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Optical and lasing properties of crystals for diode pumped solid state lasers

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Spectroscopic properties of yttrium-aluminium garnet $Y_3Al_5O_{12}$ (YAG) doped with Ce, Pr, Nd, Sm, Eu, Ho, Er, Tm, Yb ions and Nd:YAP, Nd:$SrLaGa_3O_7$, Nd:$SrLaAlO_4$, Nd:YVO_4, Nd:$LiYF_4$, Nd:$PbMoO_4$, Nd:LGS, Nd:GGG, Nd:SVAP monocrystals have been investigated. Absorption spectra of the monocrystals in the range of 200 nm – 20 μm and the luminescence spectra in the range of 200–800 nm for Pr:YAG, Pr:YAP and Pr:$SrLaGa_3O_7$ were determined. Except for Pr:YAG, Sm:YAG, Eu:YAG and Pr, Yb:YAG, in all other materials strong absorption bands appeared in the range of 780–840 nm, which enabled an efficiency analysis of selective pumping to be carried out with the use of GaAlAs laser diodes.

1. Introduction

Since 1984 when Spectra Diode Labs introduced on the market GaAlAs laser diodes working in the cw-mode with 100 mW output power, solid state lasers pumped with semiconductor laser diodes have become the most dynamical laser group with wide potential applications in industry, medicine, telecommunication scientific research work, and optical velocimetry. They offer considerable advantages over flashlamp pumped lasers, such as long life, compact size, high efficiency, lower heat dissipation and solid state reliability.

Among diode-pumped lasers, Nd:YAG and Nd:YLF active media with frequency multiplication possibilities are the most popular and commercially available. Even though YAG and YLF are both good hosts, they can be doped with a maximum of only about 1 at.%Nd^{3+} without unacceptable degradation of crystal quality. As a result, the pump light absorption is weak and long samples (about 6–10 mm) are needed for effective diode pumping. Long samples require more complex focusing optics due to the poor beam quality of diode laser pump light. The result is increased complexity and cost of products. To further improve diode pumped laser design, there is a need for higher Nd doping host. The potential range of active materials for such applications is very broad.

2. Samples and experimental procedures

Optical homogeneity of the crystals measured was examined by the plane-polariscope and Mach–Zehnder interferometer. Samples with diameters of 10 mm and thickness of 1–2 mm were cut out from the most homogeneous parts of the crystals made in the Institute of Electronic Materials Technology, Warsaw, and Institute of Materials, Lvov. These samples have undergone spectroscopic and luminescence investigations. In order to calculate the absorption coefficient of investigated crystals, transmission measurements were carried out using LAMBDA-2 Perkin–Elmer spectrophotometer in the spectral range of 200–1100 nm, BECKMAN ACTA MVII spectrophotometer in the spectral range of 1100–1400 nm and FTIR 1725 Perkin–Elmer Fourier spectrophotometer in the spectral range of 1.4–25 μm. In the range of 750–850 nm investigations were made with 0.1 nm accuracy.

Dispersion of the absorption coefficient $\alpha(\lambda)$ was calculated from transmission $T(\lambda)$ measurements with the consideration of multiple reflections within a sample.

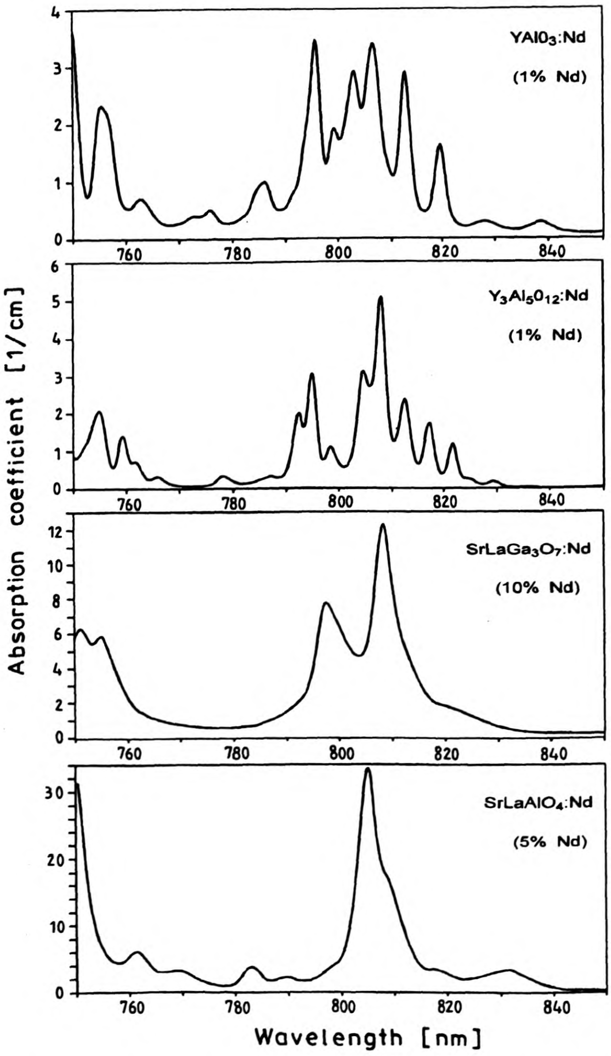

Fig. 1. Absorption spectrum for Nd:$YAlO_3$, Nd:$SrLaGa_3O_7$ and Nd:$SrLaAlO_4$ compared with Nd:$Y_3Al_5O_{12}$ for laser diode pumped region of 750–850 nm

The absorption spectra for investigated crystals, by comparison to Nd:YAG one, are shown in Figs. 1–4 in the range of 750–850 nm. The biggest value of the peak absorption coefficient equal to 33.6 cm^{-1} appears for $Nd{:}SrLaAlO_4$ crystal and 808.4 nm line, but the other most interesting crystal for diode pumped laser devices is $Nd{:}YVO_4$ with the value of peak absorption coefficient of 16.8 cm^{-1} for 808 nm.

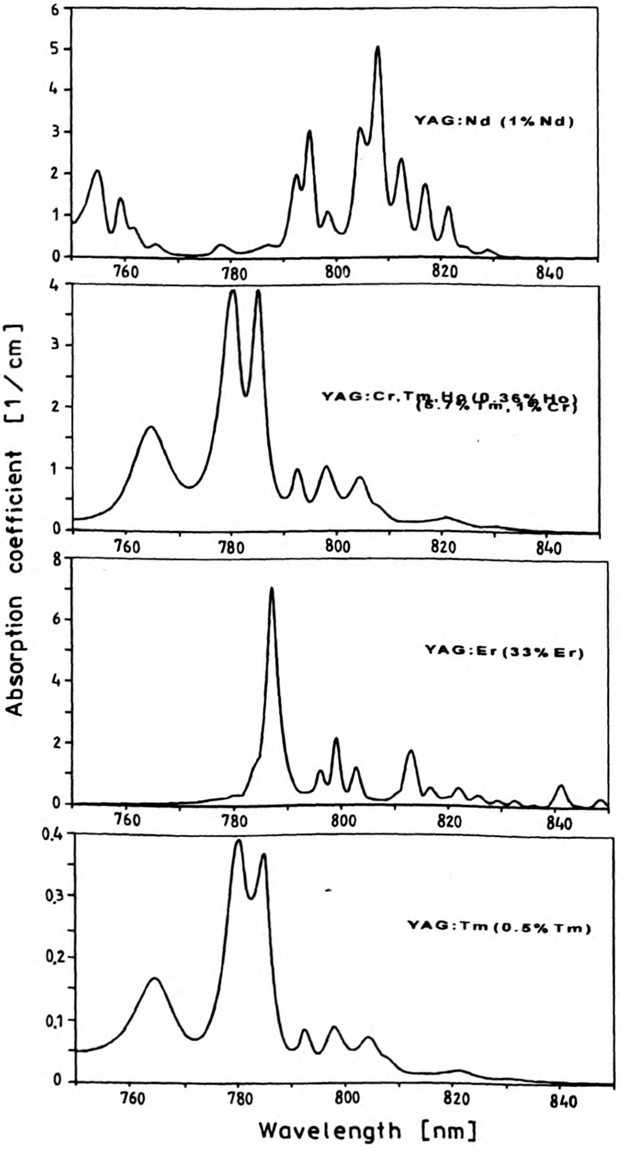

Fig. 2. Absorption spectrum for CTH:YAG, Er:YAG and Tm:YAG compared with Nd:YAG for laser diode pumped region of 750–850 nm

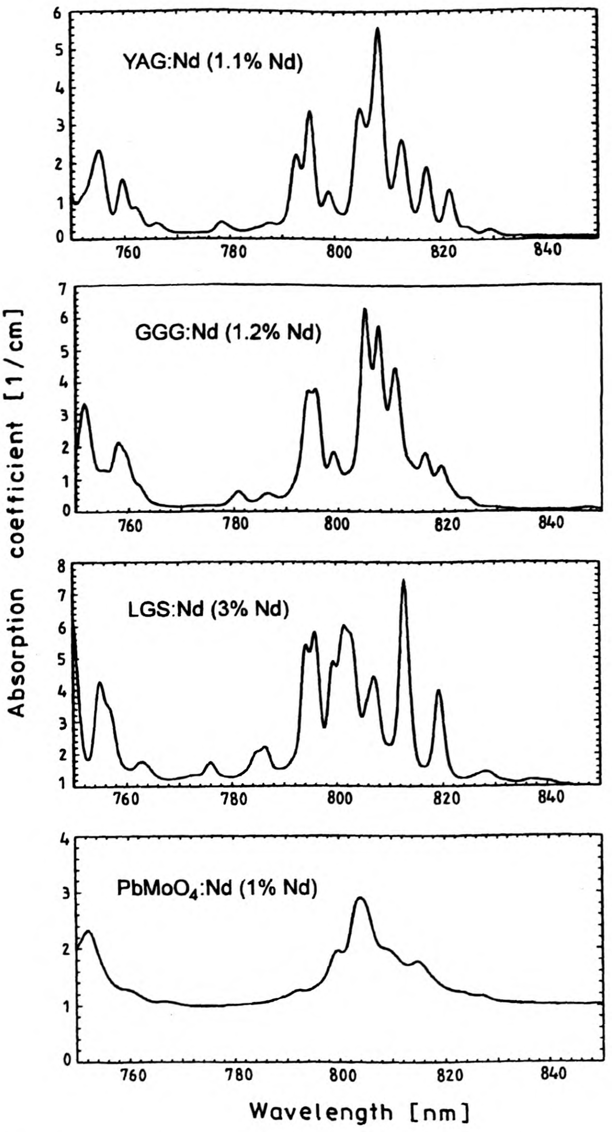

Fig. 3. Absorption spectrum for Nd:GGG, Nd:LGS and Nd:$PbMoO_4$ compared with Nd:YAG at laser diode pumped region of 750–850 nm

Among the crystals investigated at room temperature and the range of 200–800 nm the appearance of the strongest emission lines has been recorded in the case of Pr:YAG (489, 565.5, 620 nm), Pr:YAP (494, 502.5, 503.5) and Pr:$SrLaGa_3O_7$ (489 nm). A free-running laser emission of $\lambda = 620$ nm for Pr:YAG and Pr:SLG has been obtained for lamp pumped system.

There are many different parameters of the active medium that are very important for diode pumped application. The list of the most important ones in-

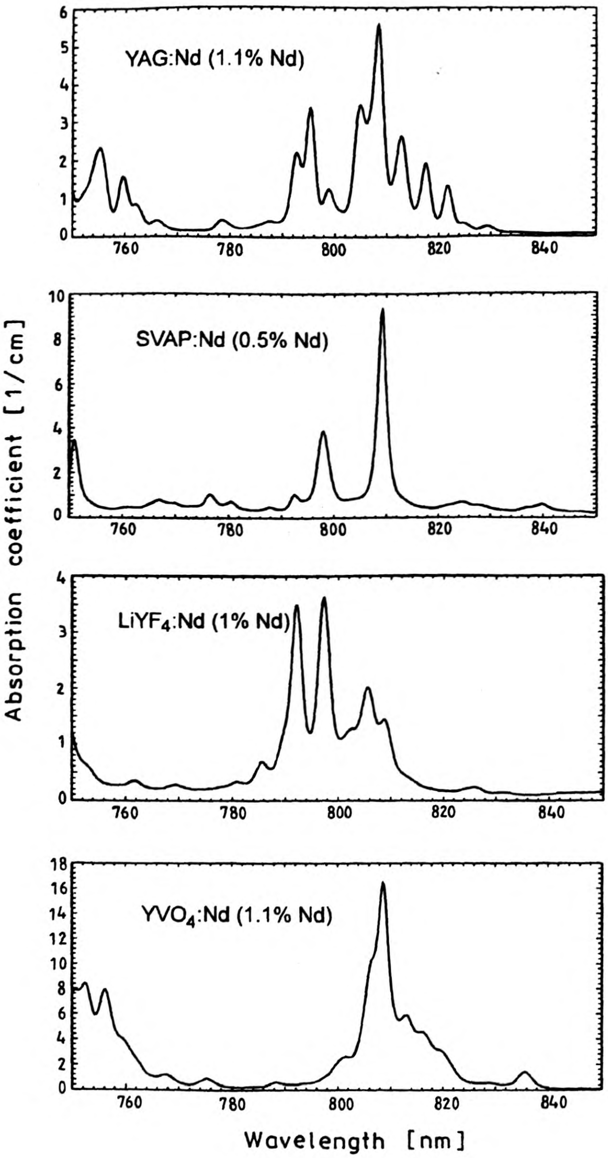

Fig. 4. Absorption spectrum for Nd:SVAP, Nd:YLF and Nd:YVO compared with Nd:YAG at laser diode pumped region

cludes: effective laser cross-section, laser wavelength, linewidth, polarization of the output beam, radiative lifetime, pump wavelength and bandwidth, thermal conductivity, heat capacity and slope efficiency of laser. These features for three vanadate crystals are compared to Nd:YAG in Table 1.

Vanadate crystals have some very important advantages. Laser gains and efficiencies are higher than those of Nd:YAG. The laser cross-sections for the vanadate crystals are from 1.8 to 5.6 times greater than in the case of Nd:YAG. They are uniaxial, producing only polarized laser output and maintain a strong single-line emission at 1.06 μm. Pump bandwidths are from 2.4 to 6.3 times that of Nd:YAG. The peak pump wavelength is 808 nm, the standard for laser pumping and currently manufactured high power diodes. But vanadate laser host materials do have some disadvantages. The principal one is that they have shorter excited-state lifetimes. On average, the lifetime for vanadate crystals is only 45% of the lifetime of Nd:YAG. Another disadvantage is that their thermal conductivities are lower than that of Nd:YAG which leads to heat-load, thermal lensing and phase distortion in end pump configuration. Vanadate crystals are also difficult to grow (different defects in doping process).

The next group of crystals for diode pumped solid state laser devices are gellate crystals. Some features of crystals that belong to gellate family are shown in Tab. 2.

Table 1. Comparison of some properties of vanadate crystals and Nd:YAG

	YAG	YVO_4	$GdVO_4$	$Sr_5(VO_4)_3F$
Effective laser cross-section [10^{-19} cm^{-2}]	2.8	15.6	7.6	5.0
Laser wavelength [nm]	1064.2	1064.3	1062.9	1065
Linewidth [nm]	0.6	0.8	–	1.2
Polarization	none	//c	//c	//c
Radiative lifetime [μs]	255	115	–	220
Lifetime at 1 at.% [μs]	230	100	94	–
Peak pump wavelength [nm]	808	808.5	808.4	809.6
Peak pump absorption cm^{-1} at 1 at.%	8	40.7	57	28
Pump bandwidth (FW75%) [nm]	2.5	15.7	13.5	5.9
Thermal conductivity [W/mK]	10.3	5.14	–	1.7
Slope efficiency	60	72	54	66

YVO_4 – yttrium orthovanadate, $GdVO_4$ – gadolinium orthovanadate, $Sr_5(VO_4)_3F$ – strontium fluorovanadate.

Table 2. Comparison of some properties of gallate crystals

	Pump peak wavelength [nm]	Absorption coefficient [cm^{-1}]	Pump FWHM [nm]	τ [μs]	Laser cross-section [$10^{-20}cm^{-2}$]	Slope eff.
1.1% Nd:YAG	808	8	1	230	28	
2% Nd:SGGM	809	6	8	245	6.6	
4% Nd:SGGM	809	12	8	212	–	40%
2% Nd:LGS	809	8	5	220	7.4	
4% Nd:LGS	809	16	5	195	–	48%
2% Nd:LGG	809	68	7	220	8.8	
12% Tm:SGGM	790	1.7	15	6900	0.63	

$SrGdGa_3O_7$ (SGGM) – strontium gadolinium gallium melilite, $SrLaGa_3O_7$ (SLG) – strontium lantanium gallium melilite, $SrLaAlO_4$ (SLA) – strontium lantanium alluminate melilite, $La_3Ga_5GeO_{14}$ (LGG) – gallogermanates, $La_3Ga_5SiO_{14}$ (LGS) – silicate isomorph.

They are easy to grow using the Czochralski technique and can be obtained with a high level of doping with Nd ions. The thermal conductivities of gellate crystals are relatively high in comparison to that for Nd:YAG. In spite of the high level of doping with Nd ions, gellate crystals have smallest $\sigma\tau$ quotient and thus, larger threshold and lower efficiency.

For the phosphate materials (Tab. 3) it is also easy to obtain a high level of Nd ion doping (even 15–30%) and efficiency of 30–35%. They have a wide pump bandwidth which means more efficient pumping and operation at a wider range of temperatures. But the peak of absorption appears at 789 nm line. The principal disadvantage of phosphate laser host materials is that they have shorter excited-state lifetime. Pump absorption increases linearly with neodymium concentration, presenting a trade-off between pump absorption and lifetime.

Table 3. Comparison of some properties of phosphate crystals

	LNP	NNP	NdPP	YAG
Laser wavelength [nm]	1047	1061	1061	1064
Effective laser cross-section [10^{-19}cm^{-2}]	3.2	2.1	1.13	2.8
Lifetime at 1 at.% [μs]	120	110	120	230
Peak pump absorption [cm^{-1} at 1 at.%]	40	39	32	1.1

LNP – $LiNdP_4O_{12}$, NdPP – NdP_5O_{15}, LMA – $LaNdMgAl_{11}O_{19}$.

Laser efficiency of 60% characterizes fluoride crystals (Tab. 4) with a doping level of about 4%. For YLF and GLF the peak absorption line appears at 792 nm and absorption coefficient equal to 28 cm^{-1} for π polarization and 10 cm^{-1} for σ polarization. FAP and SFAP crystals can be doped also with Yb, Er, Tm, Ho, Cr ions. YLF crystals are uniaxial and have two principal lasing transmissions, one at 1053 nm and one at 1047 nm. The lifetime of the upper laser level is twice as long as that of Nd:YAG, resulting in improved energy storage in the upper laser level. YLF is thus performed for pulse operation.

Table 4. Comparison of some properties of fluoride crystals

	YAG	YLF	GLF	FAP
Effective laser cross-section [10^{-19} cm^{-2}]	2.8	2.1	7.6	5.0
Laser wavelength [nm]	1064.2	1047	1047	1065
Linewidth [nm]	0.6	2	2	2.5
Polarization	none	//c	//c	//c
Radiative lifetime [μs]	255	570	500	256
Lifetime at 1 at.% [μs]	230	520	475	197
Peak pump wavelength [nm]	808	797	792	807
Peak pump absorption cm^{-1} at 1 at.%	8	3.5	28	12
Pump bandwidth (FW75%) [nm]	2.5	3.5	5	3
Thermal conductivity [W/mK]	13	7.2	6.8	0.2
Slope efficiency			60	67

$LiYF_4$ – (YLF), $GdLiF_4$ – (GLF), $Ca_5(PO_4)_3F$ – (FAP) calcium fluoropatite, $(Ca_{1-x}Sr_x)_5PO_4)_3F$ – (SFAP) calcium-strontium fluoropatite.

The negative value of dependence of refractive index on temperature reduces thermal effects. The dependence of refractive index on temperature is a very important parameter. For fluorides, this parameter is normally negative, positive value of this parameter is for oxides such as YAG crystals. Phosphates and silicates may have both positive and negative values depending on the composition and structure.

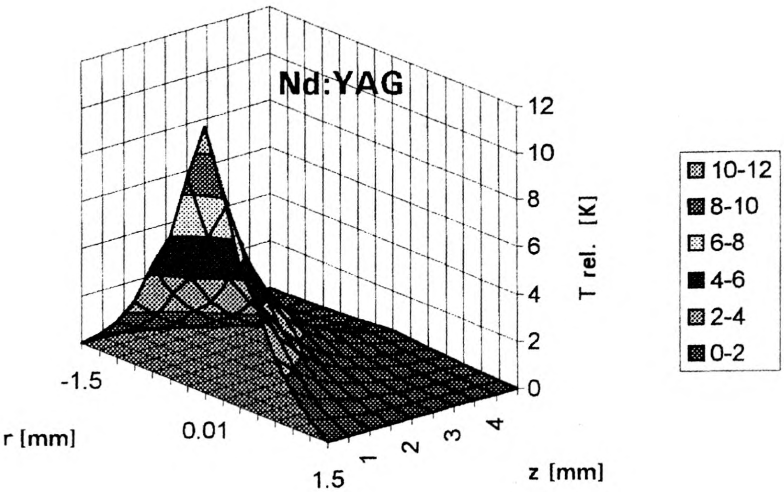

Fig. 5. Calculated cw temperature distribution in an optically end-pumped laser rod for the 1 W pump power. The heat source is assumed to be radially symmetric of Gaussian shape with constant radius along z-axis

The temperature distribution in diode pumped active medium takes the fundamental role in creating the laser radiation. Despite of significantly lower heat load in diode pumped, compared to lamp pump one, the thermally induced gradients of physical properties of the crystals are the main source of problems with the beam quality. The temperature distribution in diode pumped Nd:YAG laser rod for 1 W of pump power is shown in Fig. 5.

3. Conclusions

The potential range of active materials for novel solid state lasers application in coherent optical velocimetry is very broad. Diode pumped solid state lasers working as the stable single frequency, double frequency, chirped frequency sources started to dominate in the last years. They can replace many classical laser systems and increase the velocity range.

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