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The properties of the samarium fibre laser

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Abstract

The optical properties of trivalent Samarium doped silica glass fibres are described. This material has a narrow fluorescence of 2.2 nm f.w.h.m. at a wavelength of 650 nm. Visible laser emission is obtained at this wavelength when the fibre is pumped in a Fabry Perot cavity. The performance of the laser in continuous, Q-switched and self mode-locked operation is described.

Introduction

We achieved visible laser operation in a glass host for the first time with Samarium 3+ doped silica optical fibre [1]. Optical fibres are ideal hosts for rare-earth lasers because high intensities (10^{11} W/m^2) may be confined for long interaction lengths of many metres in a single mode waveguide. A single mode optical fibre enables efficient longitudinal pumping of a glass in which the dopant concentration is less than 1%. Continuous room temperature operation of some rare earth lasers has only been achieved in an optical fibre geometry because of the efficient pumping and cooling [2].

Samarium doped glass is well known as a cladding for Nd-glass laser rods due to its high absorption at 1064 nm but low absorption between 500 nm and 900 nm. Reports of laser action in samarium to date have been limited to Sm^{2+} in crystal hosts [3]. Kazakov [4] has reported observation of induced emission of Sm^{3+} ions in TbF_3 crystals at 77 k under pulsed excitation, but until our work this was the only report of laser action in Sm^{3+}. We show here that laser action of Sm^{3+} in glass is only possible with low concentrations which require a fibre geometry for successful operation. This laser may be operated continuously, Q-switched or self mode-locked.

Our spectroscopic study of samarium doped silica in low concentrations (0.1%) reveals a very narrow transition from the $^4G_{5/2}$ level which has a linewidth of 2.2 nm. We use this narrow spectral line as a spectroscopic tool to determine the influence of temperature, electric field, host glass and excitation wavelength on the samarium in glass.

Fabrication of Samarium doped fibre.

Optical fibres were fabricated by the solution doping technique [5]. A variety of samarium doped fibres with different host glasses were fabricated. The silica fibres were fabricated by MOCVD and doped with Ge, Al_2O_3 or P_2O_5 to produce fibres with numerical apertures of 0.18-0.24.

Soft glass fibres doped with samarium were also fabricated either by rod in tube techniques with commercial samarium filter glass or by doping the phosphorus glass PK50. The most convenient pump band is from ground to the $^4I_{9/2}$ level which has a strong absorption at of the 488 nm line from an argon-ion laser. Unfortunately this corresponds to a two photon absorption of germania defect centres in GeO_2 doped fibres. The effect of this colour centre excitation is to increase the absorption of the fibre from the uv to the red part of the spectrum [6]. As a result samarium fibre lasers containing germanium experience an increase in the lasing threshold pump power after long periods of pumping at 488 nm. To overcome this problem fibres were made without germania, either with pure silica cores or with Al_2O_3 doping.

Energy levels of Samarium in silica.

The energy level diagram, shown in fig(1), is produced from data for Sm^{3+} in $LaCl_3$ from Dieka[7] with the levels adjusted to correlate with peaks in the absorption spectrum of a typical fibre which is also shown. There is a good correlation between the measured absorption peaks and the expected position of the energy levels. Samarium unlike most rare earths in glass has a particularly narrow linewidth of 2.2 nm f.w.h.m. for fluorescence and absorption from the $^4G_{5/2}$ metastable level. The gaussian shape of this line indicates that there is only one Stark level active.

Silica glass has approximately a tetragonal symmetry. There should be 3 possible Stark levels of both the $^4G_{5/2}$ metastable level and the $^6H_{5/2}$ ground state.

Influence of host glass

The host glass is seen to strongly influence the fluorescence spectra shown in figures (2 -6). In all cases the fibre was weakly pumped with 488 nm to prevent distortion of the spectra by amplification.
Si/Ge fibres have a narrow main transition between $^4G_{5/2}$ level and the ^6H levels with only one Stark component dominating but there is evidence of weak components either side. These weak components are smeared out into a continuum which decreases in intensity with temperature due to a reduction in the thermal population of these the upper Stark components. The lifetime of the peak fluorescence in silica fibres was measured as 1.5 ms. Fibres containing phosphorus have the fluorescence spread more evenly among the Stark components than Si/Ge fibres which leads to a reduction in the peak cross sections. This is probably due to the different symmetry of phosphorus glass.
The most significant change in fluorescence with host glass occurs in fibres doped with phosphorus and aluminium (fig. 5.). Strong fluorescence from the $^6H_{11/2}$ level is seen for the first time in these glasses. The peak at 680nm has a cross section of 2.5×10^{-21} which is larger than that at 650 nm. The wide spread of fluorescence from 560nm to 750nm in these glasses suggests that it may be possible to achieve laser action over this range in a correctly designed host glass with efficient pumping.

For comparison we also include our results from 1% Sm^{3+} doped PK50 phosphorus glass. In this glass the largest cross-section is at 600 nm (fig 6). This is weaker than the 650 nm peak cross section in silica glass but the lifetime of 1.9mS is the longest that we have observed in any glass. Samarium doped PK50 may provide a way of making short visible fibre lasers. The long life time and short length will be particularly suitable for high power Q_switching. Fibre fabricated from commercial Sm^{3+} doped glasses with 5 and 10% concentrations have lifetimes of less than 100us at 650 nm, which is probably due to concentration quenching.

We have to date only achieved laser action in silica-germania and silica-phosphorus germania glasses. This is due to the large cross section of $6.4x10^{-21}$ at the 650 nm fluorescence peak.

Line width measurements.

The narrow fluorescence line enables examination of broadening mechanisms of the samarium ions in glass. Non-resonant fluorescence line narrowing was used to determine the inhomogenious line width. Pumping with a range of wavelengths available from an argon ion laser accesses different crystal sites. For clarity only the two extreme fluorescence spectra corresponding to pump wavelengths of 488 nm and 496.5 nm are shown in figure (7). The maximum line shift was measure as 0.35 nm (8 cm^{-1}). Assuming that there is negligible cross site relaxation we take this to be the materials inhomogeneous linewidth. This width is much narrower than reported in lanthanum alluminium silicate glass [10].in which the inhomogeneous line width was measured as 240 cm^{-1}. The residual linewidth of 70 cm^{-1} may be attributed to homogeneous broadening. The homogeneous line width is typical of rare earth doped glasses at 20 C. On cooling to 77 K a linewidth reduction would be expected but no change was observed in Samarium doped silica.

The narrow inhomogeneous linewidth indicates that the optically active levels in Sm^{3+} in silica are well shielded from the lattice. This leads to a larger cross section and hence the possibility of laser action in Sm^{3+} doped silica glass. Further evidence of shielding is observed when electric fields are applied to a samarium doped fibre during fluorescence measurements. Figure 8 shows fluorescence spectra measured in zero field and in an electric field of 150 kV/mm. A fibre incorporating metal electrodes [11] was used to obtain such high fields. No change in the width or position of the fluorescence spectra was observed within the measurement resolution of 1 Å.

Continuous laser operation

A narrow fluorescence spectra and long life time provide the basis for a laser material. We reported the first observation of continuous stimulated emission in Samarium doped glass[12]. The laser is formed from into a Fabry Perot cavity by butting dielectric mirrors to each cleaved end of the fibre. One mirror is 99% reflecting at the lasing wavelength and nonreflecting at the pump wavelength of 488 nm. Output mirrors ranging from 97% reflectivity to 4%, due to Fresnel reflection at the fibre end, have been used to obtain lasing. Laser output verses pump power is shown in figure 9. An efficiency of 12.7% was obtained with an output coupler of 60% reflectivity. The gain is estimated at 0.02 dB/mW/m in a fibre with a dopant concentration of 250 ppm and a core area of 7×10^{-12} m^2. Laser operation is restricted by fibre absorption and scatter loss at the laser wavelength. In the un-pumped state the loss at 650 nm is 50 dB/km, but this increase in germania doped fibres due to pumping.

Q switched operation

The long life time (1.6 ms) of Samarium in silica glass provides a large energy storage capacity in the laser cavity. Q-switched operation is achieved with a AO modulator in the cavity between the fibre and the output mirror. The low dopant concentrations used here require fibre lengths of 2 m for efficient operation. A Q-switched pulse from a 2 m long fibre laser with an output mirror of 60% reflectivity is shown in figure(10). It has a long tail of 40 ns duration due to the cavity decay time. Some reduction in decay time is possible by slicing the end of the pulse with the AO modulator. Peak powers of 10 W have been achieved with pulse widths of 300 ns. This is below expected power levels due to intracavity loss in the fibre. To fully utilise the energy storage capacity of samarium doped glass fibres for high power pulses the dopant concentration must be increased to 10000 ppm without increase in loss at 650 nm or decrease in lifetime.

Self mode-locking.

In Q switched operation a high intensity is maintained in the fibre for several metres of interaction length. This leads to a break up of the pulse into narrow mode-locked pulses as shown in fig(11). A nonlinear index change is produced by the Q-switched pulse with in the laser cavity. The phase change per round trip of the cavity is given by

$$\Delta \varnothing = \frac{4 \pi l n_2 P}{\lambda c e_o n A} \qquad 1.$$

where l is the cavity length taken as 8m, n_2 is the nonlinear index of fused silica, P is the inter cavity pulse power taken as 2W and A is the mode spot size taken as 7×10^{-12} m^2. The resultant phase shift is 0.9π which is sufficient to couple the modes together and produce self mode-locking.

Alternatively this phenomena may be considered as a set of coupled nonlinear wave equations of the form

$$\frac{dE_i}{dx} = gE_i + Sp(w_i) + e_o c^3 \sum E(w_j).E(w_k).E(w_l) \qquad 2.$$

where c^3 is the third order nonlinear susceptibility and $E(\omega_i)$ are the fields of each longitudinal mode in the fibre. The gain is given by g and the spontaneous emission is Sp. The summation is taken over all the modes, which are assumed to be equally spaced, that contribute by 4 wave mixing to the generated mode. Therefore if the generated mode has a frequency w the mode spacing is Δ then for example modes with frequencies w-3D ,w+D, w+2D will contribute to the generated mode if the phases add constructively. The condition for phase matching requires that the propagation constants obey this condition

$$k(w)= k(w-3D)+k(w+D)+k(w+2D) \qquad 3.$$

There are similar equations for the phase matching between all the other modes. We argue that a self consistent solution is only possible if all the modes are in phase. The effect of the nonlinear coupling in eqn (2) is to drive the phases of all the modes together. The spontaneous emission coupled into a mode will act against this but when operating well above threshold this effect is small.

Figure 11 shows the Q-switched pulse envelope with a train of self mode locked pulses starting from the peak of the envelope. Measurement of the pulse widths were instrument limited to 1nS. Sampling methods were not possible because the timing of the pulses is unstable due to amplitude fluctuations in the Q-switched pulse. These mode-locked pulses are different from the sub-pulses that are seen when a few modes are Q-switched. The modulation in the Q-switch envelope in the few moded case is due to beating between the modes at the detector. The self-mode-locked pulses are distinguished by starting from the peak of the Q-switch envelope and they are much narrower.

Laser emission spectra

Further understanding of the self mode-locking process is gained from the laser emission spectra in the cw, Q switched and self mode-locked operation shown in figures 12 and 13. The mode spacing of 2 fibre laser with 8m cavity length is 12.5 MHz. which is not resolved on the monochromator. The cw spectrum consists of a series of narrow spikes separated by 0.3 nm . This corresponds to a 0.7 mm cavity and is probably due to an etalon effect in the laser mirrors. When the cavity is Q-switched with an acousto-optic modulator the mirror etalon effect is disrupted to produce a smooth laser emission spectrum with a line width of 1 nm (fwhm).

As the laser is driven harder and the inter cavity intensity is increased the laser begins to self mode-lock. The emission spectra in figure 13 shows that power is coupled from the centre of the lasing spectrum to the weaker modes in the wings, therefore broadening the laser spectrum. The result of coupling power to the modes in the wings is to narrow the pulses of the laser.

Conclusions

Samarium doped silica glass is a very unusual laser material. Its narrow linewidth and long fluorescence decay time enable laser action to be obtained in the single-mode fibre geometry. This narrow line is shown to be well shielded from the effects of temperature and external electric fields. Continuous visible emission from a glass laser has never been achieved before so this laser may find many applications. The fluorescence spectrum was seen to vary considerably with different host glass compositions from which fibres were made. This leads to the possibility of laser emmision over a wide range of wavelengths from 570 nm to 750 nm. Currently the laser has to be pumped in the blue-green region of the spectrum but co-doping may provide a means of pumping at longer wavelengths.

The samarium fibre laser is a useful pulsed source. When Q-switched 10 W pulses were obtained but over 100 W is believed to be possible with optimised fibre design. Self-modelocking provides more intense short pulses than Q-switching on its own. The samarium fibre laser maintains a high intensity throughout its long cavity length leading to nonlinear coupling of the laser modes. The 2 nm linewidth of samarium should lead to sub picosecond pulses but competing nonlinearities and fibre dispersion will frustrate this process.

References

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Figure captions

1. Energy level diagram and absorption spectrum of Sm^{3+} doped silica optical fibre.

2. Fluorescence spectra of samarium in various glass hosts.

3. Fluorescence spectra of samarium in germania doped silica.

4. Fluorescence spectra of samarium in phosphorus-germania doped silica.

5. Fluorescence spectra of samarium in phosphorus-alumina doped silica.

6. Fluorescence spectra of samarium in PK50 glass fibres.

7. Fluorescence line narrowing in Sm^{3+} doped Ge-silica glass fibres.

8. Fluorescence from Sm^{3+} dope fibre in an applied electric field of 150 V/mm.

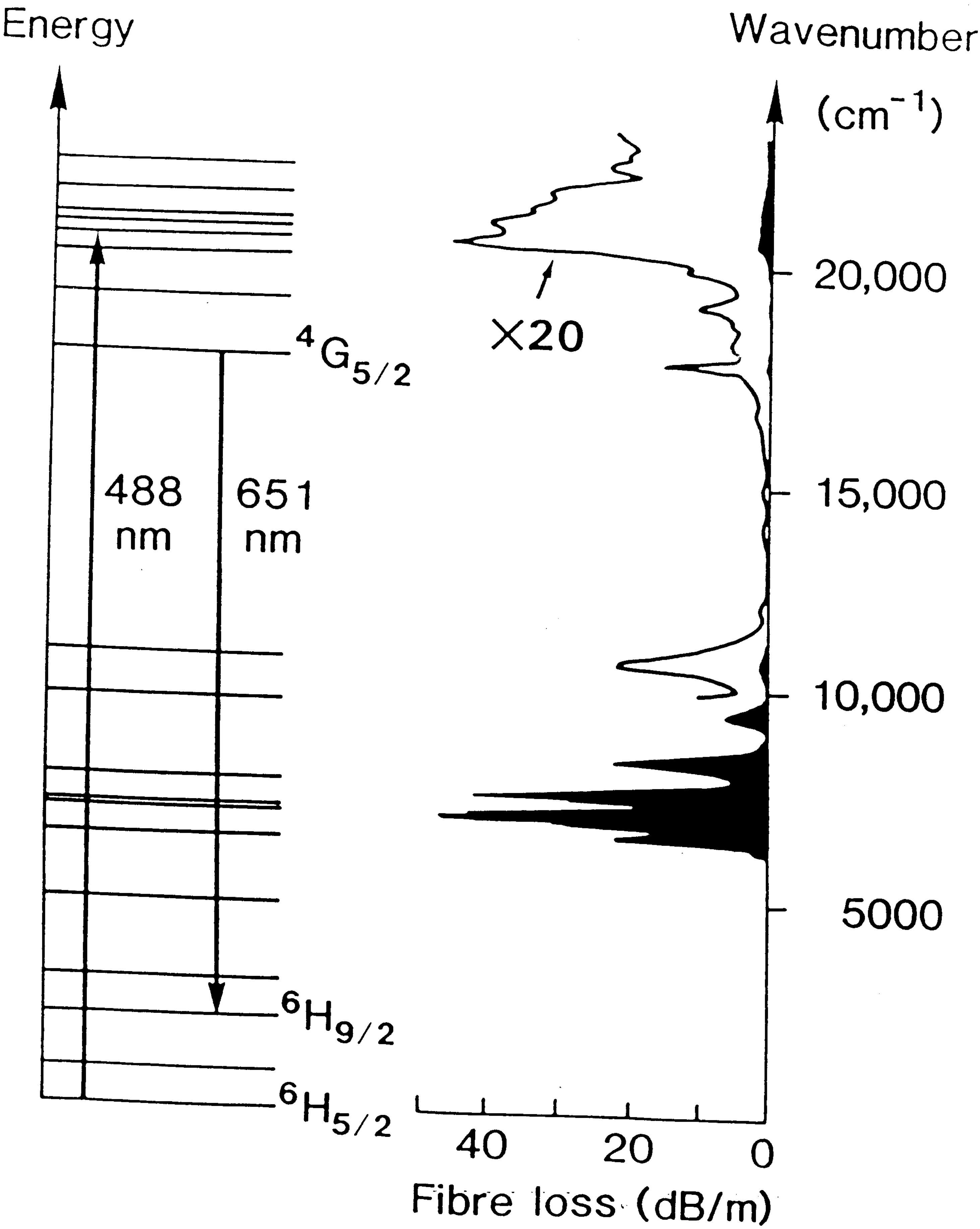
9. CW. laser characteristic of Sm^{3+} fibre laser.

10. 10 W Q-switched pulse from a samarium fibre laser.

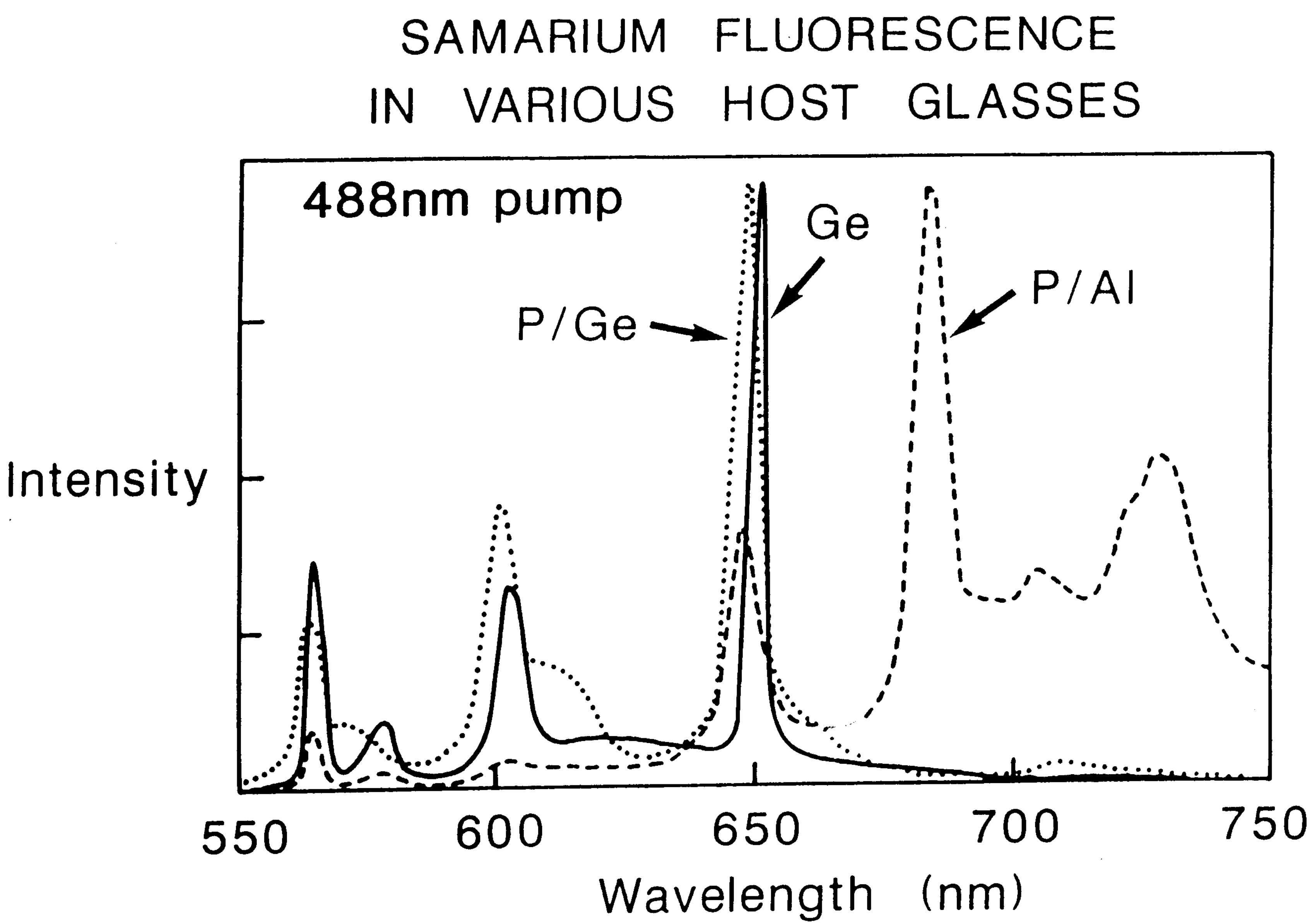
11. Self mode-locked pulses from a Q-switched samarium fibre laser.

12. Emmission spectra of samarium fibre laser operated cw, Q-switched.

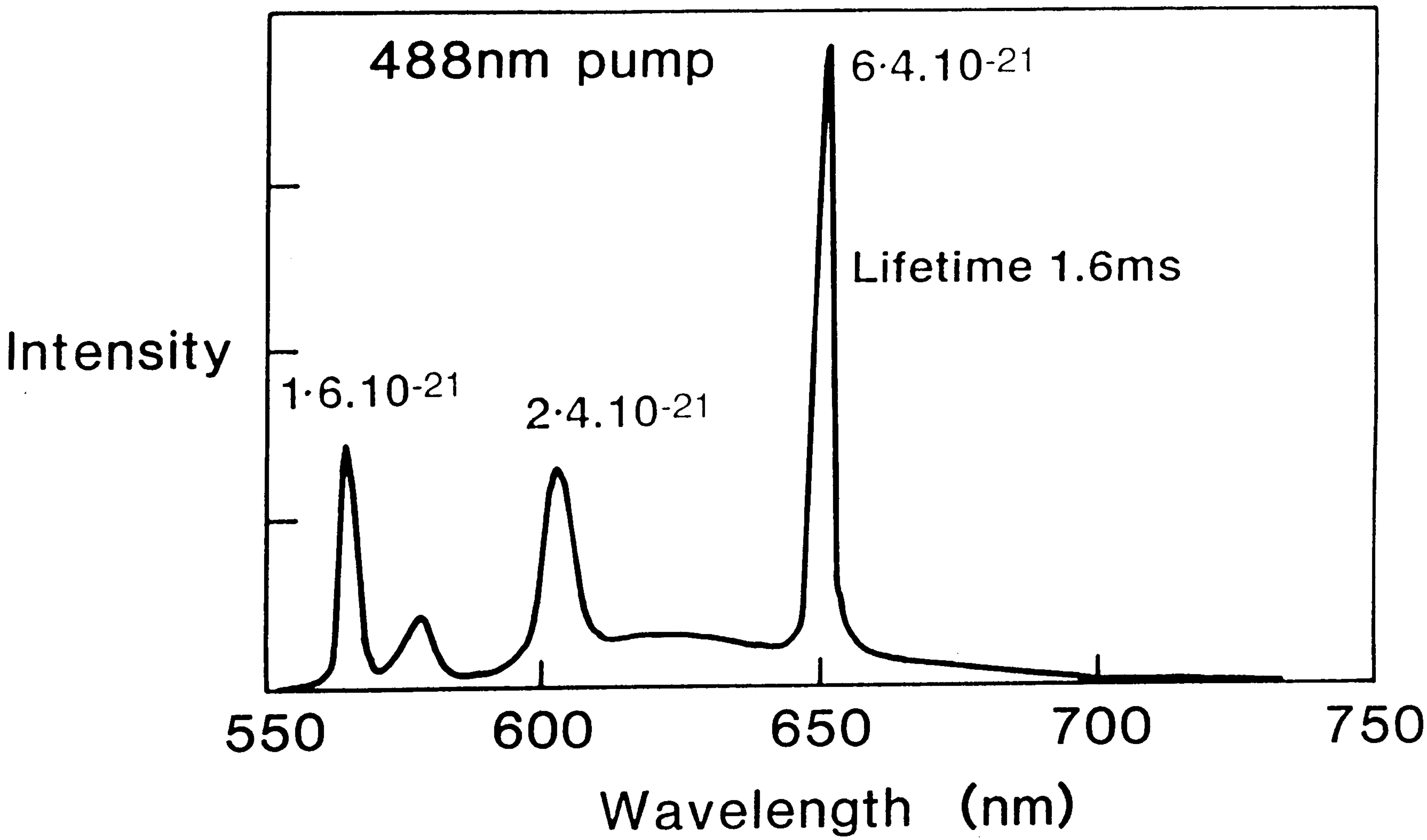
13 Emmision spectra of samarium fibre laser operated Q-switched and self mode-locked.

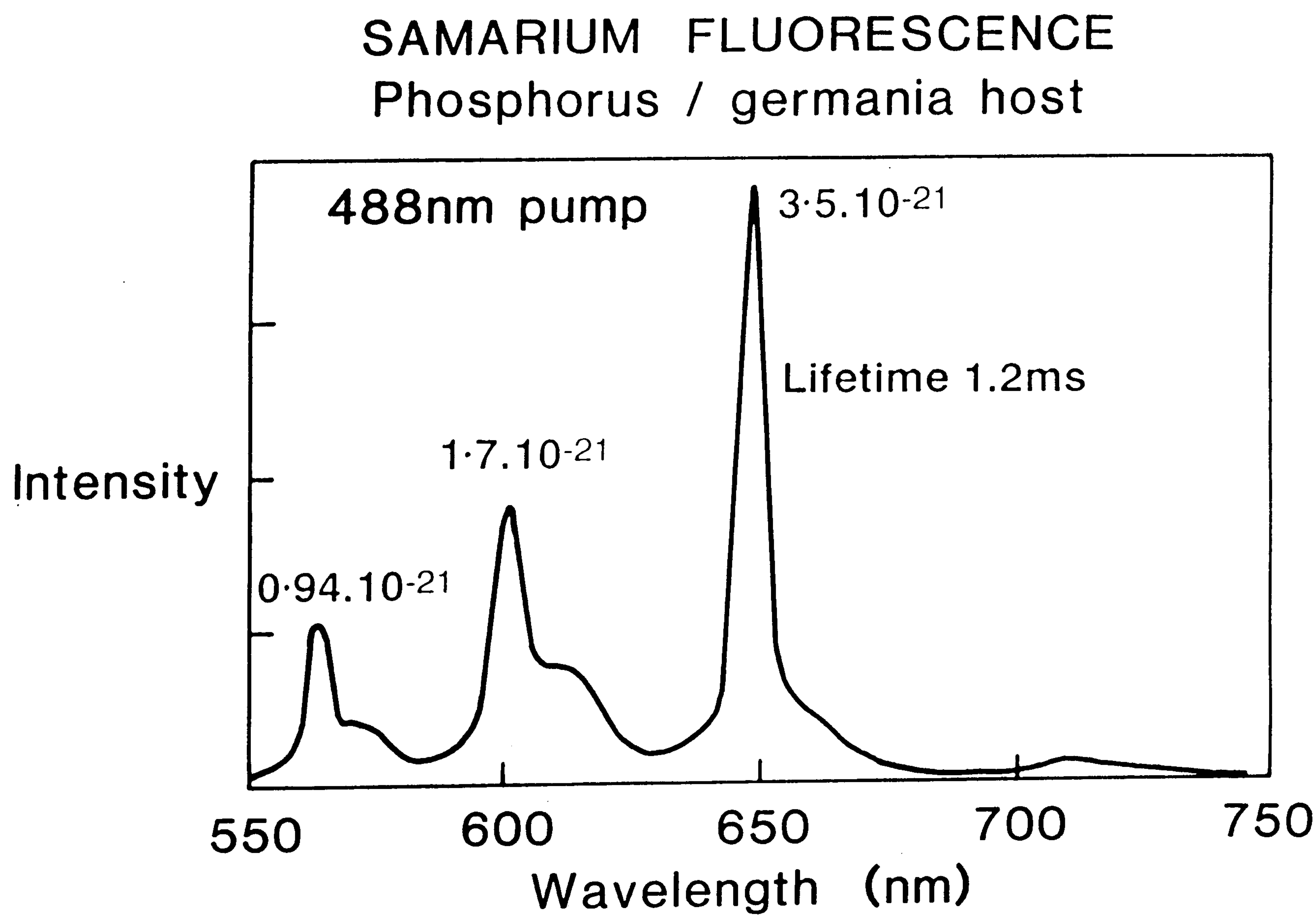


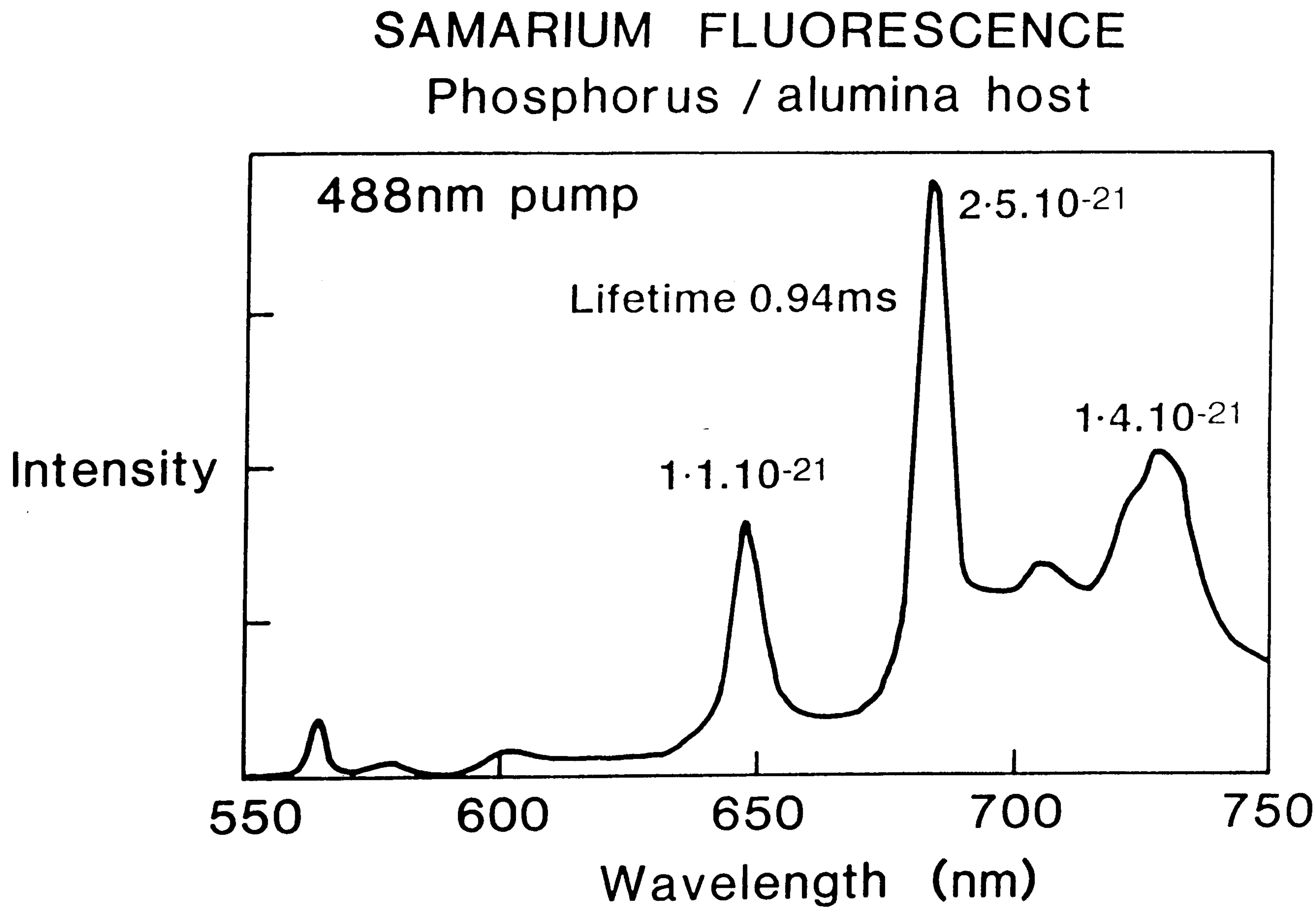
Energy
Wavenumber
(cm^{-1})
20,000
15,000
10,000
5000
×20
$^4G_{5/2}$
488
nm
651
nm
$^6H_{9/2}$
$^6H_{5/2}$
40
20
0
Fibre loss (dB/m)


SAMARIUM FLUORESCENCE
IN VARIOUS HOST GLASSES
488nm pump
Ge
P/Ge
P/Al
Intensity
550
600
650
700
750
Wavelength (nm)

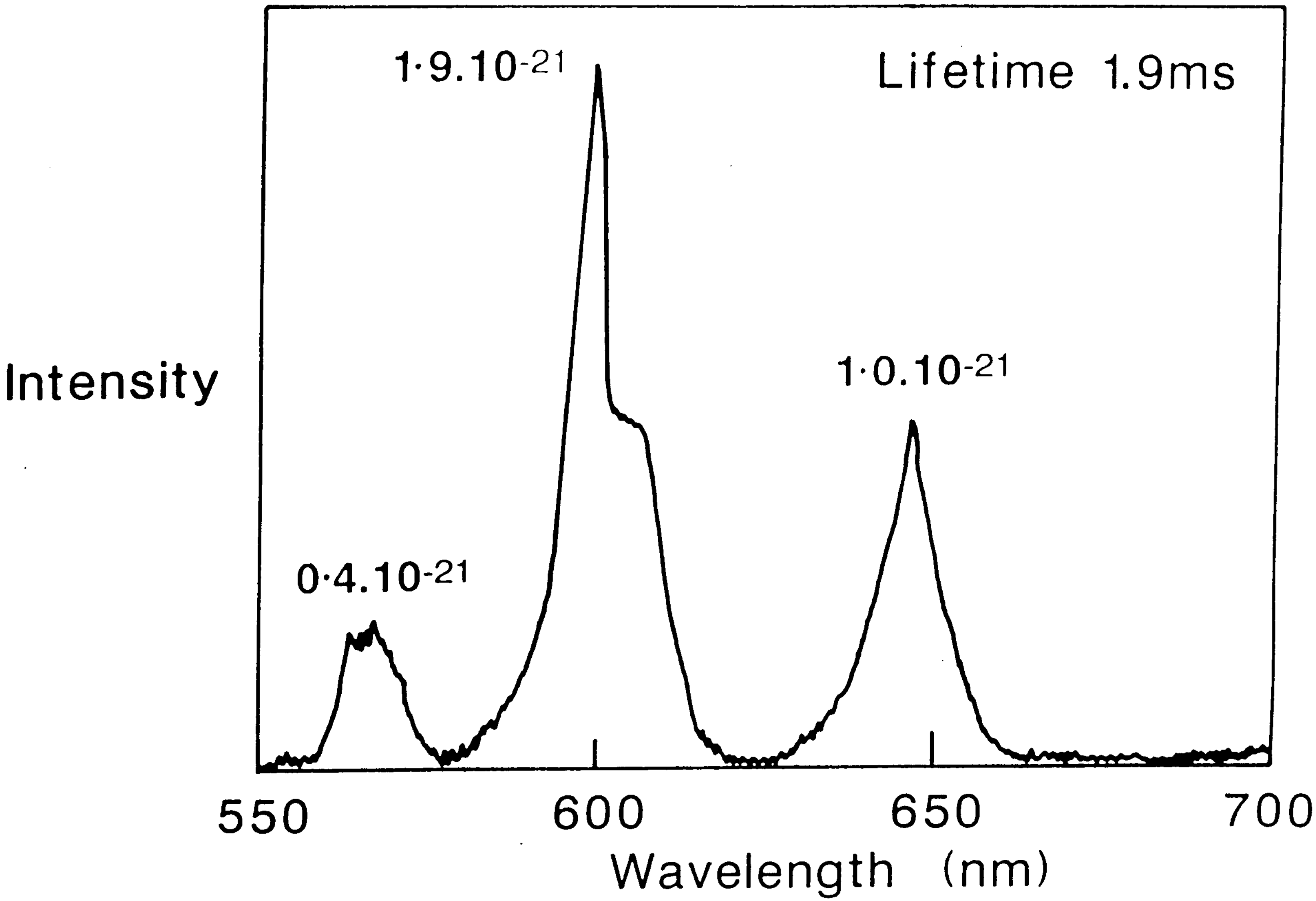
SAMARIUM FLUORESCENCE
Germania host



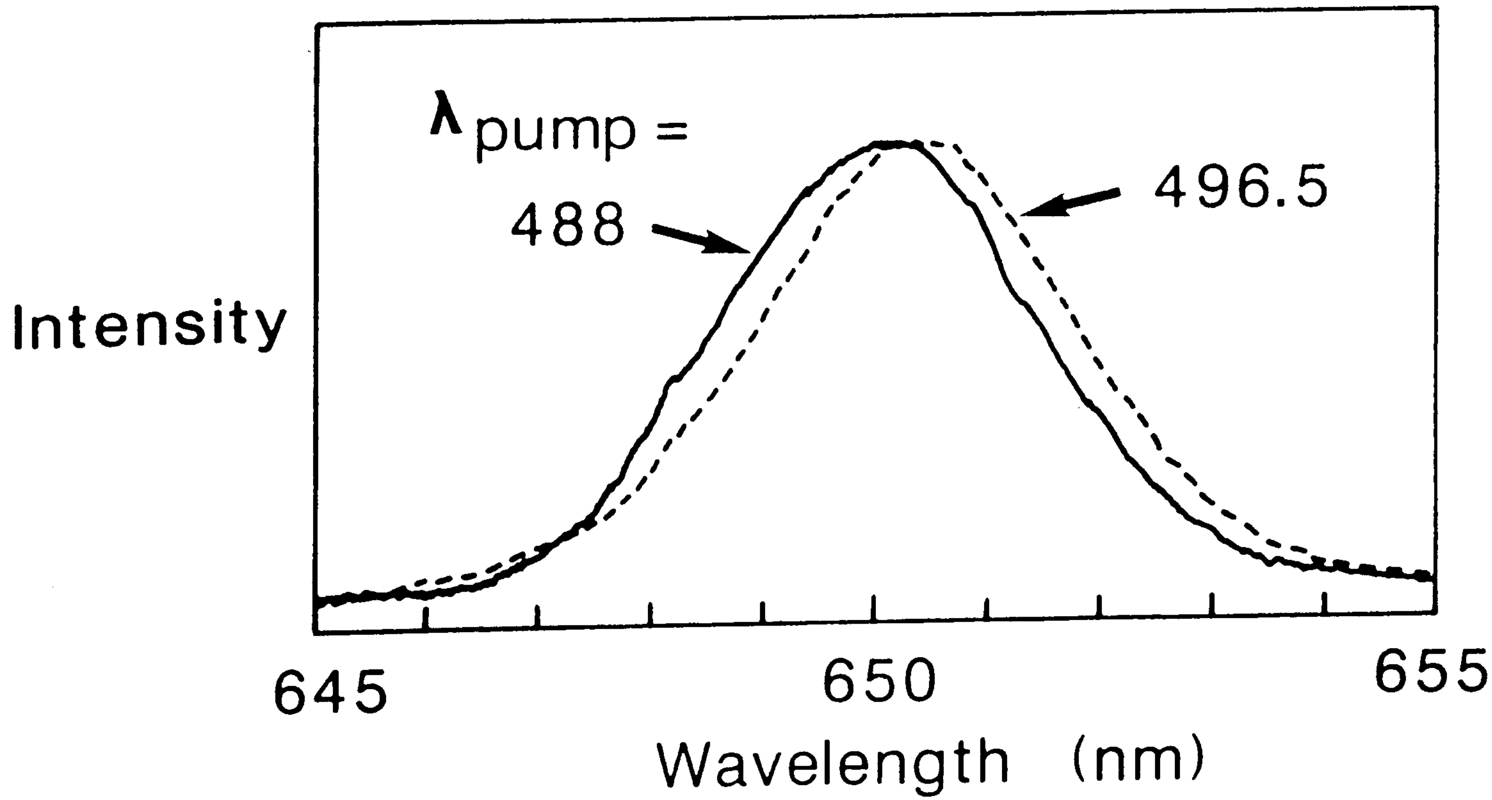

SAMARIUM FLUORESCENCE
Phosphorus / germania host
488nm pump
3·5.10-21
Lifetime 1.2ms
1·7.10-21
0·94.10-21
Intensity
550
600
650
700
750
Wavelength (nm)


SAMARIUM FLUORESCENCE
Phosphorus / alumina host
488nm pump
Lifetime 0.94ms
2·5.10-21
1·1.10-21
1·4.10-21
Intensity
550
600
650
700
750
Wavelength (nm)

SAMARIUM FLUORESCENCE SPECTRUM
1%Sm in Pk50 pumped at 488nm

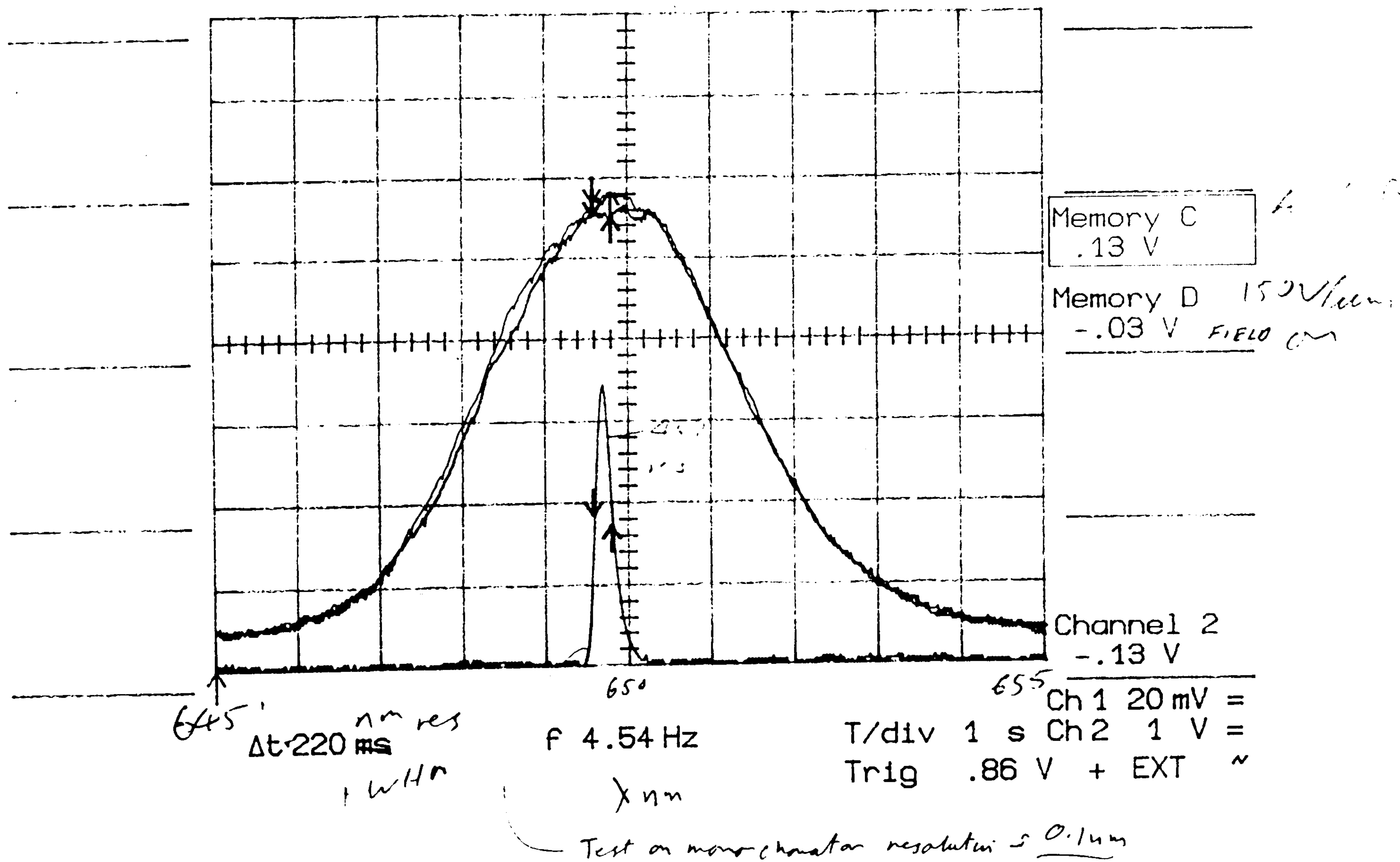


VARIATION OF SAMARIUM FLUORESCENCE SPECTRUM WITH PUMP WAVELENGTH



Effect of 150V/μm on fluorescence spectra of Sm

488nm pump



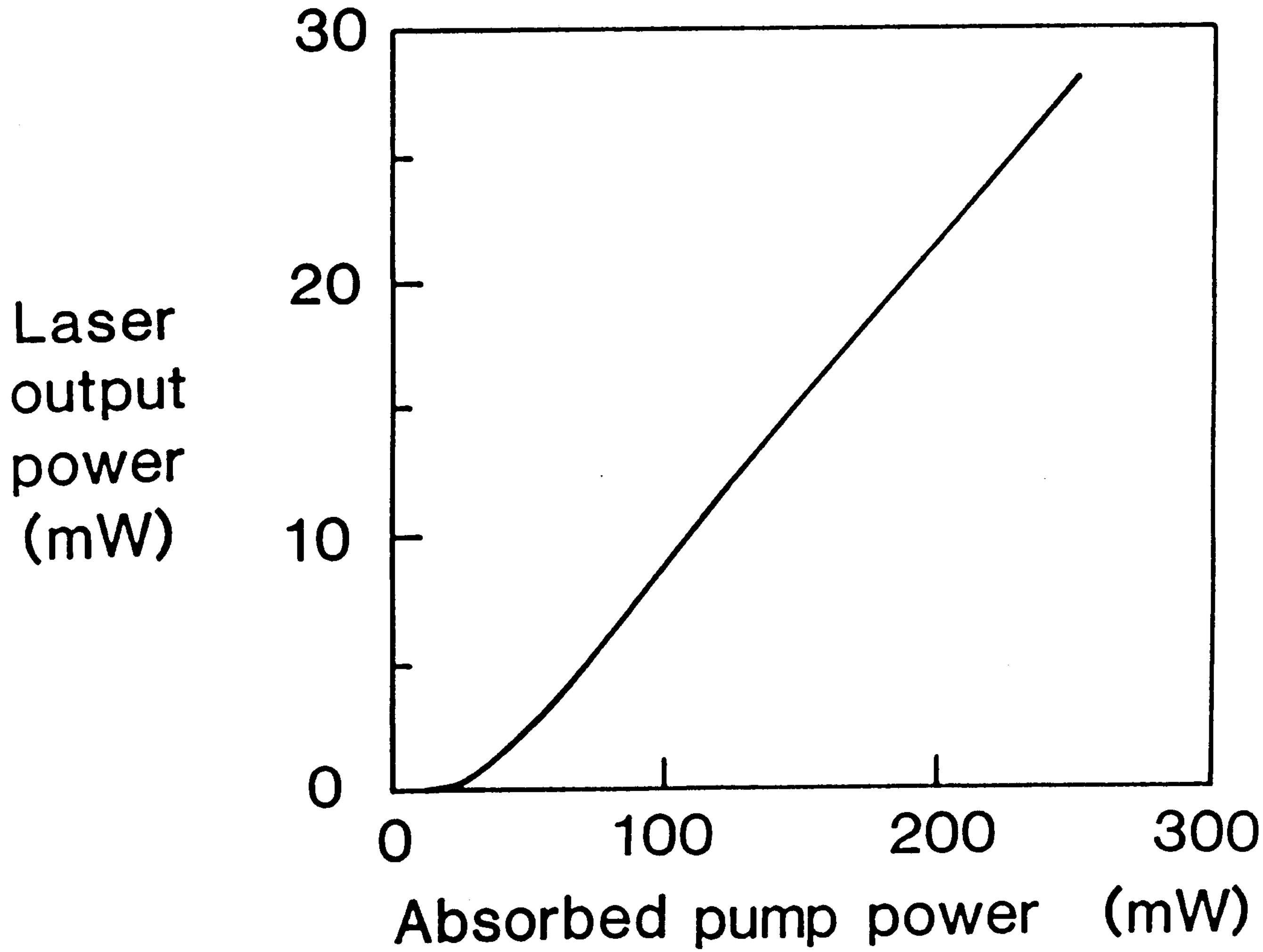
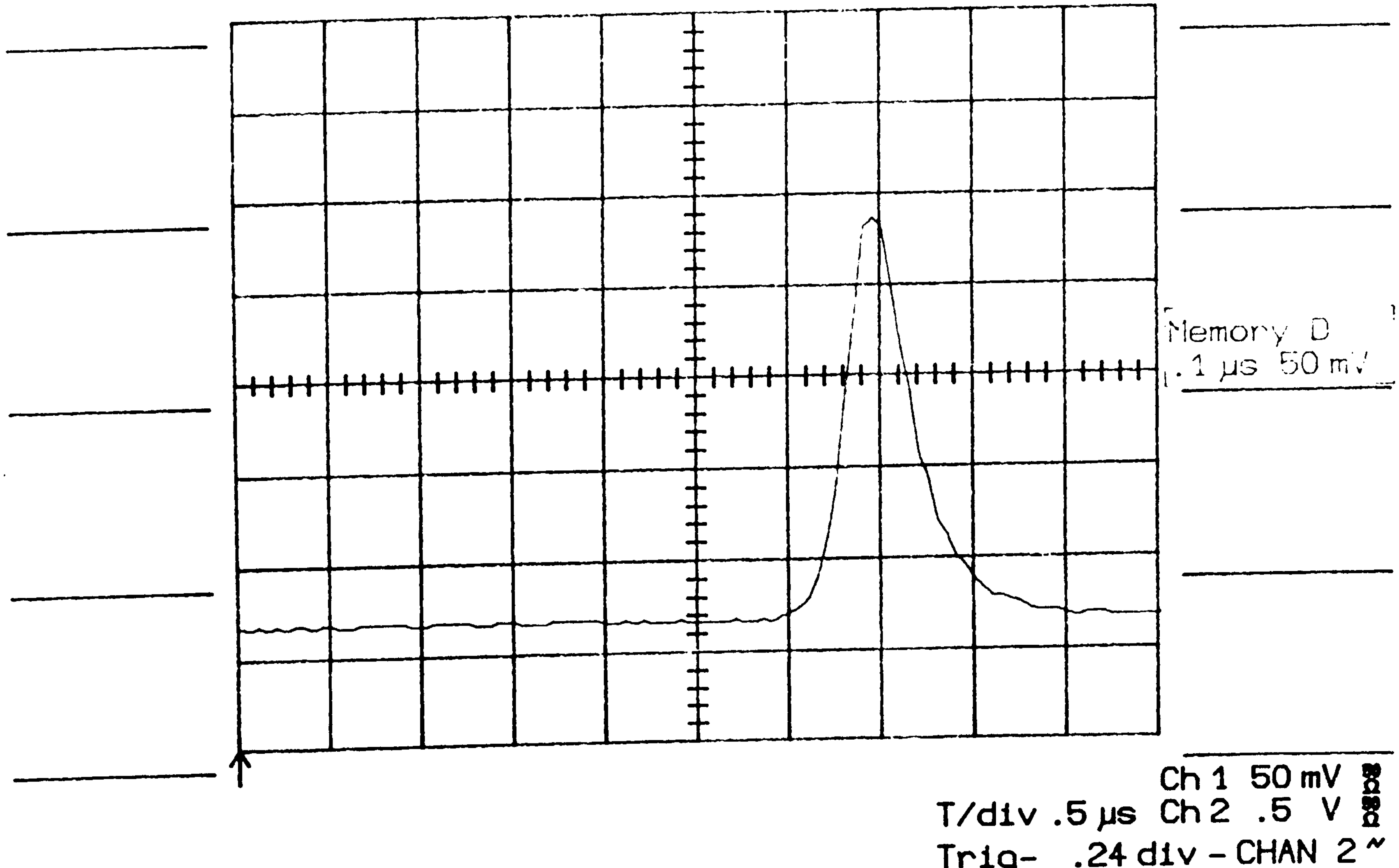

Laser
output
power
(mW)
30
20
10
0
0
100
200
300
Absorbed pump power (mW)

fig 3

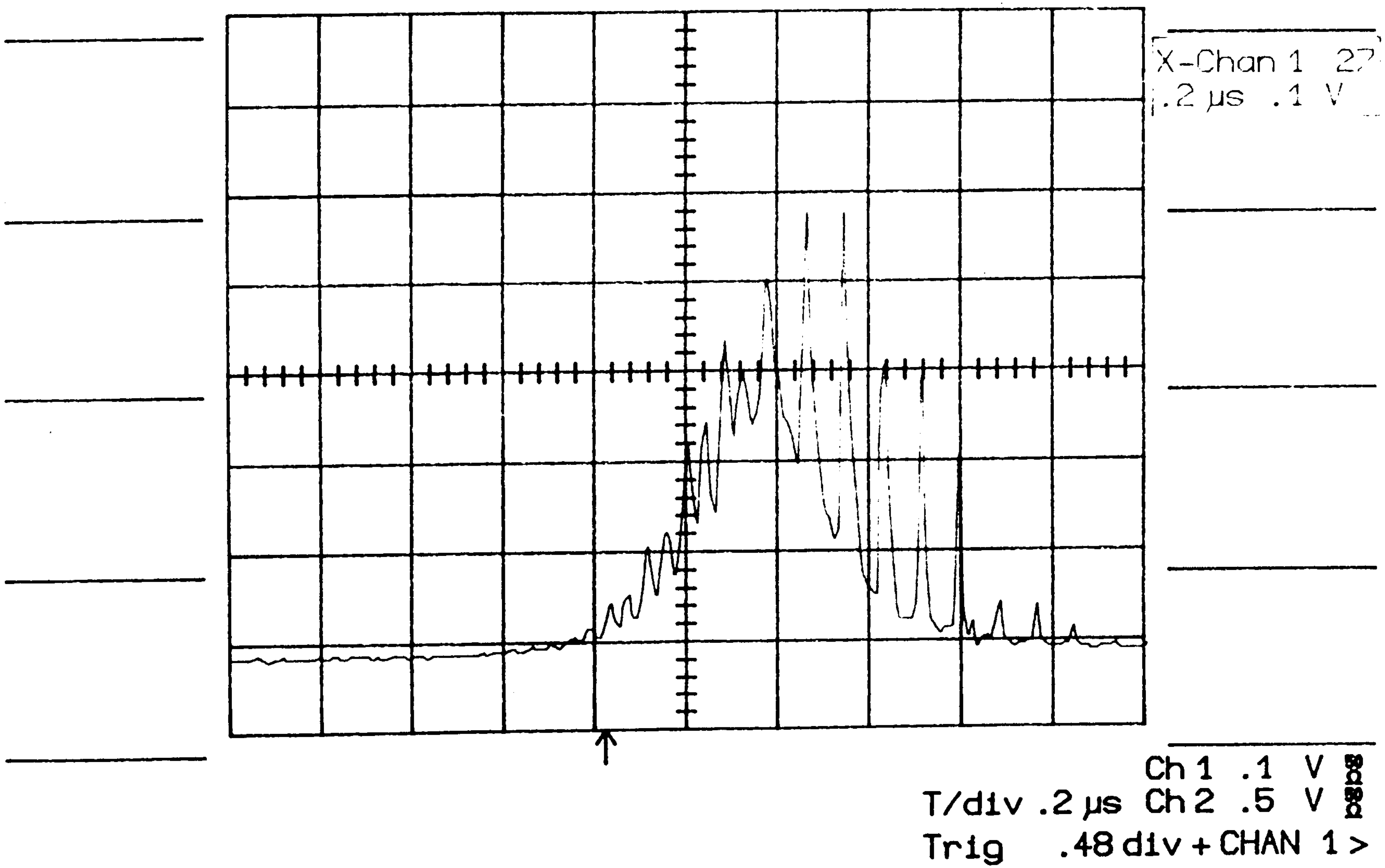
Best Q switch result

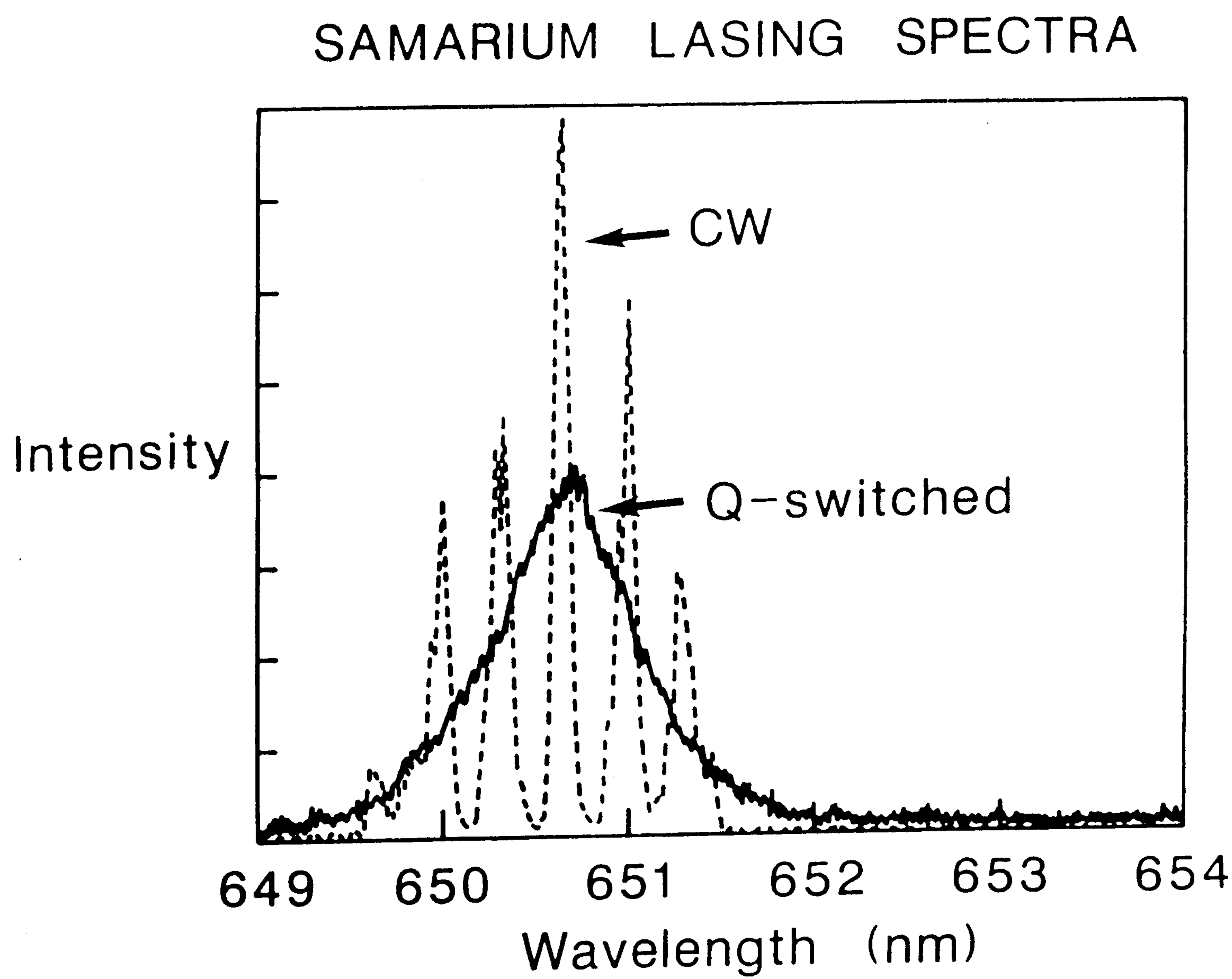
2m fibre Peak = 10W O/p mirror = 6%

Pump = 488 ⇒ 0.1w absorbed.



Q switched O/p of Sm fibre laser.


X-Chan 1 27
.2 µs .1 V
Ch 1 .1 V
T/div .2 µs Ch 2 .5 V
Trig .48 div + CHAN 1 >


SAMARIUM LASING SPECTRA
Intensity
CW
Q-switched
649
650
651
652
653
654
Wavelength (nm)

LASING SPECTRA OF Q-SWITCHED SAMARIUM LASER