Article ID: 1000-7032(2022)11-1733-08

Fabrication and Characterization of Dy,Tb:LuAG Transparent Ceramics for Yellow Lasers

LIU Qiang[1], WU Long-fei[1,2], LI Xiao-ying[2,3], LIU Zi-yu[2,3], CHEN Peng-hui[2,3], TIAN Feng[2,3], XIE Teng-fei[2], PIRRI Angela[4], TOCI Guido[5], LI Jiang[2,3*]

(1. *School of Material Science and Engineering, Jiangsu University, Zhenjiang* 212013, *China*;
2. *Transparent Ceramics Research Center, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai* 201899, *China*;
3. *Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing* 100049, *China*;
4. *Istituto di Fisica Applicata "N. Carrara", Consiglio Nazionale delle Ricerche, CNR-IFAC, Via Madonna del Piano* 10*C*, 50019 *Sesto Fiorentino(Fi), Italy*;
5. *Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche, CNR-INO, Via Madonna del Piano* 10*C*, 50019 *Sesto Fiorentino(Fi), Italy*)

* *Corresponding Author, E-mail: lijiang@mail.sic.ac.cn*

Abstract: 3%Dy, 1%Tb:LuAG(Dy, Tb:LuAG) nanopowders with good dispersibility were synthesized by the co-precipitation method using NH_4HCO_3 as a precipitant. The thermal decomposition behavior of the precursor, and the phase and microstructure of powders were studied. Dy, Tb:LuAG ceramics with high transparency were fabricated by vacuum pre-sintering and hot isostatic pressing(HIP) post-treatment without any sintering additives for the first time. The influences of pre-sintering temperature on the microstructure and the optical quality of the ceramics were investigated. When the pre-sintering temperature is 1 600 ℃, the in-line transmittance of the annealed Dy, Tb:LuAG ceramics (1.5 mm in thickness) reaches 83.6% at 578 nm, and the average grain size of the annealed ceramics is 0.9 μm. In addition, the absorption cross section of the 3%Dy, 1%Tb:LuAG ceramics at 447 nm is calculated to be 1.3×10^{-21} cm^2, with a full width at half maximum(FWHM) of 3.0 nm, which matches that of commercial GaN blue laser diodes. This study shows that Dy, Tb:LuAG transparent ceramics have potential application value in the yellow lasers.

Key words: Dy, Tb:LuAG; transparent ceramics; co-precipitation method; hot isostatic pressing

CLC number: O482.31 **Document code**: A **DOI**: 10.37188/CJL.20220153

黄光激光用Dy,Tb:LuAG透明陶瓷的制备与性能研究

刘 强[1], 武龙飞[1,2], 李晓英[2,3], 刘子玉[2,3], 陈鹏辉[2,3], 田 丰[2,3], 谢腾飞[2], PIRRI Angela[4], TOCI Guido[5], 李 江[2,3*]

(1. 江苏大学 材料科学与工程学院, 江苏 镇江 212013;
2. 中国科学院上海硅酸盐研究所 透明光功能无机材料重点实验室, 上海 201899;
3. 中国科学院大学 材料与光电研究中心, 北京 100049;
4. *Istituto di Fisica Applicata "N. Carrara", Consiglio Nazionale delle Ricerche, CNR-IFAC, Via Madonna del Piano* 10*C*, 50019 *Sesto Fiorentino(Fi), Italy*;
5. *Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche, CNR-INO, Via Madonna del Piano* 10*C*, 50019 *Sesto Fiorentino(Fi), Italy*)

摘要: 以NH_4HCO_3为沉淀剂,通过共沉淀法合成了分散性良好的Dy,Tb:LuAG纳米粉体,并研究了前驱体的

收稿日期: 2022-04-23; **修订日期**: 2022-05-11
基金项目: 中国科学院国际伙伴计划(121631KYSB20200039); 上海市科委国际合作项目(20520750200)资助
Supported by The International Partnership Program of Chinese Academy of Sciences(121631KYSB20200039); The International Cooperation Project of Shanghai Science and Technology Commission(20520750200)

热分解行为、粉体的物相及显微形貌。在不添加任何烧结助剂的情况下，采用真空预烧结合热等静压烧结技术首次制备出高透明的 Dy，Tb∶LuAG 陶瓷，并研究了预烧温度对陶瓷显微形貌及光学质量的影响。当预烧温度为 1 600 ℃时，退火后的 Dy，Tb∶LuAG 陶瓷（厚度为 1.5 mm）在 578 nm 处的直线透过率达到 83.6%，平均晶粒尺寸为 0.9 μm。此外，退火后的 3%Dy，1%Tb∶LuAG 透明陶瓷在 447 nm 的吸收截面积为 1.3×10^{-21} cm^2，半高宽为 3.0 nm，与商用 GaN 蓝色激光二极管具有良好的匹配性。研究表明，Dy，Tb∶LuAG 透明陶瓷在黄光激光领域具有潜在的应用价值。

关 键 词：Dy，Tb∶LuAG；透明陶瓷；共沉淀法；热等静压烧结

1 Introduction

A yellow laser at 578 nm plays an important role in the treatment of retinal maculopathy[1] and excitation of the Yb lattice clock[2], which can be directly obtained by pumping Dy^{3+} doped gain media at about 450 nm with a GaN or InGaN laser diode (LD), corresponding to the $^4F_{9/2}\rightarrow{}^6H_{13/2}$ transition of Dy^{3+}[3-4].

Previous reports on Dy^{3+} doped gain media mainly focused on single crystals such as Dy，Tb∶$LiLuF_4$, Dy，Tb∶YAG and Dy，Tb∶$Na_2Gd_4(MoO_4)_7$[5-7]. Compared with single crystals, transparent ceramics can be easily fabricated with large size and high doping concentration, which are beneficial to improve the absorption efficiency of Dy^{3+} at 450 nm[8]. In recent years, Dy∶YAG, Dy∶Y_2O_3 and Dy∶LuAG transparent ceramics prepared by the solid-state reaction method have been reported one after another[9-11]. However, no laser oscillation was demonstrated due to the poor optical quality of available ceramics. Currently, the preparation methods of laser ceramics mainly include the solid-state reaction method[12-15] and the non-reactive sintering method[16-17]. While the latter usually uses the co-precipitation nano-powders with more uniform mixing of various atoms and higher sintering activity[18], which can prepare transparent ceramics at lower temperatures. In addition, the residual pores inside the ceramics should be completely eliminated to improve the optical quality of the ceramics at 578 nm. The hot isostatic pressing (HIP) technology has been widely used in the preparation of YAG, Y_2O_3 and CaF_2 transparent ceramics[19-21], which is beneficial to eliminate the intergranular pores and obtain fully dense ceramics.

When Dy^{3+} and Tb^{3+} were co-doped, LuAG transparent ceramics have smaller lattice distortions than YAG transparent ceramics, because the radius of Lu^{3+} is closer to the radius of the dopant ions than that of Y^{3+}[22-24]. Besides, gain media with high phonon energies are prone to non-radiative transitions that reduce laser efficiency. However, the lower energy level $^6H_{13/2}$ of Dy^{3+} has a significantly long lifetime. LuAG transparent ceramics with high phonon energies are beneficial to quench the lifetime of the lower energy level $^6H_{13/2}$[8]. Therefore, Dy，Tb∶LuAG transparent ceramics have important research value in the yellow lasers.

In this work, 3%Dy，1%Tb∶LuAG transparent ceramics with high optical quality were fabricated by vacuum pre-sintering at different temperatures and HIP post-treatment for the first time. Moreover, the influences of pre-sintering temperature on the microstructure and optical quality of the Dy，Tb∶LuAG ceramics were investigated in detail. Finally, the absorption coefficient of the annealed Dy，Tb∶LuAG ceramics was also calculated.

2 Experiments

Dy，Tb∶LuAG nanopowders were synthesized by the reverse-strike co-precipitation method. $Dy(NO_3)_3$, $Tb(NO_3)_3$ and $Lu(NO_3)_3$ solutions were obtained by dissolving the Dy_2O_3 (99.995%, Aladdin, China), Tb_4O_7 (99.995%, Zhongkai New Materials Co., Ltd., Jining, China), Lu_2O_3 (99.995%, Jingyun Materials Technology Co., Ltd., Shanghai, China) in the hot nitric acid, respectively. while $Al(NO_3)_3$ solution was prepared by dissolving $Al(NO_3)_3\cdot9H_2O$ (99.0%, Sinopharm Chemical Reagent Co., Ltd., China) in the deionized water. NH_4HCO_3 (99.0%, Aladdin, China) solution with a concentration of 1.5

mol/L was used as a precipitant and $(NH_4)_2SO_4$ (99.0%, Sinopharm Chemical Reagent Co., Ltd., China) solution as a dispersant. In addition, extra 1.0% Lu was added to the mixed metal ion solution in order to avoid the generation of the alumina secondary phase, which may be caused by the inconsistent dissolution of the precipitate during the washing process[25]. Firstly, the metal ion solutions were mixed according to the stoichiometric ratio of 3%Dy, 1%Tb: $Lu_{3(1+x)}Al_5O_{12}$ (x=1.0%) and then added into the NH_4HCO_3 solution containing $(NH_4)_2SO_4$ solution. After aging for 1 h, the precipitates were washed three times with deionized water and twice with ethanol. The precursor was then dried at 70 ℃ for 36 h, sieved through a 200-mesh screen and finally calcined at 1 100 ℃ for 4 h in air to obtain the Dy,Tb:LuAG powders. Next, the obtained powders were dry pressed at 46 MPa and then cold isostatically pressed at 250 MPa. The green bodies were vacuum pre-sintered at different temperatures for 3 h and hot isostatically pressed (HIPed) at 1 600 ℃ for 3 h under 176 MPa in Ar atmosphere. Post-annealing was carried out at 1 200 ℃ for 10 h in air to eliminate oxygen vacancies. Finally, the pre-sintered ceramics and the annealed ceramics were mirror-polished on both surfaces into 1.5 mm thickness and the polished Dy,Tb:LuAG ceramics were then thermally etched at 1 200 ℃ for 3 h in air for further tests.

The thermogravimetry and differential thermal analysis (TG-DTA) curves of the precursor were measured by a thermal analyzer (Thermoplus EVO Ⅱ, Rigaku, Japan) at a heating rate of 10 ℃/min in the flowing air. The phase composition of the powders was identified by the X-ray diffraction system (XRD, D/max 2200PC, Rigaku, Japan) with $CuK\alpha_1$ radiation in the range of 2θ=10°−80°. The morphology of the powders and microstructures of the ceramics were observed by a field emission scanning electron microscope (FESEM, SU8220, Hitachi, Japan). The in-line transmittance and the absorption spectroscopy of mirror-polished Dy,Tb:LuAG ceramics were measured by a UV-VIS-NIR spectrophotometer (Cary-5000, Varian, USA).

3　Results and Discussion

Fig. 1 shows the TG-DTA curves of Dy,Tb:LuAG precursor. The weight loss on the TG curve is a continuous process, mainly divided into three stages. The first stage occurs before 300 ℃ with the weight loss of 24.7%. An endothermic peak is located at 122 ℃ on the DTA curve, which is mainly assigned to the removal of adsorbed water, crystallization water and residual ammonium. In addition, the hydroxycarbonate is also decomposed at this stage. The weight loss of 8.2% in the second stage occurred between 300 ℃ and 900 ℃ is mainly caused by the decomposition of lutetium carbonate, which corresponds to the endothermic peak located at 830 ℃ on the DTA curve. The third stage ranges from 900 ℃ to 1 100 ℃ with a weight loss of 4.3%. The exothermic peak at 936 ℃ on the DTA curve corresponds to the phase formation of garnet ($Lu_3Al_5O_{12}$). The endothermic peak at 970 ℃ corresponds to the decomposition of sulfates, while the exothermic peak at 1 070 ℃ is caused by the grain growth[26]. Furthermore, the weight loss of the precursor is little after 1 100 ℃ and the total weight loss is about 37.2%. Therefore, the precursor was calcined at 1 100 ℃ for 4 h in order to obtain nanopowders with pure phase and good crystallinity.

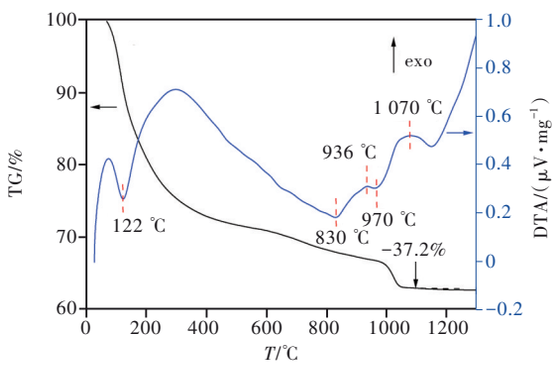

Fig.1　TG-DTA curves of the Dy,Tb:LuAG precursor

Fig. 2 shows the FT-IR spectra(a) and the XRD patterns(b) of the precursor and the Dy,Tb:LuAG powders calcined at 1 100 ℃ for 4 h. The wide absorption band at 3 420 cm^{-1} is related to the stretching vibrations of O—H bond including crystal water, aluminum hydroxide and hydroxycarbonate groups. The strong peak at 1 520 cm^{-1} can be attributed to

the bond-stretching of NH_4^+ from the precipitant and the dispersant. The absorption peaks at 1 420 cm^{-1} and 850 cm^{-1} correspond to C—O bond stretching and bending. In addition, the peak located at 1 090 cm^{-1} corresponds to the vibration of SO_4^{2-}. These indicate that the precursor contains OH^-, NH_4^+, CO_3^{2-} and SO_4^{2-} groups. However, no visible absorption of NH_4^+, CO_3^{2-} or SO_4^{2-} groups is observed in the powders calcined at 1 100 ℃. The weak absorption peaks at 3 420 cm^{-1} and 1 630 cm^{-1} demonstrate that the existence of residual OH^- groups, which may be ascribed to the molecular water absorbed from the air. Moreover, the bands resulting from the stretching of Lu—O and Al—O bonds in the 400-800 cm^{-1} region are characteristics of LuAG, which are similar to the garnet structure of YAG[27]. These show that the precursor is completely decomposed after calcination at 1 100 ℃. It can be seen from Fig. 2(b) that the precursor is amorphous and the diffraction peaks of the powders calcined at 1 100 ℃ for 4 h are identified as the LuAG phase (PDF#73-1368) without any impurity phase. This indicates that the precursor has been completely converted into the powders with the pure LuAG phase after calcination at 1 100 ℃ for 4 h.

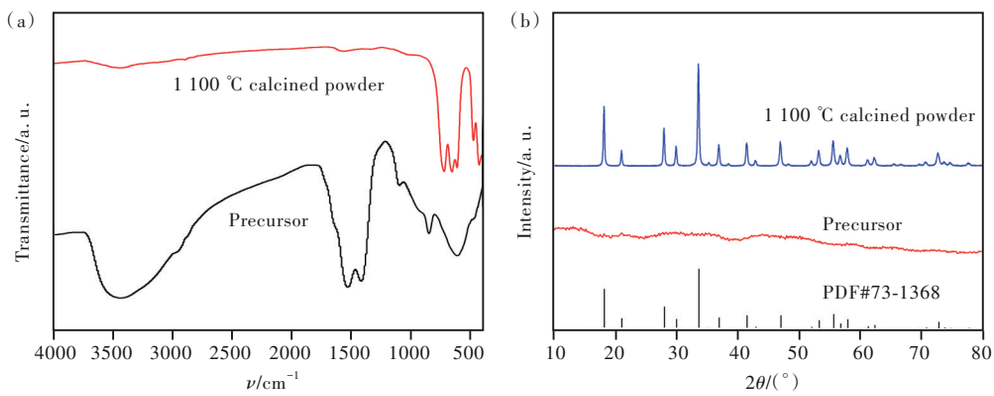

Fig.2 FT-IR spectra(a) and XRD patterns(b) of the precursor and the Dy,Tb:LuAG powders calcined at 1 100 ℃ for 4 h

Fig. 3 shows the FESEM micrographs of the Dy, Tb:LuAG precursor(a) and the powders calcined at 1 100 ℃ for 4 h(b). The precursor is severely agglomerated, which is related to the strong force of hydrogen bonds. However, the Dy, Tb: LuAG powders have good dispersibility, which indicates that the hydrogen bonds inside the precursor have been destroyed after calcination at 1 100 ℃. Moreover, it can be observed from Fig. 3(b) that the primary particle size of the powders is about several tens of nanometers.

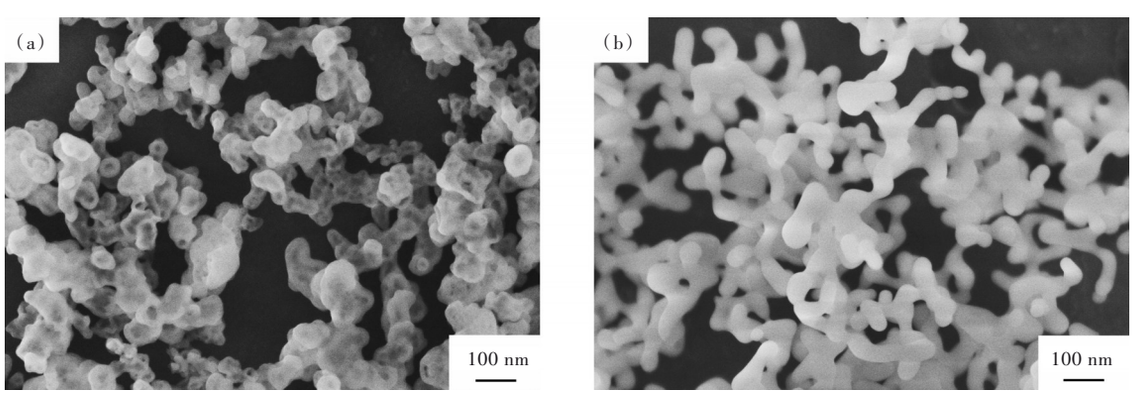

Fig.3 FESEM micrographs of the Dy,Tb:LuAG precursor(a) and the powders calcined at 1 100 ℃ for 4 h(b)

Fig. 4 shows the FESEM images of the thermally etched surfaces of the Dy,Tb:LuAG ceramics vacuum pre-sintered at different temperatures for 3 h. With the increase of the pre-sintering temperature, the submicron-scale intergranular pores gradually transform into fine intergranular pores, and the number of pores is also decreasing. The relative densities of the ceramics pre-sintered at 1 550, 1 600, 1 650, 1 700 ℃ were measured to be 88.9%, 92.8%, 94.2% and 95.9% by the Archimedes

method, respectively. The relative density change of the pre-sintered ceramics is consistent with the micromorphology of the ceramics pre-sintered at different temperatures. In addition, the average grain sizes of the ceramics pre-sintered at 1 550, 1 600, 1 650, 1 700 ℃ were calculated to be 0.6, 0.7, 0.8, 1.1 μm by the intercept method, respectively. When the pre-sintering temperature increases to 1 700 ℃, the average grain size of the ceramics increases significantly.

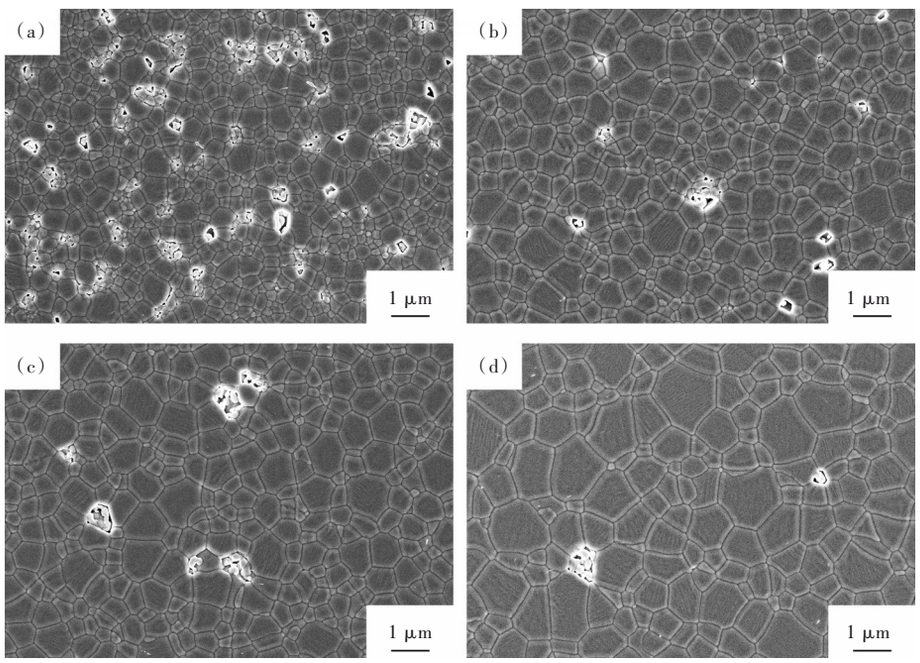

Fig.4　FESEM images of the thermally etched surfaces of the Dy, Tb:LuAG ceramics vacuum pre-sintered at different temperatures for 3 h. (a)1 550 ℃. (b)1 600 ℃. (c)1 650 ℃. (d)1 700 ℃.

Fig. 5 shows the FESEM images of the thermally etched surfaces of the ceramics after the HIP post-treatment. When the pre-sintering temperature is in the range of 1 550–1 650 ℃, no pores and secondary phases exist inside the ceramics. The average grain sizes of the HIPed ceramics are 0.7, 0.9, 1.0 μm, respectively. However, a small number of residual pores marked by the red circle can be observed in the Fig. 5(d). When the pre-sintering temperature increases to 1 700 ℃, the average grain size of the pre-sintered ceramics becomes larger, which is harmful to the exclusion of pores during the HIP process.

Fig. 6(a) shows the in-line transmittance of the Dy,Tb:LuAG transparent ceramics annealed at 1 200 ℃ for 10 h in air and the inset image shows the photograph of the annealed ceramics. The in-line transmittance of the annealed ceramics exceeds 83.0% at 578 nm in the pre-sintering temperature ranging from 1 550 ℃ to 1 650 ℃, which is attributed to the effective elimination of intergranular closed pores. As the pre-sintering temperature increases to 1 700 ℃, a dramatic decrease of the in-line transmittance is observed. This is due to the small number of intergranular pores acting as optical scattering centers which are still retained inside the ceramics. In addition, when the pre-sintering temperature is 1 600 ℃, the annealed ceramics obtain the optimum optical quality. The in-line transmittance reaches 83.6% at 578 nm (theoretical transmittance 83.9%@578 nm), which has been greatly improved than that of the Dy:LuAG transparent ceramics (~75%@578 nm) in the previous reports[11]. Fig. 6(b) shows the absorption spectrum of the annealed ceramics vacuum pre-sintered and HIP-treated at 1 600 ℃. The strongest absorption peak in the 420–490 nm region is located at 447 nm with the FWHM of 3.0 nm. Considering the output wavelength of the commercial GaN blue LD is 447 nm with the line width of about 2.0 nm, this indicates the GaN blue LD can be used as an effective

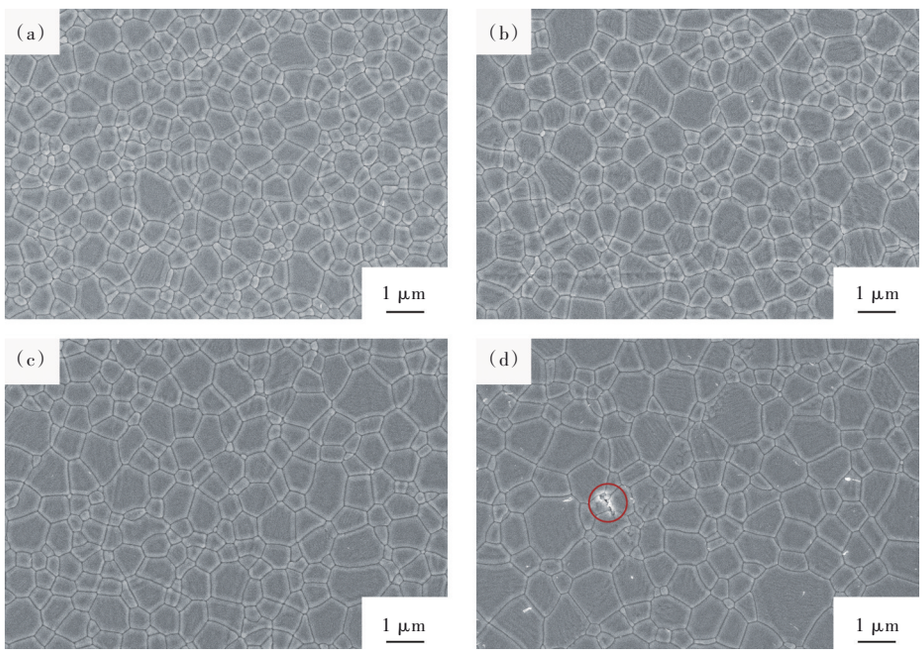

Fig.5 FESEM images of the thermally etched surfaces of the Dy, Tb∶LuAG ceramics vacuum pre-sintered at different temperatures for 3 h and HIPed at 1 600 ℃ for 3 h under 176 MPa in Ar. (a)1 550 ℃. (b)1 600 ℃. (c)1 650 ℃. (d) 1 700 ℃.

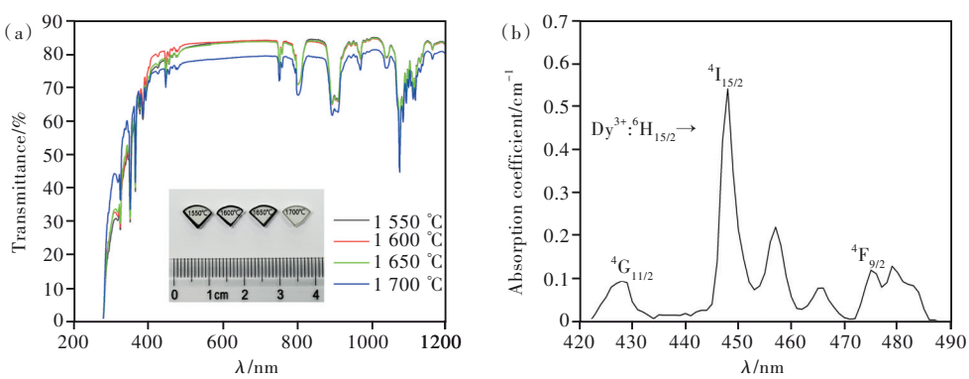

Fig.6 In-line transmittance of the Dy, Tb∶LuAG transparent ceramics(1.5 mm thick) vacuum pre-sintered at different temperatures for 3 h, HIPed at 1 600 ℃ for 3 h under 176 MPa in Ar, and annealed at 1 200 ℃ for 10 h in air(a) and the absorption spectrum of the annealed ceramics vacuum pre-sintered and HIP-treated at 1 600 ℃(b).

pumping source for the Dy, Tb∶LuAG transparent ceramics. Moreover, the larger FWHM favors the decrease of the temperature dependence of a GaN blue LD pumping source and improving the pumping efficiency[28]. Concerning the absorption cross section σ_{abs}, it can be estimated by the formula:

$$\sigma_{abs} = \alpha(\lambda)/N_C, \tag{1}$$

where N_c is the concentration of Dy^{3+} in the ceramics which is about 4.26×10^{20} cm^{-3}, $\alpha(\lambda)$ is the absorption coefficient which is calculated with the equation:

$$\alpha = \frac{2.303\lg(I_0/I)}{L}, \tag{2}$$

where L expresses the thickness of the ceramics, $\lg(I_0/I)$ is the optical density obtained by the spec-

Tab. 1 Absorption cross section of Dy^{3+}-doped materials at 447 nm

Materials	Doping concentration of Dy^{3+}/%	Absorption cross section/(10^{-21} cm^2)	References
Dy∶Y_2O_3 ceramics	3	0.54	[10]
Dy∶YAG ceramics	5	1.1	[9]
Dy, Tb∶LuAG ceramics	3	1.3	This work
Dy, Tb∶$LiLuF_4$ crystals	4	1.4	[5]

trophotometer. According to it, the absorption cross section of the Dy,Tb:LuAG ceramics at 447 nm was calculated to be 1.3×10^{-21} cm^2, which is larger than that of Dy:Y_2O_3 and Dy:YAG transparent ceramics. However, it is lower than that of Dy,Tb:$LiLuF_4$ crystals, as listed in Tab. 1. The difference of the absorption cross section is mainly caused by the difference of host materials in the Dy^{3+} doped gain media.

4 Conclusions

3%Dy,1%Tb:LuAG ceramics with high transparency were prepared from the nanopowders synthesized by the co-precipitation method without any sintering additives. After calcination at 1 100 ℃ for 4 h, the total weight loss of the precursor was 37.2% and Dy,Tb:LuAG nanopowders with high sintering activity were obtained. In addition, the influences of pre-sintering temperature on the microstructure and the optical transmittance of the ceramics were studied. When the pre-sintering temperature of the ceramics is in the range of 1 550–1 650 ℃, the average grain size of pre-sintered ceramics does not exceed 1 μm, which is conducive to the exclusion of intergranular closed pores inside the ceramics during the HIP post-treatment. When the pre-sintering temperature is 1 600 ℃, the in-line transmittance of the annealed ceramics reaches 83.6%. Finally, the absorption spectrum of the annealed ceramics pre-sintered at 1 600 ℃ was calculated. The strongest absorption peak is at 447 nm with the FWHM of 3.0 nm, the absorption cross section is 1.3×10^{-21} cm^2. The results indicate that Dy,Tb:LuAG transparent ceramics are a potential candidate for the yellow laser pumped by the GaN blue LD.

Response Letter is available for this paper at:http://cjl.lightpublishing.cn/thesisDetails#10.37188/CJL.20220153.

References:

[1] YADAV N K, JAYADEV C, MOHAN A, *et al*. Subthreshold micropulse yellow laser(577 nm) in chronic central serous chorioretinopathy: safety profile and treatment outcome [J]. *Eye*, 2015, 29(2): 258-265.

[2] PIZZOCARO M, COSTANZO G A, GODONE A, *et al*. Realization of an ultrastable 578-nm laser for an Yb lattice clock [J]. *IEEE. Trans. Ultrason. Ferroelectr. Freq. Control*, 2012, 59(3): 426-431.

[3] BOWMAN S R, O'CONNOR S, CONDON N J. Diode pumped yellow dysprosium lasers [J]. *Opt. Express*, 2012, 20(12): 12906-12911.

[4] PENG F, LIU W P, LUO J Q, *et al*. Study of growth, defects and thermal and spectroscopic properties of Dy:$GdScO_3$ and Dy,Tb:$GdScO_3$ as promising 578 nm laser crystals [J]. *CrystEngComm*, 2018, 20(40): 6291-6299.

[5] BOLOGNESI G, PARISI D, CALONICO D, *et al*. Yellow laser performance of Dy^{3+} in co-doped Dy,Tb:$LiLuF_4$ [J]. *Opt. Lett.*, 2014, 39(23): 6628-6631.

[6] 李长磊, 姚文明, 陈建生, 等. 基于共掺杂Dy-Tb:YAG晶体的全固态黄光激光特性研究 [J]. 中国激光, 2019, 46(11): 1101008-1-6.
LI C L, YAO W M, CHEN J S, *et al*. All-solid-state yellow-laser characteristics based on co-doped Dy-Tb:YAG crystal [J]. *Chin. J. Lasers*, 2019, 46(11): 1101008-1-6. (in Chinese)

[7] HUANG R S, ZHANG P X, HUANG X B, *et al*. Enhanced 573 nm yellow emissions of Dy^{3+} *via* Tb^{3+} deactivation in $Na_2Gd_4(MoO_4)_7$ crystal [J]. *Opt. Mater. Express*, 2017, 7(10): 3673-3679.

[8] KRÄNKEL C, MARZAHL D T, MOGLIA F, *et al*. Out of the blue: semiconductor laser pumped visible rare-earth doped lasers [J]. *Laser Photonics Rev.*, 2016, 10(4): 548-568.

[9] LUPEI A, LUPEI V, GHEORGHE C, *et al*. Spectroscopic characteristics of Dy^{3+} doped $Y_3Al_5O_{12}$ transparent ceramics [J]. *J. Appl. Phys.*, 2011, 110(8): 083120-1-8.

[10] HU Z W, XU X D, WANG J, *et al*. Fabrication and spectral properties of Dy:Y_2O_3 transparent ceramics [J]. *J. Eur. Ceram. Soc.*, 2018, 38(4): 1981-1985.

[11] HUANG S H, FENG T, JIANG B X, *et al*. J-O study of a novel Dy-doped $Lu_3Al_5O_{12}$ transparent ceramic for potential application in yellow laser generation [J]. *J. Lumin.*, 2021, 231: 117763-1-5.

[12] IKESUE A, KINOSHITA T, KAMATA K, *et al*. Fabrication and optical properties of high-performance polycrystalline Nd:YAG ceramics for solid-state lasers [J]. *J. Am. Ceram. Soc.*, 1995, 78(4): 1033-1040.

[13] JIANG N, OUYANG C, LIU Y, *et al*. Effect of air annealing on the optical properties and laser performance of Yb:YAG transparent ceramics [J]. *Opt. Mater.*, 2019, 95: 109203-1-5.

[14] WANG Q Q, SHI Y, FENG Y G, *et al*. Fabrication and laser parameters of Yb:YAG transparent ceramics with high optical quality [J]. *J. Inorg. Mater.*, 2020, 35(2): 205-210.

[15] YAVETSKIY R P, BALABANOV A E, PARKHOMENKO S V, *et al*. Effect of starting materials and sintering temperature on microstructure and optical properties of Y_2O_3: Yb^{3+} 5 at% transparent ceramics [J]. *J. Adv. Ceram.*, 2021, 10(1): 49-61.

[16] LIU Z Y, TOCI G, PIRRI A, *et al*. Fabrication, microstructures, and optical properties of Yb:Lu_2O_3 laser ceramics from co-precipitated nano-powders [J]. *J. Adv. Ceram.*, 2020, 9(6): 674-682.

[17] LIU Z Y, TOCI G, PIRRI A, *et al*. Fabrication and optical property of Nd:Lu_2O_3 transparent ceramics for solid-state laser applications [J]. *J. Inorg. Mater.*, 2021, 36(2): 210-216.

[18] HUANG X Y, LIU Y M, LIU Y, *et al*. Fabrication and characterizations of Yb:YAG transparent ceramics using alcohol-water co-precipitation method [J]. *J. Inorg. Mater.*, 2021, 36(2): 217-224.

[19] LI S S, MA P, ZHU X W, *et al*. Post-treatment of nanopowders-derived Nd:YAG transparent ceramics by hot isostatic pressing [J]. *Ceram. Int.*, 2017, 43(13): 10013-10019.

[20] WANG J, MA J, ZHANG J, *et al*. Yb:Y_2O_3 transparent ceramics processed with hot isostatic pressing [J]. *Opt. Mater.*, 2017, 71: 117-120.

[21] HUANG X Y, CHEN G M, WEI J B, *et al*. Fabrication of Yb, La:CaF_2 transparent ceramics by air pre-sintering with hot isostatic pressing [J]. *Opt. Mater.*, 2021, 116: 111108-1-8.

[22] BEIL K, FREDRICH-THORNTON S T, TELLKAMP F, *et al*. Thermal and laser properties of Yb:LuAG for kW thin disk lasers [J]. *Opt. Express*, 2010, 18(20): 20712-20722.

[23] FU Y L, LI J, LIU Y, *et al*. Fabrication, microstructure and laser performance of Nd^{3+}-doped $Lu_3Al_5O_{12}$ transparent ceramics [J]. *J. Eur. Ceram. Soc.*, 2016, 36(3): 655-661.

[24] ZHOU D, SHI Y, XIE J J, *et al*. Laser grade Yb:LuAG transparent ceramic prepared by nanocrystalline pressure-less sintering in reducing H_2 [J]. *Opt. Mater. Express*, 2017, 7(4): 1274-1280.

[25] HU Z W, CHEN X P, LIU X, *et al*. Fabrication and scintillation properties of Pr:$Lu_3Al_5O_{12}$ transparent ceramics from co-precipitated nanopowders [J]. *J. Alloys Compd.*, 2020, 818: 152885-1-9.

[26] TIAN F, CHEN C, LIU Q, *et al*. Optimizing co-precipitated Nd:YAG nanopowders for transparent ceramics [J]. *Opt. Mater.*, 2020, 108: 110427-1-10.

[27] MARLOT C, BARRAUD E, LE GALLET S, *et al*. Synthesis of YAG nanopowder by the co-precipitation method: influence of pH and study of the reaction mechanisms [J]. *J. Solid State Chem.*, 2012, 191: 114-120.

[28] DING S J, LI H Y, ZHANG Q L, *et al*. The investigations of Dy:YAG and Dy, Tb:YAG as potentially efficient GaN blue LD pumped solid state yellow laser crystals [J]. *J. Lumin.*, 2021, 237: 118174-1-6.

刘强(1964-),男,江苏镇江人,博士,教授,硕士生导师,2005年于江苏大学获得博士学位,主要从事发光材料和透明陶瓷等方向的研究。

E-mail: lq88611338@163.com

李江(1977-),男,浙江绍兴人,博士,研究员,博士生导师,2007年于中国科学院上海硅酸盐研究所获得博士学位,主要从事光功能透明陶瓷方向的研究。

E-mail: lijiang@mail.sic.ac.cn