solid-state reaction route

(Dr. A. Ikesue)

Oxides Y_2O_3 + Al_2O_3

Ball milling,
Ethanol + $(C_2H_5O)_4Si$
Spray drying

Fine silica-coated Y_2O_3 + Al_2O_3 particles (size <1μm)

Binder

Isostatic pressing

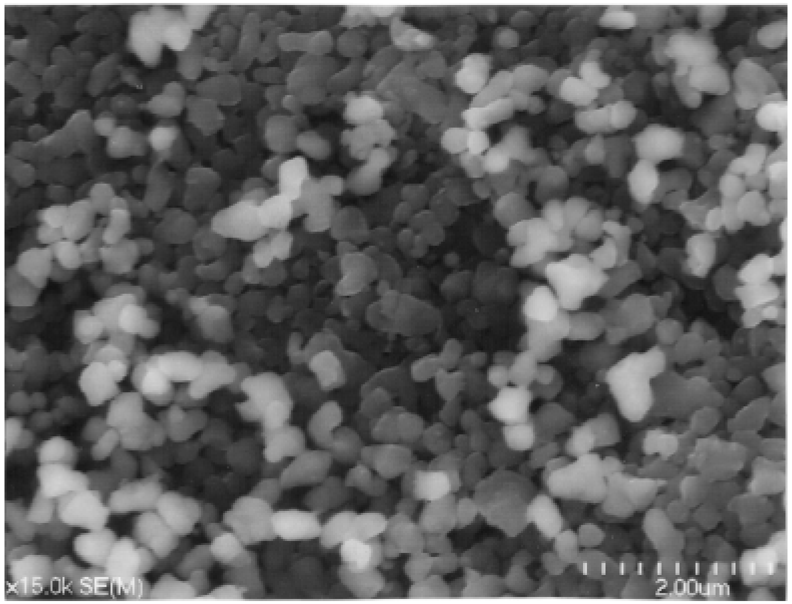
Vacuum sintering at 1750°C, 10^{-6} torr during 10 h

Transparent Nd^{3+} :YAG ceramic

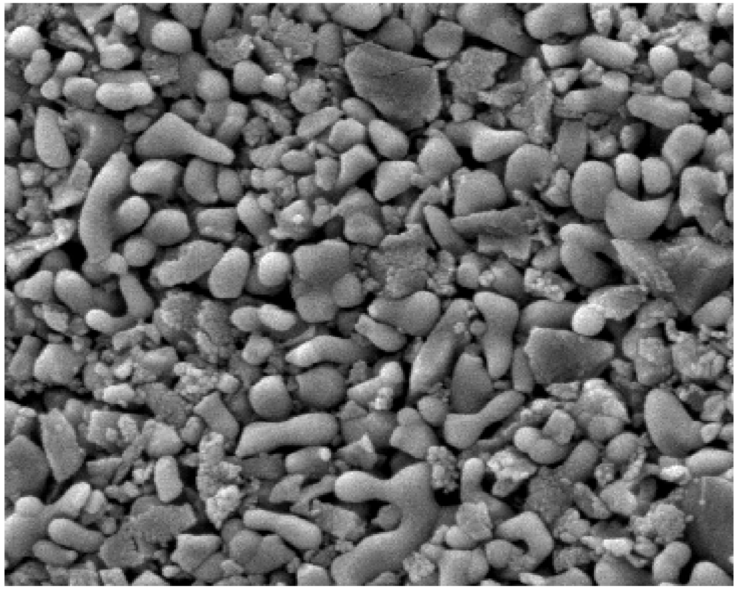
There are two approaches to transparent ceramic fabrication

Green body before sintering

Non-reactive sintering
Konoshima Ceramics



Traditional reactive sintering



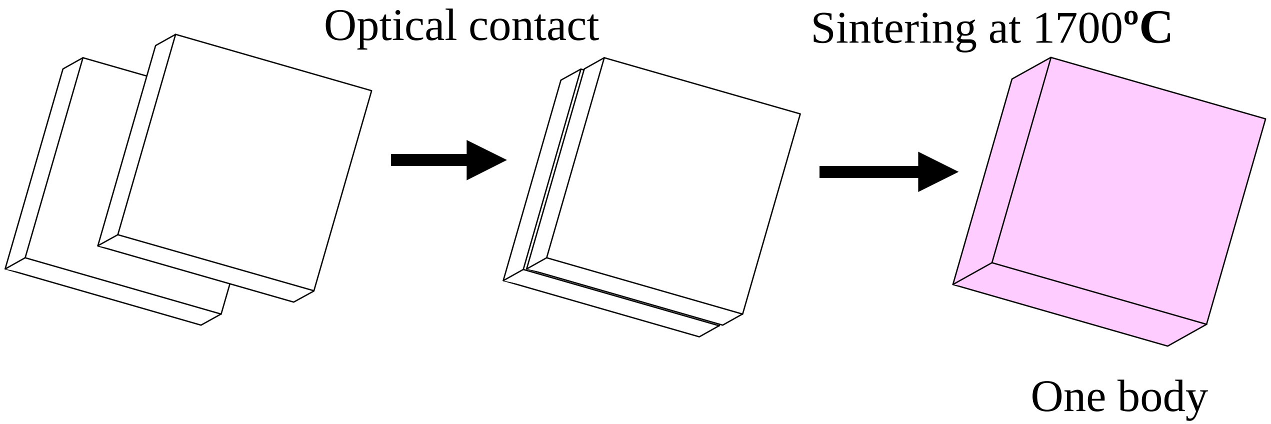
Highest quality
Scaling is good
Real commercial material
YAG, RE sesquioxide, disordered materials

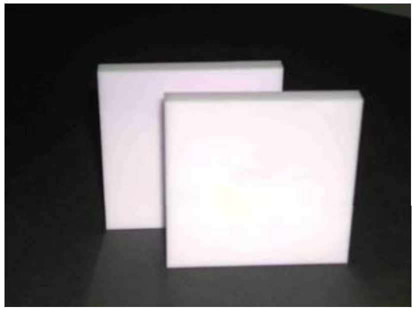
Ceramics bonding

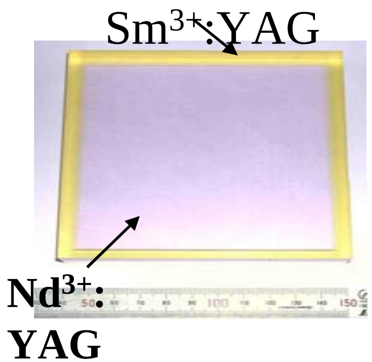
White ceramics by sintering at 1400°C

Optical polish (<λ/10)

Sintering at 1700°C



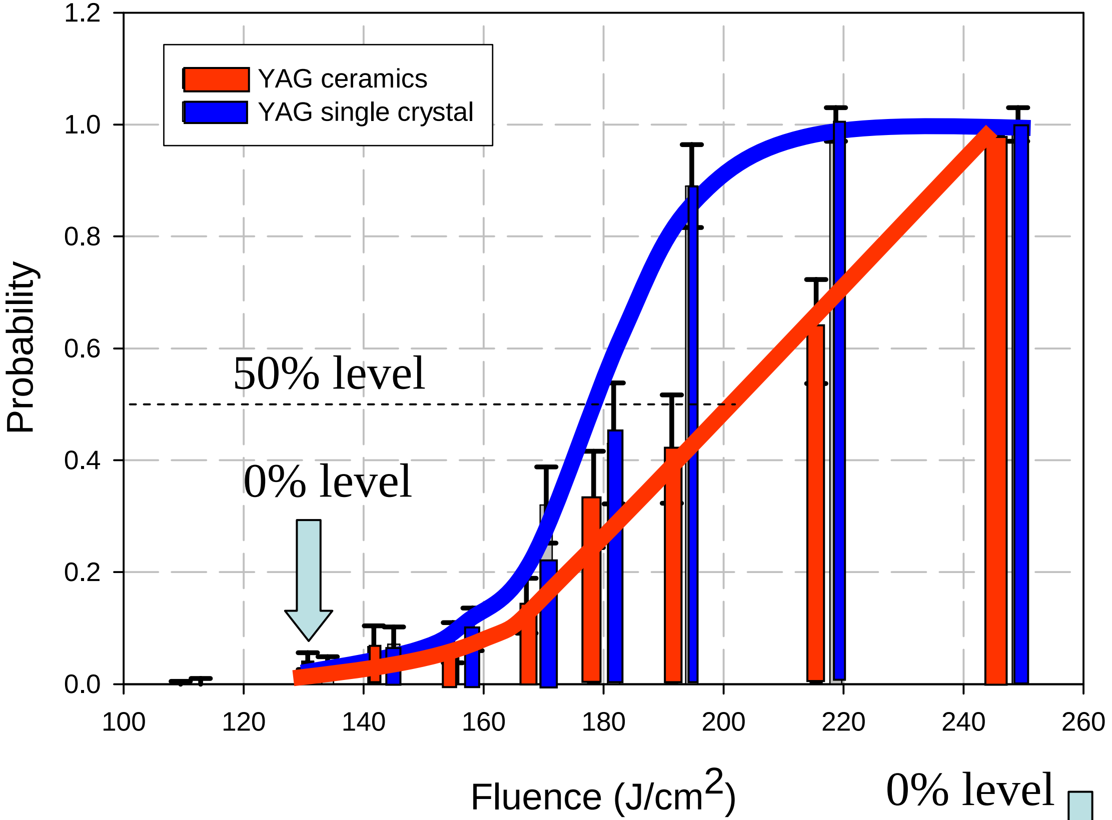




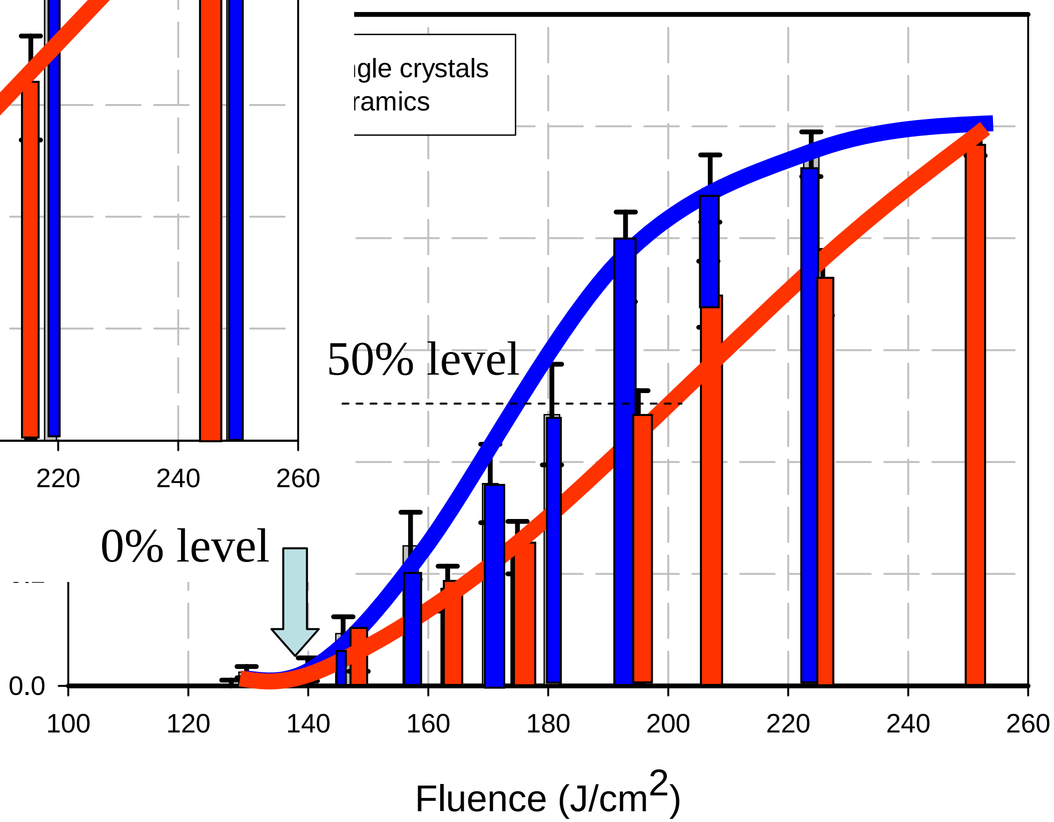
Damage threshold measurement

Nd doping: no effect

Undoped samples



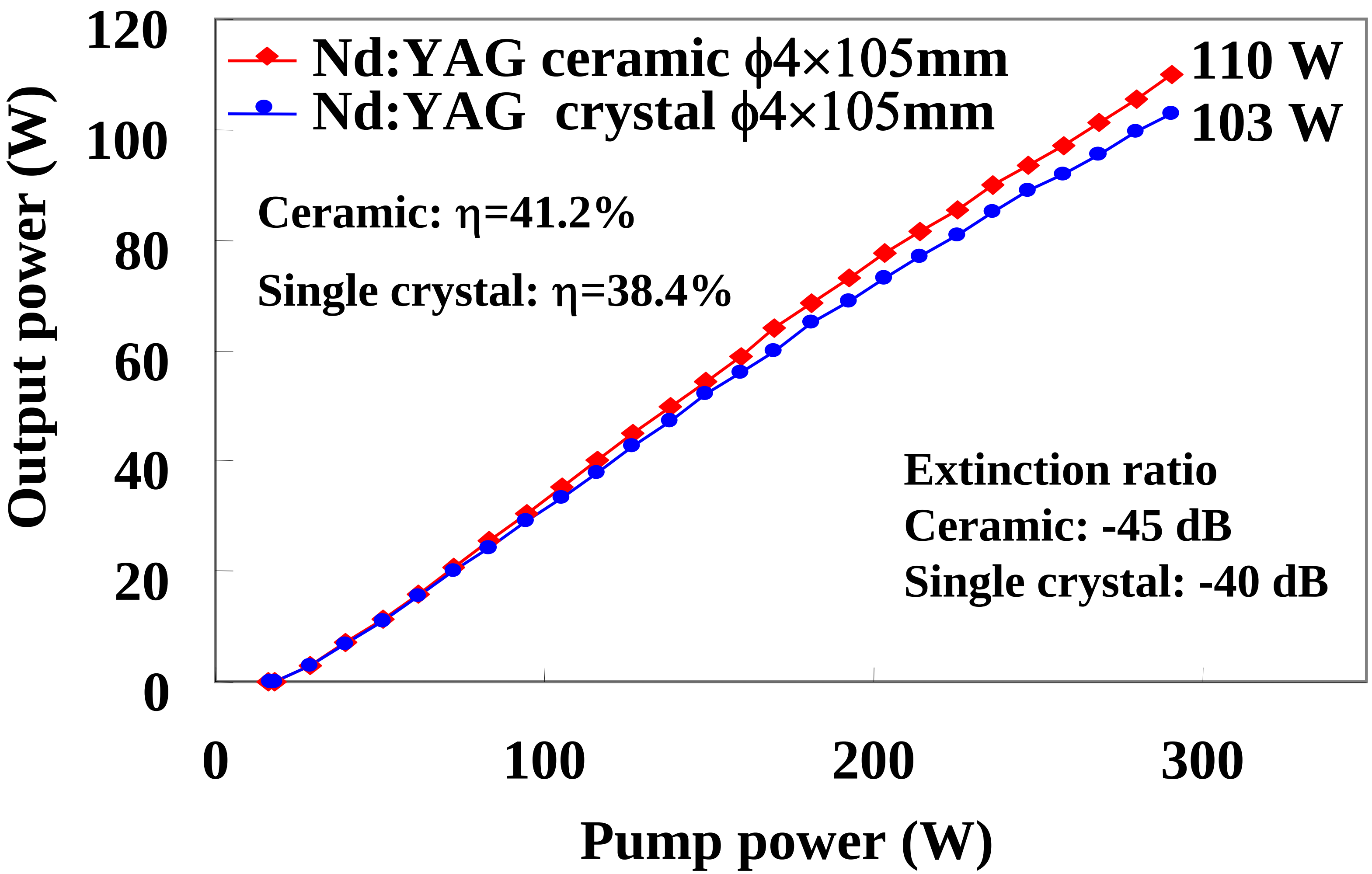
Doped samples



Ceramics vs Crystal

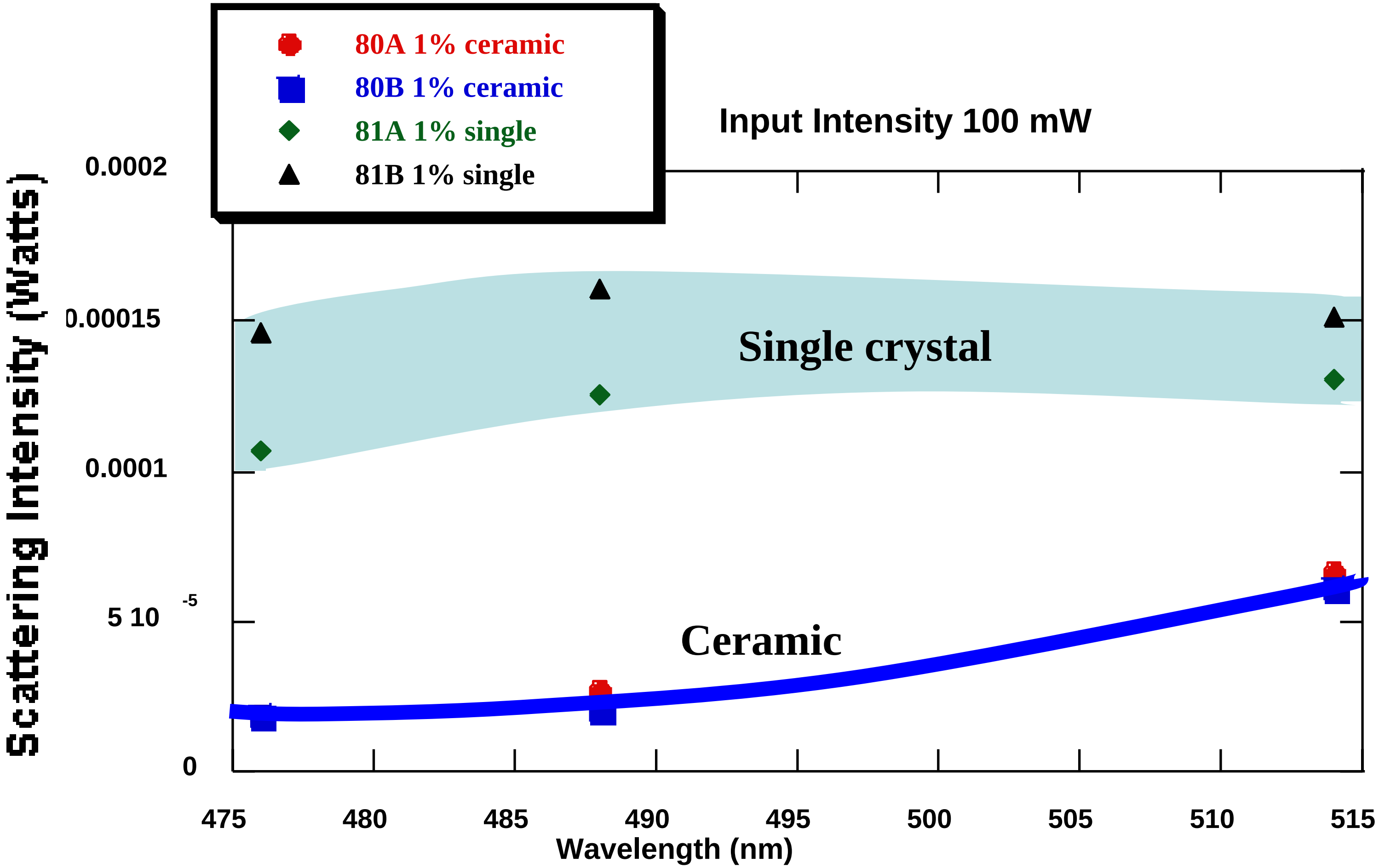
Equal or better

Ceramic lasers demonstrate higher efficiency. (2004)



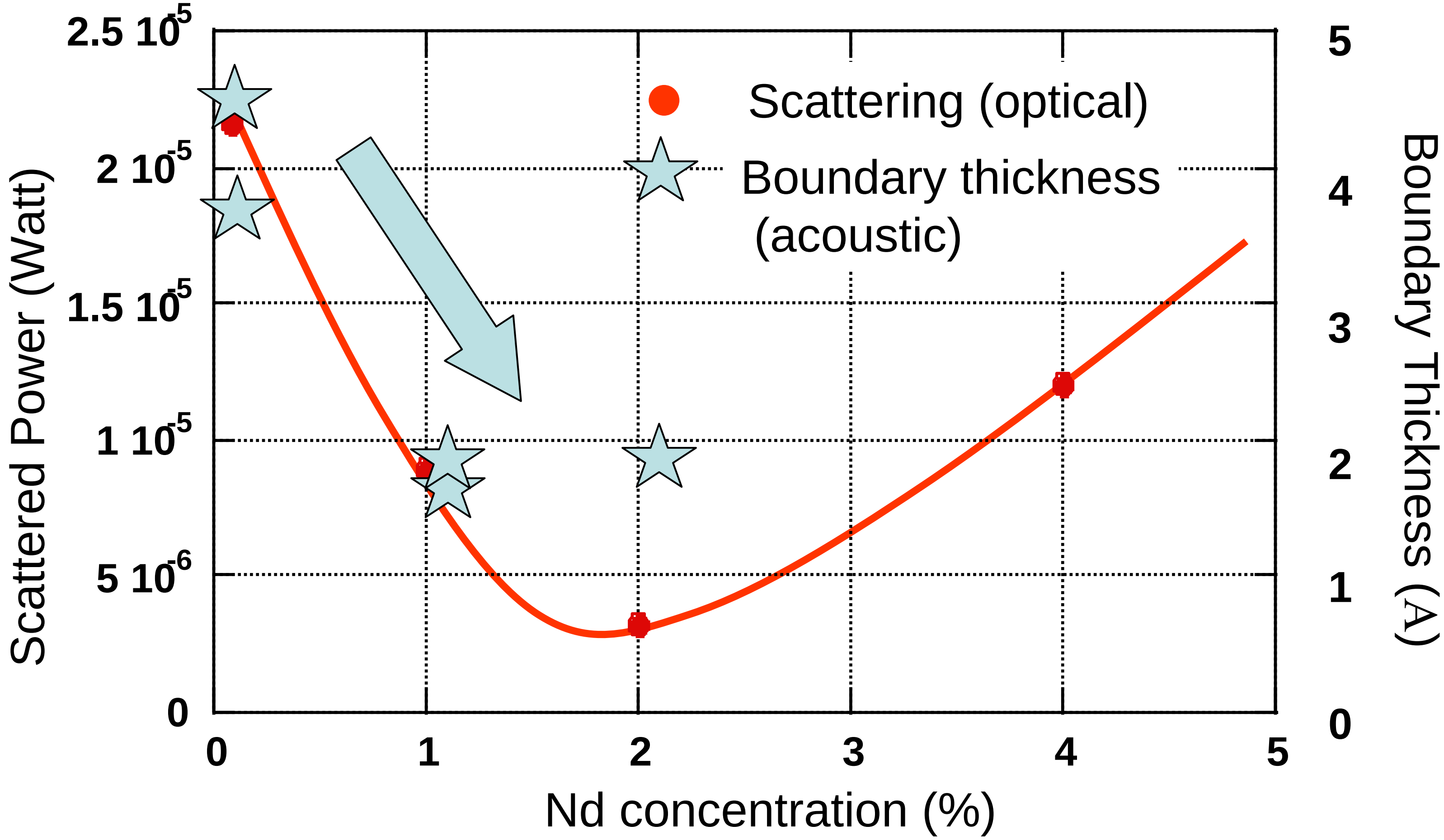
High power Nd:YAG ceramic laser reached the same level
or even higher in efficiency with Nd:YAG single crystal laser

Scattering vs. λ



G. Quarles: Paper 5707-19-Photonics West 2005-January 25, 2005

Correlation between Optical Scattering and Acoustic Thickness of Grain Boundary

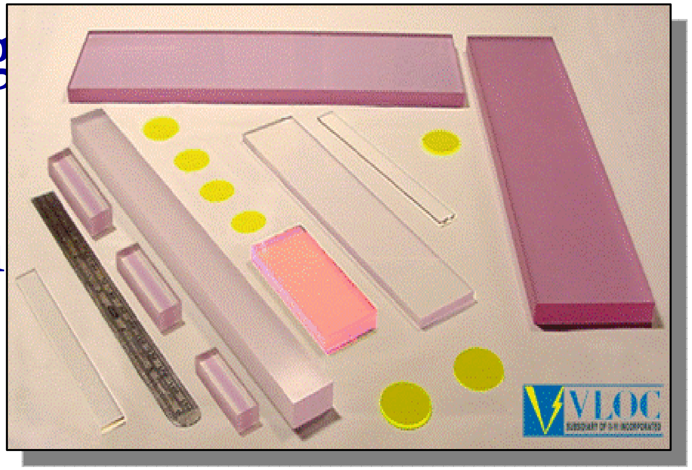


Systematic Studies on Ceramic YAG in US

Ceramics for Next Generation Tactical Laser Systems, Contract# N66001-00-C-6008 : G. Qaurles et al

Motivation

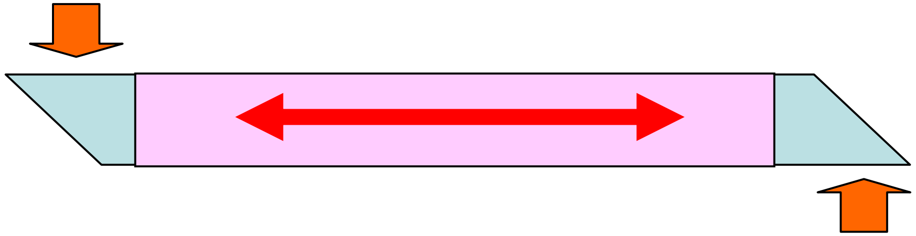
- Unbiased Comparison of VLOC Single Crystal YAG with ***Konoshima Ceramic YAG***
- Development of Database for Hig
  Laser Development Engineers
- Development of Next-Generation
  Systems with Ceramics

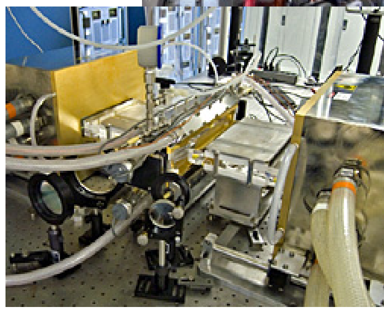


→ ***Higher Power Solid State Lasers***

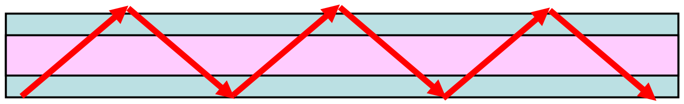
“Electric Lasers” in US toward >100kW use our ceramic YAG

1. Northrop Grumman: End-pumped Slab: Yb:YAG

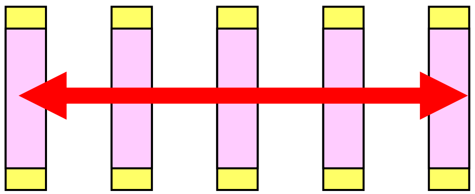


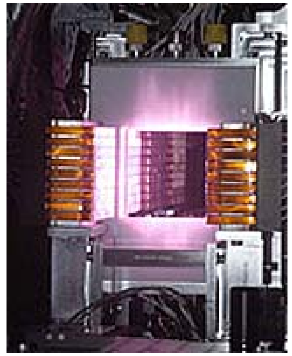


2. Textron: Zigzag Thin Slab Laser: Nd:YAG



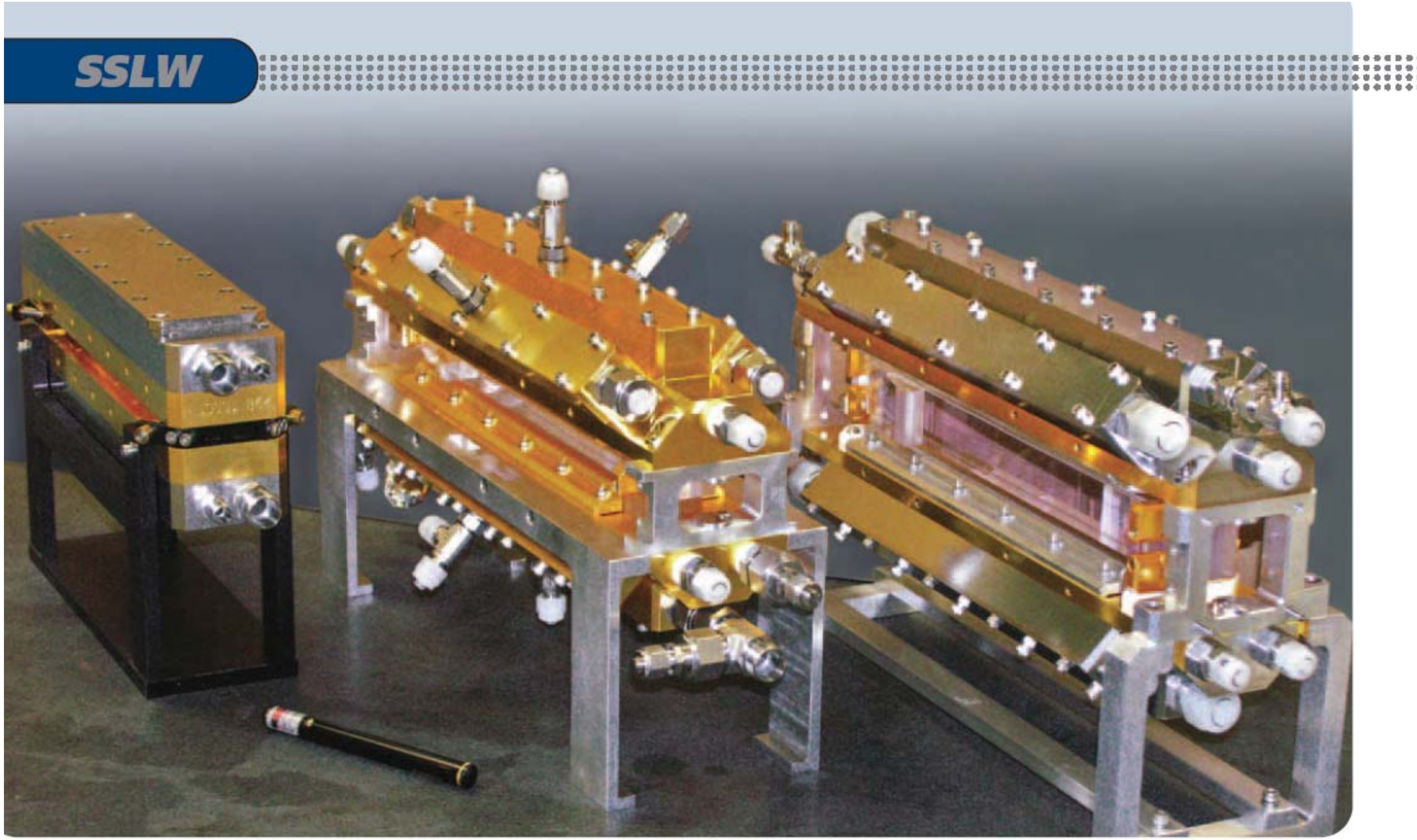
3.LLNL: Thermo Capacity Laser; Nd:Sm:YAG





Solution of high rep rate high power pump source

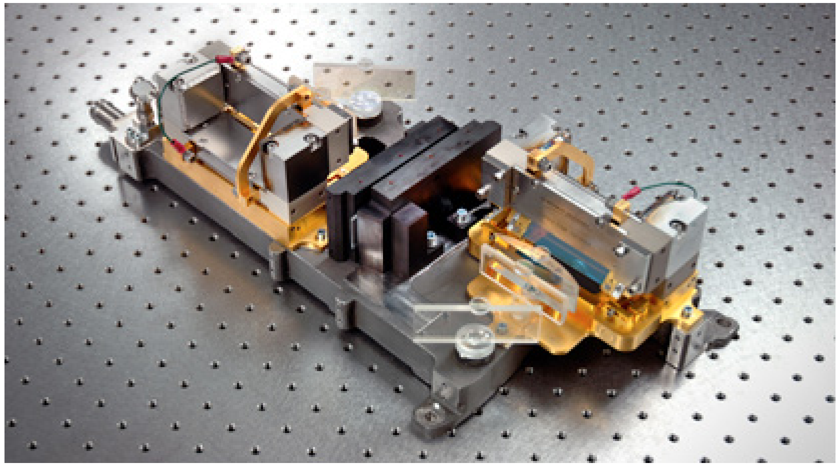
TEXTRON 100kW Solid State Lasers



Moving from 1 kW to 5 kW to 15kW to 100 kW Solid State Lasers
Textron Systems engineers are developing tomorrow's precision-strike weapons today

Northrop-Grumman
Joint High Powered Solid State Laser

In Phase 3 of the US$56.68 million JHPSSL program, eight 15kW laser chains of four modules each will combine to achieve a total power of 100kW.



The laser chain was tested on December 20 last year, and reached 15.3kW - 2.6kW ahead of expectations. Vertical beam quality was measured at 1.58x diffraction limit, surpassing the 2.0 target; turn-on time was 0.8 seconds, below the 1.0 second target; LC1's run time was more than 300 seconds, far beyond the target of 200 seconds; and the Electro-Optical Efficiency was 19.5%.

Yb-doped Ceramics

for ultra-broadband and ultra-short pulse generation

1. Yb:YAG, Yb:Y_2O_3, Yb:Lu_2O_3, Yb:Sc_2O_3
   high concentration 10%-20% doping
2. Fluoride ceramics: Yb:CaF_2 and Yb:SrF_2
   long lived and broadband
3. Disordered ceramics: Yb-doped Lumicera
   Nd:$\{Gd_{3-x}Y_x\}Sc_2\{Al_{3-x}Ga_x\}O_{12}$ $(0<x<3)$

Big issues: High doping, high pumping
What is the possible pumping density?
What is the intrinsic limit of high density pumping?

International collaboration with Huber's lab. In Germany.

Problem of the Yb:YAG Thin-Disk Laser

In the Thin-Disk Laser set-up, laser operation is not possible for Yb:YAG samples with a doping concentration higher than 15%.[1)]

Heat and gain measurements show that:

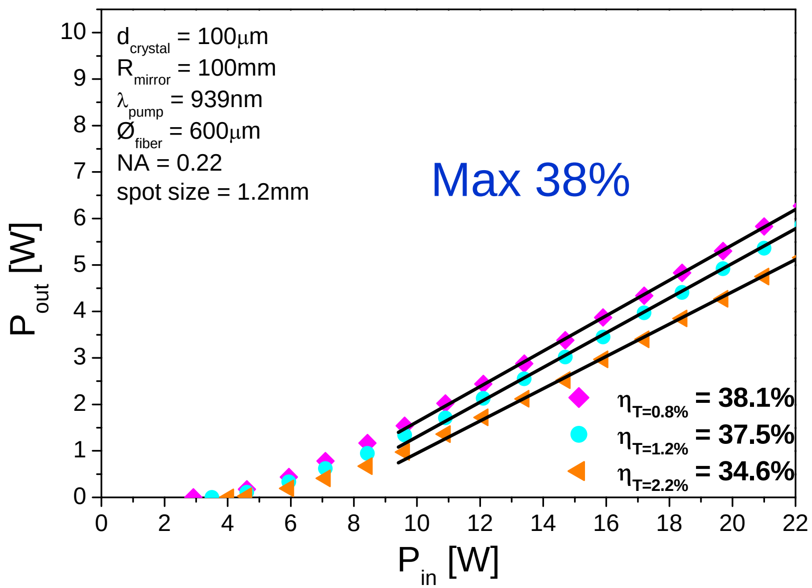
→ highly doped Yb:YAG crystals suffer decay processes that generate heat,

- → these processes are excitation density dependent,
- → these processes are temperature dependent.

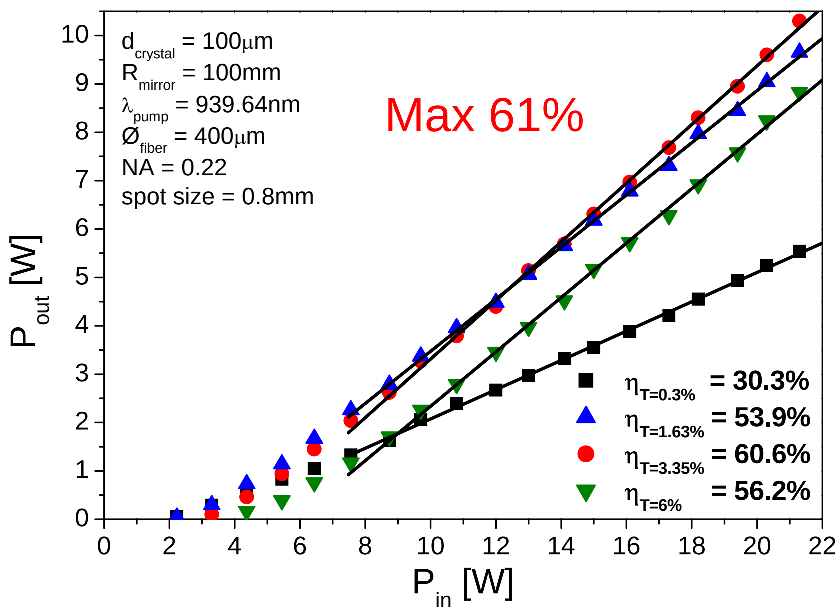
[1)] M. Larionov et al. "*Nonlinear Decay of Excited State in Yb:YAG*", OSA Trends in Optics and Photonics, Advanced Solid-State Photonics, Proceedings Vol **98**, 18-23 (2005).

Better performance
in high doping Yb:YAG ceramics

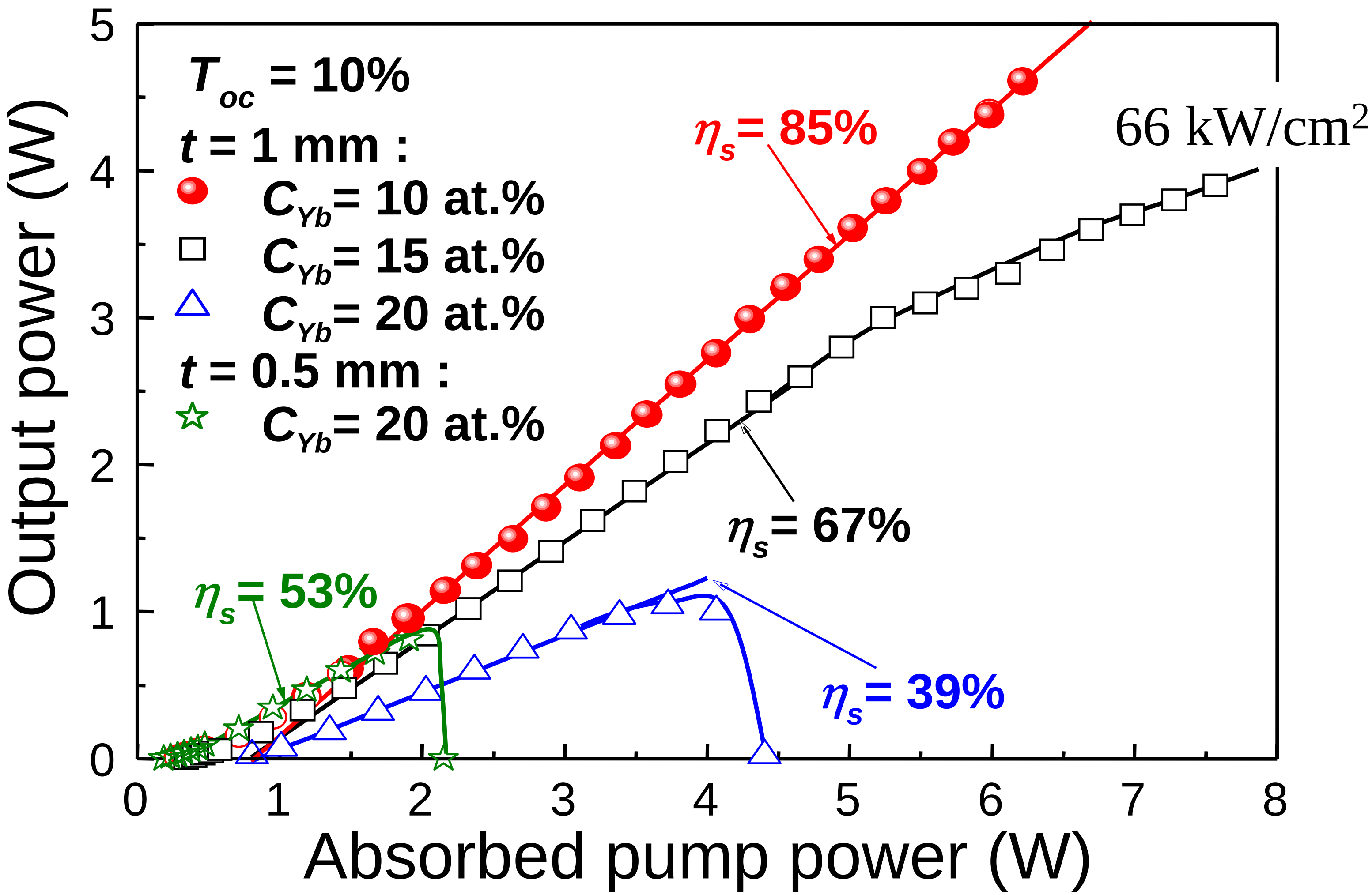
16.5% Yb:YAG single crystal



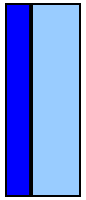
20% Yb:YAG ceramics



Efficient Yb:YAG microchip lasers at High Pump and High Doping even at Room Temperature (J. Dong)

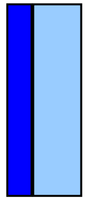


Nonlinear and gain control by combined ceramics



1 mm 3at.% Yb^{3+}:Lu_2O_3 &

2mm Undoped Y_2O_3 combined ceramics

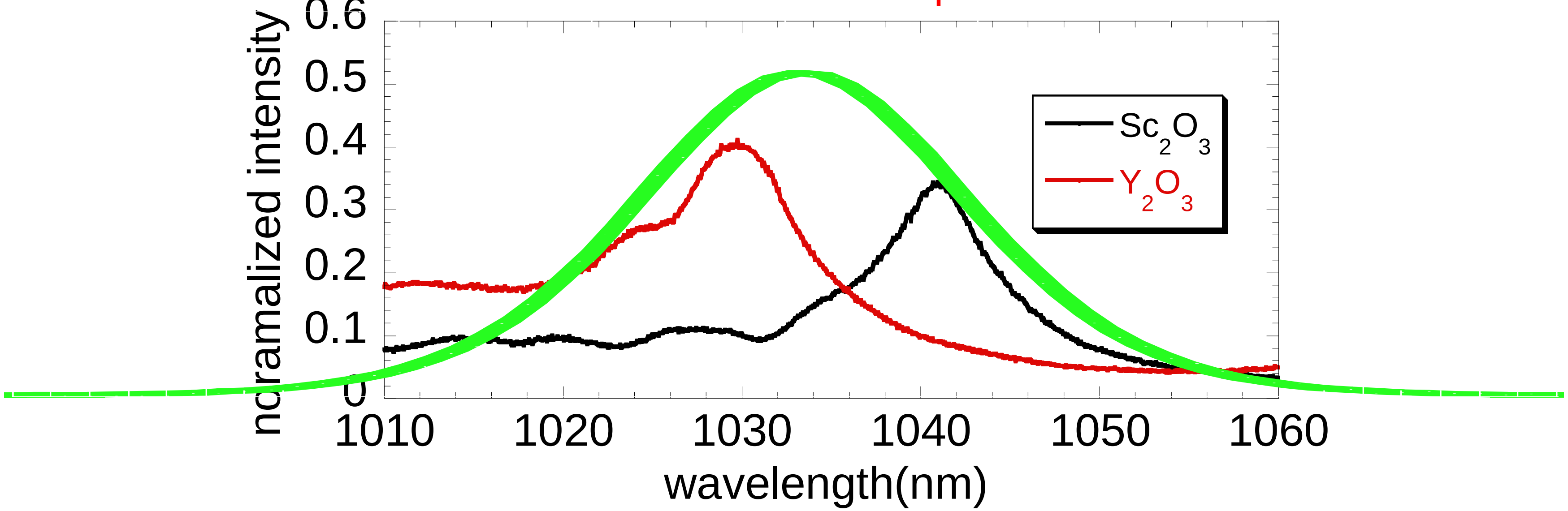


1 mm 2.5at.% Yb^{3+}:Sc_2O_3 &

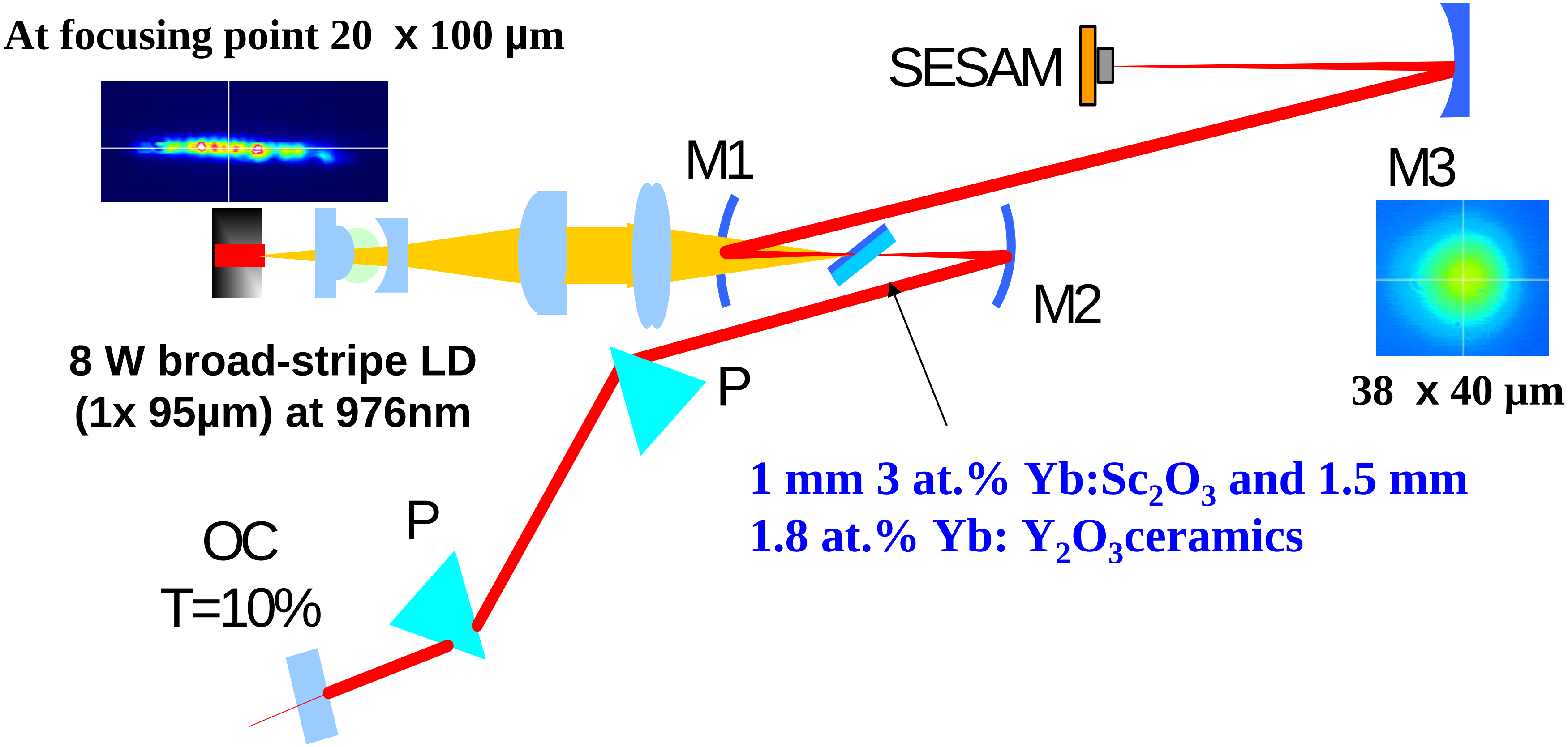
2mm 1.8at.% Yb^{3+}: Y_2O_3 active combined ceramics

Broader emission spectrum and absorption spectrum

Luminescence spectra



Kerr-lens mode-locked $Yb^{3+}:Sc_2O_3$ with $Yb^{3+}:Y_2O_3$ combined active media ceramic laser **(with SESAM)**



Mode-matching factor is about 40%

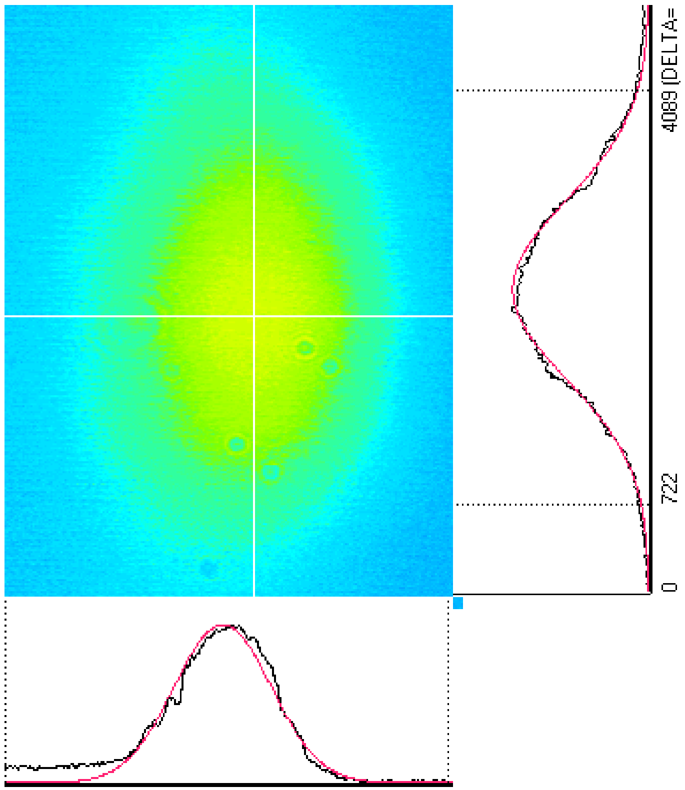
The distance of prism pair was about 40 cm

Property of SESAM
A_0=1% t_L=10 ps
$F_{sat,A}$=30 mJ/cm^2
F_{damage}~1 mJ/cm^2

Improvement of beam profile

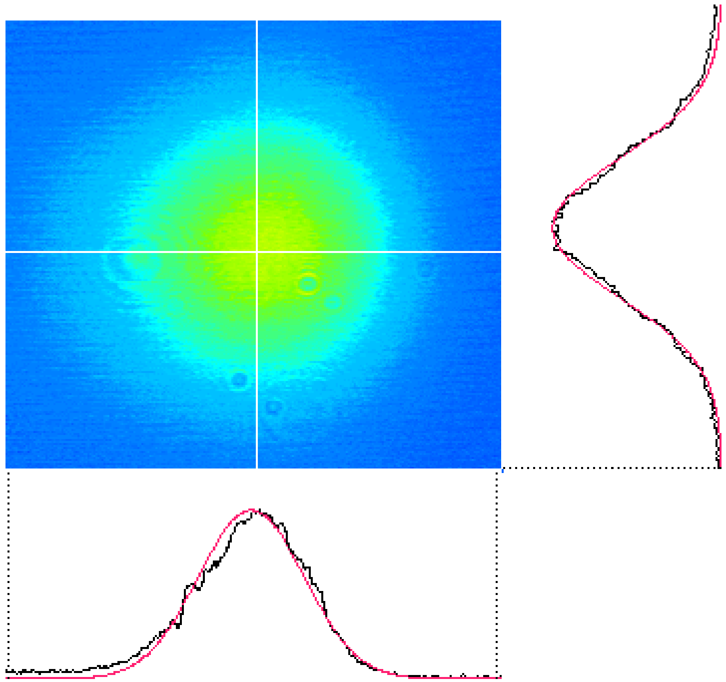
The measured laser mode of the leaking beam at the point X

In the CW operation



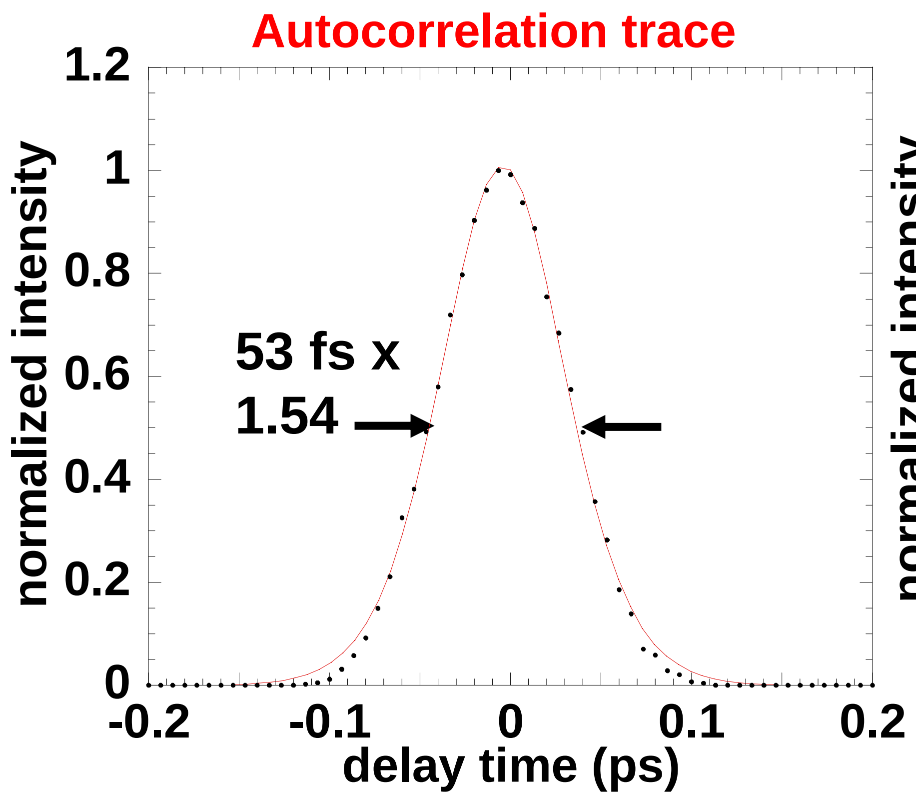
$1830 \times 2940\mu m$

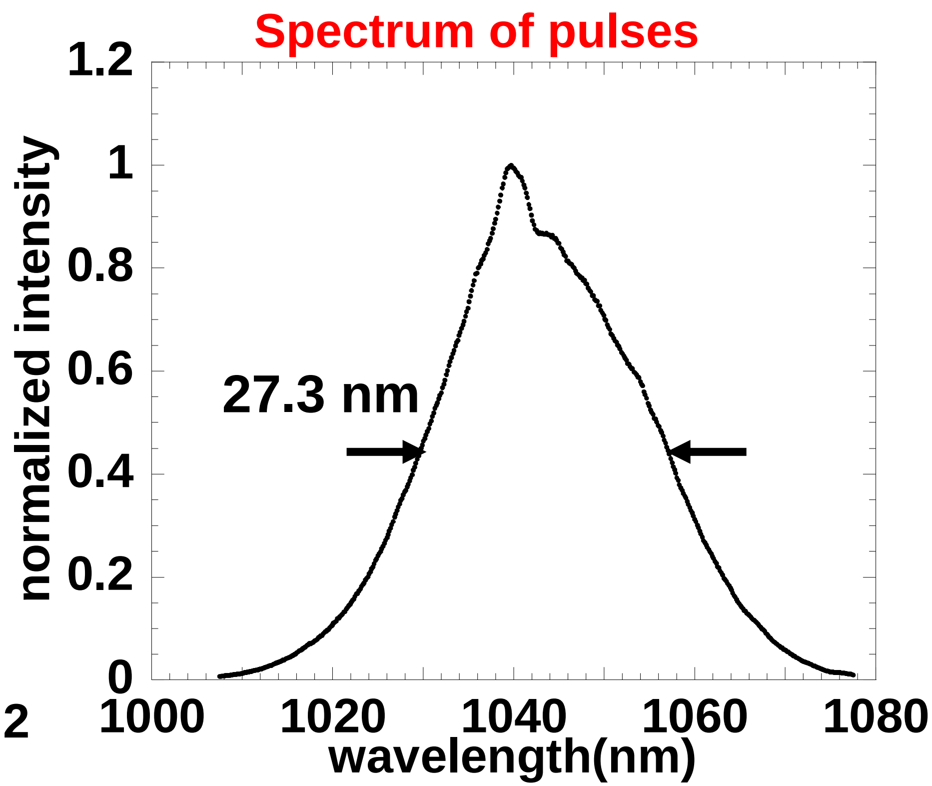
In the Mode-locked operation



$1800 \times 2050\mu m$

53 fs pulse duration with the average power of 1 W





53 fs, P_{max}=1 W 8 W LD ,1041 nm $\Delta t \cdot \Delta \nu$ = 0.399

86 MHz, Opt-opt efficiency is about 12.5%

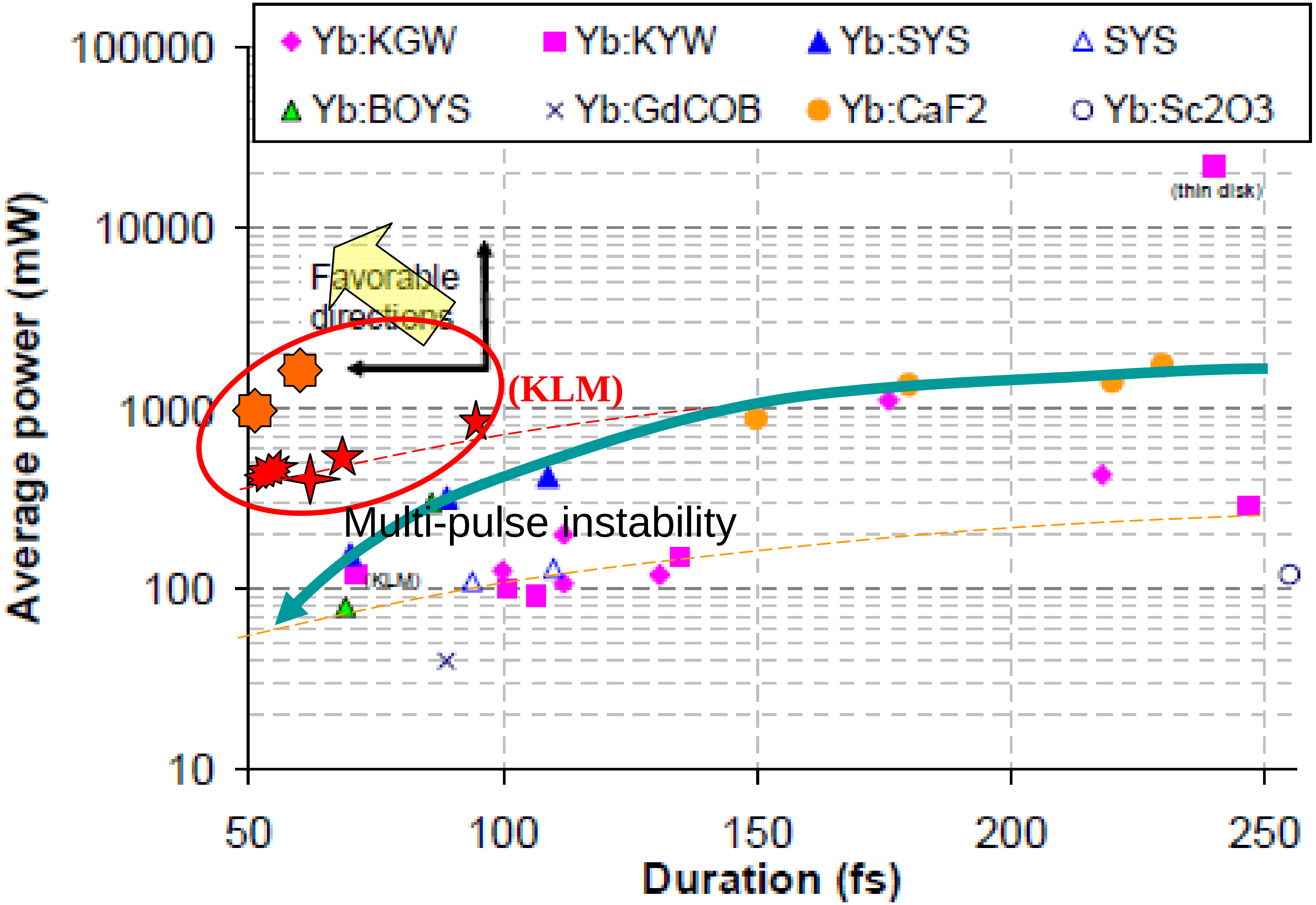
The pulse durations were independent on saturation depth of the SESAM

Comparison of Sub-100 fs Yb-doped lasers

Yb-doped Material	P_{out} (mW)	Δt (fs)	P_{pump} (W)	method	Pump source	Year	reference
KYW	120	71	3.2	KLM	two LD	2001	H. Liu *et al.* Opt.Lett. **26**,1723
BOYS	80	69	3.6	SESAM	two LD	2002	F. Druon *et al.* Opt. Lett. **27**, 197
SYS	156	70	4	SESAM	LD**	2004	F. Druon *et al.* Opt. Express **12**, 5005
YVO_4	54	61	0.4*	KLM	FCLD	2005	A. A. Lagatsky *et al.* Opt. Lett. **30**, 3234
$CaGdAlO_4$	520	68	15	SESAM	FCLD	2007	J. Boudeile *et al.* Opt. Lett. **32**,1962
Sc_2O_3	850	92	4.5	KLM	LD	2007	ILS/UEC ceramics
Sc_2O_3	415	70	5	KLM	FCLD	2007	ILS/UEC ceramics
Lu_2O_3	320	65	5	KLM	FCLD	2007	ILS/UEC ceramics
Sc_2O_3/ Y_2O_3	380	56	5	KLM	FCLD	2007	ILS/UEC ceramics
Sc_2O_3/ Y_2O_3	1000	53	8	KLM	LD	2008	ILS/UEC ceramics
Sc_2O_3/	1500	66	8	KLM	LD	2008	ILS/UEC ceramics

The shortest and highest pulse operation for Yb-doped solid-state laser without external element(*ex.* dispersion compensation)ever reported also was achieved.

LD-pumped sub 100 fs solid state lasers



Yb:Sc_2O_3

Yb:Lu_2O_3

Yb:Sc_2O_3
Yb:Y_2O_3

F. Druon, et al, Optics Express, **12**, 5005, 2004.

Ceramic Lasers: Solid State Laser in 21st century

- **Scaling to large aperture active elements**

  Large and thin (1m x 1m) : effectively no limit

  Industrial lasers, Fusion drivers, and so on

  Glass-like fabricated polycrystalline material

- **New materials**
- **Spectral control, combined activators**
- **Gain uniformity**

New Laser

- **Wave guide and gain profile control**
- **Multi-functional elements**
- **Low cost, mass production**

Engineering Ceramics

Asian Core Program (Research and Education) by JSPS

Next Generation Ultra-High Intensity Solid State Laser for High Field Sciences

Target:
- High field science
- Relativistic plasma
- Laser accelerator
- Young scientists

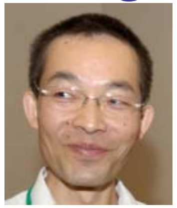
using
- >PW peak power laser
- New laser materials
- New Ceramic Laser

Collaborators and Acknowledgement

Institute for Laser Science, UEC

M. Tokurakawa, A. Shirakawa, J-F Bisson, J. Dong, K. Takaichi,




Konoshima Chemical Co. Ltd

H. Yagi, T. Yanagitani


Institute of Laser Engieering/Osaka Univ.

J. Kawanaka

Institute of Crystallography, RAS

A. Kaminskii and Joint Open Laboratory for Laser Crystals

Institute of Laser Physics, Univ. Hamburg

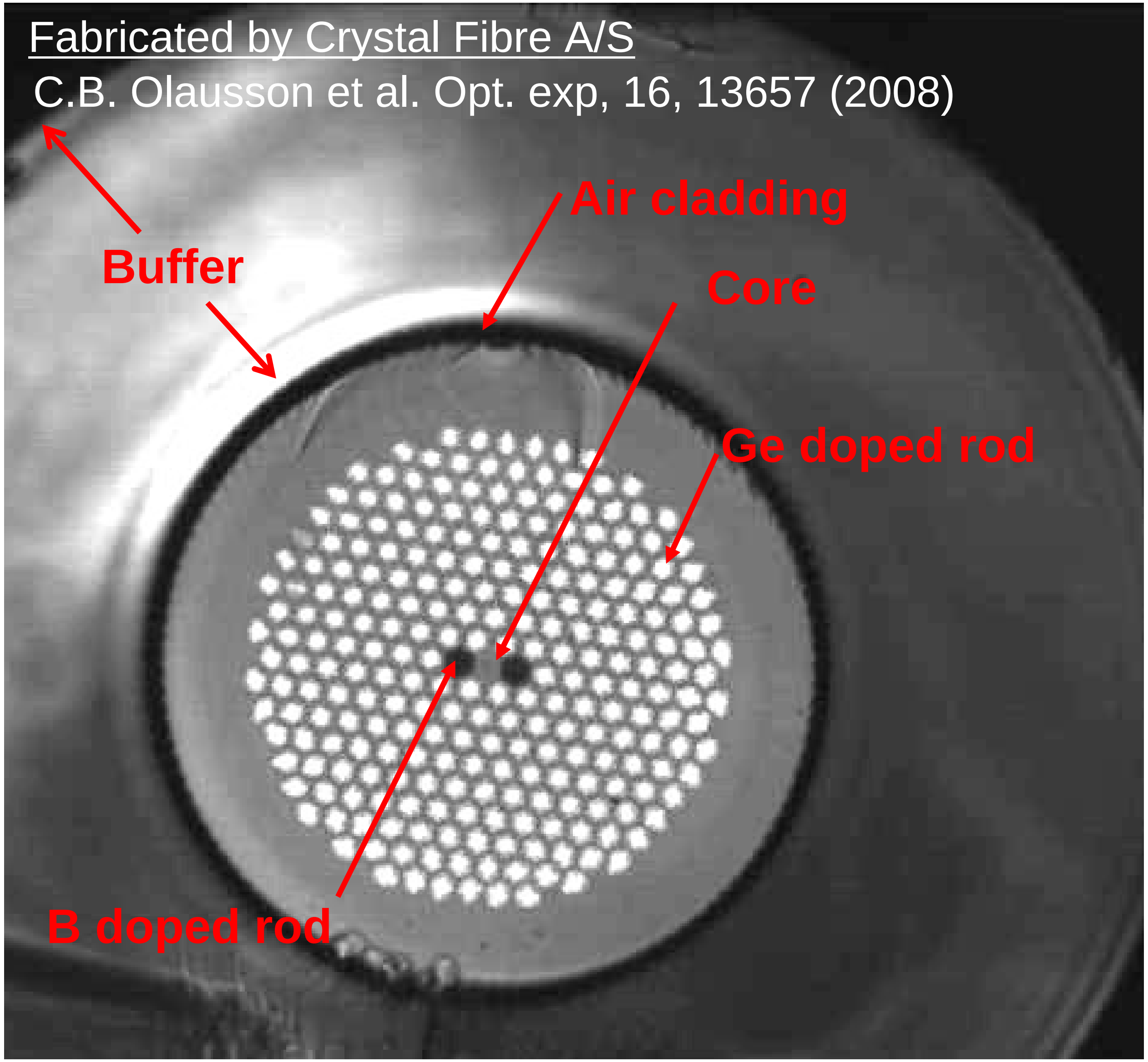
S. Fredrich, G. Huber

景德鎮 Jingdezhen
“Ceramics Metropolis" of China

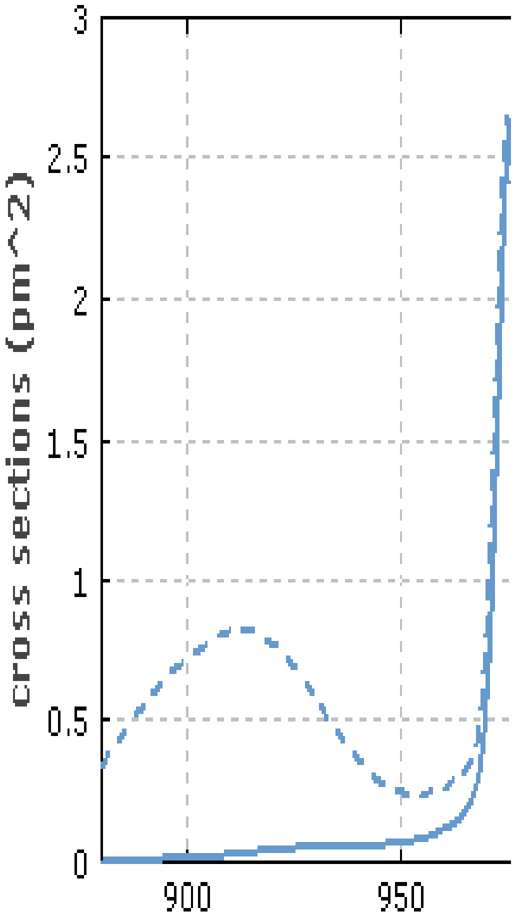
Transluscent Ceramics in Jingdezhen

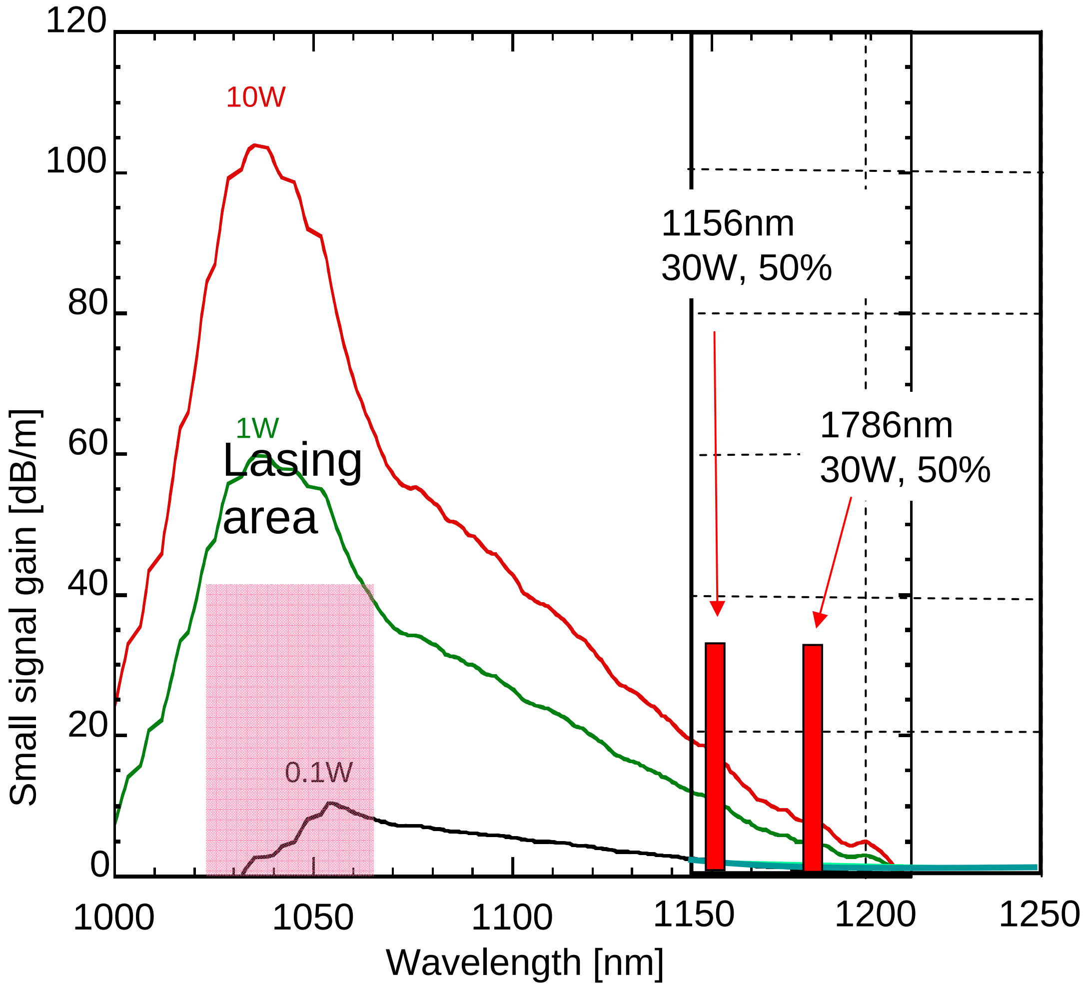
薄胎 （清代）

ASE control by Photonic Band Gap

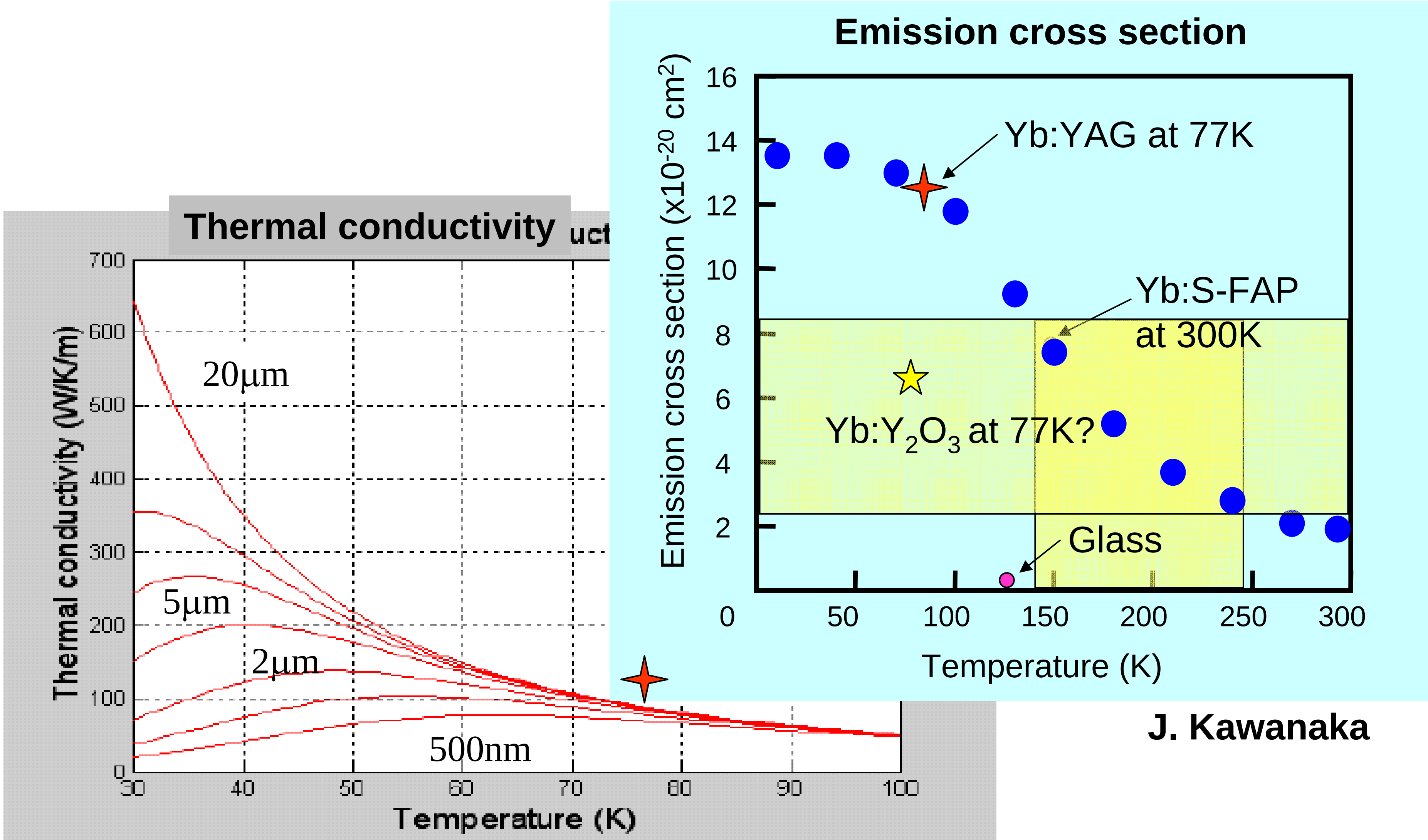


Photonic Bandgap Fiber broke the gain limit by full control of ASE and parasitic lasing.





Proposal on Temperature Tuned IFE Driver
Yb:YAG at low temperature (Kawanaka & Bisson& Ueda) WS on
Critical Issues on Solid State Lasers, APLS 2003



J. Kawanaka

J.F. Bisson

Thermal lens effect of sapphire mirror at 20K was measured to be at least 10^{-4} smaller than room temperature in the LCGT program (GW telescope)

Thermal lens $$ds \propto \frac{\alpha\beta}{\kappa}$$

α : absorption coeff.
β : thermal conductivity
κ : thermal expansion

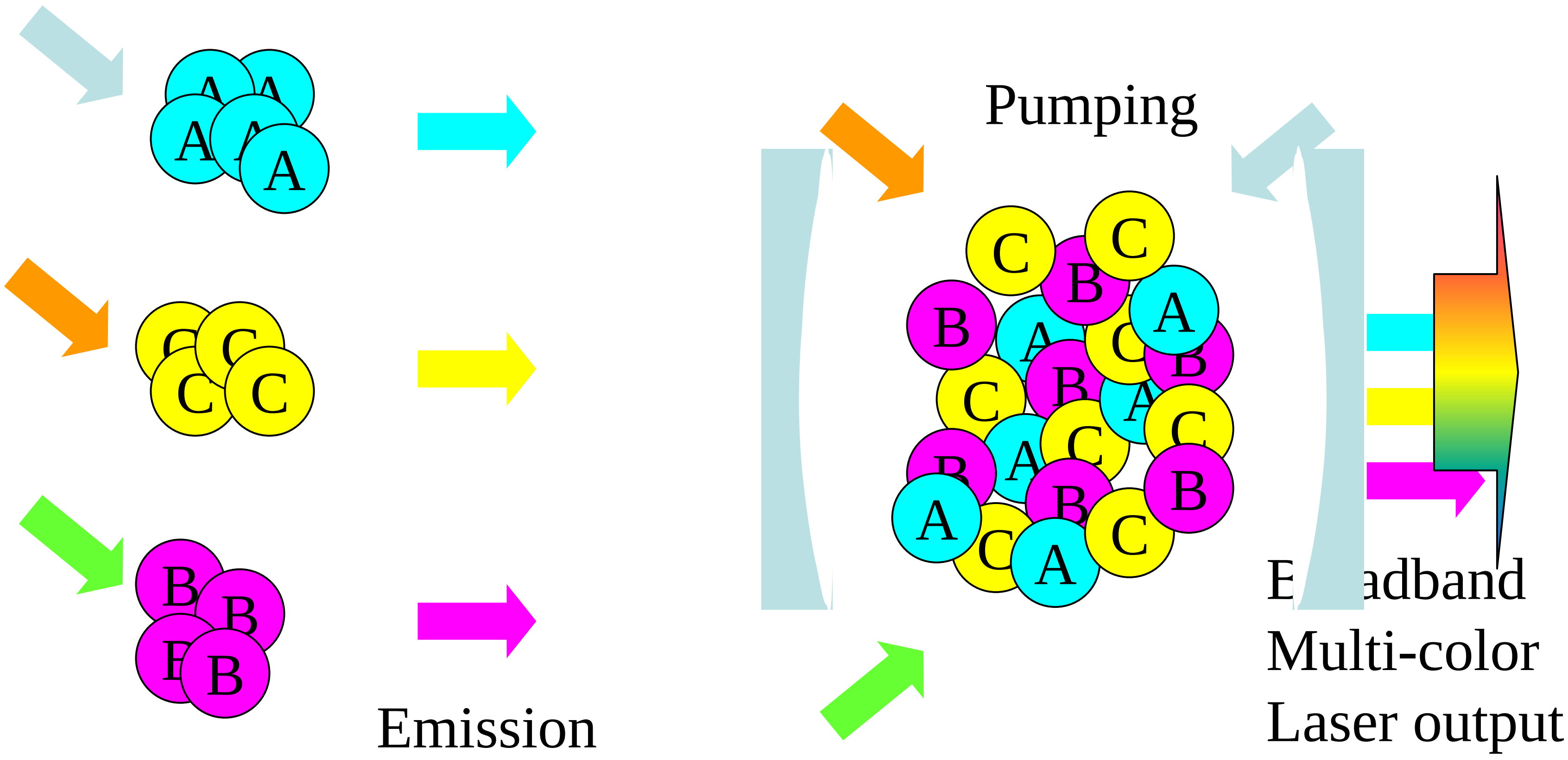
Measurement for LCGT mirror

	Fused silica (300k)	Sapphire (300K)	Sapphire (20K)
α [ppm/cm]	2 - 20	40 - 100	90
β [W/m/K]	1.4	46	4.3×10^{3}
κ [K^{-1}]	1.4×10^{-5}	1.3×10^{-5}	$<\|9 \times 10^{-8}\|$
$\alpha\ \beta/\ \kappa$ [W^{-1}] $\times 10^{-9}$	2 - 20	1 - 3	$<\|2 \times 10^{-4}\|$

Spectral Control
100% inhomogeneous broadening

ILS/UEC

Absorption Laser materials are the emission converter.

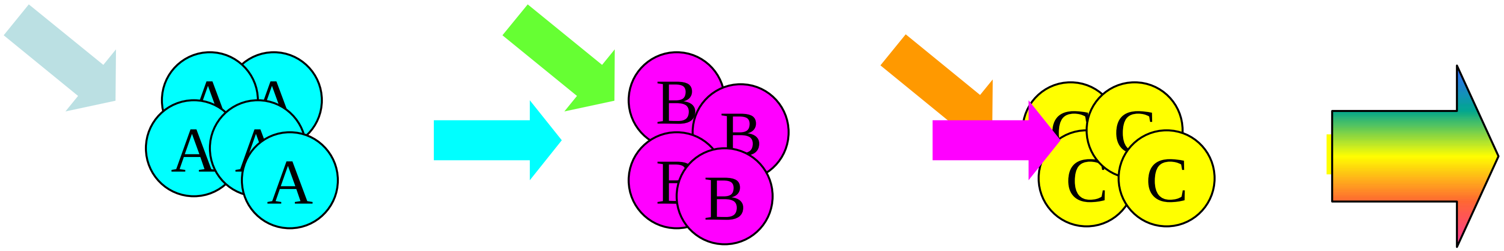


Combined Active Media for Broadband Lasers are possible?

ILS/UEC

Absorption

Laser materials are the emission converter.



Emission