Vol 17 No 9, September 2008
1674-1056/2008/17(09)/3407-05

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

Comparative spectroscopic investigation of Yb-doped YAG, YSAG and $YLaO_3$ transparent ceramics*

Jiang Ben-Xue(姜本学)[a], Huang Tong-De(黄同德)[a], Wu Yu-Song(吴玉松)[a],
Liu Wen-Bin(刘文斌)[a], Pan Yu-Bai(潘裕柏)[a]†,
Feng Tao(冯 涛)[a], and Yang Qiu-Hong(杨秋红)[b]

[a] *Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai* 200050, *China*

[b] *Shanghai University, Shanghai* 200072, *China*

(Received 20 February 2008; revised manuscript received 31 March 2008)

Transparent Yb doped YAG, YSAG and $YaLaO_3$ ceramics are fabricated by using the co-precipitation method. The spectral properties and thermal parameters of these Yb doped cubic phase transparent ceramics are compared, and their different and potential applications are also analysed. The absorption cross-section and the emission cross-section of these ceramics are measured and calculated. The essential properties of these materials especially for the rep-rated pulsed high-energy diode-pumped solid-state lasers are investigated. The results show that Yb doped YAG, YSAG and $YaLaO_3$ are all suitable materials used for diode-pumped solid-state lasers.

Keywords: spectral properties, Yb:YAG, Yb:$YLaO_3$, transparent ceramics
PACC: 6150K, 7800, 8120L

1. Introduction

Yb^{3+} ion spectroscopy has received considerable attention over the past years for it is related to an attractive high power and high efficiency diode-pumped solid-state laser.[1−3] This kind of laser has a high quantum efficiency of over 90% (Figs.1 and 2),[4] less heat generation in the laser material and a longer upper-state lifetime of ∼1 ms. Moreover, it has no undesirable loss processes such as excited-state absorption, up-conversion, and concentration quenching due to its simple electric structure. As a result, Yb:YAG has several advantages compared with Nd:YAG for diode laser pumping.[5−7] In addition, the wide emission bandwidth of the Yb^{3+}-doped material, around 1 μm, allows high power tunable ultra-fast lasers.[8−10]

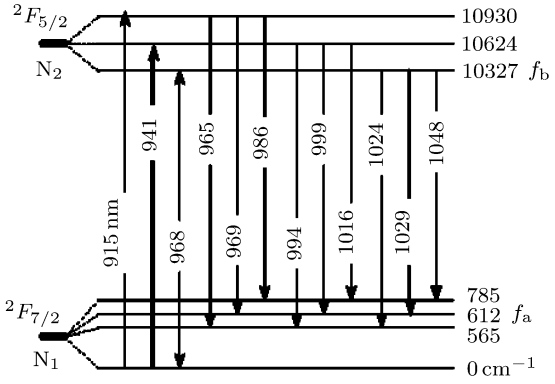


Fig.1. Energy level diagram of Yb:YAG crystal.

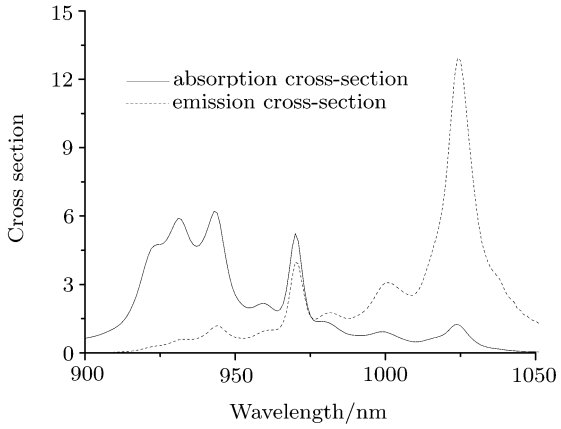


Fig.2. Calculated absorption and emission cross sections of Yb:YAG crystal.

*Project supported by National Science Foundation for Post-doctoral Scientists of China (Grant No 20070420677), Applied Basic Research Program of Sciences and Technology Commission Foundation of Shanghai, China (Grant No 06DZ11417), High Technology Research and Development Program of China (Grant No 2007AA03Z523).

†Corresponding author. E-mail: ybpan@mail.sic.ac.cn

The aim of this paper is to report the spectral and thermal properties of Yb doped $Y_3Al_5O_{12}$(YAG), $Y_3Sc_xAl_{5-x}O_{12}$(YSAG) and $Y_{2-x}La_xO_3$($YLaO_3$) transparent ceramics. Emphasis is laid on results obtained for their application to rep-rated pulsed high-energy diode-pumped solid-state lasers.

2. Experiment

The preparation of Yb:YAG powders were carried out by using the co-precipitation method that is shown in Fig.3. The Yb:YSAG and $YLaO_3$ powders were also prepared by using the co-precipitation method, just with the start aqueous solution changed.

After being sintered in vacuum, the Yb doped transparent ceramics were annealed at 1450°C for 20 h in air. This process made the Yb^{2+} ions turn into Yb^{3+} ions. Both surfaces of the sample were polished and used to measure the optical transmittance and the absorbed spectrum by using a Model U-2800 Spectrophotometer (Hitachi, Japan) and the fluorescence spectra by using a Triax 550 spectrophotometer with an InGaAs laser diode as a pump source (excited at 940 nm).

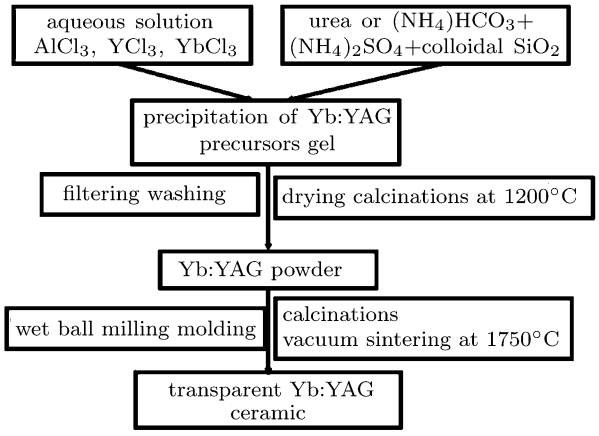


Fig.3. Schematic diagram for the procedure of Yb:YAG powder synthesis in the co-precipitation method.

3. Results and discussion

The absorptions of Yb^{3+} doped YAG, YSAG and $YLaO_3$ ceramics occur in a wavelength range of 850–1050 nm, as illustrated in Fig.4. From Fig.4 we can see there are four main absorption bands in these Yb doped ceramics. The absorption centres are listed in Table 1.

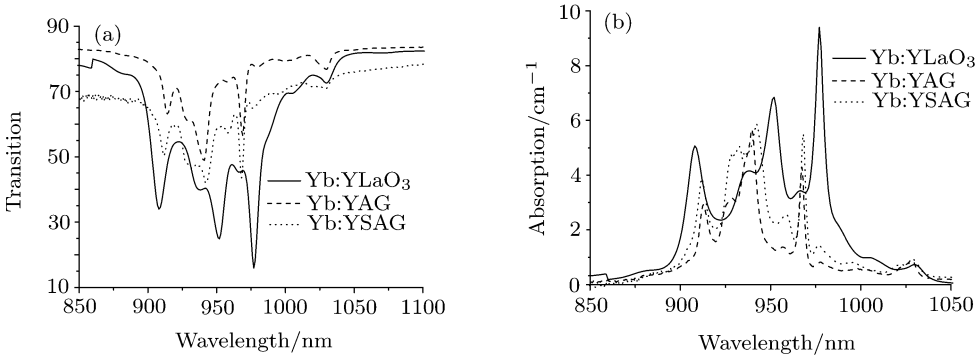


Fig.4. Absorption and transition spectra of 5at% Yb doped $YLaO_3$, YAG and YSAG ceramics.

Table 1. Absorption centres of Yb^{3+} doped YAG, YSAG and $YLaO_3$ ceramics.

	absorption centres				re-absorption centres
YAG ceramics	912.8 nm	929.0 nm	939.6 nm	967.4 nm	1028.2 nm
YSAG ceramics	912.0 nm	932.8 nm	942.4 nm	968.3 nm	1029.4 nm
$YLaO_3$ ceramics	908 nm	938 nm	952 nm	977 nm	1030 nm

The biggest absorption coefficients of 5at% Yb^{3+} doped YAG, YSAG and $YLaO_3$ ceramics are 5.67, 4.34, and 9.4 cm^{-1} centred at 939.6, 942.4 and 977 nm respectively. The absorption coefficient of Yb:$YLaO_3$ ceramics is almost double of those of the other two ceramics. So we can achieve the same absorption materials with a small doping level, and this will lead to a higher thermal conductivity (at a high doping

level, the thermal conductivity turns lower). This is very useful for making high-energy diode-pumped solid-state lasers.

The line-widths (FWHM) of absorption band of Yb:YAG ceramics at 939.6 nm and 967.4nm are about 12 and 3 nm, respectively, while those of Yb:YSAG ceramics at 942.4 nm and 968.3 nm are about 16 and 4 nm, and the absorption bands of Yb:$YLaO_3$ ceramics at 952 nm and 977 nm are about 16 and 7 nm, respectively. A wide full width at half maximum (FWHM) means that the laser crystal can accommodate some thermal shift of the pump light wavelength, and the power output of the laser remains stable. Therefore, the FWHM of absorption band at pump wavelength is one of important parameters for a laser crystal. We can see that Yb:$YLaO_3$ ceramics have the widest FWHM, so it has the most tolerant thermal shift of the pump light wavelength.

The absorption spectra in Fig.5 are 5at%, 10at% and 20at% Yb doped YAG and YSAG ceramics. From them we can see that with a higher Yb doping level, the FWHM becomes wider and the absorption centres around 941 and 970 nm shift toward blue, and also the re-absorption coefficient turns larger. So with a higher Yb doping level, the laser thresholds of these ceramics turn higher, which an adverse factor influencing their performance.

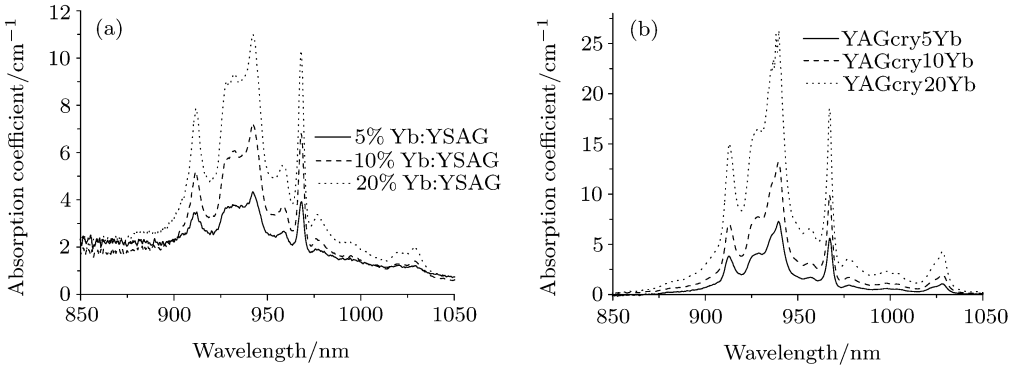


Fig.5. Absorption spectra of YAG and Yb:YSAG ceramics with different Yb doped levels.

The phosphorescence spectra of 5at% Yb:YAG, Yb:YSAG and $YLaO_3$ ceramics at room temperature are shown in Fig.6. It was acquired by using a TRIAX 550 spectrophotometer with InGaAs LD used as a pump source (excited at 940 nm). The decay times of 1.2, 1.4 and 1.1 ms for 5at% Yb:YAG, Yb:YSAG and $YLaO_3$ ceramics were measured by a using a computer-controlled transient digitizer. The strongest emission peaks of Yb:YAG and Yb:YSAG ceramics are located at wavelengths of 1030 and 1029.2 nm. From the absorption spectra and the phosphorescence spectra of the three Yb doped ceramics we can see that Yb:$YLaO_3$ has the weakest Stokes shift, which leads to the smallest energy loss.

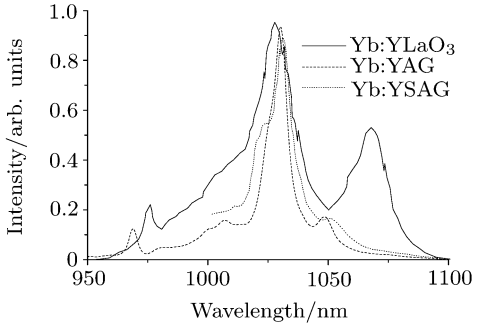


Fig.6. Fluorescence spectra of Yb:YAG, Yb:YSAG and Yb:$YLaO_3$ ceramics.

The absorption cross-section and the emission cross-section in the rare earth doped transparent ceramics produced by solid-state synthesis are similar to those measured in the corresponding single crystals for all the systems where data on single crystals are available. Thus, in the case of the Yb-doped YAG YSAG and $YLaO_3$ ceramics, the relative intensities of the absorption line and the emission line and their peak cross-sections are quite similar to those measured from Czochralski single crystals. The absorption of Yb can

be estimated according to the following expression:[11]

$$\sigma_{\rm abs}=\frac{2.303\lg(I/I_0)}{dc}, \tag{1}$$

where $\lg(I_0/I)$ is the common logarithm of optical density ratio, c is the concentration of active ions in unit volume and d is the thickness of the sample. The emission cross sections can be determined by using either the method of the reciprocity, or the Füchtbauer–Ladenburg (F–L) formula. And the emission cross-sections can be evaluated by using the method of reciprocity (RM) (expression 2) and the Füchtbauer–Ladenburg formula (expression 3) as follows:[11]

$$\sigma_{\rm em}(\lambda) =\sigma_{\rm abs}\frac{Z_{\rm l}}{Z_{\rm u}}\exp\frac{E_{\rm zl}-hc/\lambda}{kT}, \tag{2}$$

and

$$\sigma^{\alpha}_{\rm em}(v) = \frac{\lambda^2 g^{\rm a}(v)}{8\pi n^2\tau_{\rm rad}}, \tag{3}$$

where $Z_{\rm l}$, $Z_{\rm u}$, k and $E_{\rm zl}$ represent the partition functions for lower and upper levels, Boltzmann's constant and zero-line energy that is defined as the energy separation between the lowest components of upper and lower states, respectively, and $g^{\rm a}(v)$ is the normalized line shape function for polarization in units of photons per second.

The absorption cross-section and the emission cross-sections of Yb doped YAG, YSAG and $YLaO_3$ ceramics, calculated Eqs.(1) and (2), are shown in Fig.7. From Fig.7 we can see that the peak absorption cross-sections of Yb doped YAG, YSAG and $YLaO_3$ ceramics at 939.6, 942.4and 977 nm are 0.76×10^{-20}, 0.58×10^{-20} and 0.63×10^{-20} cm^2 respectively, while their peak emission cross-sections at 1028.6, 1029.4 and 1030 nm are 1.89×10^{-20}, 1.45×10^{-20} and 1.25×10^{-20} cm^2.

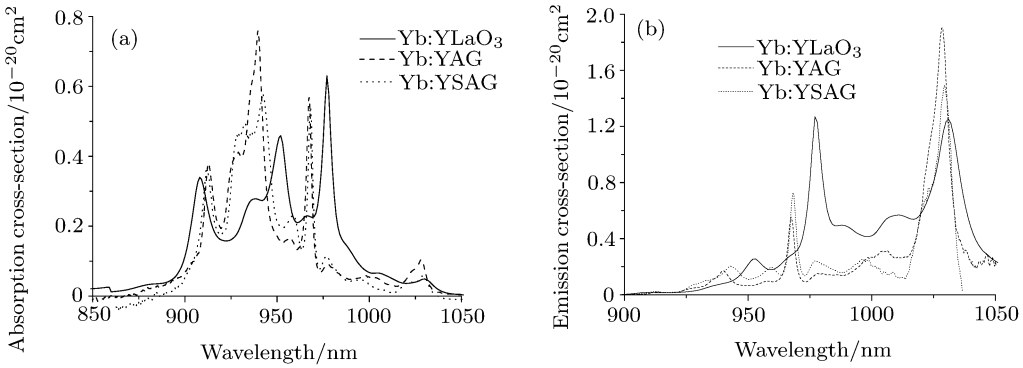


Fig.7. Absorption and emission cross-sections of Yb doped $YLaO_3$, YAG and YSAG ceramics.

4. Thermal conductivity properties

The thermal conductivity of solids has become a key parameter in electronics and optics, which leads to a present tendency to increase the energy density in functional materials.

The thermal conductivity κ of solids is a function of several physical parameters, such as the material density ρ, the sound velocity υ , the Gruneisen anharmonicity parameter γ, and the Debye frequency $\omega_{\rm D}$, and it is expressed as[12,13]

$$\kappa = \frac{1}{T}\frac{\rho\upsilon^4}{\gamma^2\omega_{\rm D}}. \tag{4}$$

The γ parameter measures the deviation from a pure harmonic behaviour of chemical bonds. A deeper analysis yields

$$\kappa = \frac{1}{T}\frac{A\cdot T^{3/2}_{\rm mp}\rho^{2/3}M^{1/3}}{\gamma^2\varepsilon^3 n^{1/3}\mu^{3/2}} \tag{5}$$

or

$$\kappa \propto \frac{T^{3/2}_{\rm mp}\rho^{2/3}M^{1/3}}{\gamma^2 n^{1/3}\mu^{3/2}}. \tag{6}$$

In these expressions, $T_{\rm mp}$ is the melting point of crystalline solid, M and n are, respectively, the molar mass and the number of atoms per formula unit. The reduced mass μ is the harmonic average of all ion masses of the formula unit. In order to obtain a large value of κ, the following requirements must be fulfilled: large molar mass M; high melting-point $T_{\rm mp}$; high-strength atomic bonds; compact crystal structures (which will lead to small values of n and μ); covalent character of the host. As we can see, the structures of YSAG, YAG and $YLaO_3$ become compact and the value of

T_{mp} turns higher according to the order, the values of thermal conductivity κ of YSAG, YAG and $YLaO_3$ become larger according to this order.

5. Conclusion

Transparent Yb doped YAG, YSAG and $YaLaO_3$ ceramics are fabricated by using the co-precipitation method. The spectral properties and the thermal parameters of these Yb doped cubic phase transparent ceramics are compared, and their different and potential applications are also analysed. The absorption cross-sections of Yb doped YAG, YSAG and $YLaO_3$ ceramics at 939.6, 942.4 and 977 nm are 0.76×10^{-20}, 0.58×10^{-20} and 0.63×10^{-20} cm^2 respectively. Their peak emission cross-section at 1028.6, 1029.4 and 1030 nm are 1.89×10^{-20}, 1.45×10^{-20} and 1.25×10^{-20} cm^2 respectively. According to the expression of thermal conductivity κ, $YLaO_3$ has the largest thermal conductivity. These results show that Yb doped YAG, YSAG and $YaLaO_3$ ceramics are all suitable materials used for diode-pumped solid-state lasers.

Acknowledgment

The author gratefully acknowledges the support of the K. C. Wong Education Foundation, Hong Kong.

References

[1] Pruss D, Huber G and Beimowski A 1982 *Appl. Phys.* B **28** 335
[2] Morris J A and Pollock C R 1990 *Opt. Lett.* **15** 440
[3] Wu H S, Yan P and Gong M L 2004 *Chin. Phys.* **13** 871
[4] Takunori Taira 2007 *C. R. Physique* **8** 138
[5] Fan T Y 1991 *Opt. Lett.* **14** 1089
[6] Taira T, Tulloch W M and Byer R L 1997 *Appl. Opt.* **36** 1867
[7] Brauch U, Giesen A and Karszewski M 1995 *Opt. Lett.* **20** 713
[8] Saikawa J, Kurimura S and Pavel N 2000 *OSA TOPS on Advanced Solid-State Lasers* **34** 106
[9] Saikawa J, Kurimura S and Shoji I 2002 *Opt. Mat.* **19** 169
[10] Innerhofer E, Südmeyer T and Brunner F 2003 *Opt. Lett.* **28** 367
[11] Zhang H W, Yang Q H and Xu J 2006 *J. Chinese Ceramic Society* **55** 1207
[12] Gaume R, Viana B and Vivien D 2003 *Appl. Phys. Lett.* **83** 1355
[13] Slack G A and Oliver D W 1971 *Phys. Rev.* B **4** 592