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Lecture 5, Part 2: High power laser glass and its application

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High power laser glass and its application

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Outline

- History and basic theory of laser glass
- High power Nd:phosphate laser glass and its application
- High power Nd:glass fabrication technologies
- High power Yb:silica fiber and its fabrication
- Outlook on next generation high power laser material.

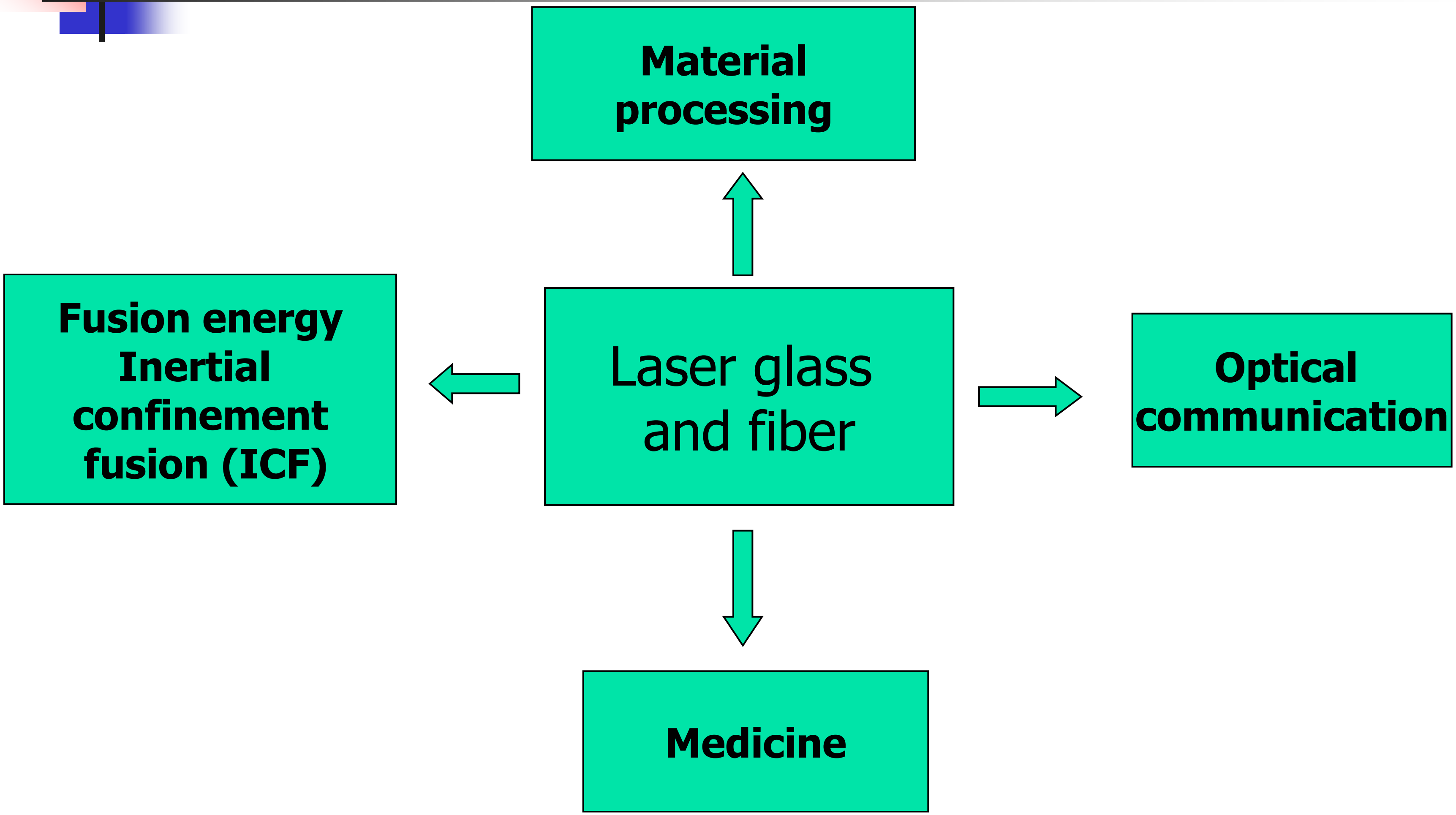
1 What's laser glass

- Laser glass is a material which can lase under xenon lamp or laser diode pumping;
- In glass, laser has been mostly observed in rare earth ion doped case;
- Nd:glass is an important high power laser glass;
- Laser glass works in both bulk and fiber forms.

History of laser glass

- In 1960, Snitzer in US found first Nd:silicate glass;
- In 1960, Snitzer found laser in Nd, Er doped glass fiber;
- A.O company in US first developed ED-2 Nd:silicate glass;
- In late 1970s, Hoya company in Japan developed Nd:phosphate glass.
- Er:phosphate glass was developed in 1980s;
- High power Yb:silica fiber laser was developed since 2000.

Application of Laser Glass and Fiber

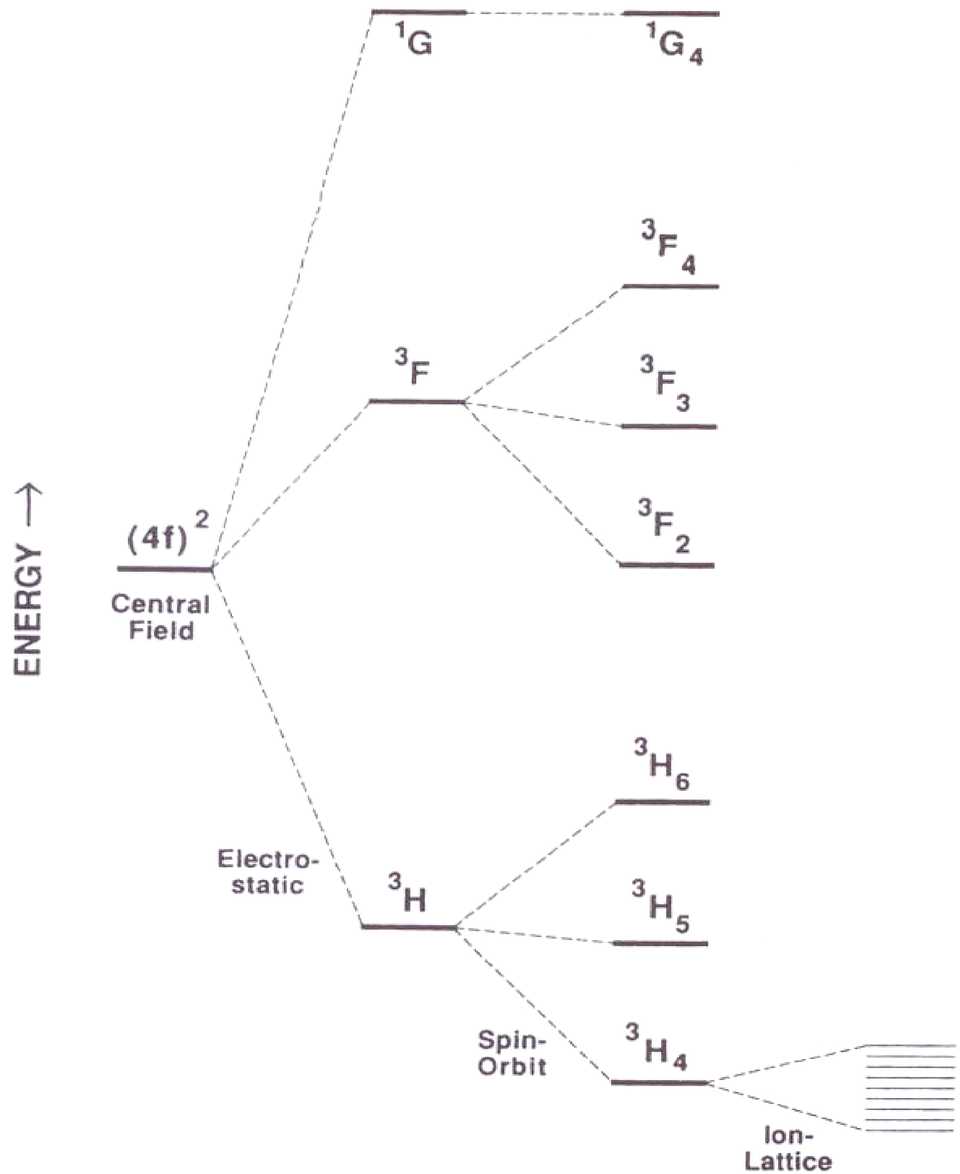


Rare earth ions in glass

- Glass is a good host for rare earth ions
  - Rare earth ion concentration can be widely adjusted in glass;
  - The spectroscopic properties of rare earth ions in glass host can be modified by composition through ion-host interaction.

Three widely used rare earth ions in glass

- The most popularly used rare earth ions in glass are neodymium, erbium and ytterbium.
- Nd^{3+} doped phosphate glass is widely used in ICF facility;
- Er^{3+} doped silica fiber is commercially applied in optical communication.
- Yb^{3+} doped silica fiber is now getting use in industrial material processing.



Splitting of energy level is caused by electron-electron and electron- host interaction

Main parameters of laser glass

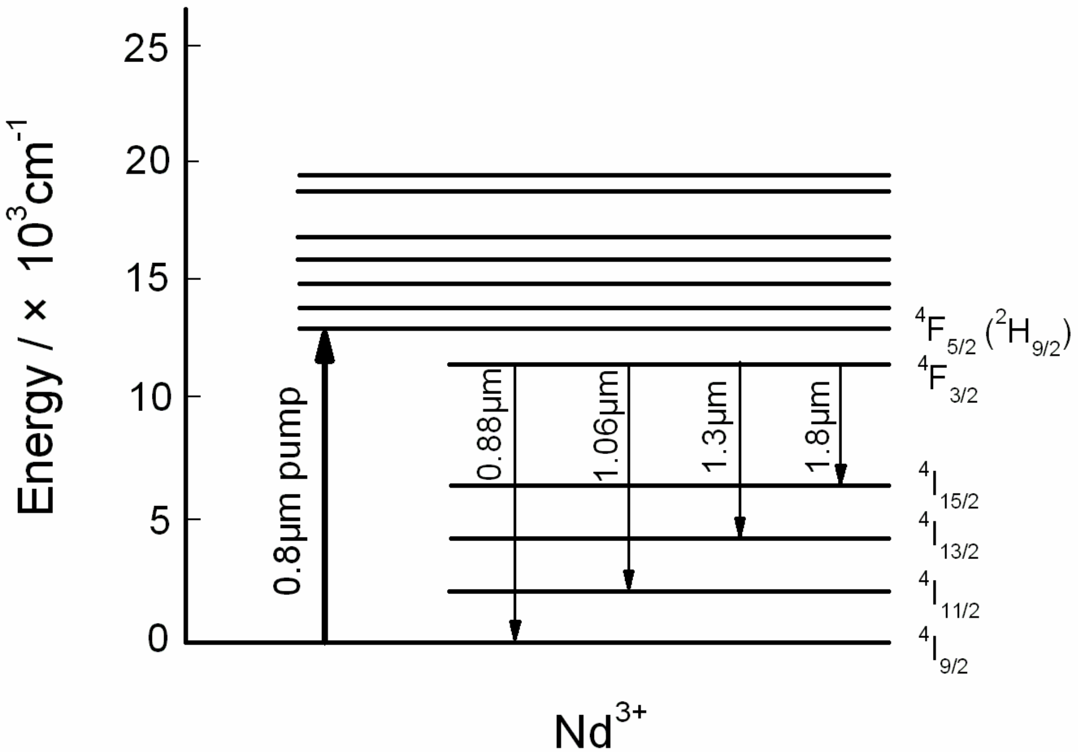
- Stimulated emission cross section;
- Effective absorption of pumping light;
- Fluorescent lifetime of up-energy level;
- Quantum efficiency.

Precondition of laser oscillation

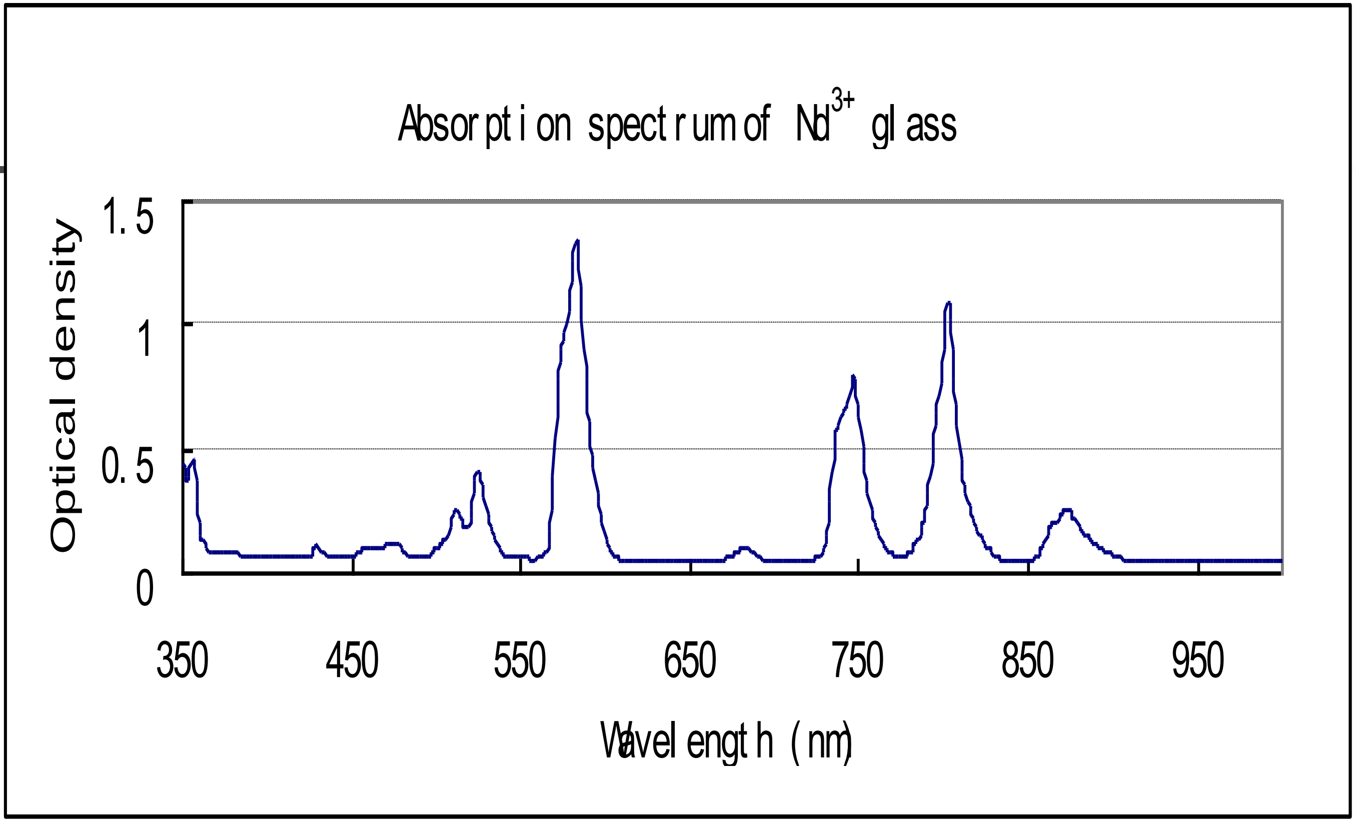
- Population inversion of lasing ion;
- Enough gain to overcome the loss from material and resonator;
- High stimulated emission cross section and long fluorescent lifetime;
- Small loss at lasing wavelength.

Basic properties of Nd^{3+} ion

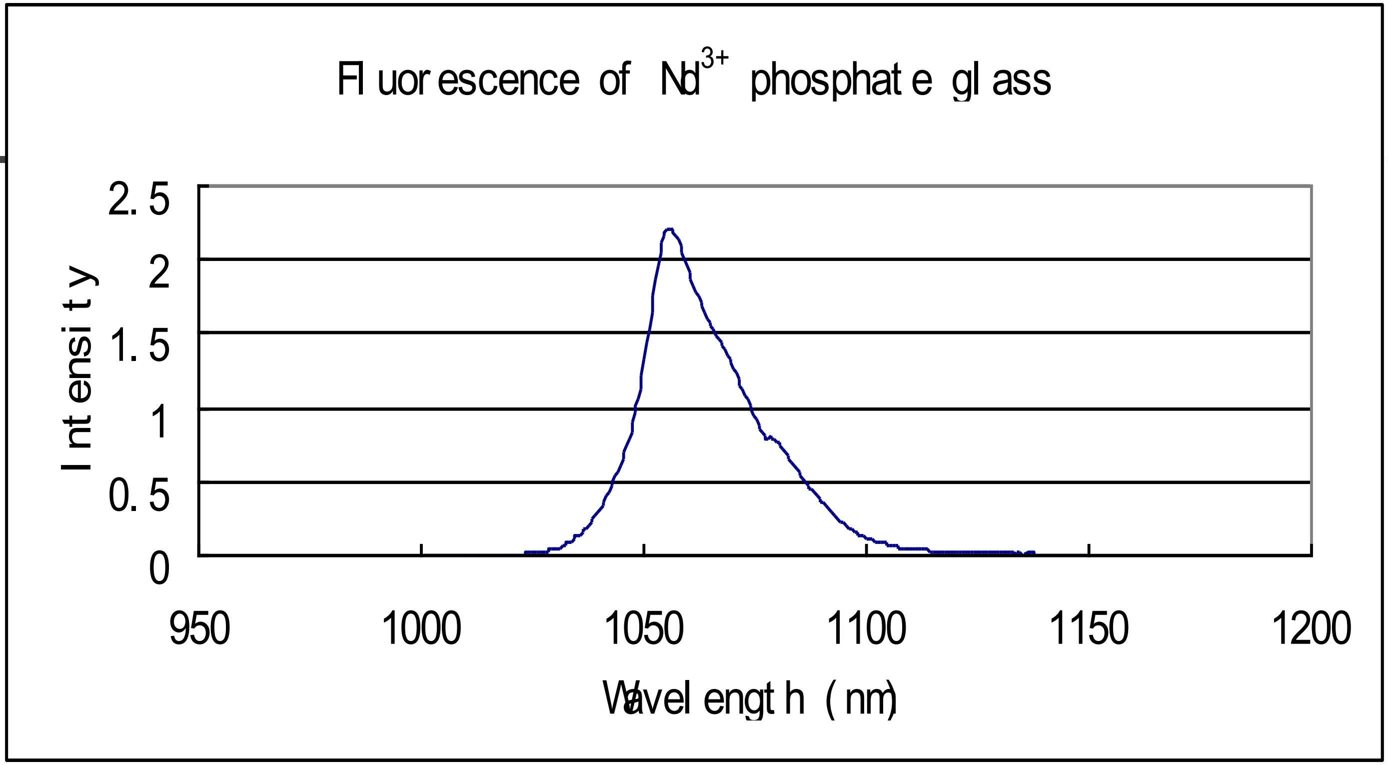
- Four energy level rare earth ion with lower laser threshold;
- Efficient lasing at 1050-1060nm wavelength;
- Relative large stimulated emission cross section and short fluorescent lifetime (hundreds of microsecond).



Energy levels of Nd^{3+} ion



Absorption spectrum of Nd^{3+} ion in glass



Main fluorescent spectrum of Nd^{3+} ion in glass

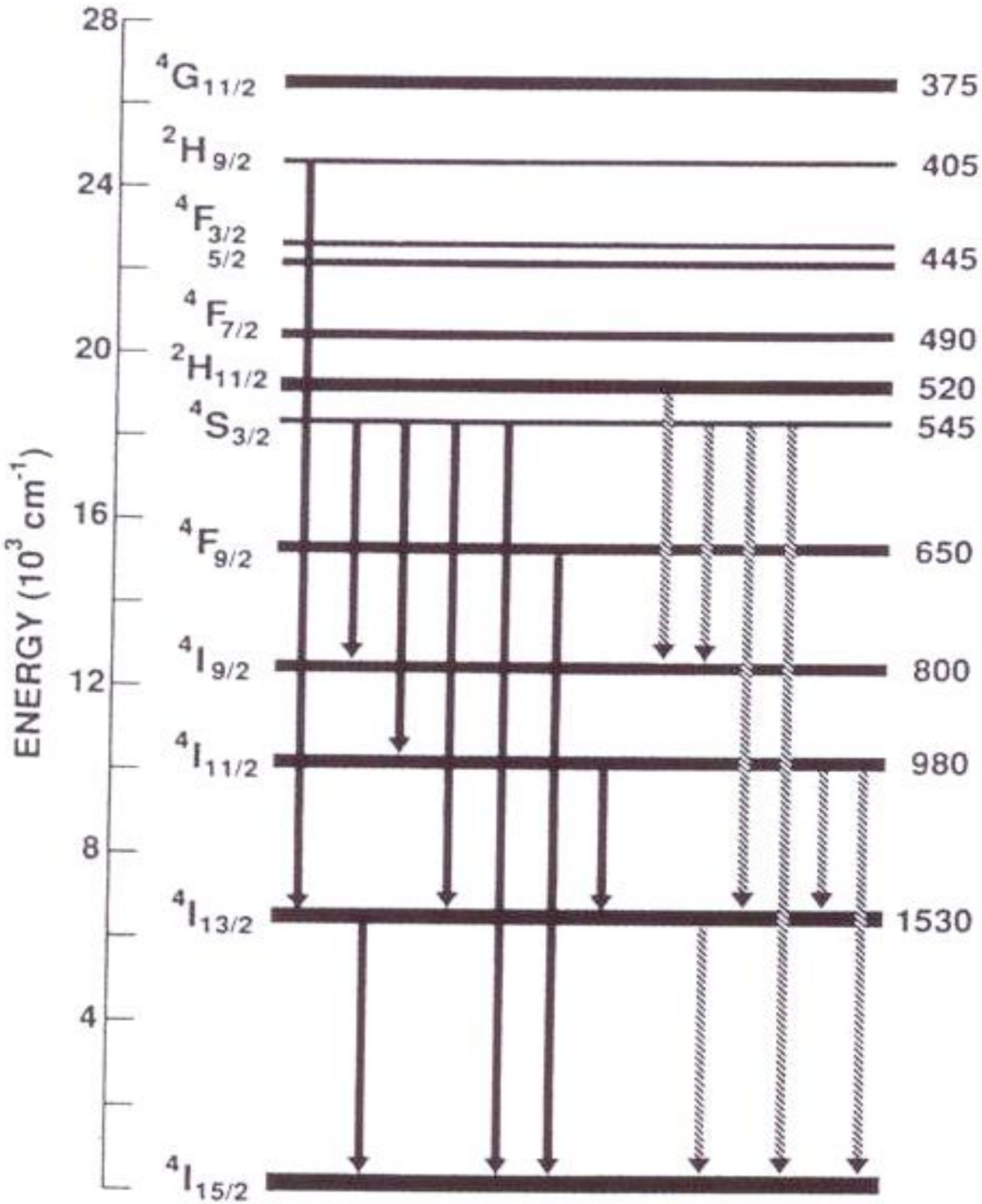
(Usually three fluorescent peaks are detected in Nd:glass)

The evaluation of spectroscopic properties of Nd^{3+} ions

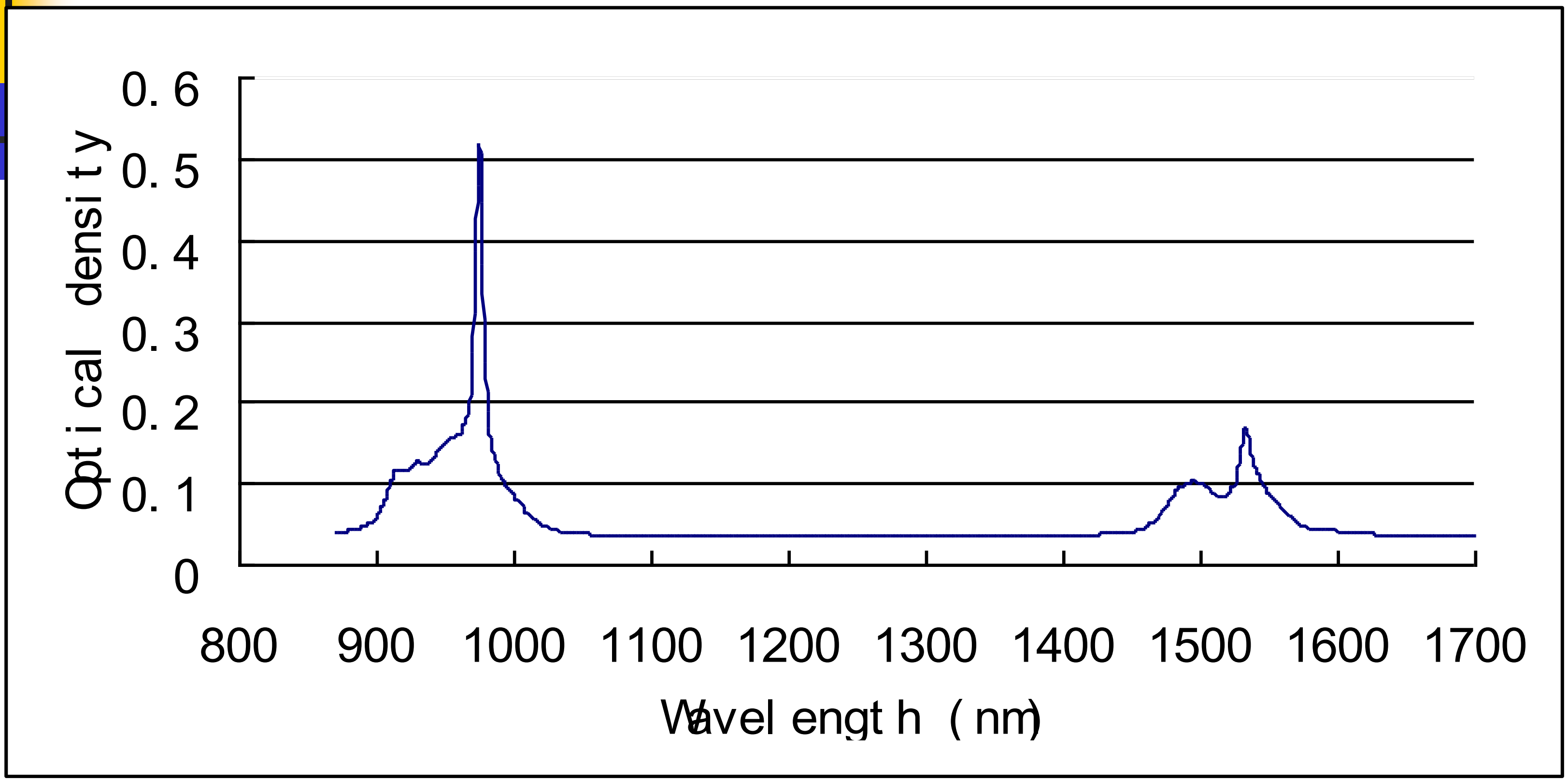
- Judd-Oflet theory is commonly used to calculate the spectroscopic properties of Nd^{3+} ion.

Basic properties of Er^{3+} ion

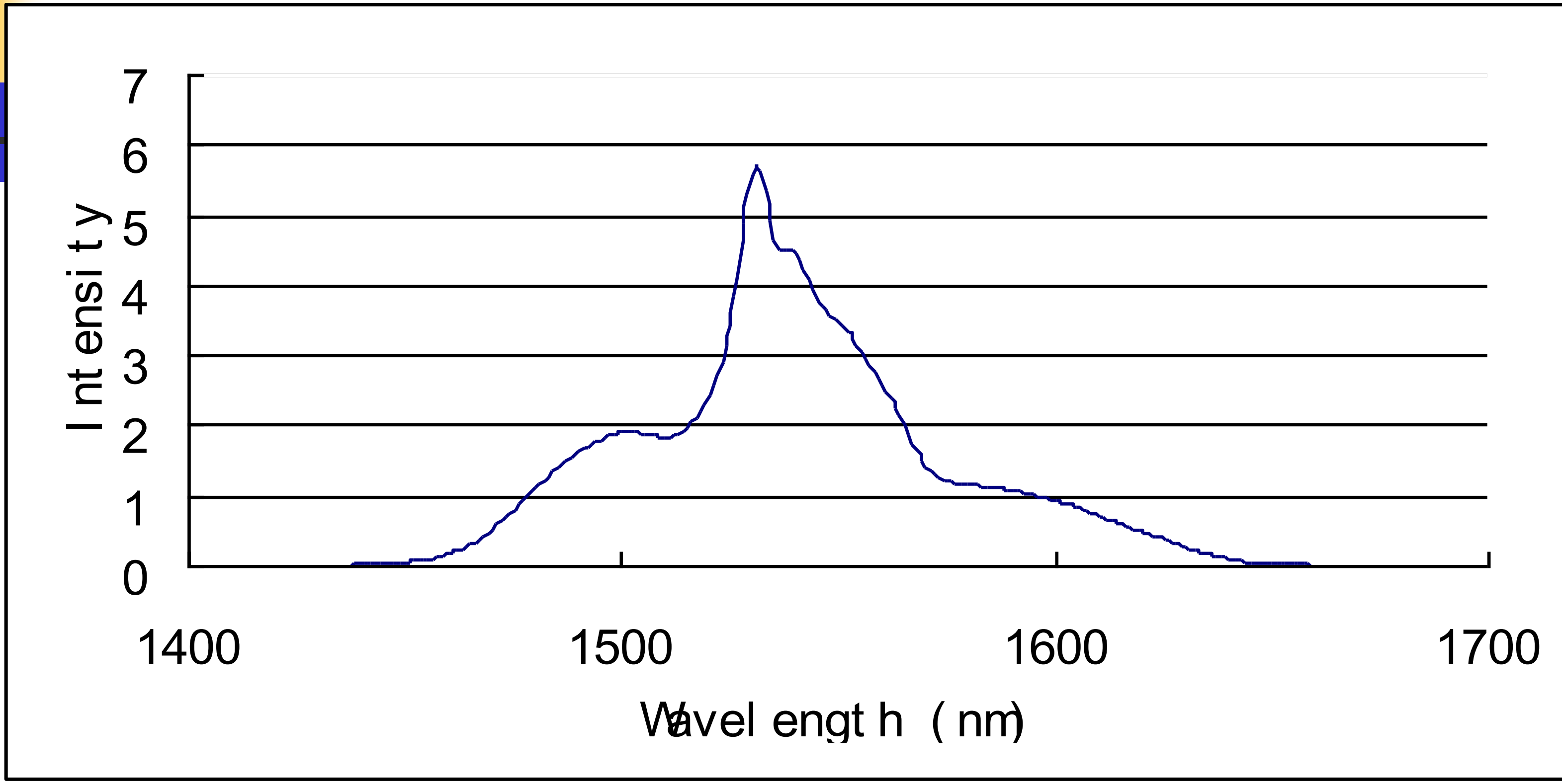
- Three energy level with high laser threshold;
- Long fluorescent lifetime (several mini-second) and small emission cross section;
- Lasing at 1530-1550nm wavelength range;
- Small absorption at pumping wavelength, co-doping with Yb^{3+} is needed.



Energy level of Er^{3+} ion



Absorption spectrum in IR range of Er^{3+},Yb^{3+} co-doped phosphate glass



Fluorescent spectrum of Er^{3+},Yb^{3+} co-doped phosphate glass

The evaluation of emission cross section of Er^{3+} ion

- McCumber method

$$\sigma_e(\lambda) = \sigma_a(\lambda)\exp[(\varepsilon - h\nu)/kT]$$

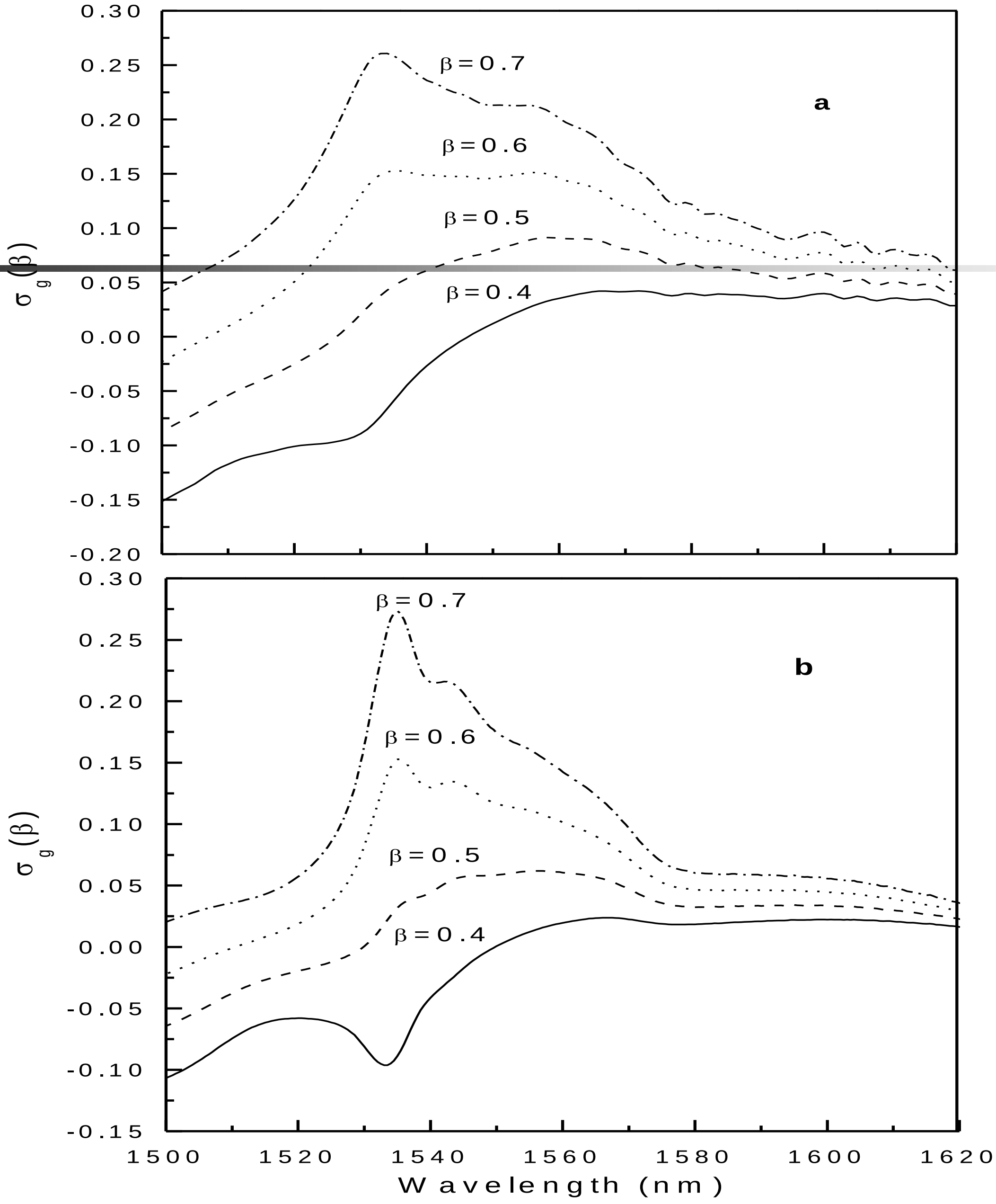
k : Boltzman constant ;

ε: transition energy from $^4I_{15/2}$ to $^4I_{13/2}$

Gain of Er^{3+} ion at different pumping power

$$\sigma_g(\beta) = \beta\sigma_{em} - (1-\beta)\sigma_{abs}$$

β is the ratio of ion concentration at upper energy level to lower energy level



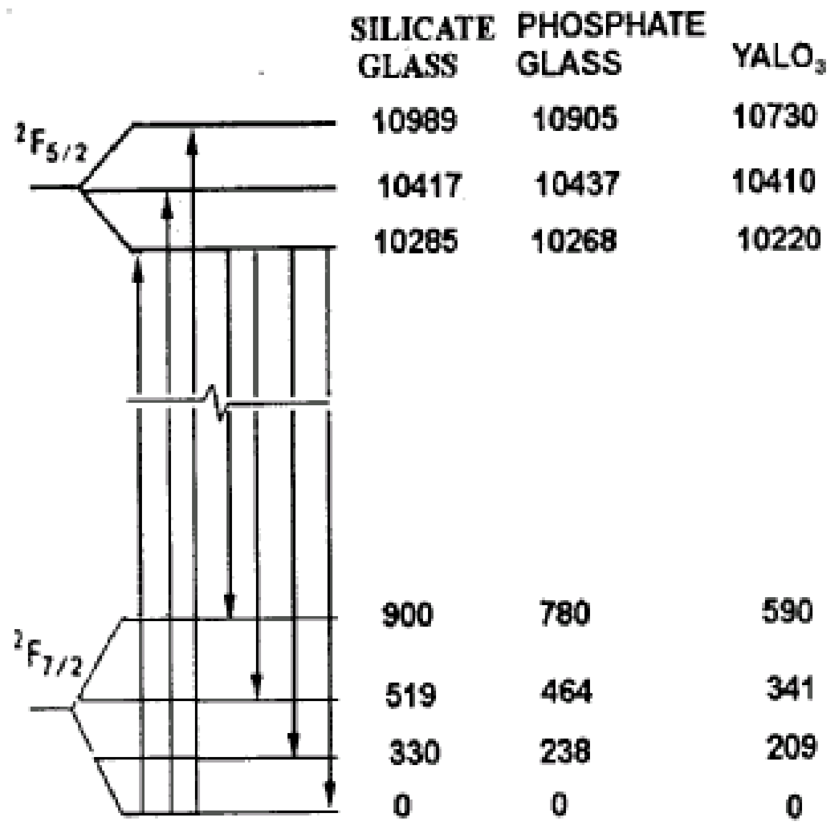
a: Gain of Er^{3+} doped fluorophosphate glass at various pump power

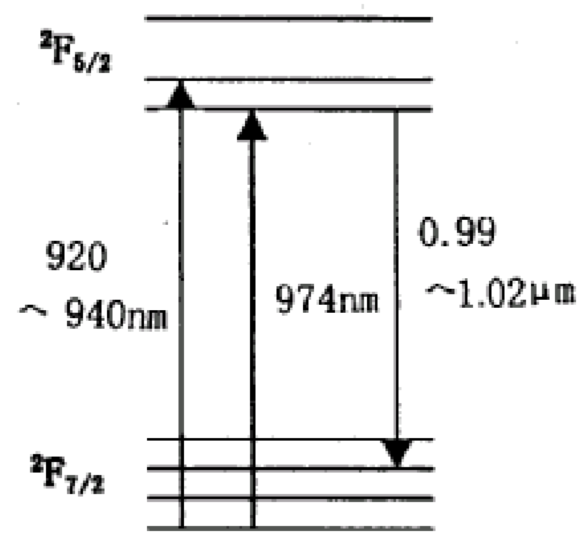
b: Gain of Er^{3+} doped phosphate glass at various pump power

Basic properties of Yb^{3+} ion

- Two energy level ions;
- Large laser threshold and lower energy level population sensitive to temperature;
- Long fluorescent lifetime (0.5-2ms)
- Lasing at 1000-1200nm range;
- Large absorption at both 940nm and 980nm;
- High laser efficiency can be obtained in Yb:silica fiber.

Energy level of Yb^{3+} ion in different matrix



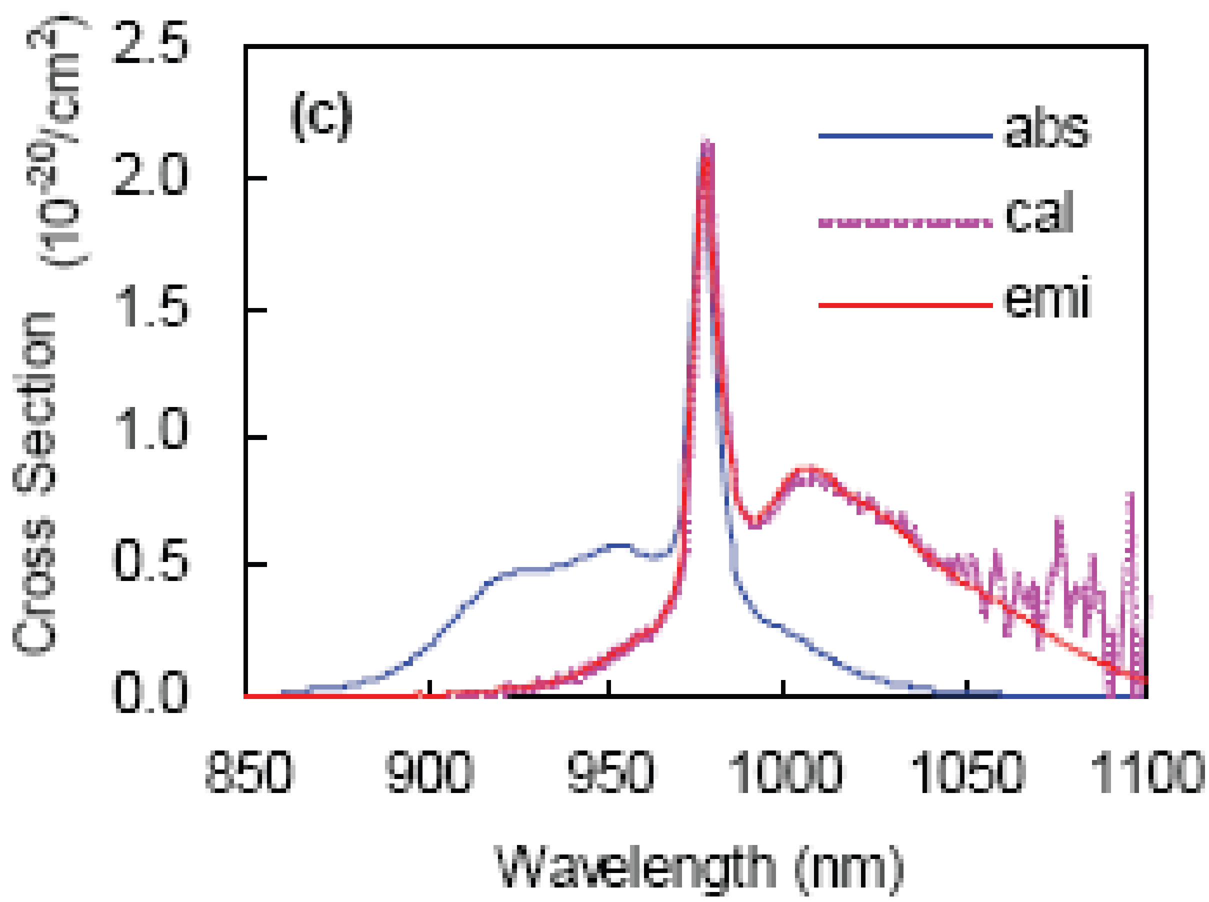


Stimulated emission cross section of Yb^{3+} ion

$$\sigma_{emi}(\lambda) = \sigma_{abs}(\lambda)\frac{Z_l}{Z_u}\exp\left(\frac{E_{zl} - hc\lambda^{-1}}{kT}\right)$$

Zl/Zu is partition function of lower and up levels ,
Ezl is zero-line energy.

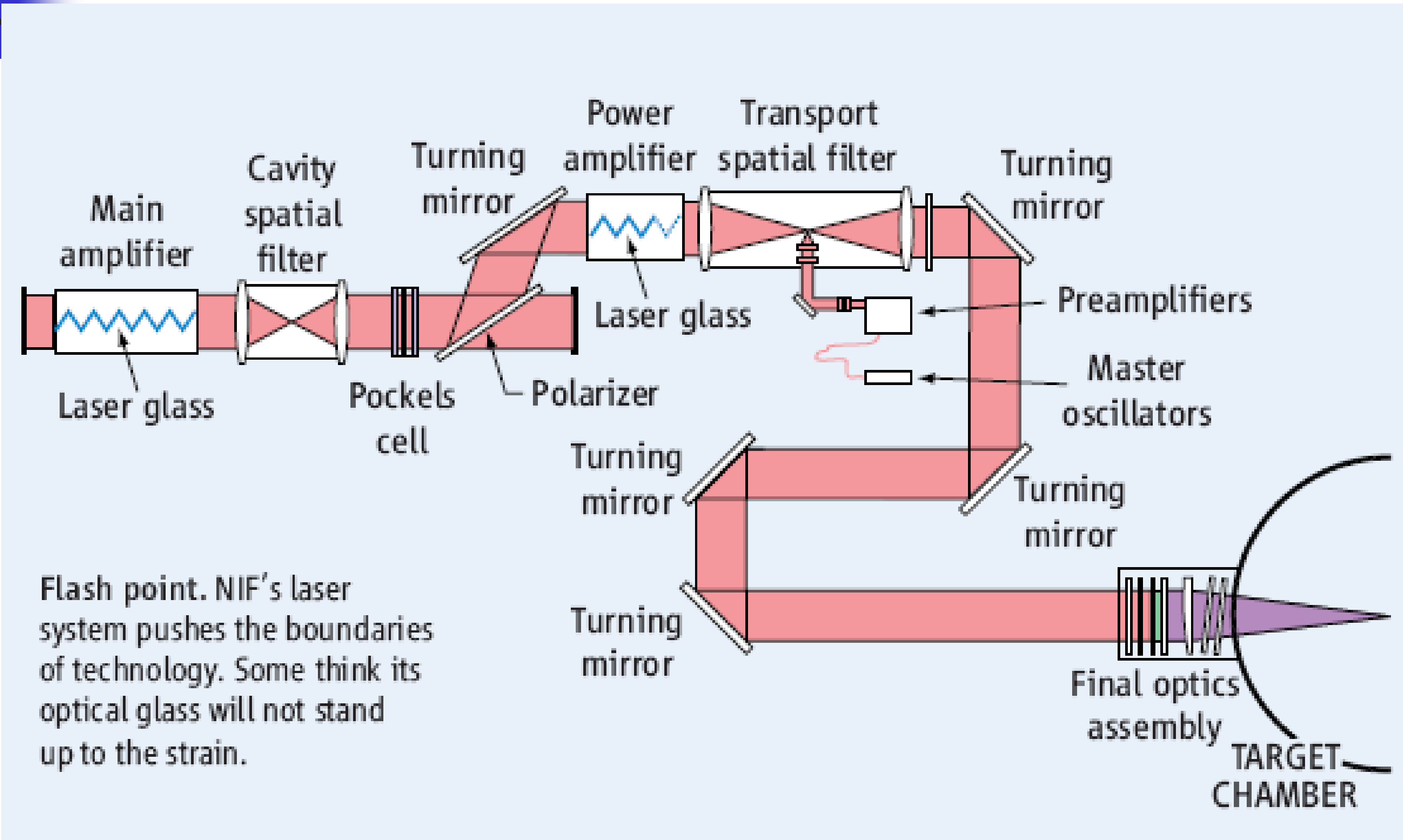
Absorption and emission cross sections of Yb^{3+} doped bismuth glass



2 High power Nd:phosphate laser glass and its application

- Nd:phosphate glass is a widely used high power laser glass since its application in early 1980s.
- Nd:phosphate laser glass is mainly used as amplifier material in high peak power laser facility.

Laser system in NIF, US



Flash point. NIF's laser system pushes the boundaries of technology. Some think its optical glass will not stand up to the strain.

The advantages of phosphate glass as laser matrix

- High rare earth ion solubility;
- Large stimulated emission cross section;
- Medium phonon energy;
- Good thermal optical property;
- Lower nonlinear refractive index;
- Lower contents of Pt inclusions.

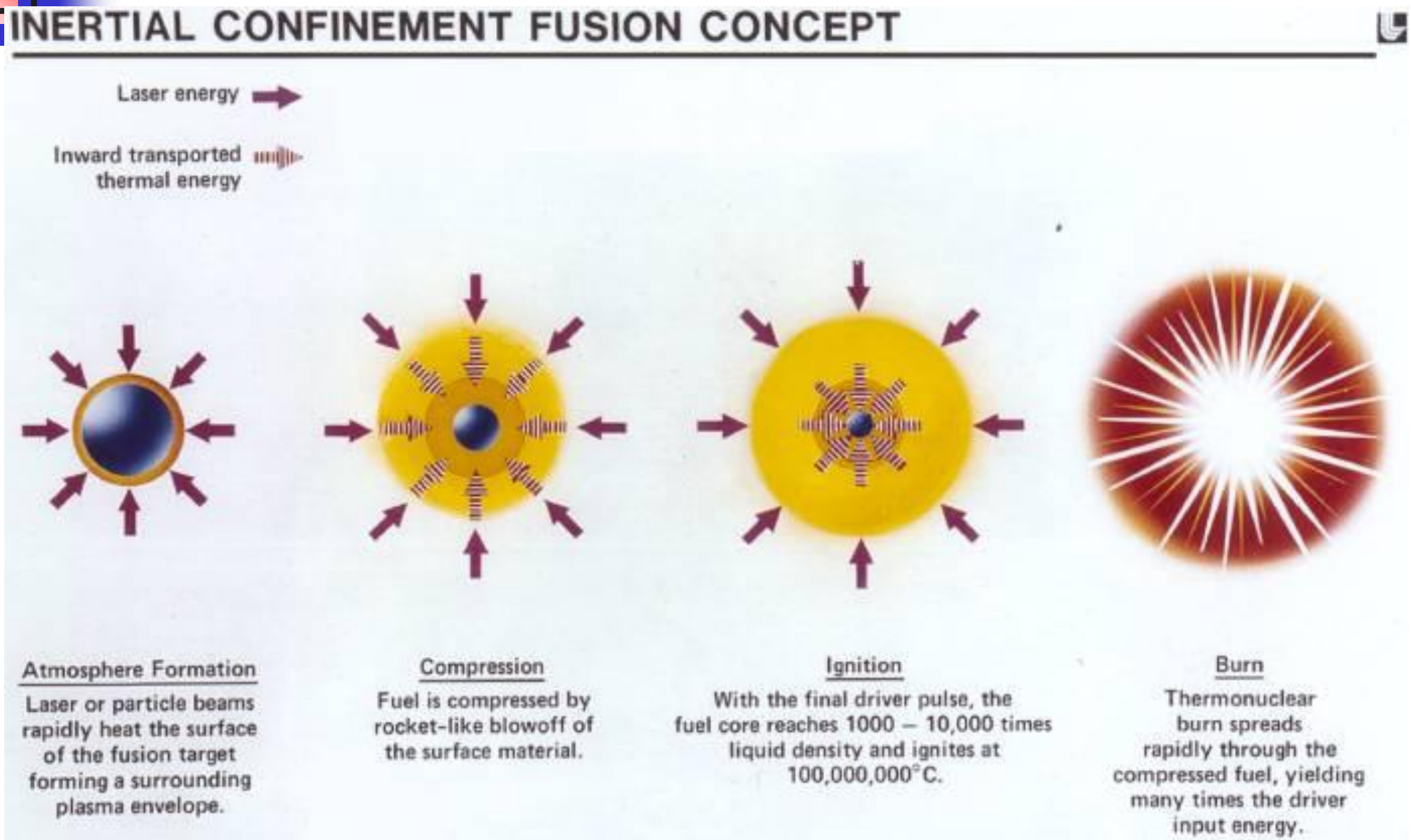
Disadvantages of phosphate glass as laser matrix

- Poor chemical and mechanical properties;
- Poor fabrication property.

Mission of large high power laser facility

- Inertial confinement fusion for future nuclear energy generation;
- Basic scientific researches on astrophysics and plasma physics.

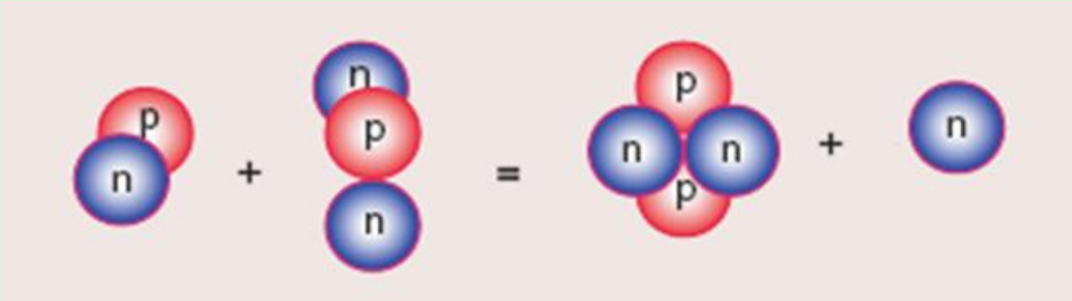
ICF concept


INERTIAL CONFINEMENT FUSION CONCEPT
Laser energy
Inward transported thermal energy
Atmosphere Formation
Laser or particle beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.
Compression
Fuel is compressed by rocket-like blowoff of the surface material.
Ignition
With the final driver pulse, the fuel core reaches 1000 – 10,000 times liquid density and ignites at 100,000,000°C.
Burn
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy.

The nuclear fusion reaction

$$^{2}D_{1}+^{3}T_{1}\rightarrow^{4}He_{2}+^{1}n_{0}+17.6MeV$$

- D and T are isotopes of hydrogen， He is helium nuclei， n is neutron。



Target of 192 beam laser in NIF,US

Pin point. All 192 beams must shine into the ends of this gold cylinder, which encloses the target.

By 1980, multibeams, multiterawatts 1um laser facilities built for ICF research

Shiva – 20 beams, 10 kJ, 20 TW
(LLNL 1977)

OMEGA – 24 beams, 4 kJ, 15 TW
(LLE 1980)

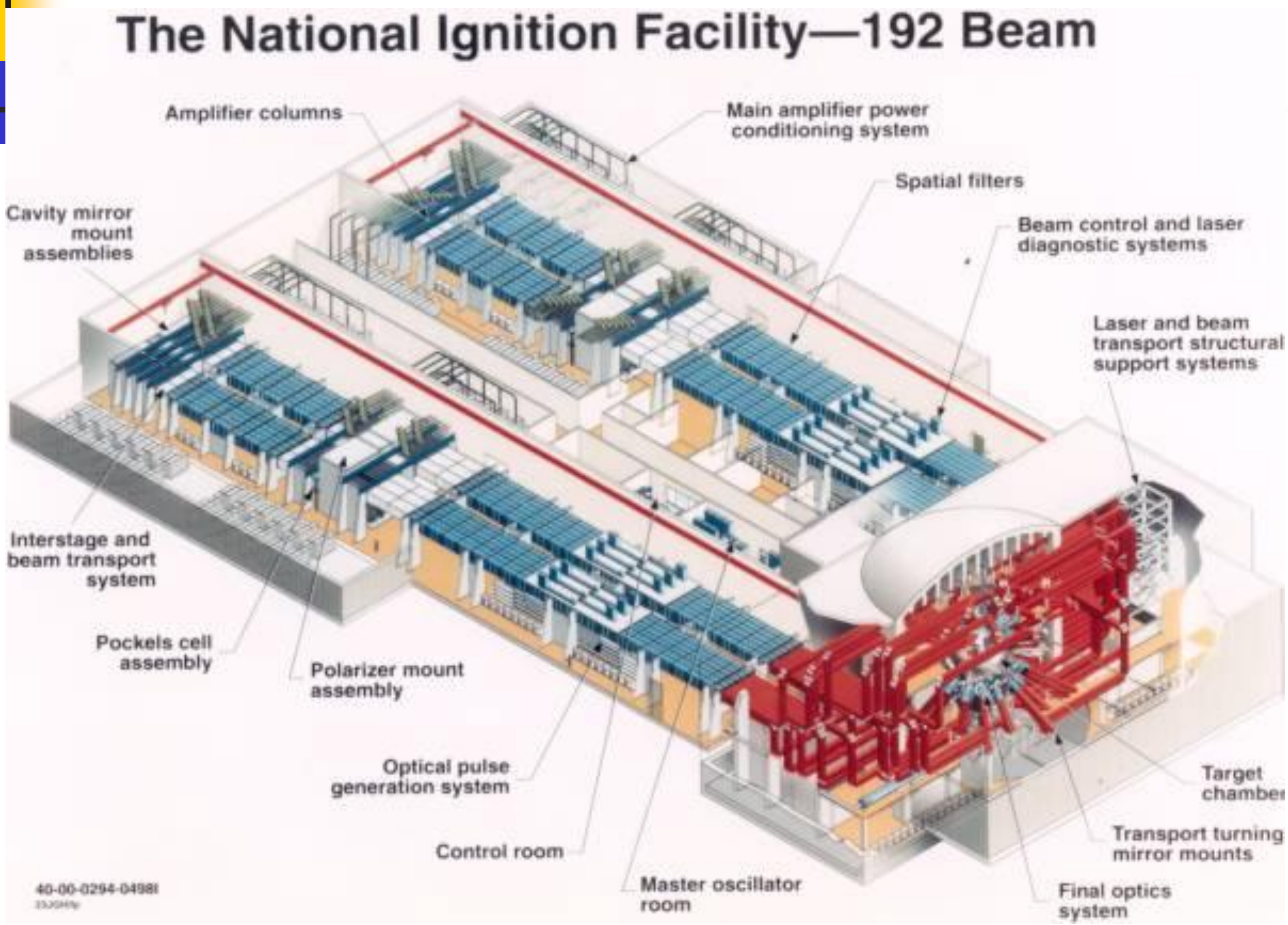
Nova facility in LLNL built with Nd:phosphate laser glass

- Nova laser at LLNL – 10 beams, ~30 kJ_{UV} (1986–1999)

OMEGA EP finished in 2008 with 60 laser beams

OMEGA EP: Completed 2008,
first user experiments in Q1 FY09

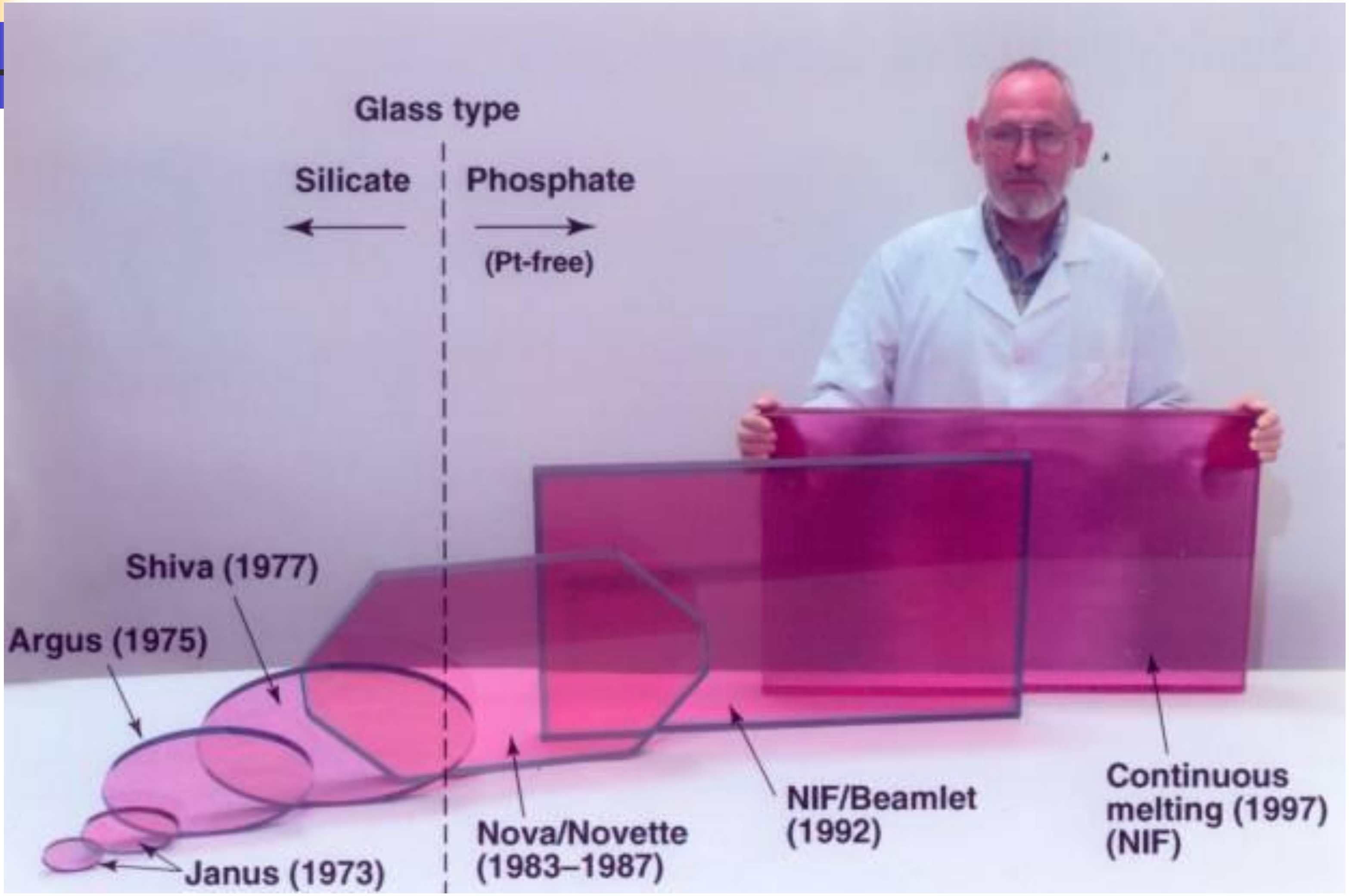
NIF facility in LLNL finished in last March



ICF facilities bulit with Nd:laser glass

Finished	Facility	Glass used	Beams	Nd:glass volume
	Omega-EP in US	LHG-8,	60	15L
	NIF in US	LHG-8,LG-770	192	15L
	Shen Guang II in China	N21,N31	8+1	3-7L
	Shen Guang III proto-type	N31	8	7.6L
	Firex in Japan	LHG-8	24	15L
Under building	Shen Guang III	N31	48	15L
	L M J in France	LHG-8,LG-770	240?	15L

The development of Nd:glass



The main requirements on Nd:glass in high peak power laser facility

- High stimulated emission cross section and long fluorescent lifetime----high gain
- Efficient stored energy
- High energy extraction efficiency
- High laser damege threshold,lower Pt inclusions,
- Small nonlinear refractive index;
- Excellent optical homogenity (2x10^{-6}) and small wavefront distortion.

FOM for high peak power Nd:glass

$$FOM_{laser} = \frac{\Delta\lambda_{abs}(\tau_0 Q)\sigma_{em}\eta_{ex}}{n_2}$$

Relation between absorption peak and line strength

Relation between integrated absorption cross section and $S_{JJ'}$ according to J-O theory

$$\int k d\lambda = \frac{8\pi^3 e^2 \lambda N_0}{3nch(2J+1)} \times \frac{(n^2+2)^2}{9} \times S_{JJ'}$$

Line strength calculation

$$S_{JJ'} = \sum_{t=2,4,6} \Omega_t \left| \left\langle 4f^N (SL) J \left\| U^{(\lambda)} \right\| 4f^N (S'L') J' \right\rangle \right|^2$$

Ω_t is determined by glass composition , line strength $S_{JJ'}$ can be calculated from measured absorption spectrum, density and refractive index of glass

Spontaneous emission probability

Spontaneous emission probability from manifold | (S',L')J'> to manifold | (S,L)J>

$$A_{J'J} = \frac{64\pi^2 e^2 n}{3h(2J'+1)\lambda^3} \times \frac{(n^2+2)}{9} \times S_{JJ'}$$

Effective fluorescent bandwidth

$$\Delta \lambda_{eff} = \int \frac{I(\lambda)\, d\lambda}{I(\lambda_p)}$$

The stimulated emission cross section

- It is most important parameter of laser material. Its peak value can be calculated from the following formula for Nd^{3+}:

$$\sigma = \frac{\lambda^4}{8\pi c h^3} \times \frac{A_{JJ'}}{\Delta \lambda_{eff}}$$

A simplified method to calculate stimulated emission cross section

- Stokowski proposed a simpified method
- $\boldsymbol{\sigma = 18.9\ [(n^2+2)^2/9n]\ S_{750}/\Delta\lambda_{eff}}$

Fluorescent lifetime

Measured fluorescent lifetime:

$$\tau = 1 / (A_{rad} + W_{nr})$$

Relation between fluorescent lifetime and Nd^{3+} ion concentration

$$\tau = \tau_0 / (1 + (N/Q)^2)$$

Quantum efficiency

$$\eta = \frac{A_{rad}}{A_{rad} + W_{nr}} = A_{rad} \cdot \tau$$

Radiative and non-radiative transitions

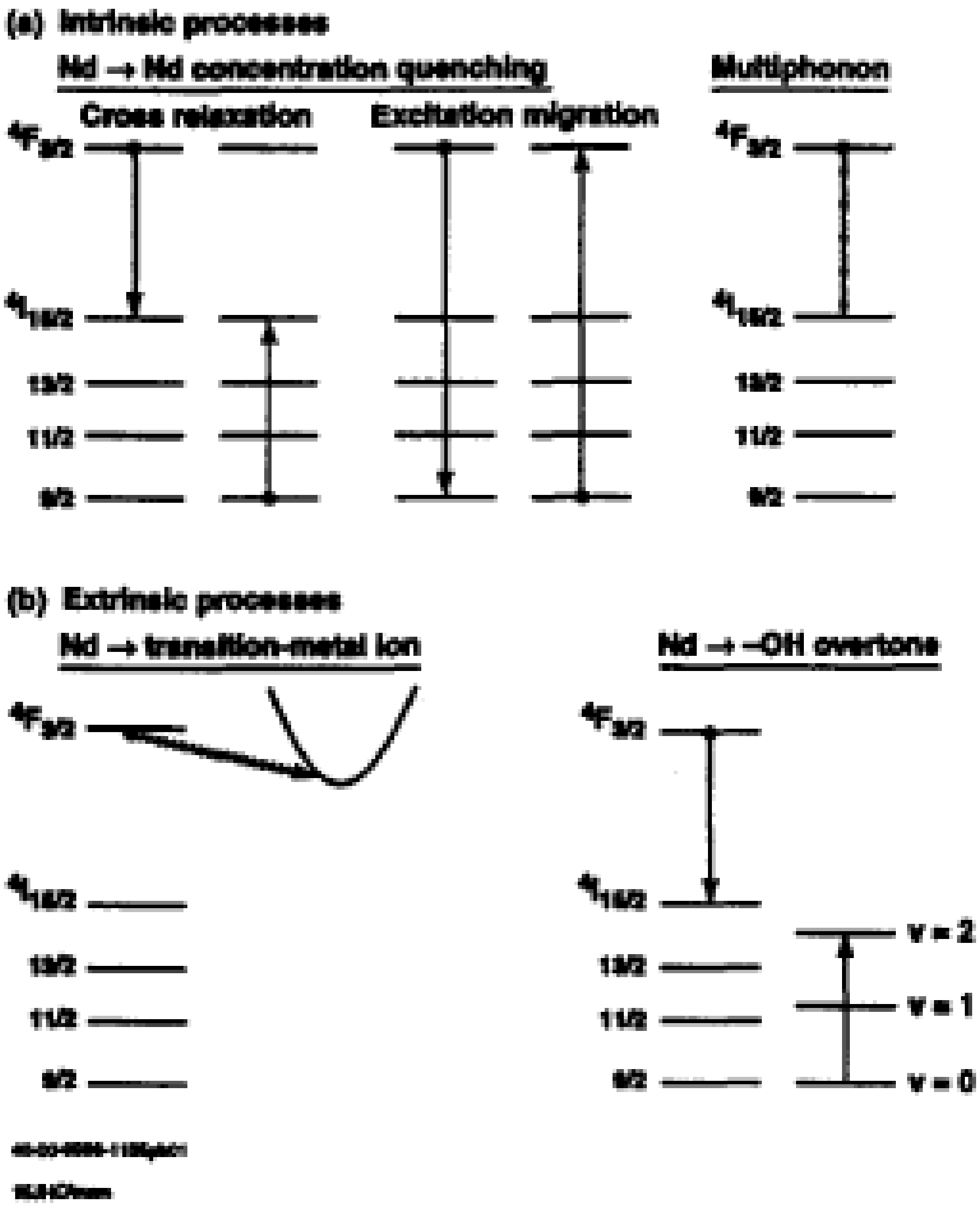
- Transition from high energy level to low energy level includes radiative and non-radiative transitions.
- Fluorescence occurs in the former, while heat effect is accompanied in the non-radiative transitions.

Non-radiative transition

- There are three main factors which affect non-radiative transition:
  - Rare earth ion interaction;
  - The interaction between rare earth ion and impurities (such as OH, transition metal ions, other rare earth ions);
  - The phonon energy of matrix.

Total nonradiative decay rate

$$W_{nr} = W_{mp} + W_{Nd} + W_{OH} + \sum_{i=1}^{n} W_{TM_i} + \sum_{j=1}^{m} W_{RE_j}$$



Nonradiative transitions of Nd^{3+} ion

Stored energy of Nd:glass

$$E_g = h\nu N$$

N is inversion density of Nd-ion.

Eg is usually 0.25J/cm^3.

Saturated fluence of Nd:glass

$$F_{sat} = h\nu_l / \sigma$$

It is usually 5J/cm^2.

Energy extraction efficiency

$$\eta_{ex} = \sigma_{em} / \sigma_{gs}$$

σgs is corss section calculated from measured gain saturation , σem is spectroscopically determined cross section.

α

Small signal gain

$$G_0 = \exp(z[\sigma N - \alpha])$$

Alpha is transmission loss coefficient,

Z is length of gain medium.

Nonlinear refractive index and B factor

Cumulative nonlinear phase retardation: B factor

$$B = \frac{2\pi}{\lambda} \int \gamma I dZ$$

Nonlinear refractive index r:

$$\gamma = \frac{40 \pi n_2}{nc}$$

Nonlinear refractive index n_2 in 10^{-13}esu ：

$$n_2 = \frac{68 (n_d^2 + 2)^2 (n_d - 1)}{\upsilon \left\{1.517 + \left[\upsilon (n_d^2 + 2)(n_d + 1)\right] / 6 n_d\right\}^{1/2}}$$

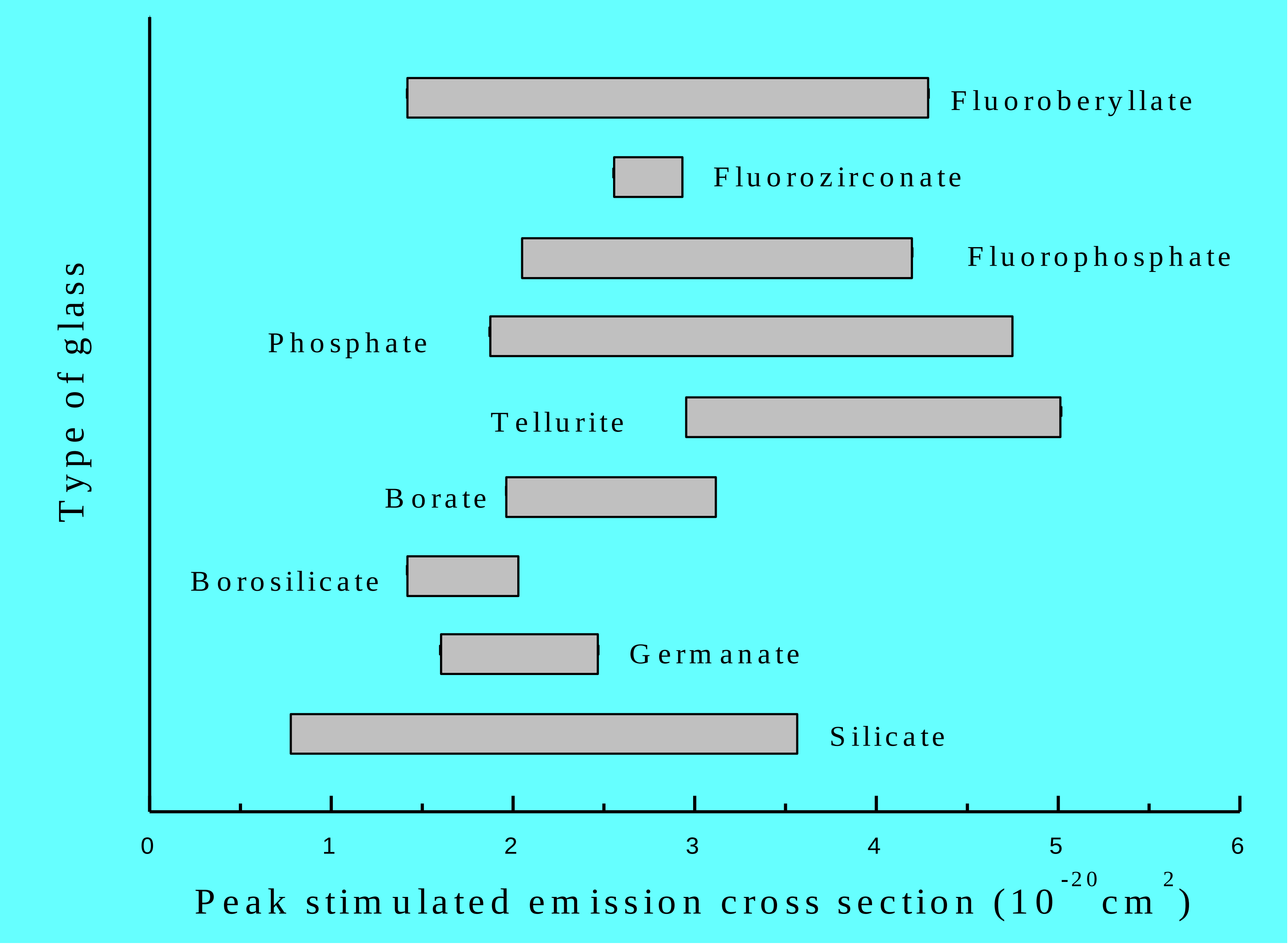
Thermal optical property

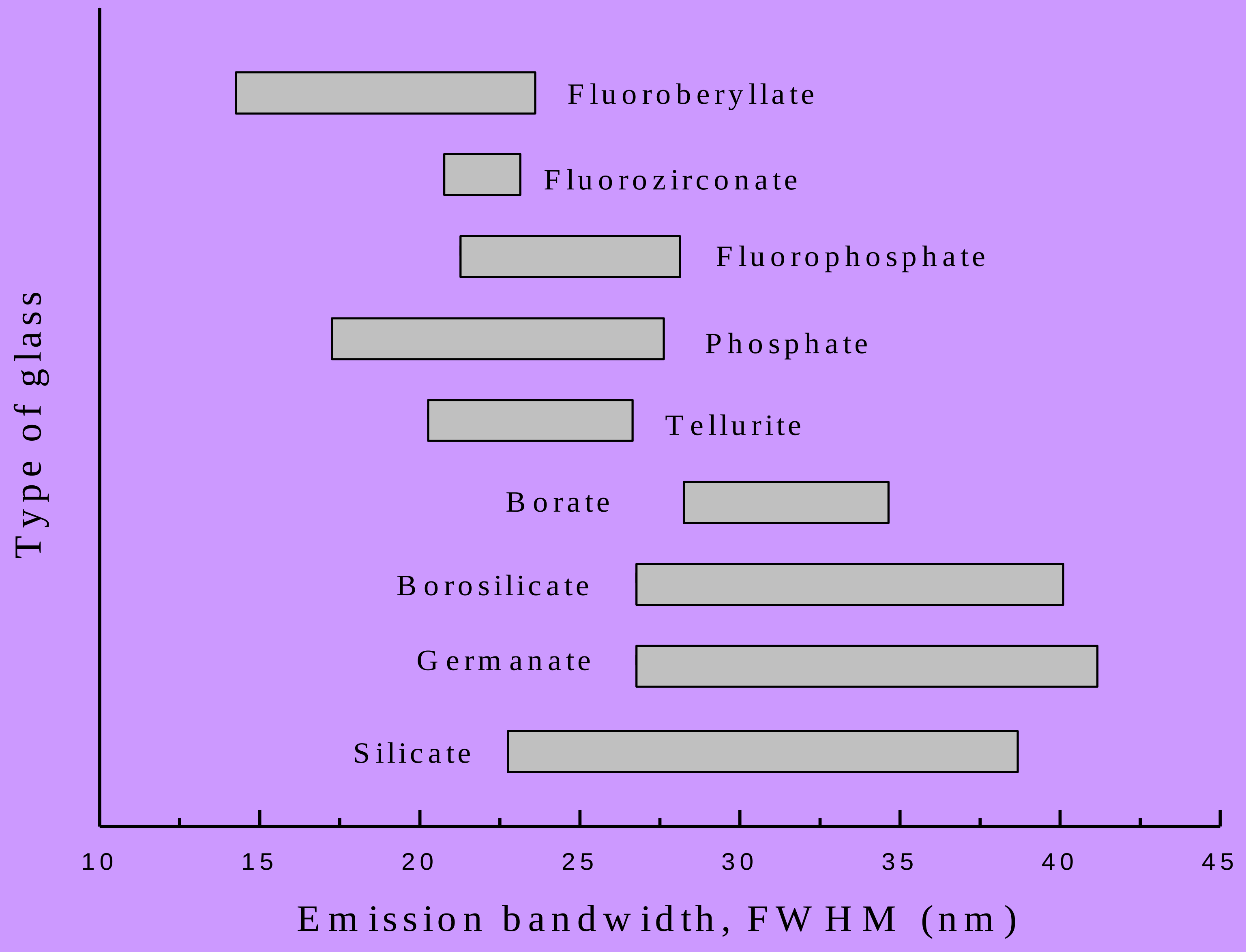
$$W = \frac{dn}{dT} + (n-1)\alpha$$

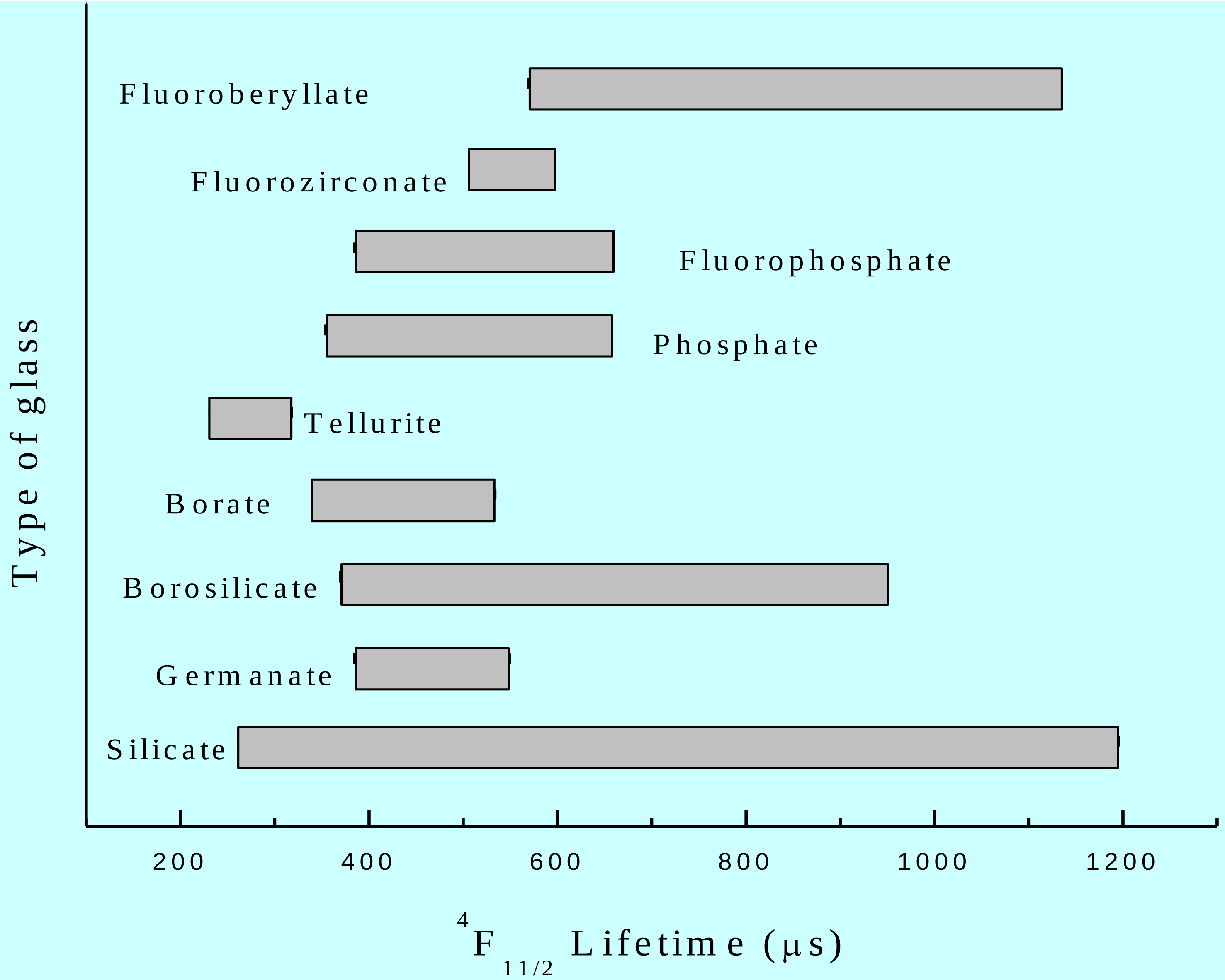
Relation between glass composition and laser properties for Nd doping

Composition research

- Most of composition research was done in the early period of laser glass research.
- Commercial laser glasses are meta-phosphate glass with P:O=1:3.


Fluoroberyllate
Fluorozirconate
Fluorophosphate
Phosphate
Tellurite
Borate
Borosilicate
Germanate
Silicate
Type of glass
0
1
2
3
4
5
6
Peak stimulated emission cross section (10^{-20} cm^2)


Fluoroberyllate
Fluorozirconate
Fluorophosphate
Phosphate
Tellurite
Borate
Borosilicate
Germanate
Silicate
Type of glass
10
15
20
25
30
35
40
45
Emission bandwidth, FWHM (nm)


Fluoroberyllate
Fluorozirconate
Fluorophosphate
Phosphate
Tellurite
Borate
Borosilicate
Germanate
Silicate
Type of glass
200
400
600
800
1000
1200
$^4F_{11/2}$ Lifetime (μs)

Nd:glass for high power laser application

- LHG-8 from Hoya ;
- LG-750,LG-760,LG-770 from Schott;
- Q88 from Kigre in US;
- N21 and N31 glasses from SIOM, China .

Companies and Institute who develop high power laser glasses

- Hoya company, Japan;
- Schott company, Germany;
- Kigre Company in USA;
- SIOM in China

Table I: Properties of commercially available HPP glasses in common use on ICF lasers.

Glass Manufacturer		Hoya		Schott		Kigre
Glass Properties	Symbol	LHG-80	LHG-8	LG-770	LG-750	Q88
Optical						
refractive index						
@ 587.3 nm	n_d	1.54291	1.52962	1.50674	1.526	1.5449
@ 1053 nm	n_L	1.53289	1.52005	1.49908	1.516	1.5363
non-linear refractive index						
(10^{-13} esu)	n_2	1.24	1.12	1.02	1.08	1.14
(10^{-20} m^2/W)	γ	3.36	3.08	2.78	2.98	3.11
Abbe number	ν	64.7	66.5	68.5	68.2	64.8
Temp-coeff. refract. index ($10^{-6}/K$)	dn/dT	-3.8	-5.3	-4.7	-5.1	-0.5
Temp-coeff. optical path ($10^{-6}/K$)	δ	1.8	0.6	1.2	0.8	2.7
Laser[a]						
emission cross-section($10^{-20}cm^2$)	σ_{em}	4.2	3.6	3.9	3.7	4.0
saturation fluence (J/cm^2)	F_{sat}	4.5	5.3	4.8	5.1	4.7
radiative lifetime (zero-Nd) (µs)	τ_o	337	365	372	383	326
Judd-Ofelt radiative lifetime (µs)	τ_r	327	351	350	367	326
Judd-Ofelt parameters ($10^{-20}cm^2$)	Ω_2	-	4.4	4.3	4.6	3.3
	Ω_4	-	5.1	5.0	4.8	5.1
	Ω_6	-	5.6	5.6	5.6	5.6
emission band width (nm)	$\Delta\lambda_{eff}$	23.9	26.5	25.4	25.3	21.9
conc. quenching factor (cm^{-3})[c]	Q	10.1	8.4	8.8	7.4	6.6
fluorescence peak (nm)	λ_L	1054	1054	1053	1053.5	1054
Thermal						
thermal conduct., (W/mK)	k	0.59	0.58	0.57	0.60	0.84
thermal diffusivity(10^{-7} m^2/s)	α	3.2	2.7	2.9	2.9	-
specific heat, (J/gK)	C_p	0.63	0.75	0.77	0.72	0.81
Coeff. thermal expan.*($10^{-7}/K$)	α_e	130	127	135	132	104
Glass transition temp (°C)	T_g	402	485	460	450	367
Mechanical						
density (g/cm^3)	ρ	2.92	2.83	2.59	2.83	2.71
Poisson's ratio	μ	0.27	0.26	0.25	0.26	0.24
Fracture toughness (MPa $m^{0.5}$)	K_{IC}	0.46	0.51	0.48	0.48	-
Hardness (GPa)	H	3.35	3.43	3.58	2.85	-
Young's modulus (GPa)	E	50.0	50.1	47.3	50.1	69.8
Stress optic coeff.(Pa)	ΔB	1.77	1.93	2.2	1.80	2.07

Properties of Nd:phosphate glass from SIOM

Properties	N21	N31
Laser properties		
Nd_2O_3(wt%)	**2.2**	**2.2**
Nd^{3+} ion conc.(10^{20}ions/cm^3)	**2.68**	**2.26**
σ_{em}($10^{-20}cm^2$)	**3.4**	**3.8**
Fluorescent lifetime(μs)	**330**	**340±10**
FWHM(nm)	**24.0**	**20.1**
Laser wavelength(nm)	**1053**	**1053**
Optical properties		
n_d	**1.5758**	**1.5357**
n_L	**1.5652**	**1.5280**
n_2(10^{-13}esu)	**1.3±0.1**	**1.1±0.1**
Abbe No.	**65.2**	**66.2**
dn/dT(10^{-6}/°C)(20-100°C)	**-4.2**	**-4.3**
ds/dT(10^{-6}/°C)(20-100°C)	**1.9**	**1.4**
Physical properties		
density(g/cm^3)	**3.40**	**2.83**
E(kg/mm^2)	**5640**	**5270**
v	**0.27**	**0.27**
Knoop hardness(kg/cm^2)	**650**	**330**

Properties of N21 and N31 glasses from SIOM (continued)

Properties	N21	N31
Thermal properties		
T_g(°C)	500	450
α(10^{-6}/°C)(20-100°C)	110	107
α(10^{-6}/°C)(100-300°C)	120	127
K(W/m.K)	0.553	0.558
C_p(25°C) (J/cm^3.°C)	0.75	0.75
Chemical durability		
D_w(H_2O,100°C,1hr,wt loss%)	0.06	0.09
D_A(HNO_3,pH2.2,100°C,1hr Wt. Loss%)	0.30	0.40

3 Fabrication technology of Nd:phosphate laser glass

- Fabrication technology is very important to laser glass because many properties of Nd:glass is concerning with fabrication processing
- By now there are two melting technologies of Nd:phosphate laser glass
  - ✓Pot melting
  - ✓Continuous melting

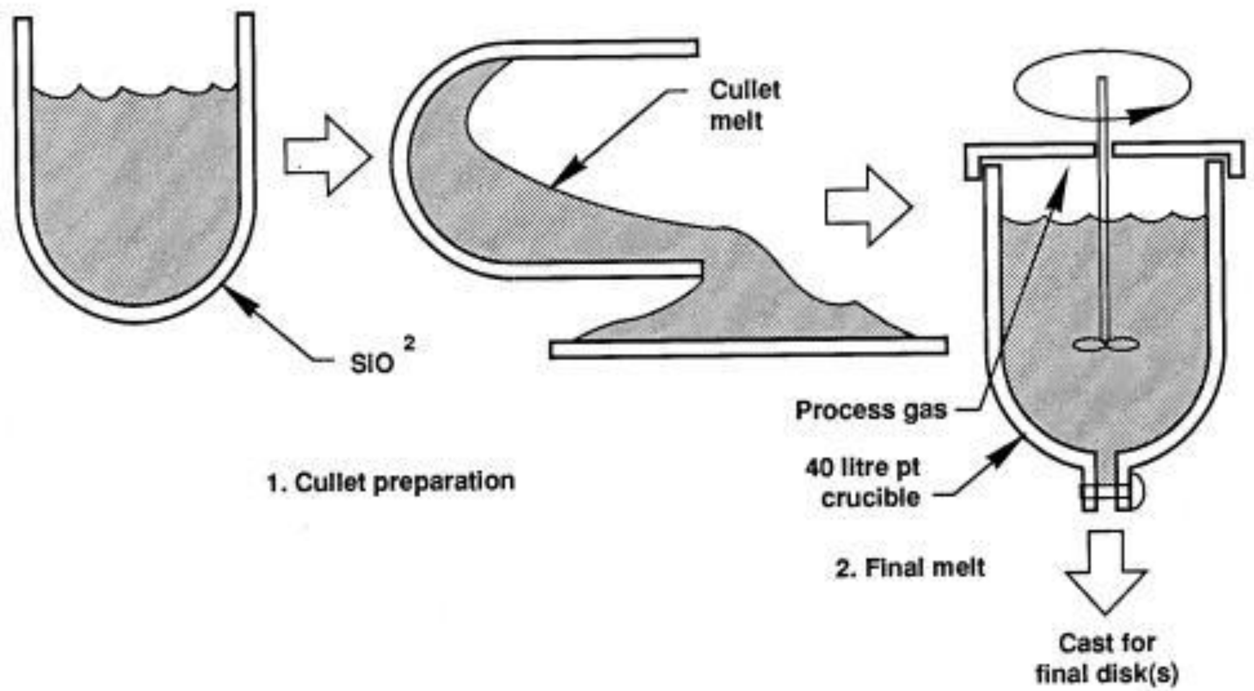
Properties concerning to fabrication processing

- Fluorescent lifetime ;
- Optical loss at laser wavelength;
- Optical quality ;
- Bubbles;
- Platinum inclusions;
- Absorption at 400nm;
- Residual stress

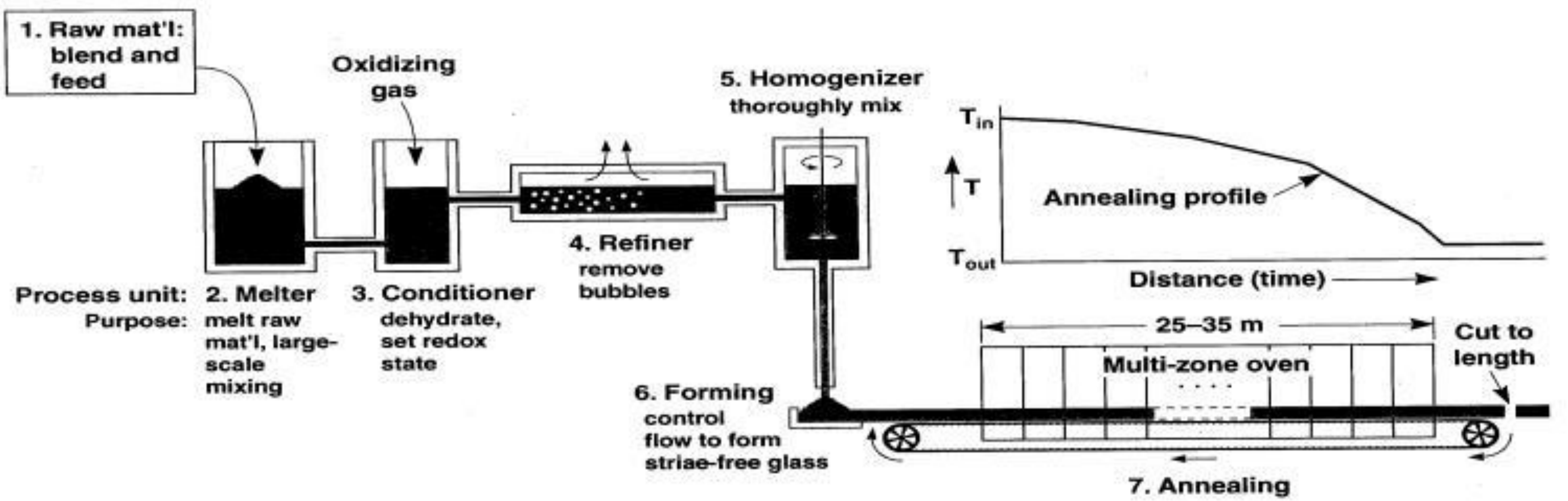
Advantages of continuous melting

- Lower cost of laser glass;
- High efficiency of production;
- Less change of properties among different glass slabs;
- Better optical homogenity;
- Less micro-crack on glass surface after annealing.

Pot melting process of laser glass



Continuous melting process of laser glass



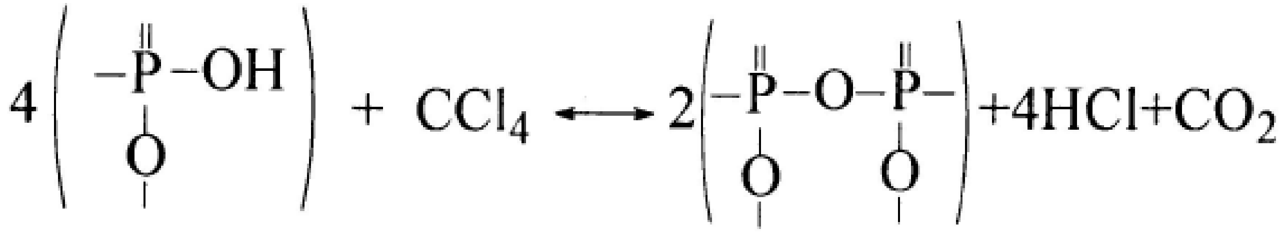
Nd:glass from continuous melting in Hoya

Key technologies of Nd:phosphate glass fabrication

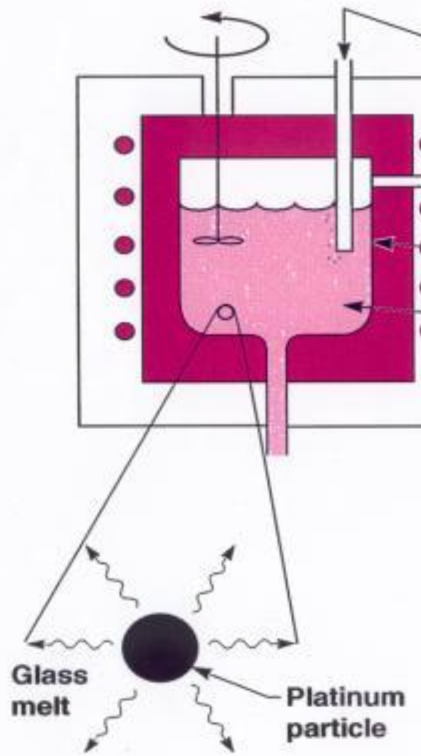
- Dehydroxylation;
- Elimination of Pt inclusions
- Forming
- Cladding with Cu ion doped phosphate glass.

Mechanism of dehydroxylation

$$CCl_4 + 2H_2O \leftrightarrow CO_2 + 4HCl$$



Mechanism of eliminating Pt inclusions



- Dissolve inclusions under oxidizing conditions ($Pt + n/4\ O^2 \rightleftharpoons Pt^{n+} + n/2\ O^{2-}$)
- Minimize thermal gradients to reduce vapor transport $Pt^o + O_2 \rightleftharpoons PtO_2$ (g)

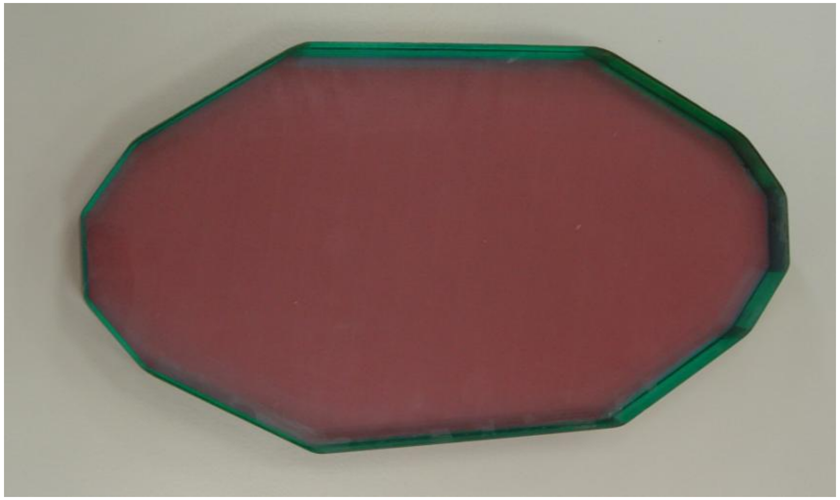
Forming

- Forming is very important for both pot melting and continuous melting.
- It affects the optical homogenity especially in forming large size glass.

Cladding of laser glass

- Cladding is an effective method to remove amplified spontaneous emission and get high gain in Nd:glass.
- Residual reflection in cladding surface less than 0.1% is required.

Nd:phosphate glass disk after cladding



4 High power fiber laser

- Yb:silica is a widely used high power fiber laser material because of its high quantum efficiency.
- Up to now several thousands watt power has been achieved in a single Yb:silica fiber.

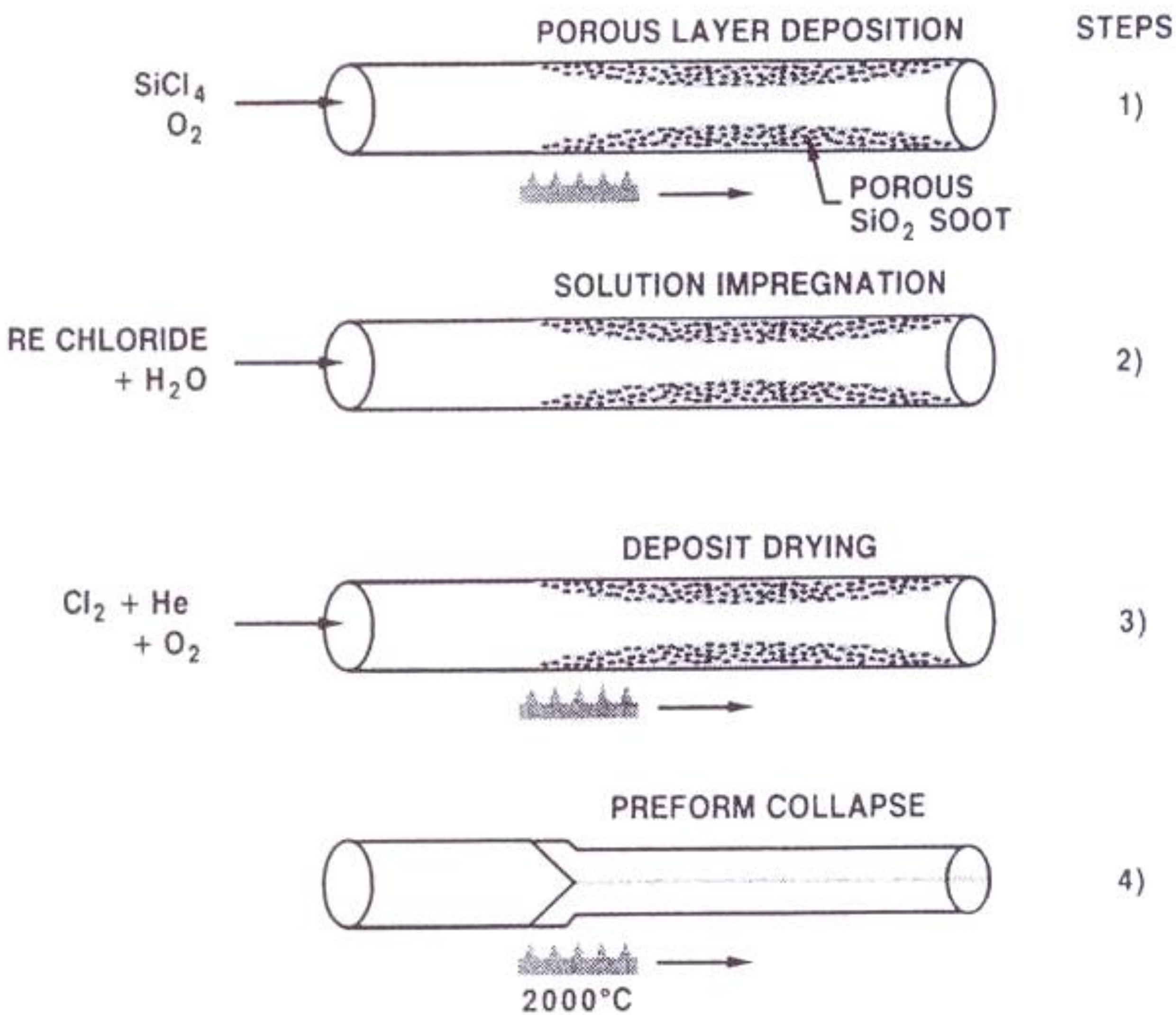
Advantage of silica fiber matrix

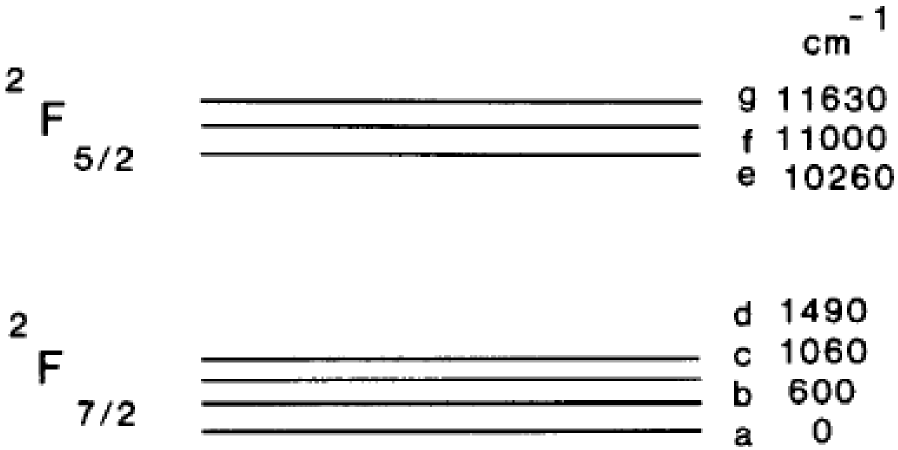
- Its extreme low loss is the main advantage of silica fiber.
- Good thermal property and mechanical strength of silica.

Fabrication of Yb:silica fiber

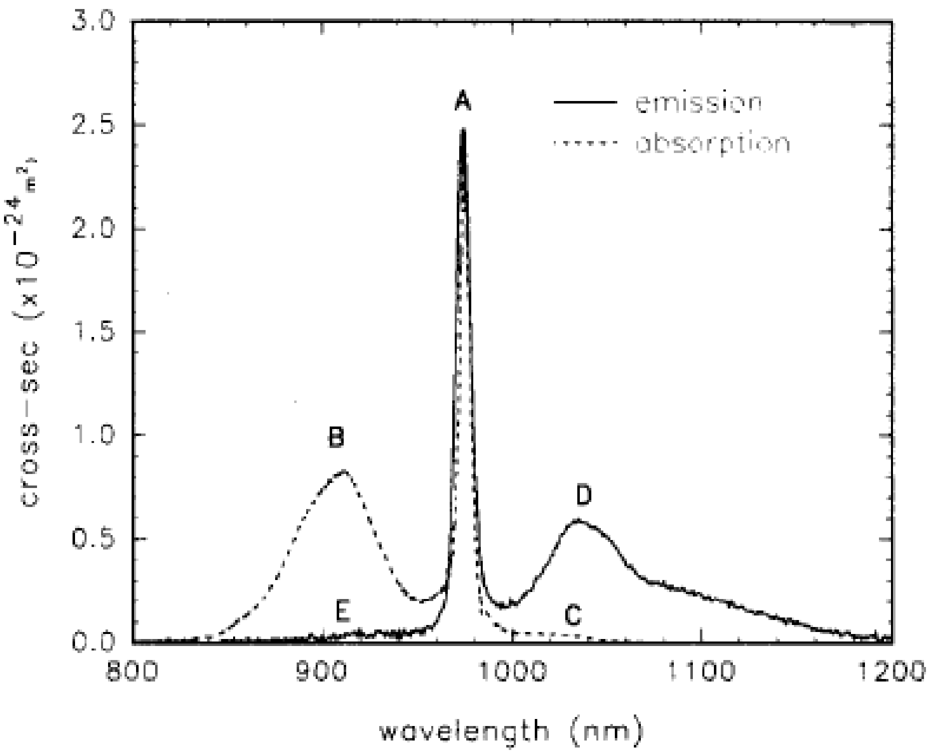
- MCVD and solution doping method are used to prepare Yb doped silica preform and then fiber is drawn from the preform.

Rare Earth Doped Fiber Fabrication





(a)

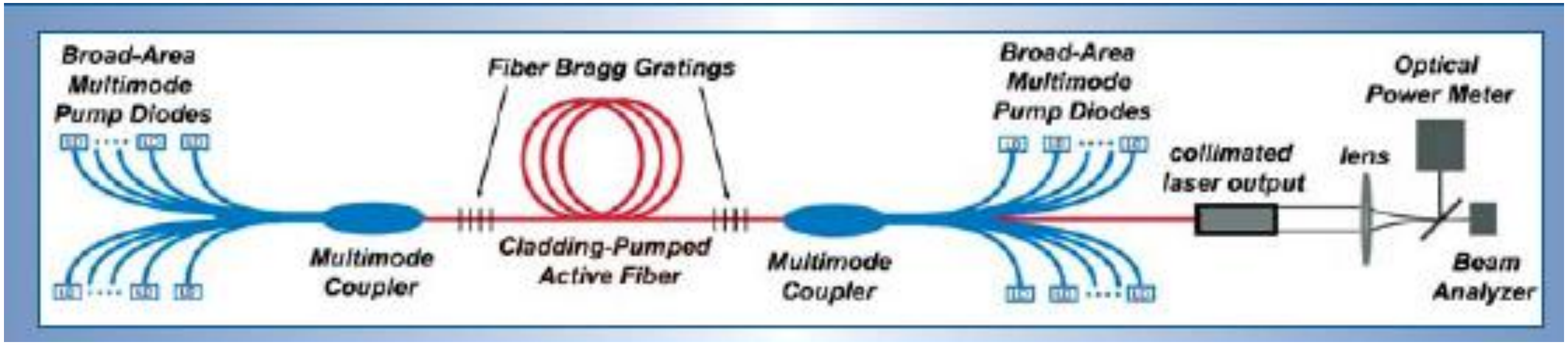


(b)

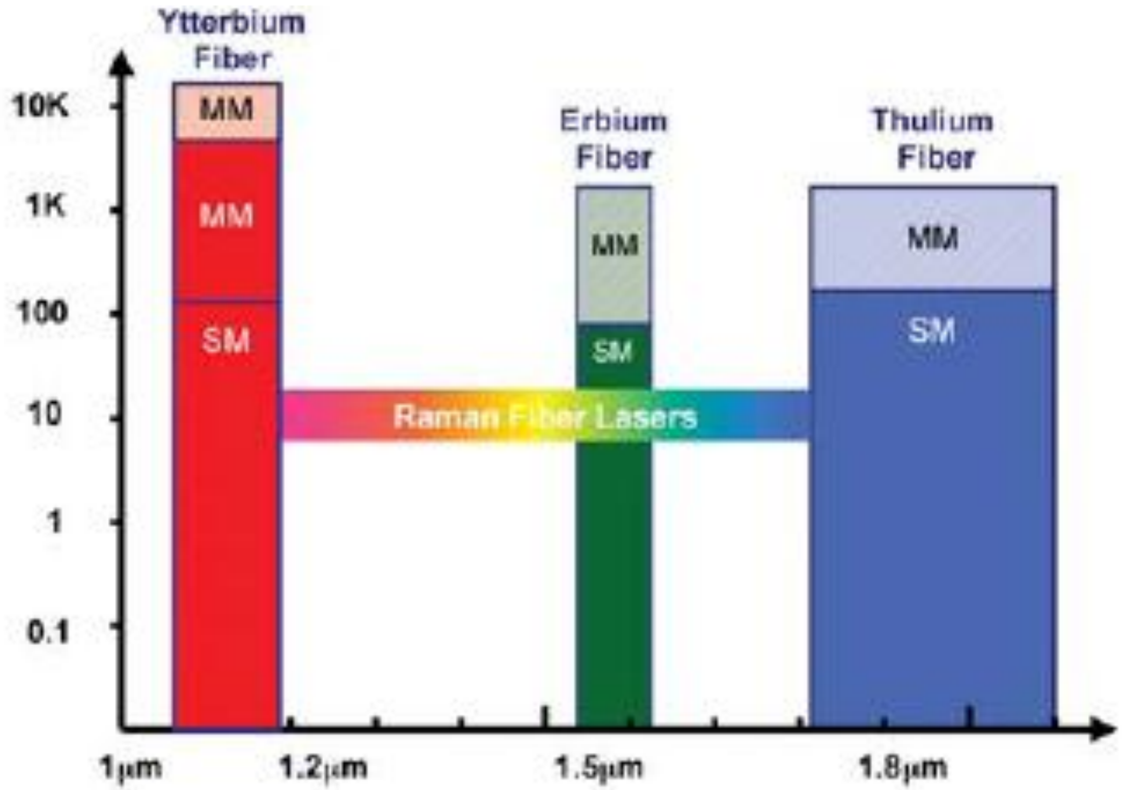
(a) Energy diagram of Yb^{3+} in silica

(b) Absorption and emission cross section of Yb^{3+} in silica

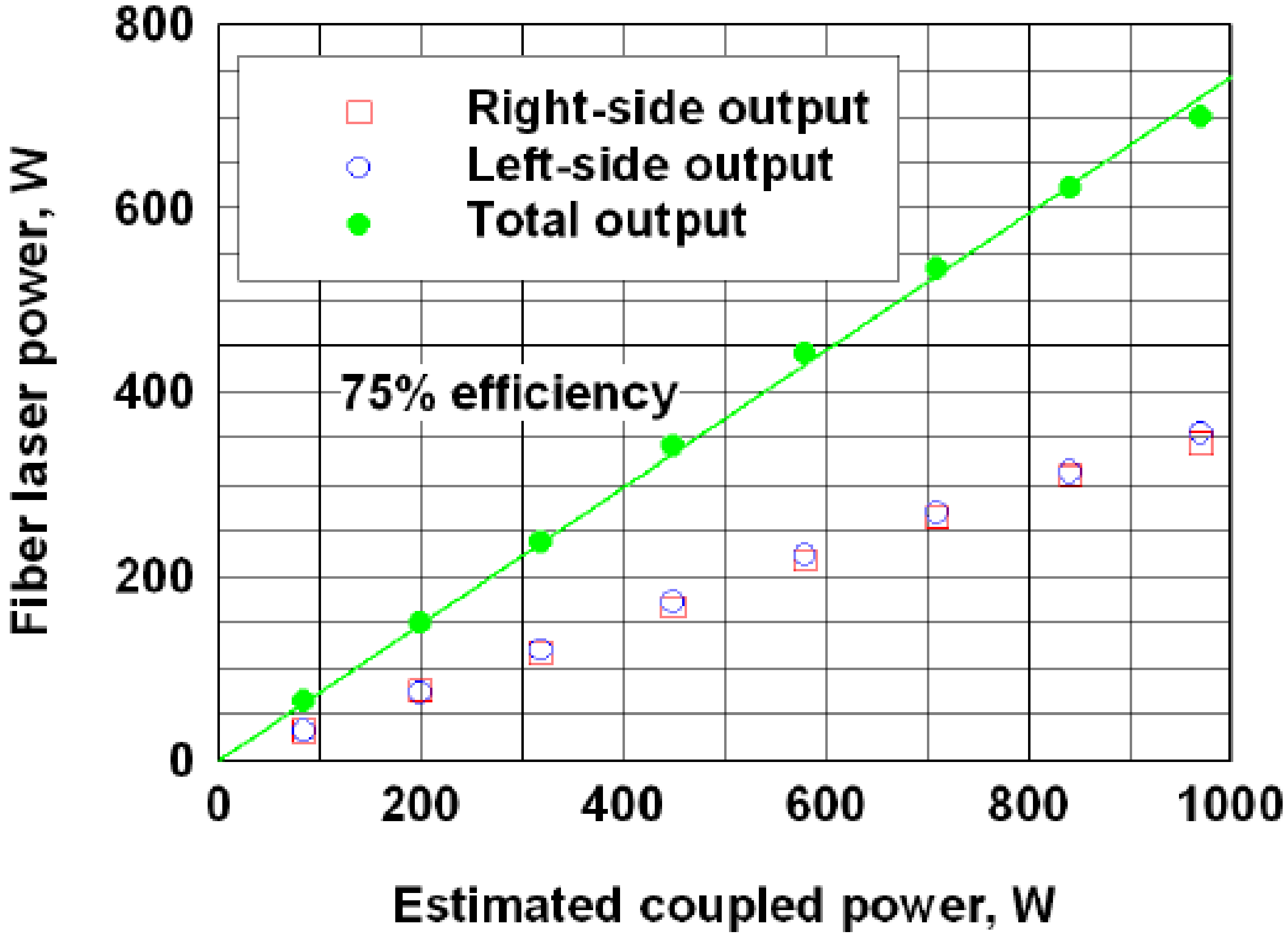
Structure of fiber laser



Spectra and output power of fiber lasers by 2004



Output and input relation of a single mode Yb:silica fiber in 2003



5 Outlook on next generation high power laser material

- Laser Fusion Energy (LFE) research project aimed on laser power plant is proposed by US and European scientists in recent years.

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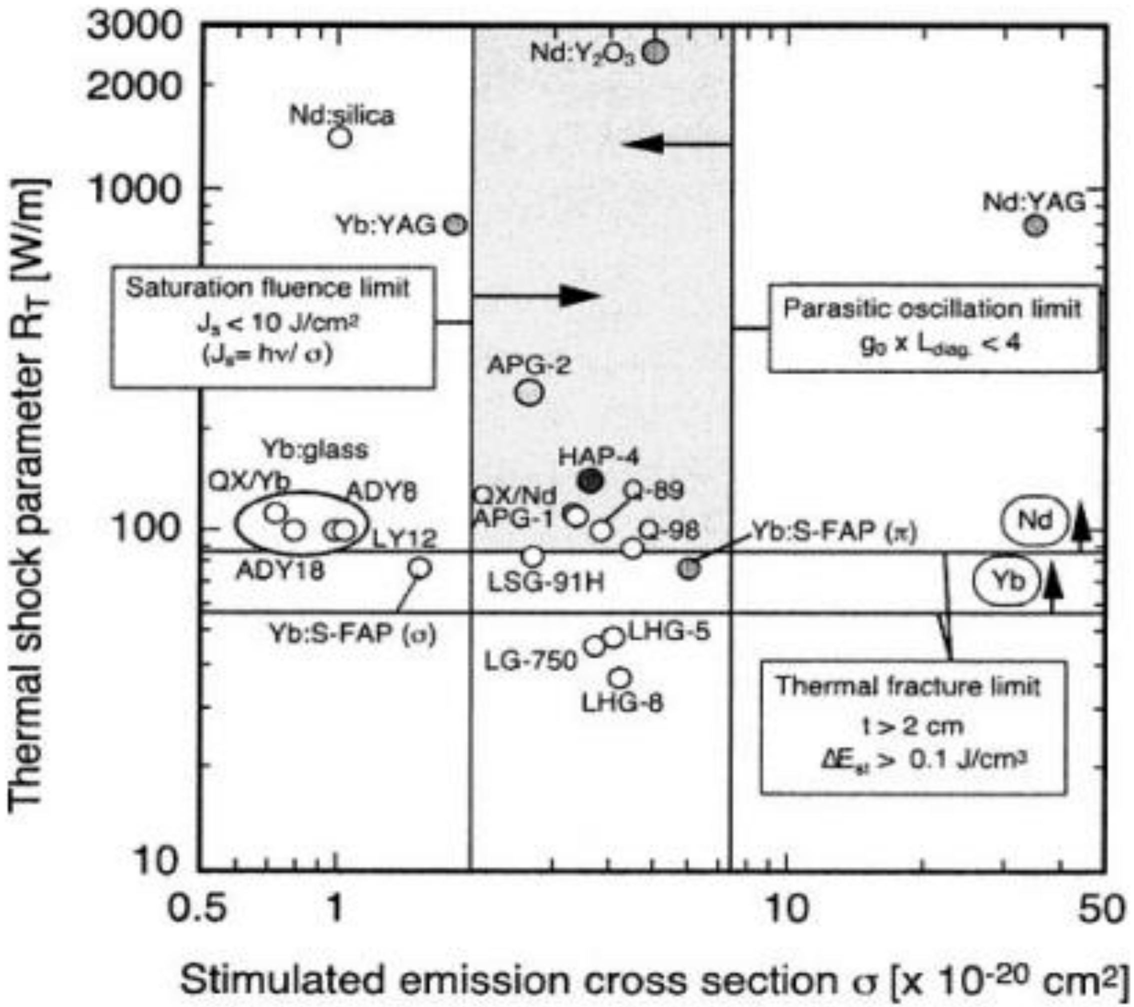
LFE requirements on laser material

- Work in several Hz repetition rate (up to 10Hz),
- High efficiency, 20-30%;
- Good thermal properties;
- Can be produced in large size.

Possible next generation laser material for LFE

- Laser ceramics?
- Nd^{3+} or Yb^{3+} doped SiO_2 bulk?
- Multi-component glass?
- Special optical fiber?
- Yb^{3+} doping?

Relation between thermal shock parameter and stimulated emission cross section



Thanks for your attention!

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