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Journal of Alloys and Compounds 323–324 (2001) 210–213

Journal of ALLOYS AND COMPOUNDS

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Overview of the best Yb^{3+}-doped laser crystals

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Abstract

Using a model for the quasi-three level laser dealing with gaussian waves, taking into account the saturation of the pump, the stimulated emission at the pump wavelength, the variation of the pump and laser waists along propagation (important for laser diode pumping) and the variation of the laser intensity along propagation, we evaluate the more promising Yb^{3+}-doped crystals for laser applications: YAG, LNB, GdCOB, YCOB, YAB, C-FAP, S-FAP, KGdW, KYW, Sc_2O_3, Y_2O_3, Lu_2O_3. Our evaluation differs from Deloach et al. (IEEE J. Quant. Electron. 1993;29:1179). KYW, KGdW, YAB and Sc_2O_3 are found to be the most efficient when considering the laser extracted power and the slope efficiency.

Keywords: Insulators; Crystal growth; Electronic states (localized); Optical properties; Luminescence

1. Introduction

The most promising ion that can be used in a non-Nd laser in the same range of emission wavelength is Yb^{3+}. The Yb^{3+} ion have some advantages over the Nd^{3+} ion as laser emitting center due to its very simple energy level scheme, constituted of only two levels: the $^2F_{7/2}$ ground state and the $^2F_{5/2}$ exited state. There is no excited state absorption reducing the effective laser cross-section, no up-conversion, no concentration quenching. The intense Yb^{3+}absorption lines are well suited for laser diode pumping near 980 nm and the small Stokes shift (about 650 cm^{-1}) between absorption and emission reduces the thermal loading of the material during laser operation. The disadvantage of Yb^{3+} is that the final laser level is thermally populated (quasi three-level laser), increasing the threshold.

$Ca_5(PO_4)_3F$ (C-FAP) and $Y_3Al_5O_{12}$ (YAG) were soon recognized to be favorable hosts for Yb lasing. This fact was supported by an evaluation [1] of the spectroscopic properties of several Yb-doped crystals useful for laser action. This evaluation is based on two parameters known from spectroscopy: the emission cross-section σ_e at the laser wavelength and the minimum pump intensity I_{min} required to achieve transparency at the laser wavelength:

$$I_{min} = \frac{\sigma_a}{\sigma_e + \sigma_a} \frac{h\nu}{\sigma_{ap}\tau} \tag{1}$$

where σ_a is the absorption cross-section at the laser wavelength, σ_{ap} is the the absorption cross-section at the pump wavelength and τ is the $^2F_{5/2}$ lifetime. σ_e and I_{min} were used in Ref. [1] as figure-of-merit to classify the hosts, in a two-dimensional diagram. In the diagram (Fig. 1 drawn with the help of data from Refs. [2–12]), C-FAP ($Ca_5(PO_4)_3F$) and S-FAP ($Sr_5(PO_4)_3F$) appear to be exceptionally good, and YAB ($YAl_3(BO_3)_4$), GdCOB ($CaGd_4(BO_3)_3O$) and YCOB ($CaY_4(BO_3)_3O$) appear modest. This is somewhat in contradiction with experimental laser tests in which these latter materials are revealed very efficient: 73% slope efficiency in YAB, 77% in GdCOB, 78% in KYW($KGd(WO_4)_2$), 72% in KGdW ($KGd(WO_4)_2$), to be compared to 71 and 79% for S-FAP and C-FAP, respectively. We think that there is a need of a new evaluation of Yb-doped crystals in order to predict the laser efficiency in a more realistic manner in CW longitudinal pumping.

2. Approach of the evaluation

The purpose of this work is to present a new evaluation

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PII: S0925-8388(01)01112-4

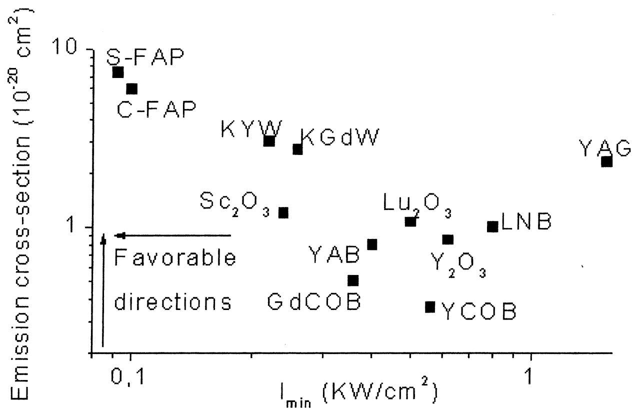

Fig. 1. Figure of merit from Ref. [1] for several promising Yb-doped hosts.

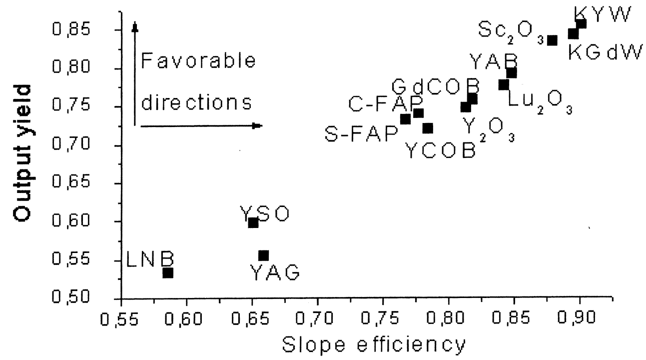

Fig. 2. Output yield ($P_{out}/Pump$) and differential slope predicted by our model for different crystals located inside the same laser cavity (see text).

based on a quasi-three level laser model (Eqs. (2)–(4) below), checked to be close to experimental laser data. The model deals with Gaussian waves, takes into account the saturation of the pump (which occurs for Yb ion because the $^2F_{5/2}$ level has a long lifetime up to 2.5 ms and accumulates population), the stimulated emission at the pump wavelength, the variation of the pump and laser waists along propagation (important for laser diode pumping) and the variation of the laser intensity along propagation. It is an extension of the model of Risk [13] and Taira et al. [14].

The fractions of population of the initial laser level ($^2F_{5/2}$) and of the ground state ($^2F_{7/2}$), N and N_0, respectively, in a steady state, are such that:

$$N_0(r,z) + N(r,z) = 1$$

$$0 = -\frac{N}{\tau} + I_p(r,z)(\sigma_{ap}N_0 - \sigma_{ep}N) + I_L(r,z)(\sigma_a N_0 - \sigma_e N) \quad (2)$$

τ is the initial laser level lifetime, $I_p(r,z)$, $I_L(r,z)$ are, respectively, the densities (photons/(cm^2 s)) of the pump beam and of the two counter-propagating laser waves inside the crystal. σ_{ep}, σ_{ap} are, respectively, the emission and absorption cross-sections of the pump and σ_e, σ_a the emission and absorption cross-sections of the laser beam.

The equation of propagation for the $\psi_1^+(r,z)\exp(-k_1 z)$ electric field of the laser wave stands in a nonparabolic approximation as:

$$\frac{\partial \psi_1^+}{\partial z} + \frac{i}{2k_1}\nabla_t^2 \psi_1^+ = \left[\sigma_e N(r,z)\frac{C}{2} - \sigma_a N_0(r,z)\frac{C}{2} - \frac{\alpha_1}{2}\right]\psi_1^+ \quad (3)$$

C is the laser ion concentration. Eq. (3) is valid for forward propagation; for backward propagation (ψ_1^- electric field), we have to change the signs of k_1, n_1 and of the bracket. The equation of propagation for the $\psi_p(r,z)\exp(-k_p z)$ electric field of the pump wave stands as:

$$\frac{\partial \psi_p}{\partial z} + \frac{i}{2k_p}\nabla_t^2 \psi_p = \left[\sigma_{ep}N(r,z)\frac{C}{2} - \sigma_{ap}N_0(r,z)\frac{C}{2}\right]\psi_p \quad (4)$$

Our evaluation is based on the laser output power and the

Table 1
Spectroscopic data of Yb-doped crystals evaluated in this work

	Conc. (10^{20} ions cm^{-3})	σ_{ap} (10^{-20} cm^2)	σ_{ep} (10^{-20} cm^2)	σ_e (10^{-20} cm^2)	σ_a (10^{-20} cm^2)	λ_p (nm)	λ_e (nm)	τ (μs)	L_{opt} (mm)	R_{opt} (%)
YAG	8.97	0.8	0.159	2.3	0.149	942	1029	951	2.9	93
YCOB	8.97	1.0	0.959	0.36	0.026	976.4	1032	2280	3.4	98
GdCOB	8.97	1.1	1.12	0.5	0.027	975	1035.3	2500	3.4	98.5
YAB	8.97	3.4	2.99	0.8	0.040	975	1040.3	680	1.2	99.5
C-FAP	0.36	10.0	0.132	5.9	0.377	905	1043.3	1100	8.5	95
S-FAP	0.36	8.6	0.076	7.3	0.407	899	1047.3	1260	9.5	92
KGdW	8.97	12	14.6	2.7	0.289	981	1023.3	600	0.45	99.5
KYW	8.97	13.3	16.0	3	0.299	981.2	1025.3	600	0.4	99.5
LNB	1.89	1	1.02	1	0.023	980	1060	540	9	98
Sc_2O_3	8.97	4	4.0	1.2	0.05	975	1041	800	1.2	99.5
Y_2O_3	8.97	2.4	2.3	0.85	0.06	975	1031	850	1.6	99
Lu_2O_3	8.97	3	2.9	1.07	0.07	975	1032	820	1.4	99.5
YSO	8.97	0.47	0.007	0.29	0.007	901	1059	1400	5.2	98.7

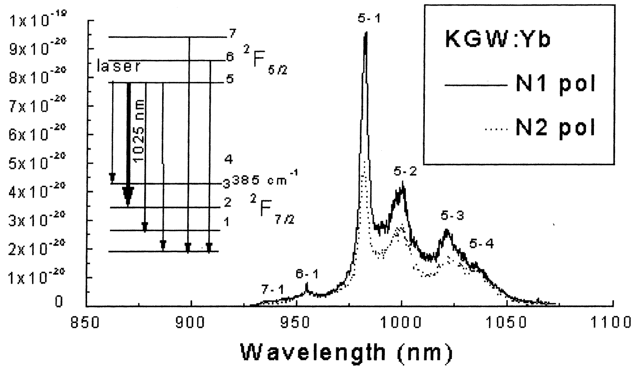

Fig. 3. Emission cross-section of KGdW:Yb.

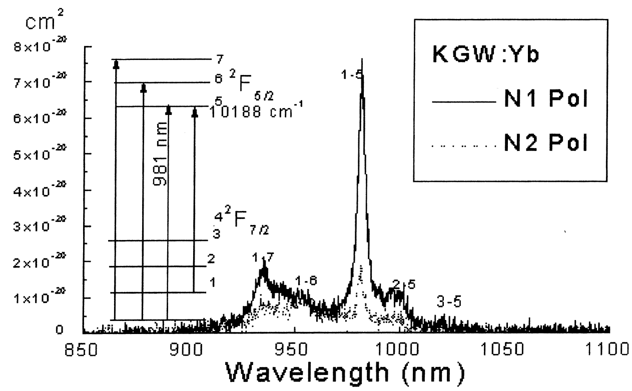

Fig. 4. Absorption cross-section of KGdW:Yb.

differential slope extracted from the crystals ($Sr_5(PO_4)_3F$ (S-FAP), $KY(WO_4)_2$ (KYW), $KGd(WO_4)_2$ (KGdW), $CaGd_4(BO_3)_3O$ (GdCOB), $CaY_4(BO_3)_3O$ (YCOB), $YAl_3(BO_3)_4$ (YAB), Y_2O_3, Lu_2O_3, Sc_2O_3, Y_2SiO_5 (YSO), $LiNbO_3$ (LNB)) located inside the same laser cavity and calculated numerically with the model. The pump power has been fixed to 1 W. The laser waist was 22 μm and the pump waist 29 μm. The crystals concentration was chosen typical in laser experiments for each crystal. We used a rather high concentration: 8.97×10^{20} ions cm^{-3} for crystals having a rare earth crystallographic site (YAG, YCOB, GdCOB, YAB, KGdW, KYW), and a lower concentration: 0.36×10^{20} ions cm^{-3} [1] for crystals having a low segregation coefficient (C-FAP and S-FAP).

For each crystal we have determined numerically with the model the crystal length L_{opt} and the reflectivity R_{opt} of the output mirror leading to the maximum laser output power.

3. Results

All spectroscopic data of Yb-doped crystals which have been evaluated in this work are given in Table 1.

The results of calculation (P_{out} and $dP_{out}/dPump$) are shown Fig. 2. We can see that KGdW and KYW have the highest laser potentialities, it is surprising that YAG has the lowest. S-FAP and C-FAP appear less efficient than GdCOB and YAB. Cubic sesquioxides (Sc_2O_3, Lu_2O_3, Y_2O_3) are also well positioned in this evaluation. They are

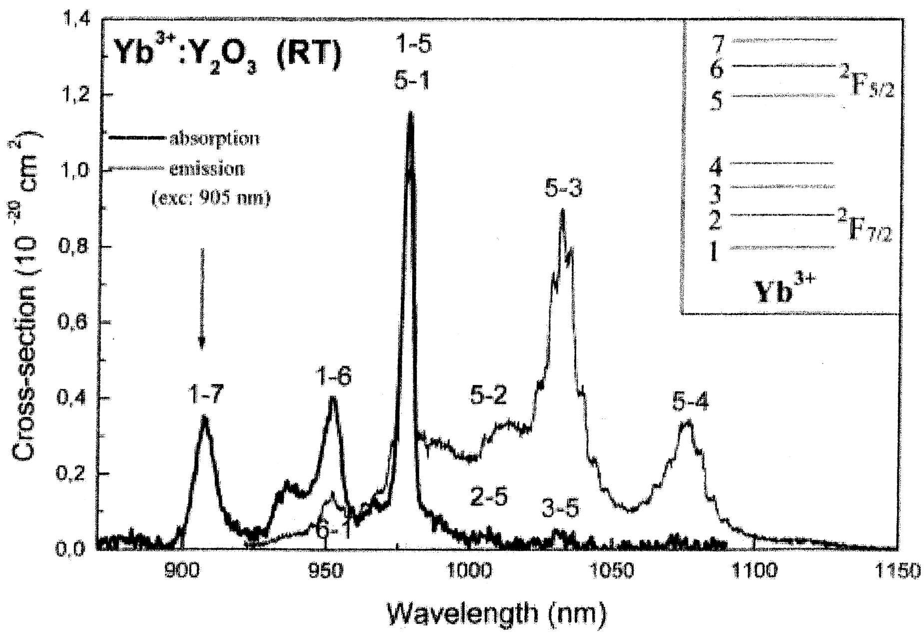

Fig. 5. Absorption and emission cross-sections of Yb^{3+} in Y_2O_3.

in addition characterized by the highest thermal conductivity (27 W m^{-1} °C).

Let us noticed that KYW and KGdW have the advantage to be grown in the adequate size in 1 day by the top nucleated floating crystal (TNFC) method [15] and that the Yb-doped sesquioxides can be grown by the laser heated pedestal growth method (LHPG) [16–18]. In Figs. 3 and 4 we present the emission and absorption cross-sections in KGW:Yb grown in our laboratory by the TNFC method and in Fig. 5 we show the emission and absorption cross-sections of Y_2O_3:Yb grown in our laboratory by LHPG method. In Figs. 3 and 4, N_1 and N_2 polarizations are such that the light propagates in the *b*-direction with the index of refraction n_m (=1.986 at 1.06 μm) and n_g (=2.033 at 1.06 m), respectively. The spectra can be interpreted in agreement with the Yb^{3+} scheme of levels. We can see that the emission cross-section near 1025 nm is high enough and so this material is a good candidate for several applications such for example the replacement of argon ion laser, after frequency doubling.

4. Conclusion

We have presented an accurate model for a quasi-three level laser. It deals with Gaussian waves, it takes into account the saturation of the pump (which occurs for Yb ion), the stimulated emission at the pump wavelength, the variation of the pump and laser waists along propagation (important for laser diode pumping) and the variation of the laser intensity along propagation. The model is used to predict the output power and the differential slope of lasers constituted with the most promising (at the present time) Yb-doped crystals located inside the same cavity. This evaluation shows that KYW, KGdW and Sc_2O_3 crystals are the most efficient, with YAB and GdCOB. Contrary to the Deloach et al. evaluation [1], C-FAP and S-FAP crystals no longer have an exceptional position in our evaluation.

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