

Judd-Ofelt analysis, concentration quenching behavior, and thermal stability of red-emitting Sm^{3+} -doped BaZnGeO_4 phosphors

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Sm^{3+} -doped BaZnGeO_4 phosphors with various Sm^{3+} doping concentration were synthesized via a high-temperature solid-state method. X-ray diffraction (XRD) confirmed the single-phase BaZnGeO_4 structure with no impurities. Photoluminescence spectra showed concentration quenching behavior, where dipole-dipole interactions were identified as the main energy transfer mechanism between Sm^{3+} ions. Thermal stability analysis revealed that the thermal quenching of the $\text{Sm}^{3+} {}^4\text{G}_{5/2}$ level follows a crossover process, with an activation energy (ΔE) of 0.24 eV, as described by the Arrhenius model. Additionally, Judd-Ofelt analysis provided the optical transition probabilities and radiative characteristics of Sm^{3+} in the BaZnGeO_4 host, with calculated Ω_λ ($\lambda = 2, 4, 6$) values of $6.83 \times 10^{-20} \text{ cm}^2$, $5.10 \times 10^{-20} \text{ cm}^2$, and $2.80 \times 10^{-20} \text{ cm}^2$.

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1. Introduction

In recent years, rare-earth-doped luminescent materials have attracted extensive research interest owing to their remarkable optical properties. These phosphors exhibit broad potential for applications in lighting, laser media, solar energy conversion, and biomedicine. In particular, they have been widely employed in solid-state lasers [1-5], light-emitting diodes (LEDs) [6-10], solar cells [11-13], multicolor displays [14-16], and bioimaging fluorescent probes [17-20]. Among these, rare-earth-based phosphors play an especially vital role in the solid-state lighting industry.

The color quality of white light-emitting diodes (W-LEDs) largely depends on the emission characteristics of both the semiconductor chips and the combined phosphors. Although considerable progress has been achieved in developing blue and green emitters, efficient red-emitting phosphors remain relatively less explored [20-28]. The design of high-performance red phosphors therefore requires careful selection of the host lattice. Among various candidates, BaZnGeO_4 is a promising host due to its facile synthesis, low phonon energy, and excellent structural and chemical stability. Recent studies have shown that BaZnGeO_4 -based

phosphors can exhibit tunable photoluminescence and persistent luminescence through suitable activator doping and defect regulation. For example, Sun et al. reported a defect-induced orange persistent luminescence phosphor based on Bi^{3+} -activated BaZnGeO_4 , in which the luminescence behavior was closely related to the local coordination environment of Bi^{3+} and vacancy-related defects [29]. In addition, Eu^{3+} -activated BaZnGeO_4 phosphors have recently been investigated for lighting and latent fingerprint visualization applications, where Judd-Ofelt analysis was employed to evaluate the local crystal-field environment and optical transition properties of Eu^{3+} ions [30]. These results indicate that BaZnGeO_4 is not only structurally stable but also suitable for constructing rare-earth or transition-metal-ion-activated phosphors with diverse optical functions. Compared with Eu^{3+} , which is commonly used in commercial red phosphors, Sm^{3+} ions offer several advantages, including lower cost, broader emission range, and superior color saturation. Consequently, Sm^{3+} -activated BaZnGeO_4 emerges as a cost-effective and easily synthesized red-emitting material suitable for W-LED applications [31-37].

To assess the optical performance of rare-earth-activated phosphors, it is essential to

determine their optical transition parameters based on the Judd-Ofelt (J-O) theory. As one of the most established models for analyzing f-f transitions in trivalent rare-earth ions, J-O theory provides three intensity parameters, Ω_λ ($\lambda = 2, 4, 6$), which can be used to calculate critical radiative properties such as oscillator strength, spontaneous emission probability, fluorescence branching ratio, radiative lifetime, and quantum efficiency. For transparent systems, the J-O parameters can be directly derived from absorption spectra once the ion concentration and refractive index are known. However, in non-transparent media, absorption data are difficult to obtain, limiting the conventional J-O approach. Meanwhile, since diffuse reflectance spectra correlate closely with absorption spectra, combining diffuse reflectance and fluorescence lifetime data provides an effective method for evaluating the J-O intensity parameters of opaque phosphors.

In this study, BaZnGeO₄ phosphors with varying concentrations of Sm³⁺ were synthesized using a high-temperature solid-state method. The samples were characterized using X-ray diffraction (XRD) and photoluminescence (PL) spectroscopy. The spectral characteristics and energy transfer behavior of the phosphors were investigated through excitation spectra, emission spectra, and fluorescence decay. By studying the diffuse reflectance spectra and fluorescence the real J-O parameters can be derived.

2. Experimental

2.1. Experimental chemicals

High-purity reagents ZnO (99.99%), GeO₂ (99.99%), BaCO₃ (99.99%), and Sm₂O₃ (99.99%) were obtained from Tianjin Jinke Fine Chemical Research Institute. A series of Sm³⁺-doped BaZnGeO₄ phosphors were synthesized via a conventional high-temperature solid-state reaction. The starting materials were weighed according to the stoichiometric ratios and thoroughly homogenized in an agate mortar for 30 minutes. The

well-mixed powders were transferred into Al₂O₃ crucibles and calcined in air at 1140 °C for 6 h, with a heating rate of 9.5 °C min⁻¹. After the sintering process, the samples were naturally cooled to room temperature and reground for 10 min to obtain uniform luminescent powders.

2.2. Characterization

The crystal structure of the samples was characterized by X-ray diffraction (XRD) using a Shimadzu XRD-6000 powder diffractometer (Japan). Photoluminescence properties, including excitation and emission spectra as well as fluorescence decay, were measured on a Hitachi F-4600 fluorescence spectrophotometer with a 150 W xenon lamp as the excitation source. Diffuse reflectance spectra were recorded using a Shimadzu UV-3600 spectrophotometer (Japan) equipped with an integrating sphere (Labsphere 206-23851-91, China). Sample temperature during measurements was maintained using a custom-built constant-temperature device (DMU-TC 450).

3. Results and discussion

3.1. Crystal structure analysis

The phase purity of the prepared samples was confirmed using XRD. Moreover, Rietveld structure refinement was performed using the GSAS program, with single-crystal crystallographic data of BZGO adopted as the initial model. Fig. 1 shows the refinement patterns of BZGO: 1 mol% Sm³⁺ where the cross symbols represent the experimental data and the red solid line represents the calculated results. This figure highlights the significant consistency between the experimental data set and the theoretical data set, with differences falling within acceptable ranges. This strong consistency supports the conclusion that our prepared sample exhibits a hexagonal crystal phase.

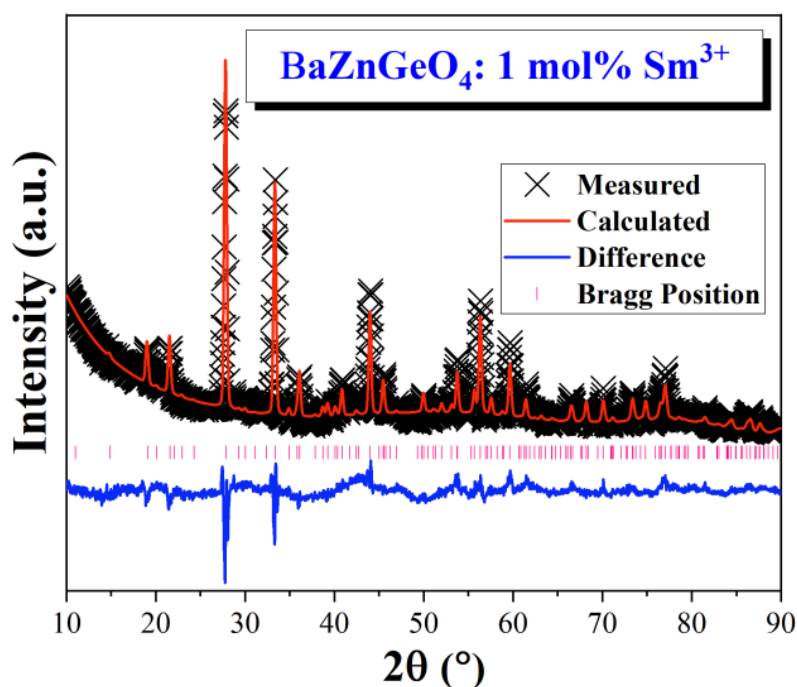


Fig. 1. Refinement pattern of optimal sample $\text{BaZnGeO}_4: 1 \text{ mol\% Sm}^{3+}$ (colour online)

For comprehensive details on the cell parameters and the refinement results from the Rietveld refinement procedure were listed in Table 1. The refinement results of $\text{BZGO}: 1 \text{ mol\% Sm}^{3+}$ ($\chi^2=3.18$, $R_p=7.84\%$, $R_{wp}=10.45\%$) indicate that the fraction factors, atomic positions, and temperature factors of the sample are in

good agreement with the reflection conditions. BZGO crystals belong to the hexagonal system with a structure derived from the high-temperature tridymite phase. The space group is P6, with lattice parameters $a=b=9.296 \text{ \AA}$, $c=8.826 \text{ \AA}$, $V=660.554 \text{ \AA}^3$ for $\text{BZGO}: 1 \text{ mol\% Sm}^{3+}$.

Table 1. Rietveld refinement results and cell parameters of $\text{BaZnGeO}_4: 1 \text{ mol\% Sm}^{3+}$ phosphor

Formula	$\text{BaZnGeO}_4: 1 \text{ mol\% Sm}^{3+}$
Radiation type	Cu $K\alpha_1$ radiation with $\lambda = 1.5406 \text{ \AA}$
2θ range	$10\text{--}90^\circ$
Symmetry	Hexagonal Symmetry
Space group	P6
Cell parameters	$a = 9.296 \text{ \AA}$
	$b = 9.296 \text{ \AA}$
	$c = 8.826 \text{ \AA}$
	$\alpha = \beta = 90^\circ$
	$\gamma = 120^\circ$
Reliability factors	$V = 660.554 \text{ \AA}^3$
	$\chi^2 = 3.18$
	$R_{wp} = 10.45\%$
	$R_p = 7.84\%$

The crystal structure of BZGO was shown in Fig. 2, where there are two independent tetrahedral sites: one occupied by Ge^{4+} and the other by Zn^{2+} . $[\text{TO}_4]$ tetrahedra are connected by corners to form layers perpendicular to

the c -axis. These layers are linked to form a three-dimensional framework by sharing $\text{O}(4)$. This framework contains three types of cavities filled with Ba^{2+} ions. Each of the three Ba^{2+} sites is surrounded by

nine oxygen atoms, with Ba^{2+} ions located on the midplane between two neighboring layers. The ionic radius of Sm^{3+} (1.02 Å) is similar to that of Ba^{2+} (1.35 Å) and much larger than those of Zn^{2+} (0.74 Å) and Ge^{4+}

(0.53 Å) with the same coordination number. Therefore, it is believed that the doped Sm^{3+} ions occupy the Ba^{2+} sites in BZGO.

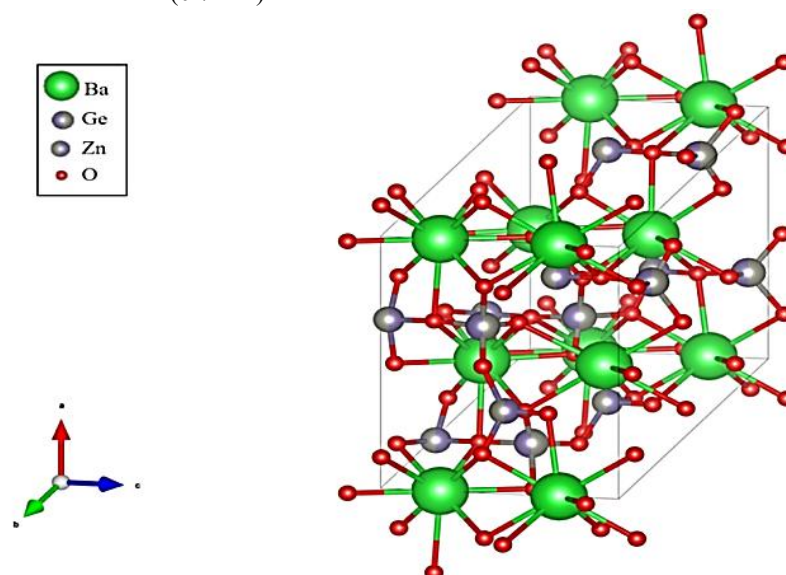


Fig. 2. The unit cell structure of the BaZnGeO_4 host (colour online)

3.2. Luminescence properties

The excitation spectra of powder samples with different Sm^{3+} concentrations were obtained by monitoring 598 nm emission, corresponding to the $\text{Sm}^{3+}:^4\text{G}_{5/2} \rightarrow ^6\text{H}_{7/2}$ transition, as shown in Fig. 3. All excitation spectra exhibit the same profile, featuring 10 excitation peaks at 317, 345, 363, 375, 404, 419, 442, 466, 480, and 501 nm. These peaks correspond to transitions from the ground state $^6\text{H}_{5/2}$ to the excited

states $^4\text{K}_{17/2}$, $^4\text{H}_{9/2}$, $^4\text{D}_{5/2}$, $^6\text{P}_{7/2}$, $^4\text{F}_{7/2}$, $^6\text{P}_{5/2}$, $^4\text{G}_{9/2}$, $^4\text{I}_{11/2}$, $^4\text{M}_{15/2}$, and $^4\text{G}_{7/2}$, respectively. The most prominent excitation peak at 404 nm, which matches the output wavelength region of commercial semiconductor LEDs, suggesting that $\text{BaZnGeO}_4:\text{Sm}^{3+}$ phosphors could be potential candidates for white LEDs. Additionally, the excitation spectra indicate that the intensity increases with the Sm^{3+} concentration, reaching a maximum at 1 mol%. Beyond this concentration, the intensity gradually decreases.

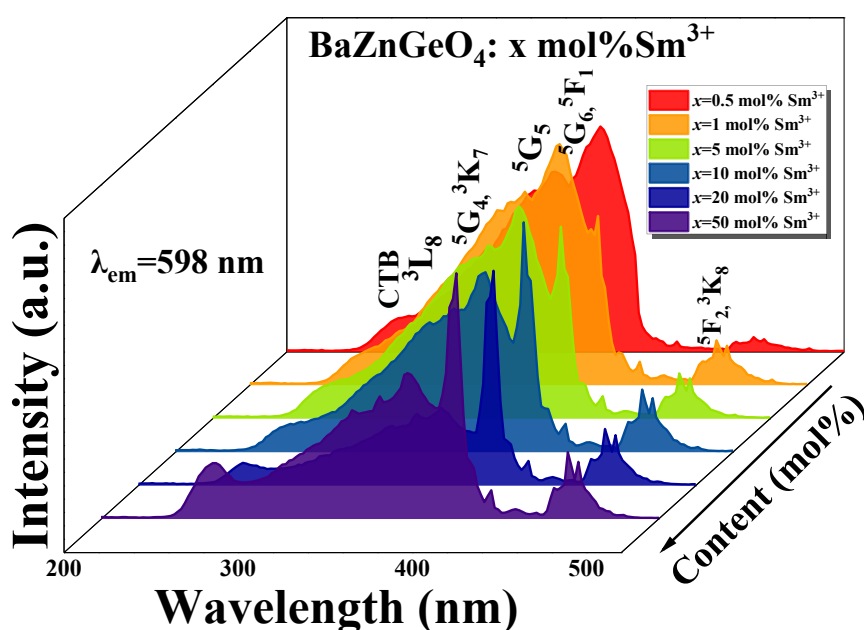


Fig. 3. Excitation spectra of $\text{BaZnGeO}_4:\text{Sm}^{3+}$ phosphors doped with varying Sm^{3+} concentrations by monitoring 598 nm emission (colour online)

The emission spectra of BaZnGeO₄ samples with varying concentrations of Sm³⁺ are presented in Fig. 4. These spectra were recorded under 404 nm excitation, corresponding to the ⁶H_{5/2}→⁴F_{7/2} transition of Sm³⁺. Four characteristic emissions of Sm³⁺ are observed, corresponding to transitions from ⁴G_{5/2} to ⁶H_{5/2} (562 nm), ⁶H_{7/2} (596 nm), ⁶H_{9/2} (646 nm), and ⁶H_{11/2} (720 nm). The ⁴G_{5/2}→⁶H_{9/2} and ⁴G_{5/2}→⁶H_{11/2} transitions are pure electric dipole transitions (ΔJ≤6), while the ⁴G_{5/2}→⁶H_{5/2} and ⁴G_{5/2}→⁶H_{7/2} transitions involve both electric dipole and

magnetic dipole transitions, following the principle of (ΔJ=0±1). Despite the different Sm³⁺ concentrations in each sample, the emission profiles remain similar. Additionally, the fluorescence intensity varies significantly with the doping concentration. As the concentration increases, the intensity initially rises, reaching its peak at 1.0 mol% Sm³⁺, and then gradually decreases. This reduction in luminescence intensity at higher concentrations indicates that concentration quenching occurs at elevated Sm³⁺ doping levels.

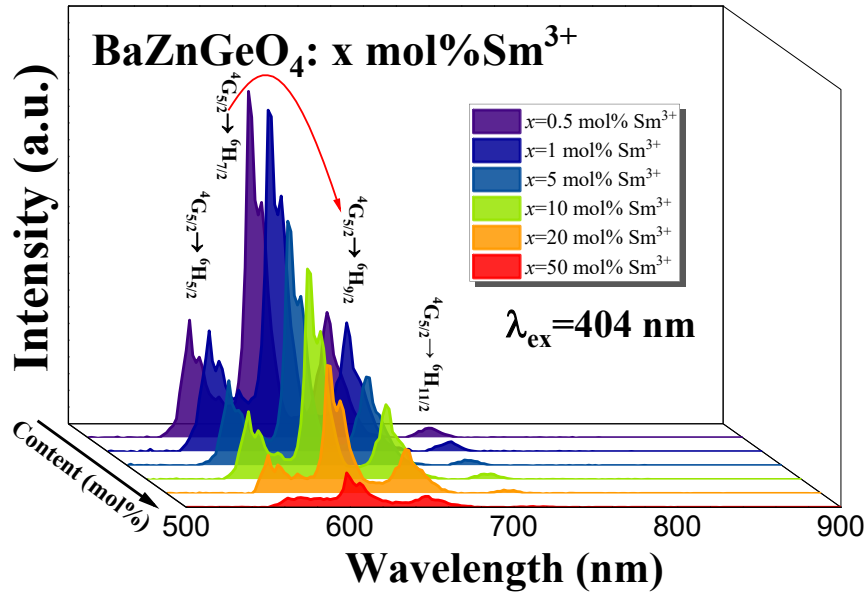


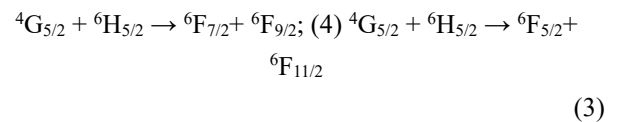
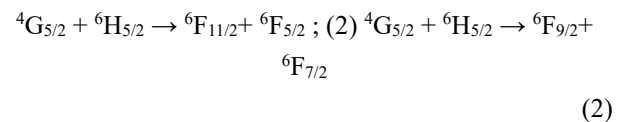
Fig. 4. Emission spectra of BaZnGeO₄ phosphors with varying Sm³⁺ concentrations under 404 nm excitation (colour online)

A model for describing the concentration quenching behavior, which involves the electric-multipole interactions between luminescent centers, was established by Van Uitert and can be expressed as [36-39]:

$$I(c) = \frac{c}{k[1 + \beta c^Q]} \quad (1)$$

In this study, c represents the doping concentration, while k and β are constants specific to the research system. (Q) denotes the interaction mechanism between RE³⁺ ions, where ($Q = 6, 8$ and 10) correspond to dipole-dipole (D-D), dipole-quadrupole (D-Q), and quadrupole-quadrupole (Q-Q) interactions, respectively. To investigate the concentration quenching behavior, the integrated fluorescence intensity of Sm³⁺:⁴G_{5/2}→⁶H_{7/2} in BaZnGeO₄ powder samples with varying Sm³⁺ concentrations was calculated. The concentration-dependent luminescence intensity is shown by the square symbols in Fig. 5 (a). Nonlinear curve fitting was performed using equation (1), with the fitting

result represented by the solid line in Fig. 5(a). During the fitting process, it was verified that the value of Q is 6, which is close to the theoretical value of 6. This indicates that the D-D interaction is the primary cause of the concentration quenching of Sm³⁺ in BaZnGeO₄ phosphors. As the Sm³⁺ concentration increases, the distance between Sm³⁺ ions decreases, leading to stronger interactions and a reduction in the ⁴G_{5/2} level. According to the energy level diagram and the energy matching rules of Sm³⁺ ions, four possible cross-relaxation pathways are given in Fig. 5 (b).



All these pathways contribute to the concentration

quenching behavior of the luminescence emissions from the ⁴G_{5/2} level to lower energy levels of Sm³⁺ in

BaZnGeO₄ samples.

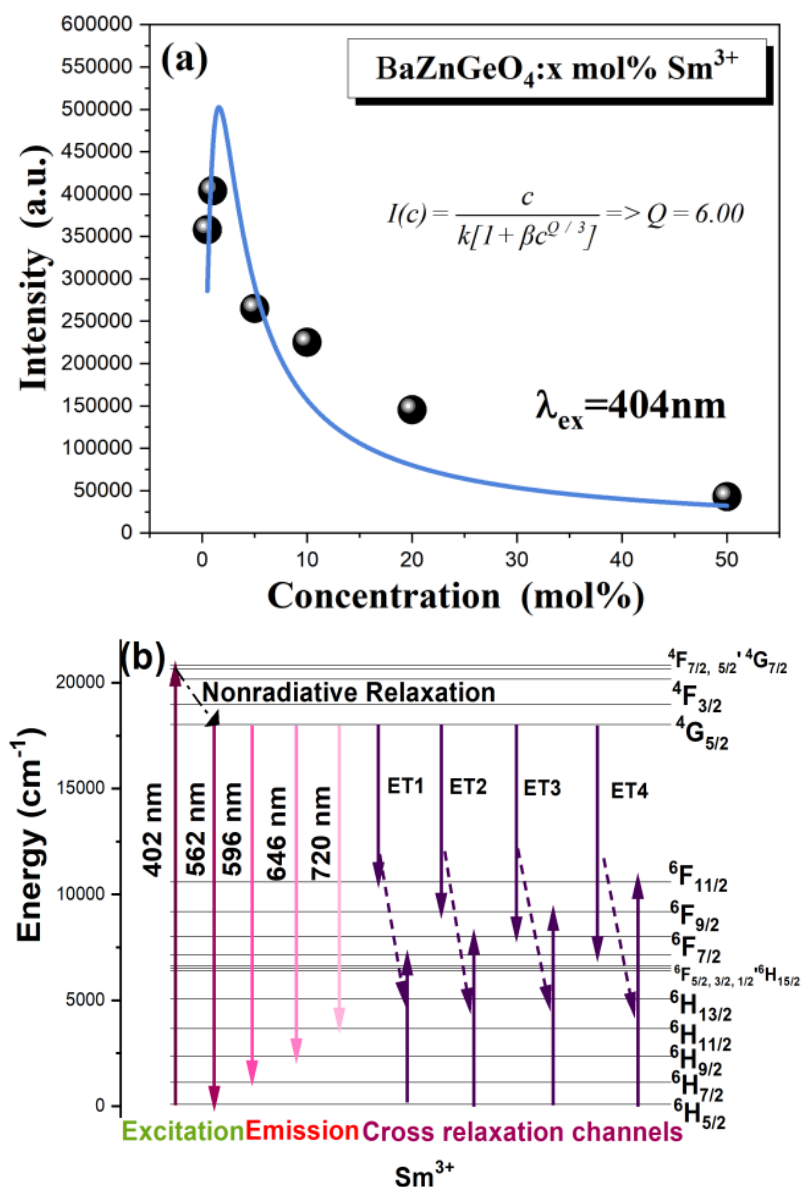


Fig. 5. (a) Dependence of the ⁴G_{5/2}→⁶H_{7/2} emission integrated intensity on doping concentration of Sm³⁺. Solid circle represents experimental data, while the solid line is the fitting curve based on Van Uitert's model. (b) Energy level diagram and cross-relaxation pathways of Sm³⁺ in BaZnGeO₄: Sm³⁺ phosphors (colour online)

To explore the energy transfer behavior between Sm³⁺ ions, the fluorescence decay of Sm³⁺ in BaZnGeO₄ phosphors were examined. Fig. 6 presents the fluorescence decay of the Sm³⁺:⁴G_{5/2} level at varying Sm³⁺ concentrations, measured by monitoring 598 nm emission under 404 nm pulsed light excitation. As shown in Fig. 6, the decay curves follow a single-exponential model in the semi-logarithmic coordinate system. A single-exponential function was applied to process the experimental data. Notably, as the Sm³⁺ concentration increases, the fluorescence decay rate remains unchanged. This suggests that the 4f electron orbitals of Sm³⁺ are minimally influenced by the surrounding environment,

and therefore, the fluorescence properties remain largely consistent across different concentrations. The BaZnGeO₄ matrix exhibits a well-ordered crystal structure and a stable chemical environment, which effectively isolates the Sm³⁺ ions and reduces interionic interactions. This isolation helps to minimize concentration quenching effects, preserving a stable fluorescence lifetime within a certain concentration range. Furthermore, the crystal structure of BaZnGeO₄ and the coordination environment of Sm³⁺ ions likely suppress non-radiative relaxation pathways, decreasing the likelihood of non-radiative transitions as concentration increases, thus stabilizing the fluorescence lifetime.

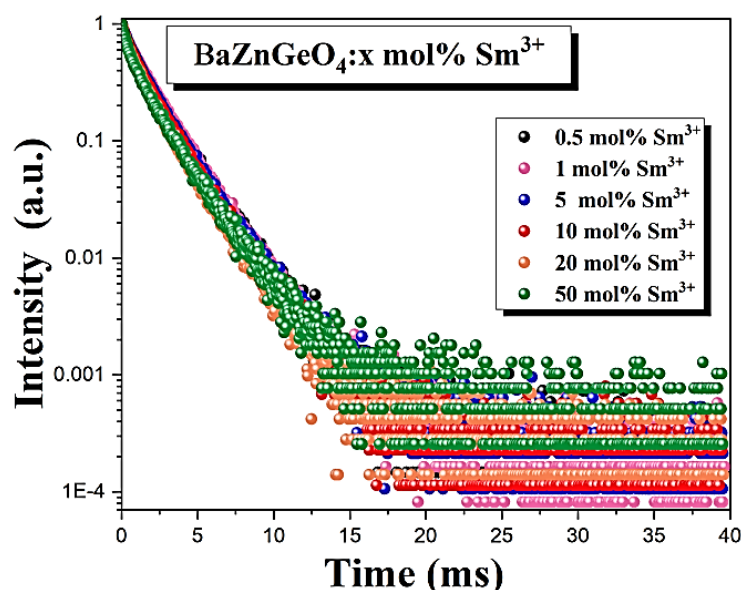


Fig. 6. Under 404 nm pulsed excitation, the fluorescence decay of the $\text{Sm}^{3+} : ^4\text{G}_{5/2}$ level in BaZnGeO_4 phosphors with different Sm^{3+} concentrations was measured by monitoring 598 nm emission (colour online)

3.3. Optical transition property of Sm^{3+}

In a previous report, our research group proposed a method for calculating the J-O parameters of RE^{3+} -doped phosphors using diffuse reflection spectra. This method was proven to be suitable for $\text{BaZnGeO}_4:\text{Er}^{3+}/\text{Yb}^{3+}$ phosphors [35,36]. According to this method, the relative absorption cross-section spectrum can be determined from the diffuse reflection spectra using the Kubelka-Munk function. This spectrum is then calibrated to the true absorption cross-section using the fluorescence decay of the $^4\text{I}_{13/2}$ level of Er^{3+} , allowing for the calculation of the J-O parameters.

Similarly, after obtaining the absorption cross-section spectrum of Sm^{3+} -doped phosphors, the J-O parameters can be derived according to the J-O theory. Since the experimental oscillator's relative intensity values are used in the J-O calculations, the measured J-O parameters are relative values and need to be calibrated using the ratio of the true radiative transition rate to the relative radiative transition rate. Fig. 7 shows the relative absorption cross-section spectrum of a $\text{BaZnGeO}_4:1 \text{ mol}\% \text{ Sm}^{3+}$ sample, which was obtained from the diffuse reflection spectrum derived using the Kubelka-Munk function [40].

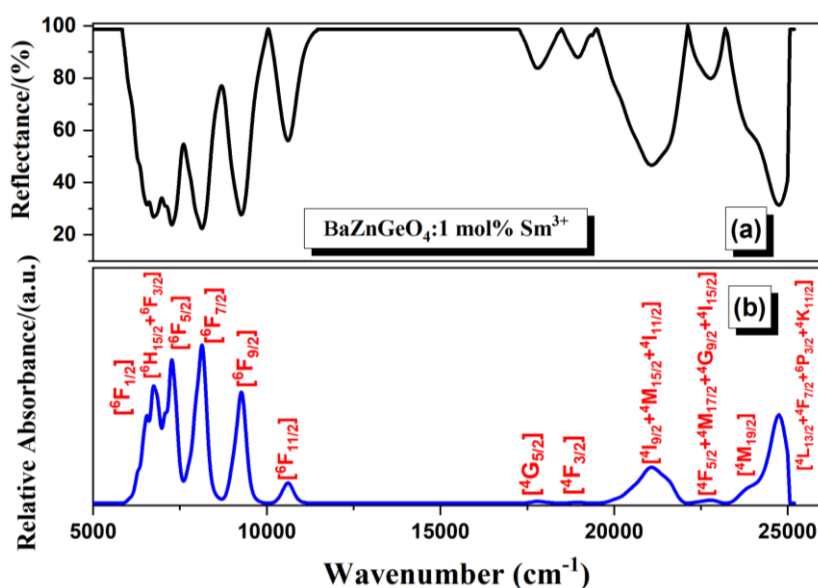


Fig. 7. Diffuse-reflection (a) and relative absorption spectrum (b) of the $\text{BaZnGeO}_4: 1 \text{ mol}\% \text{ Sm}^{3+}$ sample (colour online)

As shown in Fig. 7 (b), these absorption spectra are divided into two parts. The first part, ranging from 5000 to 12000 cm⁻¹, belongs to the infrared-absorption region. This region corresponds to transitions from the ⁶H_{5/2} level to the ⁶F_{1/2}, ⁶H_{15/2}, ⁶F_{3/2}, ⁶F_{5/2}, ⁶F_{7/2}, ⁶F_{9/2}, and ⁶F_{11/2} levels, respectively. The second part, ranging from 15000 to 30000 cm⁻¹ in the ultraviolet-visible range, corresponds to transitions from the ⁶H_{5/2} level to the ⁶F_{1/2}, ⁶H_{15/2}/⁶F_{3/2}/⁶F_{5/2}/⁶F_{7/2}/⁶F_{9/2}, and ⁶F_{11/2} levels, respectively. Due to severe spectral overlap that may lead to significant errors, the absorption peaks from the ground state ⁶H_{5/2} level to the ⁴G_{5/2}, ⁴F_{3/2}, ⁴I_{9/2}/⁴M_{15/2}/⁴I_{11/2}, ⁴F_{5/2}/⁴M_{17/2}/⁴G_{9/2}/⁴I_{15/2}, ⁴M_{19/2}, ⁴L_{13/2}/⁴F_{7/2}/⁶P_{3/2}/⁴K_{11/2} levels were excluded from the subsequent Judd-Ofelt calculations. As it is well known that the transitions from the ⁶F_{3/2}, ⁶F_{5/2}, and ⁶F_{7/2} levels are magnetic dipole transitions [41,42], the peaks corresponding to these levels were disregarded in the subsequent calculations. The relative J-O parameter values were calculated to be $\Omega_2' = 9.28 \times 10^{-21} \text{ cm}^2$; $\Omega_4' = 6.93 \times 10^{-21} \text{ cm}^2$; $\Omega_6' = 3.8 \times 10^{-21} \text{ cm}^2$ according to the relative absorption cross-section.

Meanwhile, the relative electric dipole transition rate can be calculated using the following equation [42].

$$A_{rad}^{ed} = \frac{64\pi^4 e^2 v_i^3}{3h(2J+1)} \frac{n(n^2+2)^2}{9} \sum_{\lambda=2,4,6} \Omega_{\lambda}' \left| \langle (S,L)J | U^{\lambda} | (S',L')J' \rangle \right|^2 \quad (2)$$

In the equation, e represents the charge of an electron, h is Planck's constant, n is the refractive index of the matrix, and Ω_{λ} ($\lambda=2, 4, 6$) are the relative Judd-Ofelt parameters. The terms refer to the angular momentum quantum numbers of the initial and final states, and $\langle (S,L)J | U^{\lambda} | (S',L')J' \rangle$ denotes the reduced matrix elements, which are generally considered to have little dependence on the matrix. The values of A_{rad}^{ed} from the ⁴G_{5/2} level to all its lower energy levels are listed in Table 1, and the total relative electric dipole transition rate A_{rad}^{ed} of the ⁴G_{5/2} level could be determined.

Table 2. Relative/real theoretical oscillator strengths, relative/real electric dipole transition rate, total electric dipole radiative rate and branch ratios of Sm³⁺ in BaZnGeO₄ phosphor

Initial level	Final level	Wave-number	Relative theoretical oscillator strengths (10 ⁻⁸)	Real oscillator strengths (10 ⁻⁸)	Relative electric dipole transition rate(s ⁻¹)	Real electric dipole transition rate(s ⁻¹)	Total electric dipole radiative rate (s ⁻¹)	Branch Ratio(%)
⁴ G _{5/2}	⁶ F _{11/2}	7448	0.00	0.00	0.00	0.00	8083.12	0.00
⁴ G _{5/2}	⁶ F _{9/2}	8842	0.00	0.00	10.58	77.87		0.01
⁴ G _{5/2}	⁶ F _{7/2}	10022	0.00	0.00	9.76	71.83		0.01
⁴ G _{5/2}	⁶ F _{5/2}	10890	0.11	0.81	78.22	575.70		0.07
⁴ G _{5/2}	⁶ F _{3/2}	11394	0.00	0.00	12.36	90.97		0.01
⁴ G _{5/2}	⁶ H _{15/2}	11511	0.00	0.00	0.00	0.00		0.00
⁴ G _{5/2}	⁶ F _{1/2}	11644	0.00	0.00	0.00	0.00		0.00
⁴ G _{5/2}	⁶ H _{13/2}	12959	0.00	0.00	10.41	76.62		0.01
⁴ G _{5/2}	⁶ H _{11/2}	14364	0.06	0.44	101.47	746.82		0.09
⁴ G _{5/2}	⁶ H _{9/2}	15690	0.52	3.83	482.16	3548.70		0.44
⁴ G _{5/2}	⁶ H _{7/2}	16896	0.31	2.28	358.47	2638.34		0.33
⁴ G _{5/2}	⁶ H _{5/2}	17930	0.00	0.00	34.82	256.28		0.03
⁶ F _{11/2}	⁶ F _{9/2}	1394	1.11	8.17	1.18	8.68	21595.05	0.00
⁶ F _{11/2}	⁶ F _{7/2}	2574	0.85	6.26	4.14	30.47		0.00
⁶ F _{11/2}	⁶ F _{5/2}	3442	0.68	5.00	6.42	47.25		0.00
⁶ F _{11/2}	⁶ F _{3/2}	3946	0.53	3.90	5.92	43.57		0.00
⁶ F _{11/2}	⁶ H _{15/2}	4063	852.09	6271.38	485.51	3573.35		0.17
⁶ F _{11/2}	⁶ F _{1/2}	4196	0.19	1.40	3.62	26.64		0.00
⁶ F _{11/2}	⁶ H _{13/2}	5511	378.91	2788.78	630.88	4643.28		0.22
⁶ F _{11/2}	⁶ H _{11/2}	6916	272.51	2005.67	716.21	5271.31		0.24
⁶ F _{11/2}	⁶ H _{9/2}	8242	129.91	956.14	620.44	4566.44		0.21
⁶ F _{11/2}	⁶ H _{7/2}	9448	27.80	204.61	356.09	2620.82		0.12
⁶ F _{11/2}	⁶ H _{5/2}	10482	1.57	11.56	103.70	763.23		0.04

Initial level	Final level	Wave-number	Relative theoretical oscillator strengths (10^{-8})	Real oscillator strengths (10^{-8})	Relative electric dipole transition rate(s^{-1})	Real electric dipole transition rate(s^{-1})	Total electric dipole radiative rate (s^{-1})	Branch Ratio(%)
${}^6F_{9/2}$	${}^6F_{7/2}$	1180	0.86	6.33	0.68	5.00	20126.58	0.00
${}^6F_{9/2}$	${}^6F_{5/2}$	2048	0.46	3.39	2.18	16.04		0.00
${}^6F_{9/2}$	${}^6F_{3/2}$	2552	0.30	2.21	2.20	16.19		0.00
${}^6F_{9/2}$	${}^6H_{15/2}$	2669	209.06	1538.68	69.96	514.91		0.03
${}^6F_{9/2}$	${}^6F_{1/2}$	2802	0.01	0.07	0.58	4.27		0.00
${}^6F_{9/2}$	${}^6H_{13/2}$	4117	394.15	2900.94	318.38	2343.28		0.12
${}^6F_{9/2}$	${}^6H_{11/2}$	5522	138.41	1018.70	430.00	3164.80		0.16
${}^6F_{9/2}$	${}^6H_{9/2}$	6848	110.77	815.27	574.97	4231.78		0.21
${}^6F_{9/2}$	${}^6H_{7/2}$	8054	130.53	960.70	752.26	5536.63		0.28
${}^6F_{9/2}$	${}^6H_{5/2}$	9088	72.17	531.17	583.38	4293.68		0.21
${}^6F_{7/2}$	${}^6F_{5/2}$	868	0.28	2.06	0.18	1.32	17143.50	0.00
${}^6F_{7/2}$	${}^6F_{3/2}$	1372	0.10	0.74	0.39	2.87		0.00
${}^6F_{7/2}$	${}^6H_{15/2}$	1489	67.73	498.49	8.04	59.17		0.00
${}^6F_{7/2}$	${}^6F_{1/2}$	1622	0.23	1.69	0.61	4.49		0.00
${}^6F_{7/2}$	${}^6H_{13/2}$	2937	86.66	637.82	51.86	381.69		0.02
${}^6F_{7/2}$	${}^6H_{11/2}$	4342	253.90	1868.70	331.07	2436.68		0.14
${}^6F_{7/2}$	${}^6H_{9/2}$	5668	121.08	891.15	519.68	3824.84		0.22
${}^6F_{7/2}$	${}^6H_{7/2}$	6874	95.16	700.38	535.22	3939.22		0.23
${}^6F_{7/2}$	${}^6H_{5/2}$	7908	148.57	1093.48	882.23	6493.21		0.38
${}^6F_{5/2}$	${}^6F_{3/2}$	504	0.15	1.10	0.04	0.29	14641.47	0.00
${}^6F_{5/2}$	${}^6H_{15/2}$	621	8.08	59.47	0.27	1.99		0.00
${}^6F_{5/2}$	${}^6F_{1/2}$	754	0.04	0.29	0.05	0.37		0.00
${}^6F_{5/2}$	${}^6H_{13/2}$	2069	38.23	281.37	20.37	149.92		0.01
${}^6F_{5/2}$	${}^6H_{11/2}$	3474	55.04	405.09	90.22	664.02		0.05
${}^6F_{5/2}$	${}^6H_{9/2}$	4800	161.99	1192.25	399.84	2942.82		0.20
${}^6F_{5/2}$	${}^6H_{7/2}$	6006	196.38	1445.36	762.57	5612.52		0.38
${}^6F_{5/2}$	${}^6H_{5/2}$	7040	119.33	878.27	715.97	5269.54		0.36
${}^6F_{3/2}$	${}^6H_{15/2}$	117	0.07	0.52	0.00	0.00	13687.39	0.00
${}^6F_{3/2}$	${}^6F_{1/2}$	250	0.03	0.22	0.00	0.00		0.00
${}^6F_{3/2}$	${}^6H_{13/2}$	1565	43.09	317.14	7.93	58.36		0.00
${}^6F_{3/2}$	${}^6H_{11/2}$	2970	41.58	306.03	55.83	410.91		0.03
${}^6F_{3/2}$	${}^6H_{9/2}$	4296	123.03	905.50	241.98	1780.97		0.13
${}^6F_{3/2}$	${}^6H_{7/2}$	5502	158.20	1164.35	691.48	5089.29		0.37
${}^6F_{3/2}$	${}^6H_{5/2}$	6536	93.95	691.47	862.48	6347.85		0.46
${}^6H_{15/2}$	${}^6F_{1/2}$	133	0.00	0.00	0.00	0.00	456.32	0.00
${}^6H_{15/2}$	${}^6H_{13/2}$	1448	58.53	430.78	8.05	59.25		0.13
${}^6H_{15/2}$	${}^6H_{11/2}$	2853	32.55	239.57	21.95	161.55		0.35
${}^6H_{15/2}$	${}^6H_{9/2}$	4179	7.41	54.54	21.10	155.30		0.34
${}^6H_{15/2}$	${}^6H_{7/2}$	5385	0.49	3.61	9.45	69.55		0.15
${}^6H_{15/2}$	${}^6H_{5/2}$	6419	0.00	0.00	1.45	10.67		0.02
${}^6F_{1/2}$	${}^6H_{13/2}$	1315	4.67	34.37	2.39	17.59	13570.29	0.00
${}^6F_{1/2}$	${}^6H_{11/2}$	2720	104.12	766.32	69.42	510.93		0.04
${}^6F_{1/2}$	${}^6H_{9/2}$	4046	57.79	425.33	188.65	1388.46		0.10
${}^6F_{1/2}$	${}^6H_{7/2}$	5252	62.29	458.45	376.00	2767.36		0.20
${}^6F_{1/2}$	${}^6H_{5/2}$	6286	195.25	1437.04	1207.33	8885.95		0.65
${}^6H_{13/2}$	${}^6H_{11/2}$	1405	36.01	265.03	6.48	47.69	524.84	0.09
${}^6H_{13/2}$	${}^6H_{9/2}$	2731	27.80	204.61	23.61	173.77		0.33
${}^6H_{13/2}$	${}^6H_{7/2}$	3937	15.23	112.09	29.12	214.32		0.41
${}^6H_{13/2}$	${}^6H_{5/2}$	4971	1.05	7.73	12.10	89.06		0.17
${}^6H_{11/2}$	${}^6H_{9/2}$	1326	28.85	212.34	5.03	37.02	350.85	0.11

Initial level	Final level	Wave-number	Relative theoretical oscillator strengths (10 ⁻⁸)	Real oscillator strengths (10 ⁻⁸)	Relative electric dipole transition rate(s ⁻¹)	Real electric dipole transition rate(s ⁻¹)	Total electric dipole radiative rate (s ⁻¹)	Branch Ratio(%)
⁶ H _{11/2}	⁶ H _{7/2}	2532	18.09	133.14	18.72	137.78		0.39
⁶ H _{11/2}	⁶ H _{5/2}	3566	14.31	105.32	23.92	176.05		0.50
⁶ H _{9/2}	⁶ H _{7/2}	1206	21.28	156.62	3.69	27.16	136.38	0.20
⁶ H _{9/2}	⁶ H _{5/2}	2240	21.75	160.08	14.84	109.22		0.80
⁶ H _{7/2}	⁶ H _{5/2}	1034	16.03	117.98	2.71	19.95	19.95	1.00

The above calculations determined the relative Judd-Ofelt parameters, but these relative values cannot accurately assess the true optical transition properties. Therefore, it is necessary to obtain the real values of the Judd-Ofelt parameters. To achieve this, the total radiative transition rate of the ⁴G_{5/2} level of Sm³⁺ will be used to correct the relative values and obtain the real values.

To further refine the J-O parameters, under 404 nm excitation, the fluorescence decay at 598 nm of BaZnGeO₄:1 mol%Sm³⁺ phosphor doped with the lowest concentration of Sm³⁺ was fitted to a single exponential function, resulting in a decay time of 5.04 ms, as shown in the inset of Fig. 6. Additionally, the radiative transition rate A_{rad} of the ⁴G_{5/2} level can be calculated as the reciprocal of the radiative transition lifetime τ (5.04 ms) of the ⁴G_{5/2} level of Sm³⁺, yielding 198 s⁻¹. Furthermore, due to the large energy gap between the ⁴G_{5/2} level and the adjacent lower energy levels, multiphonon cascade non-radiative relaxation from ⁴G_{5/2} to lower levels is impossible at room temperature. Thus, the total radiative transition rate $\sum_i A_{rad}$ of the ⁴G_{5/2} level can be described as follows:

$$\sum_i A_{rad} = \sum_i A_{rad}^{ed} + \sum_i A_{rad}^{md} \quad (3)$$

Therefore, the total actual electric dipole transition

rate $\sum_i A_{rad}^{ed}$ of the ⁴G_{5/2} level can be expressed by the

following equation:

$$\begin{aligned} \sum_i A_{rad}^{ed} &= \sum_i A_{rad} - \sum_i A_{rad}^{md} \\ &= \frac{1}{\tau_{4G5/2}} - \sum_i A_{rad}^{md} \\ &= \frac{1}{\tau_{4G5/2}} - \sum_i \left[\frac{16\pi^4 e^2 n^3}{3h(2J+1)m^2 c^2} \left| \langle \psi J | U^\lambda | \psi' J' \rangle \right|^2 \right] \end{aligned} \quad (4)$$

where $\sum_i A_{rad}^{md}$ represents the total magnetic dipole transition rate of the ⁴G_{5/2} level. From Eq. (4), it can be seen that for a certain doping ion, the magnetic dipole transition rate is an absolute value and has a linear relationship with the cubic power of the refractive index n . The value of $\sum_i A_{rad}^{md}$ can be obtained from semitransparent glass doped with the same ion, where the refractive index n is known. In this study, based on the reported magnetic dipole transition rate results of Sm³⁺ in glass with a refractive index n value of 1.66 [38,39], and the magnetic dipole radiation transition rate for the ⁴G_{5/2} level of Sm³⁺ in BaZnGeO₄:Sm³⁺ phosphors with a refractive index n value of 2.13, the results are listed in Table 2. Thus, the total value of the magnetic dipole transition rate $\sum_i A_{rad}^{md}$ for the ⁴G_{5/2} level of Sm³⁺ could be calculated. Consequently, the total real electric dipole transition rate $\sum_i A_{rad}^{ed}$ can be determined based on Eq. (4).

Table 3. A_{rad}^{md} of Sm^{3+} in LYAS glasses and BaZnGeO₄ phosphor

Transition $^4G_{5/2} \rightarrow$	A_{rad}^{md} in LYAS: Sm^{3+} (n=1.66) (s ⁻¹)	A_{rad}^{md} in BaZnGeO ₄ : Sm^{3+} (n=2.13) (s ⁻¹)
$^6F_{7/2}$	1.26	2.67
$^6F_{5/2}$	4.08	8.66
$^6F_{3/2}$	6.01	12.75
$^6H_{7/2}$	15.25	32.36
$^6H_{5/2}$	18.15	38.52

Finally, the real Judd-Ofelt parameters Ω_λ ($\lambda=2, 4, 6$) can be calculated using the following equation:

$$\Omega_\lambda = \frac{A_{rad}^{ed}}{A_{rad}^{ed}} \Omega'_\lambda \quad (5)$$

The term $\frac{A_{rad}^{ed}}{A_{rad}^{ed}}$ represents the linear factor

between the real value and the relative value of the electric dipole transition rate, which has been determined to be 7.36. Thus, the real Judd-Ofelt parameters can be obtained by multiplying the relative Judd-Ofelt parameters by this proportional coefficient. Therefore, the real Judd-Ofelt parameters Ω_λ ($\lambda=2, 4, 6$) have been confirmed as follows: $\Omega_2 = 6.83 \times 10^{-20} \text{ cm}^2$, $\Omega_4 =$

$5.10 \times 10^{-20} \text{ cm}^2$, and $\Omega_6 = 2.80 \times 10^{-20} \text{ cm}^2$. To further evaluate the optical transition characteristics of Sm^{3+} ions in the BaZnGeO₄ host, the obtained Judd-Ofelt intensity parameters were compared with those reported for other Sm^{3+} -doped host materials, as summarized in Table 4. It can be seen from Table 4 that the Ω_2 value of BaZnGeO₄: Sm^{3+} is higher than those of most listed Sm^{3+} -doped hosts. Since Ω_2 is sensitive to the local asymmetry and covalency around rare-earth ions, the relatively large Ω_2 value suggests that Sm^{3+} ions occupy a low-symmetry local environment in the BaZnGeO₄ lattice. In addition, the Ω_4 value of BaZnGeO₄: Sm^{3+} is also relatively high compared with those of the listed phosphors, indicating that the BaZnGeO₄ host provides a strong crystal-field environment for Sm^{3+} ions. The trend of the J-O parameters for BaZnGeO₄: Sm^{3+} is $\Omega_2 > \Omega_4 > \Omega_6$, which further indicates that BaZnGeO₄ is a suitable host lattice for Sm^{3+} -activated red-emitting phosphors.

Table 4. Judd-Ofelt parameters Ω_λ ($\lambda = 2, 4, 6$) for various phosphors

Phosphors	$\Omega_2 / 10^{-20} (\text{cm}^2)$	$\Omega_4 / 10^{-20} (\text{cm}^2)$	$\Omega_6 / 10^{-20} (\text{cm}^2)$	Trend	Reference
YNbO ₄ : Sm^{3+}	5.48	3.91	2.86	$\Omega_2 > \Omega_4 > \Omega_6$	46
K ₂ YF ₅ : Sm^{3+}	0.38	3.55	2.18	$\Omega_4 > \Omega_6 > \Omega_2$	47
NaCaAlPO ₄ F ₃ : Sm^{3+}	3.90	3.51	2.89	$\Omega_2 > \Omega_4 > \Omega_6$	48
BaWO ₄ : Sm^{3+}	1.09	1.40	0.88	$\Omega_4 > \Omega_2 > \Omega_6$	49
Sr _{0.5} Ca _{0.5} SiO ₃ : Sm^{3+}	0.51	0.32	0.24	$\Omega_2 > \Omega_4 > \Omega_6$	50
LaOCl: Sm^{3+}	0.41	0.48	0.62	$\Omega_6 > \Omega_4 > \Omega_2$	51
LaAlO ₃ : Sm^{3+}	1.01	0.54	—	$\Omega_2 > \Omega_4$	52
Sr ₂ SiO ₄ : Sm^{3+}	0.52	0.28	0.39	$\Omega_2 > \Omega_6 > \Omega_4$	53
BaZnGeO ₄ : Sm^{3+}	6.83	5.10	2.80	$\Omega_2 > \Omega_4 > \Omega_6$	This work

3.4. Thermal quenching properties

The luminescent thermal stability of rare-earth-doped fluorescent materials is a key factor in evaluating their performance. Thus, investigating the

thermal stability of phosphor luminescence is essential. To assess this, the temperature-dependent emission spectra of the BaZnGeO₄:1 mol% Sm^{3+} sample were measured across a temperature range from 303 K to 723 K, with 30 K increments, under 404 nm excitation, as

shown in Fig. 8. As depicted in Fig. 8, the luminescence intensity progressively decreases with increasing temperature, which indicates the occurrence of thermal quenching. Generally, thermal quenching of

luminescence is attributed to multi-phonon cascade nonradiative relaxation, energy transfer processes, and the crossover mechanism [42].

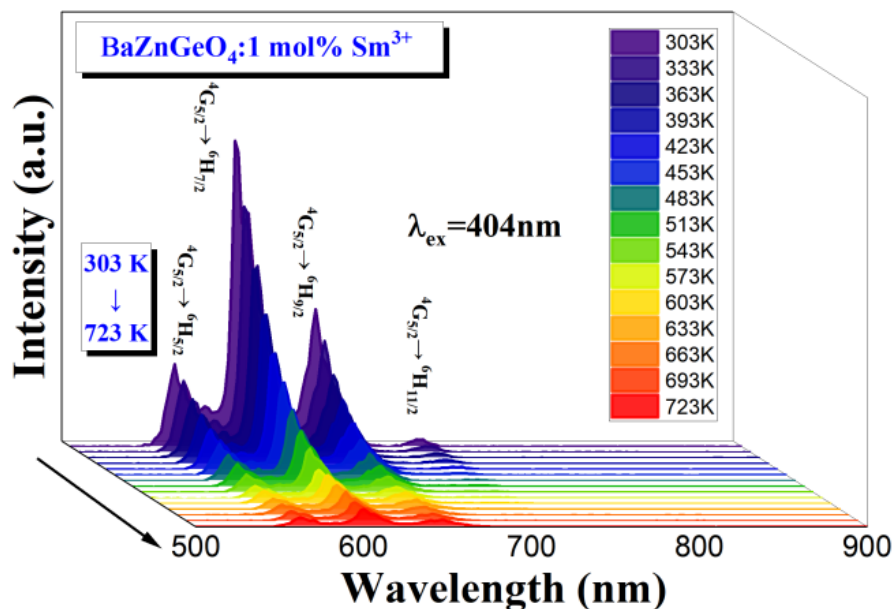


Fig. 8. Emission spectra of BaZnGeO_4 : 1 mol% Sm^{3+} under 404 nm excitation at various temperatures (colour online)

To discover the luminescence thermal quenching mechanism of Sm^{3+} in BaZnGeO_4 : Sm^{3+} , the temperature-dependent fluorescence decay curves for the BaZnGeO_4 :1 mol% Sm^{3+} sample were measured by monitoring 598 nm emission while under 404 nm

excitation wavelength in the temperature range of 303–723 K. The initial intensity-normalized decays in the semi-logarithmic coordinate system are displayed in Fig. 9.

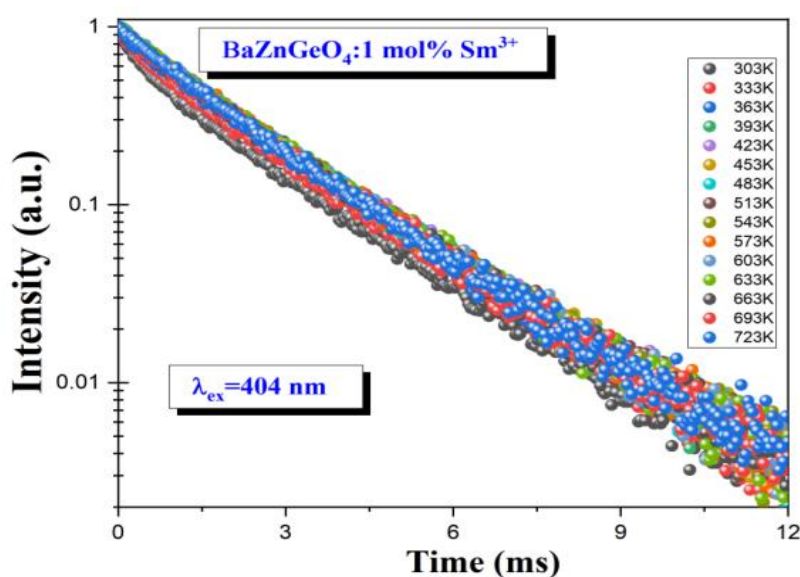


Fig. 9. Fluorescence decay of BaZnGeO_4 : 1 mol% Sm^{3+} under 404 nm excitation at different temperatures (colour online)

It was clearly observed that the fluorescence decay curves exhibited consistent behavior, following a single-exponential function at all measured temperatures. This suggests that the energy transfer processes between Sm^{3+} ions remain largely unaffected by temperature. Therefore, it can be concluded that the thermal quenching of Sm^{3+} is not due to energy transfer between the ions. Furthermore, since the energy gap (7421 cm^{-1}) between the $^4\text{G}_{5/2}$ and $^6\text{F}_{11/2}$ levels is significantly larger than the maximum phonon energy of BaZnGeO_4 [35-37], multi-phonon cascade non-radiative relaxation from the $^4\text{G}_{5/2}$ level can be disregarded. This indicates that the luminescence thermal quenching of Sm^{3+} in $\text{BaZnGeO}_4\text{:Sm}^{3+}$ is not driven by multi-phonon cascade non-radiative relaxation. Thus, the crossover mechanism is identified as the primary cause of the luminescence thermal quenching behavior of Sm^{3+} in $\text{BaZnGeO}_4\text{:Sm}^{3+}$. In this crossover process, the relationship between luminescence intensity and temperature can be described using the Arrhenius model, as shown below [38,39-45].

$$I(T) = \frac{I_0}{1 + c \times \exp(-\Delta E / kT)} \quad (9)$$

where I_0 represents the luminescence intensity at a temperature close to zero, and $I(T)$ denotes the luminescence intensity at temperature T ; C is a constant independent of temperature; k is the Boltzmann constant, and ΔE is the activation energy associated with the

thermal quenching process. To investigate the crossover process, the integrals of the emission intensities for the $^4\text{G}_{5/2} \rightarrow ^6\text{H}_{7/2}$ transition of Sm^{3+} at various temperatures were calculated from the data shown in Fig. 8, with the results clearly displayed in Fig. 10 (a). The solid squares in Fig. 10 (a) represent the temperature dependence of the emission intensity. Additionally, the experimental data in Fig. 10 (a) were fitted to Eq. (9). As shown, the Arrhenius model fits the experimental data well, confirming that the crossover process is responsible for the thermal quenching of Sm^{3+} in $\text{BaZnGeO}_4\text{:Sm}^{3+}$ phosphors. The activation energy (ΔE) was calculated to be 0.24 eV . To illustrate the associated processes, a schematic diagram of the crossover process is provided in Fig. 10 (b). As is well known, after excitation, the ion in the ground state transitions to the excited state. The ion then relaxes non-radiatively to a lower energy level and eventually returns to the ground state through a radiative transition. When the temperature of the host lattice is sufficiently high, the ion at the $^4\text{G}_{5/2}$ energy level overcomes the corresponding energy barrier (ΔE) and reaches a higher vibrational energy level, which corresponds to the intersection of the two configuration curves (process I). The ion then returns to the ground state via a nonradiative transition (process II). The distance between the excited state and the intersection of the two configuration curves represents the activation energy (ΔE) required to overcome the energy barrier during the luminescence thermal quenching process.

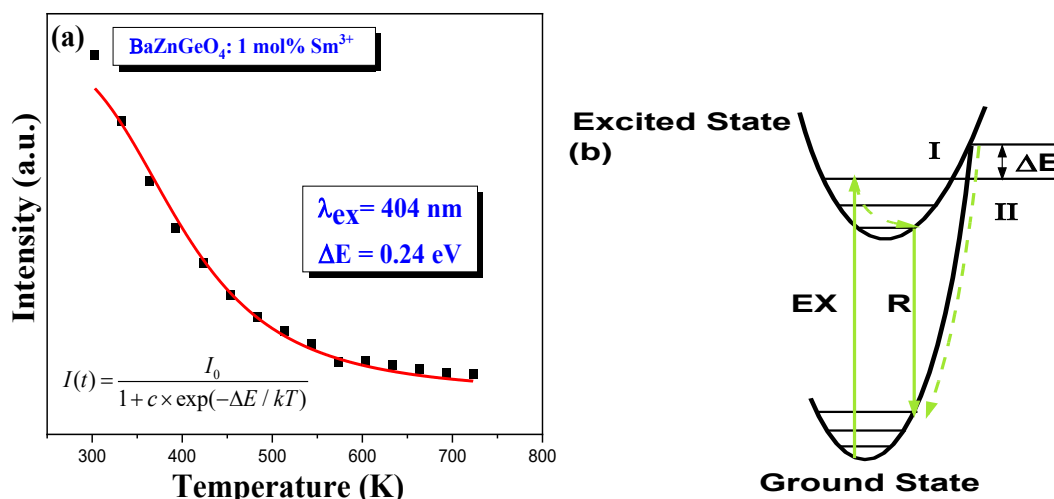


Fig. 10. (a) Dependence of the integrated emission intensities values on experimental temperature for $\text{BaZnGeO}_4\text{: 1 mol\% Sm}^{3+}$ sample; (b) Mechanism of luminescence thermal quenching (colour online)

4. Conclusion

$\text{BaZnGeO}_4\text{:Sm}^{3+}$ red-emitting phosphors with different Sm^{3+} doping concentrations were successfully synthesized by a conventional high-temperature

solid-state reaction method. XRD and Rietveld refinement results confirmed that the prepared samples maintained the single-phase BaZnGeO_4 structure, indicating that Sm^{3+} ions could be effectively incorporated into the host lattice. Under near-ultraviolet

excitation, the samples exhibited characteristic Sm³⁺ emissions originating from the ⁴G_{5/2} excited level, among which the red emission corresponding to the ⁴G_{5/2}→⁶H_{7/2} transition was dominant. The optimal Sm³⁺ doping concentration was determined to be 1 mol% based on the concentration-dependent emission intensity. With increasing Sm³⁺ concentration, concentration quenching occurred due to enhanced energy transfer between Sm³⁺ ions. The Van Uitert model revealed that the concentration quenching behavior was mainly governed by dipole-dipole interaction. Possible cross-relaxation channels among Sm³⁺ ions were proposed to explain the decrease in emission intensity at higher doping concentrations. Temperature-dependent emission spectra demonstrated that the luminescence intensity gradually decreased from 303 to 723 K. The thermal quenching behavior could be well fitted by the Arrhenius equation, and the activation energy was calculated to be 0.24 eV, suggesting that the crossover process is the dominant thermal quenching mechanism. In addition, the Judd-Ofelt intensity parameters of Sm³⁺ in the BaZnGeO₄ host were calculated to be $\Omega_2 = 6.83 \times 10^{-20} \text{ cm}^2$, $\Omega_4 = 5.10 \times 10^{-20} \text{ cm}^2$, and $\Omega_6 = 2.80 \times 10^{-20} \text{ cm}^2$. The relatively large Ω_2 value indicates that Sm³⁺ ions occupy a low-symmetry local environment with appreciable covalent character in the BaZnGeO₄ lattice, while the Ω_4 and Ω_6 values reflect the stable crystal-field environment provided by the host. These results demonstrate that BaZnGeO₄ is a suitable host lattice for Sm³⁺-activated red-emitting phosphors, showing potential application in near-UV-excited solid-state lighting.

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References

- [1] Y. Du, S. Jabeen, H. Zhao, Y. Zhang, Y. Yang, Y. Yang, M. Xie, R. Yu, *Applied Materials Today* **47**, 102931 (2025).
- [2] P. Cui, Y. Xue, Y. Wang, *Results in Engineering* **28**, 107414 (2025).
- [3] P. Pathak, J. Saji, D. Verma, B. Sharma, A. Mishra, V. Dubey, *Journal of Fluorescence* **36**, 203 (2026).
- [4] M. Ge, C. Deng, M. Zhang, *Ceramics International* **51**, 45669 (2025).
- [5] C. M. Nandanwar, A. N. Yerpude, M. A. Patwardhan, N. S. Kokode, R. L. Kohale, *Journal of Molecular Structure* **1350**, 143941 (2026).
- [6] W. Gao, Y. Li, H. Ruan, L. Wang, S. Liao, Y. Huang, *Optical Materials* **168**, 117441 (2025).
- [7] H. Dong, L. Xiao, Z. Tang, J. Liu, L. Jiang, X. Wu, L. Jiang, *Journal of Photochemistry and Photobiology A: Chemistry* **472**, 116777 (2026).
- [8] R. Raji, P. Anjana, N. Gopakumar, *Materials Science and Engineering B* **323**, 118761 (2026).
- [9] Y. Ran, H. Yu, J. Feng, Y. Zhang, N. Wu, C. Wang, M. Xie, Y. Yang, R. Yu, *Journal of Photochemistry and Photobiology A: Chemistry* **470**, 116620 (2026).
- [10] C. Nie, J. Li, J. Gao, S. Sun, Q. Xu, X. Shi, Y. Wu, X. Sun, B. Zhang, J. Zhao, B. Teng, D. Zhong, *Optics Communications* **594**, 132341 (2025).
- [11] V. A. Raj, V. R. Mala, S. M. M. Kennedy, H. G. Evangeline, *Optical Materials* **168**, 117418 (2025).
- [12] A. R. Pusdekar, N. S. Ugemuge, C. Gayner, E. J. Ansari, N. B. Shinde, S. K. Patle, P. A. Patil, S. V. Moharil, *Journal of Luminescence* **287**, 121501 (2025).
- [13] L. Tang, X. Zhang, P. Li, Y. Duan, W. Zheng, J. Du, J. Zhang, *Chemical Engineering Journal* **522**, 167971 (2025).
- [14] K. Kardam, A. Rao, R. Sinha, *Journal of Luminescence* **286**, 121351 (2025).
- [15] A. S. Altowyan, S. C. Kaynar, H. Aydin, U. H. Kaynar, M. B. Coban, J. Hakami, A. Canimoglu, Y. Ozcan, N. Can, *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* **346**, 126870 (2026).
- [16] V. R. Tikale, R. A. Kadam, J. S. Dhoble, *Optical and Quantum Electronics* **57**, 478 (2025).
- [17] H. Cui, Y. Li, R. Li, H. Zhang, A. A. Haider, J. Xie, G. Zhou, Z. Huang, Y. Xu, D. Gao, W. Qian, J. Zhu, *Ceramics International* **51**, 27793 (2025).
- [18] A. N. Yerpude, R. T. Maske, A. S. Padole, R. S. Wandhare, N. R. Pawar, *Chemical Papers* **79**, 6935 (2025).
- [19] W. Li, J. Feng, L. Zhang, Y. Zhang, H. Sun, L. Guan, F. Zeng, F. Li, D. Zhang, M. Xie, R. Yu, *Solid State Sciences* **168**, 108022 (2025).
- [20] Y. Pi, R. Cui, M. Zhang, X. Gong, C. Deng, *Journal of Molecular Structure* **1345**, 143152 (2025).
- [21] Z. Pan, H. Lin, C. Li, W. Yang, F. Zeng, H. Liu, J. Sun, *Journal of Molecular Structure* **1346**, 143262 (2025).
- [22] Z. Wang, R. Zhou, N. Liu, J. Kong, Y. Wang, *Materials Research Bulletin* **193**, 113647 (2026).
- [23] İ. Pekgözlü, *Journal of Applied Spectroscopy* **92**(3), 698 (2025).
- [24] P. P. Khode, A. R. Kadam, N. G. Nikolay, S. J. Dhoble, *Journal of Molecular Structure* **1345**, 143030 (2025).
- [25] K. C. Shilpa, V. S. Jasira, P. V. Veena, S. V. Sajith, A. M. Huda Thasneem, K. Greeshma, S. S. Ancy, S. Pandurengan, K. M. Nissamudeen, *Scientific Reports* **15**(1), 24205 (2025).
- [26] Z. Li, L. Wei, Z. Cui, Q. Liu, Z. Bai, X. Mi, *Journal*

- of Alloys and Compounds **1036**, 181744 (2025).
- [27] Tejas, R. Sharanya, K. Panda, N. Karunakara, M. I. Sayyed, A. H. Almuqrin, D. Negi, S. D. Kamath, *Journal of Photochemistry and Photobiology A: Chemistry* **469**, 116578 (2025).
- [28] A. Pimpalkar, M. R. Bhagat, P. S. Dhale, A. A. Mistry, N. S. Ugemuge, R. Joshi, R. Nithya, P. A. Patil, K. M. Nissamudeen, *Journal of Luminescence* **286**, 121363 (2025).
- [29] W. Sun, M. Jiao, L. Fan, R. Zhang, X. Zhang, H. Zhang, *Journal of the American Ceramic Society* **105**, 2128 (2022).
- [30] D. Gao, S. Gao, S. Liu, X. Chen, X. Zhang, L. Wang, W. Song, H. Yin, Y. Zhu, Q. Yu, *Journal of the Korean Ceramic Society* **62**, 1040 (2025).
- [31] M. İlhan, İ.M. Kati, F.L. Güler, S. Kılıç, *Journal of Luminescence* **286**, 121361 (2025).
- [32] P. Yang, W. Verhoef, H. Fang, W. Fan, C. van der Tol, *Remote Sensing of the Environment* **321**, 114680 (2025).
- [33] S. Liu, D. Gao, X. Chen, H. Yin, Y. Zhu, L. Wang, W. Song, J. Zhang, S. Gao, *Journal of Luminescence* **281**, 121172 (2025).
- [34] A. Pimpalkar, N. Ugemuge, A. Mistry, S. Dhale, A. Muke, R. B. Joshi, S. Khapre, S. Moharil, *Brazilian Journal of Physics* **55**, 22 (2025).
- [35] D. Li, X. Zhang, Y. Cheng, R. Wang, S. Zhao, Z. Lv, Q. Wang, Y. Zhang, Y. Wan, X. Zou, H. Zhang, *Journal of Non-Crystalline Solids* **647**, 123280 (2025).
- [36] H. Li, J. Cai, R. Pang, G. Liu, S. Zhang, L. Jiang, D. Li, C. Li, J. Feng, H. Zhang, *Journal of Materials Chemistry C* **7**, 13088 (2019).
- [37] H. Shirai, Y. Morioka, I. Nakagawa, H. Takei, *Journal of the Physical Society of Japan* **53**, 456 (1984).
- [38] Q. Xu, Y. Zhang, D. L. Zhang, *Physical Chemistry Chemical Physics* **21**, 10834 (2019).
- [39] Y. Q. Zhang, B. J. Chen, S. Xu, X. P. Li, J. S. Zhang, J. S. Sun, X. Q. Zhang, H. P. Xia, R. N. Hua, *Physical Chemistry Chemical Physics* **21**, 10840 (2019).
- [40] P. Kumar, D. Singh, S. Kadyan, H. Kumar, R. Kumar, *Ceramics International* **50**, 34596 (2024).
- [41] A. Indhriyadarshini, K. A. Naseer, M. K. Komal Poojha, I. Kebaili, K. Marimuthu, *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* **324**, 124963 (2025).
- [42] K. M. S. Dawngliana, L. Puia, A. L. Fanai, S. Rai, *Optical Materials* **155**, 115841 (2024).
- [43] Z. Zhao, C. Peng, Q. Yin, Y. Wang, K. Li, C. Liu, Y. Tian, *Ceramics International* **50**, 33472 (2024).
- [44] N. Ma, Z. Luo, H. Liang, L. He, A. Lu, T. Liu, *Journal of Alloys and Compounds* **1003**, 175596 (2024).
- [45] A. Princy, S. M. M. Kennedy, K. J. Albert, V. R. Mala, *Ceramics International* **50**, 30229 (2024).
- [46] C. H. Niu, Y. J. Deng, *Journal of Luminescence* **204**, 528 (2018).
- [47] P. V. Do, V. P. Tuyen, V. X. Quang, N. T. Thanh, V. T. T. Ha, N. M. Khaidukov, Y. I. Lee, B. T. Huy, *Journal of Alloys and Compounds* **520**, 262 (2012).
- [48] R. Nagaraja, V. P. Manjari, B. Sailaja, R. V. S. S. N. Ravikumar, *Journal of Molecular Structure* **1130**, 96 (2017).
- [49] Y. S. Shi, J. J. Shi, C. Dong, *Ceramics International* **43**, 16356 (2017).
- [50] V. Vidyadharan, M. P. Remya, S. Gopi, S. Thomas, C. Joseph, N. V. Unnikrishnan, P. R. Biju, *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* **150**, 419 (2015).
- [51] S. R. Yashodha, N. Dhananjaya, C. Manjunath, *Materials Research Express* **7**, 015003 (2020).
- [52] T. Manohar, S. C. Prashantha, R. Naik, H. Nagabhushana, H. P. Nagaswarupa, K. S. Anantharaju, K. M. Girish, H. B. Premkumar, *Sensors and Actuators B: Chemical* **243**, 1057 (2017).
- [53] C. Manjunath, M. S. Rudresha, B. M. Walsh, R. Hari Krishna, B. S. Panigrahi, B. M. Nagabhushana, *Dyes and Pigments* **148**, 118 (2018).

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