783.

A Highly Efficient Nd^{3+}-Doped Lead Silicate Glass Fibre Laser

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OUTLINE

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1. INTRODUCTION

WHY FIBRE LASERS?

- **Small modal volume gives high gain & low threshold**
- **Longitudinal geometry gives minimal thermal effects**
- **Strong mode selection**
- **Low cost (potentially)**

D.N. Payne, Proc. ACOFT'91, Sydney, Austrilia, pp. 201.

E. Snitzer, Proc. OFC'92, USA, pp. 417.

WHY LEAD SILICATE FIBRES?

Potential: high emission and absorption cross-sections, and long fluorescent lifetime

Egorova et al. Opt. Spectr. 23 (1967) 148.

Weber et al. J. Non-cryst. Solids 74 (1985) 167.

Problem in past bulk lasers:

Thermal effects (principally)

St. John et al. J. Opt. Soc. Amer. B9 (1992) 610.

Okay for fibre lasers:

No thermal effect yet to be observed in single-mode fibres

2. FABRICATION OF Nd^{3+}-DOPED LEAD SILICATE GLASSES AND FIBRES

GLASSES:

For the ease of fibre production:

Commercial Schott (flint) lead-silicate optical glasses are used

F7 (core) : F2 (clad)

Compositional system: SiO_2 - PbO - K_2O

Doping Nd_2O_3 powder into F7:

(1) High viscous state stirring

(2) shortening time for low viscous stir

Stirrer: silica rod

FIBRES: Rod-in-tube Method

Thermally and optically matched pair:

F7: N_D 1.625, Tg (Ts) 429°C (580°C), α 98×10^{-7} /K

F2: N_D 1.620, Tg (Ts) 432°C (593°C), α 82×10^{-7} /K

Conventional soft glass drawing tower

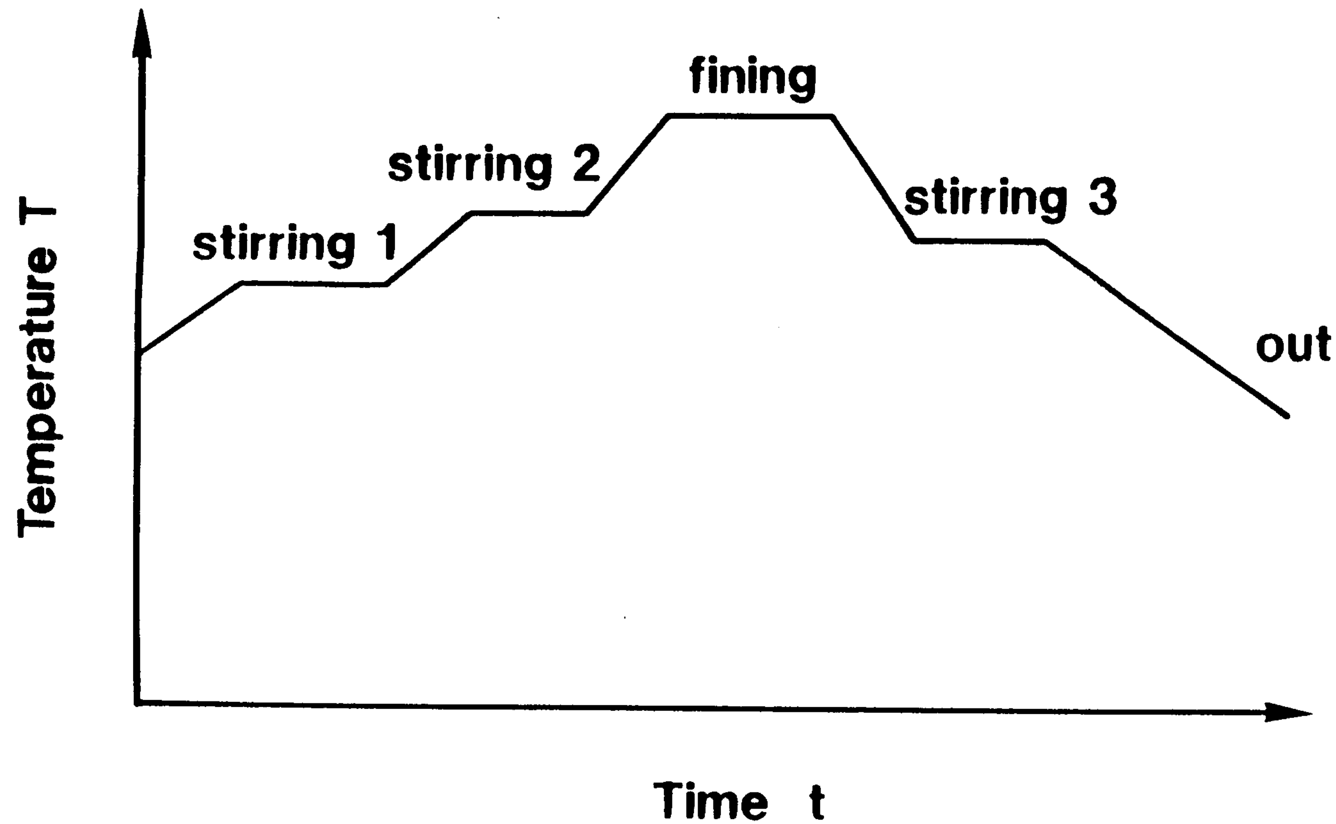
Hot zone: 20 x 20 mm (diameter and length)

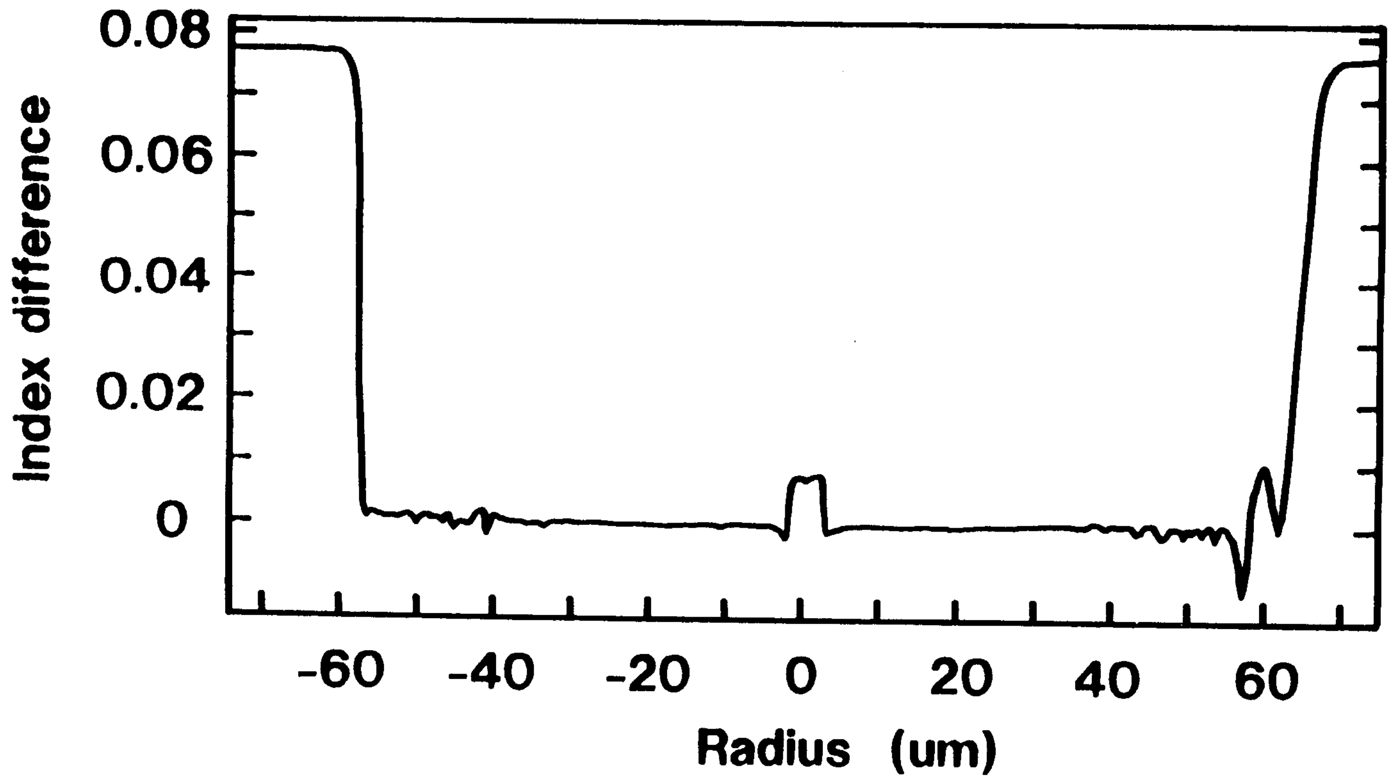
Fibre preform size: 10 x 700 mm

Pulling temp.: 700°C, Feed rate: 0.7 mm/min, pulling rate: 3m/min.

Typical size: Core 3-10 μm, clad 125 μm

Fibre length: 50 to 100 meters


fining
stirring 2
stirring 1
stirring 3
out
Temperature T
Time t


0.08
0.06
0.04
0.02
0
Index difference
-60
-40
-20
0
20
40
60
Radius (um)

3. SPECTROSCOPY

a. Absorption

Lightly doped fibres: conventional cut-back method

Heavily doped fibres: a proposed insertion technique

$$\alpha_{dB} = \frac{10}{L}\log_{10}\frac{P_2}{P_1}$$

Laser performance related parameters:

Background loss at the lasing wavelength:

1 to 1.5 dB/m

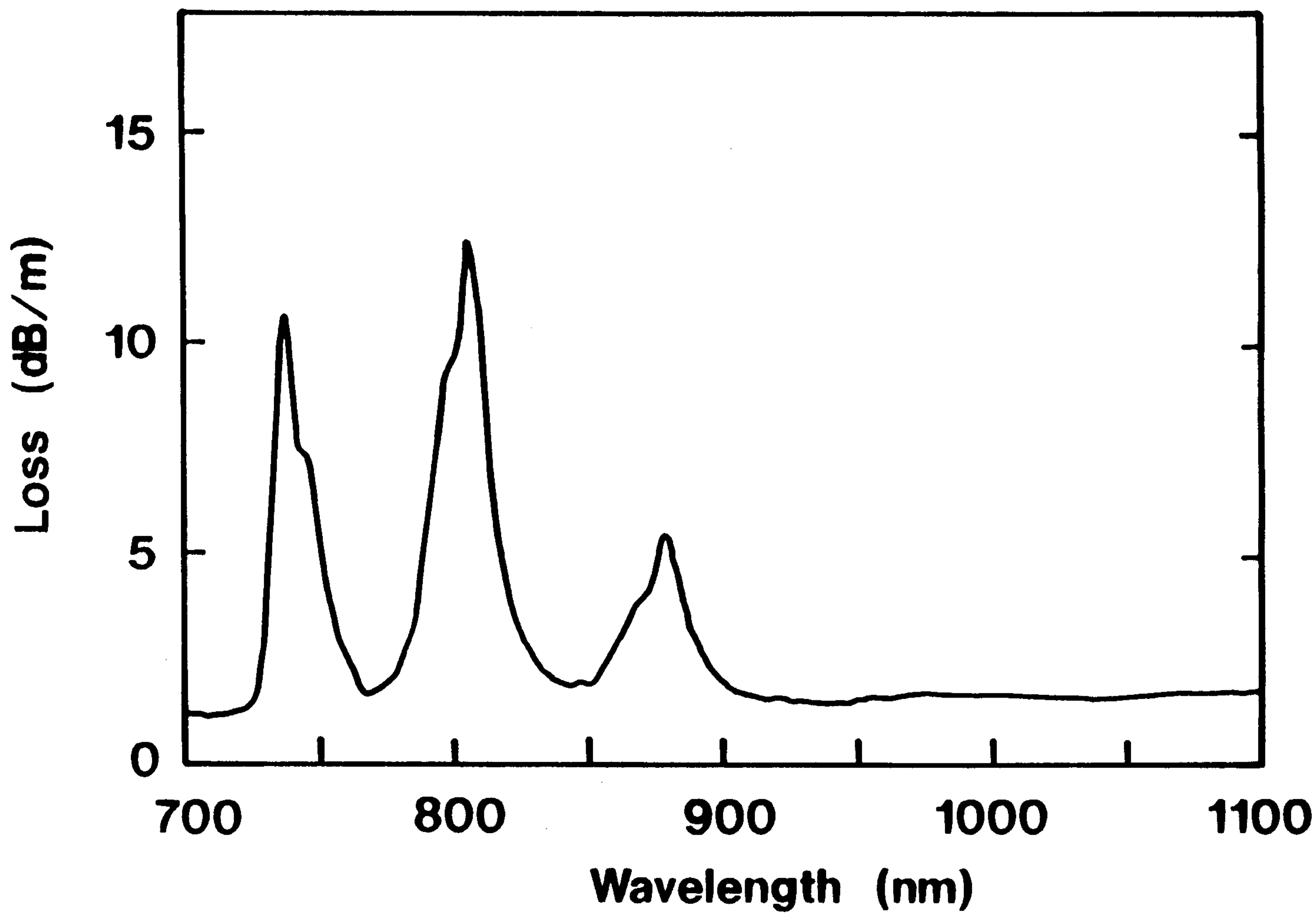
Absorption cross-section at the peak (807 nm) of the pump ($^4I_{9/2} \rightarrow$ $^4F_{5/2}$ transition) band:

$$\sigma_a = 4.3 \times 10^{-20}\ \mathrm{cm}^2$$

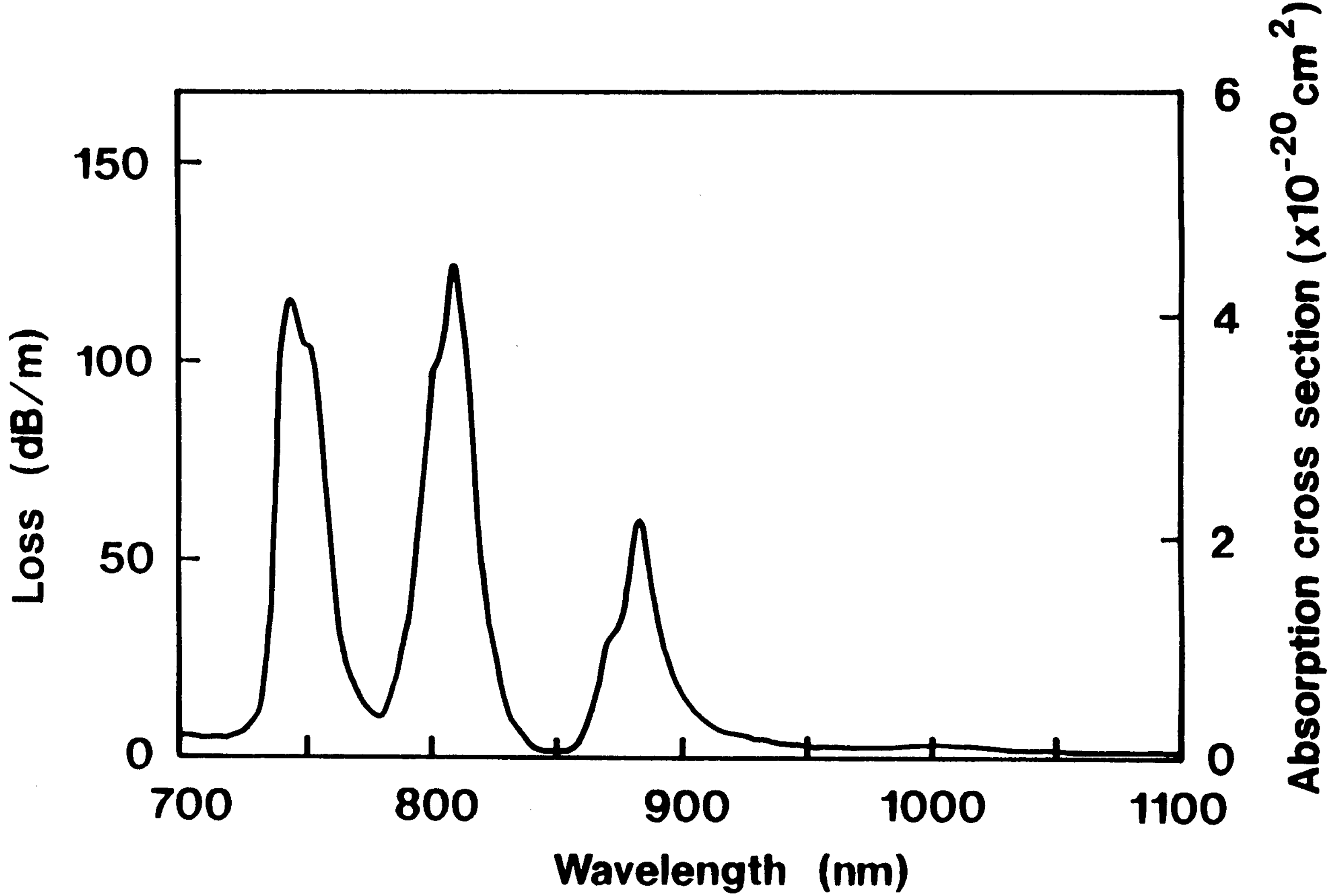
Pumping efficiency (p):

$$p = \frac{I_p \sigma_a}{h\nu_p}$$

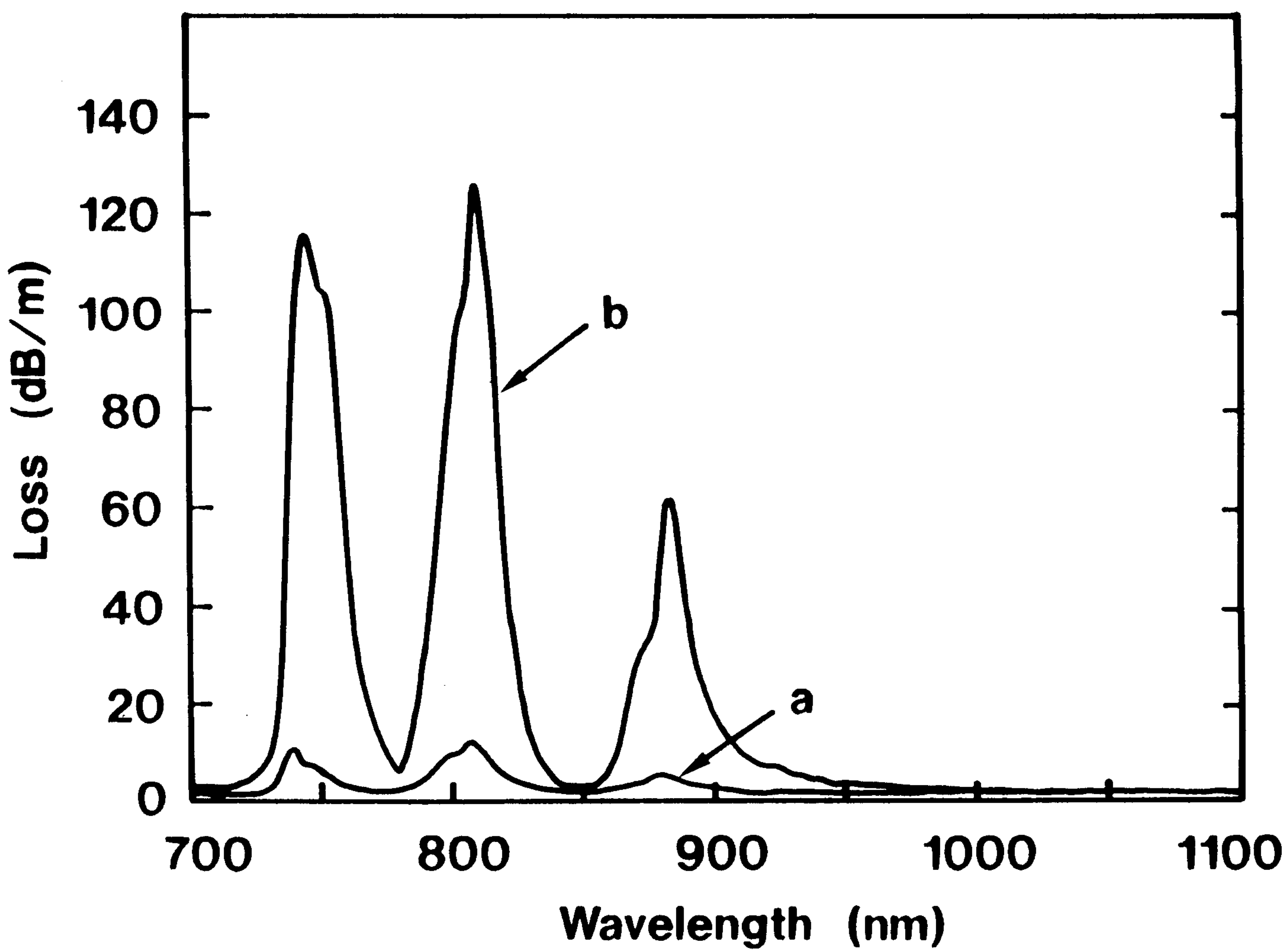
where I_p is the pump intensity and $h\nu_p$ is the pump photon.



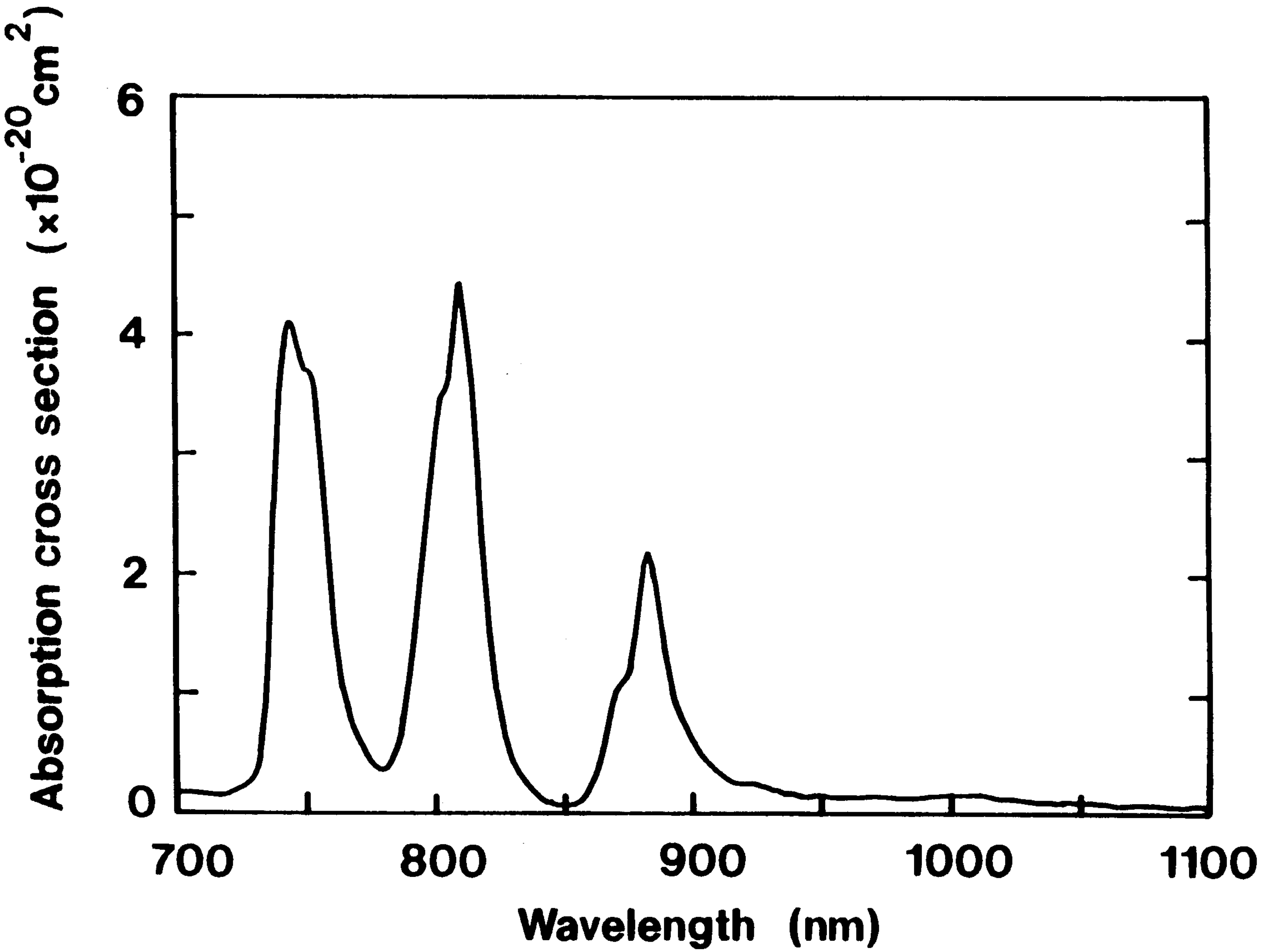
15
10
5
0
Loss (dB/m)
700
800
900
1000
1100
Wavelength (nm)



150
100
50
0
Loss (dB/m)
6
4
2
0
Absorption cross section (x10^-20 cm^2)
700
800
900
1000
1100
Wavelength (nm)



Loss (dB/m)
140
120
100
80
60
40
20
0
700
800
900
1000
1100
Wavelength (nm)
a
b



Absorption cross section (×10⁻²⁰cm²)
6
4
2
0
700
800
900
1000
1100
Wavelength (nm)

b. FLUORESCENCE

Nd^{3+} in lead silicate host shows narrower transition-Linewidth:

FWHW of 17 nm at 1.06 μm measured

for Nd_2O_3 concentration below 3 wt%

WHY ?

Cause 1. Strong covalent Pb-O bond induce a weak ligand field around the Rare-earth (i.e. small Stark-splitting)

Cause 2. High ionicity induced between Nd^{3+} and ligand O^{2-} by Pb^{2+} brings on a high degree of Nd^{3+} site regularity

Peak emission cross-section (σ_p) for Nd^{3+} 1.06 μm $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition:

$$\sigma_p = \frac{\lambda^4}{8\pi c n^2 \Delta\lambda_{eff}} A({}^4F_{3/2} \rightarrow {}^4I_{11/2})$$

where λ_p the peak wavelength, $\Delta\lambda_{eff}$ the effective emission linewidth given by:

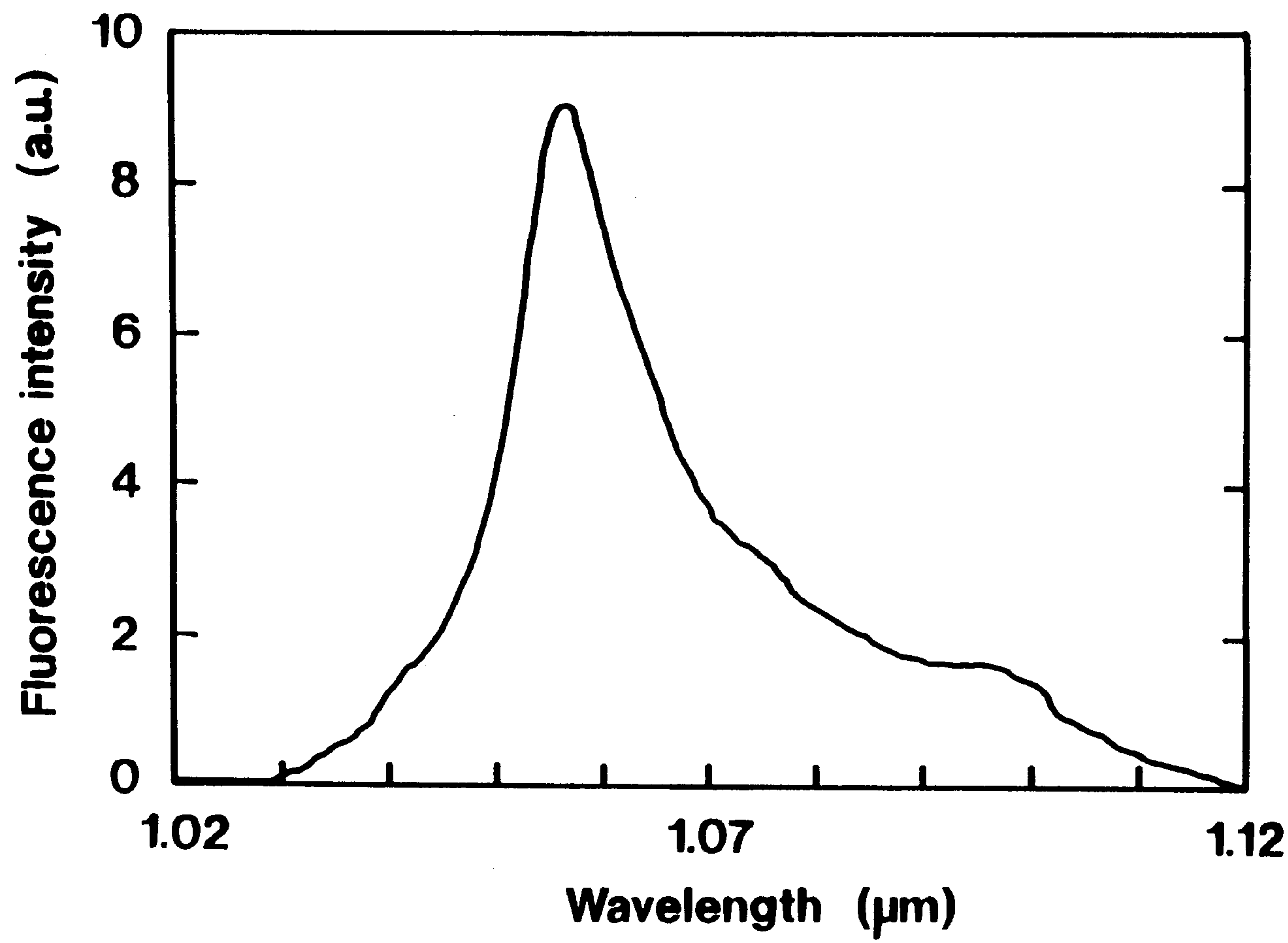
$$\Delta\lambda_{eff} = \int I(\lambda)/I(\lambda_p)\, d\lambda$$

and $A({}^4F_{3/2} \rightarrow {}^4I_{11/2})$ is the radiative decay rate obtained by:

$$A({}^4F_{3/2} \rightarrow {}^4I_{11/2}) = \beta({}^4F_{3/2} \rightarrow {}^4I_{11/2})/\tau$$

where β is the branching ratio and τ is the radiative lifetime.

σ_p:	2.4×10^{-20} cm^2	in lead-silicate F7
	$\approx 1.5 \times 10^{-20}$ cm^2	in alkali-silicate
	$1\text{-}1.3 \times 10^{-20}$ cm^2	in silica



10
8
6
4
2
0
Fluorescence intensity (a.u.)
1.02
1.07
1.12
Wavelength (μm)

c. LIFETIMES

Upper laser level Lifetime affects:

(1) population inversion, and (2) lasing threshold

Nd^{3+} $^4F_{3/2}$ level lifetime in lead-silicate F7:

500 μsec for Nd_2O_3 concentration < 3wt.%

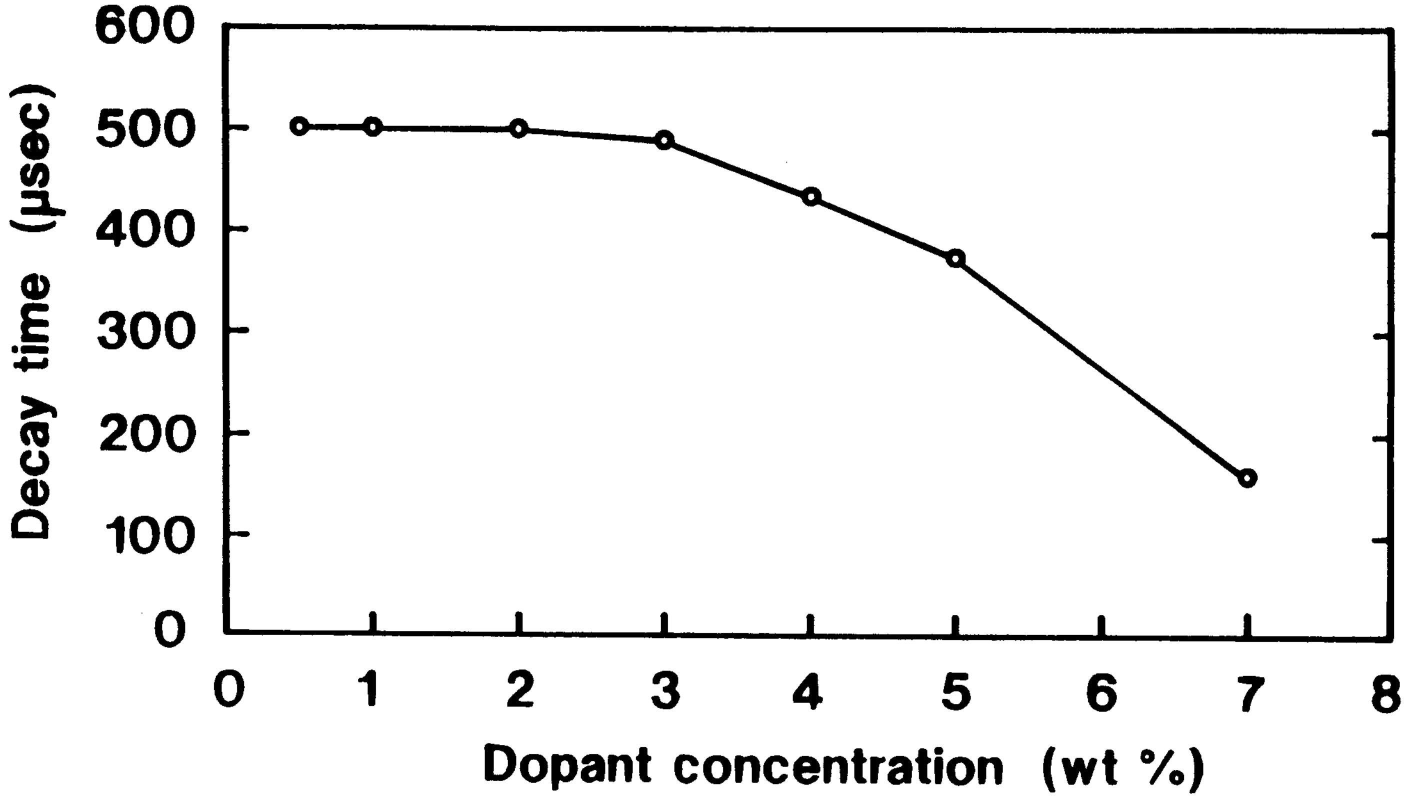
Thus:

Higher doping level attainable in this host
Only short length fibre required
Background loss at the lasing wavelength minimized

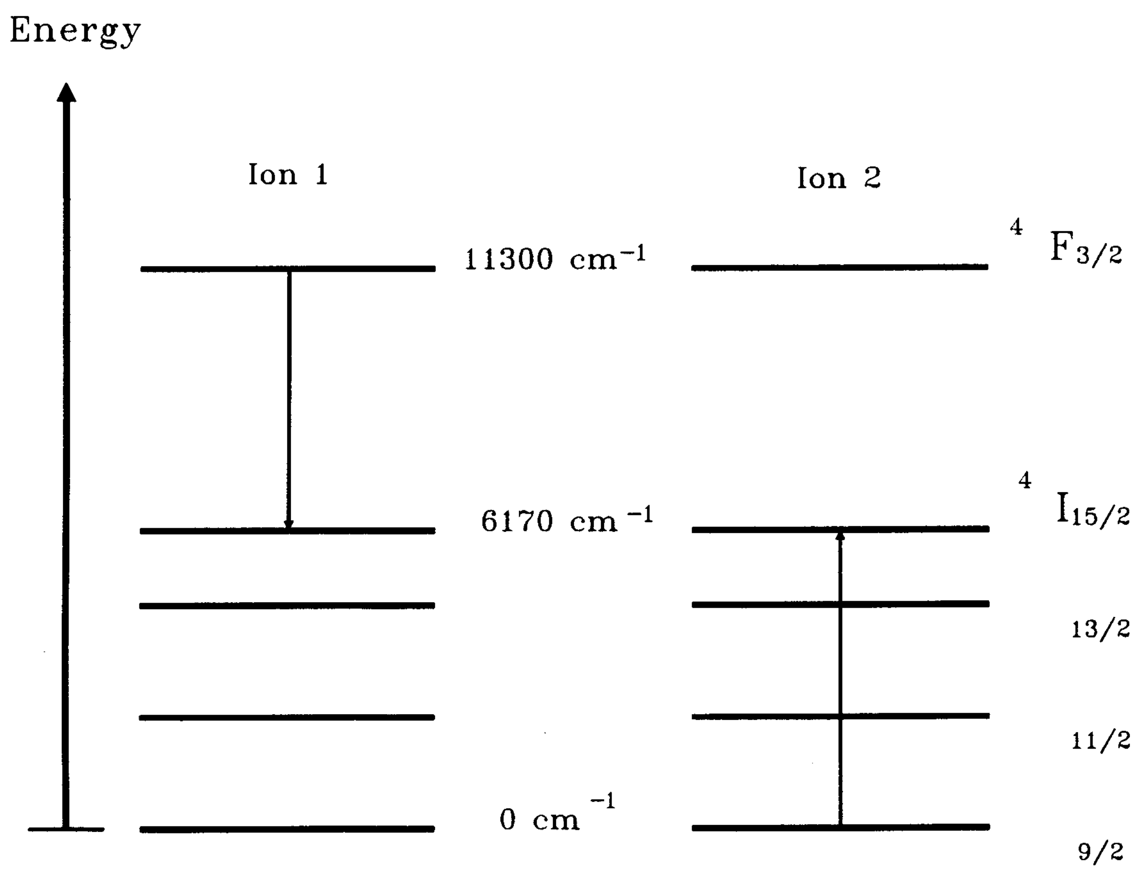
Quenching mechanism:

$$E(^4F_{3/2} \rightarrow {}^4I_{15/2}) + (\sim 1040\,cm^{-1}) \Rightarrow E(^4I_{9/2} \rightarrow {}^4I_{15/2})$$

A non-resonant phonon-assisted quenching process



600
500
400
300
200
100
0
Decay time (µsec)
0
1
2
3
4
5
6
7
8
Dopant concentration (wt %)


Energy
Ion 1
Ion 2
11300 cm⁻¹
6170 cm⁻¹
0 cm⁻¹
4 F3/2
4 I15/2
13/2
11/2
9/2

4. FIBRE LASER CHARACTERISTICS

Properties of the fibre used:

0.5 wt.% Nd_2O_3 doped, Numerical Aperture 0.13,

Fibre diameter 125 μm, Second mode cutoff 0.85 μm.

Pump source: Sharp LTO17MDO laser diode at 807nm

Fibre laser configuration: Fabry-perot

Optimum output mirror: 50 %

Typical fibre length: 14.5 cm

Laser threshold: 2.15 mW (when 50% coupler used)

Slope efficiency: 59.2 % (when 50% coupler used)

The best Nd^{3+} laser efficiency in oxide glasses to our knowledge

WHY SO GOOD ?

Small-signal gain coefficient:

$$g = \sigma \cdot \Delta N \propto N_0 \cdot p \cdot \sigma\tau$$

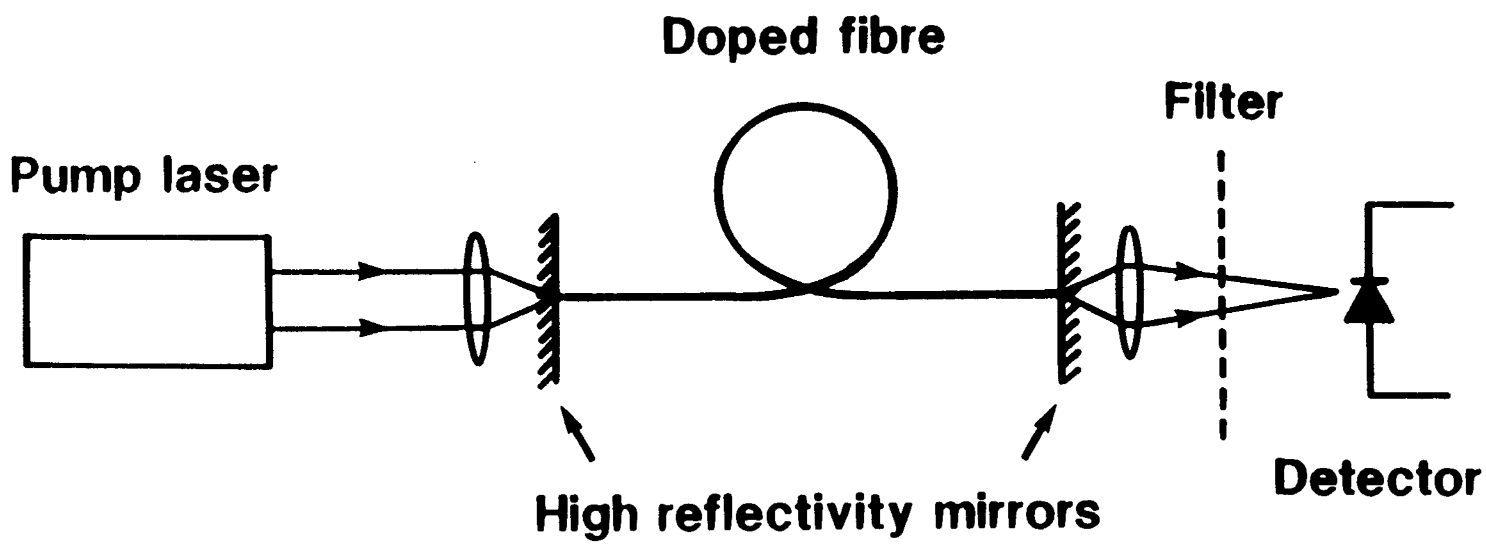
N_0: the ground state population, ΔN: the population inversion, p: the pumping efficiency, σ: emission cross-section, τ: the radiative lifetime.

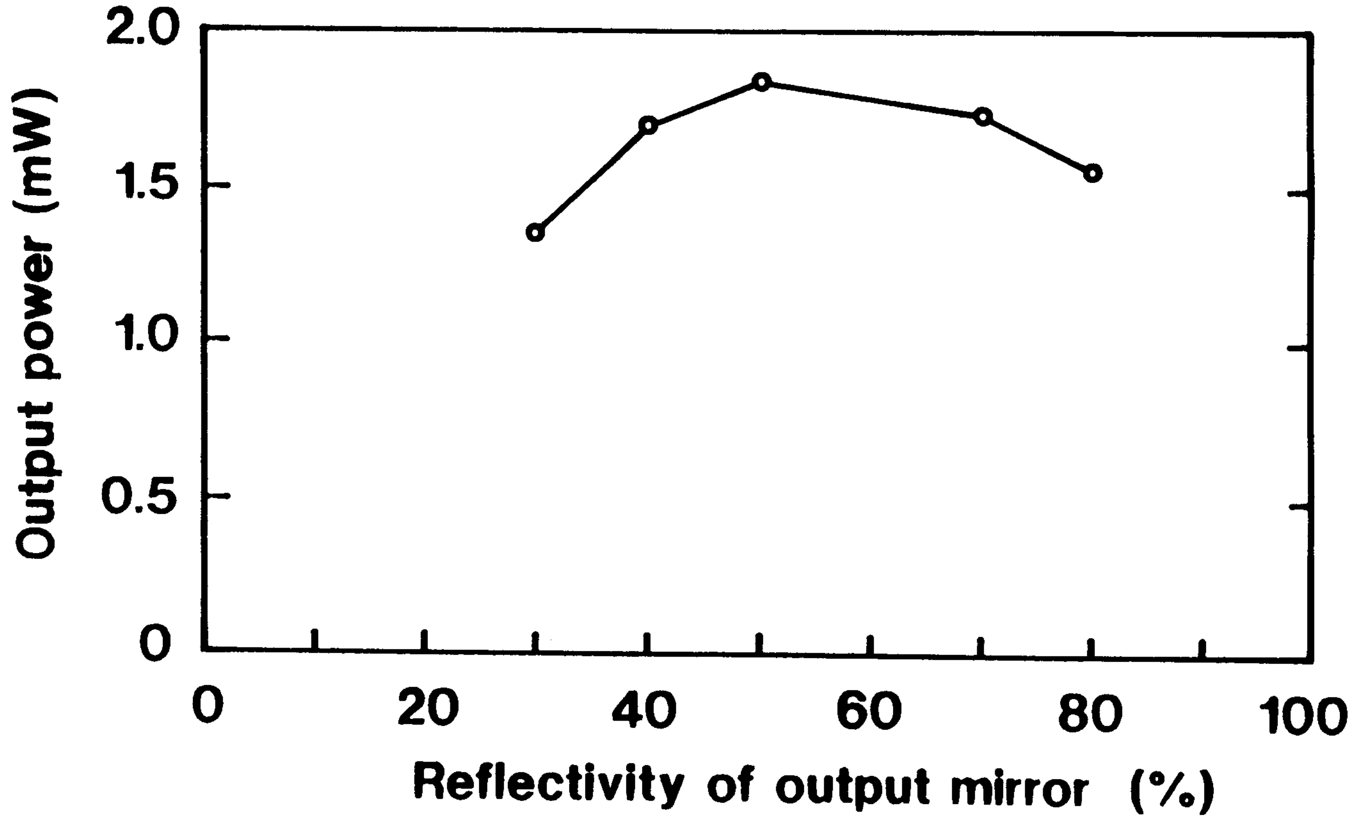
The $\sigma \circ \tau$ value:

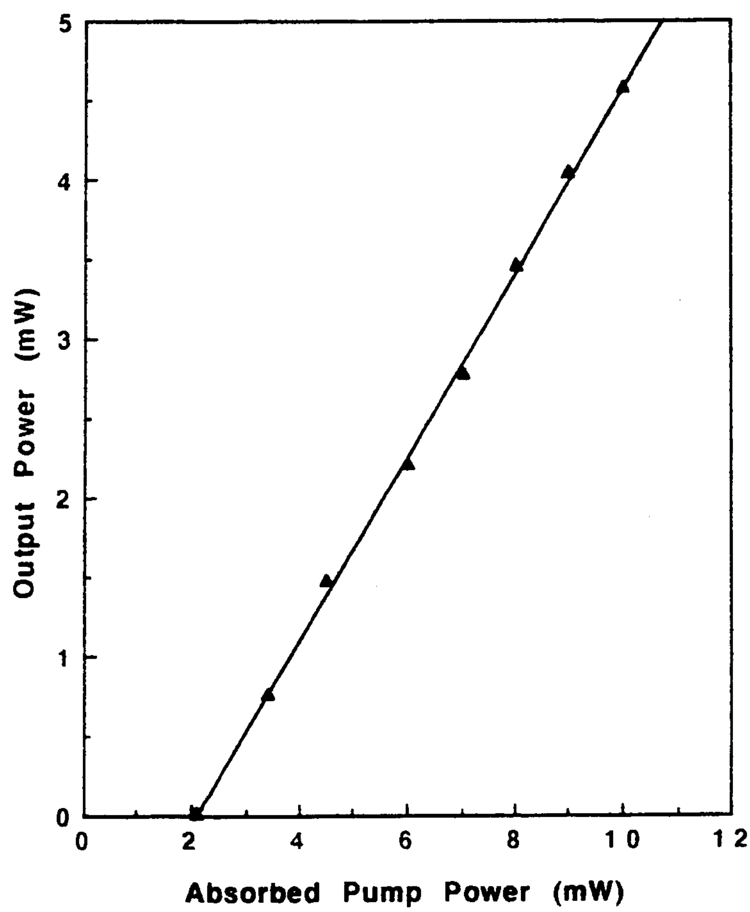
1.2×10^{-20} msec.cm^2 for lead-silicate F7

0.6×10^{-20} msec.cm^2 for silica

Pumping efficiency p is also better in lead silicate F7 because of a factor of two improvement in absorption cross-section at the pump.


Doped fibre
Filter
Pump laser
Detector
High reflectivity mirrors


2.0
1.5
1.0
0.5
0
Output power (mW)
0
20
40
60
80
100
Reflectivity of output mirror (%)



Output Power (mW)
Absorbed Pump Power (mW)
0
1
2
3
4
5
0
2
4
6
8
10
12

5. CONCLUSIONS

a. **A method for doping RE into commercial optical glass presented**

b. **A technique for measuring heavily doped fibres introduced**

c. **The role of Pb^{2+} on spectral properties investigated**

d. **A highly efficient Nd^{3+} fibre laser demonstrated**