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The geometrical structure and electronic properties of trivalent Ho³⁺ doped Y₂O₃ crystals: a first-principles study

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Trivalent rare-earth holmium ion (Ho³⁺) doped yttrium oxide (Y₂O₃) has attracted great research interest owing to its unique optoelectronic properties and excellent performances in many new-type laser devices. But the crystal structures of the Ho³⁺-doped Y₂O₃ system (Y₂O₃ : Ho) are still unclear. Here, we have carried out a first-principle study on the structural evolution of the trivalent Ho³⁺ doped Y₂O₃ by using the CALYPSO structure search method. The results indicate that the lowest-energy structure of Ho³⁺-doped Y₂O₃ possesses a standardized monoclinic *P2* phase. It is found that the doped Ho³⁺ ion are likely to occupy the sites of Y³⁺ in the host crystal lattice, forming the [HoO₆]⁹⁻ local structure with C₂ site symmetry. Electronic structure calculations reveal that the band gap value of Ho³⁺-doped Y₂O₃ is approximately 4.27 eV, suggesting the insulating character of Y₂O₃ : Ho system. These findings could provide fundamental insights to understand the atomic interactions in crystals as well as the information of electronic properties for other rare-earth-doped materials.

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1. Introduction

Rare-earth (RE) doped laser materials have attracted enormous interests because of their abundant transition channels and sharp luminescence bands.^{1–5} The potential applications have been widely investigated in a diversity of fields, such as optical imaging, quantum cascade lasers, high-density optical data storage and biophotonic areas.^{6–9} A recent study reveals that the directly pumped Ho³⁺-doped silica microsphere may be an excellent candidate for fabricating 2 μm laser, which can serve as laser-emitting source for mid-infrared telecommunications.¹⁰

Trivalent holmium ion (4f¹⁰ configuration) is a greatly promising laser ion due to the substantial transition channels at various wavelengths in the UV, visible and infrared regions.^{11,12} A well-known emission transition ⁵I₇ → ⁵I₈ with wavelength near 2 μm of Ho³⁺ can serve as the so called “eye safe” solid-state laser system.¹³ Yttrium oxide (Y₂O₃) is a typical cubic phase crystal structure with *Ia* $\bar{3}$ space group, which possesses low phonon energy and desirable physical properties including low thermal expansion, high melting point and photochemical stability.^{14–16} The Y³⁺ ions of yttrium oxide crystal are six-fold coordinated to nearest O²⁻ ligands, forming

a [YO₆]⁹⁻ local unit with C₂ site symmetry.¹⁷ After being doped with appropriate rare-earth ions, Y₂O₃ crystals can serve as excellent laser host materials because of their high thermal conductivity and low phonon energy.¹⁸ In recent years, Ho³⁺-doped Y₂O₃ (Y₂O₃ : Ho) crystal has been the subject of intensive investigations as a great promising laser material.¹⁹ Laversenne *et al.* first demonstrated the growth of Ho³⁺-doped Y₂O₃ single crystal by using the Laser Heated Pedestal Growth (LHPG) technique.²⁰ In addition, they especially analyzed the dynamical laser resonant characteristics of Y₂O₃ : Ho. Qin *et al.* studied the luminescence spectra of Ho³⁺-doped Y₂O₃ under the excitation of a 532 nm continuous-wave laser.²¹ The results indicate that Ho³⁺ ion possesses several fluorescence transitions in the ultraviolet and violet region (306, 390 and 428 nm) which are assigned to the transitions of ³D₃ → ⁵I₈, ⁵G₄ → ⁵I₈ and ⁵G₅ → ⁵I₈, respectively. Wang *et al.* reported a high output laser operation at around 2.1 μm of Y₂O₃ : Ho with low scattering loss and excellent optical quality.²² Their results revealed that Ho³⁺-doped Y₂O₃ system shows attractive prospect in high-power and efficient laser applications as a laser gain medium. Although numerous investigations have been widely reported on Y₂O₃ : Ho, there is no systematic study to elucidate its microstructure and electronic properties.

In this paper, we perform extensive structure searches to obtain the ground-state structure of Y₂O₃ : Ho based on the CALYPSO (Crystal structure AnaLYsis by Particle Swarm Optimization)^{23–27} method coupled with the DFT (density functional theory). Furthermore, we calculate and analyze the band structure, density of states and the ELF (electron localized

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function) to gain deeper insights into the electronic properties of Ho³⁺-doped Y₂O₃ system. The outline of this paper is organized as follows. We exhibit a brief description of the calculation method in Section 2. In Section 3, we present our results and discussion. A conclusion is finally given in Section 4.

2. Computational methods

We have explored the structural evolution of Y₂O₃ : Ho crystal by using the unbiased CALYPSO^{23–27} method. The CALYPSO is a reliable structure prediction method which has been validated by a large variety of crystal structures.^{28–32} We perform an evolutionary variable-cell structure prediction with 80 atoms per simulation cell at ambient pressure. To determine the most stable structure of Y₂O₃ : Ho system, we optimized the all lowest-lying candidate structures by using the density functional theory in VASP (Vienna *Ab Initio* Simulation Package) code.^{33–35} The frozen-core all electron projector-augmented wave (PAW) method has been adopted, with 4f¹¹5s²5p⁶6s², 4d¹5s² and 2s²2p⁴ treated as valence electrons for Ho, Y and O, respectively. For describing the influence of the correlation effect introduced by 4f electrons of Ho atoms, we employ the local density approximation (LDA) with an onsite Coulomb repulsion parameter *U*³⁶ to determine the electronic band structure of Y₂O₃ : Ho. The *U* value of Ho has been determined to be 6.8 eV by Min *et al.*³⁷ Phonon dispersion curve have been calculated by the PHONOPY code.³⁸

3. Results and discussion

We carefully examine the ground-state crystal structure of Ho³⁺-doped Y₂O₃ by using the unbiased CALYPSO structure search method with the stoichiometric ratio of Ho : Y : O = 1 : 31 : 48 under ambient conditions. The lowest-energy structure of Y₂O₃ : Ho is successfully identified and displayed in Fig. 1. It can be seen from Fig. 1 that the ground-state Y₂O₃ : Ho crystal possesses the monoclinic configuration with the Ho³⁺ ion (0.901 Å) substitute for Y³⁺ ion (0.900 Å) in the Y₂O₃ host. The concentration of the impurity Ho³⁺ is equal to 3.125%, which is in excellent agreement with the result measured by Atabaev

*et al.*¹⁵ The site symmetry of [HoO₆]^{9–} local structure are calculated to be C₂ and Ho³⁺ position are six-coordinated by oxygen atoms. The three different bond lengths between Ho–O bonds are calculated to be 2.214, 2.232, and 2.318 Å, respectively. The Ho³⁺ doped Y₂O₃ crystal structure belongs to the standardized *P2* symmetry and the calculated lattice constants are *a* = *b* = *c* = 10.524 Å, β = 90°. The coordinates of all atoms for the ground state Y₂O₃ : Ho are summarized in Table 1 for further investigations. Moreover, our structure searches also predict many metastable structures of Ho³⁺-doped Y₂O₃ which can play important roles to explore the structural evolutions. The first four optimized low-lying structures (a), (b), (c) and (d)

Table 1 Coordinates of all atoms for the ground state Ho³⁺-doped Y₂O₃

| Atom | <i>x</i> | <i>y</i> | <i>z</i> | Wyckoff site symmetry |
|-------|----------|----------|----------|-----------------------|
| Ho | 0.50000 | 0.03244 | –0.00000 | 1c |
| O(1) | –0.09805 | 0.37926 | 0.39177 | 2e |
| O(2) | 0.40264 | 0.87998 | 0.89255 | 2e |
| O(5) | 0.40205 | 0.12070 | 0.60831 | 2e |
| O(6) | –0.09818 | 0.62076 | 0.10808 | 2e |
| O(9) | 0.14194 | 0.15190 | 0.37921 | 2e |
| O(10) | 0.64186 | 0.65190 | 0.87934 | 2e |
| O(11) | –0.14176 | 0.84802 | 0.87927 | 2e |
| O(12) | 0.35819 | 0.34791 | 0.37925 | 2e |
| O(17) | 0.12928 | 0.39175 | 0.15192 | 2e |
| O(18) | 0.62931 | 0.89190 | 0.65180 | 2e |
| O(19) | 0.62868 | 0.10740 | 0.84899 | 2e |
| O(20) | 0.12931 | 0.60822 | 0.34801 | 2e |
| O(25) | 0.59794 | 0.62079 | 0.60830 | 2e |
| O(26) | 0.09816 | 0.12070 | 0.10813 | 2e |
| O(29) | 0.09808 | 0.87932 | 0.39175 | 2e |
| O(30) | 0.59805 | 0.37924 | 0.89184 | 2e |
| O(33) | 0.35820 | 0.84806 | 0.62099 | 2e |
| O(34) | –0.14195 | 0.34792 | 0.12077 | 2e |
| O(35) | 0.64100 | 0.15153 | 0.12014 | 2e |
| O(36) | 0.14182 | 0.65199 | 0.62075 | 2e |
| O(41) | 0.37080 | 0.60848 | 0.84803 | 2e |
| O(42) | –0.12934 | 0.10816 | 0.34796 | 2e |
| O(43) | –0.12943 | 0.89189 | 0.15191 | 2e |
| O(44) | 0.37080 | 0.39172 | 0.65211 | 2e |
| Y(1) | 0.00004 | 0.24998 | 0.24998 | 2e |
| Y(2) | 0.49982 | 0.75036 | 0.24967 | 2e |
| Y(3) | 0.50011 | 0.24976 | 0.75024 | 2e |
| Y(4) | 0.00005 | 0.75003 | 0.75003 | 2e |
| Y(9) | –0.25020 | 0.24979 | 0.96795 | 2e |
| Y(10) | –0.25006 | 0.75002 | 0.53211 | 2e |
| Y(13) | 0.71753 | 0.00010 | 0.24967 | 2e |
| Y(15) | –0.21791 | 0.50004 | 0.24995 | 2e |
| Y(21) | –0.25026 | 0.75030 | 0.03217 | 2e |
| Y(22) | 0.25002 | 0.24997 | 0.53226 | 2e |
| Y(25) | –0.21803 | 0.00001 | 0.75019 | 2e |
| Y(26) | 0.28218 | 0.49999 | 0.24999 | 2e |
| Y(17) | 0.00000 | 0.96781 | 0.00000 | 1a |
| Y(30) | 0.00000 | 0.46784 | 0.00000 | 1a |
| Y(18) | 0.50000 | 0.53219 | –0.00000 | 1c |
| Y(19) | 0.00000 | 0.03214 | 0.50000 | 1b |
| Y(29) | 0.00000 | 0.53220 | 0.50000 | 1b |
| Y(20) | 0.50000 | 0.46778 | 0.50000 | 1d |
| Y(31) | 0.50000 | 0.96786 | 0.50000 | 1d |

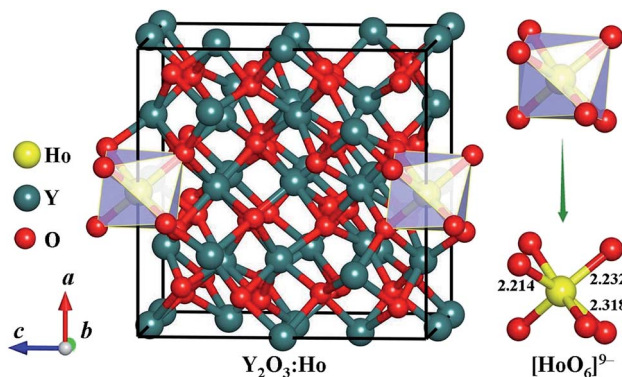


Fig. 1 Crystal structure and [HoO₆]^{9–} local unit of the ground-state Ho³⁺-doped Y₂O₃. The bond lengths are in the unit of Å.



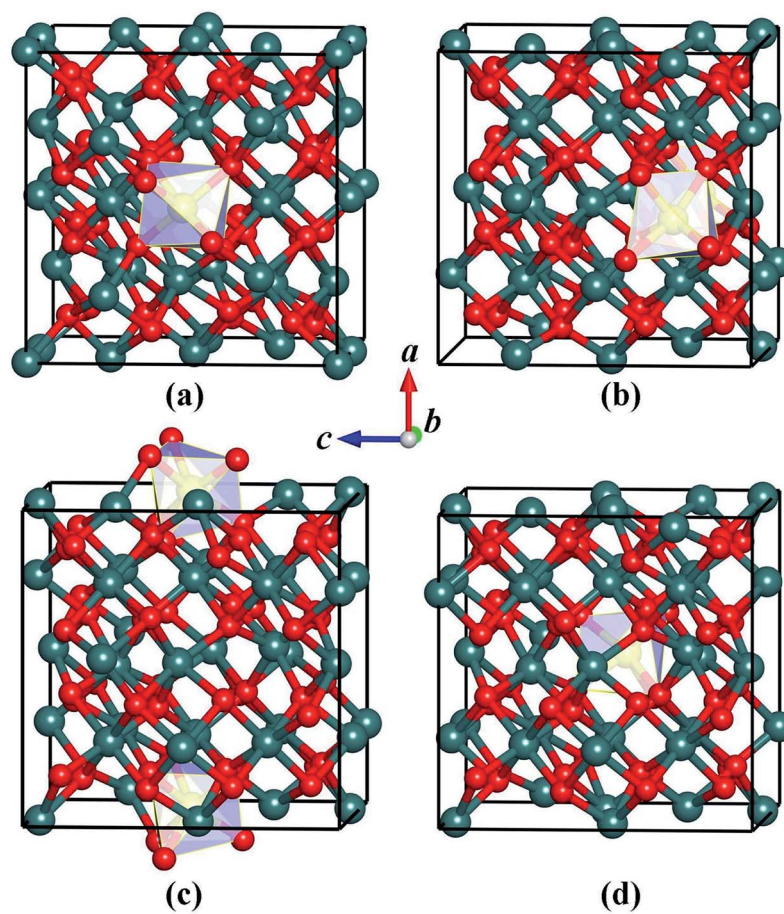


Fig. 2 Coordination structures of the metastable (a–d) for $\text{Y}_2\text{O}_3 : \text{Ho}$.

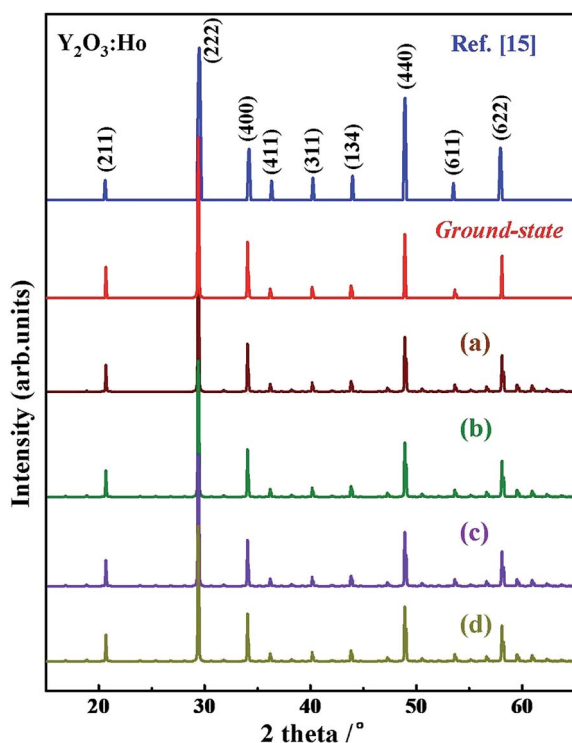


Fig. 3 Comparison of the simulated XRD spectrum for the ground-state and metastable (a–d) $\text{Y}_2\text{O}_3 : \text{Ho}$ with experimental patterns.

from low to high energy are exhibited in Fig. 2. It is found that the Y^{3+} ions of these isomers are replaced by Ho^{3+} ions at different sites in the host crystals. Interestingly, the isomer (a) possesses the same $P2$ monoclinic configuration with the ground-state structure while the isomers (b), (c) and (d) exhibit the $P1$ space group. In these metastable structures, we find that the impurity Ho^{3+} ions tend to occupy the crystal face site positions of the Y^{3+} .

To clarify the true structure of the ground-state $\text{Y}_2\text{O}_3 : \text{Ho}$, as shown in Fig. 3, we calculate the X-ray diffraction (XRD) patterns of the ground state structure. We can clearly see from Fig. 3 that the simulated spectrum of $\text{Y}_2\text{O}_3 : \text{Ho}$ are in good accordance with the observations in experiment.¹⁵ In addition, the XRD patterns of the four metastable structures are calculated and the results are also plotted in Fig. 3. It can be seen from Fig. 3 that the overall distribution of the peaks is similar, suggesting that the structural parameters of the four metastable structures are close to each other. To further validate the dynamical stability of Ho^{3+} -doped Y_2O_3 system, we have calculated the phonon dispersion curves in Fig. 4 and no imaginary phonon frequencies can be seen over the entire Brillouin zones. The result indicates that the determined ground-state structure of Ho^{3+} -doped Y_2O_3 crystal is dynamically stable. These theoretical results provide great support for the reliability of our structural prediction methodology.



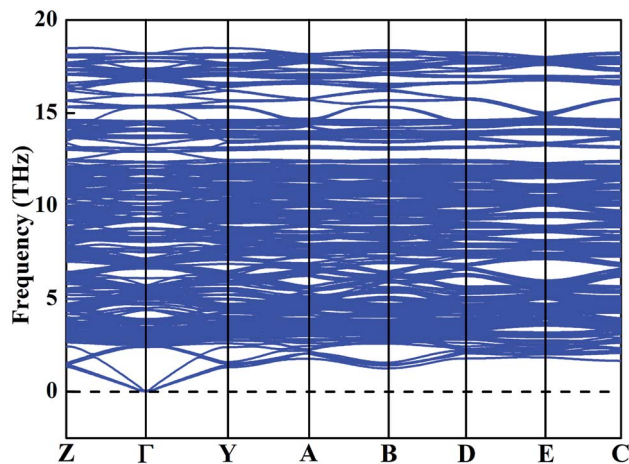


Fig. 4 Calculated phonon dispersion curve for the ground-state $\text{Y}_2\text{O}_3 : \text{Ho}$.

We have calculated the electronic band structure and the total as well as partial DOS for $\text{Y}_2\text{O}_3 : \text{Ho}$. As illustrated in Fig. 5(a), the direct band gap value for Ho^{3+} -doped Y_2O_3 is about 4.27 eV at the Γ point, which is approximately 2/3 of the experimental value ($E_g = 6.2$ eV) determined by Wallace and

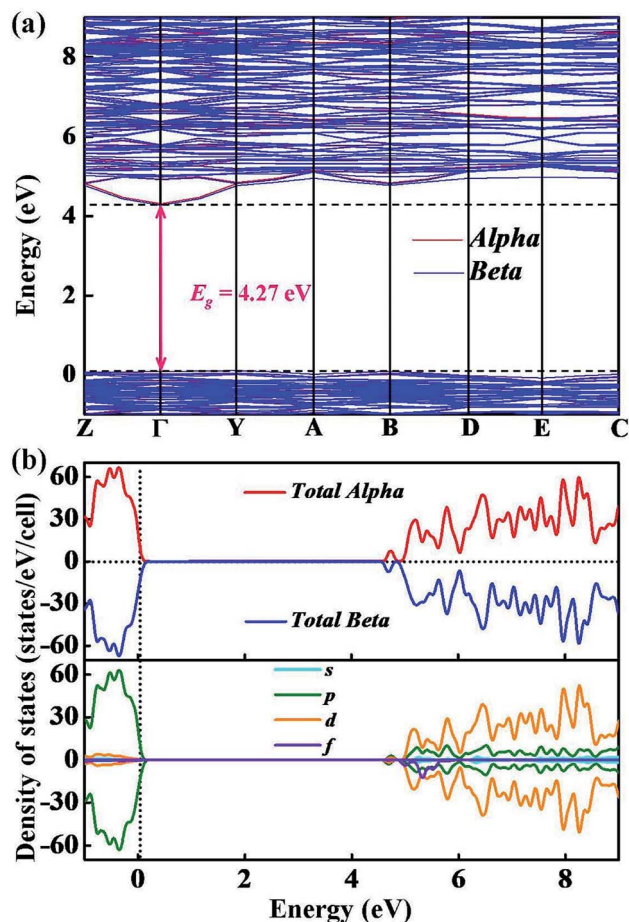


Fig. 5 The calculated (a) electronic band structure and (b) total as well as partial densities of states of $\text{Y}_2\text{O}_3 : \text{Ho}$.

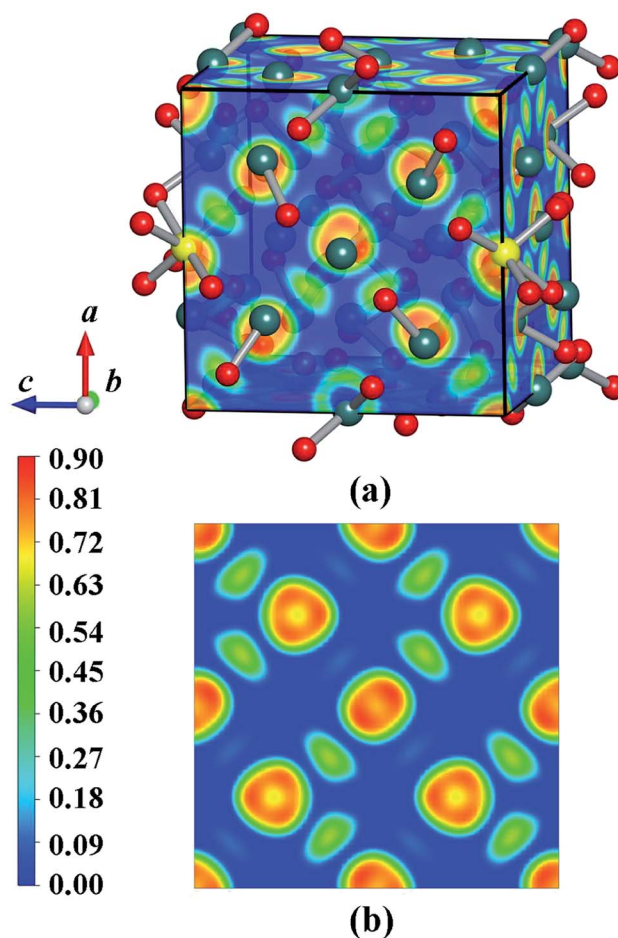


Fig. 6 ELF maps of (a) the structure and (b) $\langle 100 \rangle$ plane for the ground-state $\text{Y}_2\text{O}_3 : \text{Ho}$.

Wilk.³⁹ This result can be ascribed to the general underestimation of band gap value by the first-principle calculations. The result indicates that the Ho^{3+} impurity ion remains the insulating character of Ho^{3+} -doped Y_2O_3 crystal. From Fig. 5(b), we can clearly see that the low valence band region is mainly composed of p states with the smaller contributors of d states ranging from -1 eV to 0 eV, and the dominant contributions of the high conduction band between 4.3 eV to 9 eV are mainly occupied by p, d and f states. It should be noted that the s states is very weak from -1 eV to 9 eV. In addition, we have calculated the electron localized function (ELF) to visualize the chemical bonding character in $\text{Y}_2\text{O}_3 : \text{Ho}$ crystal. The ELF in crystal structure and the ELF of the (100) plane are presented in Fig. 6. It is shown that the ELF near the Y and Ho atoms value is close to 0.9, which suggests that the electrons are extremely localized around the Y and Ho atoms.

4. Conclusions

In summary, we have explored the ground-state crystal structure of Ho^{3+} -doped Y_2O_3 by means of the unbiased CALYPSO method combined with first-principle calculations. It is shown that the ground-state $\text{Y}_2\text{O}_3 : \text{Ho}$ structure possesses a novel $P2$



phase with the monoclinic symmetry. We carry out a systematic investigation to the microstructure evolutions for the ground-state $\text{Y}_2\text{O}_3 : \text{Ho}$ crystal. The results indicate that the impurity Ho^{3+} ion substitutes the positions of Y^{3+} ions in the host crystal lattice, forming the $[\text{HoO}_6]^{9-}$ local structure. We find that the impurity Ho^{3+} ions tend to occupy the crystal face positions of the Y^{3+} ions from the structural features of the ground-state and metastable structures. We further calculate the band structure and density of states by LDA + U method for $\text{Y}_2\text{O}_3 : \text{Ho}$. Our result reveals that the electronic band gap of Ho^{3+} -doped Y_2O_3 is 4.27 eV. We hope that these findings can provide valuable guidance for future experiment research of $\text{Y}_2\text{O}_3 : \text{Ho}$.

Conflicts of interest

The authors declare no competing interests.

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References

- P. S. J. Bharadwaj, S. Kundu, V. S. Kollipara and K. B. R. Varma, Synergistic effect of trivalent (Gd^{3+} , Sm^{3+}) and high-valent (Ti^{4+}) co-doping on antiferromagnetic YFeO_3 , *RSC Adv.*, 2020, **10**, 22183–22195.
- J. Bai, P. Duan, X. Wang, G. Han, M. Wang and G. Diao, Upconversion luminescence enhancement by Fe^{3+} doping in $\text{CeO}_2 : \text{Yb/Er}$ nanomaterials and their application in dye-sensitized solar cells, *RSC Adv.*, 2020, **10**, 18868–18874.
- Monika, R. S. Yadav, A. Bahadur and S. B. Rai, Concentration and pump-mediated color tenability, optical heating and temperature sensing via TCLs of red emission in an $\text{Er}^{3+}/\text{Yb}^{3+}/\text{Li}^+$ co-doped ZnGa_2O_4 phosphor, *RSC Adv.*, 2019, **9**, 40092–40108.
- N. Choudhary, M. K. Verma, N. D. Sharma, S. Sharma and D. Singh, Correlation between magnetic and transport properties of rare earth doped perovskite manganites $\text{La}_{0.6}\text{R}_{0.1}\text{Ca}_{0.3}\text{MnO}_3$ ($\text{R} = \text{La}, \text{Nd}, \text{Sm}, \text{Gd}, \text{and Dy}$) synthesized by Pechini process, *Mater. Chem. Phys.*, 2020, **242**, 122482.
- M. P. Ghosh, S. Sharma, H. K. Satyapal, K. Tanbir, R. K. Singh and S. Mukherjee, Tuning the microstructural, optical and superexchange interactions with rare earth Eu doping in nickel ferrite nanoparticles, *Mater. Chem. Phys.*, 2020, **241**, 122383.
- S. D. Jackson, Towards high-power mid-infrared emission from a fibre laser, *Nat. Photonics*, 2012, **6**, 423–431.
- I. Cieslik, T. Bolek, M. J. Wozniak, A. Majchrowski, S. Hirano and A. Budzianowski, Potassium gadolinium tungstate nanocrystals doped with holmium ions as candidates for optical imaging, *Appl. Surf. Sci.*, 2018, **446**, 139–144.
- Y. R. Fang and M. T. Sun, Nanoplasmonic waveguides: towards applications in integrated nanophotonic circuits, *Light: Sci. Appl.*, 2015, **4**, e294.
- X. Y. Wang, Y. L. Wang, S. Wang, B. Li, X. W. Zhang, L. Dai and R. M. Ma, Lasing Enhanced Surface Plasmon Resonance Sensing, *Nanophotonics*, 2017, **6**, 472–478.
- A. Z. Li, M. Zhang, X. Wang, S. B. Wang, B. G. Guo, E. Lewis and P. F. Wang, Directly pumped Ho^{3+} -doped microspheres lasing at 2.0 μm , *IEEE Photonics Technol. Lett.*, 2019, **31**, 1366–1368.
- S. Balaji, G. Gupta, K. Biswas, D. Ghosh and K. Annapurna, Role of Yb^{3+} ions on enhanced $\sim 2.9 \mu\text{m}$ emission from Ho^{3+} ions in low phonon oxide glass system, *Sci. Rep.*, 2016, **6**, 29203.
- M. Eichhorn, Quasi-three-level solid-state lasers in the near and mid infrared based on trivalent rare earth ions, *Appl. Phys. B*, 2008, **93**, 269–316.
- M. C. Pujol, J. Massons, M. Aguiló, F. Díaz, M. Rico and C. Zaldo, Emission Cross Sections and Spectroscopy of Ho^{3+} Laser Channels in $\text{KGd}(\text{WO}_4)_2$ Single Crystal, *IEEE J. Quantum Electron.*, 2002, **38**, 93–100.
- A. Ciric and S. Stojadinovic, Structural and photoluminescence properties of Y_2O_3 and $\text{Y}_2\text{O}_3 : \text{Ln}^{3+}$ ($\text{Ln} = \text{Eu}, \text{Er}, \text{Ho}$) films synthesized by plasma electrolytic oxidation of yttrium substrate, *J. Lumin.*, 2020, **217**, 116762.
- T. S. Atabaev, H. H. T. Vu, Y. D. Kim, J. H. Lee, H. K. Kim and Y. H. Hwang, Synthesis and luminescence properties of Ho^{3+} doped Y_2O_3 submicron particles, *J. Phys. Chem. Solids*, 2012, **73**, 176–181.
- B. M. Walsh, J. M. McMahon, W. C. Edwards, N. P. Barnes, R. W. Equall and R. L. Hutcheson, Spectroscopic characterization of $\text{Nd} : \text{Y}_2\text{O}_3$: application toward a differential absorption lidar system for remote sensing of ozone, *J. Opt. Soc. Am. B*, 2002, **19**, 2893–2903.
- M. Ju, Y. Xiao, W. G. Sun, C. Lu and Y. Y. Yeung, In-depth determination of the microstructure and energy transition mechanism for Nd^{3+} -doped yttrium oxide laser crystals, *J. Phys. Chem. C*, 2020, **124**, 2113–2119.
- V. Singh, V. K. Rai, B. Voss, M. Haase, R. P. S. Chakradhar, D. T. Naidu and S. H. Kim, Photoluminescence study of nanocrystalline $\text{Y}_2\text{O}_3 : \text{Ho}^{3+}$ phosphor, *Spectrochim. Acta, Part A*, 2013, **109**, 206–212.
- G. A. Newburgh, A. W. Daniels, A. Michael, L. D. Merkle, A. Ikesue and M. Dubinskii, Resonantly diode-pumped $\text{Ho}^{3+} : \text{Y}_2\text{O}_3$ ceramic, *Opt. Express*, 2011, **19**, 3604–3611.
- L. Laversenne, C. Goutaudier, Y. Guyot, M. T. Cohen-Adad and G. Boulon, Growth of rare earth (RE) doped concentration gradient crystal fibers and analysis of dynamical processes of laser resonant transitions in RE-doped Y_2O_3 ($\text{RE} = \text{Yb}^{3+}, \text{Er}^{3+}, \text{Ho}^{3+}$), *J. Alloys Compd.*, 2002, **341**, 214–219.
- F. Qin, Y. D. Zheng, Y. Yu, Z. M. Chen, P. S. Tayebi, W. W. Cao and Z. G. Zhang, Ultraviolet and violet upconversion luminescence in Ho^{3+} -doped Y_2O_3 ceramic



- induced by 532-nm CW laser, *J. Alloys Compd.*, 2011, **509**, 1115–1118.
- 22 F. Wang, J. W. Tang, E. H. Li, C. F. Shen, J. Wang, D. Y. Tang and D. Y. Shen, Ho³⁺:Y₂O₃ ceramic laser generated over 113 W of output power at 2117 nm, *Opt. Lett.*, 2019, **44**, 5933–5936.
- 23 Y. C. Wang, J. Lv, L. Zhu and Y. M. Ma, Crystal structure prediction *via* particle-swarm optimization, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2010, **82**, 094116.
- 24 Y. C. Wang, J. Lv, L. Zhu and Y. M. Ma, CALYPSO: a method for crystal structure prediction, *Comput. Phys. Commun.*, 2012, **183**, 2063–2070.
- 25 Y. C. Wang, M. S. Miao, J. Lv, L. Zhu, K. T. Yin, H. Y. Liu and Y. M. Ma, An effective structure prediction method for layered materials based on 2D particle swarm optimization algorithm, *J. Chem. Phys.*, 2012, **137**, 224108.
- 26 S. H. Lu, Y. C. Wang, H. Y. Liu, M. S. Miao and Y. M. Ma, Self-assembled ultrathin nanotubes on diamond (100) surface, *Nat. Commun.*, 2014, **5**, 3666.
- 27 L. Zhu, H. Y. Liu, C. J. Pickard, G. T. Zou and Y. M. Ma, Reactions of xenon with iron and nickel are predicted in the Earth's inner core, *Nat. Chem.*, 2014, **6**, 644–648.
- 28 J. Lv, Y. C. Wang, L. Zhu and Y. M. Ma, Particle-swarm structure prediction on clusters, *J. Chem. Phys.*, 2012, **137**, 084104.
- 29 Y. Xiao, M. Ju, X. Y. Kuang and Y. Y. Yeung, A systematic study of the microstructure and laser characteristics of Pr³⁺-doped lithium lutetium fluoride, *J. Alloys Compd.*, 2018, **749**, 391–398.
- 30 G. Bo, P. Gao, S. Lu, J. Lv, Y. Wang and Y. Ma, Interface structure prediction *via* CALYPSO method, *Sci. Bull.*, 2019, **64**, 301.
- 31 C. Lu and C. Chen, Indentation-strain stiffening in tungsten nitrides: mechanisms and implications, *Phys. Rev. Mater.*, 2020, **4**, 043402.
- 32 C. Lu and C. Chen, Structure-strength relations of distinct MoN phases from first-principles calculations, *Phys. Rev. Mater.*, 2020, **4**, 044002.
- 33 G. Kresse and J. Furthmüller, Efficient iterative schemes for *ab initio* total-energy calculations using a plane-wave basis set, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1996, **54**, 11169–11186.
- 34 G. Kresse and J. Hafner, *Ab initio* molecular dynamics for liquid metals, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1993, **47**, 558–561.
- 35 J. P. Perdew, K. Burke and M. Ernzerhof, Generalized gradient approximation made simple, *Phys. Rev. Lett.*, 1996, **77**, 3865–3868.
- 36 V. I. Anisimov, F. Aryasetiawan and A. I. Lichtenstein, First-principles calculations of the electronic structure and spectra of strongly correlated systems: the LDA + *U* Method, *J. Phys.: Condens. Matter*, 1997, **9**, 767–808.
- 37 B. I. Min, H. J. F. Jansen, T. Oguchi and A. J. Freeman, Local density total energy description of ground and excited state properties of the rare earth metals, *J. Magn. Magn. Mater.*, 1986, **61**, 139–150.
- 38 A. Togo, F. Oba and I. Tanaka, First-principles calculations of the ferroelastic transition between rutile-type and CaCl₂-type SiO₂ at high pressures, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2008, **78**, 134106.
- 39 R. M. Wallace and G. Wilk, Alternative gate dielectrics for microelectronics, *Bulletin*, 2002, **27**, 186.

