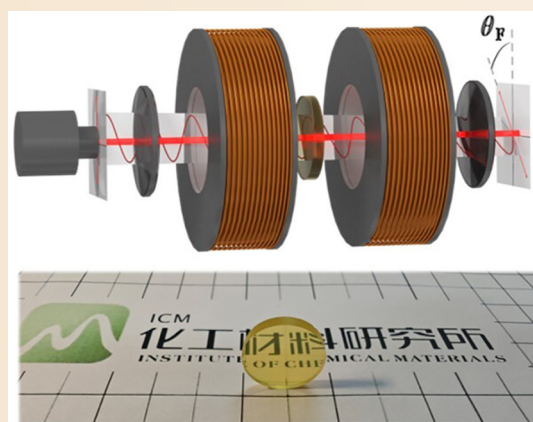


Preparation of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ transparent ceramics with high Verdet constants for magneto-optical applications

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ABSTRACT: Magneto-optical transparent ceramics exhibiting the Faraday effect provide new opportunities for optical isolator applications. In this study, magneto-optical transparent ceramics $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ($x = 0, 0.005, 0.01, 0.0125$, and 0.015) were successfully fabricated by reducing atmosphere sintering and hot isostatic pressing (HIP) posttreatment. The effects of x on the microstructure, in-line transmittance, and magneto-optical properties were studied. The addition of Ho^{3+} promoted the densification of the ceramics, increasing their transmittance, with the in-line transmittance of $(\text{Tb}_{0.93}\text{Lu}_{0.06}\text{Ho}_{0.01})_2\text{O}_3$ reaching 79.05% at 1064 nm. Importantly, the Verdet constant was influenced by the doping of Ho^{3+} . The highest Verdet constant of $(\text{Tb}_{0.925}\text{Lu}_{0.06}\text{Ho}_{0.015})_2\text{O}_3$ was approximately $-404 \text{ rad}\cdot\text{T}^{-1}\cdot\text{m}^{-1}$, which was approximately 6% greater than that of the undoped sample and more than 3 times that of the terbium gallium garnet (TGG) crystal.



KEYWORDS: magneto-optical materials; Tb_2O_3 ; Verdet constant; optical quality; transparent ceramics

1 Introduction

Optical isolators can be applied in diverse applications, including magnetic field sensors, microwave technology, and high-power lasers [1,2]. Based on the non-reciprocity of Faraday rotation, controlling the unidirectional passage of light and preventing back-reflected light from interfering with the normal output of a light source can be achieved. To do so, magneto-optical materials—which serve as core components of optical isolators—should possess excellent optical quality, large Verdet constants, and high thermal conductivities [3–5].

Terbium(III) oxide (Tb_2O_3) is a promising material for near-infrared and visible wavelength band isolation, exhibiting a larger Verdet constant and superior laser damage threshold than other terbium-based materials. Nonetheless, the scalability of pure Tb_2O_3 single crystals is limited by their high melting point and phase transition, which can present a considerable challenge for realizing their large-scale preparation. The development of transparent Tb_2O_3 ceramics represents a major advance in the field of materials science. However, the Tb_2O_3 ceramic manufacturing process remains in its infancy.

The primary technical challenges include the instability of the valence state and the transformation of the crystal structure at

high temperatures. One approach is to introduce other rare-earth ions with higher solubilities and stabilities, such as Lu^{3+} and Y^{3+} , into the lattice structure via solid-state doping [6–9]. However, the incorporation of these ions (with their lower spin magnetic moments) can result in a reduction in the Verdet constant owing to the dilution of Tb^{3+} ions. Previous studies have shown that certain rare-earth ions with high effective magnetic moments or effective transition wavelengths—such as Ho^{3+} [10], Dy^{3+} [11,12], Ce^{3+} [13–15], and Pr^{3+} [16,17]—can enhance the optical properties of materials through spin interactions. The quantum interaction between ions and Tb^{3+} ions modifies the material's crystal field, resulting in a notable increase in the material's Verdet constant. Dai *et al.* [18] and Li *et al.* [19] achieved 7% and 3% increases in the Verdet constant by doping terbium gallium garnet (TGG) and terbium aluminum garnet (TAG) ceramic matrices with Ce^{3+} and Ho^{3+} ions, respectively. However, the impact of high-spin magnetic rare earth ion doping on the optical qualities and magnetic photophysical properties of Tb_2O_3 transparent ceramics remains unexplored.

In this study, $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ($x = 0, 0.005, 0.01, 0.0125, 0.015$) magneto-optical transparent ceramics were successfully prepared by sintering under 5% argon–hydrogen mixed reducing atmosphere combined with hot isostatic pressing (HIP) post-

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treatment. The impacts of the physical phase and microstructure of the corresponding ceramics were investigated. The impacts of different Ho^{3+} doping concentrations on the optical quality and Verdet constant were also examined. The magneto-optical properties of the $(\text{Tb}_{0.93}\text{Lu}_{0.06}\text{Ho}_{0.01})_2\text{O}_3$ transparent ceramics were compared with those of other terbium-based materials.

2 Experimental

2.1 Experimental procedures

High-purity Tb_4O_7 (Eternal-Element Co., Ltd.; 99.999%), Lu_2O_3 (Eternal-Element Co., Ltd.; 99.999%), and Ho_2O_3 (Eternal-Element Co., Ltd.; 99.99%) were used as raw materials, and ZrO_2 (Aladdin; 99.99%) was used as a sintering aid at a concentration of 0.1 at%. The powder was mixed using mechanical ball milling at a stoichiometric ratio of 0.1 at% ZrO_2 : $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ($x = 0, 0.005, 0.01, 0.0125, 0.015$) for 24 h. Zirconia balls and pure alcohol were used as the ball milling media. The ball-milled powder was dried in a rotary evaporative dryer and sieved through a 200-mesh screen. The dried powder obtained was uniaxially pressed at 20 MPa and subjected to cold isostatic pressing at 200 MPa, followed by pre-sintering in air for 10 h to remove residual organic impurities. The resulting green body was sintered at 1500 °C for 10 h under a 5% argon-hydrogen mixed reducing atmosphere (KSL-1700X, Hefei Kejing Material Technology Co., Ltd., China), after which HIP post-treatment was performed at 1550 °C for 4 h under a 180 MPa argon atmosphere. Finally, the ceramic samples were mirror-polished on both sides ($\phi 15 \text{ mm} \times 4 \text{ mm}$) and thermally etched at 1400 °C under a nitrogen atmosphere for surface observation.

2.2 Characterizations

The phase structures of the sintered ceramic samples were characterized by an X-ray diffractometer (XRD; D2 Phaser, Bruker Co., Ltd., Germany) using $\text{Cu K}\alpha$ radiation, with a scanning step increment of 0.05°, scanning time of 0.2 s, and a 2θ range of 10°–90°. The microstructures of the ceramics were

analyzed using a field-emission scanning electron microscope (FE-SEM; JSM-6700, JEOL, Japan), while the phase distributions of the samples were analyzed by energy dispersive X-ray spectroscopy (EDS) using both face and line scans. The grain sizes of the ceramics were measured using the linear intercept method and were calculated with 200 grains. The bulk densities of the ceramic samples were determined using the Archimedes method. Linear transmittance in the 200–1400 nm range and absorbance in the 400–800 nm range were determined using a visible–near–infrared (UV–vis–NIR) spectrometer (Lambda950, PerkinElmer, USA). The Verdet constants of the ceramic samples at 633 nm were measured using a homemade Faraday effect test instrument.

3 Results and discussion

3.1 Phase characterization and microstructure of manufactured ceramics

Figure 1(a) shows the schematic crystal structure of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramics. Tb_2O_3 is classified as a cubic crystal system, where oxygen ions (O^{2-}) form the closest packing arrangement within the cubic lattice, and terbium ions (Tb^{3+}) occupy the octahedral interstices. 75% of Tb ions are situated at the C2 lattice position, while the remaining 25% reside at the S6 lattice sites. Holmium (Ho^{3+}) and lutetium (Lu^{3+}) ions are substituted for the host terbium ions (Tb^{3+}) to create a continuous solid solution upon doping.

Figure 1(b) depicts the XRD patterns of the ceramic target products obtained from $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ pre-sintered compactly followed by high-temperature HIP treatment at 1550 °C. The diffraction patterns of the ceramic samples were successfully matched to the standard card of the cubic phase of Tb_2O_3 (JCPDS No. 43-1032), confirming the complete solid solubility of the dopant ions within the main phase (terbium oxide). This result demonstrates that no secondary-phase impurities were generated or introduced during the doping process. In the control group $(\text{Tb}_{0.94}\text{Lu}_{0.06})_2\text{O}_3$, the XRD diffraction peak (222) slightly shifted

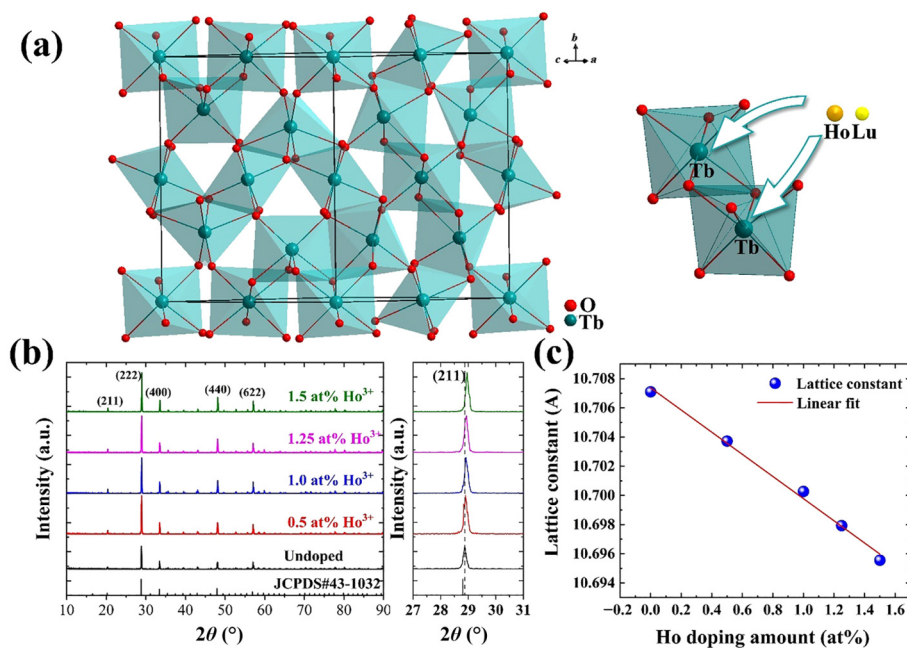


Fig. 1 Structural characterizations of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramics: (a) crystalline cell structure of ceramic samples; (b) XRD pattern, where the inset in right-hand panel shows an enlarged view of main diffraction peak (222); (c) results of linear fitting of lattice constants and theoretical densities as a function of Ho^{3+} concentration.

compared with that of the standard Tb_2O_3 cards, which can be attributed to the differing radii of Lu^{3+} (0.848 Å) and Tb^{3+} (0.923 Å) ions. When the control group $(\text{Tb}_{0.94}\text{Lu}_{0.06})_2\text{O}_3$ is used as the baseline, the gradual increase in the Ho^{3+} doping concentration results in a shift of the diffraction peaks towards higher angles.

Figure 1(c) shows the lattice constant of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramics. The calculation of the lattice constant—based on the XRD data and Bragg equation [20]—indicates that the lattice constant decreases with increasing concentration of Ho^{3+} ions. This lattice-shrinkage phenomenon is consistent with Vegard's law, which implies the formation of a homogeneous sesquioxide solid solution. Ho^{3+} doping induces lattice distortion owing to the substitution of Tb^{3+} ions by Ho^{3+} ions (with an ion radius of 0.894 Å).

Figure 2 shows the fracture surface field emission scanning electron microscopy (FE-SEM) images of the pre-sintered ceramics. The microstructures and porosities of the ceramic samples clearly change in response to variations in the concentration of doped Ho_2O_3 . Figures 2(a)–2(e) show the structural characterization results of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ($x = 0, 0.005, 0.01, 0.0125, 0.015$) ceramics samples sintered at 1500 °C for 10 h under a reducing atmosphere. The distribution of the ceramic microstructure is relatively uniform. However, as the Ho^{3+} ion concentration increases further to 1.5 at%, densification of the ceramic is observed, accompanied by a significant reduction in porosity and a consequent decrease in the size of the residual pores.

Figure 3 shows the fracture surface FESEM structure of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramic samples following HIP sintering at

1550 °C. Compared with their pre-sintered counterparts, the densities of all the samples increased, with a concurrent reduction in porosity.

Figure 4 shows the microstructure of the thermally etched surface of the HIP-treated $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ samples. The white circles in Figs. 3 and 4 represent pores. In the absence of Ho addition, a sparse number of pores are found in the intergranular space, with a diameter of approximately 90 nm. At the same sintering temperature, isolated sealed pores are encased in the interior of the grains. This is because the addition of Ho^{3+} provides solid-solution defects in which the sintering barriers are lower. Consequently, the original sintering temperature no longer represents the optimal condition for densification.

The average grain size and relative density of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramic samples are shown in Fig. 5. The distribution of grain size was obtained from the statistics of 200 grains. The particle size distribution of all samples exhibited a normal distribution, with a mean diameter of 0.4–2.4 μm, and abnormally large grains were not observed. When the Ho^{3+} concentration increased from 0 to 1.5 at%, the average grain sizes were 1.06, 1.11, 1.12, 1.13, and 1.30 μm, respectively.

The ratio of the experimental density to the theoretical density—which is the exact relative density—was determined using the Archimedes drainage method, as shown in Fig. 5(b). The theoretical density (d_{th}) of the solid solution used in this study can be determined by Eq. (1):

$$d_{th} = \frac{16}{a^3 N_A} \{ [nM_{Lu} + mM_{Tb} + (1 - m - n) M_{Ho}] \times 2 + 3M_O \} \quad (1)$$

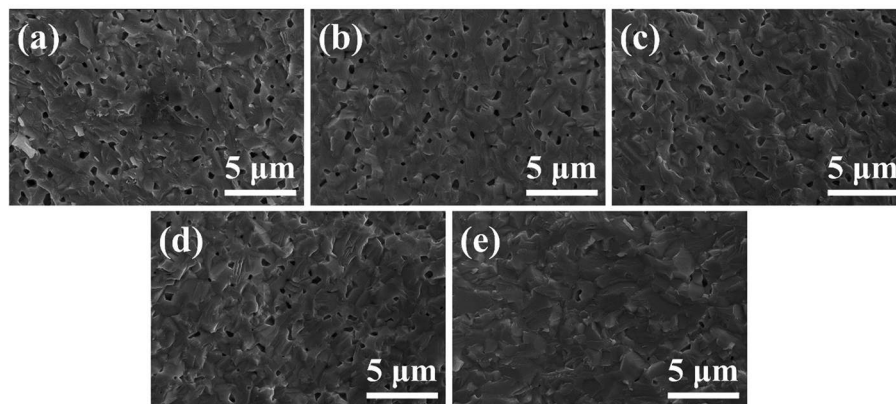


Fig. 2 Fracture surface FE-SEM images of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramics after sintering at 1500 °C for 10 h under a reducing atmosphere: (a) $x = 0$, (b) $x = 0.005$, (c) $x = 0.01$, (d) $x = 0.0125$, and (e) $x = 0.015$.

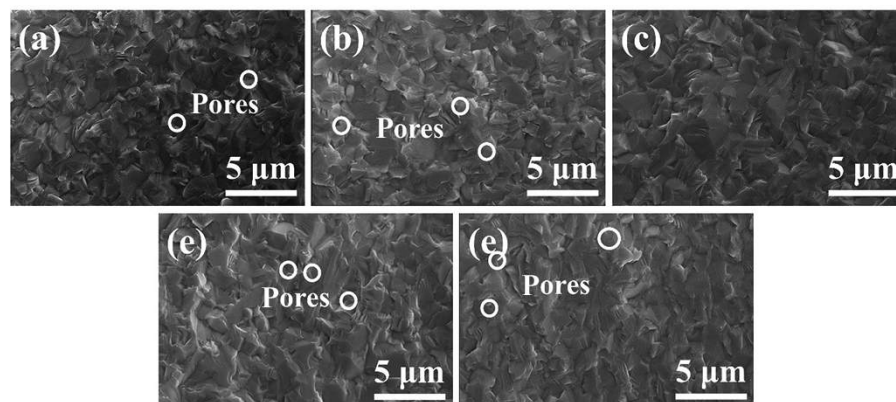


Fig. 3 Fracture surface FE-SEM images of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramics after HIP sintering at 1550 °C: (a) $x = 0$, (b) $x = 0.005$, (c) $x = 0.01$, (d) $x = 0.0125$, and (e) $x = 0.015$.

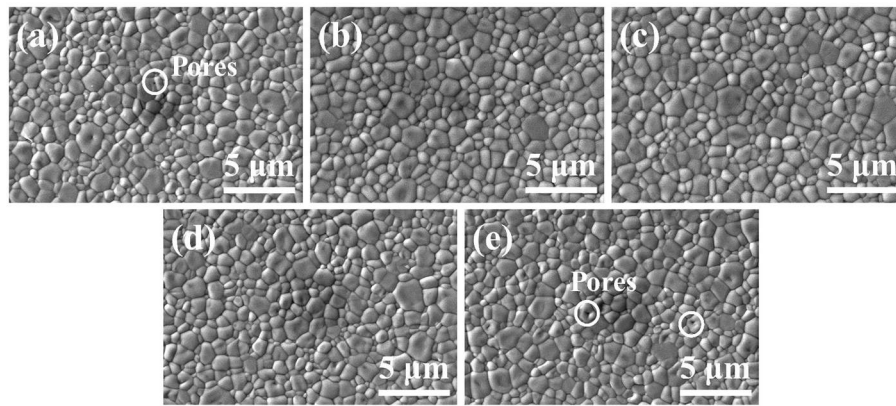


Fig. 4 Thermally etched surface FESEM images of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramics after HIP sintering at 1550 °C: (a) $x = 0$, (b) $x = 0.005$, (c) $x = 0.01$, (d) $x = 0.0125$, and (e) $x = 0.015$.

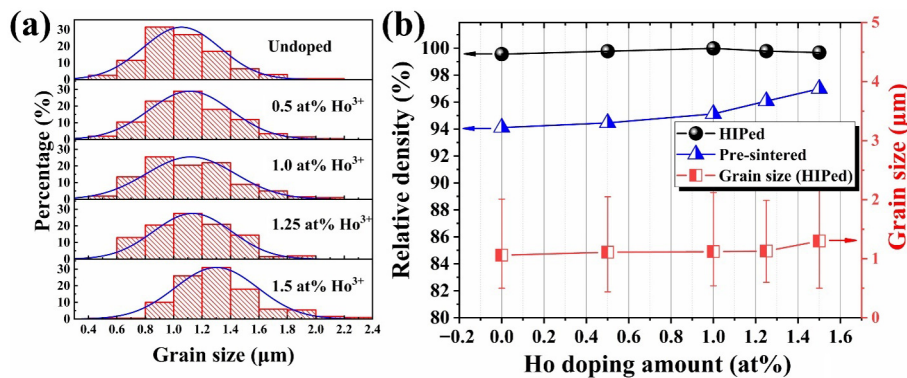


Fig. 5 Variability in (a) average grain size and (b) relative density of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ ceramic samples with respect to Ho^{3+} concentration.

where a denotes the lattice constant; N_A denotes the Avogadro constant; M denotes the relative atomic mass of each element; m and n denote the percentages of normal lattice sites occupied by plasmids [21]. As illustrated in Fig. 1, the introduction of Ho^{3+} resulted in a reduction in the lattice constant of Tb_2O_3 , accompanied by a corresponding decrease in the mass per unit cell. The theoretical density of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ increases from 8.99 to 9.03 $\text{g}\cdot\text{cm}^{-3}$ with the introduction of Ho^{3+} . The results of the calculations clearly show that the relative densities of the pre-sintered samples are gradually increased from 94.11% to 97.09%. However, the HIP-treated $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ shows different results, with relative densities of 99.56%, 99.77%, 99.98%, 99.78%, and 99.67%, respectively. The decrease in the density of samples with a Ho concentration of 1.5 at% could be attributed to the creation of intracrystalline pores, which was observed in the FESEM images.

The EDS surface scanning results of $(\text{Tb}_{0.93}\text{Lu}_{0.06}\text{Ho}_{0.01})_2\text{O}_3$ are shown in Figs. 6(a) and 6(b), enabling characterization of the elemental distribution and homogeneity of the elements, as well as the solid-solution state of each ion after doping. The green spot represents Tb, whereas the yellow, red, and brown spots correspond to Lu, Ho, and Zr, respectively. Following HIP treatment at 1550 °C, a complete solid solution formed among the phases. Overall, the cationic elements were uniformly distributed, and no obvious aggregation of discrete single phases or secondary phases can be detected.

Figure 6(c) shows the EDS spot-scan results for $(\text{Tb}_{0.93}\text{Lu}_{0.06}\text{Ho}_{0.01})_2\text{O}_3$, where the selected scanning area is the center of the cross shown in Fig. 6(a). The molar contents of Tb, Lu, Ho, and Zr are shown in the figures, with molar percentages of 92.79%, 5.87%, 1.20%, and 0.15%, respectively. The discrepancies between the actual values and the design parameters

are minimal, with few discrepant values originating from EDS test errors and the weighing procedures of raw materials during the mechanical ball milling processes.

Figure 6(d) shows the EDS line-scan results for $(\text{Tb}_{0.93}\text{Lu}_{0.06}\text{Ho}_{0.01})_2\text{O}_3$, where the scanning area is indicated by the dashed line in the figure. The line-scan profiles of the cations—including Tb, Lu, Ho, and Zr—exhibit a tendency to converge towards straight parallel lines, which indicate a uniform distribution in the selected region. However, the O content clearly fluctuated, indicating the presence of oxygen vacancies as well as oxygen enrichment phenomena. This may be attributed to the susceptibility of the phase structure as well as the valence state owing to atmospheric conditions during the sintering process. The defects typically manifest within the lattice as absorption centers, leading to a reduction in the sample transmittance [22].

3.2 Performance characterizations

Figure 7 shows the optical in-line transmittance and images of the transparent ceramic $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ with a thickness of 4 mm at wavelengths ranging from 200 to 1400 nm. All the ceramic samples exhibited a certain degree of transparency. The introduction of Ho ions renders the samples yellowish. The theoretical transmittance (T) for Tb_2O_3 can be deduced from the relationship between the refractive index (n) and the wavelength (λ) as Eqs. (2) and (3):

$$T = \left[1 - \left(\frac{n-1}{n+1} \right)^2 \right]^2 \cdot \exp(-\alpha L) \quad (2)$$

$$n = \left(1 + \frac{\lambda^2}{B\lambda^2 - A} \right)^{1/2} \quad (3)$$

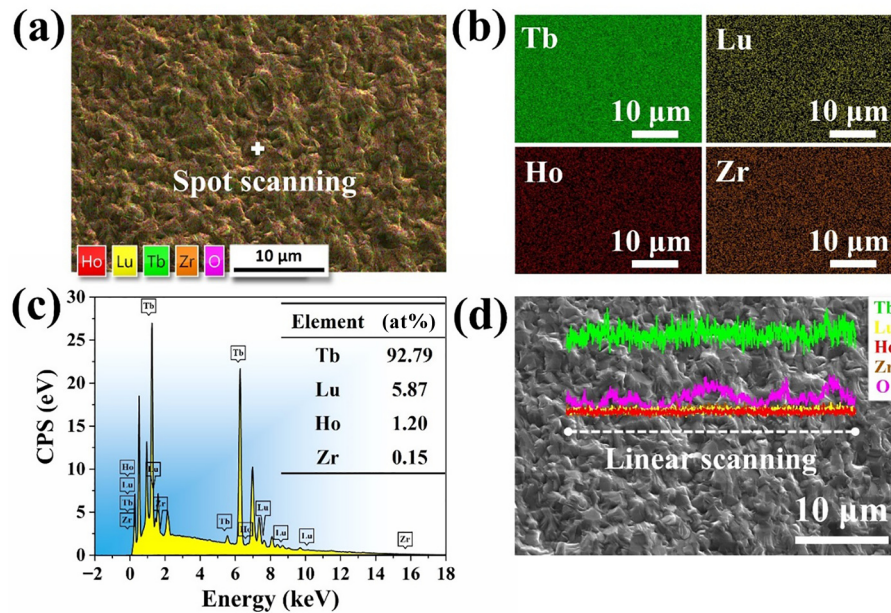


Fig. 6 $(\text{Tb}_{0.93}\text{Lu}_{0.06}\text{Ho}_{0.01})_2\text{O}_3$ energy dispersive X-ray test characterizations: (a) SEM microscopic elemental distribution of total map; (b) EDS surface scanning results; (c) target point scanning results (scanning the area denoted by the center of the cross in (a)); (d) target line scanning results (scanning the area denoted by the dotted portion of the figure). The line length is 30 μm .

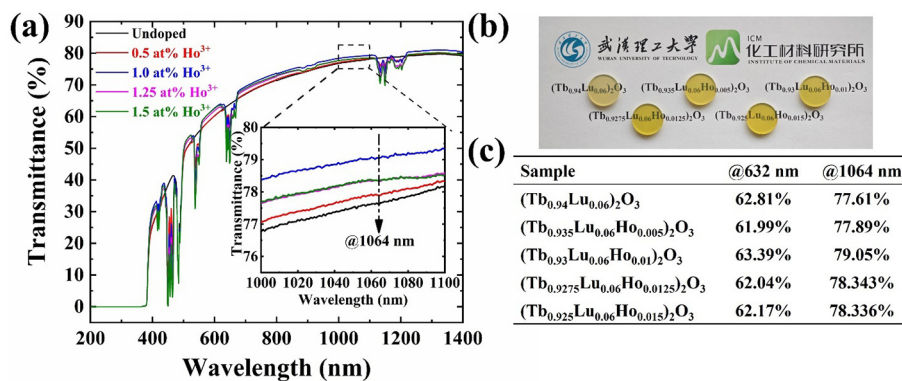


Fig. 7 Characterizations of optical properties of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ transparent ceramics: (a) ceramic transmittance curves (including local magnification in 1000–1100 nm band), (b) appearance of ceramic samples, and (c) list of experimental transmittances of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ transparent ceramics at 632 and 1064 nm.

where n denotes the refractive index, λ is the wavelength of light, α is the loss coefficient, and L is the transparent ceramic sample thickness. $A = 0.0122$ and $B = 0.3853$ are the mean dispersion parameter and intercept values, respectively, obtained from Refs. [23,24].

Under ideal conditions, the internal light loss is negligible, and the calculated refractive index and theoretical transmittance values are 1.916 and 81.25% at 1064 nm, respectively. Compared with the experimental data, the highest optical transmittance of $(\text{Tb}_{0.93}\text{Lu}_{0.06}\text{Ho}_{0.01})_2\text{O}_3$ is approximately 79.05% with a sample thickness of 4 mm, which is very close to the corresponding theoretical values. However, the linear transmittance of the blank control sample $(\text{Tb}_{0.94}\text{Lu}_{0.06})_2\text{O}_3$ is comparatively diminished, possibly due to the intergranular porosity indicated by the microstructural analysis. The absorption peaks observed in the transmittance curves could be attributed to the intra- f^0 transition of Ho^{3+} and the intra- $4f^8$ transition of Tb^{3+} [10]. All of the samples exhibit no characteristic optical absorption in the 630 nm and 1 μm bands, making them appropriate for 1 μm Faraday optical isolators in laser systems based on materials with Yb^{3+} and Nd^{3+} doping [25–31]. Nevertheless, compared with the near-infrared region at 1064 nm, the transmittance in the visible region at

633 nm is significantly diminished, a reduction attributed to optical scattering induced by the presence of micropores.

To characterize and compare the magneto-optical properties of $(\text{Tb}_{0.94-x}\text{Lu}_{0.06}\text{Ho}_x)_2\text{O}_3$ transparent ceramics, we used a homemade Faraday effect tester, as shown in Fig. 8(a). Device 1 was a laser fixed at a wavelength of 633 nm. The devices 2 and 5 represent the polarizers. The device 3 was a magnetic coil. The magnetic field intensity ranged from 0 to 0.5 T. The horizontal position was adjusted to ensure that the light path was parallel to the magnetic field and that the light passed through the magneto-optical sample. The rotation angle of the detector was adjusted to find the extinction position of the magneto-optical sample under different magnetic field strengths, which was calculated as Eq. (4):

$$\theta = VBL \quad (4)$$

where θ denotes the angle of light polarization, V is the Verdet constant, B is the tuneable magnetic field intensity, and L is the length of light passing through the magneto-optical material. The linear relationship between the Faraday rotation angle per unit length and the magnetic field strength was fitted to calculate the slope, namely, the Verdet constant.

Figures 8(b) and 8(c) show the change in the Verdet constant of ceramics with different Ho³⁺ doping concentrations and a comparison with a commercial TGG single crystal. The magnitudes of the Verdet constants are presented as absolute values to facilitate comparative analysis. The highest Verdet constant of (Tb_{0.925}Lu_{0.06}Ho_{0.015})₂O₃ was -403.8 ± 2.9 rad·T⁻¹·m⁻¹, which resulted in a 6% improvement over that of (Tb_{0.94}Lu_{0.06})₂O₃ sample without Ho³⁺ doping (-380.9 ± 2.3 rad·T⁻¹·m⁻¹). Moreover, the values of (Tb_{0.94-x}Lu_{0.06}Ho_x)₂O₃ with $x = 0.005, 0.01$, and 0.0125 were measured to be $-384.2 \pm 5.6, 389.8 \pm 5.8$, and 397.9 ± 2.7 rad·T⁻¹·m⁻¹, respectively. The Verdet constant value of (Tb_{0.925}Lu_{0.06}Ho_{0.015})₂O₃ sample was more than 3 times that of TGG single crystals [32] (-134 rad·T⁻¹·m⁻¹ at 633 nm).

The values of the Verdet constants at 633 and 1064 nm for (Tb_{0.94-x}Lu_{0.06}Ho_x)₂O₃ transparent ceramics and other materials are shown in Table 1 for comparison. Ho-doped TGG crystals are almost twice as large as normal TGG single crystals, suggesting a generalization of the magneto-optical property enhancement effect of Ho for Tb-based materials. The magneto-optical effect level of paramagnetic ions can be explained by Eq. (5) using van Vleck–Hebb's quantum mechanical mechanism.

$$V = \frac{4\pi^2 v^2 \chi}{g \mu_B c \hbar} \sum_{ij} \frac{C_{ij}}{v^2 - v_{ij}^2} \quad (5)$$

where v is the incident light frequency; χ is the atomic susceptibility; g is the Lande splitting factor; μ_B is a Bohr magneton; $\hbar$ is the Planck constant; the value of C_{ij} represents the probability of a frequency jump occurring at the v_{ij} level; c is the speed of light. Once the values of other parameters have been established, the atomic susceptibility χ will be proportional to the value of the Verdet constant (V).

At a certain temperature, the atomic susceptibility χ of Ho is several times greater than that of Tb, which causes a beneficial impact of Ho³⁺ ions on the magneto-optical characteristics of Tb₂O₃. Furthermore, superexchange interactions between Ho³⁺ and Tb³⁺ ions, in conjunction with the orbit interactions, result in ground-state structural splitting [39]. Therefore, a small amount of Ho³⁺ can increase the magnetic susceptibility of Tb₂O₃ matrix and thus increase the Verdet constant.

Figure 8(d) shows the UV–vis absorption coefficient curves of (Tb_{0.94-x}Lu_{0.06}Ho_x)₂O₃ transparent ceramics. The absorption bands identified at 416, 450, 464, 537, 550, and 638 nm are associated

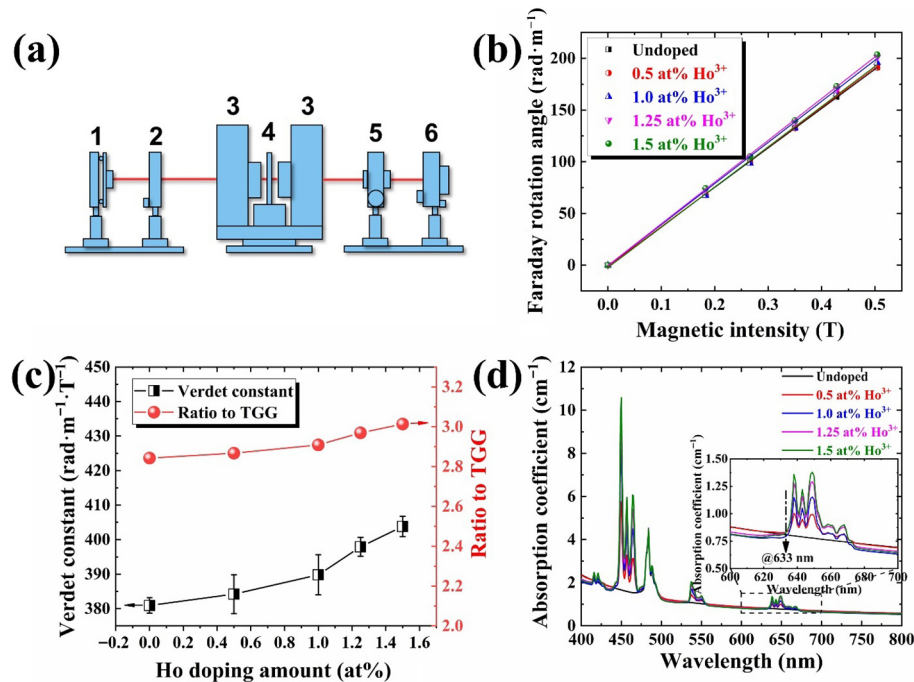


Fig. 8 Characterizations and comparison of magneto-optical properties of (Tb_{0.94-x}Lu_{0.06}Ho_x)₂O₃ transparent ceramics: (a) experimental scheme for determining magneto-optical properties: 1—laser light source (633 nm wavelength), 2—polarizer, 3—applied magnetic field, 4—experimental sample, 5—polarizer, and 6—optical receiver; (b) effect of Ho³⁺ doping concentration on Faraday rotation angle; (c) variation rule of Verdet constant with Ho³⁺ doping concentration and comparison with commercial TGG single crystals; (d) UV–vis absorption coefficient curves of (Tb_{0.94-x}Lu_{0.06}Ho_x)₂O₃ transparent ceramics.

Table 1 Verdet constants (V) for (Tb_{0.94-x}Lu_{0.06}Ho_x)₂O₃ transparent ceramics and other materials for comparison

Composition	Material	$V/633$ nm (rad·T ⁻¹ ·m ⁻¹)	$V/1064$ nm (rad·T ⁻¹ ·m ⁻¹)	Ref.
(Tb _{0.925} Lu _{0.06} Ho _{0.015}) ₂ O ₃	Ceramic	-404	—	This work
(Tb _{0.94} Lu _{0.06}) ₂ O ₃	Ceramic	-381	—	This work
TGG	Single crystal	-134	-39.0	[33]
TAG	Ceramic	-178	-51.0	[34,35]
(Tb _{0.995} Ho _{0.005}) ₃ Al ₅ O ₁₂	Ceramic	-183	—	[18]
Ho ₂ O ₃	Ceramic	-195	-46.3	[36,37]
Tb ₂ O ₃	Ceramic	-466	-154.0	[38]

with the 4f⁰ transitions from the ground state ⁵I₈ to the excited states ⁵G₅, ⁵F₁-⁵G₆, ⁵F₂, ⁵F₄, ⁵S₂, and ⁵F₅, respectively. Additionally, the absorption coefficients are positively correlated with the Ho³⁺ content.

4 Conclusions

In this study, magneto-optical ceramics (Tb_{0.94-x}Lu_{0.06}Ho_x)₂O₃ were prepared using reducing atmosphere sintering combined with HIP post-treatment. The XRD results showed that Ho³⁺ ions were introduced into the cubic lattice of Tb₂O₃ with a pure single solid-solution phase and that the lattice constant decreased with increasing Ho₂O₃ content. Moreover, trace Ho doping could facilitate the densification of ceramic materials, whereas excess doping led to the aggregation of intracrystalline pores. The highest in-line transmittance was 79.05% at 1064 nm. (Tb_{0.925}Lu_{0.06}Ho_{0.015})₂O₃ ceramics possessed the highest Verdet constant in this work, that is, -404 rad·T⁻¹·m⁻¹ at 633 nm, almost three times that of the TGG crystals.

Author contributions

Yaozhi Wang: Software, data curation, writing original draft, preparation, writing, review & editing, and investigation. Wei Jing: Conceptualization, methodology, funding acquisition, analysis, and writing-review & editing. Tao Xu: Investigation. Jie Li: Investigation. Renxin Zhang: Investigation. Weiwei Li: Investigation. Xilong Qin: Investigation. Binchu Mei: Methodology, funding acquisition, validation, and conceptualization.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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