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Comparison of the laser performance of various neodymium doped materials in a compact diode pumped cavity

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I. INTRODUCTION

The need for compact and highly efficient laser sources has led us to study new neodymium doped materials, better matched to diode pumping than the commercially available Nd:YAG and Nd:YLF. Typical Nd doped single crystals with highly ordered structure exhibit narrow absorption bands (such as YAG). Then, precise control of the diode wavelength around 800nm (by the diode temperature adjustment) is required to efficiently pump such crystals but is detrimental to the wall plug efficiency.

On the opposite, disordered crystal structures usually present broadening of the absorption bands characteristic of the lanthanide ions, but are often correlated with a decrease in the stimulated emission cross section, and thus in the laser performance. Yttrium vanadate YVO₄ is the only well known lattice which simultaneously presents a broad absorption band around 800nm and a narrow and intense emission band in the near infra-red range. Nevertheless, its relatively short lifetime (about 90μs) doesn't allow an efficient energy storage for pulsed applications, and its crystal growth is especially tough. Another point of interest could be a large absorption coefficient well fitted to microchip lasers application.

Crystals with various structure have been grown by the Czochralski method, spectroscopically characterized and tested in a diode pumped cavity.

II. CRYSTAL GROWTH

The structure, melting point and growth conditions of the different Nd doped laser crystals are presented on Table I.

III. OPTICAL PROPERTIES

Polarized absorption and emission spectra of the different Nd doped materials have been recorded at room temperature and are used to calculate the polarized absorption cross sections near 800nm, zone of interest for the AlAsGa diode pumping. The absorption cross section of Nd:Y₂SiO₅ is compared to the one of Nd:YAG on Figure 1.

Using the Judd-Ofelt theory [1,2], the adjustable phenomenological Judd-Ofelt parameters Ω_t have been calculated from the measured oscillator strengths (table II). These Judd-Ofelt parameters have then be used to determine the electric dipolar transition line strengths $f^{DE}_{JJ'}$ between any two levels of Nd³⁺ in crystals, and especially the radiative emission rates $A^{DE}_{JJ'}$, branching ratio β and the radiative lifetime τ_r .

According to the theory used by FUCHTBAUER-LADENBURG [3], the absolute polarized emission cross section have been calculated (Table II) by knowing the branching ratio and the radiative lifetime:

$$\sigma_a^p(\lambda) = \frac{3\lambda^2 \cdot \beta}{8\pi n^2 \tau_r c} \frac{I^p(\lambda)}{\sum_p \int \frac{I^p(\lambda) d\lambda}{\lambda^2}}$$

where $I^p(\lambda)$ is the relative fluorescence intensity
 β and τ_r are respectively the branching ratio and the radiative lifetime
 previously calculated by the Judd-Ofelt theory.

IV. LASER TESTS IN A DIODE PUMPING CAVITY

Uncoated rods 5mm long and 5mm in diameter from different crystals have been tested in a cavity longitudinally pumped by a 1W SDL 2460 laser diode. The cavity was plano-concave with an output mirror radius $R_{oc}=10\text{cm}$. The waist of the laser cavity was $\omega_c=130\mu\text{m}$. Table III and Figure 2 present the laser performance of the materials tested for different output couplers transmissions.

The dependence of the laser output power versus the diode temperature has also been measured for YSO, YAG and YVO₄. The amplitude of the variation $\Delta\rho/\rho_0^{\text{max}}$, where ρ_0 is the optical efficiency ($P_{\text{out}}/P_{\text{inc}}$) has then been calculated for an arbitrary chosen 20°C variation in the diode temperature. For comparison, the Full Width at Half Maximum (FWHM) of the absorption coefficient has been measured from the absorption spectra and are reported on the following table:

MATERIAL	YSO (pol b)	YAG	YVO ₄
$\Delta\rho/\rho_0^{\text{max}}$	29%	64%	~7%
FWHM (nm)	2	1,5	9

V. CONCLUSION

As predicted, Nd:YVO₄ presents the best laser performance as a diode pumped material (high slope efficiency nearly independent of the diode temperature). However its tough crystal growth still limits its application.

Among the other Nd doped single crystals studied here, Nd:YSO seems to be one of the most promising laser materials:

- It reaches slope efficiencies of 54% for uncoated rods, which is slightly superior to the Nd:YAG performance without adjustment of any parameters.
- Crystals of large sizes and good optical quality can be grown, especially due to the large distribution coefficient of the neodymium ions in the lattice ($k\sim 0,7$).
- Its large absorption cross section makes it an interesting material for compact laser designs.
- Thanks to its absorption band near 810nm, slightly broader than the YAG one, it could be one of the possible trade-off between increased inhomogenous line broadening and reduced emission cross section and slope efficiency.

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Figure 1: Absorption band of Nd: YSO (X-axis)

Figure 2: Laser Efficiency of different Nd doped laser Materials

MATERIAL	Structure	Melting point (°C)	Nd ³⁺ concentration in the melt (%)	Nd ³⁺ concentration in the melt (10 ²⁰ at/cm ³)	Growth direction and atmosphere	Distribution coefficient (k)
YAG Y ₃ Al ₅ O ₁₂	Garnet (Cubic)	~1950	1,1	1,52	sample from Crismatec	k~0,18
YVO ₄	Tetragonal	~1850	2	2	sample from NEC	
YSO Y ₂ SiO ₅	Monoclinic	1930	1	1,87	<010> = b N ₂	k~0,7
GSO Gd ₂ SiO ₅	Monoclinic	~1900	2	3,86	<1 0 4> N ₂	k=1
SGS Sr ₂ Gd ₈ (SiO ₄) ₆ O ₂	Apatite (hexagonal)	~1900	1,5	2,22	<0 0 1> N ₂	k=1
CASIO Ca ₂ Al ₂ SiO ₇	Gehlenite (tetragonal)	1580	1	1,34	<1 1 0> N ₂	k>1
LMA LaMgAl ₁₁ O ₁₉	hexagonal	1910	13	4,42	<1 1 0> or <1 0 0>, N ₂	k=0,7-0,8
CYAO CaYAlO ₄	tetragonal	1810	1	1,3	<1 0 0> N ₂	k=1

Table I: Presentation of the different Nd doped crystals

Material	Ω_2 (10 ⁻²⁰ cm ²)	Ω_4 (10 ⁻²⁰ cm ²)	Ω_6 (10 ⁻²⁰ cm ²)	$X=\Omega_4/\Omega_6$	β	τ_r (μ s)	σ_e (10 ⁻¹⁹ cm ²)	$\sigma_e \tau_r$ (10 ⁻²⁵)
YAG	0,16	3,2	4,76	0,67	0,5	258	2,25	581
YVO ₄	-	-	-	-	-	98*	10-20	980-1960
GSO	0,65	3,53	4,86	0,73	0,48	230	0,96	221
YSO	2,84	4,78	5,41	0,88	0,46	220	0,87	191
CaYAlO ₄	1,59	7,93	7,90	1	0,45	140	0,77	108
SGS	3,36	5,78	5,83	0,99	0,46	199	0,65	129
LMA	1,23	1,75	2,24	0,78	0,47	560	0,58	325
CASIO	1,09	3,6	4,84	0,74	0,48	275	0,5	138

*: Measured fluorescence lifetime

Table II: Judd Ofelt Parameters

Material	CNd ³⁺ in the melt (E ₂₀ at/cm ³)	Absorption coeff. at λ_{pump} in the cavity (cm ⁻¹)	absorption coeff. at $\lambda_{\text{abs max}}$ (cm ⁻¹)	FWHM in absorption (nm)	Fluorescence lifetime (μ s)	rod axis (l=5 mm)	P _{th abs} (mW)	P _{out max} (mW)	Slope efficiency (%)	Output mirror reflectivity (%)
YAG	1,52	3,41 at 806 nm	11,3 at 808,5 nm	1,5	255	a	π : 49	235,8	52	94,8
YVO ₄	2	11,5 at 809,4 nm		9		a (4 mm)	π : 32	396,8	65	92
LNA	4,42	α : 4,54 at 798 nm		17,3	260	c	α : 168	251,1	40	97,25
SGS	2,22 (k=1)	σ : 6,6 at 808,5 nm π : 8,5 at 808,5 nm	9,6 at 809,5 nm 15,3 at 809,5 nm	4,1 3,8	168	a	σ : 138 π : 134	169,3 191,5	34 36	97,25 97,25
GSO	3,86	E//X E//Y : 7,4 at 799 nm E//Z : 7,8 at 800 nm	17,4 at 804,5 nm 14,1 at 801 nm 17,4 at 810 nm	2 2,3 1,6	185	b	E//Y : 134 E//Z : 198	138,8 122,8	23 22	96,9 96,9
YSO	1,87	E//X : 5,4 at 810 nm E//Z : 3,9 at 810 nm	10,2 at 810,8 nm 6,7 at 810,8 nm	1,8 1,8	~ 200	D1	E//b : 69 E//D2 : 80	259,5 200	54 48	97,25 97,25
(k= 0,6)										
CASIO	1,3	α : 7,10 at 807 nm		4,9	276	c	α : 198	149,9	36	95,9
CYAO	1,3	α : 9 at 806 nm	9,52 at 806,5 nm	4,3	123	c	α : 317	98,8	25	94,8

Table III: Laser Results of the different Nd doped crystals