High performance of La-doped Y_2O_3 transparent ceramics

Lei ZHANG^{a,b,*}, Jun YANG^{b,c}, Hongyu YU^a, Wei PAN^{c,*}

^aShenzhen Institute of Wide-Bandgap Semiconductors and Engineering Research Center of Integrated Circuits for Next-Generation Communications of Ministry of Education, School of Microelectronics, Southern University of Science and Technology, Shenzhen 518055, China

^bState Key Laboratory of New Ceramics and Fine Processing, School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China

^cDepartment of General Education, Army Engineering University of PLA, Nanjing 211101, China

Received: February 18, 2020; Revised: May 7, 2020; Accepted: May 25, 2020

© The Author(s) 2020.

Abstract: As an optical material, Y_2O_3 transparent ceramics are desirable for application as laser host materials. However, it is difficult to sinter and dense of Y_2O_3 hinders the preparation of high-quality optical ceramics via traditional processes. In this work, we use La_2O_3 as a sintering aid for fabricating high-transparency Y_2O_3 ceramics using a vacuum sintering process. It is demonstrated that the in-line optical transmittance of 15.0 at% La-doped Y_2O_3 at a wavelength of 1100 nm achieves a transmittance of 81.2%. A sintering kinetics analysis reveals that a grain-boundary-diffusion-controlled mechanism dominates the faster densification at high La^{3+} concentrations. It is also shown that both the mechanical and thermal properties of Y_2O_3 transparent ceramics are significantly improved upon the increase of La_2O_3 sintering additives. The results indicate that a La-doped Y_2O_3 transparent ceramic is a promising candidate for a laser host material.

Keywords: Y_2O_3 transparent ceramics; optical transmittance; sintering kinetics; mechanical properties; thermal properties

1 Introduction

As an attractive optical material, Y_2O_3 has attracted significant interest for use in infrared dome, refractory, and semi-conductor devices and up-converters, owing to its broad transmission region, high refractive index, high corrosion resistance, low phonon energy, etc. [1]. In that regard, a typical cubic crystal of Y_2O_3 is suitable for laser ceramics. Compared to $\text{Y}_3\text{Al}_5\text{O}_{12}$ (thermal

conductivity of $10.5 \text{ W}/(\text{m}\cdot\text{K})$ and thermal expansion coefficient of $7.8\times 10^{-6} \text{ K}^{-1}$), Y_2O_3 has superior thermal properties with higher thermal conductivity of $13.6 \text{ W}/(\text{m}\cdot\text{K})$ and lower thermal expansion coefficient of $6\times 10^{-6} \text{ K}^{-1}$, which are beneficial for minimizing the thermal lensing effect and improving the laser beam quality, and thus is attracting more attention for use as a high-output-power laser host material [2–7].

Since the first demonstration of using YAG-based transparent ceramics for lasers in 1995 [8], the development of transparent ceramics has offered potential advantages over single crystals for metal rare-earth sesquioxide Y_2O_3 materials [9,10]. It is known that the heat energy generated from operating a

* Corresponding authors.

E-mail: L. Zhang, zhangl6@sustc.edu.cn;

W. Pan, panw@mail.tsinghua.edu.cn

high-power laser will congregate and induce thermo-optic aberrations, lensing, and birefringence, deteriorating the operation of laser host medium [11–13]. In addition, the mechanical properties, representing the inter-atomic and inter-particle strengths, are very important in mechanical industrial applications of laser materials [14]. Therefore, there is an urgent need to produce transparent Y_2O_3 ceramics with excellent thermal and mechanical properties.

A vacuum sintering procedure is considered to be an efficient technique for fabricating highly transparent ceramics, with technological and economic advantages [15–17]. In addition, a sintering additive is beneficial for lowering the sintering temperature and shortening the sintering time during the vacuum sintering process [18–23]. However, it has been found that sintering aids have a significant effect on the mechanical and thermal properties (in addition to the physical characteristics), probably owing to a mismatch of ion radius and mass [24,25].

Anti-sintering properties of Y_2O_3 have hindered the use of the conventional growth method for preparation of a dense sample with good optical quality. In this work, La_2O_3 is added as sintering aid, and high transparency in Y_2O_3 laser host materials is obtained by using a vacuum sintering process. Sintering kinetics is applied to analyse the densification and grain-growth mechanisms of different sintering additive concentrations. Furthermore, the effects of the sintering additives on the mechanical and thermal properties are also examined in detail.

2 Experimental procedure

2.1 Sample fabrication

High-purity commercial Y_2O_3 (99.99%, Shanghai Yuelong New Materials Co. Ltd., Shanghai, China) is used as a raw material, and La_2O_3 (99.99%, First Rare Materials Co. Ltd., Qingyuan, China) powder is adopted as the sintering additive. As the structures of Y_2O_3 (cubic) and La_2O_3 (hexagonal) are different, the solid solubility of the La-doping concentration is within 15.0 at% [26,27]. Therefore, the samples are designed for 5.0, 10.0, and 15.0 at% La-doping content. The details of the sample fabrication are similar to the processing in our previous research [28].

2.2 Characterization

The optical transmittances of the specimens are

identified by an UV/VIS/NIR spectrometer (UV-3600, Shimadzu, Tokyo, Japan) at wavelengths of 300–2000 nm, with the spectral resolution 1–2 nm. The phase compositions of samples are determined via X-ray diffraction (XRD, D/max-2500, Cu $\text{K}\alpha$ radiation, Rigaku Smart Lab, Japan). The morphologies are characterised using field-emission scanning electron microscopy (Zeiss Merlin, Germany), whereas the diameters of the particles are analysed using the obtained SEM images and ImageJ software. The bulk density of a sample is measured using the Archimedes method. To achieve the sound wave velocities of the samples, both v_t and v_l are determined by ultrasonic method using an Ultrasonic Pulser/Received machine (5900 PR, Panametrics-NDT, Waltham, USA), and the following equation is used [29]:

$$v_i = \frac{2d}{t_i} \quad (1)$$

Here, $i = l$ and t denote the longitudinal and transverse modes, respectively, d is the thickness of the sample (2 mm), and t_i is measured between two successive echoes for the longitudinal and transverse modes. The mechanical parameters (shear modulus (G), bulk modulus (B), Young's modulus (E), Pugh's modulus ratio (k), Poisson's ratio (σ), and Vickers hardness (H_v)) are estimated from Eqs. (2)–(6) [30–32]:

$$G = \rho v_t^2 \quad (2)$$

$$B = \rho \left(v_l^2 - \frac{4}{3} v_t^2 \right) \quad (3)$$

$$E = \frac{9BG}{3B + G} \quad (4)$$

$$k = \frac{G}{B} \quad (5)$$

$$\sigma = \frac{1 - 2 \left(\frac{v_t}{v_l} \right)^2}{2 - 2 \left(\frac{v_t}{v_l} \right)^2} \quad (6)$$

$$H_v = 2.0(k^2 G)^{0.585} - 3.0 \quad (7)$$

The measurement of the thermal properties can be obtained in our previous work [33]. The thermal diffusivity coefficient (λ) of sample (φ 10.0 mm $\times$ 1.0 mm) is measured using the laser flash method by a laser flash apparatus (LFA427, Netzsch, Selb, Germany). The heat capacity (C_p) is determined by differential

scanning calorimeter using a sapphire standard (DSC403PC, Netzsch, Selb, Germany). The relative densities (ρ) are obtained by dimensional and mass determinations on cylindrical slab sample (ϕ 13.0 mm $\times$ 2.0 mm).

3 Results and discussion

3.1 Microstructure and phase

The optical transmittance is known as the key performance indicator in the application of transparent ceramics. As shown in Fig. 1(a), after 1750 °C sintering for 15 h, the in-line transmittances increase significantly at a wavelength of 400–2000 nm as the La doping increases, and the maximum value of the in-line transmittances achieves 80.2%. Evidently, a significant enhancement of optical transmittance is obtained owing to the significantly increased La^{3+} concentration. Figure 1(b) illustrates the XRD patterns of the La-doped Y_2O_3 ceramics. As the concentration of La-doping increases, each peak matches well with the Y_2O_3 cubic phase (JCPDS 41-1105), and the diffraction peaks move to lower angles, implying the increasing of lattice constant. The changes of lattice parameters can be attributed to the difference of radius between La^{3+} ion (1.06 Å) and Y^{3+} ion (0.89 Å) [34]. As shown in the inset picture of Fig. 1(b), unit-cell parameters increase with La^{3+} concentration increasing. Furthermore, no second phase is detected, implying that La^{3+} is completely soluble in the matrix material.

As shown in Fig. 2, the average grain size increases with a decrease in La concentration for the La-doped Y_2O_3 ceramic at a sintering temperature of 1750 °C

for 15 h. For example, the 5.0 at% La-doped sample has an average grain size of approximately 35 μm and local compositional inhomogeneity, as compared to the 15.0 at% La-doped Y_2O_3 , which has an average grain size of approximately 18 μm and a pore-free or heterogeneous phase. This implies that the grain size and pores could be remarkably suppressed by an increase of La^{3+} concentration [35,36].

3.2 Sintering kinetics analysis

As shown in Fig. 3(a), the effects of both the temperature and La^{3+} doping concentration on the transparency of the samples are evident. One can see that, at a fixed doping concentration, the optical transmission increases with increasing temperature for the samples, in agreement with the findings of Zhou *et al.* [19]. Moreover, the transparency increases significantly with an increase of sintering additive content at a certain temperature, which confirmed by the in-line transmittance results.

To probe the densification mechanisms of La-doped Y_2O_3 transparent ceramics, we conducted a kinetics analysis of samples with varied sintering processing. Figure 3(b) plots the relative density vs. sintering temperature for the 5.0, 10.0, and 15.0 at% La-doped Y_2O_3 ceramics. Sintering time kept 10 h at each sintering temperature. It is shown that, for both the 5.0 and 10.0 at% La-doped, the sample densification occurred from 1600 to 1800 °C. In contrast, no increase in the relative density appeared as the sintering temperature increased to higher than 1700 °C for the 15.0 at% La-doped Y_2O_3 ceramics. Thus, a high sintering additive content can significantly reduce the sintering temperature. In addition, the densification

Fig. 1 (a) In-line transmittance and (b) X-ray diffraction (XRD) patterns of 5.0, 10.0, and 15.0 at% La-doped Y_2O_3 ceramics under a sintering temperature of 1750 °C for 15 h.

Fig. 2 Surface and fracture FESEM of (a, b) 5.0 at%, (c, d) 10.0 at%, and (e, f) 15.0 at% La-doped Y_2O_3 ceramics at a sintering temperature of 1750 °C for 15 h.

rate can be calculated by [37]:

$$\frac{d\rho}{dt} = \frac{C\gamma_s D N_g}{G^n} \quad (8)$$

In the above, ρ is the density of the sample, C is a constant, γ_s is the surface energy for solid/gas, D is either the coefficient of the lattice diffusion (D_L) or the coefficient of the grain-boundary diffusion (D_b), N_g is the number of pores per grain (assuming N_g is a constant here), and G is the average grain size. In that regard, n is a constant on behalf of the grain-size exponent. Here, the densification mechanism is dependent on the value of the constant n . It is known that a lattice-diffusion control mechanism is confirmed when $n = 3$, whereas a grain-boundary-diffusion control mechanism is dominant when $n = 4$. As shown in Figs. 3(c) and 3(d), according to Eq. (8), the n value of the samples is fit to 3.6, 3.8, and 4.2, corresponding to the 5.0, 10.0 and 15.0 at% La-doped samples,

respectively. This indicates that the grain-boundary-diffusion control mechanism is the predominant densification process for La-doped Y_2O_3 . The densification rates of the samples with 5.0, 10.0, and 15.0 at% La-doped concentrations are 9, 12, and 18 [38], respectively. Thus, the Y_2O_3 ceramic with 15.0 at% La-doping shows the highest rate of grain-boundary diffusion. This is possibly due to the difference in ionic radius between the La^{3+} ion and Y^{3+} ion, which is beneficial for generating elastic strain energy and promoting the diffusion of the Y^{3+} ion in Y_2O_3 [39,40].

Additionally, the grain-growth kinetics can be calculated, for further study of the sintering mechanisms. A grain-growth rate equation is applied for the Y_2O_3 ceramics as follows [34]:

$$G_t^m - G_0^m = k(t - t_0) \quad (9)$$

Here, G_0 and G_t are the grain sizes with sintering time

Fig. 3 (a) Optical pictures of La-doped Y₂O₃ ceramics at the different sintering temperatures ($\phi = 13 \text{ mm} \times 1.5 \text{ mm}$). (b) Relative density vs. sintering temperature, (c) relative density vs. sintering time, and (d) densification rate vs. grain size for La-doped Y₂O₃ ceramics at a sintering temperature of 1750 °C.

of t_0 and t , respectively, m is the exponent of the grain growth, and k is the rate constant (confirmed using data of grain growth). From Figs. 4(a) and 4(b), the experimental values of m are fit to a line with a slope of approximately 3, and the k values of the samples with 5.0, 10.0, and 15.0 at% La are 1.3×10^{-16} , 7.9×10^{-17} , and $2.1 \times 10^{-17} \text{ m}^3/\text{s}$, respectively. This indicates that higher La³⁺ doping results in inhibiting the grain-growth process.

The activation energies of the samples sintered from 1600 to 1800 °C for 2–10 h are calculated according to the Arrhenius equation [41]:

$$\ln k = \frac{-E_a}{RT} + C \quad (10)$$

In the above, k is the rate constant from Eq. (9), E_a is the activation energy, and both R and C are constants. As shown in Fig. 4(c), we fit $\ln k$, and obtain the activation energies $E_a = 710$, 670, and 650 kJ/mol for the samples with 5.0, 10.0, and 15.0 at% La concentrations, respectively, which corresponds to the findings of Borovkova *et al.* [42]. According to a

previous kinetic analysis, the grain-size–density (G – ρ) trajectory of La-doped Y₂O₃ with a sintering temperature of 1750 °C for 2–40 h is presented in Fig. 4(d). It is found that the increase of La concentration promotes the densification rate, but reduces the grain-growth rate. Thus, the faster densification kinetics in Y₂O₃ samples with a higher La concentration leads to transparency at a lower sintering temperature, as confirmed through the optical experimental results.

3.3 Mechanical properties

Generally speaking, mechanical properties are very important for the application of laser matrix materials [43]. In this work, the mechanical parameters (B , G , E , k , σ , and H_v) are obtained by calculation from the longitudinal and transverse sound velocities. As shown in Table 1, the observed values of G are much smaller than those of B , indicating that G is a key parameter for the mechanical stability of La-doped samples. In particular, the values of G in Y₂O₃ doped with 5.0 at% La are higher than those in Y₂O₃ ceramics, owing to

the smaller particle size [50]. It is well known that k (G/B) refers to the brittle and ductile behaviour of materials, and the critical value for distinguishing ductility from brittleness is approximately 0.57. From Table 1, the k values are 0.50, 0.47, and 0.46 for the 5.0, 10.0, and 15.0 at% La^{3+} concentrations, respectively. In particular, the k value of the 15.0 at% La-doped Y_2O_3 is approximately 0.46, corresponding to a brittle material. Furthermore, the values of σ (as determined from G and E data) are 0.285, 0.298, and 0.303 for the

5.0, 10.0, and 15.0 at% La-doped Y_2O_3 , respectively, consistent with the reported values of Ramzan *et al.* [45]. Moreover, the values of H_v for the La-doped Y_2O_3 increase with increasing La concentrations owing to the Hall–Petch effect [47], and are still higher than the values of a Y_2O_3 single crystal [44]. In addition, from Table 1, it can be observed that the value of E of the 15.0 at% La-doped Y_2O_3 is approximately 179.8, which is beneficial to alleviating stress accumulations in the host material.

Fig. 4 (a) Grain size and (b) grain growth kinetics as a function of the sintering time for La-doped Y_2O_3 ceramics at a sintering temperature of 1750 °C. (c) Arrhenius analysis of samples at a sintering temperature of 1650–1800 °C for 2–10 h. (d) Grain size vs. relative density of samples at a sintering temperature of 1750 °C for 2–40 h.

Table 1 Mechanical properties and sound wave velocities of La-doped Y_2O_3 ceramics

La concentration (at%)	v_l (m/s)	v_t (m/s)	B (GPa)	G (GPa)	k	E (GPa)	σ	H_v (GPa)
5.0	6802	3733	139.1	70.0	0.50	172.0	0.285	7.1
10.0	6786	3637	144.5	67.3	0.47	174.8	0.298	7.8
15.0	6733	3582	145.3	66.0	0.46	179.8	0.303	8.2
Y_2O_3 crystal [44]	—	—	149.5	66.3	0.44	173.0	0.307	7.6
Y_2O_3 crystal [45]	—	—	153.8	62.4	0.41	165.0	0.320	—
Y_2O_3 ceramic [46]	6931	3712	148.9	69.2	0.46	179.8	0.299	—
Y_2O_3 ceramic [47]	6876	3670	—	—	—	176.2	0.300	8.8
La– Y_2O_3 ceramic [48]	6680	3640	142.0	65.0	0.46	170.0	0.300	—
La– Y_2O_3 ceramic [49]	6687	3522	144.5	63.6	0.44	144.5	0.308	—

3.4 Thermal properties

In laser transparent ceramics, the thermal expansion coefficient is closely related to the material life. To obtain the thermal expansion coefficient (α) for the isotropic La-doped Y_2O_3 phase, the following equation is used [48]:

$$\alpha = \frac{dL / L_0}{\Delta T} \quad (11)$$

Here, ΔT is the difference in temperature. As shown in Fig. 5(a), the experimental data of the thermal expansion length vs. temperature approximates to a line, implying that no phase transition occurs with an increase of temperature. It is also found that, as shown in Fig. 5(b), owing to the lattice relaxation induced by doping, the thermal expansion coefficient is generally increased upon an increase of doping concentration.

To investigate the effects of the concentrations of sintering additives on the thermal conductivity of the 5.0, 10.0, and 15.0 at% La-doped Y_2O_3 samples, the thermal conductivity is estimated as follows:

$$\kappa = \lambda \cdot C_p \cdot \rho \quad (12)$$

In here, κ is the thermal conductivity, λ is the thermal diffusivity, C_p is the constant pressure heat capacity, and ρ is the relative density. As the grain size is several orders of magnitude larger than the average phonon-free path in the sample, the impact of the grain size on the heat transfer is not dominant [51]. As shown in Fig. 6(a), with an increase of the concentration of doped La^{3+} ions, both the thermal diffusivity and the heat capacity of the sample significantly decrease, indicating that the thermal diffusivity and heat capacity of the Y_2O_3 samples show significant dependence on

the La_2O_3 doping concentration. In addition, the density increases, owing to the difference in atomic weight between Y^{3+} ion (88.9) and La^{3+} ion (138.9) (Fig. 6(b)). According to the method proposed in the literature [33], the thermal conductivities of the La-doped Y_2O_3 ceramics are calculated to be 7.77, 6.13, and 5.82 $\text{W}/(\text{m}\cdot\text{K})$ for the samples with 5.0, 10.0, and 15.0 at% La^{3+} concentrations, respectively. It should be pointed out that the thermal conductivity decreases slightly with an increase in La-doping concentration, owing to defects from doping (Fig. 6(b)).

The thermal diffusivity, heat capacity, and density of the 15.0 at% La-doped Y_2O_3 are acquired in the range of 25–800 $^{\circ}\text{C}$, to elucidate the temperature effects on the thermal conductivity changes. As shown in Fig. 6(c), the decrease in thermal diffusivity through the increase of temperature is attributed to the strong phonon–phonon scattering [51]. In particular, as shown in Fig. 6(d), the heat capacity increases from 0.43 (25 $^{\circ}\text{C}$) to 0.53 (800 $^{\circ}\text{C}$), whereas the thermal conductivity decreases from 5.82 (25 $^{\circ}\text{C}$) to 2.24 (800 $^{\circ}\text{C}$). The 15.0 at% La-doped Y_2O_3 ceramic exhibits a superior thermal conductivity as compared to traditional laser glasses [52]. Thus, we can provide an effective and convenient method for producing high-transparency Y_2O_3 ceramics with excellent thermal and mechanical properties.

4 Conclusions

In summary, a Y_2O_3 transparent ceramic is successfully prepared via vacuum sintering while adding La_2O_3 as a

Fig. 5 (a) Thermal expansion ration and (b) thermal expansion coefficient of La-doped Y_2O_3 ceramics dependence on temperature.

Fig. 6 (a) Thermal diffusivity and heat capacity, and (b) density and thermal conductivity as a function of La-doping concentration. (c) Thermal diffusivity and heat capacity, and (b) thermal conductivity of 15.0 at% La-doped Y_2O_3 sample dependence on temperature.

sintering aid. A sintering kinetics analysis reveals that the grain-boundary diffusion dominates the densification kinetics. The experimental results show that the diffusion in the grain boundary increases and the grain size decreases with increases of La^{3+} concentration. In the 15.0 at% La-doped Y_2O_3 ceramic, a lack of pores and a uniform microstructure are acquired at a sintering temperature of 1750°C , and the maximum in-line transmittance at a wavelength of 1100 nm reached 81.2%. Furthermore, both the mechanical and thermal properties of the transparent ceramics are improved with increases of sintering additive contents. We believe that the current study may propose a method for synthesizing high-quality laser transparent ceramics, which would be of both scientific and technological significance.

Acknowledgements

This study is supported by the National Natural Science Foundation of China (Grant Nos. 51802142 and 50990302), Foundation of Shenzhen Science and Technology Innovation Committee (Grant Nos. JCYJ20180302174439113 and JCYJ20180504170444967), and Basic Discipline Development Fund of Army Engineering University of PLA (Grant No. KYJBJQZL1905).

References

- [1] Boulon G. Fifty years of advances in solid-state laser materials. *Opt Mater* 2012, **34**: 499–512.
- [2] Lu JR, Lu JH, Murai T, *et al.* $\text{Nd}^{3+}:\text{Y}_2\text{O}_3$ ceramic laser. *Jpn J Appl Phys* 2001, **40**: L1277–L1279.
- [3] Kong J, Tang DY, Lu J, *et al.* Spectral characteristics of a Yb-doped Y_2O_3 ceramic laser. *Appl Phys B* 2004, **79**: 449–455.
- [4] Lu JR, Takaichi K, Uematsu T, *et al.* $\text{Yb}^{3+}:\text{Y}_2\text{O}_3$ ceramics—a novel solid-state laser material. *Jpn J Appl Phys* 2002, **41**: L1373–L1375.
- [5] Lu J, Guo X, Shi ZZ, *et al.* Large diameter Y_2O_3 -shield for the crystal growth of YAP. *J Synth Crystal* 1989, **18**: 341–343.
- [6] Pirri A, Toci G, Patrizi B, *et al.* An overview on Yb-doped transparent polycrystalline sesquioxide laser ceramics. *IEEE J Sel Top Quantum Electron* 2018, **24**: 1–8.
- [7] Xiao ZH, Yu SJ, Li YM, *et al.* Materials development and potential applications of transparent ceramics: A review. *Mat Sci Eng: R: Rep* 2020, **139**: 100518.
- [8] Ikesue A, Kinoshita T, Kamata K, *et al.* Fabrication and optical properties of high-performance polycrystalline Nd:YAG ceramics for solid-state lasers. *J Am Ceram Soc* 1995, **78**: 1033–1040.
- [9] Sanghera J, Kim W, Villalobos G, *et al.* Ceramic laser materials: Past and present. *Opt Mater* 2013, **35**: 693–699.
- [10] Micheli AL, Dungan DF, Mantese JV. High-density yttria

- for practical ceramic applications. *J Am Ceram Soc* 1992, **75**: 709–711.
- [11] Sarthou J, Duquesne JY, Becerra L, *et al.* Thermal conductivity measurements of Yb:CaF₂ transparent ceramics using the 3 ω method. *J Appl Phys* 2017, **121**: 245108.
- [12] Tang F, Wang WC, Yuan XY, *et al.* Dependence of optical and thermal properties on concentration and temperature for Yb:YAG laser ceramics. *J Alloys Compd* 2014, **593**: 123–127.
- [13] Hostaša J, Matějček J, Nait-Ali B, *et al.* Thermal properties of transparent Yb-doped YAG ceramics at elevated temperatures. *J Am Ceram Soc* 2014, **97**: 2602–2606.
- [14] Manning WR, Hunter O, Powell BR. Elastic properties of polycrystalline yttrium oxide, dysprosium oxide, holmium oxide, and erbium oxide: Room temperature measurements. *J Am Ceram Soc* 1969, **52**: 436–442.
- [15] Huang YH, Jiang DL, Zhang JX, *et al.* Fabrication of transparent lanthanum-doped yttria ceramics by combination of two-step sintering and vacuum sintering. *J Am Ceram Soc* 2009, **92**: 2883–2887.
- [16] Podowitz SR, Gaumé R, Feigelson RS. Effect of europium concentration on densification of transparent Eu:Y₂O₃ scintillator ceramics using hot pressing. *J Am Ceram Soc* 2010, **93**: 82–88.
- [17] Mouzon J, Maitre A, Frisk L, *et al.* Fabrication of transparent yttria by HIP and the glass-encapsulation method. *J Eur Ceram Soc* 2009, **29**: 311–316.
- [18] Lu SZ, Yang QH, Zhang HJ, *et al.* Spectroscopic characteristics and laser performance of Nd:Y_{1.8}La_{0.2}O₃ transparent ceramics. *IEEE J Quantum Electron* 2013, **49**: 293–300.
- [19] Zhou HX, Yang QH, Xu J, *et al.* Preparation and spectroscopic properties of 2%Nd:(Y_{0.9}La_{0.1})₂O₃ transparent ceramics. *J Alloys Compd* 2009, **471**: 474–476.
- [20] Hao Q, Li WX, Zeng HP, *et al.* Low-threshold and broadly tunable lasers of Yb³⁺-doped yttrium lanthanum oxide ceramic. *Appl Phys Lett* 2008, **92**: 211106.
- [21] Yang QH, Dou CG, Ding J, *et al.* Spectral characterization of transparent (Nd_{0.01}Y_{0.94}La_{0.05})₂O₃ laser ceramics. *Appl Phys Lett* 2007, **91**: 111918.
- [22] Savage JA. Preparation and properties of hard crystalline materials for optical applications—a review. *J Cryst Growth* 1991, **113**: 698–715.
- [23] Sahi S, Wang ZQ, Luo JM, *et al.* Investigation of luminescence mechanism in La_{0.2}Y_{1.8}O₃ scintillator. *J Lumin* 2016, **173**: 99–104.
- [24] Desmaison-Brut M, Montintin J, Valin F, *et al.* Influence of processing conditions on the microstructure and mechanical properties of sintered yttrium oxides. *J Am Ceram Soc* 1995, **78**: 716–722.
- [25] Mao XJ, Li XK, Feng MH, *et al.* Cracks in transparent La-doped yttria ceramics and the formation mechanism. *J Eur Ceram Soc* 2015, **35**: 3137–3143.
- [26] Rhodes WH. Controlled transient solid second-phase sintering of yttria. *J Am Ceram Soc* 1981, **64**: 13–19.
- [27] Coutures J, Foex M. Study at high-temperature of equilibrium diagram of system by lanthanum sesquioxide with yttrium sesquioxide. *J Solid State Chem* 1974, **11**: 294–300.
- [28] Zhang L, Huang ZC, Pan W. High transparency Nd:Y₂O₃ ceramics prepared with La₂O₃ and ZrO₂ additives. *J Am Ceram Soc* 2015, **98**: 824–828.
- [29] Ledbetter HM, Reed RP. Elastic properties of metals and alloys, I. iron, nickel, and iron-nickel alloys. *J Phys Chem Ref Data* 1973, **2**: 531–618.
- [30] Adhikari V, Liu ZTY, Szymanski NJ, *et al.* First-principles study of mechanical and magnetic properties of transition metal (M) nitrides in the cubic M4N structure. *J Phys Chem Solids* 2018, **120**: 197–206.
- [31] Phani KK, Niyogi SK. Elastic modulus-porosity relation in polycrystalline rare-earth oxides. *J Am Ceram Soc* 1987, **70**: C-362–C-366.
- [32] Li D, Tian FB, Duan DF, *et al.* Mechanical and metallic properties of tantalum nitrides from first-principles calculations. *RSC Adv* 2014, **4**: 10133–10139.
- [33] Zhang L, Pan W. Structural and thermo-mechanical properties of Nd:Y₂O₃ transparent ceramics. *J Am Ceram Soc* 2015, **98**: 3326–3331.
- [34] Chen PL, Chen IW. Grain boundary mobility in Y₂O₃: Defect mechanism and dopant effects. *J Am Ceram Soc* 1996, **79**: 1801–1809.
- [35] Ikesue A, Kamata K. Microstructure and optical properties of hot isostatically pressed Nd:YAG ceramics. *J Am Ceram Soc* 1996, **79**: 1927–1933.
- [36] Li XD, Li JG, Xiu ZM, *et al.* Transparent Nd:YAG ceramics fabricated using nanosized γ -alumina and yttria powders. *J Am Ceram Soc* 2009, **92**: 241–244.
- [37] Coble RL. Sintering crystalline solids. I. Intermediate and final state diffusion models. *J Appl Phys* 1961, **32**: 787–792.
- [38] Fang JX, Thompson AM, Harmer MP, *et al.* Effect of yttrium and lanthanum on the final-stage sintering behavior of ultrahigh-purity alumina. *J Am Ceram Soc* 2005, **80**: 2005–2012.
- [39] Chen PL, Chen IW. Sintering of fine oxide powders: I, microstructural evolution. *J Am Ceram Soc* 1996, **79**: 3129–3141.
- [40] Chen PL, Chen IW. Sintering of fine oxide powders: II, sintering mechanisms. *J Am Ceram Soc* 1997, **80**: 637–645.
- [41] Stevenson AJ, Li X, Martinez MA, *et al.* Effect of SiO₂ on densification and microstructure development in Nd:YAG transparent ceramics. *J Am Ceram Soc* 2011, **94**: 1380–1387.
- [42] Borovkova LB, Lukin ES, Poluboyarinov DN. Sintering and recrystallization of yttrium oxide. *Refractories* 1972, **13**: 595–600.
- [43] Wang HM, Huang ZY, Qi JQ, *et al.* A new methodology to obtain the fracture toughness of YAG transparent ceramics. *J Adv Ceram* 2019, **8**: 418–426.
- [44] Palko JW, Kriven WM, Sinogeikin SV, *et al.* Elastic constants of yttria (Y₂O₃) monocrystals to high

- temperatures. *J Appl Phys* 2001, **89**: 7791–7796.
- [45] Ramzan M, Li Y, Chimata R, *et al.* Electronic, mechanical and optical properties of Y_2O_3 with hybrid density functional (HSE06). *Comput Mater Sci* 2013, **71**: 19–24.
- [46] Yeheskel O, Tevet O. Elastic moduli of transparent yttria. *J Am Ceram Soc* 2004, **82**: 136–144.
- [47] Albayrak IC, Basu S, Sakulich A, *et al.* Elastic and mechanical properties of polycrystalline transparent yttria as determined by indentation techniques. *J Am Ceram Soc* 2010, **93**: 2028–2034.
- [48] Tropf WJ, Harrias DC. Mechanical, thermal, and optical properties of yttria and lanthana-doped yttria. In Proceedings of the SPIE 1112, Window and Dome Technologies and Material, 1989.
- [49] Wei GC, Brecher C, Pascucci MR, *et al.* Characterization of lanthana-strengthened yttria infrared transmitting materials. In Proceedings of the SPIE 0929, Infrared Optical Materials IV, 1988.
- [50] Liu YZ, Jiang YH, Zhou R, *et al.* Mechanical properties and chemical bonding characteristics of WC and W_2C compounds. *Ceram Int* 2014, **40**: 2891–2899.
- [51] Zhang L, Pan W, Feng J. Dependence of spectroscopic and thermal properties on concentration and temperature for $\text{Yb:Y}_2\text{O}_3$ transparent ceramics. *J Eur Ceram Soc* 2015, **35**: 2547–2554.
- [52] Hostaša J, Nečina V, Uhlířová T, *et al.* Effect of rare earth ions doping on the thermal properties of YAG transparent ceramics. *J Eur Ceram Soc* 2019, **39**: 53–58.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made.

The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.