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Tunable color, optical properties, and energy transfer of Tb³⁺–Sm³⁺–Yb³⁺ tri-doped lithium–niobium–tellurite glass for applications in color display devices and WLEDs†

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A TeO₂–Nb₂O₅–LiO₂–CaO (TNLC) lithium–niobium–tellurite glass single-doped and co-doped with Tb³⁺, Sm³⁺, and Yb³⁺ ions was synthesized *via* a conventional melt-quenching method. The Tb³⁺–Sm³⁺ co-doped TNLC glass could be tuned to emit white light effectively by controlling the ratio of Tb³⁺ and Sm³⁺ in the glass. The fluorescence lifetime of the Tb³⁺–Sm³⁺ co-doped TNLC glass indicated the existence of multiple energy transfer channels, including from Tb³⁺ to Sm³⁺ ions and the reverse energy transfer from Sm³⁺ to Tb³⁺ ions. Taking advantage of these energy transfer channels, the color coordinates of the material could be changed from yellowish-pink and yellowish-green emissions to white emission by controlling the ratio of ions doped in TNLC glasses. The optimal molar concentration ratio between Tb³⁺ and Sm³⁺ ions for the best white light emission was 0.83 for the TNLC-0.5Tb0.6Sm sample. Changing the ratio of these rare-earth (RE) ions allowed tuning the color temperature of the material from 5616 to 7699 K. Thus, Tb³⁺–Sm³⁺ co-doped and Tb³⁺–Sm³⁺–Yb³⁺ tri-doped TNLC glasses are promising materials for color display applications and white light-emitting diodes (WLEDs).

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1. Introduction

In recent years, with the rapid development and high demand of optoelectronic materials for color display technologies and devices,^{1,2} light-emitting diodes (LEDs)^{3,4} that emit in the visible region, display full colors and are color-tunable are in high demand, promoting extensive research on rare-earth (RE)-ion

doping in various host matrices,^{5–7} such as phosphors, glasses, and glass-ceramic containing nanocrystals. Among various host matrices, tellurite-based glasses have emerged as promising candidates owing to their unique physicochemical and optical properties.^{5,6} Tellurite-based glasses have a relatively low melting point, high thermal stability, good RE ion solubility, a wide transmission window (covering the visible (VIS) to near-infrared (NIR) region), and low phonon energy (which minimizes non-radiative (NR) losses and enhances emission efficiency).^{7,8} Co-doping RE ions in tellurite glasses facilitates sharp, well-defined intra-4f electronic transitions that result in highly stable and efficient luminescence. The incorporation of RE ions in tellurite glasses further opens up pathways for energy transfer (ET) interactions, enabling the tuning of emission intensity and chromaticity of color in the visible wavelength range.^{9,10} The combination of Sm³⁺, Tb³⁺, and Yb³⁺ ions produces a cooperative, energy-transferring, and tunable emission intensity and colorimetry for visible and upconversion (UC) emissions when excited at different wavelengths.¹¹ Sm³⁺ ions exhibit prominent orange-red emission around 600–650 nm, corresponding to ⁴G_{5/2} → ⁶H_{7/2} and ⁴G_{5/2} → ⁶H_{5/2} transitions;^{12,13} Tb³⁺ ions produce strong green emission near 546 nm, corresponding to ⁵D₄ → ⁷F₅ transition,^{14,15} and Yb³⁺ ions exhibit only one ²F_{5/2} → ²F_{7/2} transition and acts as a sensitizer owing to their strong absorption at ~980 nm and the ability to participate in UC and cross-relaxation (CR)

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mechanisms.^{16,17} Some works have explored the color tunability, luminescence properties, and ET mechanisms in RE ion co-doped glasses/glass ceramics to develop materials suitable for color display and LED applications.^{18–20} F. Nawaz *et al.*²¹ investigated and reported the influence of Yb³⁺ co-doping on the optical properties of Sm³⁺-doped sodium tellurite glasses. They found that Yb³⁺ co-doping affected the absorption and emission characteristics of Sm³⁺ ions, indicating ET between the Sm³⁺ and Yb³⁺ ions.²¹ J. Li *et al.*²² reported a multi-color afterglow in Tb³⁺–Sm³⁺ co-doped gallo-silicate glass ceramics. By adjusting the concentrations of Tb³⁺ and Sm³⁺ ions, the afterglow emission could be tuned from green to orange and then to yellow.²² This study highlighted ET and trap-sharing mechanisms between the dopants, which are significant for optical anti-counterfeiting applications. In general, these studies collectively enhance our understanding of ET dynamics and luminescence tuning in RE co-doped tellurite glass systems, contributing to the development of materials for color displays, LEDs, and other photonic applications.^{21,22}

Lithium–niobium–tellurite (Li–Nb–Te) glass is particularly advantageous as a host because the incorporation of lithium and niobium oxides enhances the structural network,²³ improves RE ion dispersion, and increases the optical bandgap and nonlinear optical properties. The presence of Nb⁵⁺ ions, which act as a glass modifier, can influence local field symmetry and aid the creation of non-centrosymmetric sites that are beneficial for RE ion emission.^{23,24} Furthermore, the addition of Li₂O serves to improve glass formability and optical clarity while also aiding ET dynamics by modifying the local coordination environment of the RE ions.²⁵ Although several studies have explored tellurite glasses single-doped and co-doped with Tb³⁺, Sm³⁺, and Yb³⁺ ions, as well as other optical materials containing these RE ions, most of them have focused on ET mechanisms from Tb³⁺ to Sm³⁺ ions. However, reverse ET

mechanisms, such as from Sm³⁺ to Tb³⁺ ions or from Yb³⁺ to both Tb³⁺ and Sm³⁺ ions, have not been reported. These mechanisms are crucial for enabling strong visible emission under 980 nm infrared excitation, corresponding to the transition of Yb³⁺ from the ²F_{7/2} to ²F_{5/2} state. In this study, TeO₂–Nb₂O₅–Li₂O–CaO (TNLC) glasses with various doping schemes, including Tb³⁺-doped, Sm³⁺-doped, Tb³⁺–Sm³⁺ co-doped, and Tb³⁺–Sm³⁺–Yb³⁺ tri-doped glasses, were synthesized *via* melt-quenching. We investigated the effect of varying the concentrations of these ions on the emission color. A detailed analysis of the ET processes from Tb³⁺ to Sm³⁺, Sm³⁺ to Tb³⁺, and Yb³⁺ to both Tb³⁺ and Sm³⁺ ions was conducted. By adjusting the ion ratios, white-light emission was achieved. These findings suggest that TNLC glasses co-doped with Tb³⁺, Sm³⁺, and Yb³⁺ ions are promising candidates for color display technologies and white light-emitting diodes (LEDs).

2. Experimental details

The lithium–niobium–tellurite glasses used in this work were synthesized using a conventional melt-quenching technique. High-purity laboratory-grade reagents (99.99%), including TeO₂, Nb₂O₅, Li₂O, CaO, TbF₃, Sm₂O₃, and Yb₂O₃, were used as raw materials. Specific compositions, molar ratios, and corresponding sample abbreviations are summarized in Table 1.

Approximately 12 grams of each glass batch was prepared by accurately weighing the required mixtures of raw materials using an electronic analytical balance. After finely grinding them using an onyx mortar and agate pestle, the mixtures were compacted, placed in a platinum crucible and then heated in a Nabertherm electric furnace (Germany) at 1150 °C for 45 minutes under an air atmosphere.^{16,26,27} Following the melting process, the molten materials were cast into molds and rapidly cooled on a stainless-steel plate to form the initial glass

Table 1 Specific glass compositions and molar concentration ratios of the as-synthesized TeO₂–Nb₂O₅–Li₂O–CaO–TbF₃–Sm₂O₃–Yb₂O₃ lithium–niobium–tellurite glasses

| Glass sample | Molar concentration ratio of the components | | | | | | |
|--------------------|---|--------------------------------|-------------------|-----|------------------|--------------------------------|--------------------------------|
| | TeO ₂ | Nb ₂ O ₅ | Li ₂ O | CaO | TbF ₃ | Sm ₂ O ₃ | Yb ₂ O ₃ |
| TNLC-0.5Tb | 60 | 18 | 12 | 9.5 | 0.5 | 0 | 0 |
| TNLC-0.5Sm | 60 | 18 | 12 | 9.5 | 0 | 0.5 | 0 |
| TNLC-0.5Tb0.5Sm | 60 | 18 | 12 | 9.0 | 0.5 | 0.5 | 0 |
| TNLC-0.6Tb0.5Sm | 60 | 18 | 12 | 8.9 | 0.6 | 0.5 | 0 |
| TNLC-0.7Tb0.5Sm | 60 | 18 | 12 | 8.8 | 0.7 | 0.5 | 0 |
| TNLC-0.8Tb0.5Sm | 60 | 18 | 12 | 8.7 | 0.8 | 0.5 | 0 |
| TNLC-0.9Tb0.5Sm | 60 | 18 | 12 | 8.6 | 0.9 | 0.5 | 0 |
| TNLC-1.0Tb0.5Sm | 60 | 18 | 12 | 8.5 | 1.0 | 0.5 | 0 |
| TNLC-0.5Tb0.6Sm | 60 | 18 | 12 | 8.9 | 0.5 | 0.6 | 0 |
| TNLC-0.5Tb0.7Sm | 60 | 18 | 12 | 8.8 | 0.5 | 0.7 | 0 |
| TNLC-0.5Tb0.8Sm | 60 | 18 | 12 | 8.7 | 0.5 | 0.8 | 0 |
| TNLC-0.5Tb0.9Sm | 60 | 18 | 12 | 8.6 | 0.5 | 0.9 | 0 |
| TNLC-0.5Tb1.0Sm | 60 | 18 | 12 | 8.5 | 0.5 | 1.0 | 0 |
| TNLC-0.5Tb0.5Sm2Yb | 60 | 18 | 12 | 7.0 | 0.5 | 0.5 | 2 |
| TNLC-0.6Tb0.5Sm2Yb | 60 | 18 | 12 | 6.9 | 0.6 | 0.5 | 2 |
| TNLC-0.7Tb0.5Sm2Yb | 60 | 18 | 12 | 6.8 | 0.7 | 0.5 | 2 |
| TNLC-0.8Tb0.5Sm2Yb | 60 | 18 | 12 | 6.7 | 0.8 | 0.5 | 2 |
| TNLC-1.0Tb0.5Sm2Yb | 60 | 18 | 12 | 6.5 | 1.0 | 0.5 | 2 |



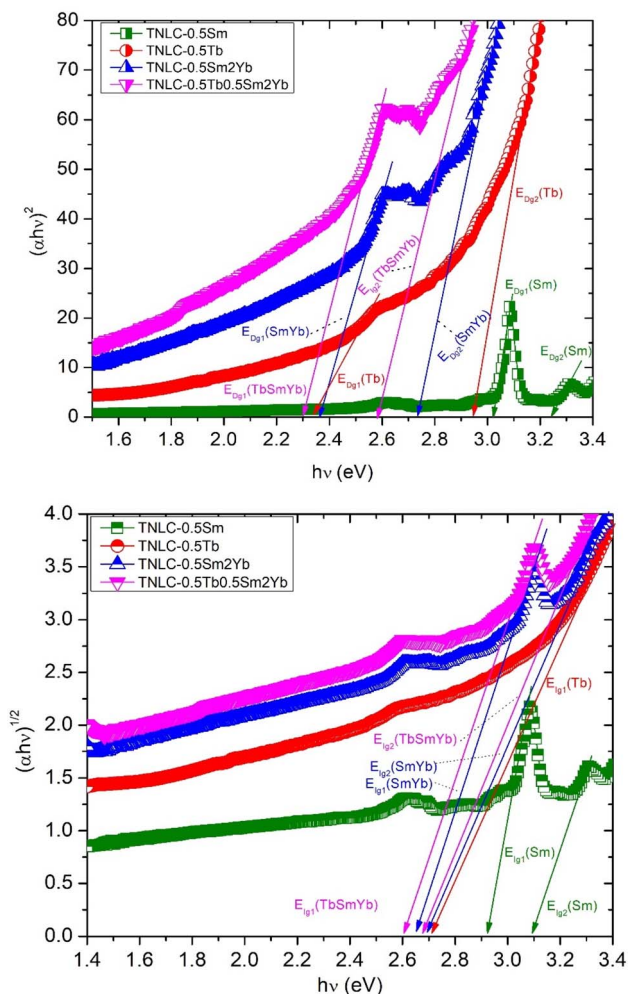


Fig. 3 (a) Direct optical bandgaps of the TNLC-0.5Sm, TNLC-0.5Tb, TNLC-0.5Sm2Yb, and TNLC-0.5Tb0.5Sm2Yb glass samples. (b) Indirect optical bandgaps of the TNLC-0.5Sm, TNLC-0.5Tb, TNLC-0.5Sm2Yb, and TNLC-0.5Tb0.5Sm2Yb glass samples.

The direct optical bandgaps (DOB) and indirect optical bandgaps (IOB) of the TNLC-0.5Sm, TNLC-0.5Tb, TNLC-0.5Sm2Yb, and TNLC-0.5Tb0.5Sm2Yb glass samples were calculated and analyzed based on their absorption spectra using the Tauc formula:^{19,35,36}

$$\alpha(\lambda) = B \frac{(h\nu - E_g)^\gamma}{h\nu} \quad (1)$$

Here, $\alpha(\lambda)$ is the absorption coefficient; λ is the wavelength; ν is the frequency; h is the Planck constant; B is the energy-independent constant;^{19,35,36} E_g is the energy gap of the glass samples; $\gamma = 2$ for DOB; $\gamma = \frac{1}{2}$ for IOB.^{19,35,36} The calculated direct optical bandgaps (DOB) of the TNLC-0.5Sm, TNLC-0.5Tb, TNLC-0.5Sm2Yb, and TNLC-0.5Tb0.5Sm2Yb glass samples are shown in Fig. 3(a).

Similarly, the indirect optical bandgaps of the TNLC-0.5Sm, TNLC-0.5Tb, TNLC-0.5Sm2Yb, and TNLC-0.5Tb0.5Sm2Yb glass samples were calculated based on their absorption spectra using the Tauc formula, as shown in Fig. 3(b). A summary of the energy indirect/direct bandgap values of the TNLC-0.5Tb, TNLC-0.5Sm, TNLC-0.5Tb0.5Sm, and TNLC-0.5Tb0.5Sm2Yb glass samples is presented in Table 2.

As shown in Table 2, all the glass samples exhibited significantly smaller bandgaps than pure TeO₂ glass. The incorporation of Nb₂O₅, CaO, and Li₂O introduces electronic states within the TeO₂ bandgap, resulting in a notable reduction in the band gap. Among the samples, the TNLC-0.5Sm glass sample had a larger bandgap than the TNLC-0.5Tb glass sample, though both remain smaller than that of pure TeO₂. This reduction is attributed to the addition of RE ions, which alter the glass network by modifying oxygen bonding, increasing non-bridging oxygen content, and affecting light absorption. Furthermore, the TNLC-0.5Sm2Yb and TNLC-0.5Tb0.5Sm2Yb glass samples showed even lower bandgaps owing to the higher RE ion concentrations, which introduced additional intermediate energy levels and further enhanced non-bridging oxygen states. The increasing concentration of RE ions in the glass matrix also increases the non-bridging oxygen bonding state, causing the band gap of the glass to decrease.

The excitation spectra of the TNLC-0.5Tb, TNLC-0.5Sm, and TNLC-0.5Tb0.5Sm glass samples were obtained, as shown in Fig. 4, to determine the excitation wavelengths for the TNLC glass samples containing both Tb³⁺ and Sm³⁺ ions. Based on the spectral data, we chose 374 nm as the excitation wavelength for the Tb³⁺-Sm³⁺ co-doped TNLC glass sample.^{37,38}

The visible emission spectra of the TNLC-0.5Tb, TNLC-0.5Sm, and TNLC-0.5Tb0.5Sm lithium–niobium–tellurite glass samples under 374 nm are shown in Fig. 5. For the TNLC-0.5Tb glass sample, the visible emission of Tb³⁺ under 374 nm excitation revealed weaker peaks at around 415 and 438 nm due to the ³D₅ → ⁷F₅ and ³D₅ → ⁷F₄ transitions.^{4,16,32} This result is intriguing because these emission peaks have not been reported in most previous works. For the TNLC-0.5Sm glass sample, the

Table 2 Indirect/direct energy bandgap values of the TNLC-0.5Tb, TNLC-0.5Sm, TNLC-0.5Tb0.5Sm, and TNLC-0.5Tb0.5Sm2Yb glass samples

| Glass sample | Direct bandgap values | | | Indirect bandgap values | | |
|--------------------|-----------------------|----------------|---------------------------------------|-------------------------|----------------|---------------------------------------|
| | E_{Dg1} (eV) | E_{Dg2} (eV) | $\Delta E_D = E_{Dg2} - E_{Dg1}$ (eV) | E_{Ig1} (eV) | E_{Ig2} (eV) | $\Delta E_I = E_{Ig2} - E_{Ig1}$ (eV) |
| TNLC-0.5Sm | 3.02 | 3.23 | 0.21 | 2.98 | 3.19 | 0.21 |
| TNLC-0.5Tb | 2.34 | 2.95 | 0.61 | 2.84 | — | — |
| TNLC-0.5Sm2Yb | 2.36 | 2.74 | 0.38 | 2.75 | 2.82 | 0.07 |
| TNLC-0.5Tb0.5Sm2Yb | 2.28 | 2.59 | 0.31 | 2.72 | 2.79 | 0.07 |



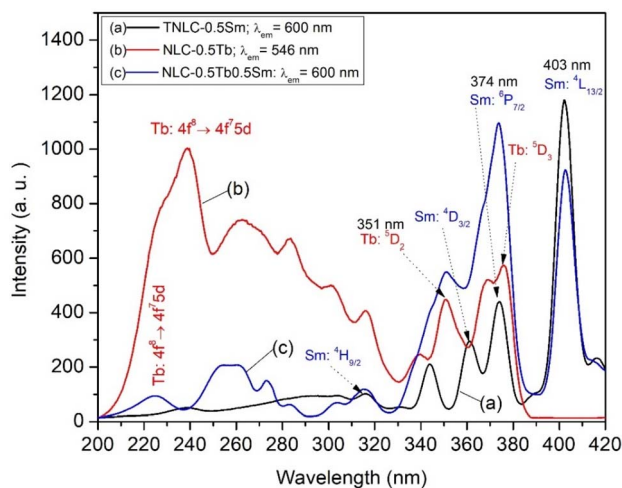


Fig. 4 Excitation spectra of the TNLC-0.5Tb, TNLC-0.5Sm, and TNLC-0.5Tb0.5Sm lithium–niobium–tellurite glass samples.

visible emission peaks of Sm^{3+} under 374 nm excitation at around 440, 564, 601, and 645 nm could be attributed to the ${}^4\text{G}_{7/2} \rightarrow {}^6\text{H}_{9/2}$, ${}^4\text{G}_{5/2} \rightarrow {}^6\text{H}_{5/2}$, ${}^4\text{G}_{5/2} \rightarrow {}^6\text{H}_{7/2}$, and ${}^4\text{G}_{5/2} \rightarrow {}^6\text{H}_{9/2}$ transitions, respectively.^{32–34} For the TNLC-0.5Tb0.5Sm glass sample, the visible emission of peaks co-doped Tb^{3+} and Sm^{3+} under 374 nm excitation were found at around 415, 438, 490, 546, 587, 622, and 645 nm due to transitions from Tb^{3+} , Sm^{3+} ions or the combination of transitions from both Tb^{3+} and Sm^{3+} ions corresponding to ($\text{Tb}^{3+}: {}^3\text{D}_5 \rightarrow {}^7\text{F}_5$), ($\text{Tb}^{3+}: {}^3\text{D}_5 \rightarrow {}^7\text{F}_4 + \text{Sm}^{3+}: {}^4\text{G}_{7/2} \rightarrow {}^6\text{H}_{9/2}$), ($\text{Tb}^{3+}: {}^3\text{D}_4 \rightarrow {}^7\text{F}_J(J=6, 5, 4, \text{ and } 3)$) and ($\text{Sm}^{3+}: {}^4\text{G}_{5/2} \rightarrow {}^6\text{H}_{9/2}$) transitions, respectively.^{4,32–34}

The Commission Internationale de L'Eclairage (CIE) 1931 (x; y) chromaticity coordinates^{19,39} for the visible emission spectra of the TNLC-0.5Tb, TNLC-0.5Sm, and TNLC-0.5Tb0.5Sm glass samples were determined to be P_{Tb} (0.2840; 0.5303), $\text{P}_{\text{Tb-Sm}}$ (0.2901; 0.3728), and P_{Sm} (0.4906; 0.3537) located in the

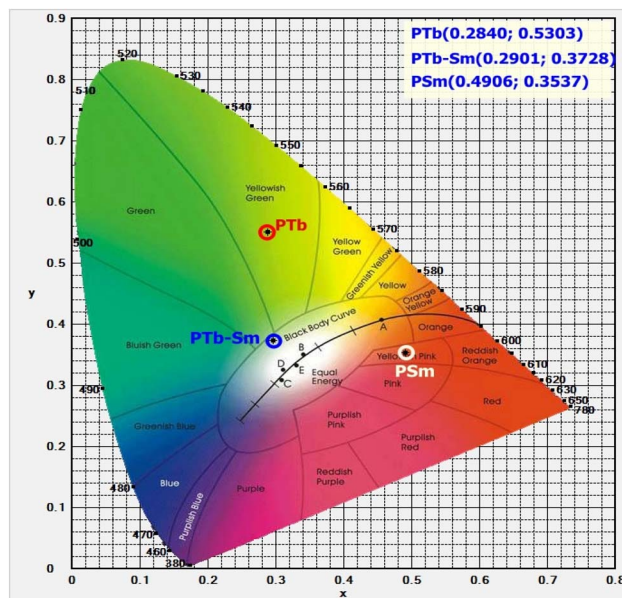


Fig. 6 CIE 1931 (x; y) color coordinates for the visible emission spectra of the TNLC-0.5Tb, TNLC-0.5Sm, and TNLC-0.5Tb0.5Sm glass samples under 374 nm excitation.

yellow-pink, yellowish-green and black body curve regions, respectively, as shown in Fig. 6.

The visible emission spectra of the TNLC-*p*Tb0.5Sm (*p* = 0.6, 0.7, 0.8, 0.9, and 1.0 mol%) lithium–niobium–tellurite glass samples under 374 nm are shown in Fig. 7. With the increase in molar concentration of Tb^{3+} from 0.6 to 1.0 mol%, the visible emission intensity of the peaks of Tb^{3+} ions at ~ 415 , 438, 490, 546, and 622 nm increased significantly.^{32,33} Similarly, the visible emission intensity of the Sm^{3+} ion peaks at around 645 nm, which is attributed to the ${}^4\text{G}_{5/2} \rightarrow {}^6\text{H}_{9/2}$ transition, was also increased. These findings confirm that energy from the neighboring states of Tb^{3+} ions were transferred to the ${}^4\text{G}_{5/2} \rightarrow {}^6\text{H}_{9/2}$ transition of Sm^{3+} ions.^{33,34,37–40}

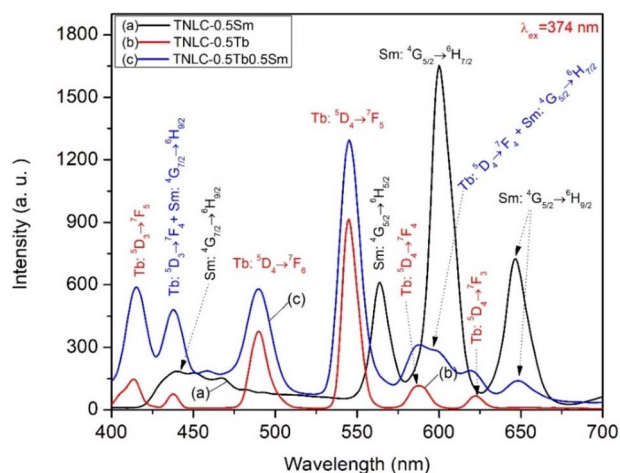


Fig. 5 Visible emission spectra of the TNLC-0.5Tb, TNLC-0.5Sm, and TNLC-0.5Tb0.5Sm lithium–niobium–tellurite glass samples under 374 nm excitation.

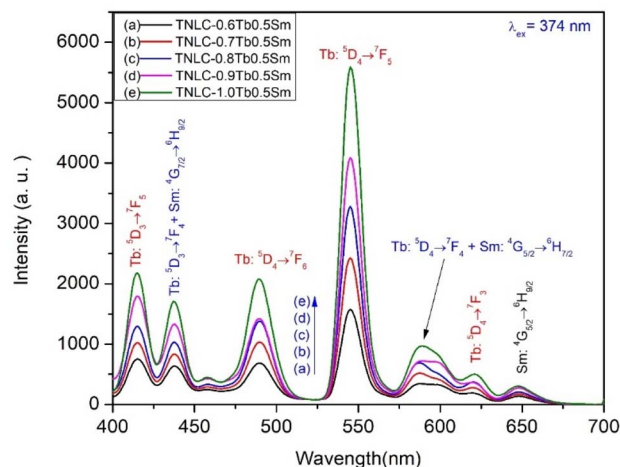


Fig. 7 Visible emission spectra of the TNLC-*p*Tb0.5Sm (*p* = 0.6, 0.7, 0.8, 0.9, and 1.0 mol%) glass samples under 374 nm excitation.



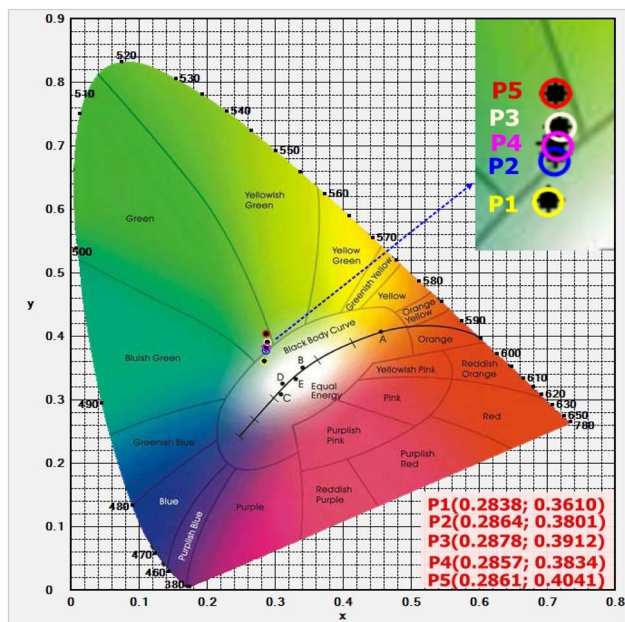


Fig. 8 CIE 1931 (x ; y) color coordinates for the visible emission spectra of the TNLC- p Tb0.5Sm ($p = 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) glass samples under 374 nm excitation.

Fig. 8 shows the CIE1931 (x ; y) color coordinates for the visible emission spectra of the TNLC- p Tb0.5Sm ($p = 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) lithium–niobium–tellurite glass samples under excitation at 374 nm. With the increase in the molar concentration of Tb^{3+} ions from 0.6 to 1.0 mol%, the color points of the visible emission spectra of the Tb^{3+} – Sm^{3+} co-doped glass shifted in the order of P1 (0.2838; 0.3610), P2 (0.2864; 0.3801), P3 (0.2878; 0.3912), P4 (0.2857; 0.3834) and P5 (0.2861; 0.4041) in the CIE1931 (x ; y) color coordinate chart, respectively,^{19,33,34} as shown in Fig. 8. From the results in Fig. 8, we can see that the TNLC-0.6Tb0.5Sm sample corresponding to the Tb^{3+}/Sm^{3+} concentration ratio of 1.2 has the color point closest to the white light region.^{33,34}

To further investigate the optimal concentration ratio between Tb^{3+} and Sm^{3+} ions for the color point to move closer to the white light region, which is necessary for application to WLEDs, the Sm^{3+} concentration was changed while keeping the Tb^{3+} concentration constant to investigate the emission of the Tb^{3+} – Sm^{3+} co-doped glass sample. The visible emission spectra of the TNLC-0.5Tb q Sm ($q = 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) lithium–niobium–tellurite glass samples under 374 nm are shown in Fig. 9.

When excited at 374 nm, with an increase in Sm^{3+} concentration from 0.6 to 1.0 mol%, most of the emission peaks of both Sm^{3+} and Tb^{3+} ions increased in intensity. This result affirms that energy from the neighboring states of Sm^{3+} ions is transferred to the Tb^{3+} ions. Simultaneously, with the increase in molar concentration of Sm^{3+} ions from 0.6 to 1.0 mol%, the tunable color for the visible emission spectra of the Tb^{3+} – Sm^{3+} co-doped glass samples shifted to color points 1 (0.3118; 0.3821), 2 (0.3093; 0.3827), 3 (0.3095; 0.3875), 4 (0.3169; 0.3937) and 5 (0.3263; 0.4049) on the CIE 1931 (x ; y) coordinate

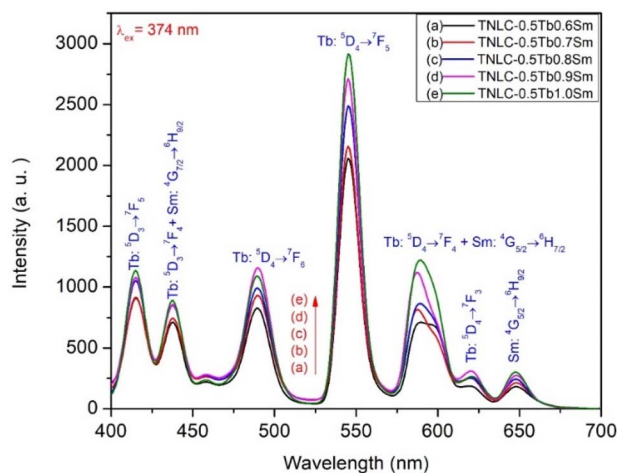


Fig. 9 Visible emission spectra of the TNLC-0.5Tb q Sm ($q = 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) glass samples under 374 nm excitation.

diagram,^{19,33,34} as shown in Fig. 10. From the visible emission spectra results of the Tb^{3+} – Sm^{3+} co-doped glass samples under 374 nm excitation (Fig. 7 and 9), as well as the color coordinates for their visible emission spectra (Fig. 8 and 10), we determined the optimal concentration ratio of Tb^{3+} and Sm^{3+} ions to be 0.83 for the color point to move the closest to the white light region, corresponding to the TNLC-0.5Tb0.6Sm glass sample.

During the analysis of the absorption capacity of the materials in the infrared region, we observed that the material strongly absorbed in the range from 940 to 1070 nm, with a maximum peak at about 980 nm. We surveyed the UC emission process of the Tb^{3+} – Sm^{3+} – Yb^{3+} co-doped material samples to investigate the ET process between Yb^{3+} ions and Tb^{3+}/Sm^{3+}

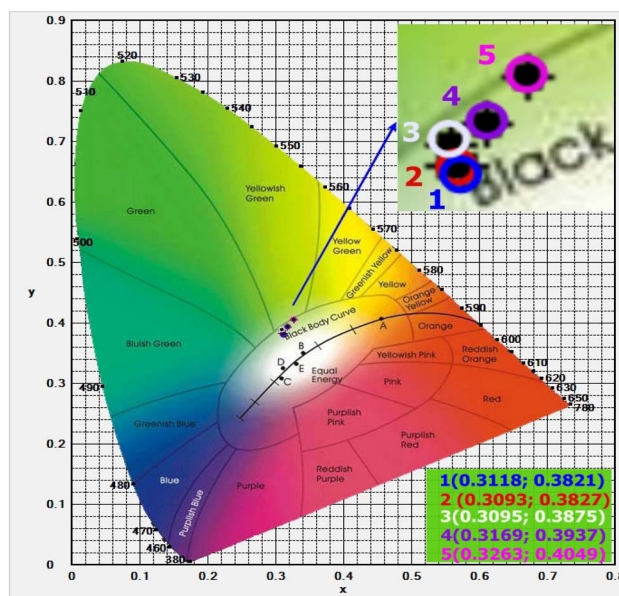


Fig. 10 CIE1931 (x ; y) color coordinates for the visible emission spectra of the TNLC-0.5Tb q Sm ($q = 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) glass samples under 374 nm excitation.



ions. In addition to investigating the VIS emission spectra of Tb³⁺–Sm³⁺ co-doped glass samples, we conducted further investigations using the UC emission spectra of these samples. Fig. 11 shows the UC emission spectra of the TNLC-*p*Tb0.5Sm2Yb (*p* = 0.5, 0.6, 0.7, 0.8, and 1.0 mol%) lithium-niobium-tellurite glass samples under a 980 nm laser diode (LD). With the increase in molar concentration of Tb³⁺ from 0.5 to 1.0 mol%, the UC emission intensity of the Tb³⁺ ion peaks at around 415, 438, 490, 546, and 622 nm increased for the Tb³⁺–Sm³⁺–Yb³⁺ co-doped glass samples.⁴¹ Meanwhile, the UC emission intensity of the peaks at around 645 nm, attributed to the ⁴G_{5/2} → ⁶H_{9/2} transition of Sm³⁺ ions, was also increased. This result confirms that energy from the neighboring states of Tb³⁺ ions was transferred to the ⁴G_{5/2} → ⁶H_{9/2} transition of Sm³⁺ ions.^{39,40}

Fig. 12 shows the CIE 1931 (*x*; *y*) color coordinates for the UC emission spectra of the TNLC-*p*Tb0.5Sm (*p* = 0.5, 0.6, 0.7, 0.8, and 1.0 mol%) lithium-niobium-tellurite glass samples under a 980 nm LD. With the increase in molar concentration of Tb³⁺ ions from 0.5 to 1.0 mol%, the color points shifted from in the order of points A (0.3277; 0.4847), B (0.2974; 0.5169), C (0.2997; 0.5441), D (0.3050; 0.5676), and E (0.3167; 0.5782) on the CIE 1931 (*x*; *y*) color coordinate diagram and were mainly located in the yellowish-green region.

To further determine the roles of excitation wavelength and the molar concentration of the doped RE ions on the CIE 1931 (*x*; *y*) color coordinates and color region, we compared the results obtained in this study with previously published reports, as listed in Table 3.

Investigation and calculation of correlated color temperature (CCT) are essential for optimizing the output light quality. From the CIE 1931 (*x*; *y*) results, the CCT of the TNLC glass samples was calculated using the McCamy formula (often called McCamy's approximation):^{50,52}

$$\text{CCT} = an^3 + bn^2 + cn + d \approx -449n^3 + 3525n^2 - 6823.3n + 5520.33 \quad (3)$$

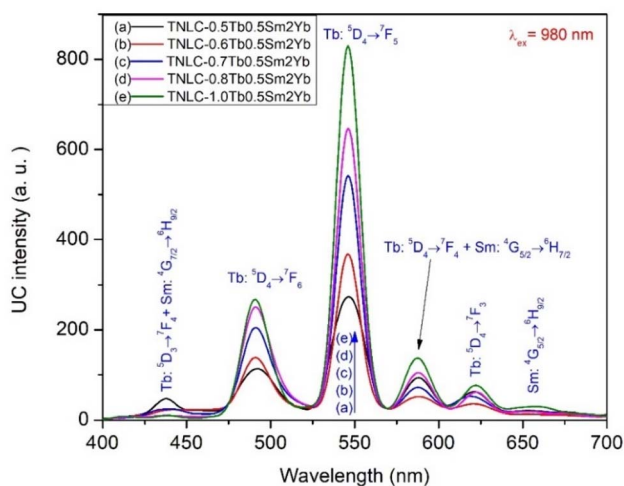


Fig. 11 UC emission spectra of the TNLC-*p*Tb0.5Sm2Yb (*p* = 0.5, 0.6, 0.7, 0.8, and 1.0 mol%) glass samples under 980 nm LD excitation.

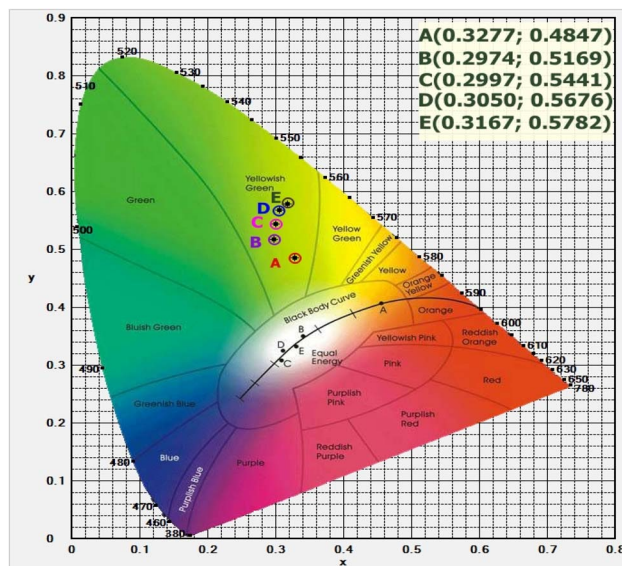


Fig. 12 CIE 1931 (*x*; *y*) color coordinates for the UC emission spectra of the TNLC-*p*Tb0.5Sm2Yb (*p* = 0.5, 0.6, 0.7, 0.8, and 1.0 mol%) glass samples excited under a 980 nm LD.

where:

$$n = \frac{x - x_e}{y - y_e} \quad (4)$$

Here, *x* and *y* are the CIE 1931 (*x*; *y*) chromaticity coordinates of the light source; *x_e* = 0.3320 and *y_e* = 0.1858 are the chromaticity coordinates of the Planckian locus.^{50,52} The CCT calculation results of the as-prepared glass samples are described in detail in Table 4.

The energy level diagram of the visible and UC emissions corresponding to the transitions of the Tb³⁺–Sm³⁺ and Tb³⁺–Sm³⁺–Yb³⁺ co-doped glass materials under excitation wavelengths of 374 nm and 980 nm is shown in Fig. 13. The Tb³⁺ ions are excited from the ground state ³H₆ to the higher-energy state ³D₅. These ions show characteristic emission in the visible region due to ³D₅ and ⁴ → ⁵F_{*J*} (*J* = 3, 4, 5, and 6) transitions.³⁹ Under 374 nm excitation, the visible emission of Tb³⁺ peaks at around 490, 546, 587, and 622 nm, which can be attributed to the ³D₄ → ⁵F_{*J*} (*J* = 6, 5, 4, and 3) transitions. The Sm³⁺ ions, when excited at 374 nm, move from the ⁶H_{5/2} ground state to a higher-energy ⁶P_{7/2} state.⁴⁰ From this ⁶P_{7/2} state, energy is transferred to ⁴G_{5/2} lower-energy states through non-radiative and ET processes. The ET1, ET2, CET1, and CET2 processes shown in Fig. 13 can be described in detail as follows:^{41,51,53}

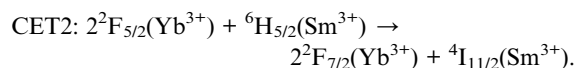
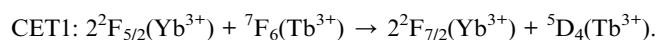
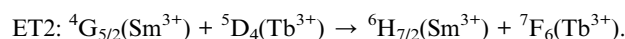
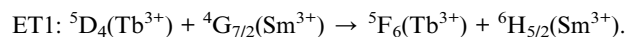


Table 3 Compare the energy transfer processes, color coordinates, and excitation wavelengths of RE ions in this study with those reported in previously published papers

| Host material | RE co-doping ratio | λ_{ex} (nm) | Energy transfer | CIE 1931 coordinates (x; y) | Color region | References |
|---|--|----------------------------|--|-----------------------------|--|--|
| Tellurite glass | 1Ce ³⁺ -1Tb ³⁺ -1Sm ³⁺ | 350 | Ce ³⁺ → Tb ³⁺ | 0.3750; 0.3245 | Pure white | T. T. Hong <i>et al.</i> ⁴² |
| LiYF ₄ single crystals | 1.24Tb ³⁺ -1.63Sm ³⁺ -0.25Ce ³⁺ | 374 | — | 0.3084; 0.3612 | Yellowish-green | Y. Z. Jiang <i>et al.</i> ⁴³ |
| Ba ₃ MgSi ₂ O ₈ :phosphors | 0.12Tb ³⁺ -0.05Sm ³⁺ | 233 | Tb ³⁺ → Sm ³⁺ | 0.555; 0.425 | Orange yellow | X. K. Sun <i>et al.</i> ⁴⁴ |
| Phosphate glasses | 0.5Sm ³⁺ -0.1Tb ³⁺ | 374 | Tb ³⁺ → Sm ³⁺ | 0.541; 0.300 | Reddish-orange | K. A. Kumar <i>et al.</i> ³⁷ |
| Zinc phosphate glasses | 1.0Sm ³⁺ -0.1Tb ³⁺ | 361 | Tb ³⁺ → Sm ³⁺ | 0.551; 0.312 | Greenish-yellow | A. N. Meza-Rocha <i>et al.</i> ⁴⁵ |
| | 0.5Sm ³⁺ -1.0Tb ³⁺ | 374 | — | 0.448; 0.459 | Yellow | N. F. Andrade Neto <i>et al.</i> ⁴⁶ |
| CaWO ₄ nanoparticles | 0.5Sm ³⁺ -0.5Tb ³⁺ | 355 | — | 0.3098; 0.4033 | White | K. Nie <i>et al.</i> ⁴⁷ |
| Ca ₂ La ₃ (SiO ₄) ₃ F phosphor | 1.0Sm ³⁺ -1.0Tb ³⁺ | 355 | — | 0.3002; 0.3997 | Blue | B. Yuan <i>et al.</i> ⁴⁸ |
| | 0.15Tb ³⁺ , 0.04Sm ³⁺ | 377 | Tb ³⁺ → Sm ³⁺ | 0.4175; 0.5658 | Yellow-green | Y. N. Guo <i>et al.</i> ⁴⁹ |
| | 0.15Tb ³⁺ -0.18Sm ³⁺ | 377 | — | 0.4691; 0.5160 | Greenish-yellow | E. J. Ansari <i>et al.</i> ⁵⁰ |
| CaLa ₄ (SiO ₄) ₃ O-phosphors | 9%Tb ³⁺ -11%Sm ³⁺ | 377 | Tb ³⁺ → Sm ³⁺ | 0.393; 0.387 | Bright white | O. Soriano-Romero <i>et al.</i> ⁵¹ |
| K ₃ Gd(PO ₄) ₂ crystalline glass ceramics | 0.3%Tb ³⁺ -0.4%Sm ³⁺ | 376 | Tb ³⁺ → Sm ³⁺ | 0.3201; 0.3297 | White | This study |
| K ₂ Y(WO ₄)(PO ₄) phosphors | 2%Sm ³⁺ -5%Tb ³⁺ | 377 | Sm ³⁺ → Tb ³⁺ | 0.37; 0.57 | Yellow-green | |
| Potassium-zinc phosphate glasses | 1.0Sm ³⁺ -1.0Tb ³⁺ | 344 | Tb ³⁺ → Sm ³⁺ | 0.529; 0.447 | Orange | |
| | 1.0Sm ³⁺ -1.0Tb ³⁺ | 360 | Tb ³⁺ → Sm ³⁺ | 0.534; 0.442 | Yellow | |
| | 1.0Sm ³⁺ -1.0Tb ³⁺ | 377 | Tb ³⁺ → Sm ³⁺ | 0.442; 0.507 | Yellow | |
| Lithium-niobium-tellurite glass | 0.5Tb ³⁺ -0.6Sm ³⁺ | 374 | Tb ³⁺ ↔ Sm ³⁺ | 0.3118; 0.3821 | White | |
| | 0.5Tb ³⁺ -0.5Sm ³⁺ -2Yb ³⁺ | 980 | Yb ³⁺ → Tb ³⁺ Yb ³⁺ → Sm ³⁺ | 0.3277; 0.4847 | (near black body curve) Yellowish-green | |



Table 4 CCT values and CIE 1931 (x; y) chromaticity coordinates of the TNLC glass samples

| Glass samples | λ_{ex} | Color point | CIE 1931 x | CIE 1931 y | CCT (K) | Color region |
|--------------------|-----------------------|--------------------|------------|------------|---------|-----------------|
| TNLC-0.5Tb | 374 nm | P _{Tb} | 0.2840 | 0.5303 | 6544 | Yellowish green |
| TNLC-0.5Tb0.5Sm | 374 nm | P _{Tb-Sm} | 0.2901 | 0.3728 | 7208 | White |
| TNLC-0.5Sm | 374 nm | P _{Sm} | 0.4906 | 0.3537 | 15 489 | Yellowish pink |
| TNLC-0.6Tb0.5Sm | 374 nm | P1 | 0.2838 | 0.3601 | 7662 | Green |
| TNLC-0.7Tb0.5Sm | 374 nm | P2 | 0.2864 | 0.3801 | 7294 | Green |
| TNLC-0.8Tb0.5Sm | 374 nm | P3 | 0.2878 | 0.3912 | 7129 | Green |
| TNLC-0.9Tb0.5Sm | 374 nm | P4 | 0.2857 | 0.3834 | 7290 | Green |
| TNLC-1.0Tb0.5Sm | 374 nm | P5 | 0.2861 | 0.4041 | 7085 | Green |
| TNLC-0.5Tb0.6Sm | 374 nm | 1 | 0.3118 | 0.3821 | 6254 | White |
| TNLC-0.5Tb0.7Sm | 374 nm | 2 | 0.3093 | 0.3827 | 6347 | White |
| TNLC-0.5Tb0.8Sm | 374 nm | 3 | 0.3095 | 0.3875 | 6318 | White |
| TNLC-0.5Tb0.9Sm | 374 nm | 4 | 0.3169 | 0.3937 | 6033 | White |
| TNLC-0.5Tb1.0Sm | 374 nm | 5 | 0.3263 | 0.4049 | 5706 | White |
| TNLC-0.5Tb0.5Sm2Yb | 980 nm | A | 0.3277 | 0.4847 | 5616 | Yellowish green |
| TNLC-0.6Tb0.5Sm2Yb | 980 nm | B | 0.2974 | 0.5169 | 6274 | Yellowish green |
| TNLC-0.7Tb0.5Sm2Yb | 980 nm | C | 0.2997 | 0.5441 | 6165 | Yellowish green |
| TNLC-0.8Tb0.5Sm2Yb | 980 nm | D | 0.3050 | 0.5676 | 6020 | Yellow |
| TNLC-1.0Tb0.5Sm2Yb | 980 nm | E | 0.3167 | 0.5782 | 5790 | Yellowish green |

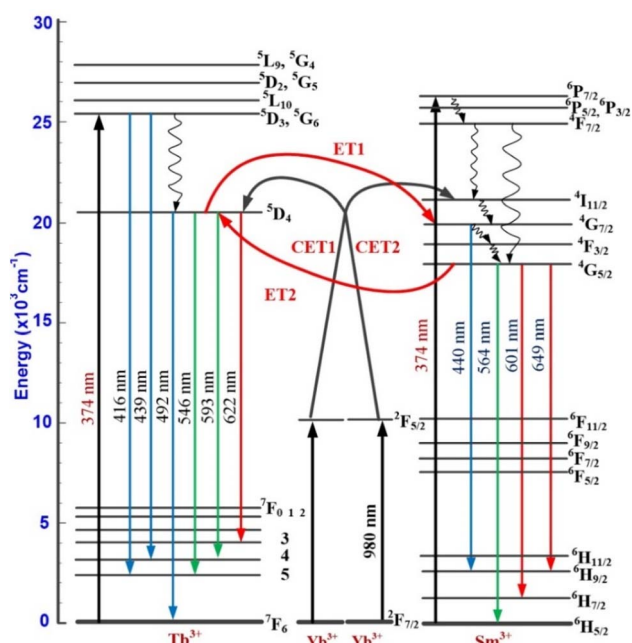


Fig. 13 Energy levels of the Tb³⁺, Sm³⁺, and Yb³⁺ ions and the mechanisms of visible and UC emissions via CET1, CET2, ET1, and ET2 processes in the TNLC glass system.

The charge transfer process between the Tb³⁺ and Sm³⁺ ions depends on the concentration of optical centers in the material. To further investigate the influence of Tb³⁺ ion concentration on the ET process, we analyzed the decay lifetimes of Tb³⁺ and Sm³⁺ ions in the synthesized TNLC glass materials. We measured the time-resolved fluorescence spectra of TNLC-0.5TbqSm ($q = 0, 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) lithium–niobium–tellurite glass samples using an excitation wavelength of 374 nm and emission at 546 nm corresponding to the $^5D_4 \rightarrow ^5F_6$ transition of Tb³⁺;^{4,32–34} the obtained results are presented in

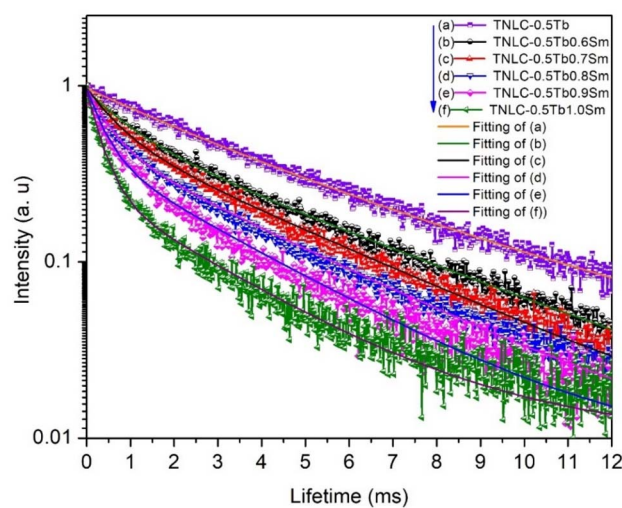


Fig. 14 Decay lifetimes of Tb³⁺ at the $^5D_4 \rightarrow ^5F_6$ transition in TNLC-0.5TbqSm ($q = 0, 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) glass samples under 374 nm excitation.

Fig. 14. Through the fitting process, we observed that the time-resolved fluorescence spectra of the materials followed the equation:^{16,50}

$$I_t = A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right), \quad (5)$$

where τ_1 and τ_2 are the decay lifetime components, and A_1 and A_2 are constants. The average decay lifetime τ was calculated as follows:^{16,51,54,55}

$$\tau = \frac{A_1 \tau_1^2 + A_2 \tau_2^2}{A_1 \tau_1 + A_2 \tau_2}. \quad (6)$$

The decay lifetimes of TNLC-0.5TbqSm ($q = 0, 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) lithium–niobium–tellurite glass samples



Table 5 Decay lifetimes of Tb³⁺ ions at 546 nm (⁵D₄ → ⁵F₆) and Sm³⁺ ions at 601 nm (⁴G_{5/2} → ⁶H_{5/2}) under 374 nm excitation

| Glass sample | Decay lifetime (ms) |
|-----------------|---------------------|
| TNLC-0.5Tb | 4.62 |
| TNLC-0.5Tb0.6Sm | 3.97 |
| TNLC-0.5Tb0.7Sm | 3.48 |
| TNLC-0.5Tb0.8Sm | 3.13 |
| TNLC-0.5Tb0.9Sm | 2.63 |
| TNLC-0.5Tb1.0Sm | 2.21 |
| TNLC-0.5Sm | 7.86 |
| TNLC-0.6Tb0.5Sm | 6.91 |
| TNLC-0.7Tb0.5Sm | 5.63 |
| TNLC-0.8Tb0.5Sm | 4.24 |
| TNLC-0.9Tb0.5Sm | 3.18 |
| TNLC-1.0Tb0.5Sm | 2.56 |

calculated according to formula (6) are listed in Table 5. The decay lifetimes at 546 nm, corresponding to the ⁵D₄ → ⁵F₆ transition of Tb³⁺ ions in the TNLC-0.5Tb q Sm ($q = 0, 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) lithium–niobium–tellurite glass samples, were found to decrease with increasing Sm³⁺ concentration. This is strong evidence for ET from Tb³⁺ to Sm³⁺ ions.^{4,32–34,44} Similarly, the decay lifetimes of Sm³⁺ ions at 601 nm, corresponding to the ⁴G_{5/2} → ⁶H_{7/2} transition of Sm³⁺ ions^{4,32–34} in the TNLC- p Tb0.5Sm ($p = 0, 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) lithium–niobium–tellurite glass samples, were measured under 374 nm excitation, as shown in Fig. 15. The average decay lifetimes of TNLC- p Tb0.5Sm ($p = 0, 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) lithium–niobium–tellurite glass samples were calculated, as presented in Table 5. The decay lifetimes of Sm³⁺ at 601 nm, corresponding to ⁴G_{5/2} → ⁶H_{7/2} transition of Sm³⁺ ions^{32,33} in these glass samples under 374 nm excitation were found to decrease with increasing Tb³⁺ concentration in the glass samples, further proving ET from Sm³⁺ to Tb³⁺ ions.^{33,34,39,40}

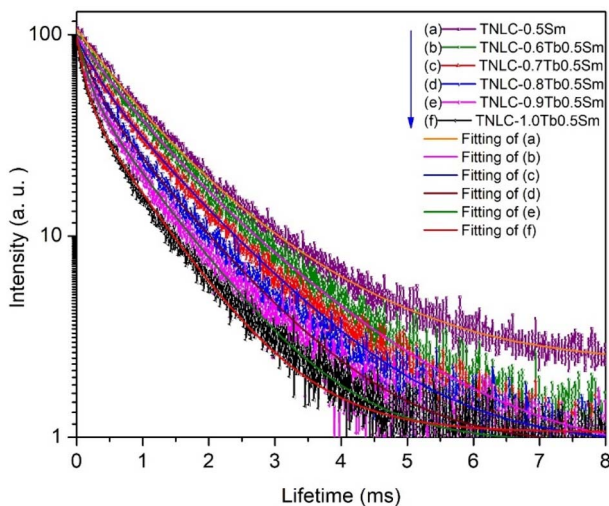


Fig. 15 Decay lifetimes of Sm³⁺ at the ⁴G_{5/2} → ⁶H_{5/2} transition in TNLC- p Tb0.5Sm ($p = 0, 0.6, 0.7, 0.8, 0.9,$ and 1.0 mol%) glass samples under 374 nm excitation.

To evaluate the energy transfer efficiency (ETE) between Tb³⁺ and Sm³⁺ ions, we carried out ETE calculations for these ET processes. The ETE from Tb³⁺ to Sm³⁺ ions is denoted as $\eta_{ET(Tb \rightarrow Sm)}$ and was estimated using the luminescence lifetimes of the donor (Tb³⁺) in the presence and absence of the acceptor (Sm³⁺), according to the following equation:

$$\eta_{ET(Tb \rightarrow Sm)} = 1 - \frac{\tau_{Tb-Sm}}{\tau_{Tb}}, \quad (7)$$

where τ_{Tb} is the luminescence lifetime of Tb³⁺ ions in the absence of Sm³⁺ ions, and τ_{Tb-Sm} is the luminescence lifetime of Tb³⁺ ions in the presence of Sm³⁺ ions (*i.e.* when energy transfer occurs).

Similarly, the ETE from Sm³⁺ to Tb³⁺ ions is denoted as $\eta_{ET(Sm \rightarrow Tb)}$ and was estimated using the luminescence lifetimes of the donor (Sm³⁺) in the presence and absence of the acceptor (Tb³⁺), according to the following equation:

$$\eta_{ET(Sm \rightarrow Tb)} = 1 - \frac{\tau_{Sm-Tb}}{\tau_{Sm}}, \quad (8)$$

where τ_{Sm} is the luminescence lifetime of Sm³⁺ ions in the absence of Tb³⁺ ions, and τ_{Sm-Tb} is the luminescence lifetime of Sm³⁺ ions in the presence of Tb³⁺ ions. Based on the results presented in Table 5, we calculated ETE values to be 52.26% and 67.43% for the ET processes from Tb³⁺ to Sm³⁺ ions and from Sm³⁺ to Tb³⁺ ions, respectively.

4. Conclusions

In this study, a series of Tb³⁺-doped, Sm³⁺-doped, Tb³⁺-Sm³⁺ co-doped, and Tb³⁺-Sm³⁺-Yb³⁺ tri-doped lithium–niobium–tellurite TeO₂-Nb₂O₅-LiO₂-CaO glasses were synthesized *via* conventional melt-quenching. These glasses exhibited tunable multi-color emissions under excitation at 374 nm and 980 nm, which could be attributed to Sm³⁺ (yellow-pink), Tb³⁺ (yellowish-green), and Yb³⁺-sensitized UC emissions of Tb³⁺-Sm³⁺-Yb³⁺ tri-doped glass materials. The DTA analysis showed the high thermal stability of the tri-doped glass, with $\Delta T = 151$ °C, suitable for heat treatment and mechanical durability. The emission color could be effectively controlled by varying the Sm³⁺-Tb³⁺ concentrations and excitation wavelengths. The optimal Tb³⁺/Sm³⁺ molar ratio was 0.83 in the TNLC-0.5Tb0.6Sm sample for achieving CIE coordinates closest to white light emission. Spectral and lifetime measurements confirmed ETE between Tb³⁺ and Sm³⁺ ions. The combination of low phonon energy, high stability, emission tunability, and efficient ET highlights the potential of Tb³⁺-Sm³⁺ co-doped and Tb³⁺-Sm³⁺-Yb³⁺ tri-doped TNLC glasses for application in advanced color display and solid-state lighting devices, including WLEDs.

Data availability

The authors confirm that the data supporting the findings of this study are available from the corresponding author upon request.

Conflicts of interest

There are no conflicts of interest to declare.



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