Comparison of energy storage in different Yb-doped laser ceramics

O. Vadimova, I. Mukhin, E.Perevezentsev, O. Palashov

Institute of Applied Physics Russian Academy of Science

Outline

1. Advantages of Yb-doped cryogenic disk laser
2. Numerical model for stored energy calculation
3. Comparison of Yb:YAG monocrystals and ceramics
4. Storage energy in sesquioxide-ceramics
5. Summary

Advantages of Yb-doped cryogenic disk laser

High average power is required from modern laser systems

The problem of heat removing and suppression of negative thermal effects arises. Such effects limit output power.

One way to this problem solution is a cryogenically cooled Yb-doped disk active element.

Yb-doped active element

1. Low quantum defect 9%
2. Long lifetime of the upper level
3. Effective diode pump
4. No upconversion

Disk

1. Effective heat removal
2. Negative thermal effects decrease: no self-focusing

Cryogenic temperatures

1. Emission and absorption cross-sections increase
2. Ion density of the lower laser level decreases
3. Heat conductivity increases
4. Thermooptical properties improve

Advantages of Yb-doped cryogenic disk laser

Features of stored energy calculation

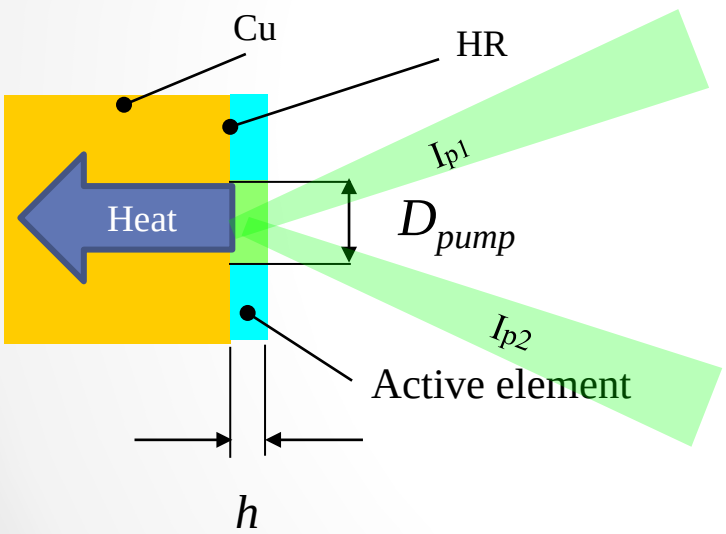
1. Small longitudinal gain is followed by high transversal gain
   - Strong ASE
   - Parasitic lasing possibility
2. Strong heat generation
   - Non-linear equation of heat conductivity
   - Non-uniform distribution of active medium parameters
3. The ratio of pump diameter to disk thickness is about 1
   - Solution in 3D is necessary
4. Broadband emission and absorption
   - It is essential to take spectral distribution into account
5. Few energy levels
   - Exact solution possibility

Numerical model for stored energy calculation: Geometry

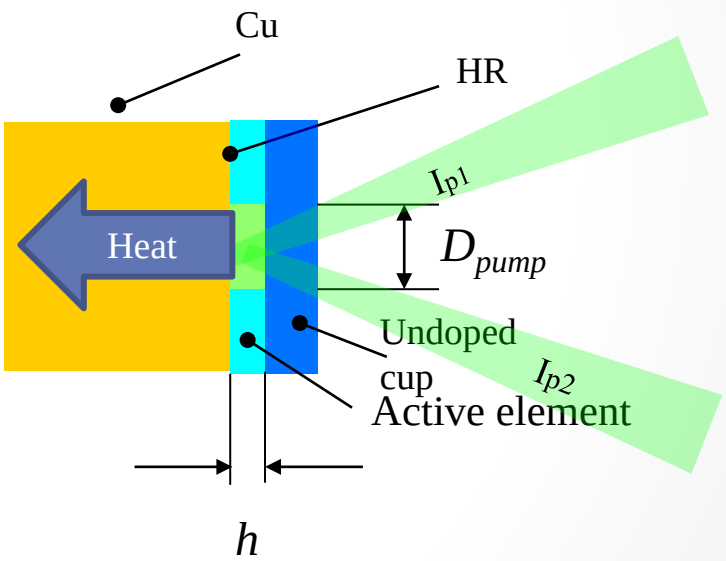
Geometrical features:

- Two passes of the pump through the active element
- Heat removal through HR disk face
- Axial symmetry

Two cases of active element disk geometry



Disk



Disk with undopped cup
which is made of Yb:YAG and YAG crystals

Heat conductivity equation is solved in all parts of system: active element, copper cooler and undopped cap.

Numerical model for stored energy calculation: Theoretical model derivation

Mathematically the problem reduces to the system of equations for pump intensity, upper level population, and temperature. We assume the Boltzmann distribution of sublevels populations.

$$\begin{cases} \dfrac{\partial I_{p1}}{\partial z} = \sigma_p \left(F_1(T) N_2 - F_2(T) N_{tot} \right) I_{p1} \\ \dfrac{\partial I_{p2}}{\partial z} = -\sigma_p \left(F_1(T) N_2 - F_2(T) N_{tot} \right) I_{p2} \\ \dfrac{\partial N_2}{\partial t} F_3(T) = -\dfrac{I_{p1} + I_{p2}}{I_2 \tau} \left(F_1(T) N_2 - F_3(T) N_{tot} \right) - \dfrac{N_2 F_3(T)}{\tau} - \iint \gamma_\lambda \Phi_\lambda d\lambda \\ \dfrac{\partial \left(a(T) T \right)}{\partial t} - div\left(\kappa(T) \nabla T \right) = Q(r,t) \end{cases}$$

$E_0, E_1, E_1', E_1'', E_2, E_2', E_2''$

energies of corresponding sublevels

$\sigma_p, \sigma_{lum}, I_s, I_{s_lum}, a, \kappa, \tau$

These parameters' dependencies on temperature was taken from experimental results and approximated with smooth functions

$Q(r,t)$ heat source, which depends on quantum defect

γ_λ gain coefficient

$\Phi_\lambda \left[\dfrac{1}{cm^2 nm\, s} \right]$ The amplified spontaneous emission flux

$$F_1(T) = \exp\left(\frac{E_2 - E_2'}{kT} \right) + \frac{1 + \exp\left(\frac{E_2 - E_2'}{kT} \right) + \exp\left(\frac{E_2 - E_2''}{kT} \right)}{1 + \exp\left(\frac{E_0 - E_1}{kT} \right) + \exp\left(\frac{E_0 - E_1'}{kT} \right) + \exp\left(\frac{E_0 - E_1''}{kT} \right)}$$

$$F_2(T) = \frac{1}{1 + \exp\left(\frac{E_0 - E_1}{kT} \right) + \exp\left(\frac{E_0 - E_1'}{kT} \right) + \exp\left(\frac{E_0 - E_1''}{kT} \right)}$$

$$F_3(T) = 1 + \exp\left(\frac{E_2 - E_2'}{kT} \right) + \exp\left(\frac{E_2 - E_2''}{kT} \right)$$

Daniel Albach, Amplified Spontaneous Emission and Thermal Management on a High Average-Power Diode Pumped Solid State Laser. The LUCIA Laser System, 2010

Numerical model for stored energy calculation:
Amplified Spontaneous Emission and temperature dependencies

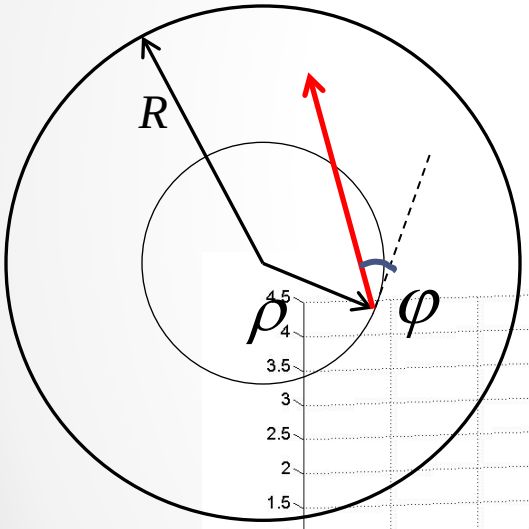
Full photon flux on wave length λ [1]

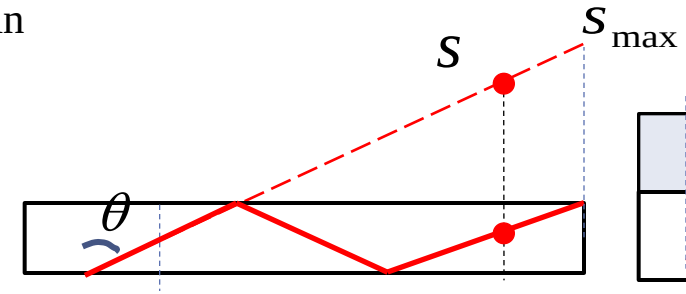
$$\Phi_\lambda = \int d\Omega \frac{\beta_\lambda}{\tau} \int_0^{s_{max}} N_2(\hat{s}\, s) \exp\left(\int_0^{s} \gamma_\lambda(\tilde{s}\,\hat{s})\, d\tilde{s} \right) ds$$

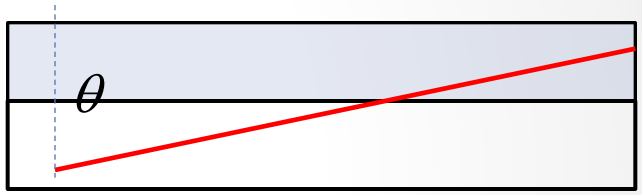
$\int \beta_\lambda d\lambda = 1$ Emission spectral distribution

τ lifetime of the upper level

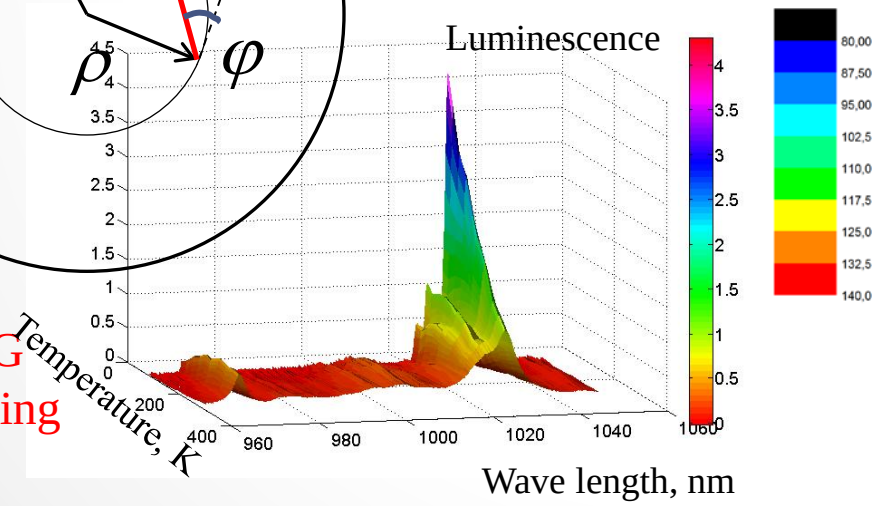
$\gamma_\lambda = \sigma_l(\lambda_l)\Delta N$ small signal gain

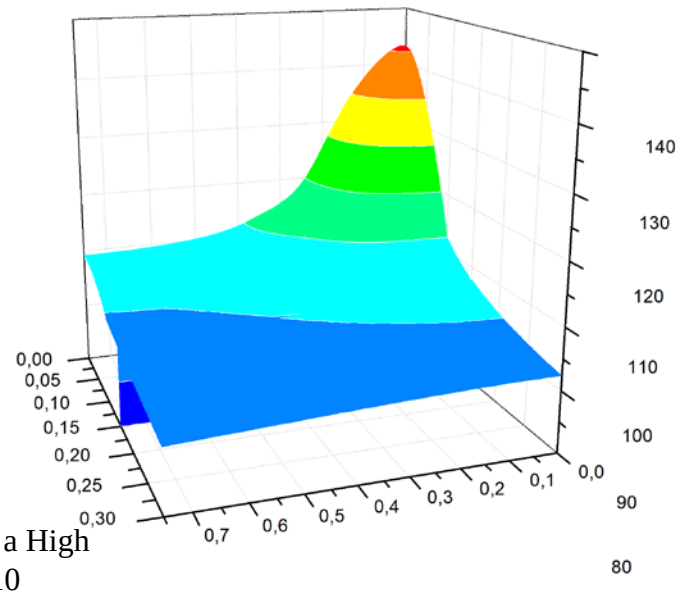






Yb:YAG
10% Doping





[1] Daniel Albach, Amplified Spontaneous Emission and Thermal Management on a High Average-Power Diode Pumped Solid State Laser. The LUCIA Laser System, 2010

Numerical model for stored energy calculation : Temperature dependencies

Advantages of developed numerical model

- Taking into account amplified spontaneous emission and parasitic lasing
- Taking into account temperature dependencies spectral and thermal characteristics what is very important at the high power
- 3-D numerical solution which is more exact and has no limitation on aspect ratio of active element thickness and pump diameter

Numerical model for stored energy calculation :

Method of numerical simulation

$t = 0 \quad N_2 = 0 \quad T = T_0$

The next time step

$$F_1(T), F_2(T), F_3(T), \sigma_p(T), \sigma_{lum}(T), I_s(T), I_{s\,lum}(T), a(T), \kappa(T), \tau(T), \Phi_\lambda$$

$$\begin{cases} \dfrac{\partial I_{p1}(z)}{\partial z} = \sigma_p (F_1 N_2 - F_2 N_{tot}) I_{p1}(z) \\ \dfrac{\partial I_{p2}(z)}{\partial z} = -\sigma_p (F_1 N_2 - F_2 N_{tot}) I_{p2}(z) \end{cases}$$

$I_{p1}(z) \quad I_{p2}(z)$

Amplified spontaneous emission

Spatial ant temporal finite difference method

$$N_2(z, t+\Delta t) = N_2(z,t) + \left(-\frac{I_{p1}(z) + I_{p2}(z)}{I_s \tau} (F_1 N_2(z,t) - F_2 N_{tot}) - \frac{N_2(z,t)}{\tau} - \iint \gamma_\lambda \Phi_\lambda d\lambda \right) \frac{\Delta t}{F_3}$$

Integration over wave length was tabulated

Explicit Euler method for heat equation solution

Heat sources

Small signal gain

$$\exp\left(\int_z \Delta N \sigma_{lum} dz \right)$$

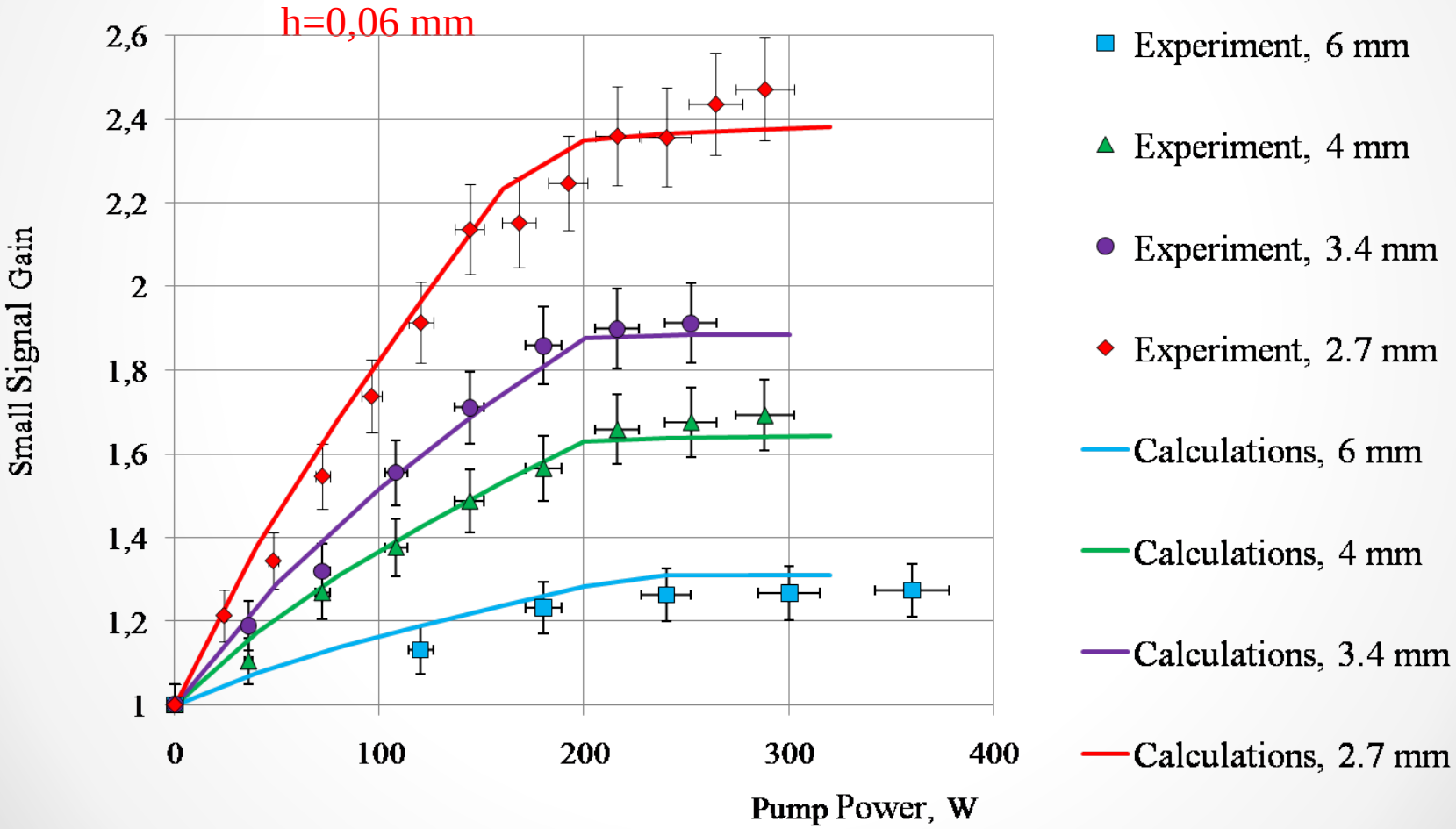
Stored energy

$$\int_V \Delta N \, h\nu \, dV$$

$$T(t+\Delta t) = T(t) + \Delta t \left(Q(r,t) + div(\kappa \nabla T) \right)$$

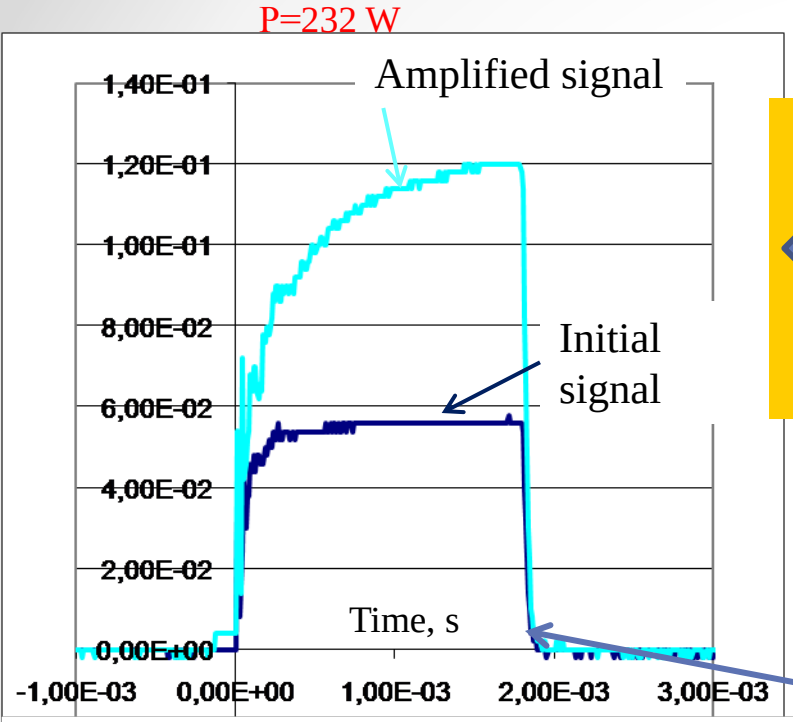
Numerical model for stored energy calculation :
Experimental validation of numerical model

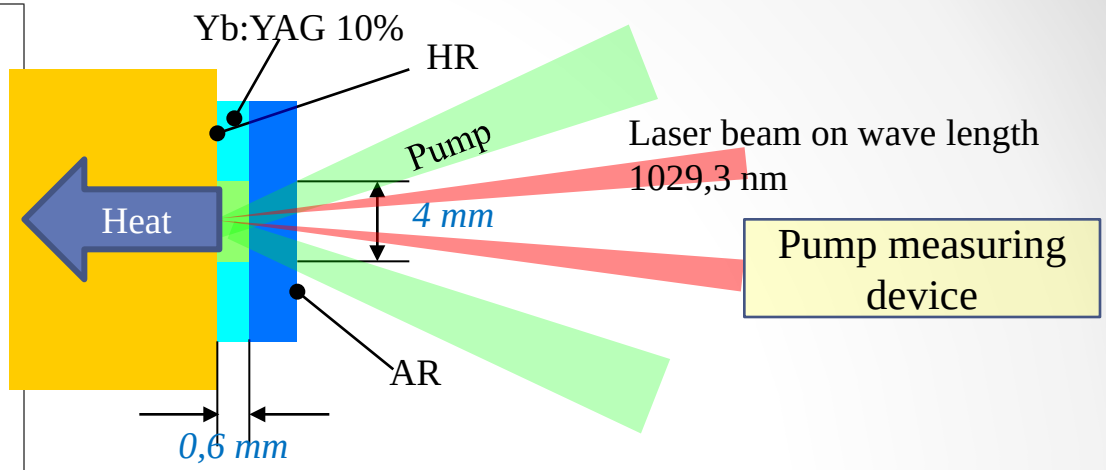
Small signal gain in the center of pump region dependencies on pump power and pump diameter

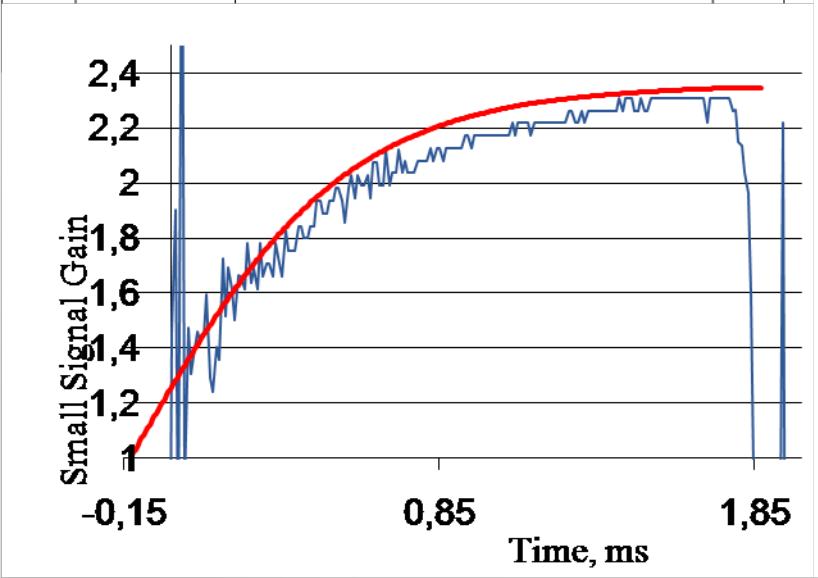


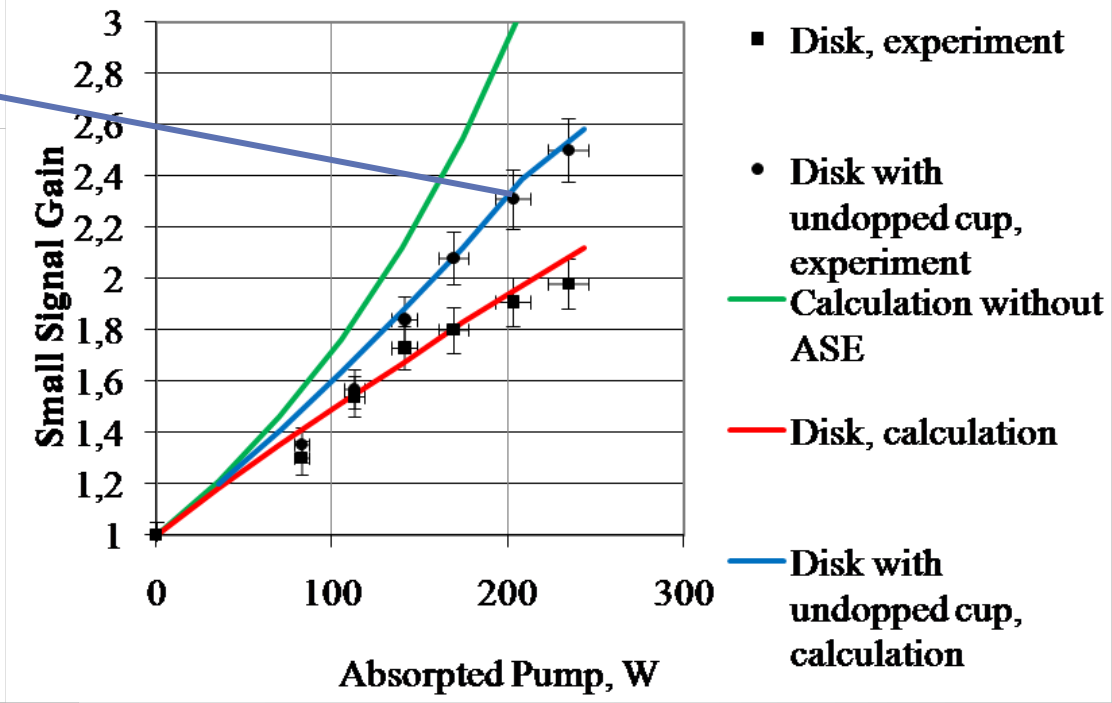
Numerical model for stored energy calculation :

Experimental validation of numerical model

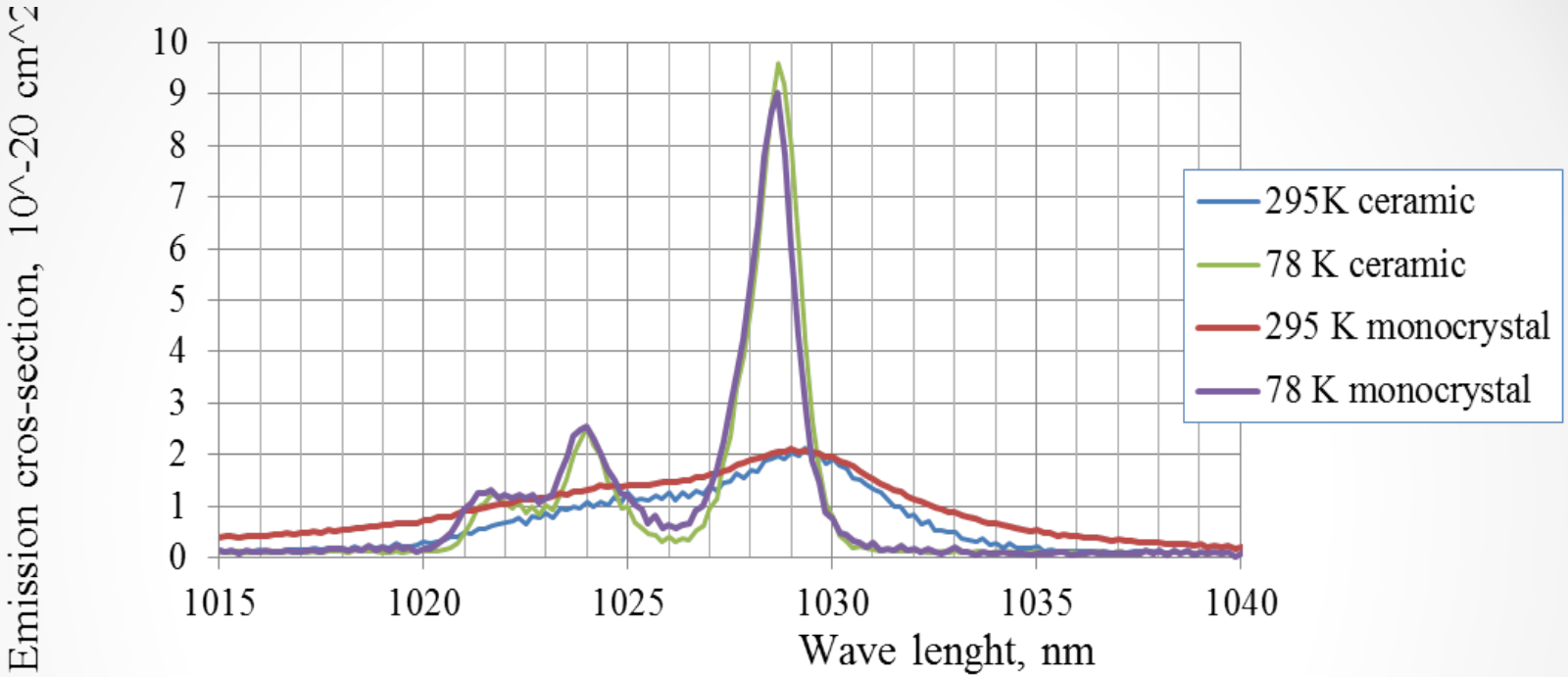








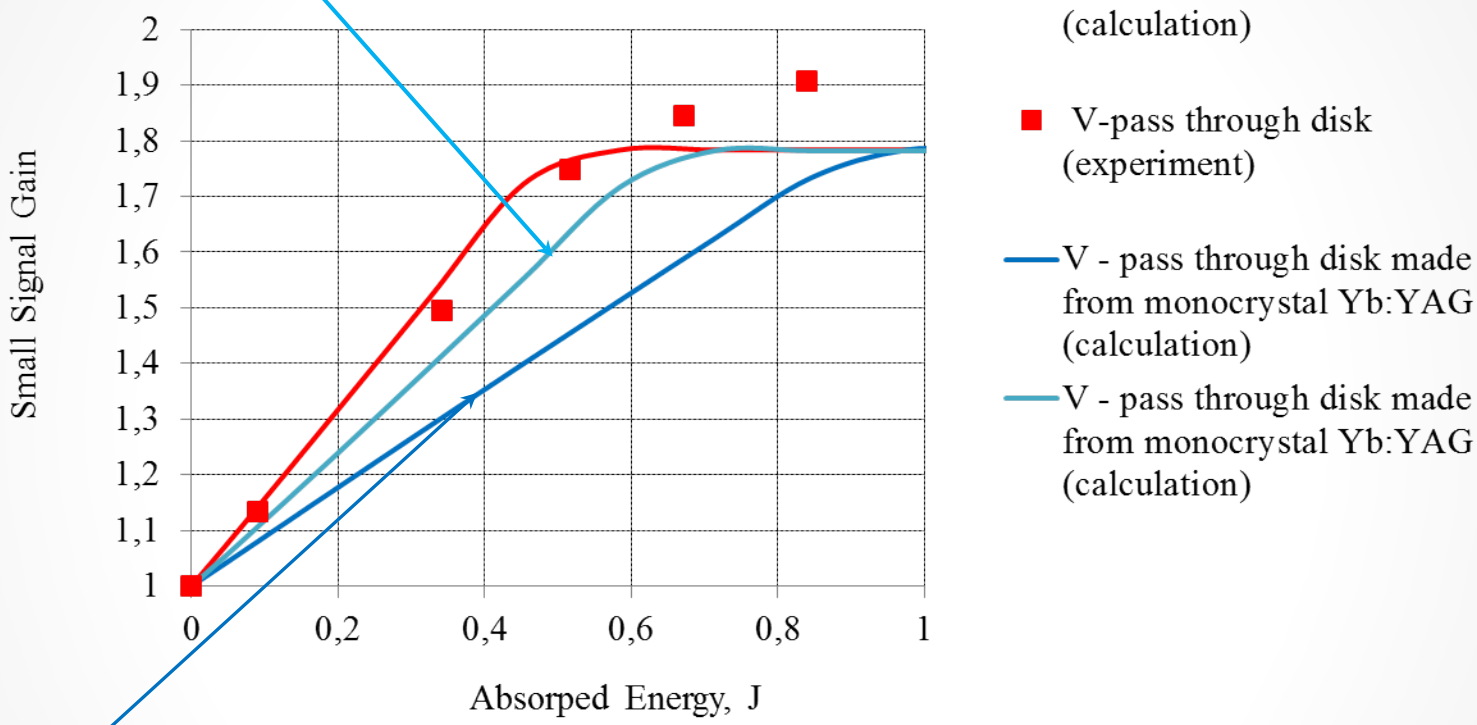
Comparison of Yb:YAG monocrystal and ceramic:



	Yb:YAG monocrystal	Yb:YAG ceramic
Lifetime at 78K	0.68 ms	0.86 ms
Emission cross-section at 78K	$9.58 \cdot 10^{-20}$ cm^2	$9.02 \cdot 10^{-20}$ cm^2

Comparison of Yb:YAG monocrystal and ceramic:

lifetime 0.88 at 78 K



lifetime 0.68 at 78 K

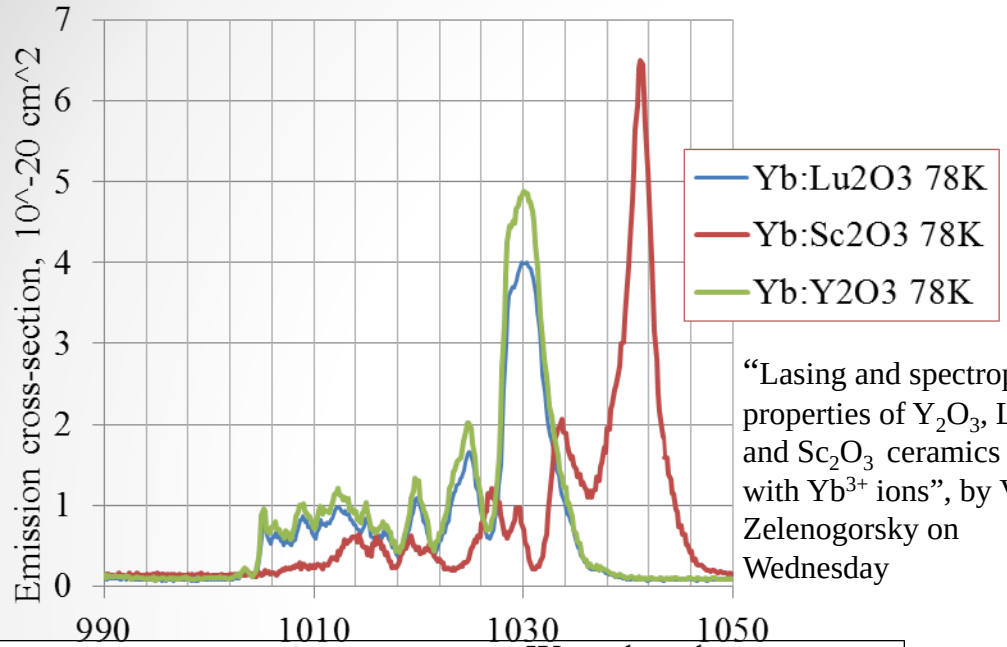
"Amplifier with high energy capacity and average power based on cryogenically cooled disk shaped Yb:YAG laser ceramics", by Evgeny Perevezentsev

Disk thickness 0.14 cm
Disk diameter 2 cm
Pump diameter 0.8 cm
Doping 5%
Pump pulse repetition rate 140 Hz
Pump pulse duration1.3 ms

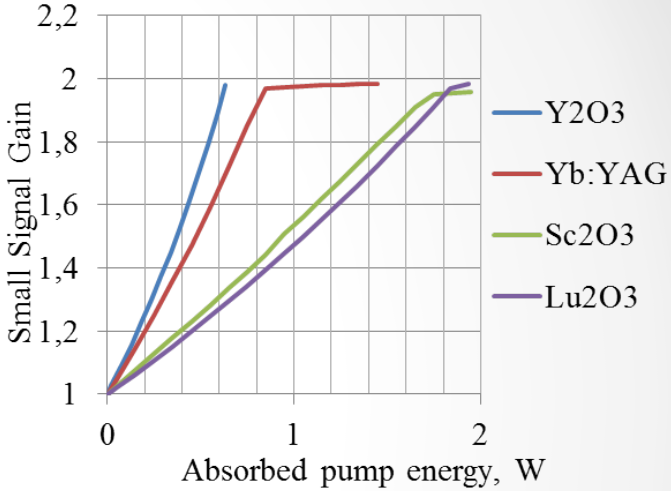
Storing energy in sesquioxide ceramics:

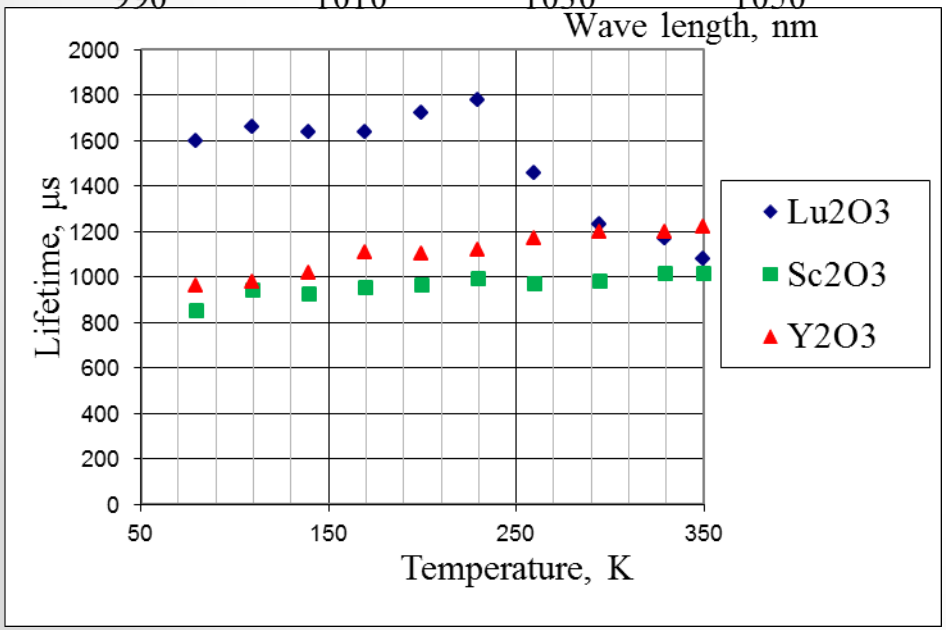
Parameters for simulation:

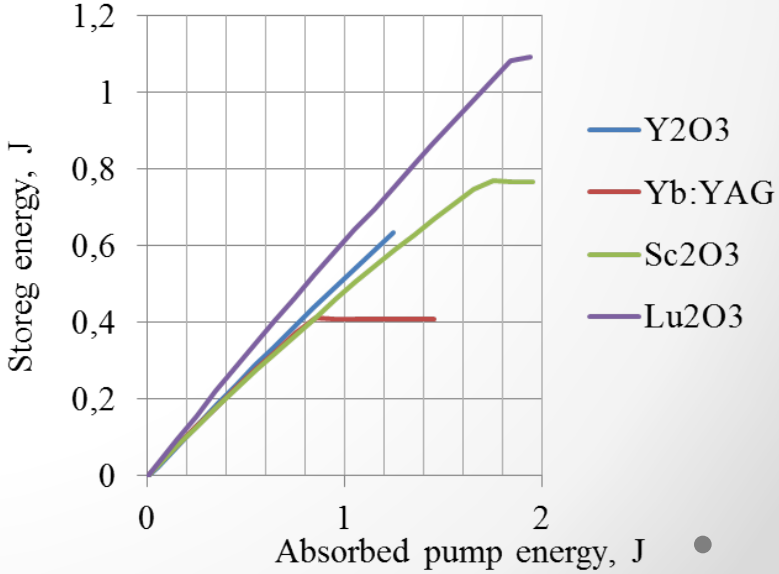
Disk thickness 0.09 cm
Disk diameter 3 cm
Pump diameter 1.0 cm
Doping 10%
Pump pulse duration 1 ms



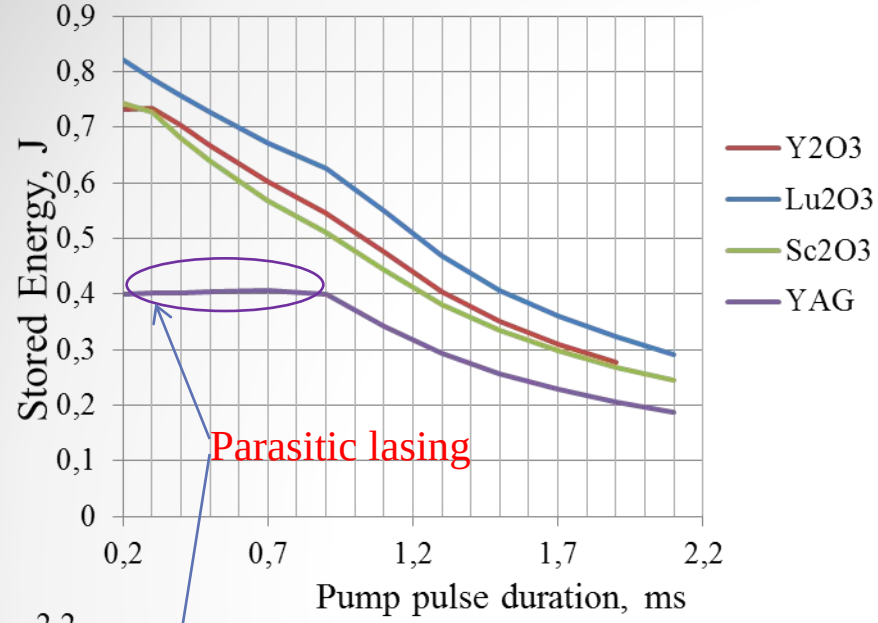
"Lasing and spectroptics properties of Y_2O_3, Lu_2O_3, and Sc_2O_3 ceramics doped with Yb^{3+} ions", by Victor Zelenogorsky on Wednesday

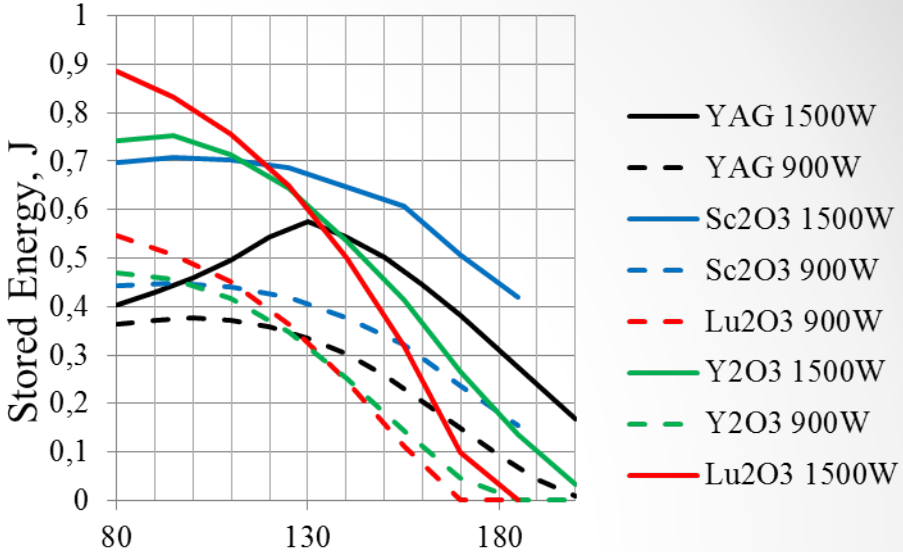


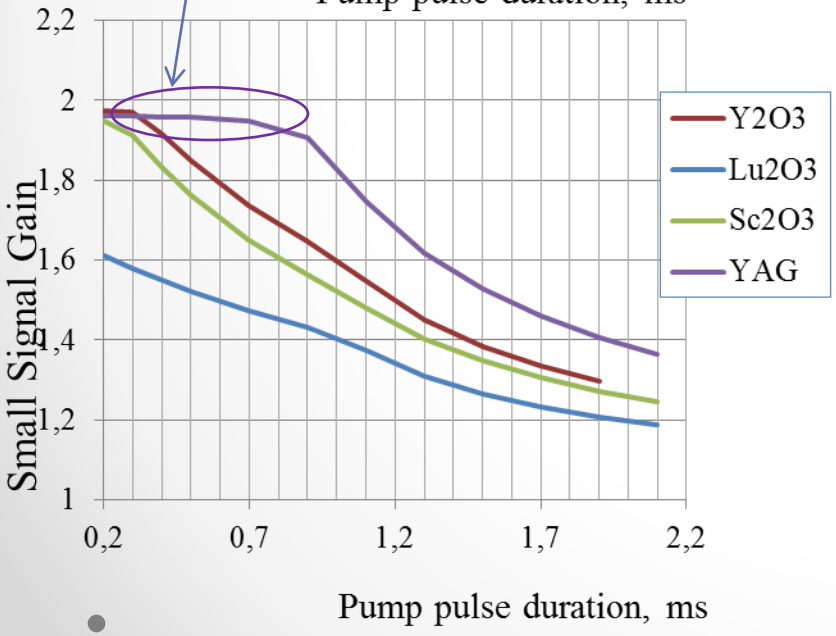


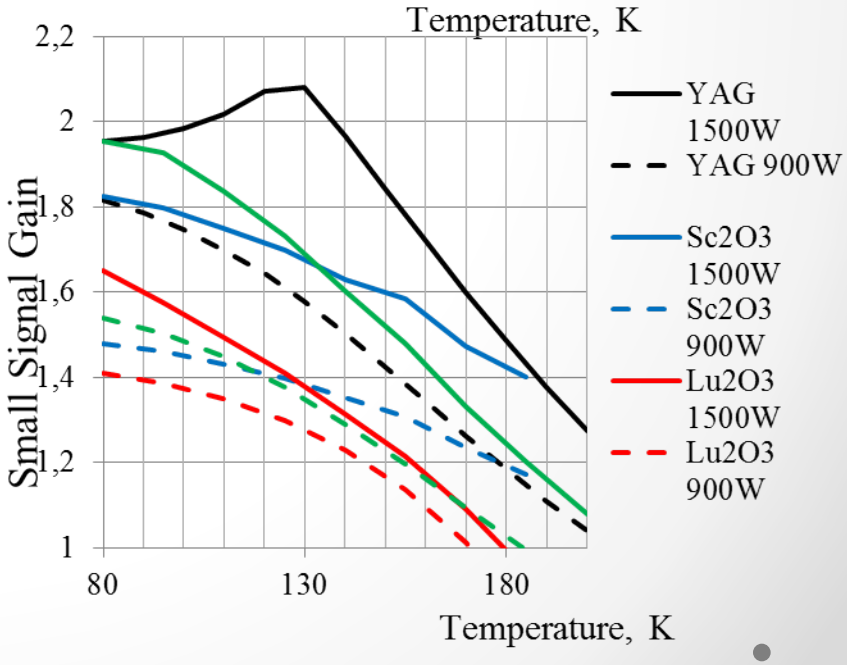


Storing energy in sesquioxide ceramics:









Summary

• The theoretical model for amplification in disk active element was derived. The software for numerical solution of balance equations and non-linear heat equation system was elaborated. Such effects as ASE and temperature dependencies of active element parameters were taken into account.

•The results of calculations correspond to experimental data including the estimation of parasitic lasing threshold.

• Use of disk with undoped cup allows to decrease ASE negative influence. This fact was shown by calculations and experiment.

• Yb:YAG ceramic laser performance is very similar to Yb:YAG monocrystal one.

• The numerical investigation of oxide ceramics doped with Yb ion was carried out. It was shown that all of them allow to store more energy at the cryogenic temperature than both Yb:YAG ceramic and monocrystal do. According to the calculation Yb:Lu_2O_3 demonstrated the highest energy capacitance properties with acceptable gain coefficient.