OPTICAL ELEMENTS MADE OF CERAMICS AND CERAMIC COMPOSITES: DIAGNOSTICS OF PROPERTIES AND APPLICATION IN LASERS

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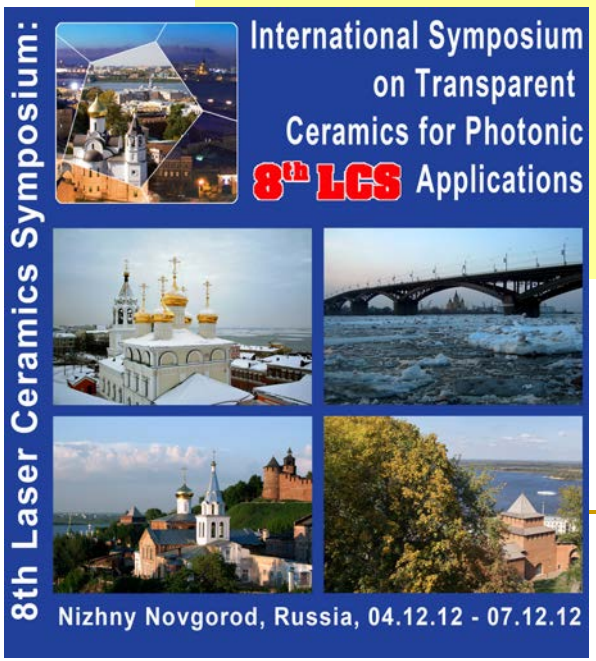
Victor Zelenogorsky, Evgeny Perevezentsev, Ivan Mukhin, Ilya Snetkov, Dmitry Silin, Ilya Kozevatov, Anton Vyatkin, Alexander Soloviev, Efim Khazanov



ИПФ РАН

Plan:

- Introduction
- Analyses of optical quality
- Research of property of ceramics
  - Parasitic thermal effects
  - As method of measurement of characteristics
- Ceramics composites in lasers
  - Disk-geometry
  - Cryogenic-cooled
- Conclusion

ИПФ РАН

Introduction

Manufacturing of high-power lasers
DPSSL / Diode-Pumped Solid-State Lasers

↓

The main problems:

parasitic thermally induced and nonlinear optical effects

↓

The use of optical ceramics

↑ *thanks to its advantages*

- having the similar to crystal optical properties, are more durable;

Kaminskii A., Yagi H., Yanagitani T., Dong J., Shirakawa A., Ueda K., Opt. Let. 32, №13, c.1890 (2007)

- it can be made of oversize;

Lu J., Song J., Prabhu M., Xu J., Ueda K., Yagi H., Yanagitani T., Kudryashov A. Applied Physics, 39, 1048, (2000)

- the active media, which cannot be grown as a single crystal

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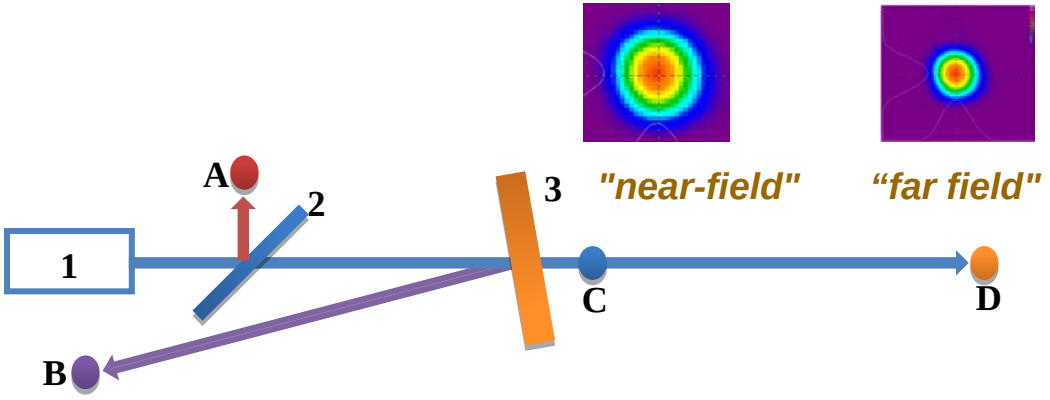
Analyses of optical quality



1 – Laser, 2 – Quartz wedge 3 – Sample

S.S. Balabanov, ... "Self-propagating high temperature synthesis of rare-earth oxide nanopowders for transparent ceramics"

S.V. Egorov... "FABRICATION OF TRANSPARENT CERAMICS BY MILLIMETER-WAVE SINTERIN"

V. Zelenogorsky, ... "Lasing and spectroscopic properties of ceramics Y2O3, Lu2O3, and Sc2O3 doped with Yb3+ ions"

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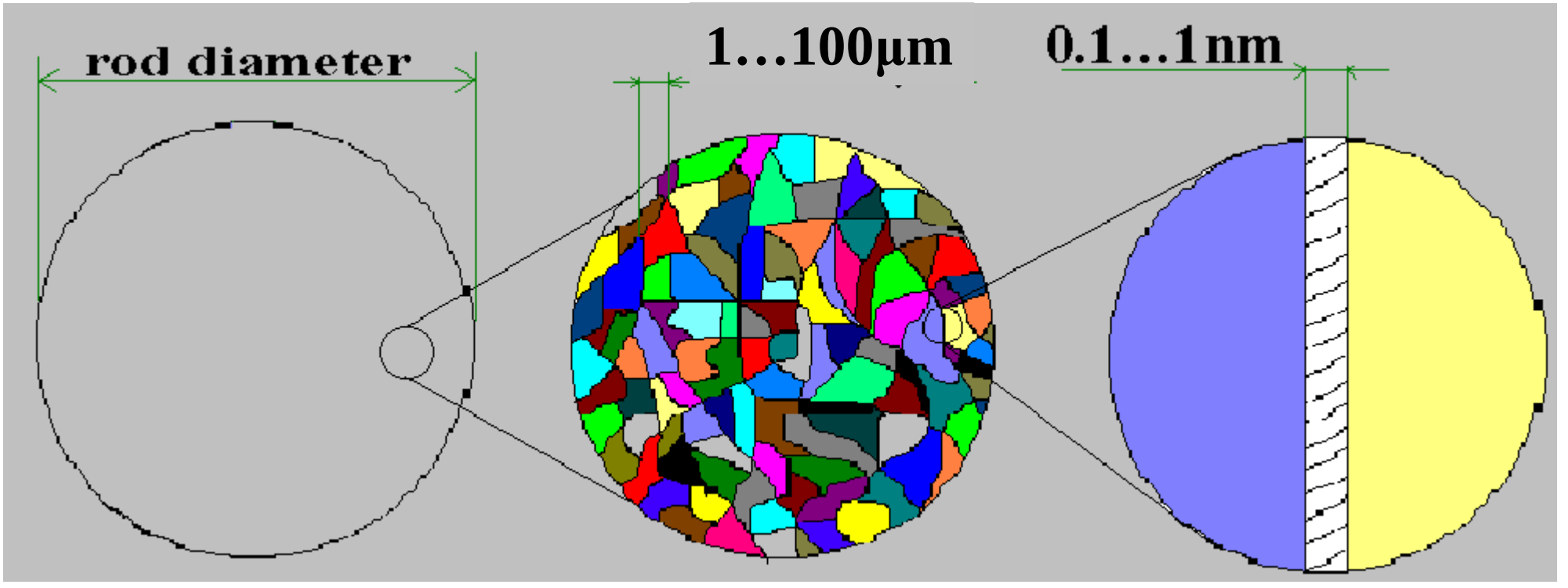
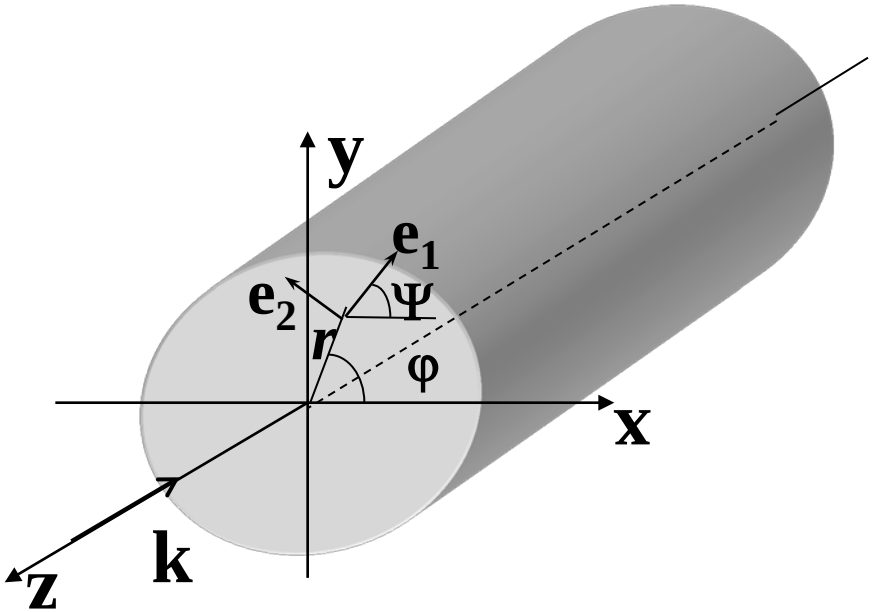
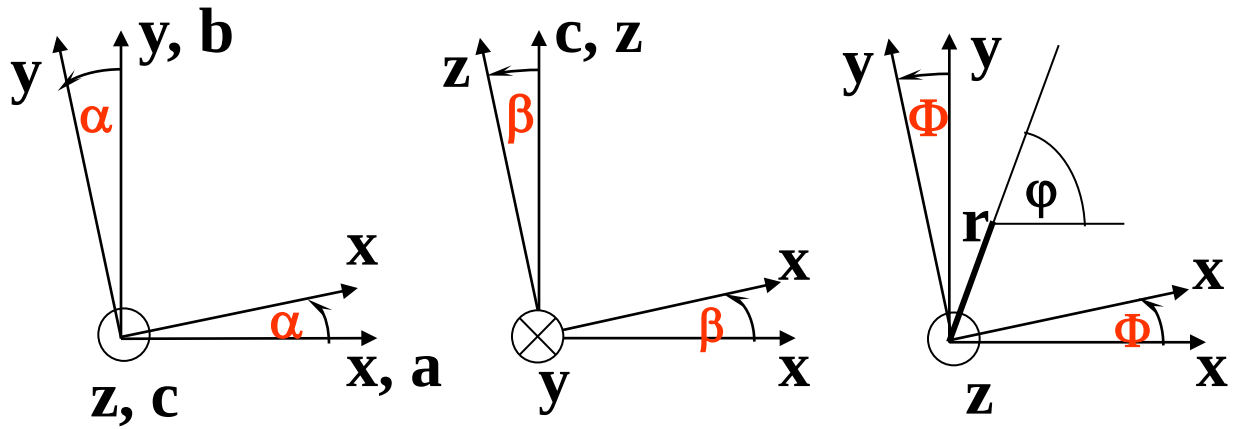
Parasitic thermal effects



E. A. Khazanov, Optics Letters 27, 716-718 (2002).

Model of thermally induced birefringence in ceramics





1. Temperature: $T(r,\varphi)$
2. Strain tensor: $\varepsilon_{rr}(r,\varphi)$, $\varepsilon_{\varphi\varphi}(r,\varphi)$, $\varepsilon_{zz}(r,\varphi)$
3. Tensor of dielectric impermeability :

$B_{ij}(r,\varphi,\alpha,\beta,\Phi) = p_{ijkl}\varepsilon_{kl}(r,\varphi)$

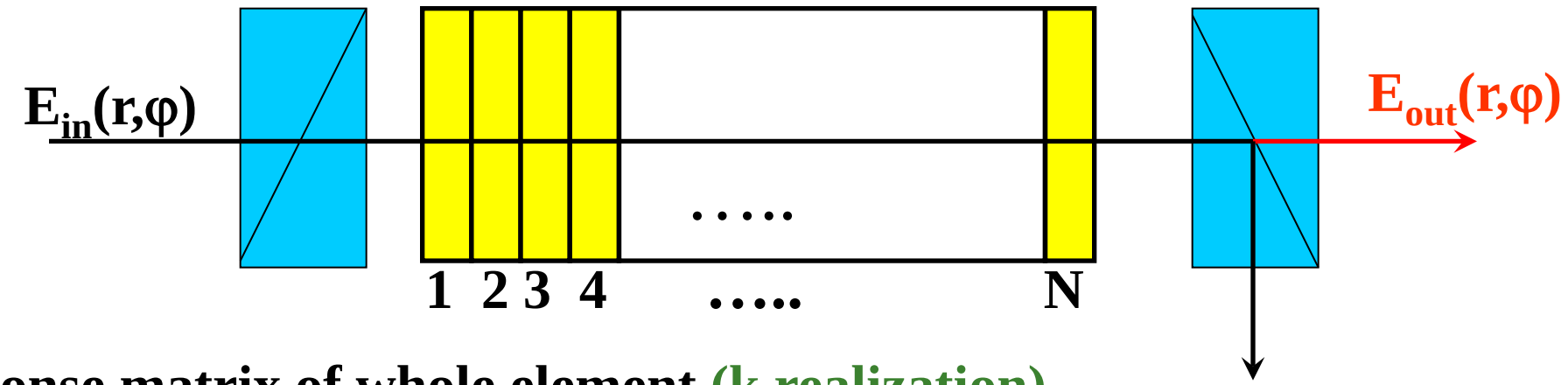
4. Angle of declination of eigen polarizations and phases delay:

$2\Psi(r,\varphi,\alpha,\beta,\Phi) = \mathrm{arctg}\{2B_{12}/(B_{11}-B_{22})\}$

$\delta(r,\varphi,\alpha,\beta,\Phi,L_g) = kL_g n_0^3(B_{11}-B_{22})/2\cos(2\Psi)$

5. Grain Jonse matrix $A_g(r,\varphi,\alpha_g,\beta_g,\Phi_g,L_g)$

Model of thermally induced birefringence in ceramics



6. Jonse matrix of whole element (k realization)

$$A(r,\varphi,k)= A_1(r,\varphi,\alpha_1,\beta_1,\Phi_1,L_1)\, A_2(r,\varphi,\alpha_2,\beta_2,\Phi_2,L_2)\ldots A_N(r,\varphi,\alpha_N,\beta_N,\Phi_N,L_N)$$

7. Local depolarization $\Gamma(r,\varphi,k)= |E_{out}(r,\varphi,k)/E_{in}(r,\varphi)|^2$

8. Average (over realizations) local depolarization and its deviation: $\langle\Gamma(r,\varphi)\rangle$ и $\sigma_\Gamma(r,\varphi)$

9. Integrated depolarization: $\gamma(k)$

10. Average integrated depolarization and its deviation : $\langle\gamma\rangle$ and σ_γ

11. Thermally induced phase and its deviation: $\langle\Psi_{thermal}\rangle$ and σ_Ψ

Model of thermally induced birefringence in ceramics

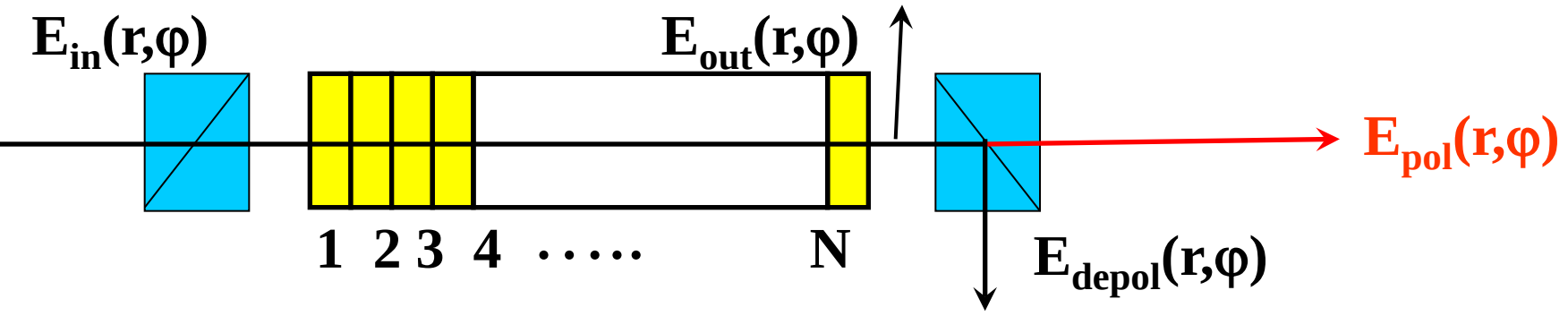
	Ceramics	Single crystal
1	$p = \frac{P_h}{\lambda}\frac{a_T}{\kappa}\frac{n_0^3}{4}\frac{1+\nu}{1-\nu}(p_{11}-p_{12})$	**- normalized heat power**
2	$\xi = \frac{2p_{44}}{p_{11}-p_{12}}$	$\xi_{YAG} = 3.2$
3	$N = \frac{L}{<L_g>}$ **ratio of the rod length to mean grain length**	**α, β, Φ - single crystal orientation**

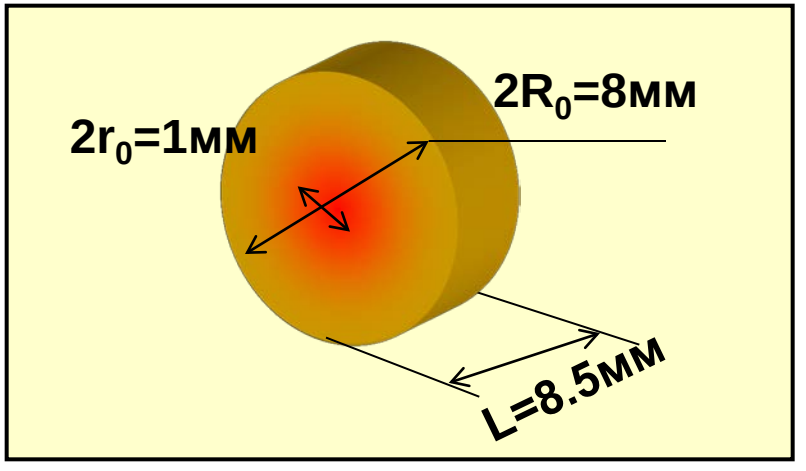
$$\sigma_\Gamma \sim \frac{p^2}{N}$$

Characteristic dimension of modulation: <Lg>

ov, Optics Letters 27, 716-718 (2002).

Experimental confirmation



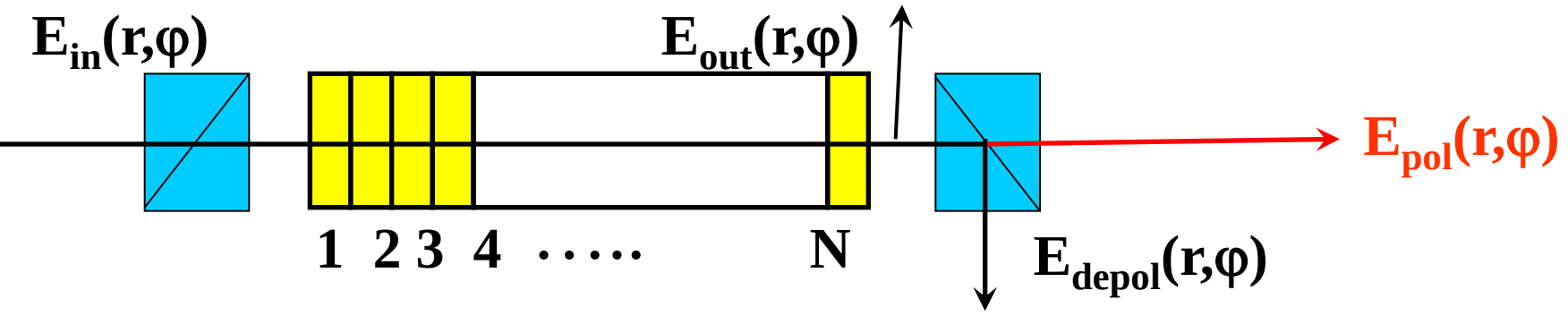


Nd:YAG ceramics (2.3at.% Nd),

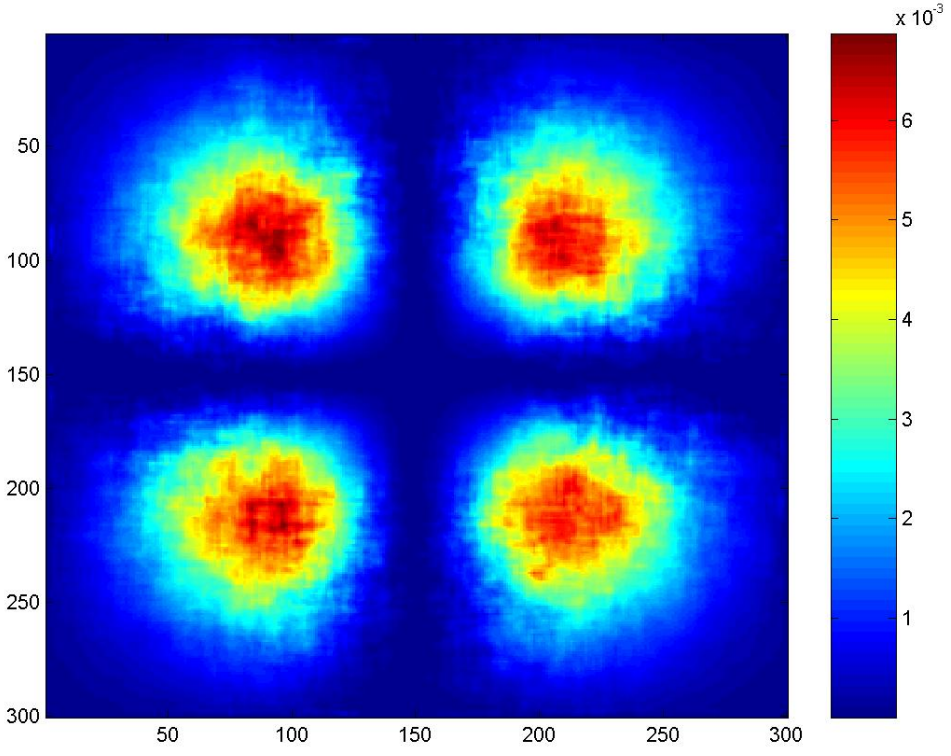
Made by Dr. A.Ikesue, Japan Fine Ceramics Center.

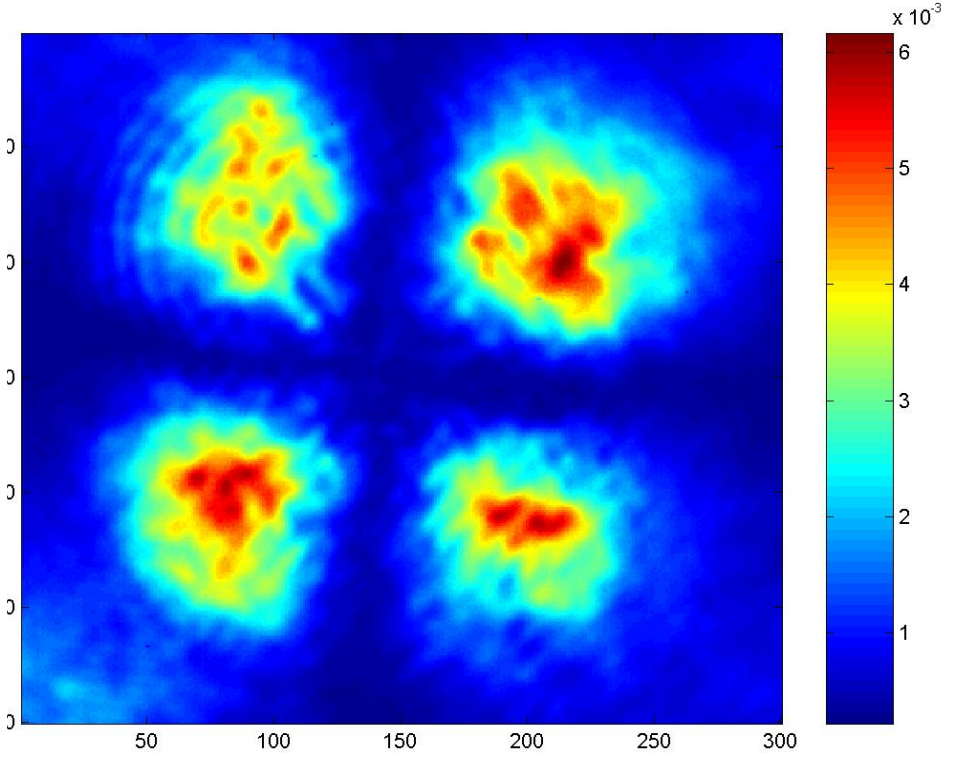
Laser: 50W CW Yb:fiber

Experimental confirmation

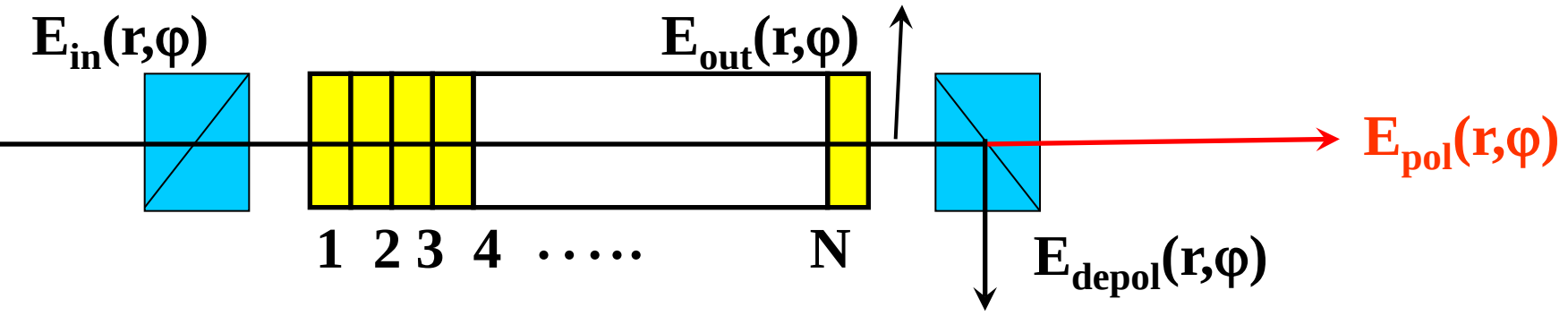


theory **single realization** **experiment**

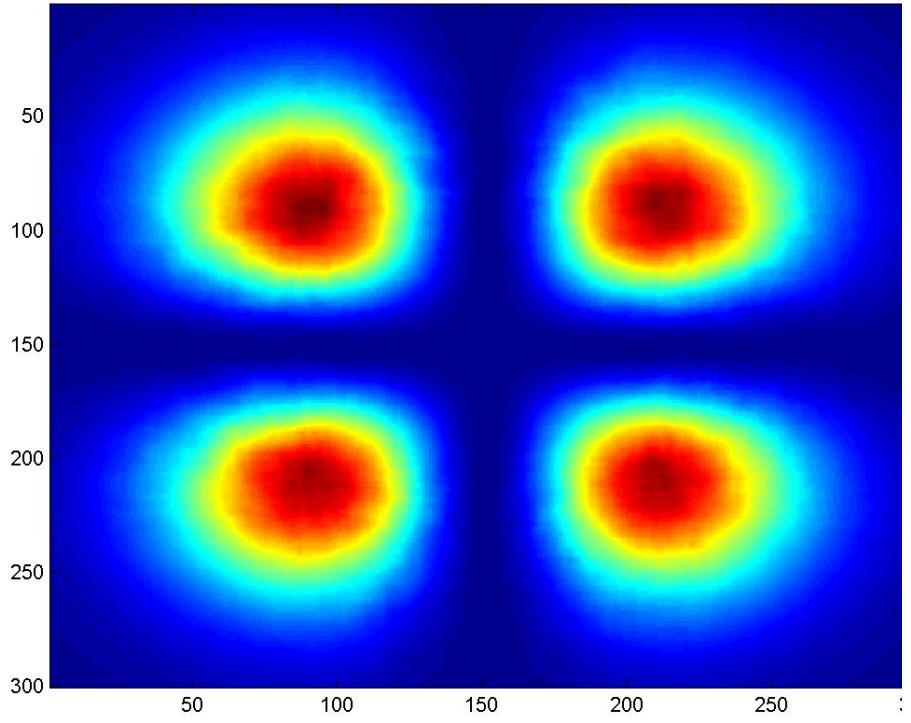


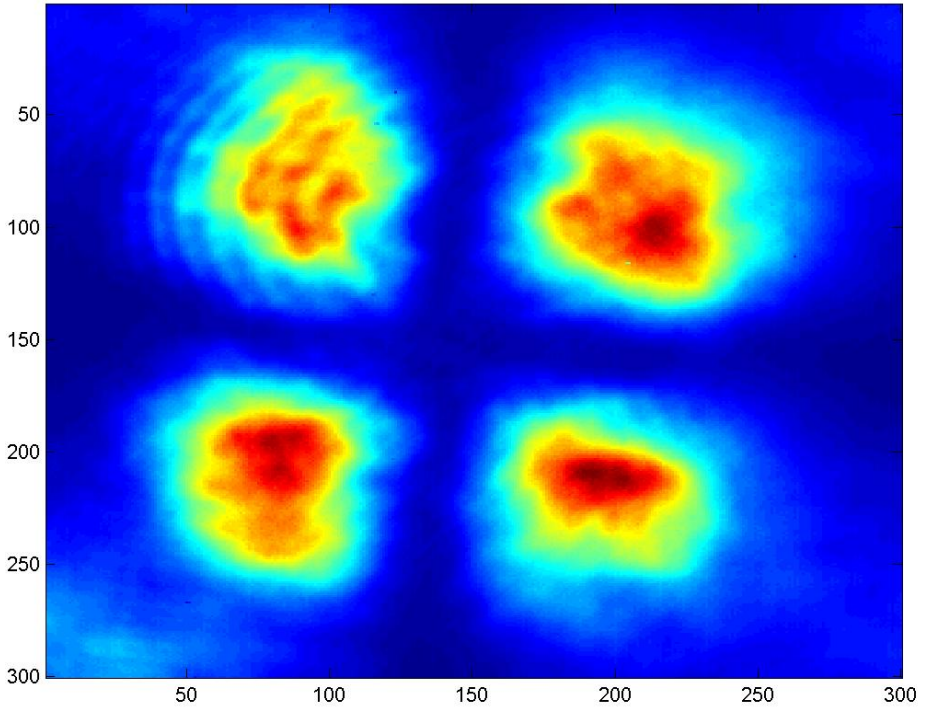


Experimental confirmation

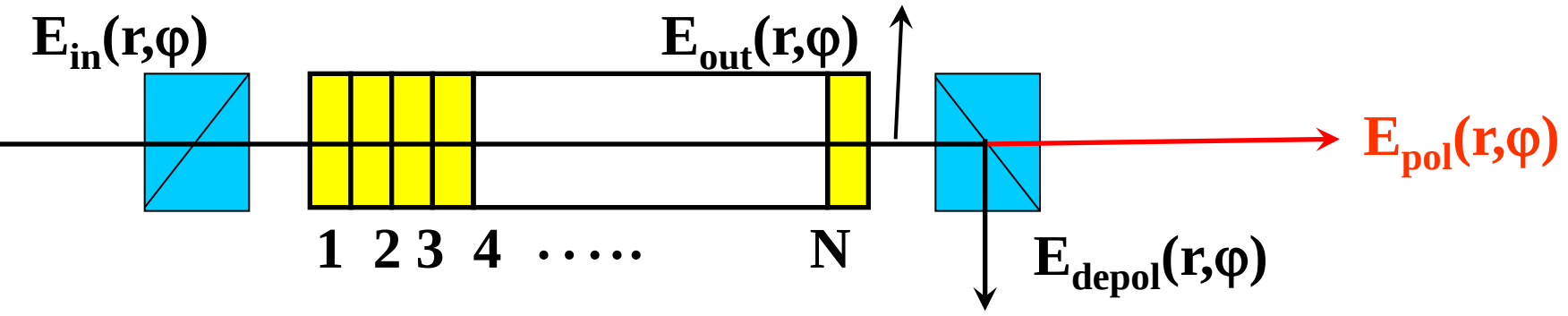


theory **average** **experiment**

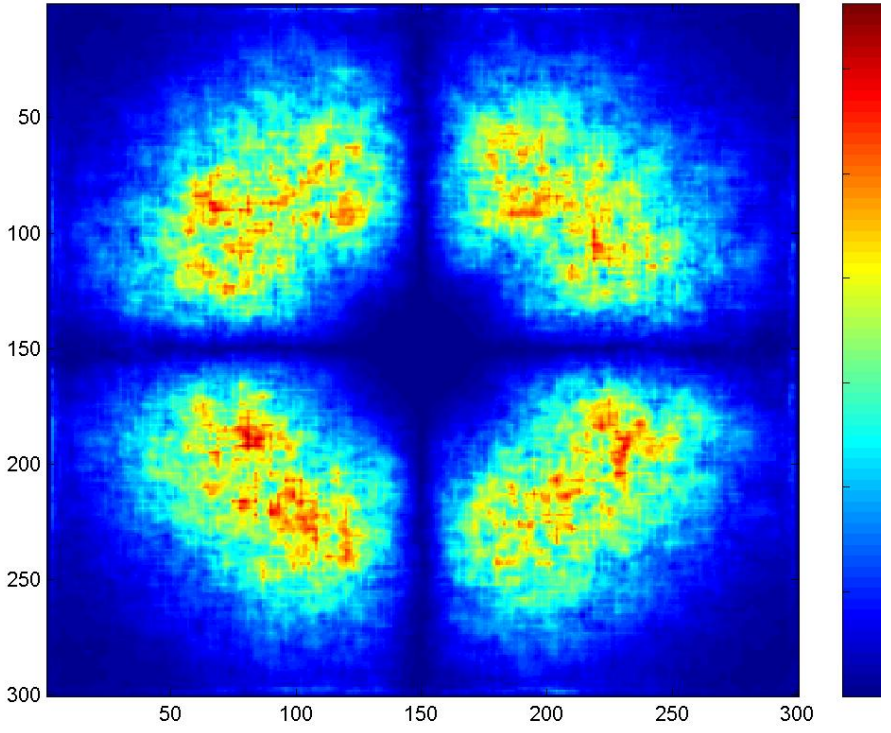


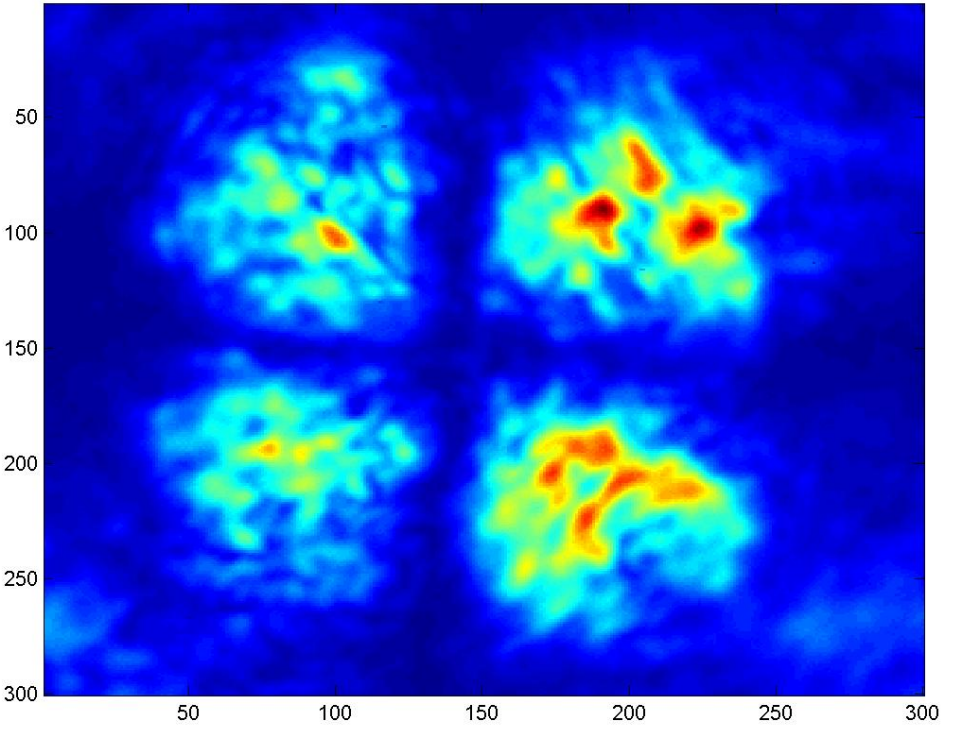


Experimental confirmation

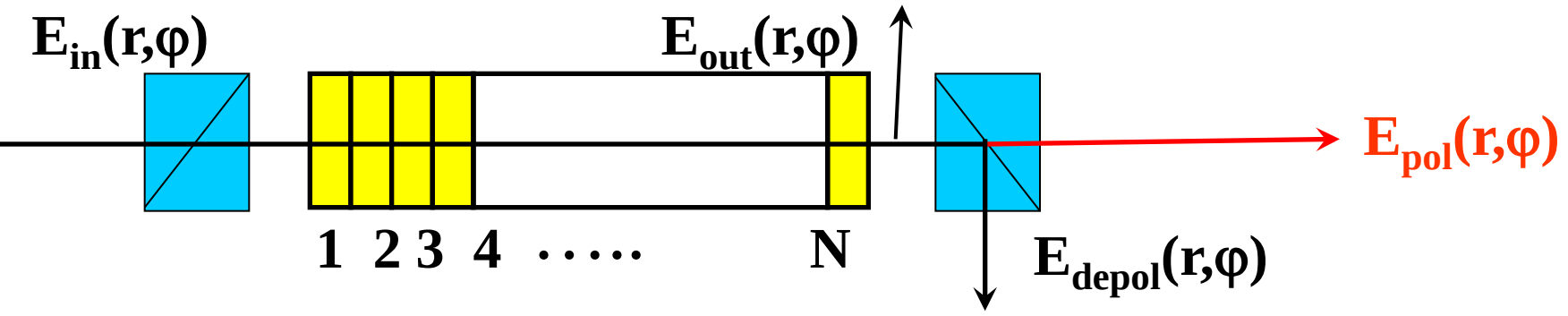


theory **dispersion** **experiment**

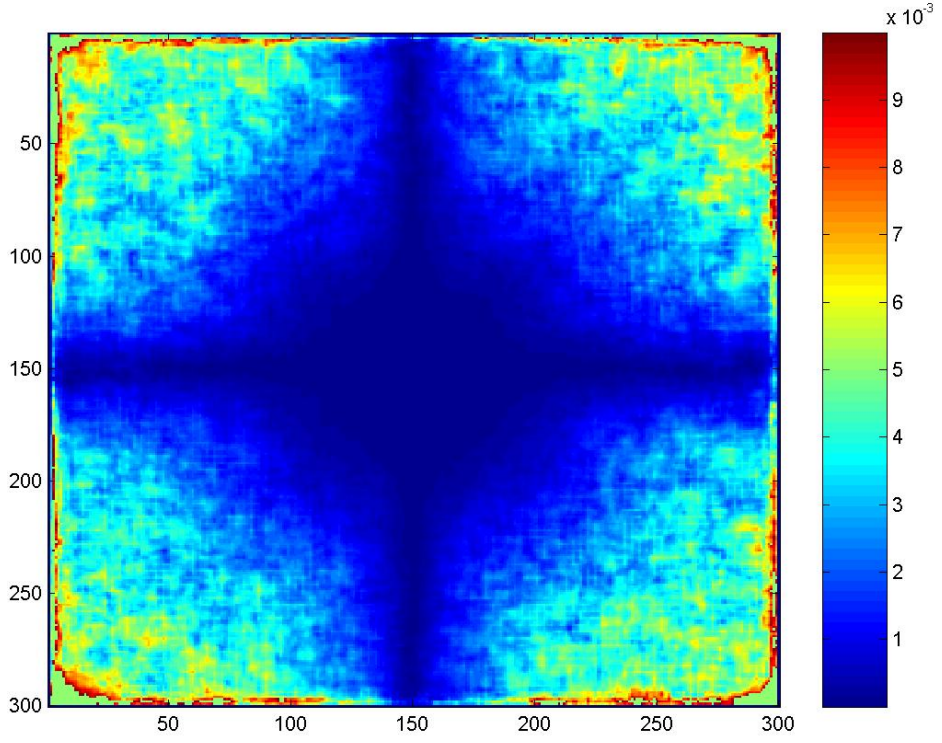


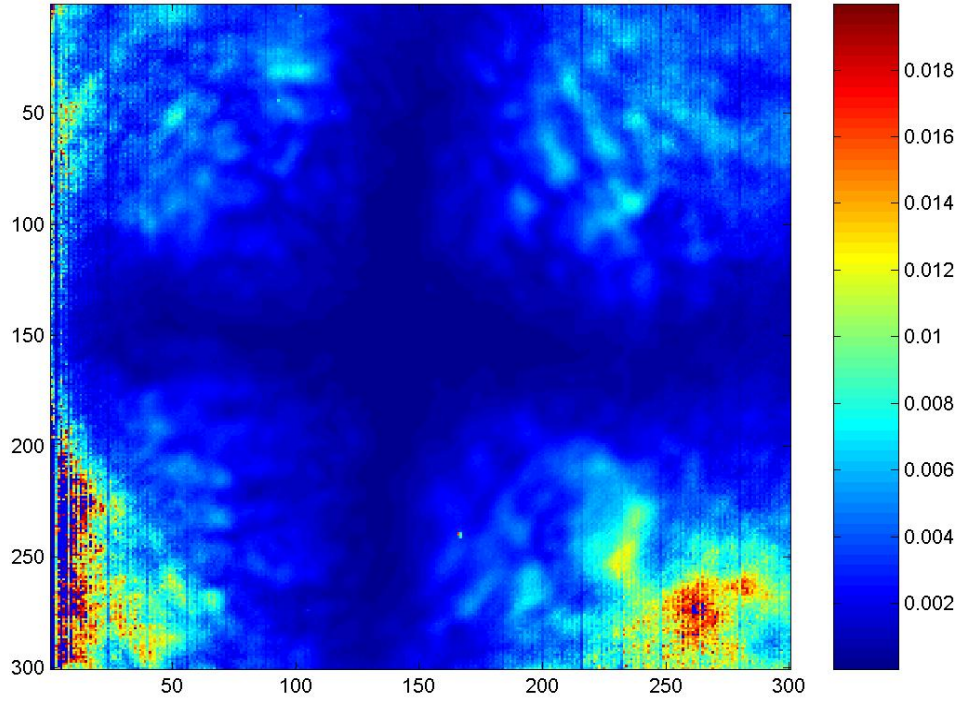


Experimental confirmation



theory **depolarization dispersion** **experiment**



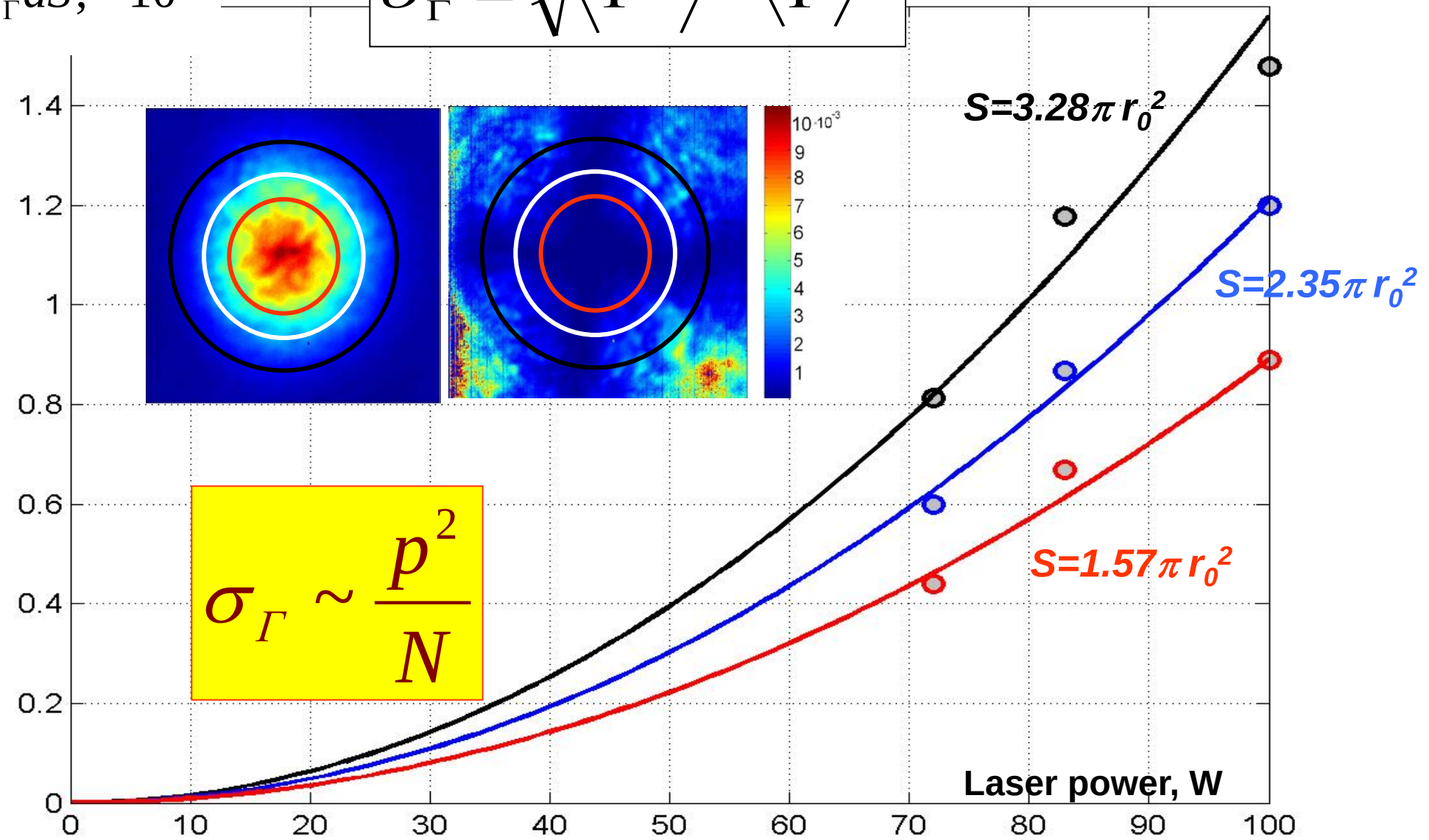


Parasitic thermal effects

Experimental confirmation

$$\frac{1}{S}\int \sigma_\Gamma dS, \quad 10^{-3}$$

$$\sigma_\Gamma = \sqrt{\langle \Gamma^2 \rangle - \langle \Gamma \rangle^2}$$



$$\sigma_\Gamma \sim \frac{p^2}{N}$$

I. B. Mukhin, O. V. Palashov, E. A. Khazanov, A. Ikesue, Y. L.Aung, Optics Express 13, 5983-5987 (2005).

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Measurement of characteristics

CaF2-ceramics

Comparison of the optical parameters of a CaF_2 single crystal and optical ceramics

O.V. Palashov, E.A. Khazanov, I.B. Mukhin, I.A. Mironov,
A.N. Smirnov, K.V. Dukel'skii, P.P. Fedorov, V.V. Osiko, T.T. Basiev

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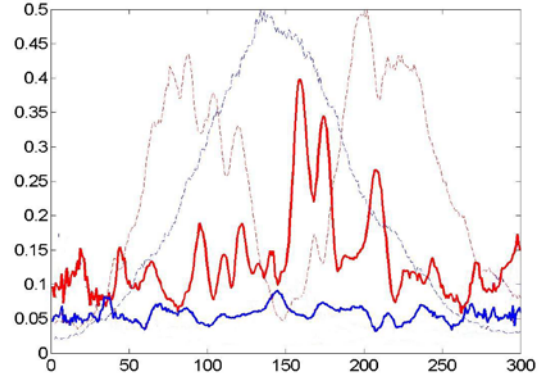
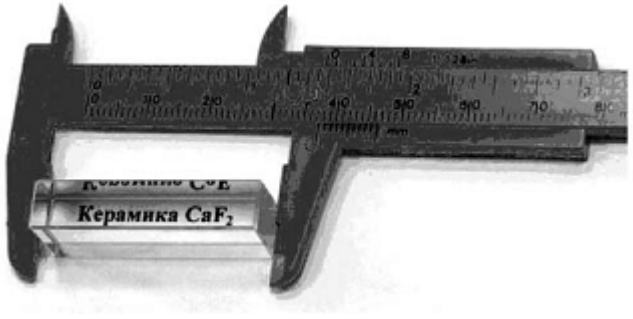
~ 3*10 cm-1





$$\gamma_{T[001]} = 0.137\frac{p^2}{8}[1 + (\xi^2 - 1)\cos^2(2\theta)],$$

$$\gamma_{Tcer} = 0.137\frac{p^2}{8}\left(\frac{1 + 2\xi_{eff}}{3}\right)^2,$$

где

$$p = \frac{Q\alpha L P_0}{\lambda k}; \quad Q = \alpha_T \frac{n_0^2}{4}\frac{1+\nu}{1-\nu}(p_{11} - p_{12});$$

$$\xi = \frac{2p_{44}}{p_{11} - p_{12}}; \quad \xi_{eff} = 1 + (\xi - 1)\frac{225}{256};$$

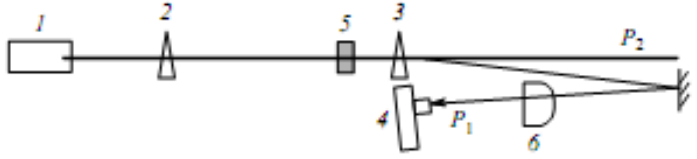


Figure 1. Scheme for measuring depolarisation in ceramic and crystal CaF_2 samples: (*1*) 1076-nm laser; (*2*, *3*) spar wedges; (*4*) CCD camera; (*5*) sample; (*6*) objective.

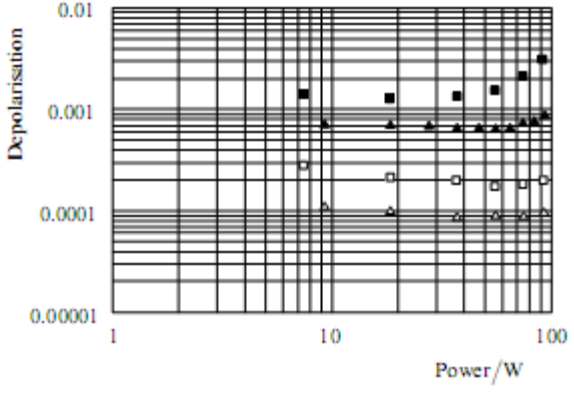
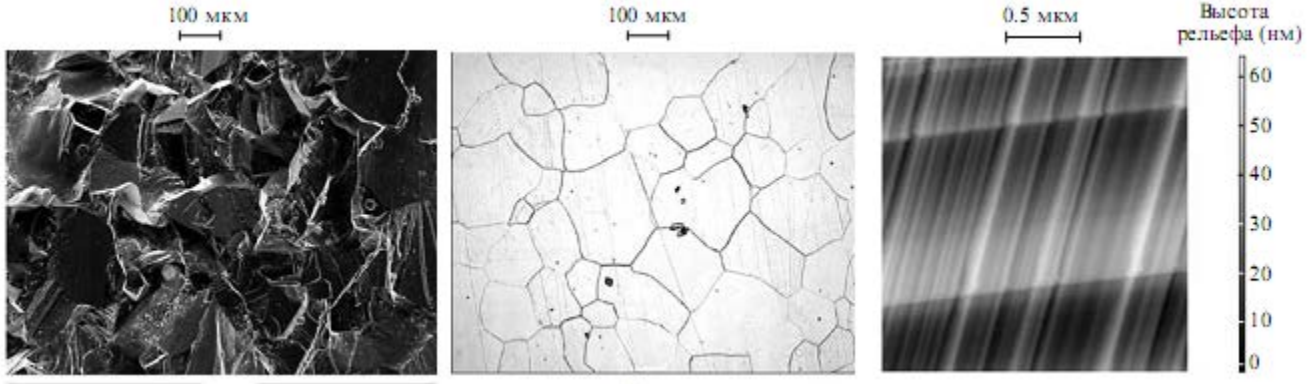
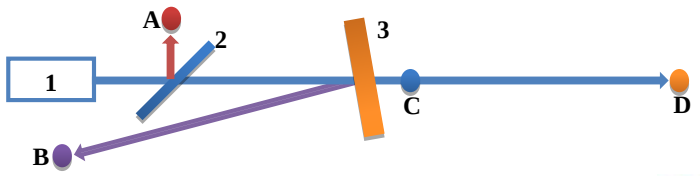


Figure 3. Dependences of depolarisation in regions indicated by circles in Fig. 2 on the radiation power for ceramics (dark squares and triangles) and single crystal (open squares and triangles) for $\theta = 45°$ (squares) and $\theta = 0$ (triangles).

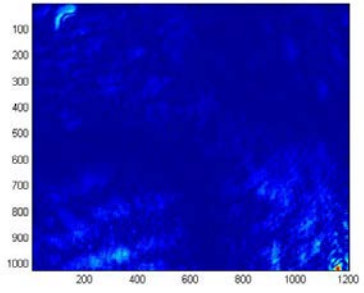


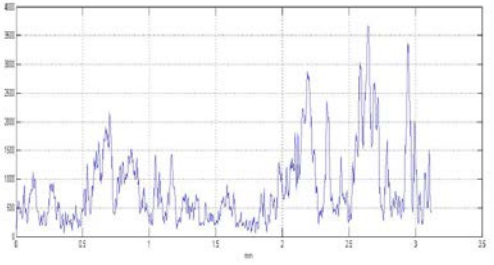
Measurement of characteristics

Yb:YAG-ceramics



deviation of depolarization:





Yb:Ln_2O_3 (Ln=Y, Sc, Lu) sesquioxide ceramics

$$\gamma = B_1 \cdot P_{abs}^2 \qquad B_1 = 0.0171\left(\frac{Q}{\lambda\kappa}\left(\frac{2+3\xi}{5}\right)\right)^2$$

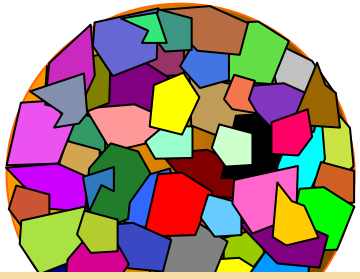
$$\frac{1}{F} = A_3 \cdot P_{abs} \qquad A_3 = \frac{P}{4\pi\kappa R_0^2}$$

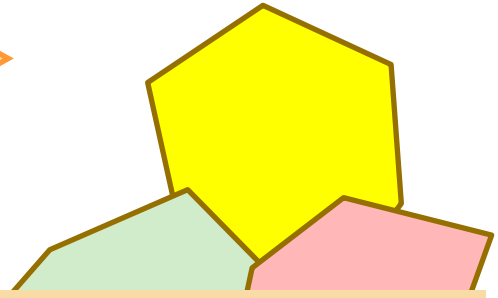
I. L. Snetkov, ... Thermo-optical constants of sesquioxide laser ceramics Yb3+:Ln2O3 (Ln=Y,Sc,Lu)

Reduction of a grain

Small grains

Large grains





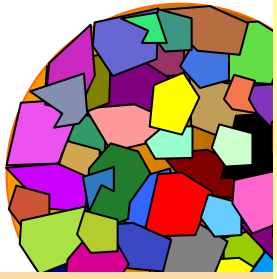
More grain boundaries and related distortions

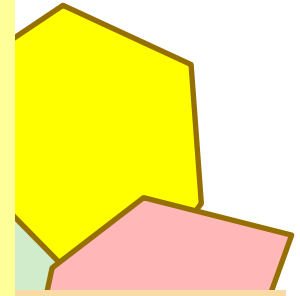
Higher level of thermally induced distortions

- Modern technologies allow fabrication of ceramics with thin grain boundaries (< 1 nm) giving the opportunity to reduce the grain size keeping optical quality of the samples and reducing the thermally induced distortions
- A new calculation of thermal effects is required when the grain size is smaller than the wavelength since the geometrical optics approximation becomes inaccurate

Reduction of a grain

Small gr ... ains





More grain ... hermally
and relatec ... ns

- Mod ... n
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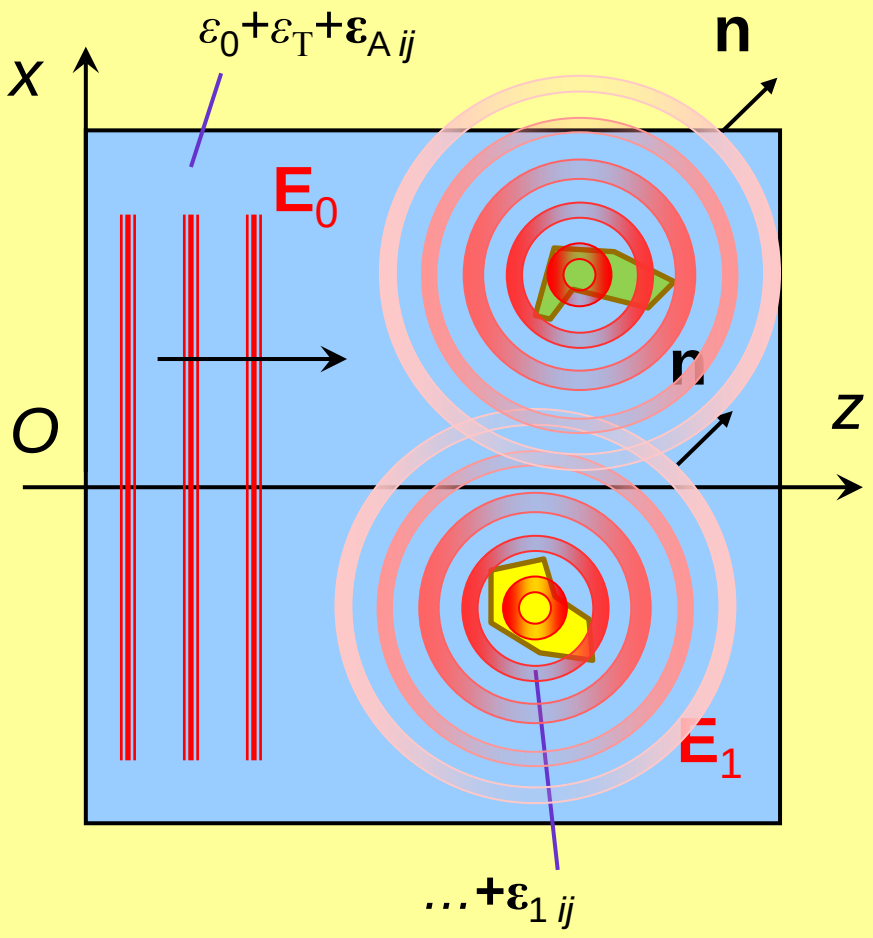

A. G. Vyatkin, ... "THERMALLY INDUCED SCATTERING OF LIGHT IN FINE-GRAINED CERAMICS"

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Disk-geometry

a conventional shape of ceramic laser elements

advantage:

Effective heat removal

Reduces the thermally induced distortions

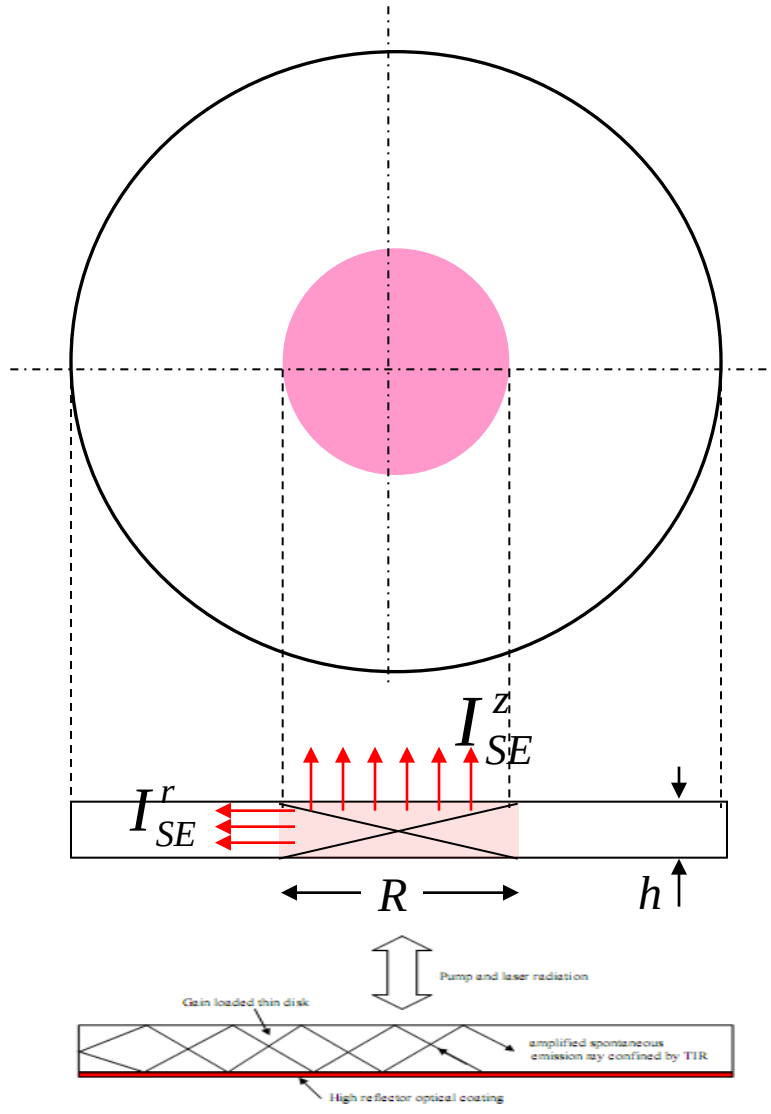
Allows to scale laser

Short interaction length

Avoid the self-focusing

disadvantage:

parasitic effect - ASE



PAH

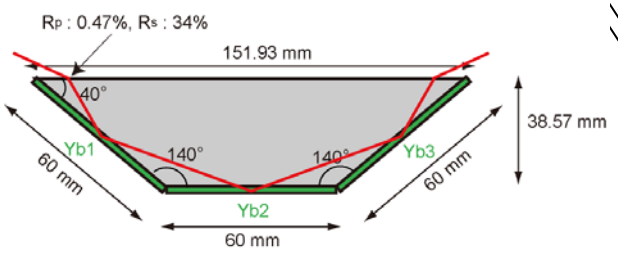
Disk-geometry

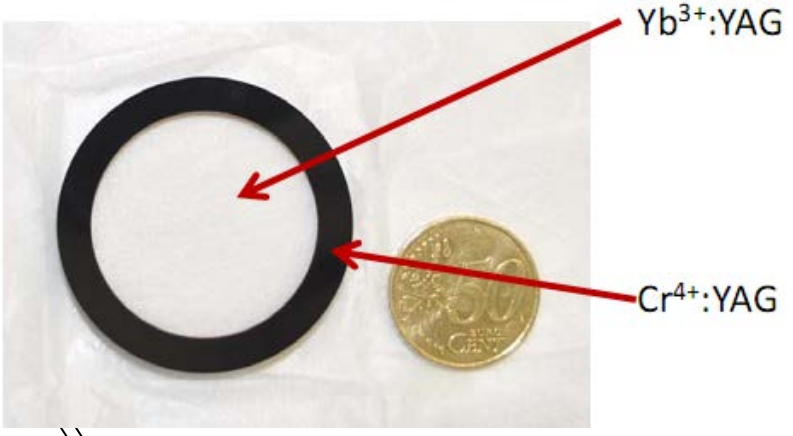
ceramic composites

"GENBU (玄武)" - laser
(Generation of ENergetic Beam Ultimate)

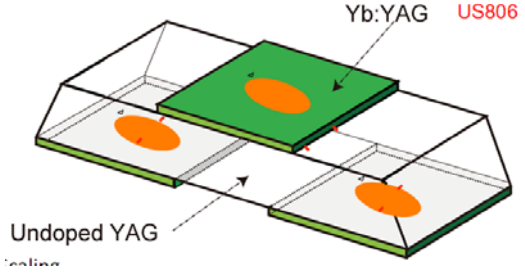
Lucia program, LULI, Ecole Polytechnique, France

New design for 1 J pulse energy

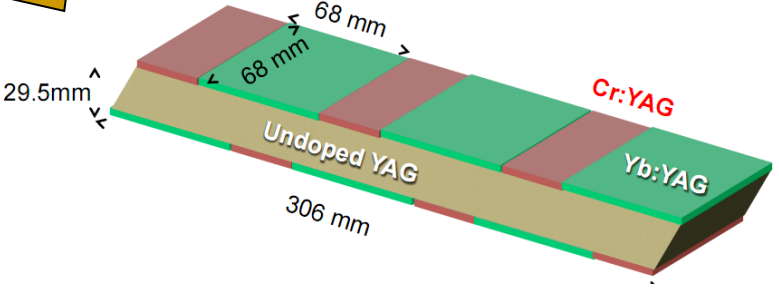




Total-Reflection Active-Mirror (TRAM)

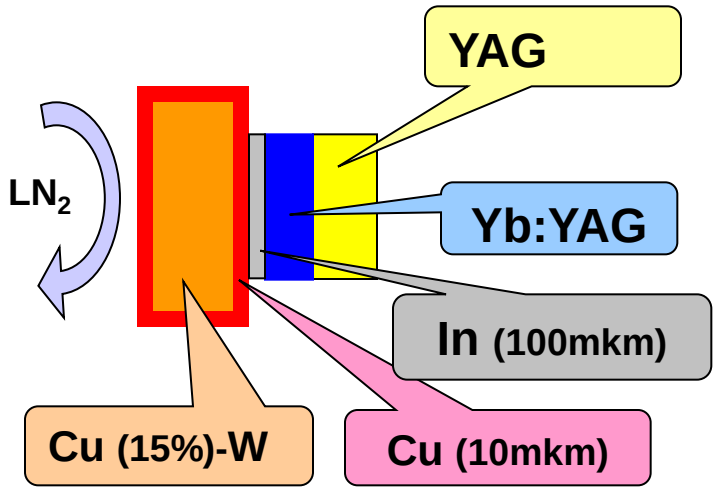


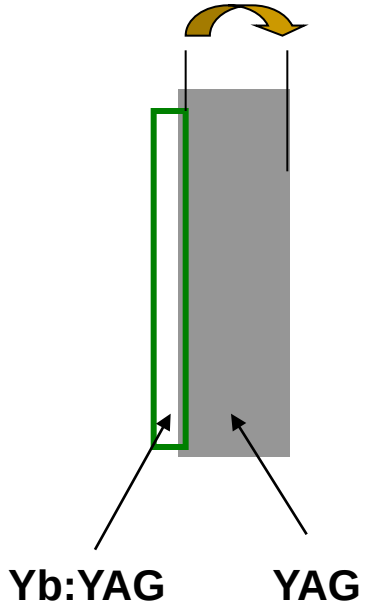
Conceptual design for > 10 kW laser system



Disk-geometry

ceramic composites





I.B. Mukhin, ... "FABRICATION OF COMPOSITE ACTIVE ELEMENTS MADE OF LASER CERAMICS BY THERMAL DIFFUSION BONDING METHOD"

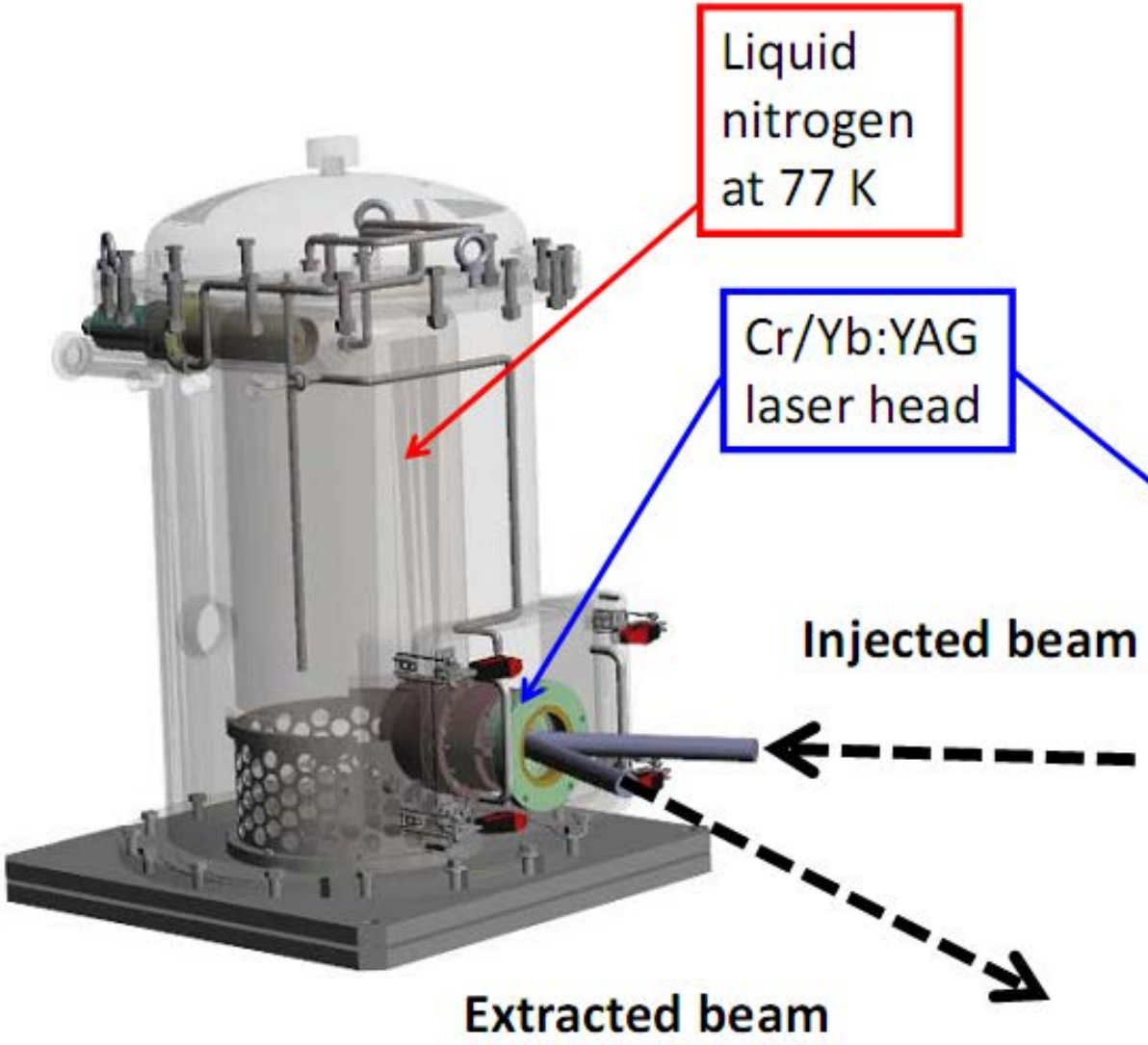
Vadimova O.L COMPARISON OF ENERGY STORING IN DIFFERENT Yb-DOPPED LASER CERAMICS

Plan:

- Introduction
- Analyses of optical quality
- Research of property of ceramics
  - Parasitic thermal effects
  - As method of measurement of characteristics
- Ceramics composites in lasers
  - Disk-geometry
  - Cryogenic-cooled
- Conclusion

Cryogenic-cooled

elenogorsky,... "LASING AND SPECTROSCOPIC PROPERTIES OF CERAMICS Y2O3, Lu2O3, AND Sc2O3 DOPED WITH Yb3+ IONS"

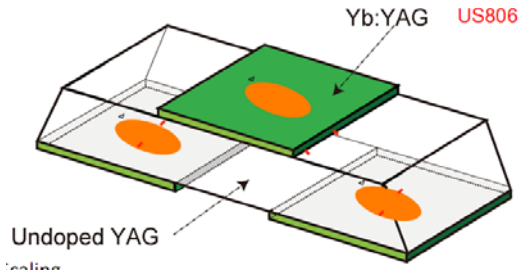


Cryogenic-cooled

elenogorsky,... "LASING AND SPECTROSCOPIC PROPERTIES OF CERAMICS Y2O3, Lu2O3, AND Sc2O3 DOPED WITH Yb3+ IONS"

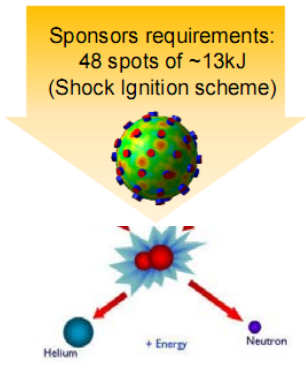
"GENBU (玄武)" - laser
(Generation of ENergetic Beam Ultimate)

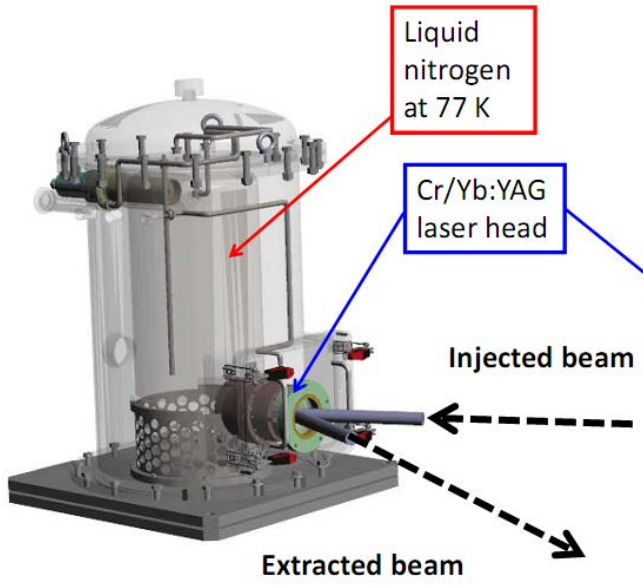
cryogenic Yb:YAG TRAM



HEC-DPSSLs: POLARIS-Jena

Lucia program, LULI, Ecole Polytechnique, France





Cryogenic-cooled

E. A. Perevezentsev, ...”AMPLIFIER WITH HIGH ENERGY CAPACITY AND AVERAGE POWER BASED ON CRYOGENICALLY COOLED DISK SHAPED Yb:YAG LASER CERAMICS”

Yb:YAG disk laser
Master oscillator

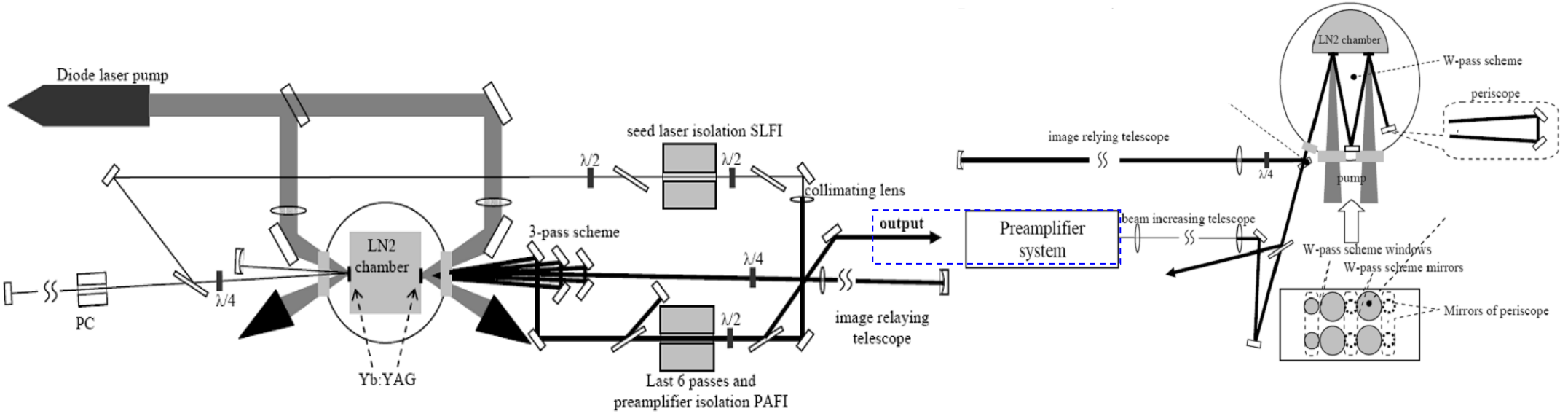
100ps / 20ns, 5 mJ, 1kHz

Yb:YAG active mirror 8V(16V) passes
Cryogenic disk preamplifier

50 mJ, 1kHz

2xYb:YAG act. mir. 4V(8V) passes
Cryogenic two disks main amplifier

Project targets:
0.5J in a ps/ns
1 kHz repetition rate
500W average power
M2~1



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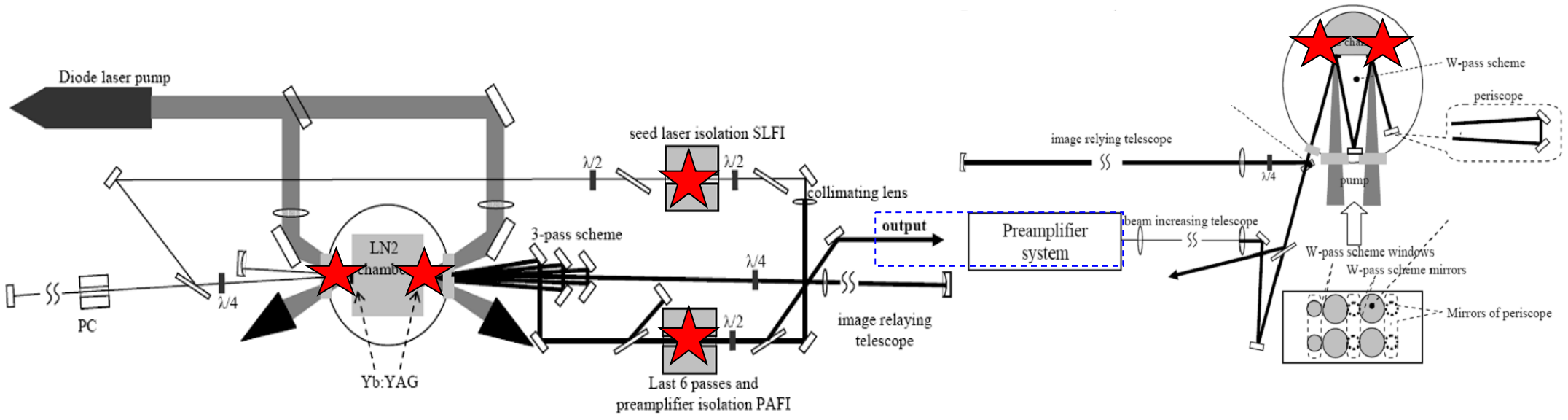
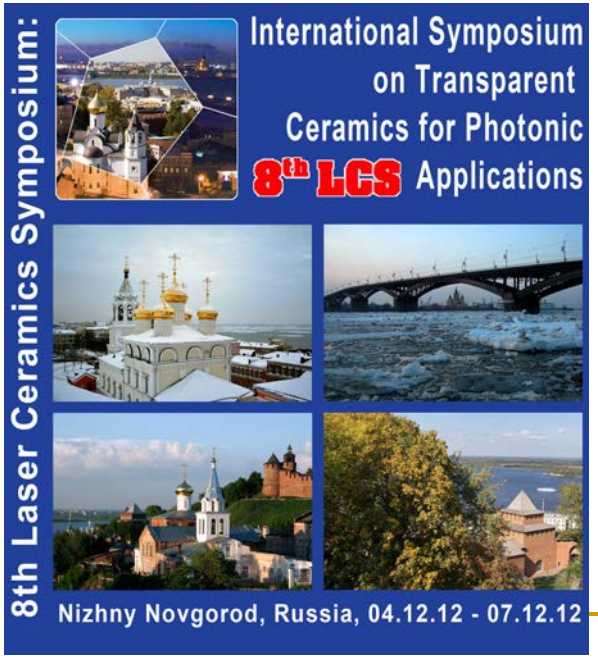
Conclusion

Parasitic thermal effects
are limits the power

We made the
Parasitic thermal effects
work for us



Conclusion

Welcome to Nizhniy Novgorod!..

Thank you for your attention!..