MEASUREMENT OF THE STIMULATED EMISSION CROSS SECTION OF Nd^{3+} IN $CaWO_4$

D. H. Arnold* and D. C. Hanna*

1. Introduction

In order to make quantitative predictions of the output powers and energies from a laser it is necessary to know the value of the stimulated emission cross section. Conversely by measuring the output power or energy it is possible to calculate the cross section. Cross sections for the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition are now known for a number of Nd doped materials (Nd:glass (refs.1-6), Nd:YAG (ref.7), Nd:$SeOCl_2$ (ref.8)) although a literature search by the authors failed to reveal any published figures for Nd:$CaWO_4$. This paper reports a measurement of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ cross section in Nd:$CaWO_4$ using a method which Edwards (ref.5) first applied to Nd glass materials. The crystal investigated was a Na-compensated crystal grown by AEI (Nd concentration nominally 1 at.%) cut in the form of a cylindrical rod 50mm long, 6mm across, with the c-axis parallel to the cylinder axis. The cross section measured is that of the σ-polarised emission at 1.065μ since the σ spectrum and axial spectrum are identical.

2. Definition of Cross Section

Edwards'(ref.5)analysis shows that for an antireflection coated rod (as used in this experiment), placed between mirrors of reflectivity R_1 and R_2, the energy output E per unit area from mirror 1 is

$$E = -\frac{h\nu\, R_2(1-R_1)\ \ln(R_1R_2)\,\rho}{2\sigma\left[R_2+(1-R_2).(R_1R_2)^{\frac{1}{2}} - R_1R_2\right]} \qquad (1)$$

ρ is the number of Nd ions which release energy into the resonator, expressed as a fraction of the threshold number of Nd ions and σ is the stimulated emission cross section. In this expression it is assumed that the Nd ions which take part in laser oscillation originate from a single energy level. In Nd:$CaWO_4$ however the $^4F_{3/2}$ level is split into two sublevels (R_1 and R_2) separated by 63cm^{-1} and it is the lower of these sublevels (R_1) that produces the 1.065μ emission. From results of work on the Nd:YAlG laser (ref.7,9) it is to be expected that the $^4F_{3/2}$ sublevels in Nd:$CaWO_4$

---

* Department of Electronics, University of Southampton

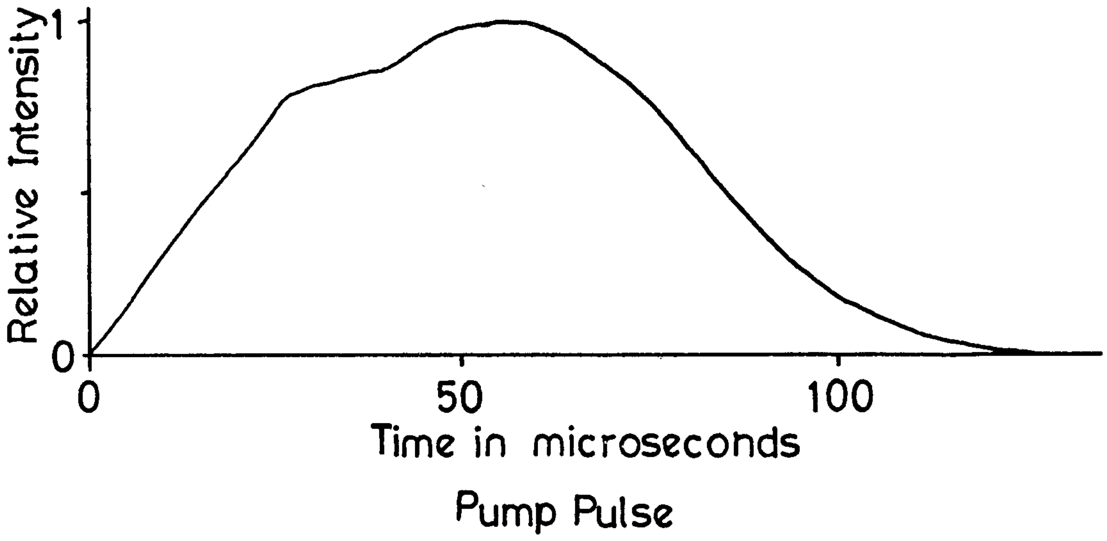
Relative Intensity
1
0
0
50
100
Time in microseconds
Pump Pulse

Fig 1

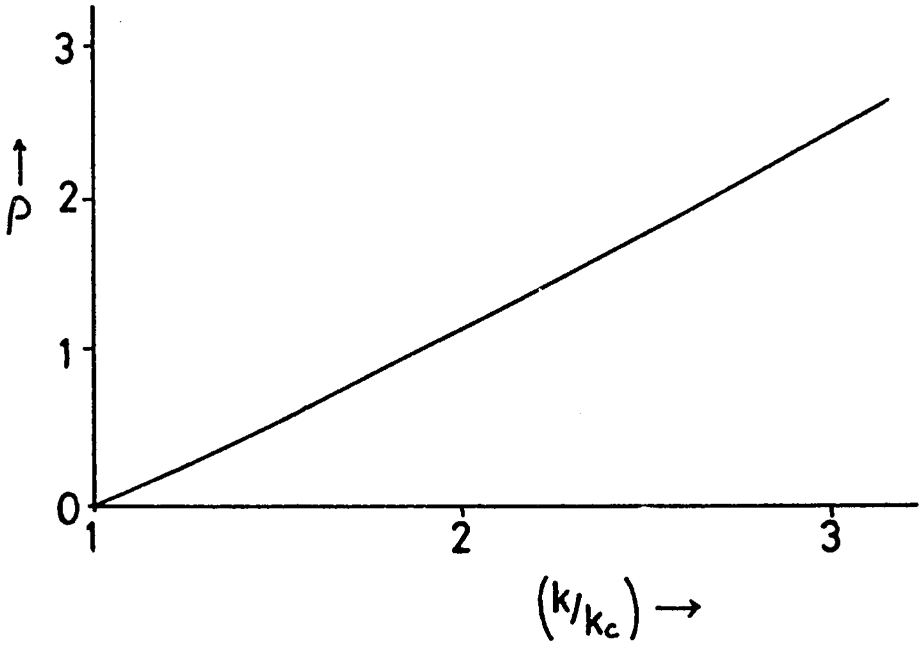
3
2
1
0
$\rho \rightarrow$
1
2
3
$(k/k_c) \rightarrow$

Fig 2

also adjust their populations to the Boltzmann distribution in a time short compared to the time scale of laser emission. This means that Nd ions in the R_2 level contribute to the laser output energy since they drop into the R_1 level during laser oscillation to maintain the equilibrium population distribution. On the other hand Nd ions in the R_2 level do not contribute to the 1.065μ gain (unlike Nd:YAG (ref.7)) since the R_2 emission at 1.058μ has little overlap with the 1.065μ line and in any case the emission at 1.058μ is π polarised and does not appear in the axial spectrum. The 1.065μ stimulated emission cross section σ is therefore defined by

$$\alpha = N_1 \sigma \qquad (2)$$

where N_1 is the population density of the R_1 level and α is the 1.065μ gain coefficient. With this definition of σ, and since the R_1 and R_2 levels have the same degeneracy, equation (1) is modified to

$$E = -\left[1 + \exp\left\{-(E_2-E_1)/kT\right\}\right] \frac{h\nu\rho R_2(1-R_1)\ \ln(R_1R_2)}{2\sigma\left[R_2+(1-R_2)(R_1R_2)^{\frac{1}{2}}-R_1R_2\right]} \qquad (3)$$

where E_2, E_1 are the energies of the R_2 and R_1 levels respectively. At room temperature the exponential term has value 0.74.

3. Calculation of ρ

ρ is a function of the fluorescent lifetime, the pump pulse shape and duration and the degree of pumping above threshold (k/k_c in Edwards' notation). ρ has been computed as a function of k/k_c for the actual pump pulse observed in this laser, (see figs. 1 and 2) and for a fluorescent lifetime of 180μs (as measured for this crystal). Since the pump pulse is shorter than the fluorescent lifetime, the value of ρ is only slightly dependent on the lifetime and on the precise pump pulse shape. In fact by computing ρ for a range of lifetimes between 160μs and 210μs, for a number of pulse shapes, triangular, rectangular and half sinusoid, with base lengths up to 180μs, and for values of k/k_c up to 3, it was found that the value of ρ differed by less than 3% from the values shown in fig.2. The fluorescent lifetime was measured (with mirrors removed) to check whether superradiance caused any lifetime shortening, but no reduction could be detected with pump levels up to $k/k_c=3$, the maximum level used in the experiment.

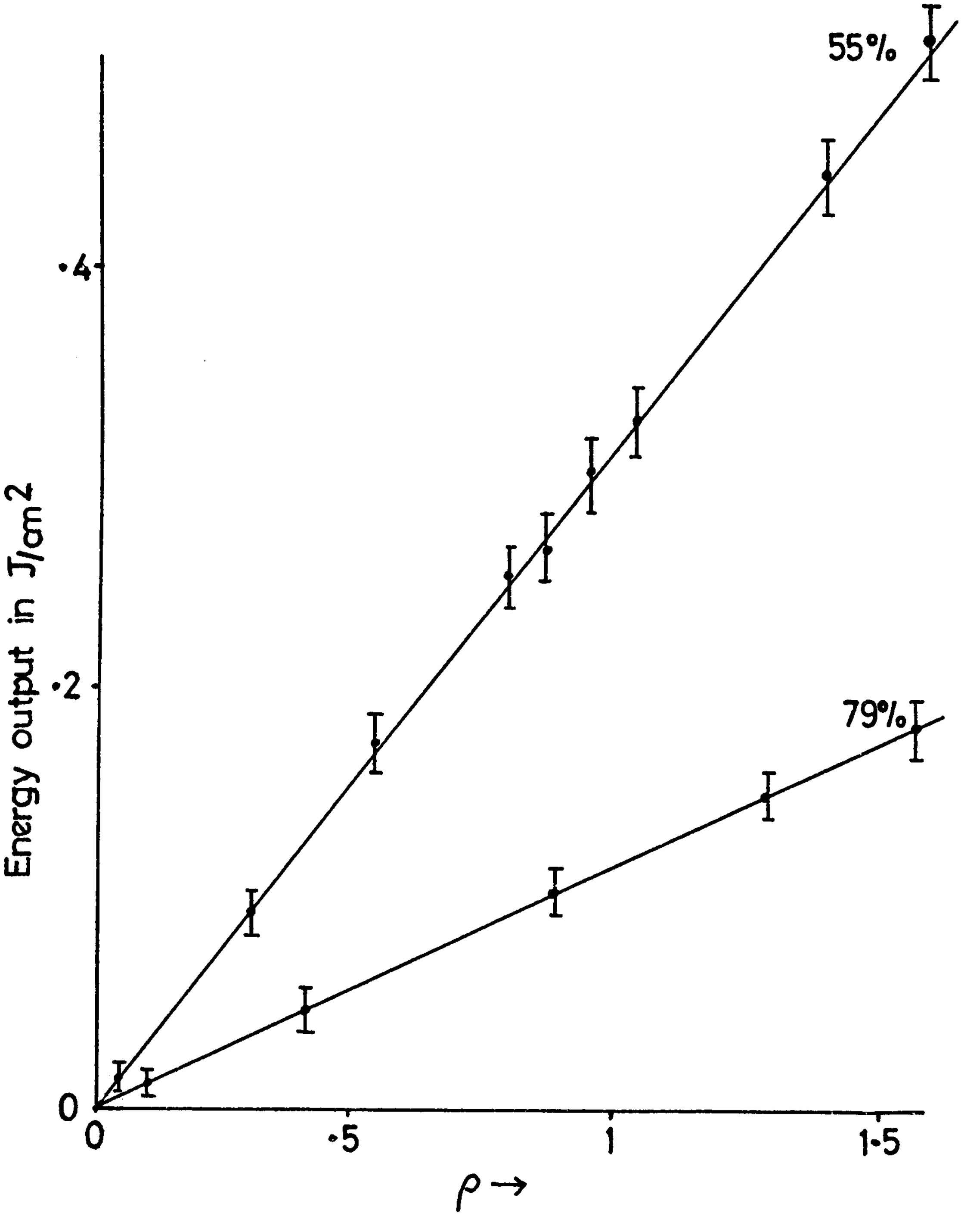

Fig 3

4. Experiment and Results

The laser resonator consisted of two plane mirrors with multilayer coatings having reflectivities of 79% and 55%, the reverse faces of the mirror blanks having antireflection coatings. The output energy was measured using a TRG calorimeter which was calibrated directly against Edwards' (ref.10) carbon cone calorimeter. Output energies could be monitored from either mirror and very close agreement was found between the two sets of results. Owing to pump nonuniformities in the laser rod (a focal ellipse pumping system was used), ρ varied across the rod. It was therefore necessary to ensure that the emitted energy per unit area was measured for that region of the rod which oscillated at threshold since it was only for this region that k/k_c, and hence ρ, was known. The large stimulated emission cross section results in small output energies and to obtain sufficient energy for the calorimeter the laser was operated at 2 p.p.s. and the energy was integrated over ten shots. A small correction was applied to allow for calorimeter cooling. The emitted energy was sampled over a circular area of 2.20mm diameter by means of an iris outside the resonator, centred on the region of maximum energy emission, and it was confirmed that threshold oscillation occurred at the centre of this circle. The variation of energy density over this area was monitored by scanning the area with a pinhole and photodiode. From this data emitted energy per unit area at the centre of the iris was calculated. Output energies were monitored for a range of pump energies (k/k_c) and fig.3 shows the emitted energy per unit area plotted as a function of ρ. The plot is a straight line as predicted by equation (2) and the value of σ is calculated from the gradient. The result obtained is $\sigma = 4.0 \times 10^{-19}\text{cm}^2$, with an estimated accuracy of ±15%. This value of σ has been used to predict output powers from the same laser when Q-switched by using the theory of Wagner and Lengyel (ref.11) (slightly modified for a 4-level system). The measured powers have been found to agree with calculated powers within the experimental errors thus giving further corroboration to the measured value of σ.

References

1. P. Mauer, "Amplification Coefficient of Neodymium-Doped Glass at 1.06 Microns", Applied Optics, 3, pp.433-434, March 1964.

2. D. W. Harper, "Assessment of Neodymium Optical Maser Glass", The Journal of Physics and Chemistry of Glasses, 5, pp.11-16, February 1964.

3. C. G. Young and J. W. Kantorski, "Saturation Operation and Gain Coefficient of a Neodymium-Glass Amplifier", Applied Optics 4, pp.1675-1677, December 1965.

4. J. G. Edwards, "Measurement of the Cross-Section for Stimulated Emission in Neodymium Glass", Nature, 212, pp.752-753, November 12, 1966.

5. J. G. Edwards, "Measurement of the Cross-Section for Stimulated Emission in Neodymium-Doped Glass from the Output of a Free-Running Oscillator". British Journal of Applied Physics ser.2, 1, pp.449-456, April 1968.

6. V. R. Belan, V.V. Grigoryants and M.E. Zhabotinski, "Use of Lasers in Measurements of the Stimulated Emission Cross Section", IEEE Transactions on Quantum Electronics, QE-3, pp.425-427, November 1967.

7. T. Kushida, H.M. Marcos and J.E. Geusic, "Laser Transition Cross-Section and Fluorescence Branching Ratio for Nd^{3+} in YAG", The Physical Review 167, pp.289-291, 10 March 1968.

8. H. Samelson, A. Heller and C. Brecher, "Determination of the Absorption Coefficient of Laser Transitions of the Nd^{3+}:SeOCl$_2$ System", Journal of the Optical Society of America, 58, pp.1054-1056, August 1968.

9. J.E. Geusic, H.M. Marcos and L.G. Van Uitert, "The Physics of Quantum Electronics", p.725 (McGraw-Hill, New York 1966).

10. J. G. Edwards, "An Accurate Carbon Cone Calorimeter for Pulsed Lasers", Journal of Scientific Instruments (GB) 44, pp.835-838, October 1967.

11. W. G. Wagner and B.A. Lengyel, "Evolution of the Giant Pulse in a Laser", Journal of Applied Physics, 34, pp.2040-2046, July 1963.