High Power Driver: Route toward Reality

Alternative Route: Ceramic Lasers
Phase Controlled SBS Beam Combining
Coating Damage

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Historical Background of Ceramics

-Origin of “Ceramics” : Greek “Keramos”

- Clay sintering

9000 years ago

<900ºC

Low quality clay

Inhomogeneous

Traditional Ceramics

1300 – 1500 ºC

High quality clay

Special harmony

Modern Ceramics

Late 20 century

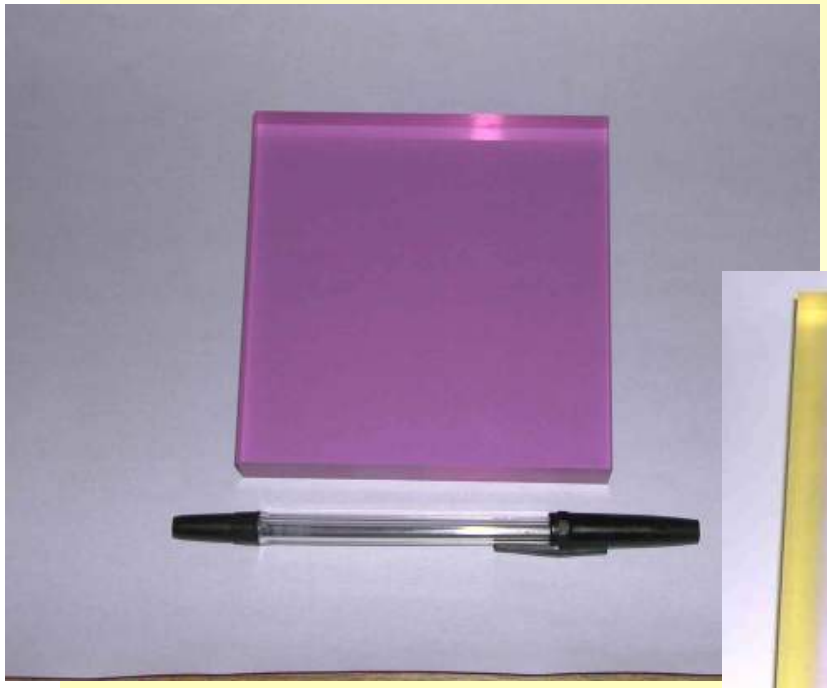
Synthesized particles

Homogeneous

Translucent Ceramics → Transparent Ceramics

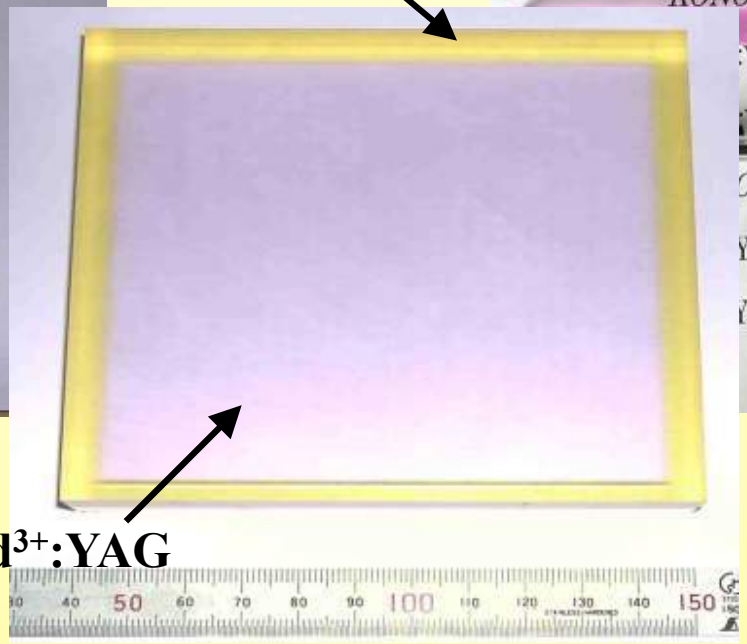
Ceramic lasers: scalable, polycrystalline lasers with high quality and high thermal conductivity.

Today, quality of laser ceramics is better than single crystal.

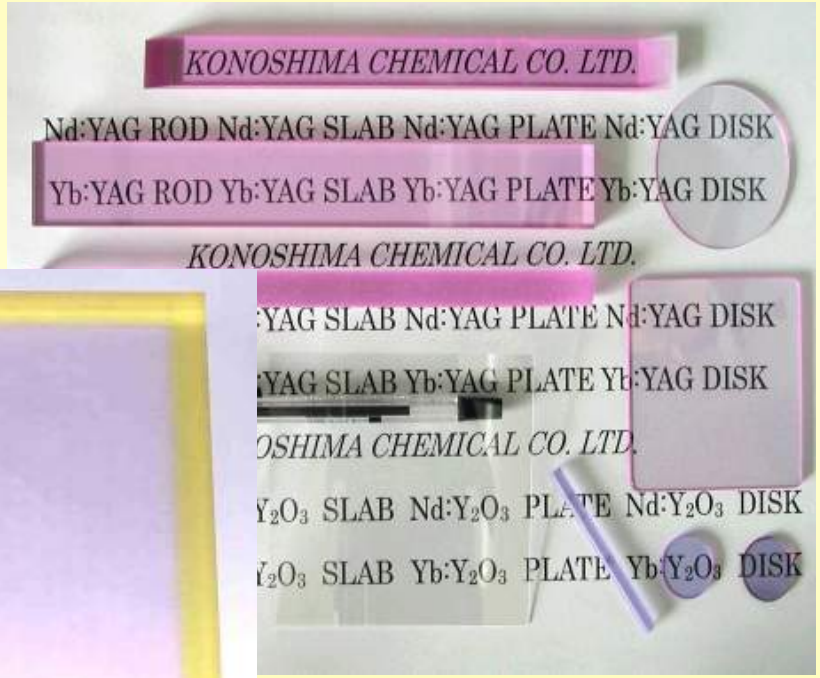


Large size Nd:YAG disk

Sm^{3+}:YAG



Nd^{3+}:YAG



Nd:YAG slab and rod

Konoshima chemical, ILS/UEC

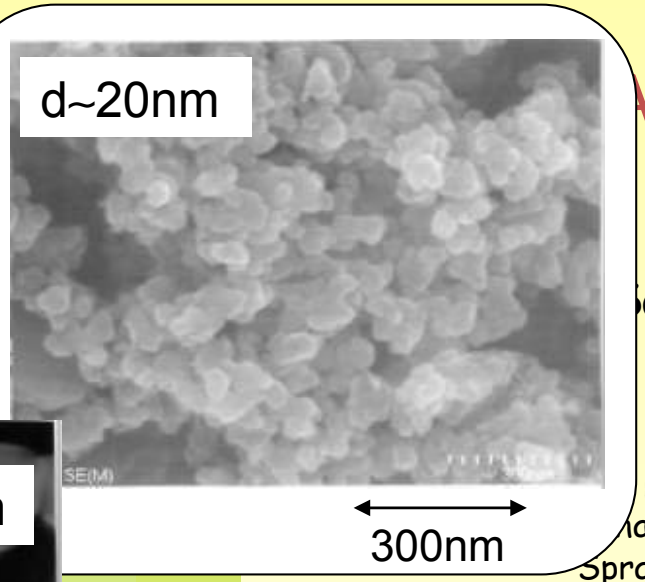
Synth … AG Ceramics

Non-Reactive s…

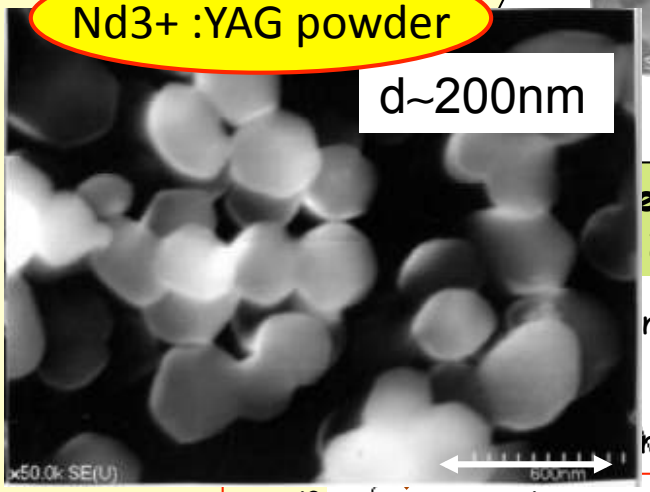
Reactive sintering

Precipitation/ Calci…

(Dr. Ueda's group, Konos…



Nd3+ :YAG powder



…ecursor
…20nm)

…n

…h at 1200°C

Nd³⁺ :YAG powder 600nm~200nm

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

Transparent Nd^{3+} :YAG ceramic

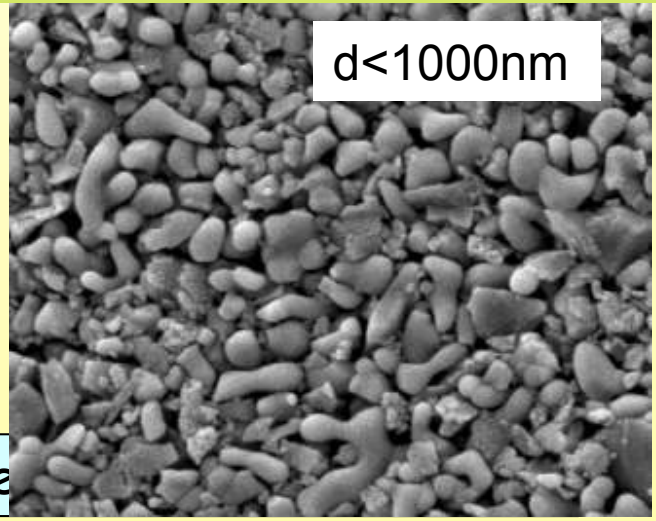
…olid-state reaction route

(Dr. A. Ikesue)

Oxides Y_2O_3 + Al_2O_3

…milling,
…anol + $(C_2H_5O)_4Si$
Spray drying

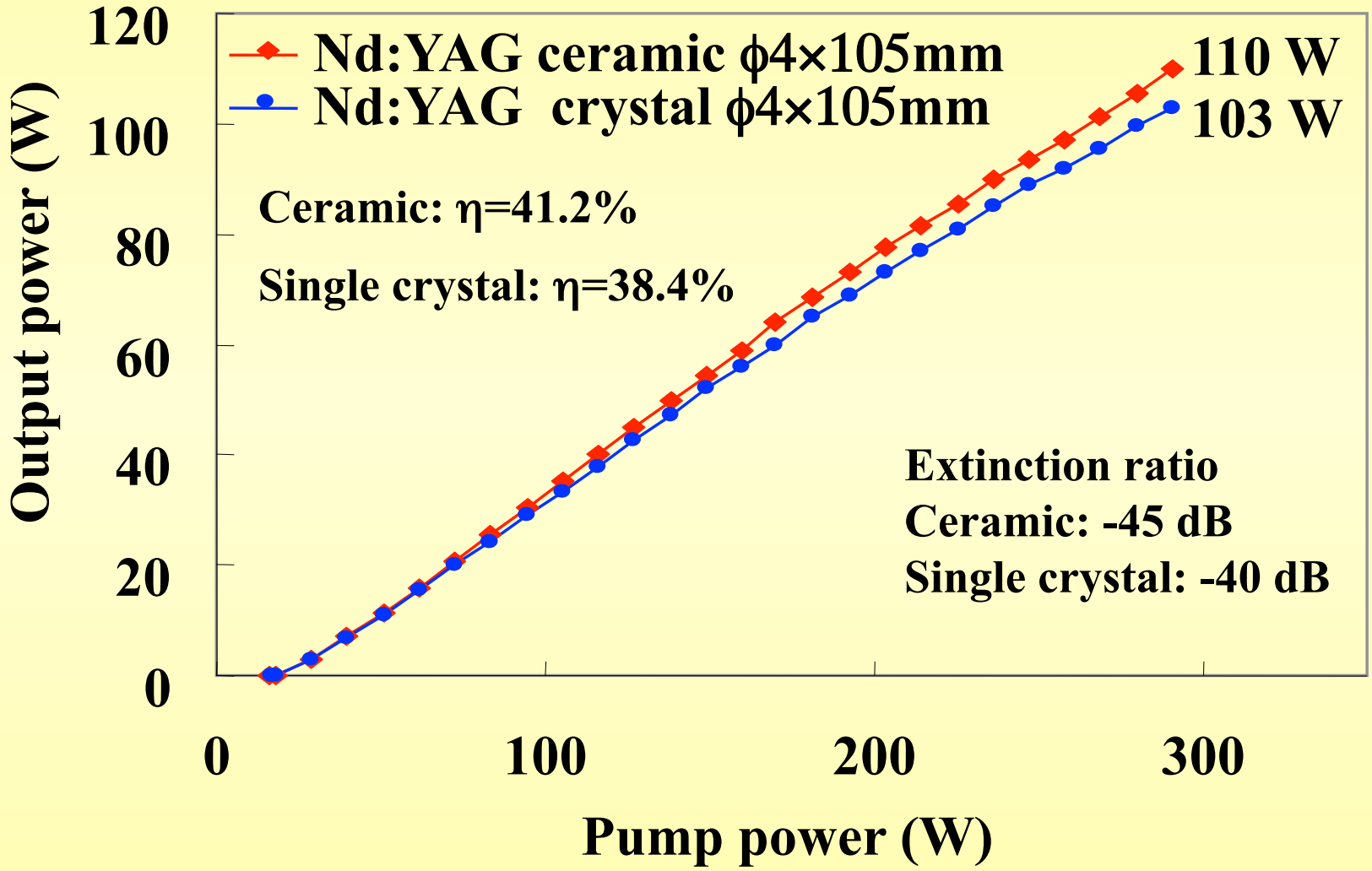
Fine silica-coated Y_2O_3 + Al_2O_3 particles (size <1μm)



There are two approaches to transpare…

Ceramic lasers demonstrate higher efficiency. (2004)

J. Lu, K. Ueda et al, Appl. Phys. B., **79**, 25, 2004.



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

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 High-Energy Laser Development Engineers
- Development of Next-Generation Laser Systems with Ceramics

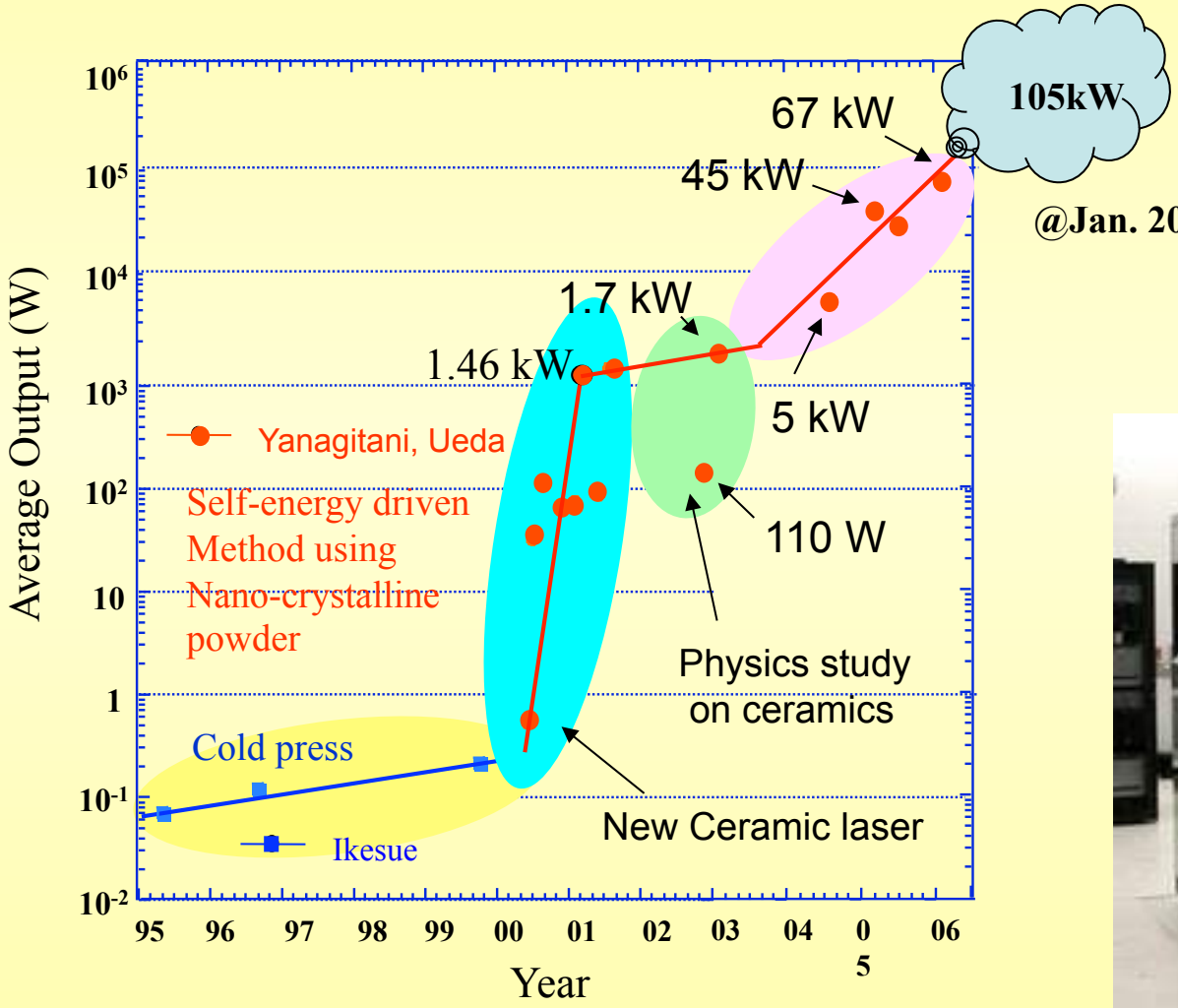
→ ***Higher Power Solid State Lasers***

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

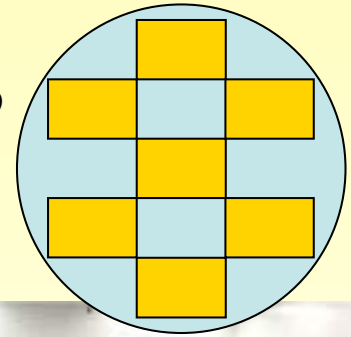
Property Comparisons

Property	Ceramic vs Single Crystal
• Thermo-optic Coefficients	**Identical**
• Spectroscopic Properties	**Identical**
• Dopant Gradient	**Ceramic superior**
• Wave front distortion	**Ceramic superior**
• Bonding ease/cost	**Ceramic superior**
• Solarization (lamp-pumped)	**Ceramic inferior**
• Diode-pumped performance	**Ceramic superior**
• Scatter loss	**Ceramic superior**
• Stress fracture	**Ceramic superior**

Ceramic laser demonstrated >100kW Output by 7 beam coherent combining in 2009.

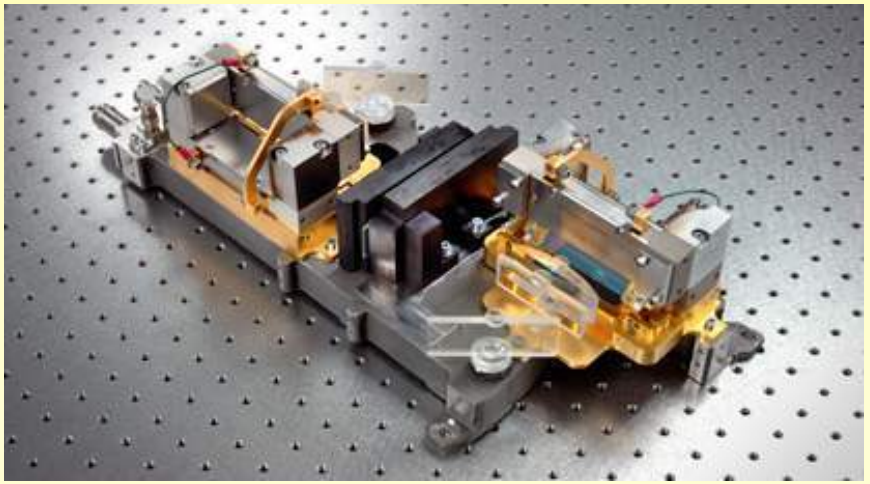


7x15kW>105kW



JHPSSL, Northrop Grumman

Northrop-Grumman
Joint High Powered Solid State Laser

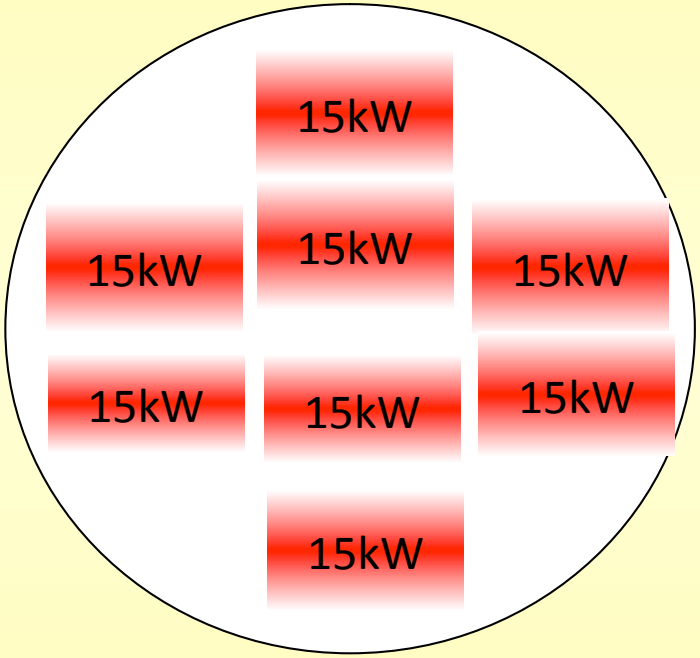


In Phase 3 of the US $56.68 million JHPSSL program, eight 15kW laser chains of four modules each will combine to achieve a total power of 100kW.

105kW@7 beams, 120kW@8 beams

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%.

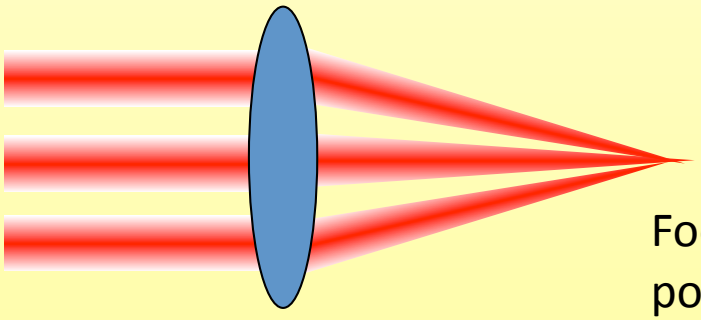
Coherent beam combining



8x15kW>120kW

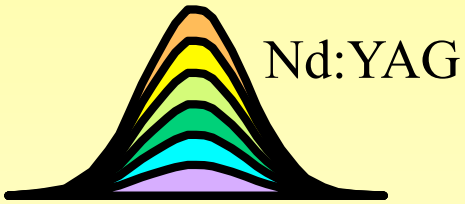
When the wavefronts are adusted, 8 beams works as a single beam.

Simple application of beam combining technique to the laser power scaling.



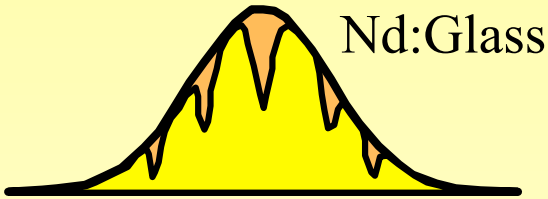
Focusing in a point

Crystal or Glass or Ceramics?



Homogeneous line

Ceramic laser: Glass-like fabricated crystal



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

Laser Ceramic Symposium (Kaminskii, Strek, Ueda)

1st International Laser Ceramic Symposium, Warsaw, Poland, 2005
2nd International Laser Ceramic Symposium, Tokyo, Japan, 2006
3rd International Laser Ceramic Symposium, Paris, France, 2007
4th International Laser Ceramic Symposium, Shanghai, China, 2008
5th International Laser Ceramic Symposium, Biobao, Spain, 2009
6th International Laser Ceramic Symposium, Munster, Germany, 2010
7th International Laser Ceramic Symposium, Singapore, 2011

5th Laser Ceramics Symposium:
International Symposium on Transparent Ceramics for Photonic Applications

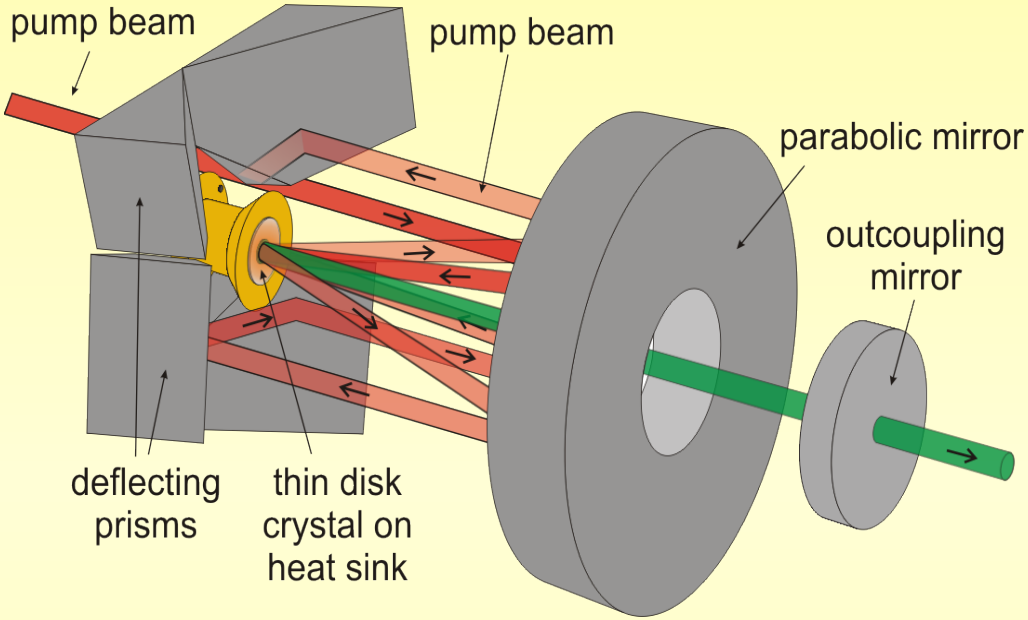
Bilbao, Spain, December 9-11, 2009

6th Laser Ceramics Symposium
International Symposium on Transparent Ceramics for Photonic Applications

Münster, Germany, December 6 - 8, 2010

Photos: Presseamt Münster

Thin-Disk Laser Design



24 absorption passes

- Thin crystals of 100–300 µm are mounted on a copper heat sink
- Efficient cooling decreases the threshold of quasi-4-level lasers
- Nearly no thermal lensing effects > excellent beam quality
- **High doping concentrations are required**

*A. Giesen et al., Appl. Phys. B **58**, 365 (1994)*

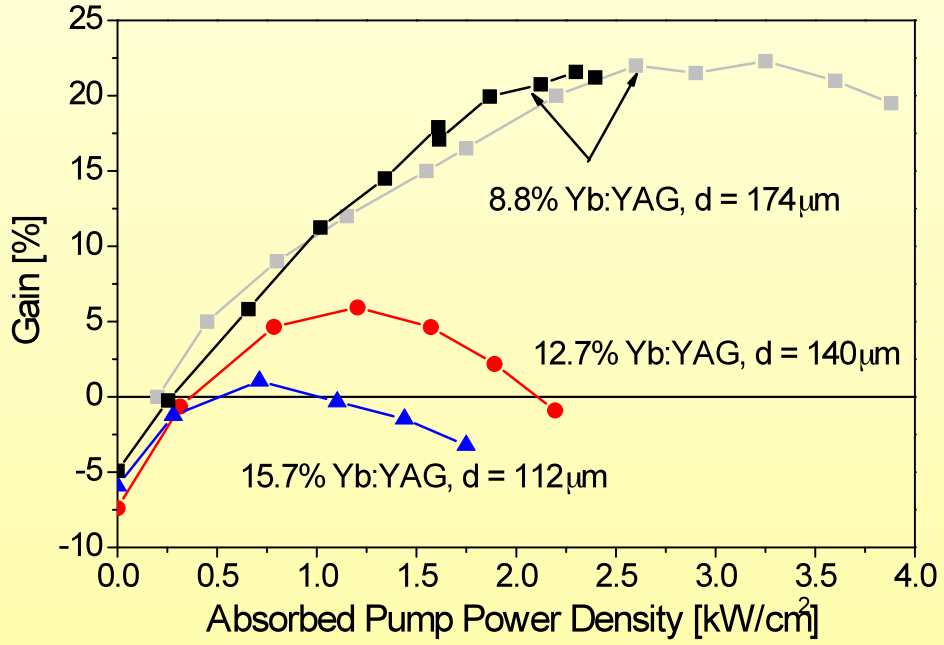
Motivation

Further development:

Thinner laser medium for even better heat removal

→ Higher doping concentrations required for sufficient absorption

However: In 2005 *non-linear losses* were reported for Yb:YAG thin-disk lasers



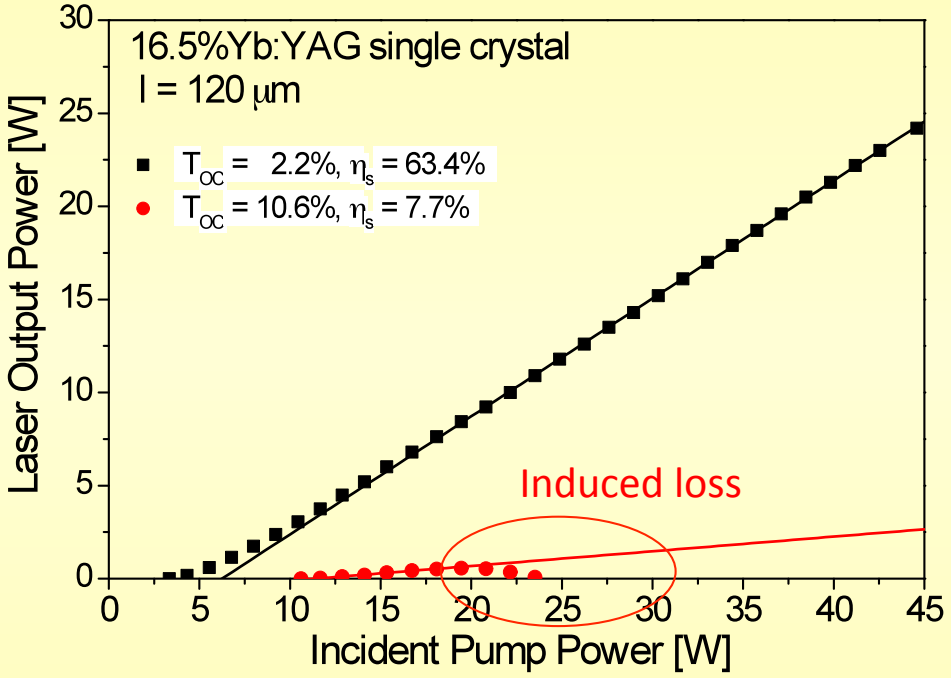
Non-linear losses depend on:

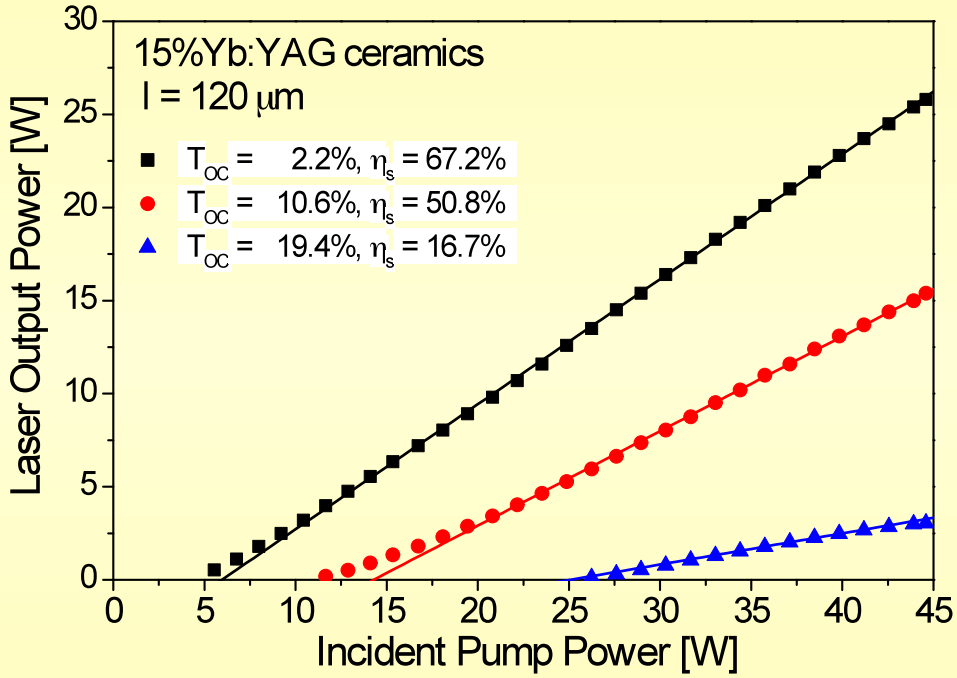
- Yb-doping concentration
- density of excited Yb-ions
- temperature

M. Larionov et al., ASSP (TOPS) ***98****, 18 (2005)*

Thin-Disk Laser Experiments

Comparison of 16.5% Yb:YAG single crystal and 15.0% Yb:YAG ceramic



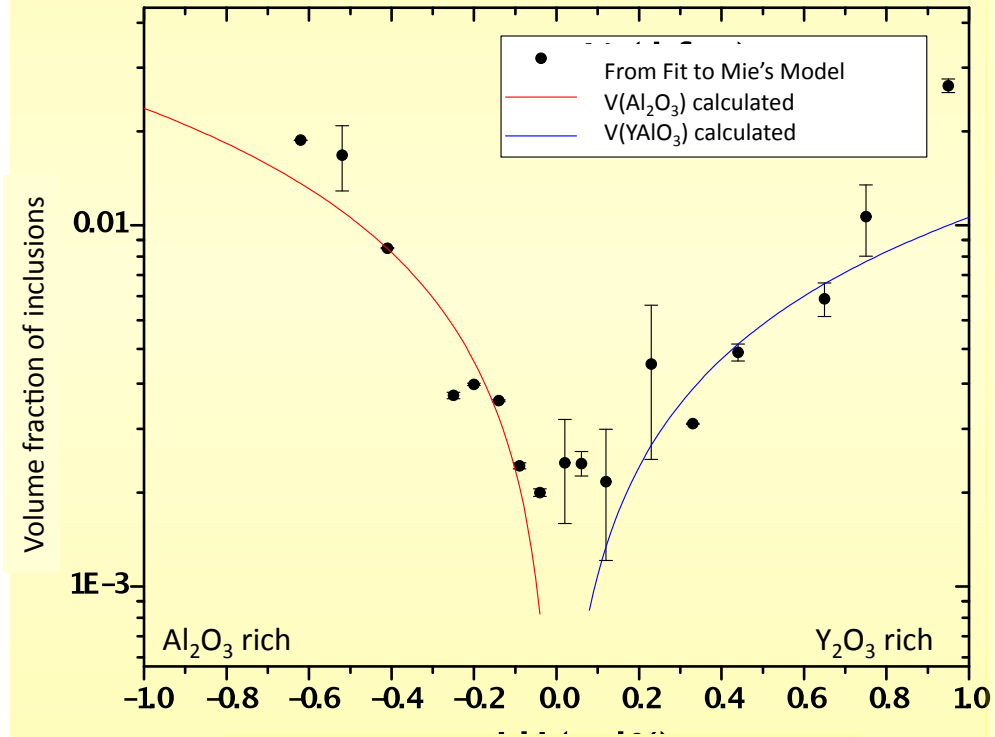


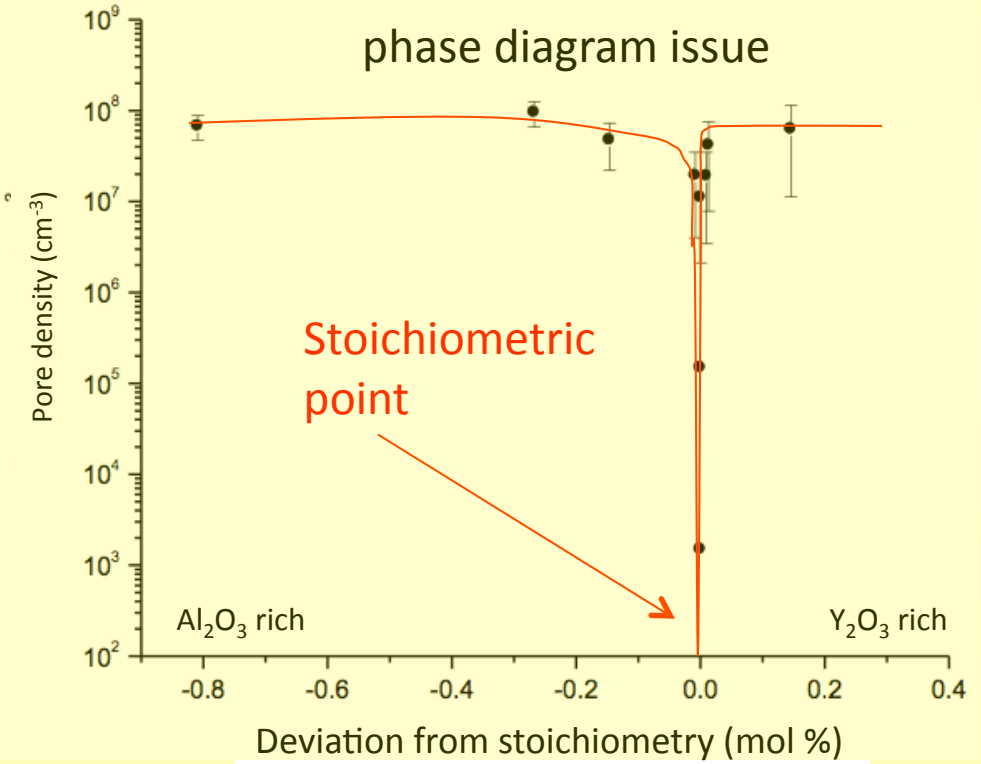
Ceramic:
- slightly higher efficiency for T_{OC} = 2.2%
- much higher efficiency for T_{OC} = 10.6%
- laser operation possible for T_{OC} = 19.4% with 15% Yb:YAG ceramics

Nature of Scattering Centers

Effect of deviations from stoichiometry on the nature of scattering centers

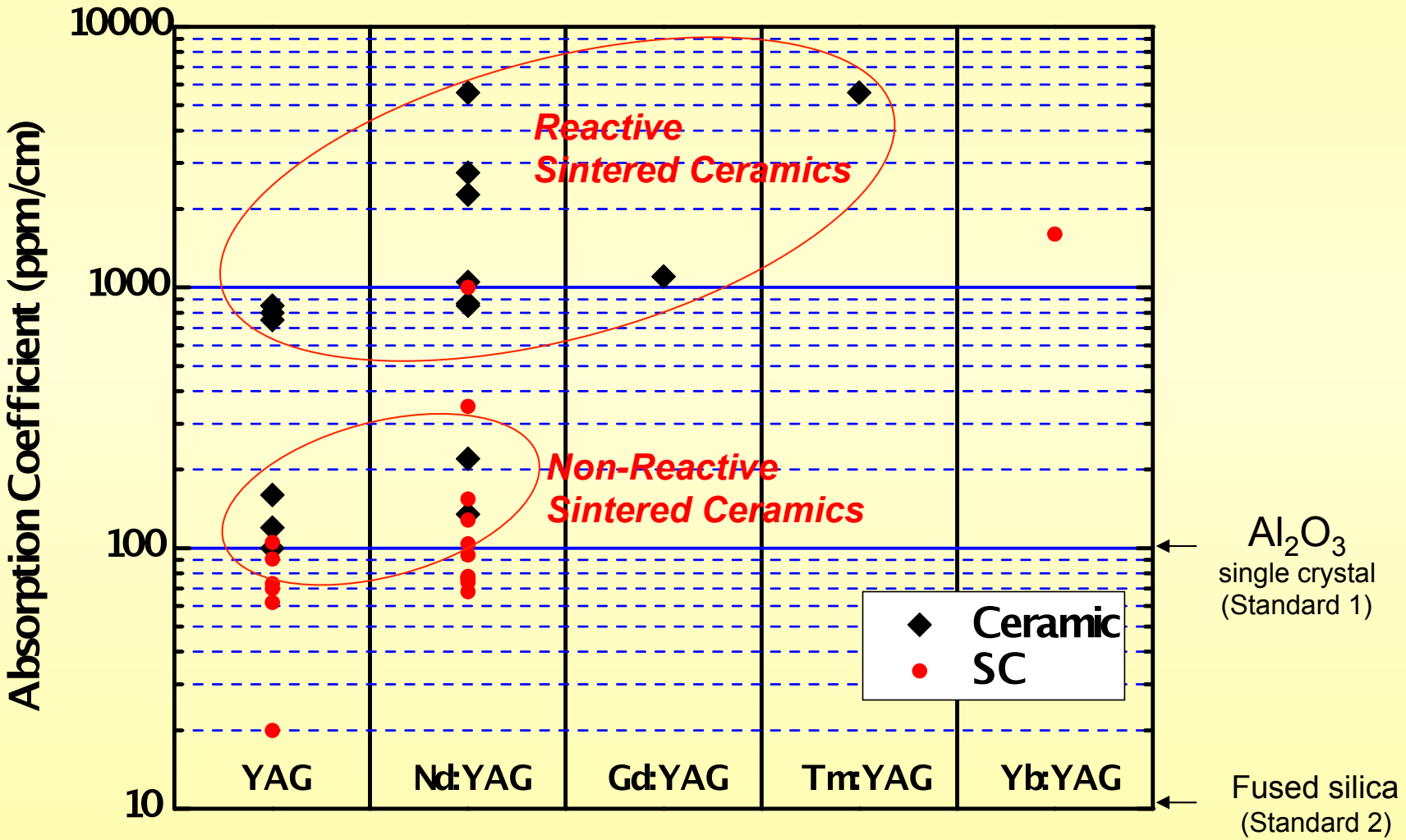
Non-reactive sintering is important for ceramics fabrication.: conclusion of Gaume and Ueda





The reason of 100 times smaller scattering in nano-crystalline powder sintering is stoichiometric control of ceramics. It is very hard to keep stoichiometric condition in reactive sintering. : Our conclusion.

1064 nm Absorption in YAG Ceramics and Single crystals



Non-reactive sintering is key.

Beam combining in solid state lasers

Phase controlled SBS PCM technique by H.J. Kong, KAIST

WS on Critical Issues of Solid State Lasers

16:30, March 4, 2004, Emerald Hall, Yong Phyong, Korea

Moderator: K. Ueda
H.J. Kong

1. Background
   - Almost 10 years development of LD pumping
   - Hard competition with high power fiber lasers

2. High average and high quality beam generation
   - Pumping geometry — K. Ueda
   - Thermal management
   - Mode selection techniques

Crazy ideas are welcome!

New proposal for fusion drivers

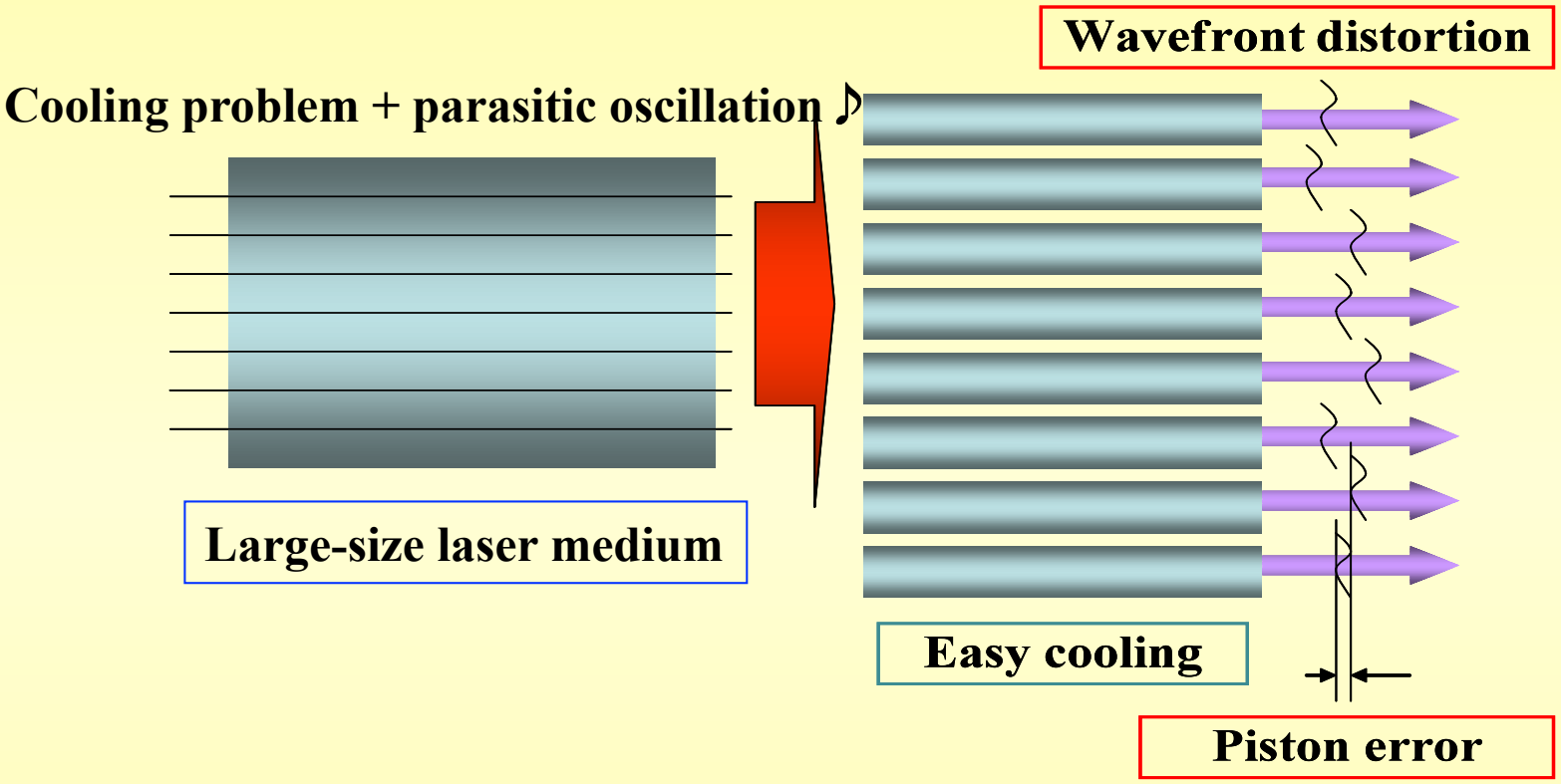
3. Femtosecond pulse generation
   - Broadband laser lines, multi-color lasers
   - Mode locking devices, SESAM, KLM etc
   - Pulse compressor

4. Coherent summation and combining techniques
   - Phase arrays — K. Ueda
   - SBS combining — H.J. Kong

Phase controlled SBS and its application to a coherent four beam combination toward a Dream Laser♪

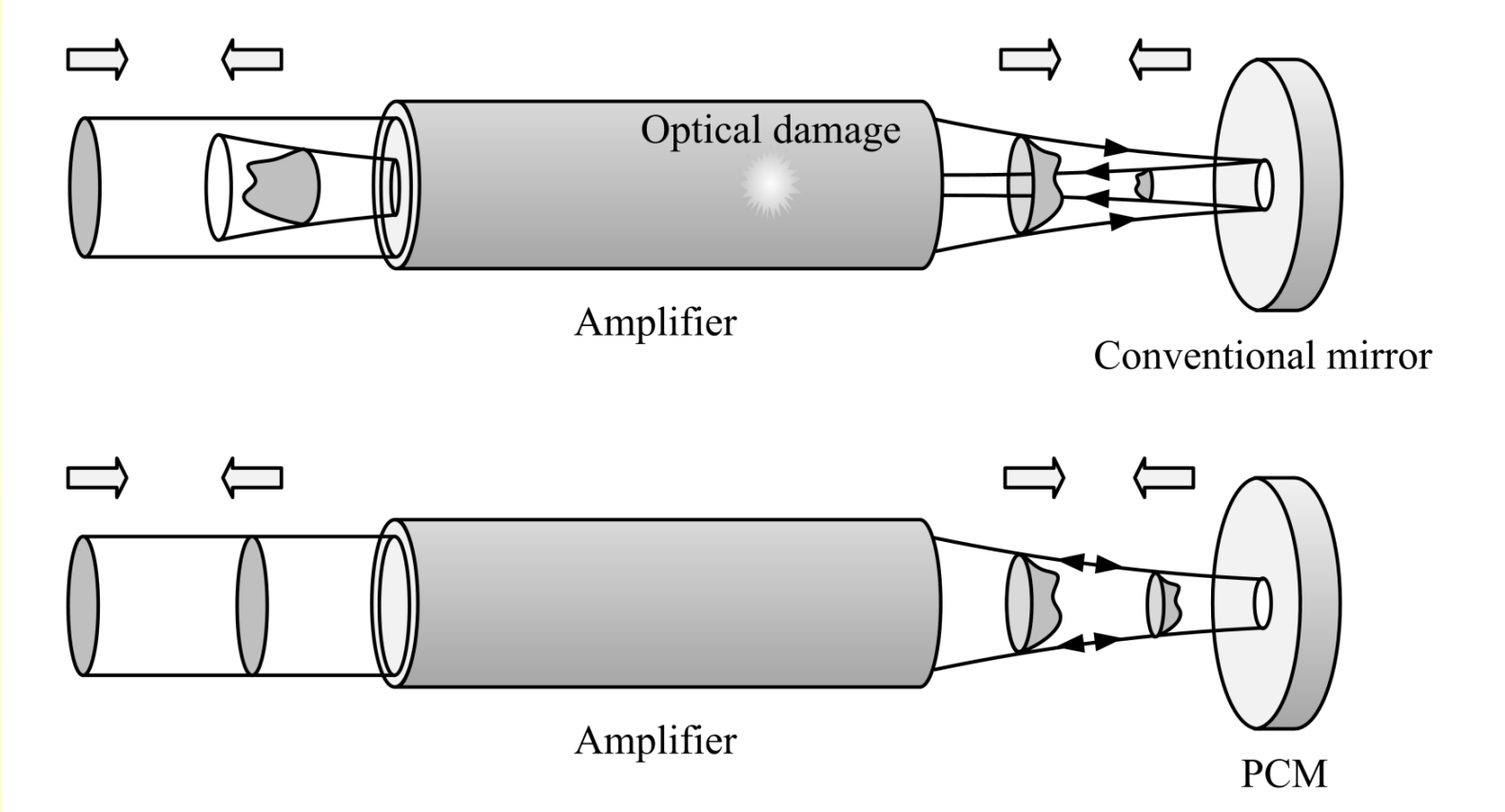
H. J. Kong, S. Park, and S. Cha
Department of Physics, KAIST, Republic of Korea♪

Beam combination and its problems



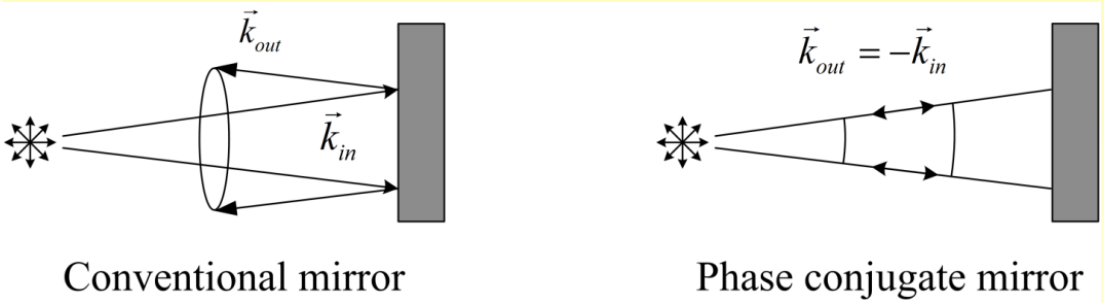
- **Wave-front distortion :** by **stimulated Brillouin scattering (SBS) phase conjugate mirrors** with the double-pass amplification
- **Piston error :** inherent problem of SBS, but it has been resolved by a new technique, **the self-phase-control technique** invented by H. J. Kong

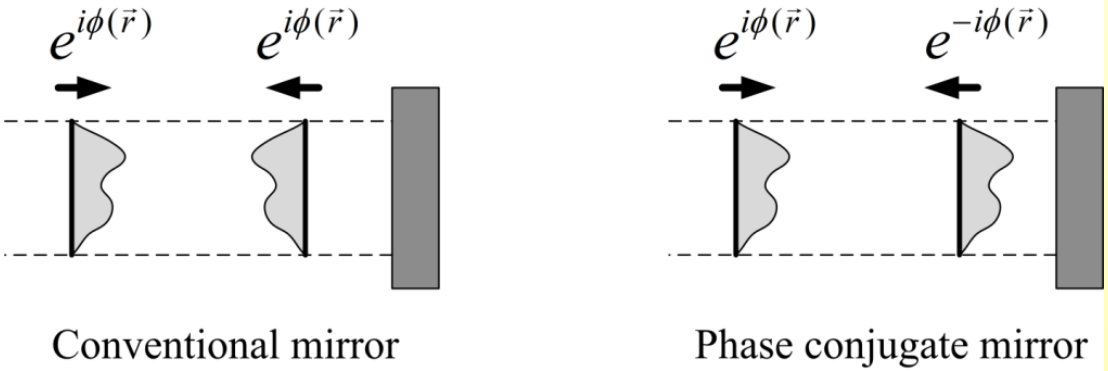
Practical Application of SBS-PCM

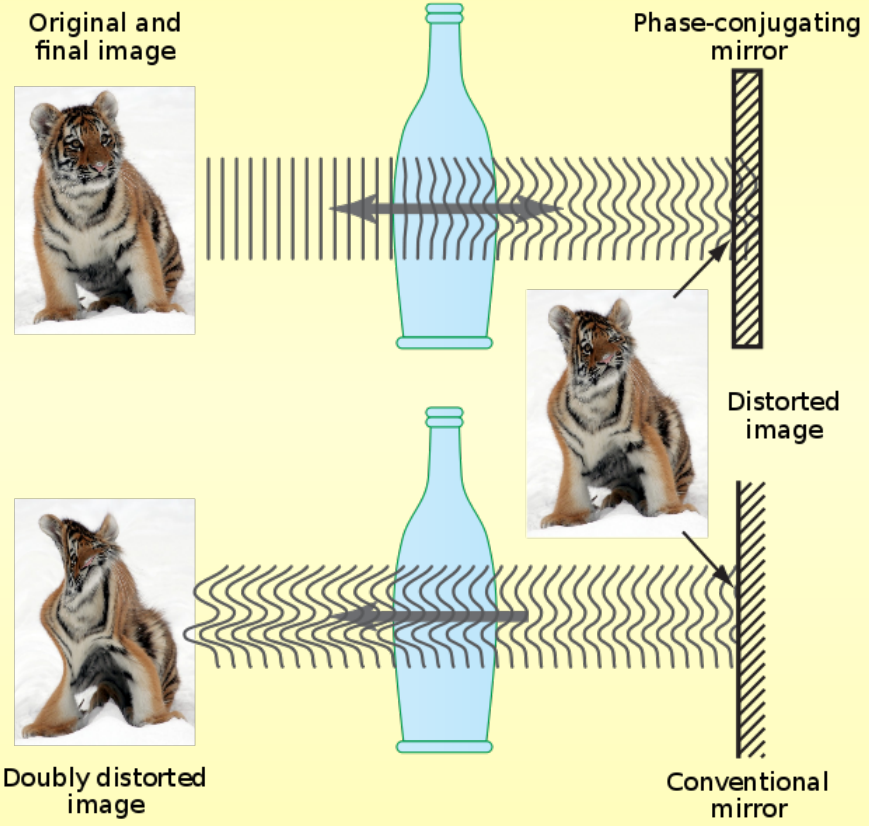


Master oscillator power amplification (MOPA) with phase conjugate mirror (PCM)

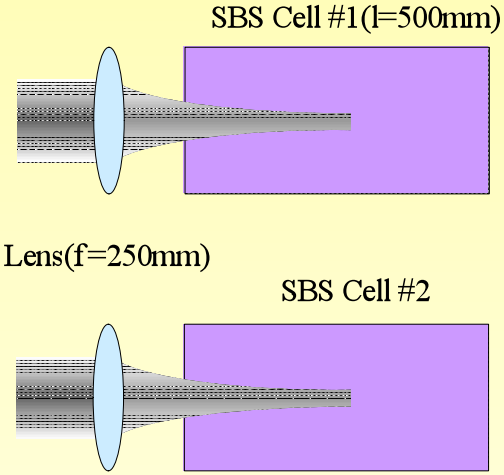
Phase conjugate mirror

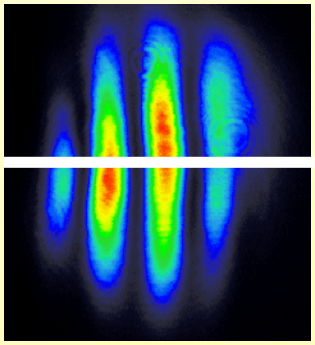




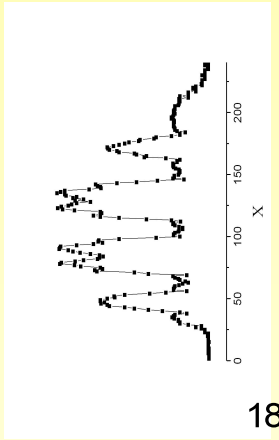


Phase of the conventional SBS-PCM

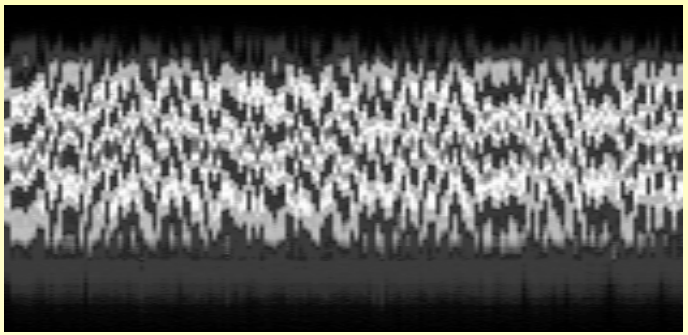


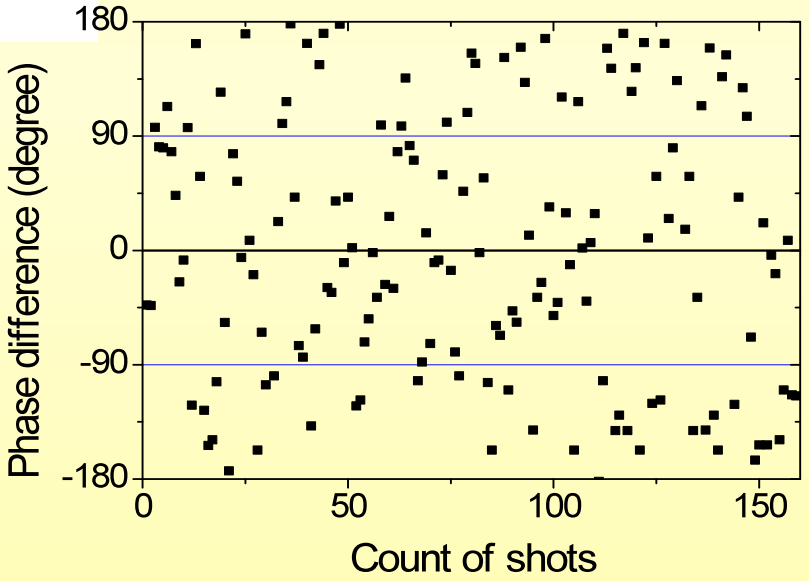


Intensity profile of interference



Intensity profile of interference for 160 shots





H. J. Kong, S. K. Lee, and Y. S. Kim, "Phase locking of two beams using stimulated Brillouin phase conjugate mirrors, LO2003, XIth Conference on Laser Optics, St. Petersburg, Russia (June 30 – July 04, 2003).

pulse duration to be long compared with the SBS onset time and intercell transit time. Similarly, for a coherent interaction it is necessary for the laser-coherence length to be at least twice the total length of the two-cell system. If the intercell transit time is long, then there will be a lengthy delay before the amplifier is seeded and power limiting becomes effective. For this reason it is desirable to use a relatively compact two-cell geometry.

A further feature demonstrated by the simulations but also observed experimentally at high powers is the ability to achieve greater than unity reflectivity on a transient basis. This overshoot by the Stokes radiation can be explained by storage of radiation in the two-cell system. The excess of Stokes power over the input pump will only be temporary since the severe depletion of the pump will reduce the seeding signal, resulting in an overshoot for a time of the order of twice the intercell transit time. The amount of overshoot is dependent on the gain of the amplifier and on the intercell losses. For low losses, the seeding level can be high, leading to a substantial overshoot.

The performance of the generator cell could be improved by the introduction of optical feedback, which has been shown to reduce the threshold and increase the phase conjugate fidelity of the SBS process [7.6], as described previously.

7.5 Laser beam combining using SBS

In the normal SBS configuration a single pump beam is incident upon the SBS medium, and the Stokes scattered output beam is generated by amplification of noise. This SBS scattered field will have a random overall phase since it starts from statistical noise and, in addition, this phase has been shown to fluctuate randomly in a time of the order of several times the phonon lifetime [7.14]. The SBS reflection, therefore, has no absolute temporal phase reference. As a consequence, if two beams are conjugated by SBS in separate interaction volumes the two Stokes beams will have a phase difference that is random and unrelated to the phase difference of the pump beams. Basov *et al* [7.15] first predicted this random phase difference and several groups demonstrated its existence [7.16–7.18]. If the random phase difference in the Stokes beams is to be avoided an absolute phase reference must be created. This can be accomplished by several methods.

7.5.1 Laser beam combining using spatial overlap in SBS

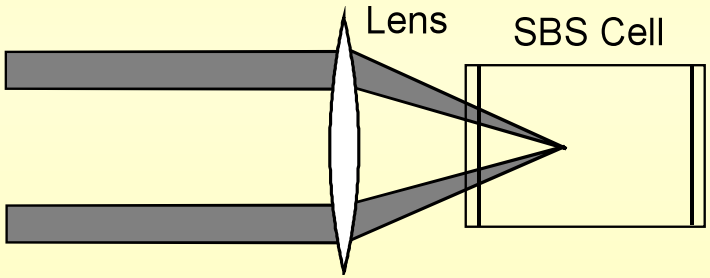
Consider the case where two or more pump beams are overlapped in the same interaction volume. They appear to the SBS process as a single, but highly aberrated, beam with the relative phase between the beams appearing as an aberrated wave front. The standard mechanisms that phase conjugate a

cation of noise. This SBS scattered field will have a random overall phase since it starts from statistical noise and, in addition, this phase has been shown to fluctuate randomly in a time of the order of several times the phonon lifetime [7.14]. The SBS reflection, therefore, has no absolute

Previously developed phase control methods

1. **Overlapping** the SBS focal points locks the phases of the beams.

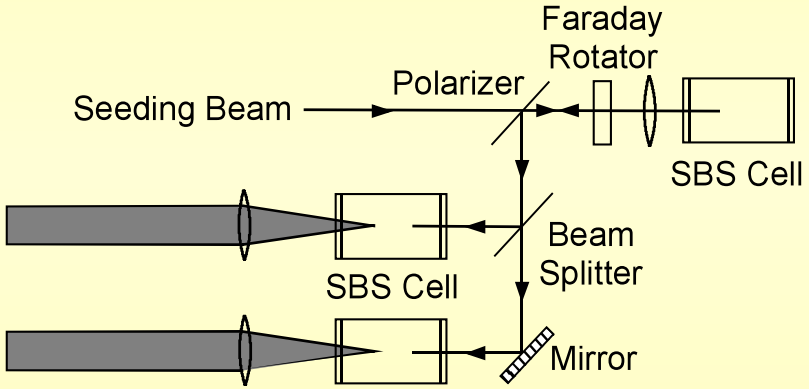
2. Phase locking by **back seeding** the Stokes shifted beam, which locks the p hase of the PC wave.



a) Overlap of two focal points

D.A.Rockwell and C.R.Giuliano, Opt. Lett. 11, 147 (1986)

Impractical for many beams > 4



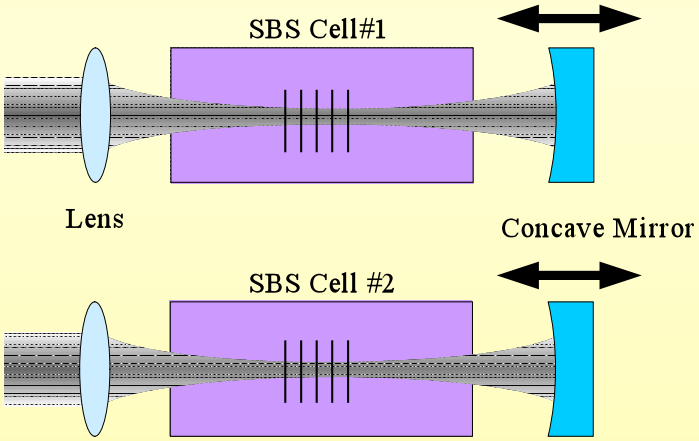
b) Back-seeding of Stokes wave

R.H.Moyer, et. al., J.Opt.Soc.Am.B, 5, 2473 (1988)

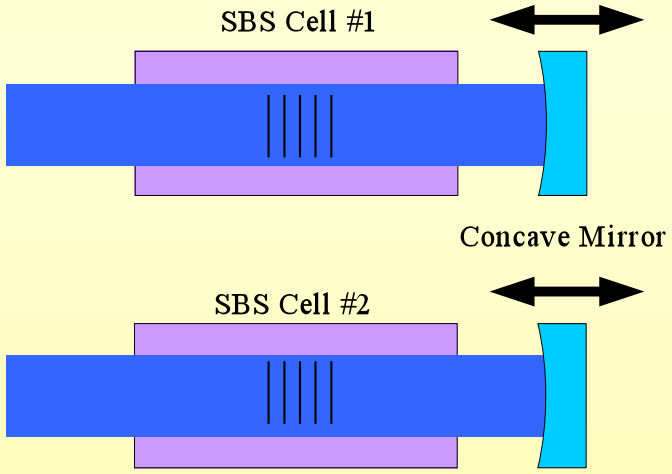
PC can be broken by back seeding beam
No PC anymore

"Self-phase control" method

- Feed back mirror > Counter propagating beams > Standing wave > Density modulation
- Standing density modulation locks the ignition position of the moving Bragg grating.
- The Bragg grating locks the phase of the SBS wave.
- Phase controlling of SBS wave is possible by positioning the feed back mirror.

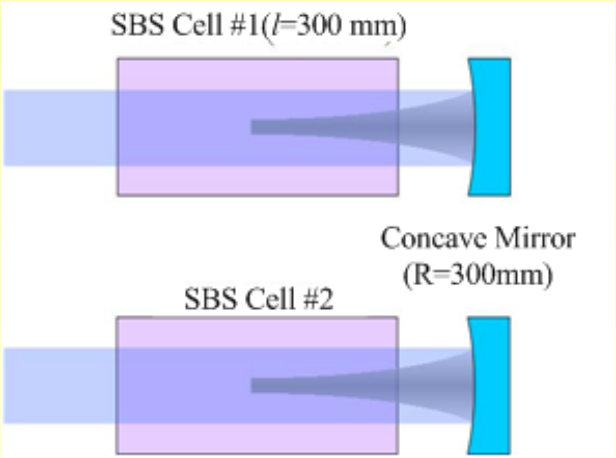


(a)Concentric type

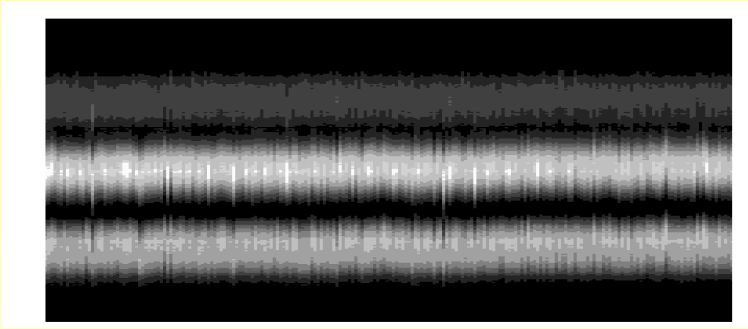


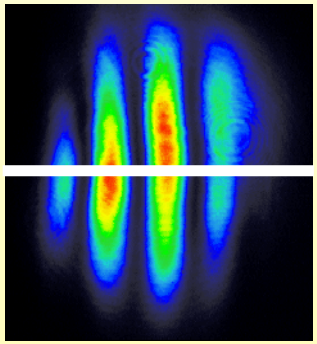
(b) Confocal type

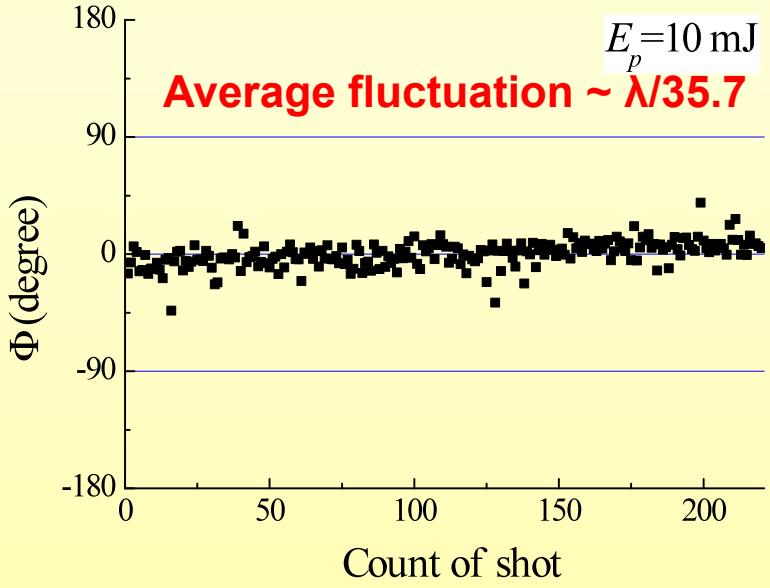
Phase controlled result – Amplitude division



Intensity profile of interference for 220 shots



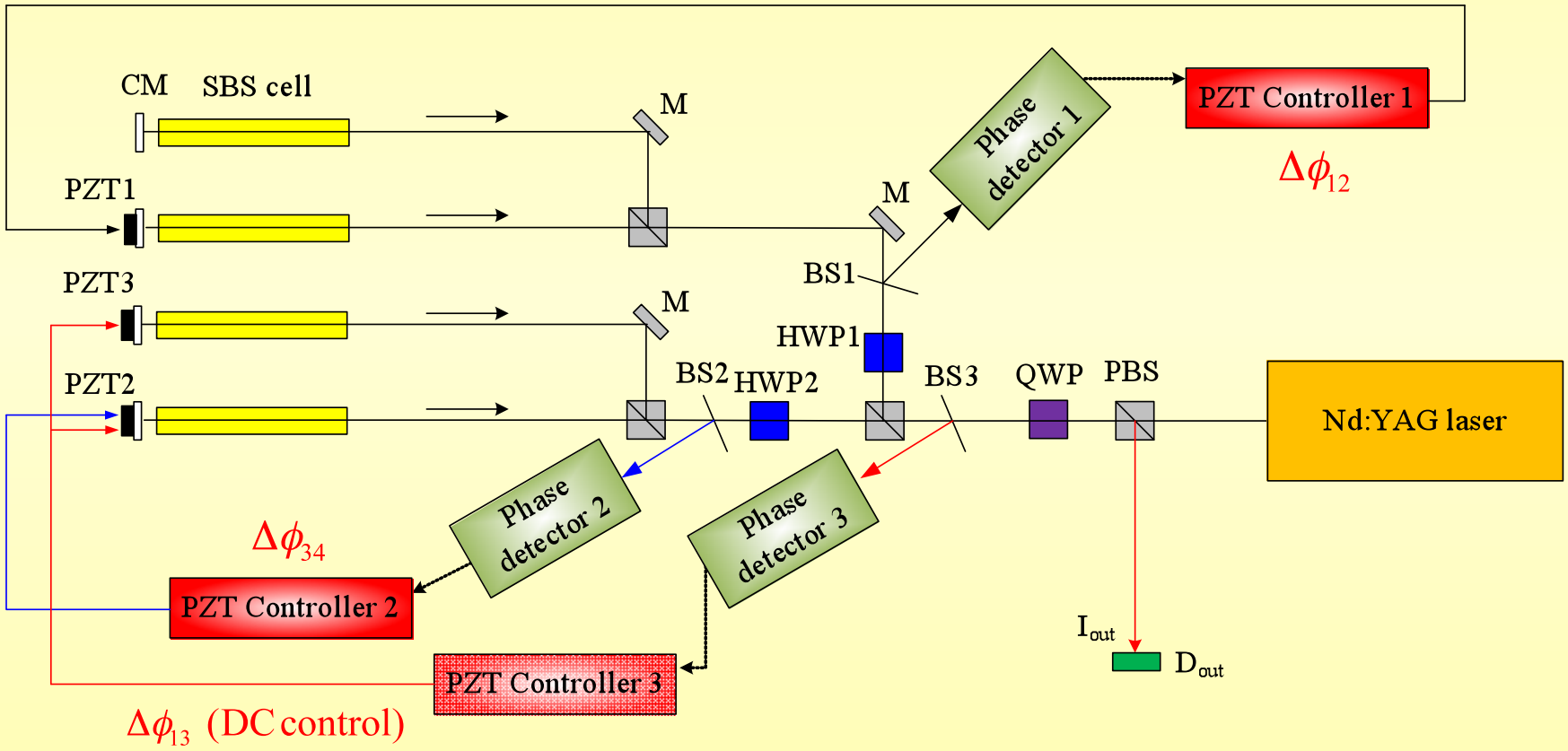




S. K. Lee, H. J. Kong, and M. Nakatsuka, Applied Physics Letters 87, 161109 (2005).♪

by courtesy of H.J. Kong, KAIST

Experimental setup for the amplitude dividing 4-beam combination

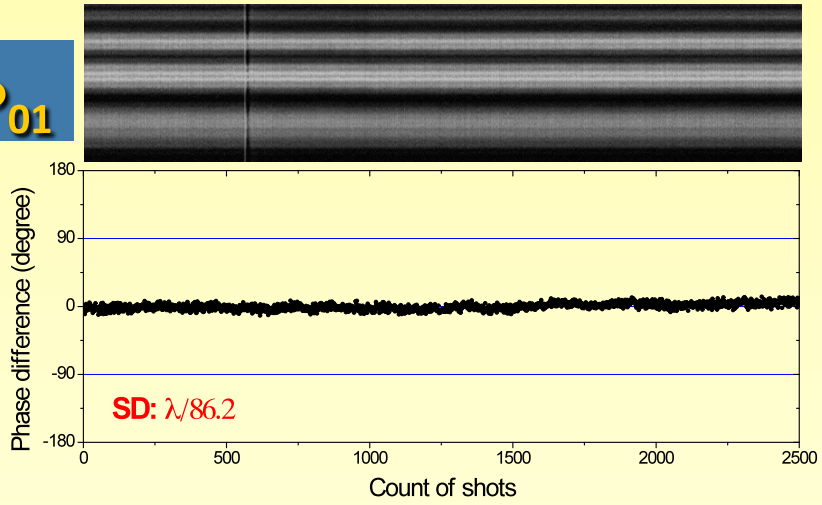


H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Laser and Particle Beams 27, 179-184, 2009.

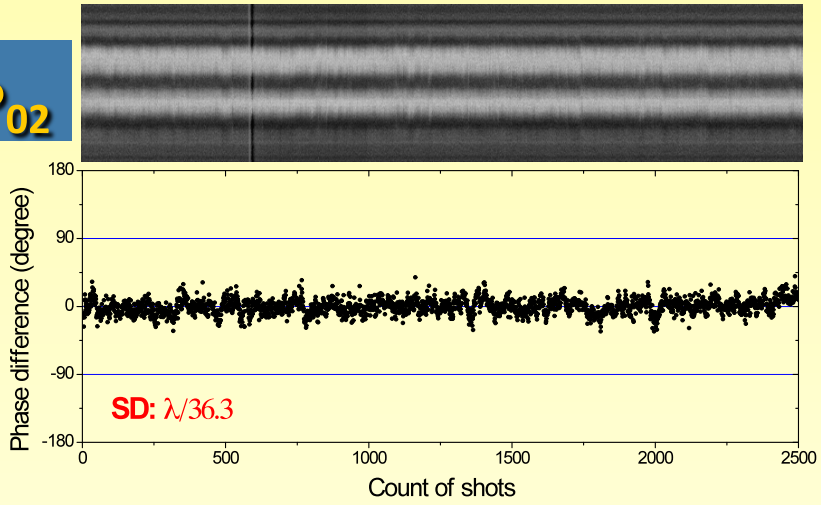
by courtesy of H.J. Kong, KAIST

Phase fluctuation without amplifier operation

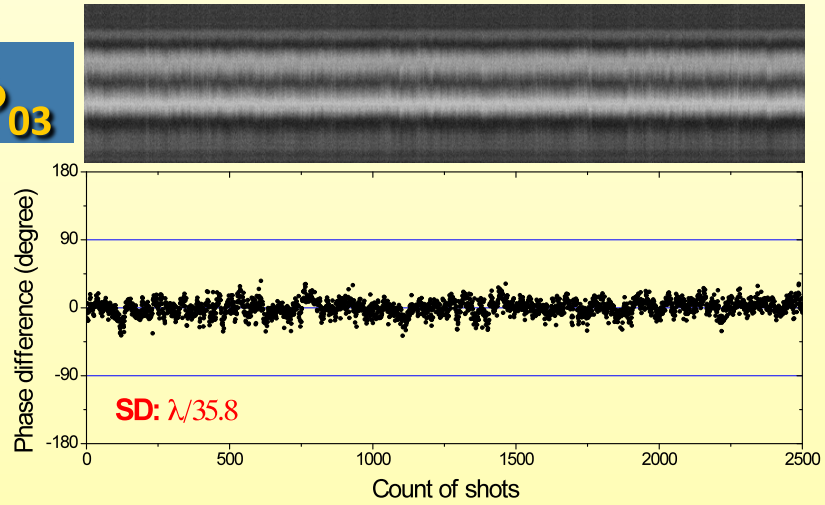
$\Delta\Phi_{01}$



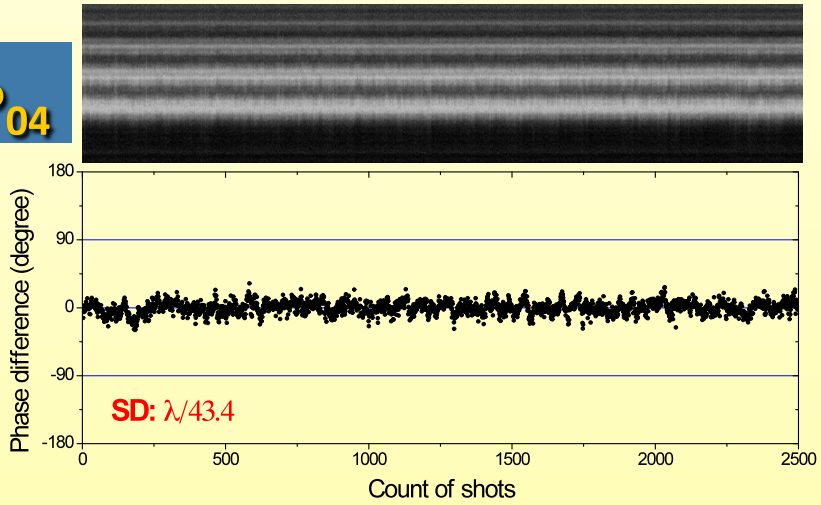
$\Delta\Phi_{02}$



$\Delta\Phi_{03}$



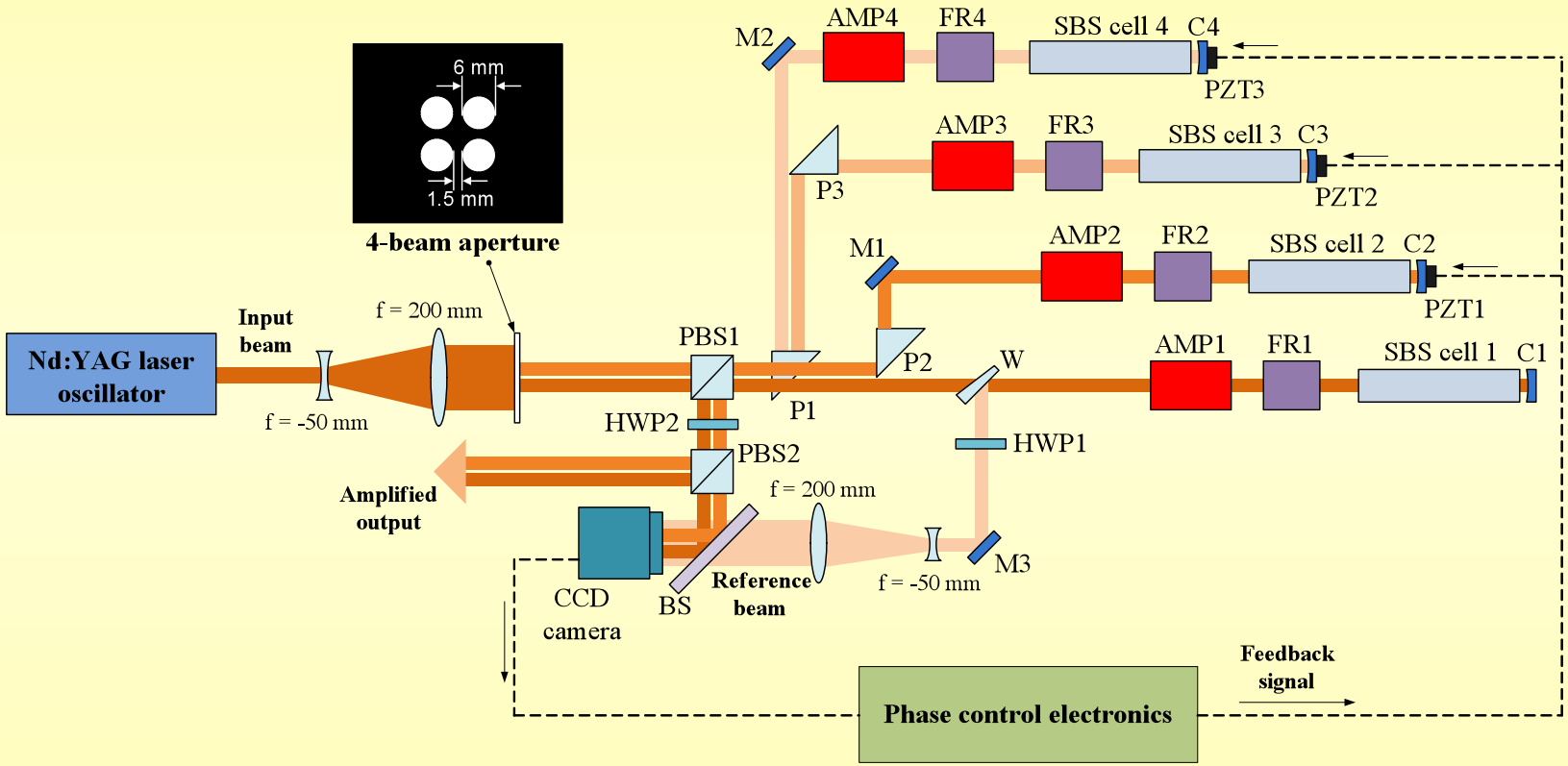
$\Delta\Phi_{04}$



J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

by courtesy of H.J. Kong, KAIST

Experimental setup for the wave-front dividing 4-beam combination



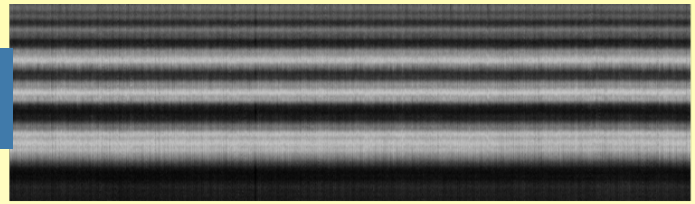
PB1&PBS2, polarizing beam splitters; HWP1&HWP2, half wave plate; P1, P2&P3, 45 degree prisms; BS, beam splitter; W, wedged window; FR1, FR2, FR3&FR4, Faraday rotators; C1, C2, C3&C4, concave mirrors; PZT1, PZT2&PZT3, piezoelectric translators.

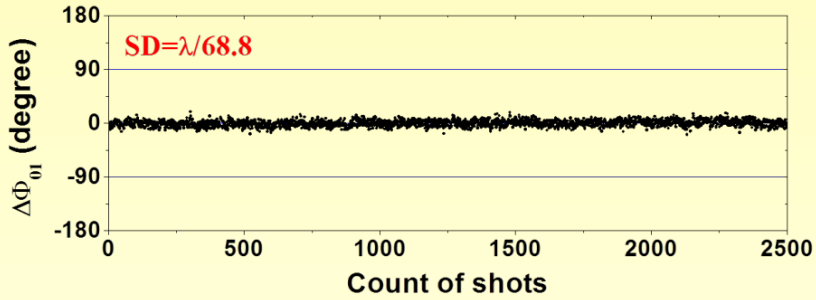
J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

by courtesy of H.J. Kong, KAIST

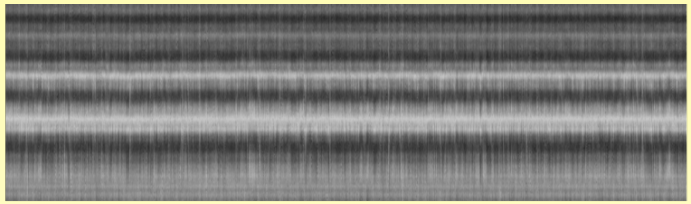
Phase fluctuation with amplifier operation

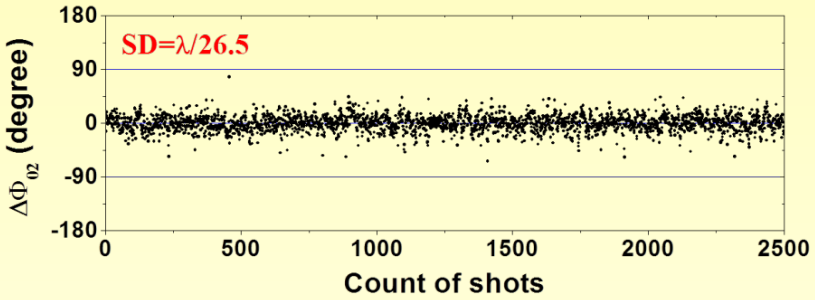
$\Delta\Phi_{01}$



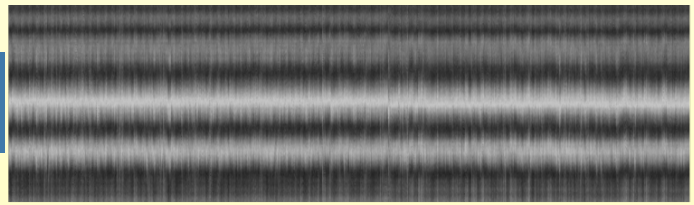


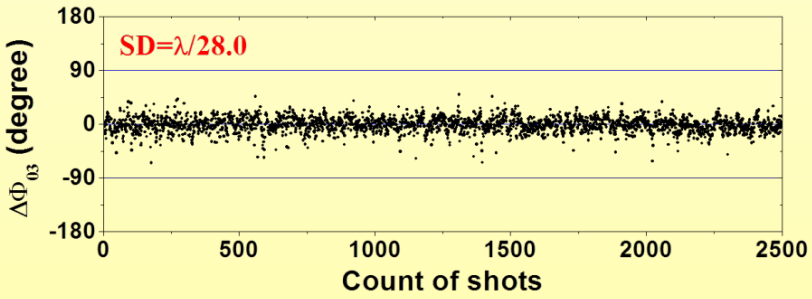
$\Delta\Phi_{02}$



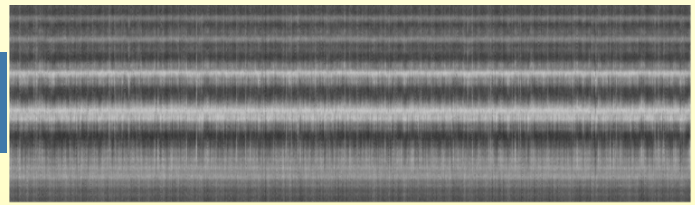


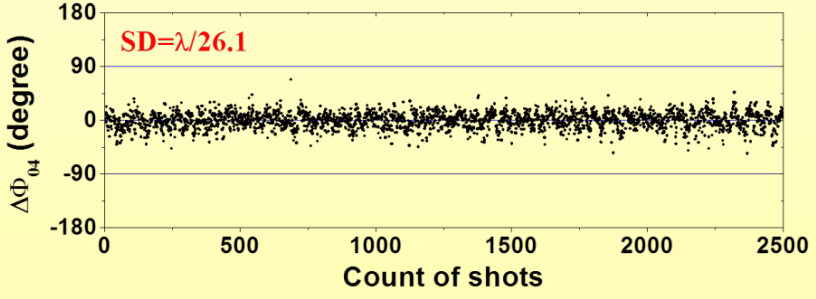
$\Delta\Phi_{03}$





$\Delta\Phi_{04}$





J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

by courtesy of H.J. Kong, KAIST

Key issue of high power laser system

High damage optics, coating damage is the limiting factor of amplifier system.

We need new research works in this field.

Our experience on UV optics

Another solution:

damage threshold of dielectric coating

Solid state laser materials for fusion driver

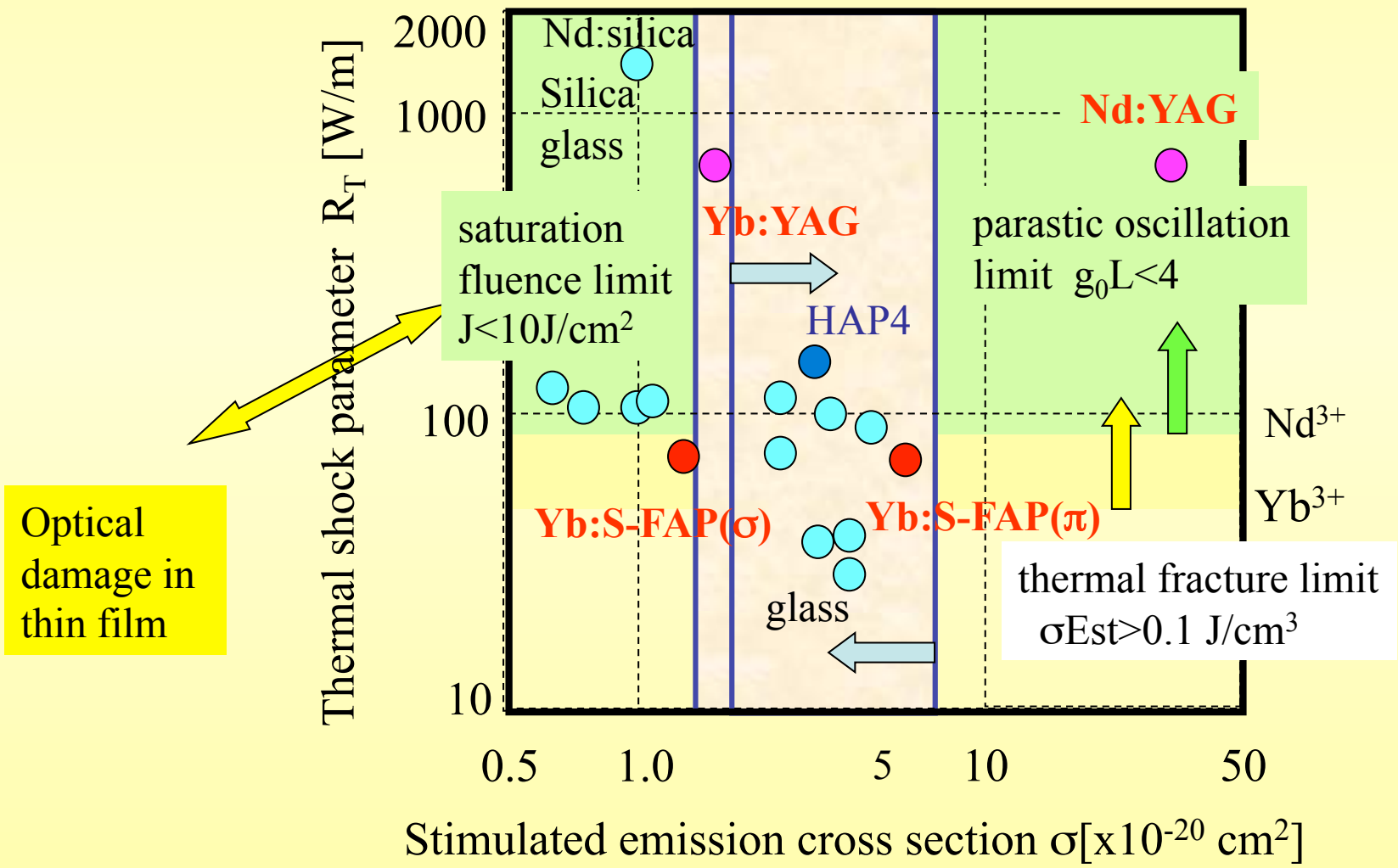
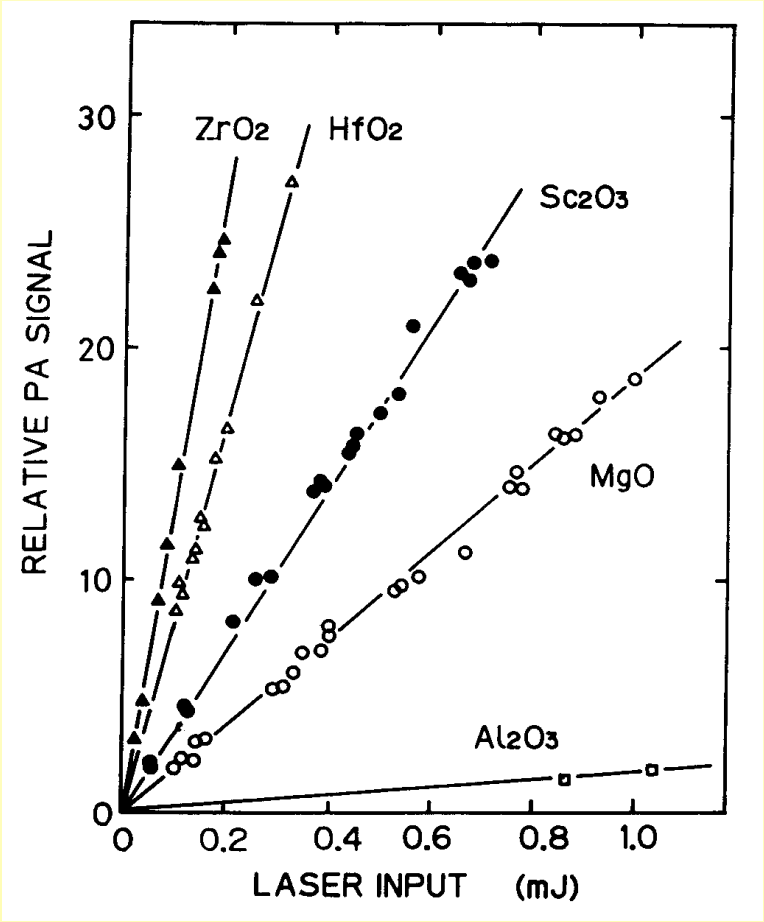


Photo-acoustic measurement of UV optical coatings

K. Ueda et al, RLE, vol.15, 22 (1987).



We measured absorption coefficients of optical coating with 3/2 wavelength thickness by photo-acoustic method.

Material	Refractive index n	Absorption coefficient k This work	Absorption coefficient k Rainer *et al.* (1985)
ZrO_2	2·25	0·011	0·006
HfO_2	2·25	0·0056	0·002
Sc_2O_3	2·11	0·0022	0·002
Y_2O_3	2·10	0·0007	0·002
ThO_2	1·90		0·005
MgO	1·83	0·0009	0·002
Al_2O_3	1·72	0·0001	<0·001
ThF_4	1·59		<0·001
LaF_3	1·59	0·0016	0·001
YF_3	1·54	0·0001	<0·001
SiO_2	1·51	<0·0001	0·001
MgF_2	1·43	0·0004	<0·001
LiF	1·37	0·0002	0·001
NaF	1·35	0·0005	0·009
Na_3AlF_6	1·35		0·007

TABLE 1. Optical properties of optical thin layers at 248 nm.

Higher sensitivity than LLNL's results.

K. Ueda, Laser & Paticle Beams, **7**, 382, 1989.

Damage Threshold vs Dielectric Materials

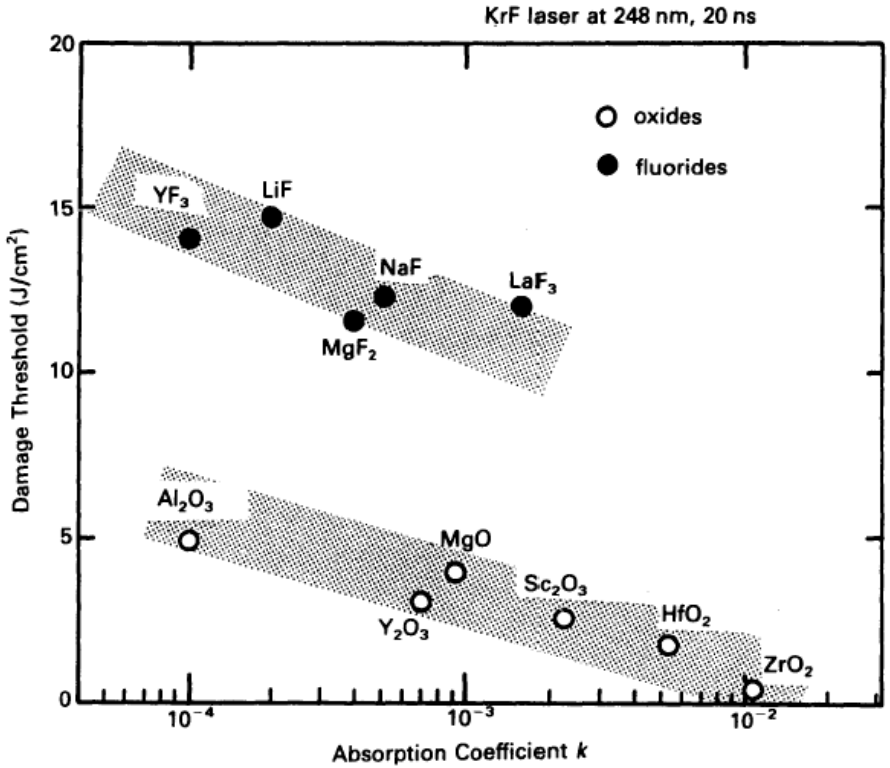


FIGURE 6. Damage threshold of single layer coatings as a function of absorption coefficient k.

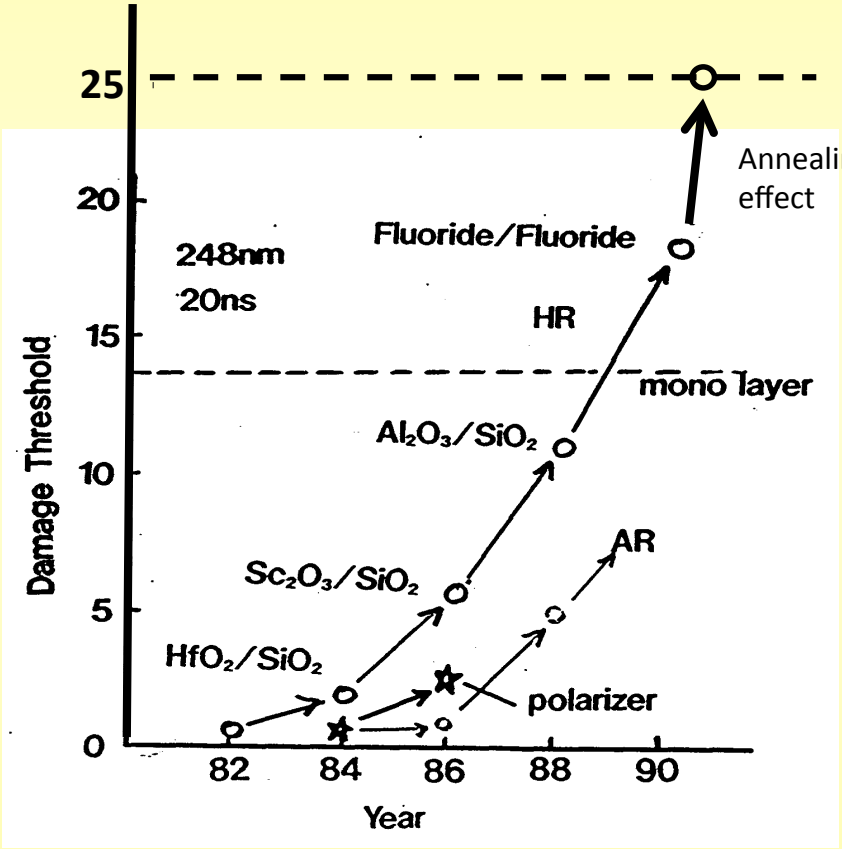
1. Strong correlation between absorption and damage.

2. Oxides and Fluorides separated completely.

Fluorides have higher damage thresholds than oxides.
Electron affinity is quite effective.

Big progress in UV optics in ’80s

We need more effort for vis and IR optics



Rapid progress of damage threshold in UV optics

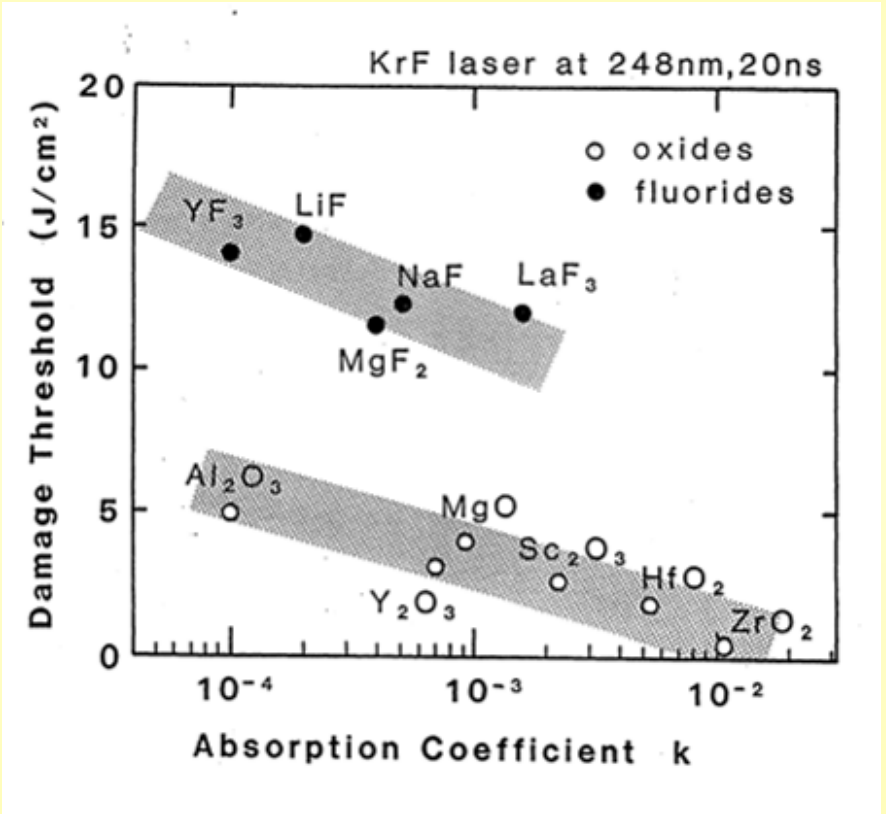


Photo-acoustic measurement of absorption coefficient and damage

Measurement of photo-induced current

F/F coating

O/O coating

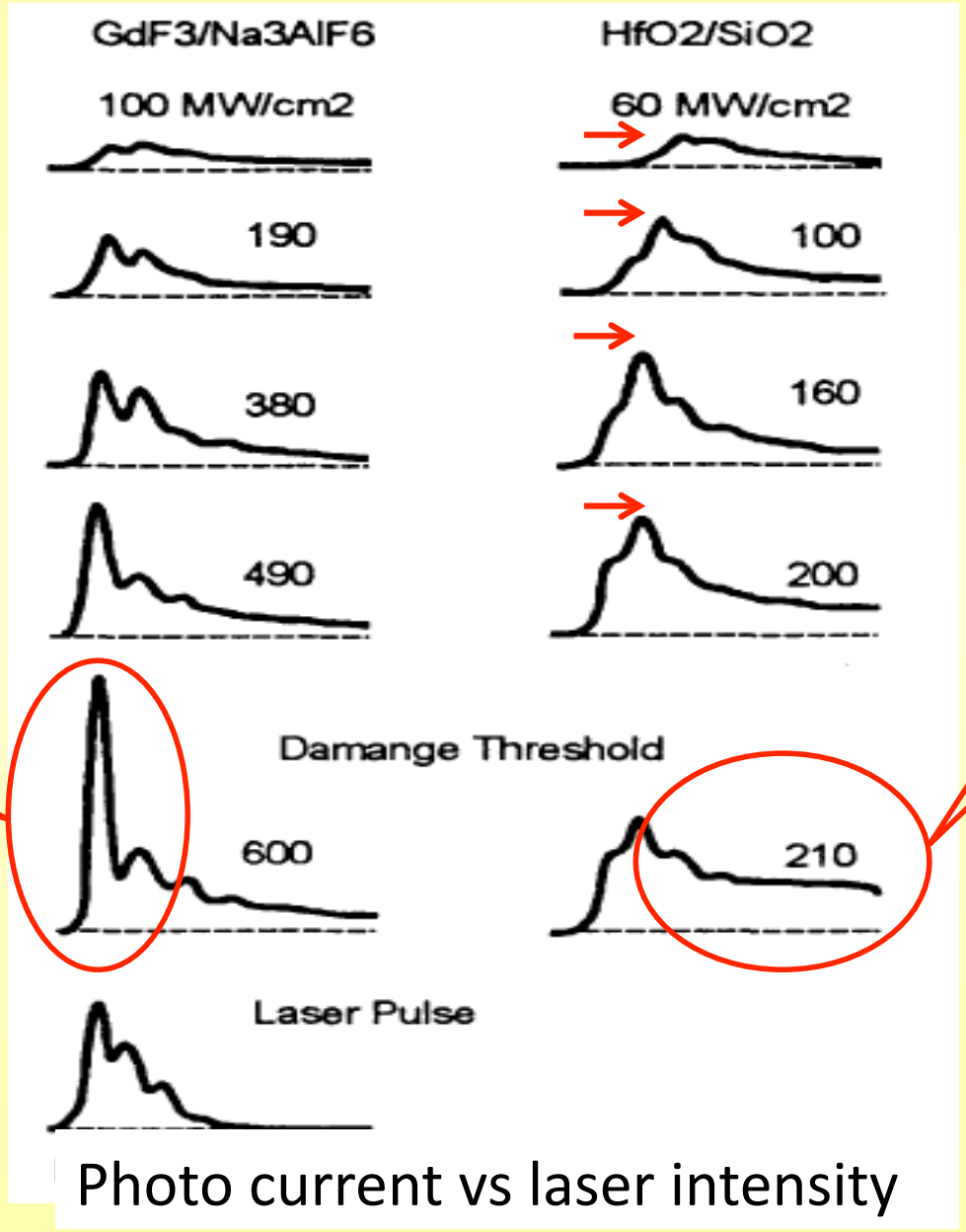


Photo current vs laser intensity

Nonlinear growth of peak current

Long decay / inegration

H.Nishioka, T.Kawasumi, K. Ueda, and H.Takuma: Detection of Avalanche Processes in Laser Induced Damage, Rev.Laser Engineer., vol. 20, 344-354 (1992).

electron excitation

(gain - loss) of electrons

$$\frac{dn_e}{dt} = \sum_{i=1}^{m} \sigma_j N \left(\frac{1}{h\nu}\right)^j + \left[\gamma(I) - \frac{1}{\tau_e}\right] n_e$$

I: laser intensity

n_e: electron density

σ_j: absorption cross section

N: impurity density

γ: electron gain coefficient

$1/\tau_e$: recombination rate

Laser damage is a result of laser-accelerated electron avalanche .

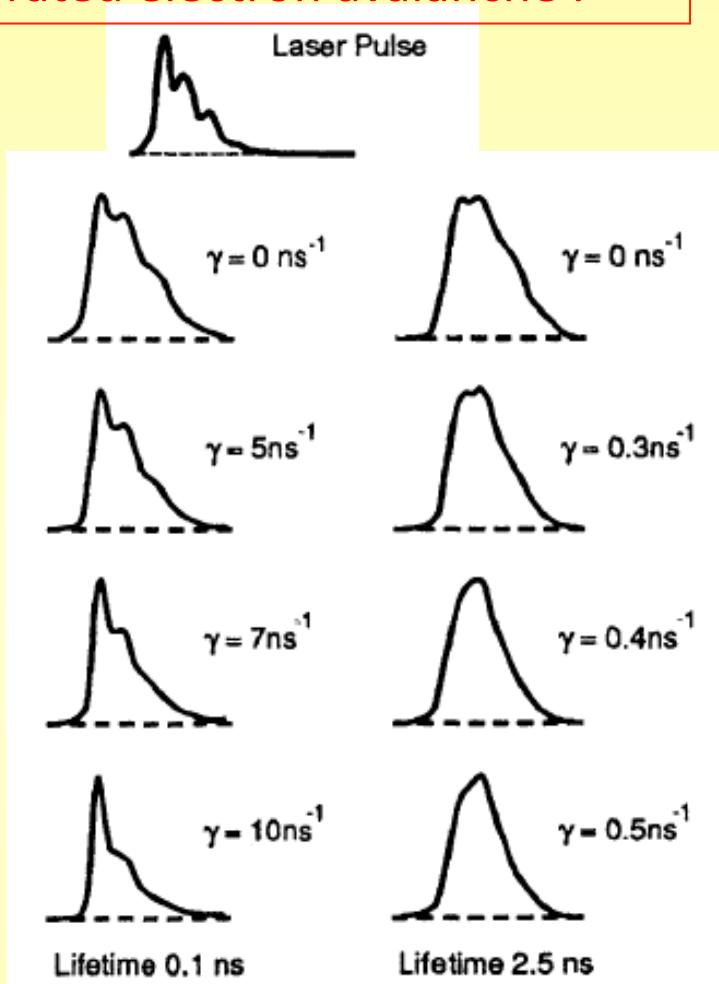


Fig. 4 電子雪崩モデルによるγ、τeの計算値。

Acceleration by laser field and secondary generation

Net gain is zero at damage threshold

Multi-layer	γ	τe	γ−1/τe
GdF3/Na3AlF6	10	0.1	0
HfO2/SiO2	0.4	2.5	0

The final stage of laser damage always induces remarkable increase of electron density.

Summary

1. Recent progress in highly transparent ceramics from LCS-6.
   Yb:YAG ceramics with high doping is better than single crystal.
   Importance of stoichiometric condition for low defects.
   Non-reactive sintering is better than reactive sintering.

2. Coherent beam combining by phase controlled SBS-PCM.
   Four beam combining with $\lambda/37$ to $\lambda/26$ phase fluctuation.

3. Old memory on high damage threshold optical coatings.
   Damage includes two steps, initial electron excitation and avalanche process by laser field. The second part should be more important for high intensity lasers. Fluoride coating will be effective to quench the electrons.

4. We need more options laser technology and science.