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# Achievement of narrow-band blue-emitting phosphors $\text{KScSr}_{1-y}\text{Ca}_y\text{Si}_2\text{O}_7:\text{Bi}^{3+}$ by the migration of luminescence centers†

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In recent years, efforts have been made to develop narrow-band emission phosphors with excellent performance. Herein, a series of  $\text{KScSr}_{1-y}\text{Ca}_y\text{Si}_2\text{O}_7:0.07\text{Bi}^{3+}$  narrow-band phosphors were synthesized by a co-substitution method, and the crystal structure, the occupancy of activated ions and luminescence properties were studied in detail. The substitution of  $\text{Ca}^{2+}$  for  $\text{Sr}^{2+}$  ions resulted in the migration of the activated  $\text{Bi}^{3+}$  from the K site to Sr site, accompanied by the regulation of the emission peak from 410 nm to 455 nm, the peak emission half width from 52 nm to 40 nm, and the color purity from the original 78% to 88%. In addition, a warm white LED with low CCT = 3401 K, CRI = 95.5, and CIE color coordinates of (0.3447, 0.3682) has been obtained through the combination of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  with a commercial green and red phosphor on a UV (370 nm) chip. The results not only provided a strategy based on the manipulation of chemical composition and crystal structure to tune spectral distribution, but also broadens the choice of activators of narrow-band blue-emitting phosphors.

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## 1. Introduction

Phosphor converted white light-emitting diodes (pc-LEDs) are emerging backlight units in modern liquid crystal display (LCD) applications.<sup>1</sup> Over the past decade, many efficient phosphors have been developed, most of these phosphors have wide-band emission. The wavelength of some phosphors exceeds the sensitive area of human eyes (700 nm), resulting in the reduction of the luminous efficiency of pc-LEDs. Therefore, over the years people have been committed to improve the resolution of the LCD, power consumption and color gamut. The luminescence characteristics of light, such as position of emission peak and full-width at half-maximum (FWHM), will directly affect the space of color gamut.<sup>2–6</sup> The improvement of color gamut is a hot issue because it can make the color of LCDs more vivid and attractive to consumers. Phosphors, often with narrow emission bands, can produce a wider gamut. Therefore, in order to obtain a large gamut in the pc-LED backlight, narrow-band emission phosphors with good performance need to be developed.

As early as a few years ago, the special luminescence characteristics of narrow-band phosphors attracted the attention of

academic and industrial circles. For example, phosphors like  $\text{Sr}[\text{Mg}_3\text{SiN}_4]:\text{Eu}^{2+}$  (SMS) and  $\text{Sr}[\text{Mg}_2\text{Al}_2\text{N}_4]:\text{Eu}^{2+}$  (SMA) were reported by Schnick's group, and they presented narrow emission, good luminescence efficient and thermal stability.<sup>7,8</sup> Recently, Hubert's group reported  $\text{KLi}_3\text{SiO}_4:\text{Eu}^{2+}$  with a broad-band, near warm white emission (FWHM = 49 nm,  $\lambda_{\text{em}} = 515$  nm) in the same oxide-based system.<sup>9,10</sup> These studies tend to focus on the effects of symmetric cation sites and highly condensed skeletons on the emissive bands, and most of them are doped  $\text{Eu}^{2+}$  or  $\text{Mn}^{4+}$  ions. However, these elements, especially  $\text{Eu}^{2+}$ , are usually reabsorbed in the visible region, resulting in a decrease in luminous efficiency. Therefore, it is necessary to develop a pair of narrow-band blue luminescent phosphors that is highly efficiently absorbed in the NUV region and matched well with NUV commercial LED chips to further improve the performance of LCD.

As a favored sensitizer or an activator in luminescent materials, the spectroscopy of  $\text{Bi}^{3+}$  ions has been extensively investigated.<sup>11</sup> Compared with rare earth luminescence centers, the absorption of  $\text{Bi}^{3+}$  is mainly concentrated in the NUV region, with no reabsorption and high energy efficiency. Depending of the nature of the host lattice in which  $\text{Bi}^{3+}$  ion is inserted, this ion may show either a regular luminescence, a cluster-related luminescence, and so on. The regular  $\text{Bi}^{3+}$  luminescence results from intra-ionic transitions between the ground  $^6\text{S}_2$  and first excited  $^6\text{S}_1^6\text{P}_1$  configurations. Absorption takes place from  $^1\text{S}_0$  fundamental state to  $^3\text{P}_1$ ,  $^3\text{P}_2$  and  $^1\text{P}_1$  excited states.<sup>12,13</sup> Benefiting from its naked 6s and 6p orbitals,  $\text{Bi}^{3+}$  has a broadly adjustable luminescence spectrum, affected by different crystal

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field environments, which opens up great possibilities for ion regulation. For instance, Peng's team reported  $\text{CaMoO}_4:\text{Bi}^{3+}$  phosphors, half peak width is about 200 nm, mainly studies the cationic alternative implementation color adjustable launch in 2014.<sup>14</sup> Moreover, they obtained  $(\text{Y}, \text{Sc})(\text{Nb}, \text{V})\text{O}_4:\text{Bi}^{3+}$  phosphors, which also changed the half-peak width from 120 nm to 230 nm through ion regulation in 2016;<sup>15</sup> In summary,  $\text{Bi}^{3+}$  ions can not only achieve efficient absorption in the NUV region, but also its naked orbits is very conducive to the matrix composition regulation, so as to obtain phosphors with excellent performance.

In our work, a series of narrow-band blue-emitting phosphors  $\text{KScSrSi}_2\text{O}_7:x\text{Bi}^{3+}$  ( $0 < x < 0.13$ ) and  $\text{KScSr}_{1-y}\text{Ca}_y\text{Si}_2\text{O}_7:0.07\text{Bi}^{3+}$  ( $0 < y < 0.05$ ) have been prepared by high temperature solid state reaction. Take advantage of the sensitivity of  $\text{Bi}^{3+}$  ions to the surrounding coordination environment and crystal field,  $\text{Ca}^{2+}$  ions were introduced into  $\text{KScSrSi}_2\text{O}_7:0.07\text{Bi}^{3+}$  to replace  $\text{Sr}^{2+}$ , control the occupying selection of activated ion  $\text{Bi}^{3+}$  from K site to Sr site and the luminescence color was adjusted from purple to blue, the structure rigidity and lattice distortion of  $\text{KScSr}_{1-y}\text{Ca}_y\text{Si}_2\text{O}_7:0.07\text{Bi}^{3+}$  were changed by cationic component regulation, and a narrow-band emission with a half-peak width of 40 nm was achieved.

## 2. Experimental section

### 2.1 Sample preparation

A series of  $\text{KScSrSi}_2\text{O}_7:x\text{Bi}^{3+}$  ( $\text{KSSS}:x\text{Bi}^{3+}$ ) ( $0 < x < 0.13$ ) and  $\text{KScSr}_{1-y}\text{Ca}_y\text{Si}_2\text{O}_7:0.07\text{Bi}^{3+}$  ( $\text{KSS}_{1-y}\text{C}_y:0.07\text{Bi}^{3+}$ ) ( $0 < y < 0.5$ ) phosphors were synthesized by high temperature solid-state method. The raw materials used are  $\text{K}_2\text{CO}_3$  (99.99%),  $\text{Sc}_2\text{O}_3$  (99.99%),  $\text{SrCO}_3$  (99.9%),  $\text{SiO}_2$  (99.9%, D50~10  $\mu\text{m}$ ),  $\text{CaCO}_3$  (99.9%) and  $\text{Bi}_2\text{O}_3$  (99.99%). The raw materials are weighed and mixed in an agate mortar according to certain stoichiometric and fully ground for 30 minutes. Then the mixed powder samples are transferred into an alumina crucible and sintered at a high temperature of 1200 degrees for 5 h. Finally, all obtained powder samples are naturally cooled to room temperature in the furnace and ground for further experimental measurement.

### 2.2 Characterization

The phase structure of the sample was characterized by Bruker D8 X-ray diffractometer. The corresponding parameters were as follows: the radiation source was  $\text{CuK}\alpha$  ( $\lambda = 0.15406$  nm), the working voltage and current were 40 kV and 40 mA, respectively. The scanning range was 10–80° and the step was 0.02° per s. And the Findit software and Crystalmaker software were used for the structure. Crystal structure refinements were implemented using General Structure Analysis System (GASA). The emission and excitation spectra of samples were recorded by using a Hitachi F-7000 spectrophotometer equipped with a 450 W xenon lamp as the excitation source. The scanning speed was 1200  $\text{nm min}^{-1}$  with a step of 0.2 nm. At room temperature, the decay curves were measured by Horiba FL3 with the width of the incident and outgoing slits is 1 nm, and the width of the slit of the sample is 29 nm.

## 3. Results and discussion

### 3.1 Crystal structure characterizations

The XRD patterns of  $\text{KSSS}:x\text{Bi}^{3+}$  ( $0 < x < 0.13$ ) and  $\text{KSS}_{1-y}\text{C}_y:0.07\text{Bi}^{3+}$  ( $0 < y < 0.5$ ) are shown in Fig. S1.† The diffraction peaks of all the samples were consistent with the structure of KSSS standard card, indicating that all the samples were pure phase and the introduction of  $\text{Bi}^{3+}$  and  $\text{Ca}^{2+}$  ions did not change the crystal structure of the matrix. According to the rule of ion radius matching,  $\text{Bi}^{3+}$  ions were expected to occupy the positions of  $\text{Sr}^{2+}$  and  $\text{K}^+$  ions. On account of  $\text{Bi}^{3+}$  was very sensitive to different coordination environments, the crystal field environment around  $\text{Bi}^{3+}$  can be changed to achieve the regulation of the luminescence performance of  $\text{Bi}^{3+}$  doped phosphors. In this paper, the luminescence properties of phosphors were improved by using cationic substitution of  $\text{Ca}^{2+}$  for  $\text{Sr}^{2+}$  to adjust the coordination environment around  $\text{Bi}^{3+}$  ions.

As shown in Fig. 1(a), the crystal structure of  $\text{KScSrSi}_2\text{O}_7$  belongs to the  $\text{KMRESi}_2\text{O}_7$  family ( $\text{M} = \text{Ba}^{2+}, \text{Sr}^{2+}, \text{RE} = \text{Y}^{3+}, \text{Sc}^{3+}$ ), which belongs to the  $P_{121}/n_1$  space group and consists of a tetrahedron and octahedron containing  $\text{Si}_2\text{O}_7$  groups and octahedral coordination with Sc atoms ( $\langle \text{Sc-O} \rangle = 2.12$  Å). The framework of  $\text{KMRESi}_2\text{O}_7$  is based on a  $\text{ScO}_6$  octahedron which shares each of its apices with an oxygen atom of the  $\text{Si}_2\text{O}_7$  group. Adjacent  $\text{ScO}_6$  octahedra is connected to each other through  $\text{Si}_2\text{O}_7$  units, whose Si-Si vectors are oriented parallel to the  $c$  axis. This connection creates layers of  $\text{ScO}_6$  polyhedra in the  $x$ - $y$  plane, furthermore, a three-dimensional framework with 8-coordinated Sr atoms ( $\langle \text{Sr-O} \rangle = 2.71$  Å) and 9-coordinated K cations ( $\langle \text{K-O} \rangle = 2.86$  Å) located in voids. The three-dimensional connectivity generates a rigid lattice exhibiting highly condensed network. And the two cations are "stacked" in narrow channels, and they are arranged in strict order.<sup>16</sup> In the  $\text{KMRESi}_2\text{O}_7$  family, KSSS has a relatively small bond angle and bond length, which infers that it has a more rigid structure. There are three cation sites in KSSS,  $\text{K}^+$  ( $r = 1.55$  Å, CN = 9),  $\text{Sr}^{2+}$  ( $r = 1.26$  Å, CN = 8) and  $\text{Sc}^{3+}$  ( $r = 0.745$  Å, CN = 6). Due to the exposed electron configuration in the outermost layer of  $\text{Bi}^{3+}$  ion, the luminescence of  $\text{Bi}^{3+}$  is very sensitive to the surrounding crystal field environment. The different symmetry of multivalent cations ( $\text{Sr}^{2+}/\text{K}^+/\text{Sc}^{3+}$ ) provide infinite possibilities for controlling the selection of  $\text{Bi}^{3+}$  at different sites and the regulation of luminescence performance. In order to further prove  $\text{Bi}^{3+}$  successfully doped into the crystal structure,  $\text{KSSS}:x\text{Bi}^{3+}$  were refined with GSAS software, and the refining results were shown in Fig. 1(b). The cross represents the experiment raw data, the red solid line represents the calculated data, the blue solid line represents the difference between the observed data and calculated data, the green solid line represents the Bragg position. This refined result shows that the parameters meet the requirements, in other words, all samples are single phase. Other concentration refining results are shown in the Fig. S2.† It is known that the generation of cationic vacancies should contribute to the shrinkage of the crystal cell volume. The cationic vacancies should be produced when the  $\text{Sr}^{2+}$  ions positions were occupied by  $\text{Bi}^{3+}$  ions because of the integral charge balance. It can be expressed by the following formula (1):<sup>17</sup>



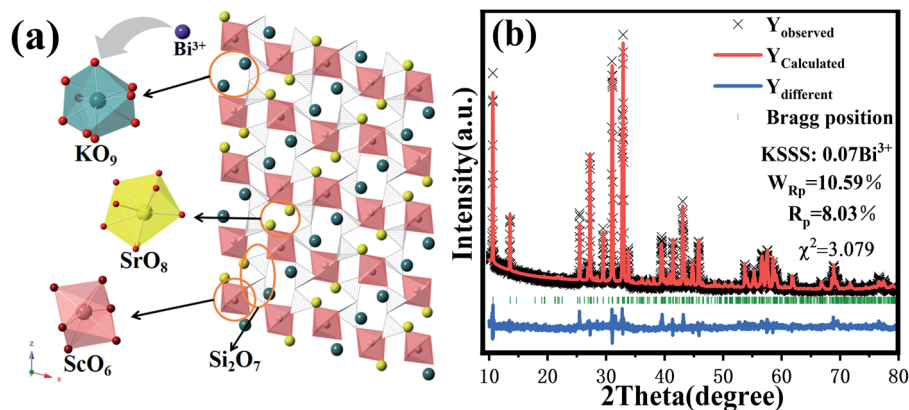
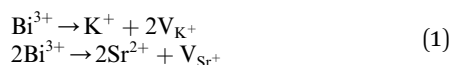


Fig. 1 (a) The crystal structure of  $\text{KScSrSi}_2\text{O}_7$ ; (b) Rietveld structure refinement patterns of  $\text{KScSrSi}_2\text{O}_7:0.07\text{Bi}^{3+}$ .



### 3.2 Luminescence properties of $\text{KScSrSi}_2\text{O}_7:x\text{Bi}^{3+}$

Fig. 2(a) shows the emission spectra of  $\text{KSSS}:0.07\text{Bi}^{3+}$  at different excitation wavelengths of 340 nm and 370 nm, as well as the excitation spectra corresponding to the main emission peak of 415 nm and 500 nm. It is obvious that  $\text{KSSS}:0.07\text{Bi}^{3+}$  has

a site-selective excitation and its emission spectrum varies with the excitation wavelength. And the excitation spectrum presents a wide 260–400 nm excitation band centering at 280 nm and 370 nm, which indicates that it can be well matched with commercial near ultraviolet LED chips. There are three different cation sites in KSSS crystal, and  $\text{Bi}^{3+}$  is extremely sensitive to the surrounding coordination environment, therefore, the asymmetric emission may be caused by the substitution of  $\text{Bi}^{3+}$  for different cation sites. It is generally believed that the doping of Bi ions at trivalent or bivalent sites with coordination number

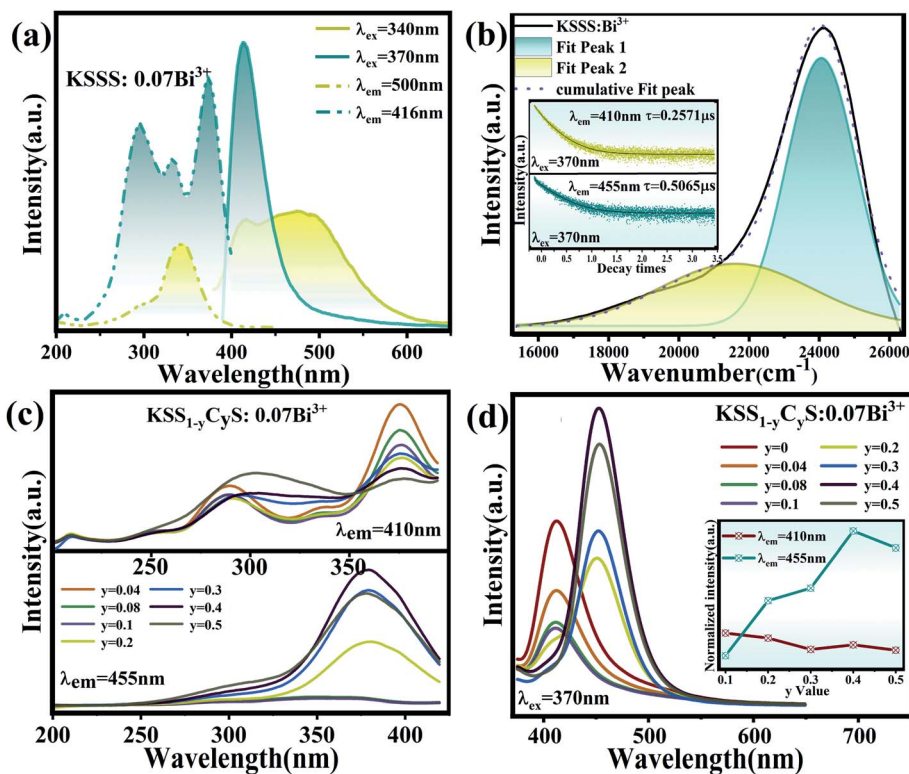


Fig. 2 (a) The different PLE and PL spectra of  $\text{KSSS}:0.07\text{Bi}^{3+}$ . (b) Gaussian fitting of  $\text{KSSS}:0.07\text{Bi}^{3+}$  emission spectra; the inset shows the average life of two sub-emission peaks (410 nm and 455 nm). (c) The PLE spectra of  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$  under 410 nm and 455 nm different emission. (d) The PL spectra of  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$  under 370 nm excitation; the inset shows the relative excitation intensity vs. various  $\text{Ca}^{2+}$  contents ( $y$ ) at  $\lambda_{\text{em}} = 410$  nm and  $\lambda_{\text{em}} = 455$  nm.



CN larger than or equal to 6 is the most probable.<sup>18</sup> In order to further determine the number of potential luminous centers, the radius percentage difference between the doped ion Bi<sup>3+</sup> and the potentially substituted ion (Sr<sup>2+</sup>/K<sup>+</sup>/Sc<sup>3+</sup>) in KSSS is calculated by using formula (2), and is listed in Table 1.<sup>19</sup>

$$D_r = 100\% \times \left| \frac{R_m(\text{CN}) - R_d(\text{CN})}{R_m(\text{CN})} \right| \quad (2)$$

where  $D_r$  is the percentage difference of ion radius, CN is the coordination number,  $R_m$  (CN) and  $R_d$  (CN) are the radii of substituted ions and doped ions, respectively. Since the data of CN = 9 of Bi<sup>3+</sup> ion is insufficient, a reasonable approximation is provided here. Table 1 presents the  $R_m$  (CN),  $R_d$  (CN) and  $D_r$  values. The corresponding  $D_r$  values between Bi<sup>3+</sup> ions and cations (K<sup>+</sup>/Sr<sup>2+</sup>/Sc<sup>3+</sup>) are 20%, 7.1% and 38.2%, respectively, among them, the possibility of Sc<sup>3+</sup> being replaced is very small and can be ignored. And Bi<sup>3+</sup> occupies K and Sr sites in KScSrSi<sub>2</sub>O<sub>7</sub>.

According to the number of luminescence centers, the emission band of KSSS:0.07Bi<sup>3+</sup> can be fitted to two sub-emission peaks, which are located at 410 nm and 455 nm, respectively, as shown in Fig. 2(b). The insets depicts the fluorescence lifetime of the two sub-emission peaks excited by 370 nm pulse laser (nano-LED), which both show second order exponential decay tendency as follows:<sup>21,22</sup>

$$I(t) = A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right) \quad (3)$$

where  $I(t)$  is the intensity at  $t$ , and  $\tau_1$  and  $\tau_2$  represent the short and long-decay components while  $A_1$  and  $A_2$  are fitting constants. The average lifetime  $\tau^*$  can be calculated by the following eqn (4):<sup>20,22</sup>

$$\tau^* = (A_1\tau_1^2 + A_2\tau_2^2)/(A_1\tau_1 + A_2\tau_2) \quad (4)$$

The lifetimes of the two sub-emission peaks (410 nm and 460 nm) are 0.2571  $\mu$ s and 0.5065  $\mu$ s, respectively, which are consistent with the lifetimes of Bi<sup>3+</sup>. The difference in lifetime between different emission peaks confirms the existence of two possible emitting centers. In order to determine the origin of the asymmetric emission peaks, the crystallographic occupancy of ions in the matrix was calculated by using Van Uitert theoretical formula:<sup>23</sup>

$$E = Q \left[ 1 - \left( \frac{V}{4} \right)^{1/V} 10^{-\text{NRE}/80} \right] \quad (5)$$

where  $E$  represents the peak ( $\text{cm}^{-1}$ ) of Bi<sup>3+</sup> ions,  $Q$  is the free Bi<sup>3+</sup> ion at the lower energy edge position,  $V$  and  $E$  represent the

valence and electron affinity of Bi<sup>3+</sup> ions, respectively.  $N$  and  $R$  represent the coordination number of the central cation and the radius of the matrix central cation replaced by the activated ion, respectively. Therefore, in the Van Uitert equation,  $Q$ ,  $V$  and  $E$  are all inherent attribute parameters of the matrix, hence the size of  $E$  only depends on the product of  $N$  and  $R$ . For K and Sr, the value of  $N \times R$  is 13.95 and 10.08, respectively. Since the  $E$  value is positively correlated with the  $N \times R$ , the origin of the two peaks can be qualitatively determined. According to the relation between  $E$  value and  $N \times R$ , the two sub-peaks at 410 nm and 455 nm are generated by Bi<sup>3+</sup> ions occupying the K and Sr positions, respectively.

For further demonstrate the source of sub-emission peak, the following formula is used to calculate the distance of the centroid shift values of each emission center in KSSS:0.07Bi<sup>3+</sup> and the crystal field splitting values and total shift values ( $D(A)$ ) of Bi<sup>3+</sup> ions at 6s6p level, as follows:<sup>24-27</sup>

$$\varepsilon_C = \frac{e^2}{4\pi\epsilon_0} (\langle r^2 \rangle_{6s6p} - \langle r^2 \rangle_{6s^2}) \sum_{i=2}^N \frac{\alpha_{sp}}{\left( R_i - \frac{1}{2} \Delta R \right)^6} \quad (6)$$

$$\alpha_{sp}^0 = 0.33 + \frac{4.8}{\chi_{av}^2} \quad (7)$$

$$\varepsilon_{cfs} = \beta_{poly} R^{-2} \quad (8)$$

$$D(A) = \varepsilon_c(A) + \frac{\varepsilon_{cfs}}{r(A)} - C \quad (9)$$

Formula (6) and (7),  $\langle r \rangle$  stands for the radial radius of an electron in 6s6p configuration or 6s<sup>2</sup> configuration,  $e$  is the elementary charge, and  $\epsilon_0$  is the permittivity of vacuum. Thus, the value of  $\frac{e^2}{4\pi\epsilon_0} (\langle r^2 \rangle_{6s6p} - \langle r^2 \rangle_{6s^2})$  is constant.  $R_i$  stands for the distance between the center atom and the anion in the lattice. The summation is over all  $N$  anions that coordinate Bi<sup>3+</sup>.  $\frac{1}{2}\Delta R$  represents a correction for lattice relaxation around Bi<sup>3+</sup>, and  $\Delta R$  for two kinds of cation and activate ion in KSSS radius difference.  $\alpha_{sp}^0$  is the spectroscopic polarizability of the anion, and its value is  $2.82 \times 10^{-30} \text{ m}^{-3}$ .  $\chi_{av}$  is the electronegativity of the cation. In formula (8),  $\beta_{poly}$  is a constant that depends on the type of the coordination polyhedron. In this case, for KSSS:0.07Bi<sup>3+</sup>,  $\beta_{poly} = 1.35 \times 10^9 \text{ pm}^2 \text{ cm}^{-1}$ . In formula (9),  $\varepsilon_c(A)$  is the centroid shift,  $\varepsilon_{cfs}(A)$  is the crystal field splitting. Finally, by formula (9), the total displacement value of energy level in KSSS:0.07Bi<sup>3+</sup> shows  $D(K) < D(\text{Sr})$ , the related data are listed in Table 2. Combined with the previous analysis, it is verified again that the sub-emission peaks at 410 nm and 455 nm are derived from the emission of Bi<sup>3+</sup> ions at K and Sr sites, respectively.

### 3.3 Controlling site-selection of Bi<sup>3+</sup> via Ca<sup>2+</sup> substitution for Sr<sup>2+</sup>

As is known to all, Bi<sup>3+</sup> ion as a commonly used transition metal doped element, it's 6s and 6p electrons are in the outermost layer of the electron shell, which makes its luminescence properties are easily affected by the surrounding

**Table 1** Ionic radii difference percentage ( $D_r$ ) between matrix cations and doped Bi<sup>3+</sup>

Matrix cation (CN)	$R_m$ (Å)	Doped ion (CN)	$R_d$ (Å)	$D_r$ (%)
K <sup>+</sup> (9)	1.55	Bi <sup>3+</sup> (9)	1.24	20
Sr <sup>2+</sup> (8)	1.26	Bi <sup>3+</sup> (8)	1.17	7.1
Sc <sup>3+</sup> (6)	0.745	Bi <sup>3+</sup> (6)	1.03	38.2



**Table 2** The relative value of the energy level displacement in  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$

Occupying	$\text{K}^+$	$\text{Sr}^{2+}$
av bond ( $R$ )	2.890	2.690
$\Delta R$	0.031	0.009
$\epsilon_c(\text{\AA})$	0.477	0.605
$\epsilon_{\text{cfs}}(\text{\AA})$	2.001	2.309
$D(\text{\AA})$	$D(\text{K}) < D(\text{Sr})$	

environment.<sup>28,29</sup> As a consequence,  $\text{Ca}^{2+}$  ions are introduced to regulate the local lattice and improve the luminescence properties. Fig. 2(c) shows the excitation spectra of  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$ . When monitored at 410 nm, the resulting PLE spectrum contained two excitation band peaks at 370 nm (in the 350–420 nm range) and 290 nm (in the 200–350 nm range), and when monitored at 455 nm, the resulting PLE spectrum contains one excitation band peaks at 370 nm (in the range of 300–420 nm), which could be attributed to the electronic transitions from the ground state ( $^1\text{S}_0$ ) to the excited state ( $^3\text{P}_1$ ) of  $\text{Bi}^{3+}$  ions. With the concentration of  $\text{Ca}^{2+}$  ( $y$ ) increasing, the emission intensities at 410 nm gradually decrease, while the emission intensities of 455 nm gradually increase and reach its maximum value when  $y = 0.4$ , and finally the concentration quenching occurs, as shown in Fig. 2(d). When  $\text{Ca}^{2+}$  concentration increased, it is speculated that  $\text{Bi}^{3+}$  ions may be transferred from one luminescence center to another in  $\text{KSS}_{1-y}\text{C}_y\text{S}$  crystals. The relationship between the emission intensity (fitting intensity at 410 nm and at 455 nm) and  $\text{Ca}^{2+}$  concentration is plotted in the inset of Fig. 2(d). The trend of monotonic decrease of emission intensity at 410 nm is in sharp contrast to that at 455 nm, which indicates that the occupation of  $\text{Bi}^{3+}$  transfers from one crystallization position to another in  $\text{KSS}_{1-y}\text{C}_y\text{S}$ .

In the above study, the occupying position of  $\text{Bi}^{3+}$  in the host was confirmed, that is, the 410 nm emission peak comes from the K site occupied by  $\text{Bi}^{3+}$  ions, and the 455 nm emission peak originates from the Sr site occupied by  $\text{Bi}^{3+}$  ions. Since the luminescence properties of  $\text{Bi}^{3+}$  are easily influenced by the surrounding crystal field environment, it is necessary to investigate the structural changes caused by the incorporation of  $\text{Ca}^{2+}$  ions. The main reason for the structural change is that  $\text{Ca}^{2+}$  has a smaller ionic radius compared with  $\text{Sr}^{2+}$ . Firstly, at the  $\text{Sr}^{2+}$  site,  $\text{Ca}^{2+}$  with small radius cannot completely coordinate with  $8\text{O}^{2-}$  ions, leading to  $\text{Ca}^{2+}$  ions moving towards the surface and the gap of  $\text{SrO}_8$  polyhedrons and coordinating with  $3\text{O}^{2-}$  ions to form an isosceles triangular plane. Secondly, the addition of  $\text{Ca}^{2+}$  increases the distance between the cations, providing space to accommodate more activated ions. Finally, the introduction of small  $\text{Ca}^{2+}$  ions not only change the local environment of the lattice but also promote the mobility of the activated ions. Importantly, we used the modification of the  $\text{SrO}_8$  polyhedron to stimulate the sensitivity of the activated ion  $\text{Bi}^{3+}$  to its surrounding crystal field environment, leading to the redistribution of  $\text{Bi}^{3+}$  at two different cation positions. In order to understand the redistribution of  $\text{Bi}^{3+}$  ions more accurately,

$\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$  was refined with GASA software. Similarly,  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$  were refined with GSAS software, and the refining results were shown in Fig. S3.† All parameters met the experimental requirements. When the small radius of  $\text{Ca}^{2+}$  ( $r = 1.12 \text{\AA}$ , CN = 8) is used to replace the large radius of  $\text{Sr}^{2+}$  ( $r = 1.26 \text{\AA}$ , CN = 8) in the crystal, the cell should shrink and the cell parameters decrease. Fig. 3(a) shows the changes of cell volume  $V$  and cell parameters  $a$ ,  $b$  and  $c$  with  $\text{Ca}^{2+}$  concentration  $y$  increasing, respectively. Curiously, when  $y$  increased from 0 to 0.2, both cell parameters and cell volume showed a decreasing trend, but when the replacement concentration was greater than 0.2, each parameter presented an increasing trend. The changes of polyhedron  $\text{SrO}_8$  are shown in the illustration. Obviously, the volume of polyhedron  $\text{SrO}_8$  also shows a trend of first increase and then decrease, which is due to the gradual entry of  $\text{Bi}^{3+}$  ( $r = 1.17 \text{\AA}$ , CN = 8) ions with a larger radius into the larger Sr site. In other words, with the gradual substitution of  $\text{Ca}^{2+}$  for  $\text{Sr}^{2+}$  ions,  $\text{Bi}^{3+}$  ions gradually transferred from the K to the Sr site. The schematic diagram of the redistribution of  $\text{Bi}^{3+}$  in Sr and K sites are presented in Fig. 3(b). When  $y < 0.2$ , since the radius of  $\text{Ca}^{2+}$  is smaller than that of  $\text{Sr}^{2+}$ , and the occupying transfer of  $\text{Bi}^{3+}$  ion is in the initial stage, the contraction degree of the crystal cell is greater than the expansion degree of the crystal cell, as a result all the parameters of the crystal cell show a state of decrease. When the substitution concentration  $y > 0.2$ , the expansion caused by the entry of  $\text{Bi}^{3+}$  ions with large radius into the Sr site is greater than the lattice contraction caused by the replacement of  $\text{Sr}^{2+}$  ions with  $\text{Ca}^{2+}$ , hence the crystal cell shows the state of expansion.

According to the above analysis, the emission peaks at 410 nm and 455 nm are originated from  $\text{Bi}^{3+}$  which occupied the K site and Sr site, respectively. Therefore, the migration of  $\text{Bi}^{3+}$  ions well explains the change of PL spectrum in Fig. 2(d). As more  $\text{Bi}^{3+}$  ions transfer from K site to Sr site, the intensity of 455 nm emission increases continuously, while that of 410 nm decreases gradually. When most of  $\text{Bi}^{3+}$  ions enter the Sr site, the emission intensity will not increase with the increase of  $\text{Ca}^{2+}$  concentration.

Generally, the luminescence of  $\text{Bi}^{3+}$  ion has a large absorption cross section and a wide emission due to its s–p transition.<sup>30</sup> Surprisingly, the emission spectra of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  shows a narrow-band blue-emission under the excitation of 370 nm, the FWHM is only 40 nm, as shown in Fig. 4(a). Generally, the coordination symmetry and rigidity of the crystal structure are the main factors affect the half-peak width of the emission spectrum, the highly symmetric and rigid structure are more likely to have a narrow emission peak. Conversely, the lower the symmetry of crystal structure, the wider the half-peak width.<sup>31–33</sup> For a polyhedron, the symmetry of the polyhedron is usually characterized by the dispersion degree of the side length. The smaller the dispersion degree of the side length, the higher the symmetry of the polyhedron. The crystal distortion can be expressed by using the set of following equations:<sup>34–36</sup>

$$D(\text{TO}) = \left( \sum_{i=1}^N |\text{TO}_i - \text{TO}_m| \right) / \text{NTO}_m \quad (10)$$

$$D_w = [D(\text{TO}_K) + D(\text{TO}_{\text{Sr}})] / 2$$



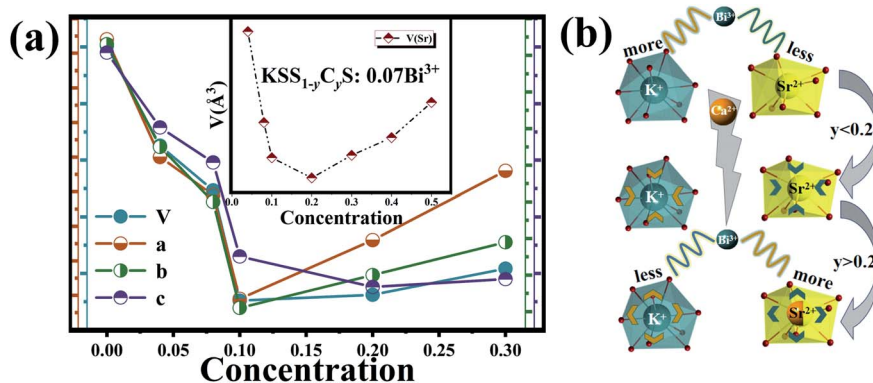


Fig. 3 (a) The changes of cell parameters ( $V$ ,  $a$ ,  $b$ ,  $c$ ) of  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$  with  $y$  increasing; the inset presents the variation of the volume of the  $\text{SrO}_8$  polyhedron. (b) Schematic diagram of the redistribution of  $\text{Bi}^{3+}$  in Sr and K sites with  $y$  increasing.

Among them,  $\text{TO}_i$  is the distances between cations and individual ligand anions,  $\text{TO}_m$  is the average bond length. The distortion  $D(\text{TO})$  is the average deviation of the bond length.  $D_w$  is the degree of distortion of the entire crystal,  $D(\text{TO}_K)$  and  $D(\text{TO}_{\text{Sr}})$  refer to the torsion resistance of polyhedra  $\text{KO}_9$  and  $\text{SrO}_8$ , respectively, and the results are listed in Table 3. Obviously, when  $\text{Sr}^{2+}$  ions are replaced by  $\text{Ca}^{2+}$  ions, the distortion degree of  $\text{SrO}_8$  polyhedron in  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$  crystal is significantly reduced (As shown in Fig. 4(b)), which indicates that the introduction of  $\text{Ca}^{2+}$  ions greatly improved the structural rigidity of Sr polyhedron, enhanced the overall symmetry of crystal cells and caused the redistribution of  $\text{Bi}^{3+}$  ions on the

occupied space. With the increase of  $\text{Ca}^{2+}$  content, the number of  $\text{Bi}^{3+}$  entering the Sr site increases, while the number of  $\text{Bi}^{3+}$  at the K site decreases gradually, thus realizing the transfer of the

Table 3 Variation of the distortion degree of  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$  samples

	$y = 0$	$y = 0.04$	$y = 0.08$	$y = 0.10$	$y = 0.20$
$D_K$	0.112	0.112	0.111	0.112	0.112
$D_{\text{Sr}}$	0.166	0.068	0.068	0.067	0.068
$D_w$	0.139	0.090	0.090	0.090	0.090

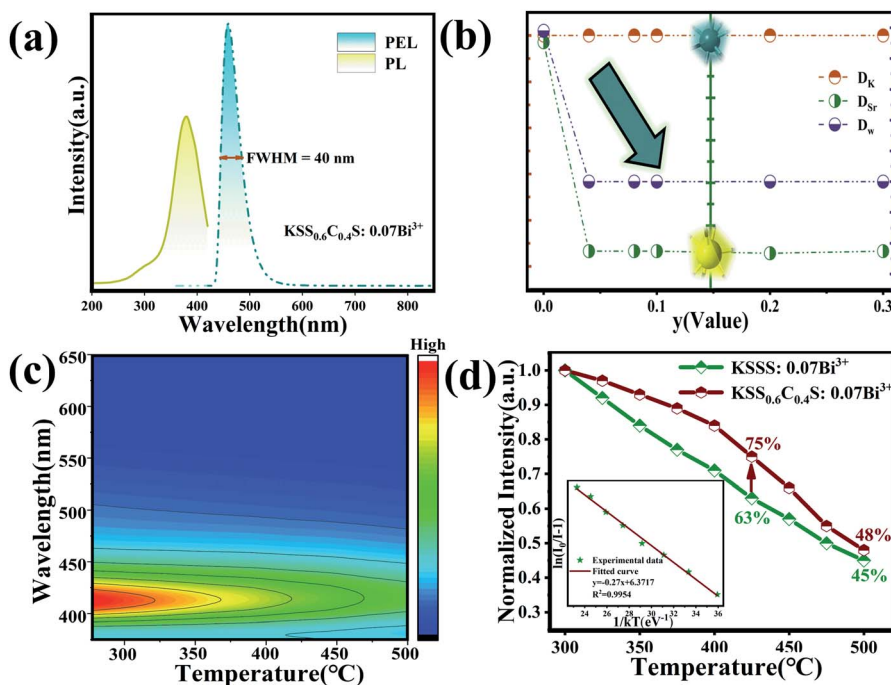


Fig. 4 (a) The emission spectrum of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  ( $\lambda_{\text{ex}} = 370$  nm). (b) Variation of the distortion degree of  $\text{KSS}_{1-y}\text{C}_y\text{S}:0.07\text{Bi}^{3+}$  samples. (c) Temperature-dependent emission spectra of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  phosphors under 370 nm excitation. (d) The temperature-dependent normalized integrated emission intensities of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  and  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$ ; The inset shows the functional relationship of  $\ln(I_0/I_7) - 1$  versus  $1/KT$  of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$ .



main emission peak from 410 nm to 455 nm. The enhancement of structural rigidity and symmetry of the crystal makes the half-peak width of the emission peak significantly narrower.

Debye temperatures for crystallographically distinct atoms ( $\theta_{D,i}$ ) were calculated with isotropic atomic displacement parameters using the high temperature approximation:<sup>37,38</sup>

$$\theta_{D,i} = \sqrt{\frac{3h^2 TN_A}{A_i k_B U_{iso,i}}} \quad (11)$$

where  $i$  represents the atomic species K or Sr, and  $A_i$  is the atomic weight of the atom. The  $U_{iso,i}$  values employed were the average of the individual atomic species in the unit cell, weighted by their Wyckoff multiplicities. Then, according to the stoichiometric coefficients of each atom in the formula  $KSS_{1-y}C_yS$ , the Debye temperature is roughly calculated. It can be seen from the formula that Debye temperature is inversely proportional to atomic displacement parameter ( $U_{iso}$ ). Relevant parameters can be obtained by using the previous refinement data. The corresponding  $U_{iso}$  of K site and Sr site before and after Ca replacement is 0.0397, 0.0419 and 0.0242, 0.0121, respectively. Relevant data are listed in Table S1.† Obviously, when Ca ions replaces  $Sr^{2+}$  ions, the average atomic displacement of K site and Sr site decreases, and the reduction of Sr site is particularly significant. The smaller  $U_{iso}$  corresponds to the higher Debye temperature. Furthermore, it is proved that when  $Bi^{3+}$  ions is transferred from K site to Sr site, the local environment of around  $Bi^{3+}$  ions becomes more symmetric and more rigid, which further proves the cause of narrow-band emission after replacement.

Generally, the enhancement of crystal structure rigidity tends to improve the stability of phosphors to a certain extent. To further verify that the introduction of Ca ions increases the structural rigidity of the overall lattice, we measured the temperature spectra of  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$  and  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$ . Fig. 4(c) shows the temperature dependent PL spectra of representative  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$  measured from 300 K to 500 K with a step of 25 K, and the temperature dependent PL spectra

of  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$  is shown in Fig. S4.† It is observed that the emission intensity gradually decreases with increasing temperatures due to thermal quenching. The temperature stability of phosphor after  $Ca^{2+}$  substitution increased by 12% at a high temperature of 423 K shown in Fig. 4(c). The PL intensity can be fitted by the Arrhenius equation:<sup>39,40</sup>

$$\ln(I_0/I) = \ln A - E_a/kT \quad (12)$$

where,  $I_0$  and  $I$  are emission intensities of the sample at 298 K and other test temperatures, respectively.  $A$  is a constant,  $k$  is Boltzmann's constant,  $T$  is the thermodynamic temperature. When taking  $1/kT$  as the  $x$ -coordinate and  $\ln(I_0/I)$  as the  $y$ -coordinate, linear fitting was performed on the obtained data. The slope of the fitted line is the activation energy  $E_a$ . As is shown in an illustrated of Fig. 4(d), the activation energy  $E_a$  of the activated ions in  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$  and  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$  were 0.203 eV and 0.270 eV respectively, which indicated that the phosphors with  $Ca^{2+}$  introduction had better thermal stability. It is also further proved that the rigidity of the structure is improved after the introduction of Ca ions, which creates a high rigidity environment for the activated ions.

The luminescence properties of phosphors (*e.g.* peak emission wavelength and full-width at half-maximum (FWHM)) directly affect the color gamut space.<sup>41</sup> As a result, phosphors with narrow half-peak width tend to produce higher color purity, which will be more suitable for high-power pc-LEDs and wide-color backlight applications.<sup>36</sup> The color purity of the phosphor can be defined by the percentage of the chromaticity coordinates of the measured light source and the linear distance between the white light source, which can be calculated by the following formula (13):<sup>42,43</sup>

$$\text{Colour purity} = \sqrt{\frac{(x - x_C)^2 + (y - y_C)^2}{(x_D - x_C)^2 + (y_D - y_C)^2}} \times 100\% \quad (13)$$

where  $(x, y)$  represents the color coordinates of phosphor.  $C(x_C, y_C)$  represents the white light source whose CIE color coordinate

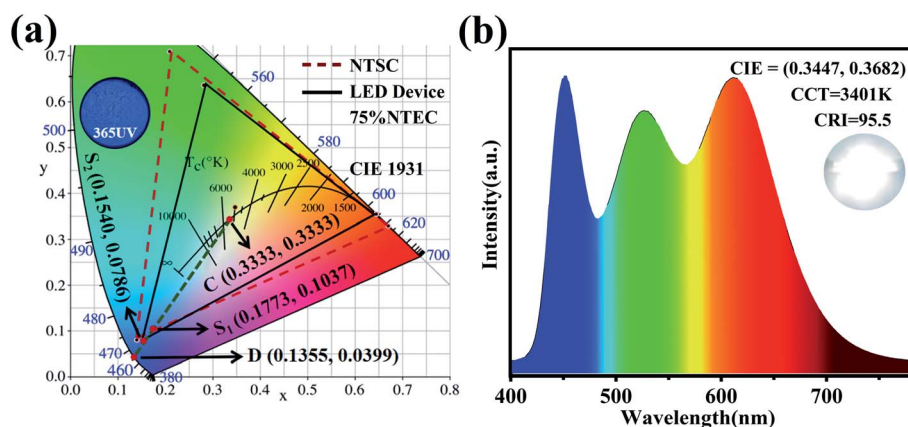


Fig. 5 (a) CIE 1931 color coordinates of main wavelength positions of  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$  and  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$ , color space of NTSC standard (red dotted line) and white LED device (black line), and luminescence photograph of  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$  phosphors under 365 nm UV lamp. (b) The EL spectrum of LED device fabricated with  $KSS_{0.6}C_{0.4}S:0.07Bi^{3+}$  and the commercial phosphors on an UV LED chip (370 nm) under a voltage of 3.2 V and current of 5 mA.



**Table 4** Summary of excitation wavelength, emission wavelength, FWHM, color purity and activation energy ( $\Delta E$ ) of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$ , some blue narrow-band phosphors and  $\text{Bi}^{3+}$  doped phosphors previously reported

Samples	$\lambda_{\text{ex}}$ (nm)	$\lambda_{\text{em}}$ (nm)	FWHM (nm)	Color purity (%)	$\Delta E$ (eV)	Ref.
$\text{Na}_3\text{Sc}_2(\text{PO}_4)_3:\text{Eu}^{2+}$	370	458	50	89	—	44
$\text{Ba}_9\text{Lu}_{1.5}\text{Al}_{0.5}\text{Si}_6\text{O}_{24}:\text{Ce}^{3+}$	400	488	117	—	0.3000	45
$\text{NaHfSi}_2\text{O}_7:\text{Eu}^{2+}$	397	460	54	90	0.1394	46
$\text{RbNa}_3(\text{Li}_3\text{SiO}_4)_4:\text{Eu}^{2+}$	400	471	22.4	83.3	—	47
$\text{Ba}_5\text{SiO}_4\text{Cl}_6:\text{Eu}^{2+}$	345	440	32	93	0.1425	48
$\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$	350	450	52	91.3	—	49
$\text{Sr}_4\text{OCl}_6:\text{Eu}^{2+}$	370	446	46	—	0.1378	50
$\text{Ca}_3(\text{BO}_3)_3\text{F}:\text{Bi}^{3+}$	322	459	100	—	—	51
$\text{Cs}_2\text{AgInCl}_6:\text{Bi}^{3+}$	380	560	160	—	—	52
$\text{KScSr}_{0.6}\text{Ca}_{0.4}\text{Si}_2\text{O}_7:\text{Bi}^{3+}$	370	455	40	88	0.2700	—

is (0.3333, 0.3333), as shown in Fig. 5(a),  $D(x_D, y_D)$  is the color coordinate of the main wavelength corresponding to the measured light source. It connects the measured light source  $S_1$  ( $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$ ) with white light source C and extends the intersection with the spectral trajectory line at point D. Main wavelength of 465 nm, the comparison wavelength and CIE1931 color coordinates table ( $x_D, y_D$ ) for (0.1355, 0.0399),  $S_2$  is the color coordinates of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$ . As a result, the color purity of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  and  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  are 78% and 88%, respectively. Obviously, the  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  phosphors showed better color purity after controlling the cationic component, which indicates that the color purity of the phosphor has been greatly improved by the substitution of  $\text{Ca}^{2+}$  for  $\text{Sr}^{2+}$ . Table 4 presents the comparison of luminescent specialties between some phosphors reported previously and  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$ . It is obvious that the color purity of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  is at a medium level. However, comprehensively comparing data such as excitation and emission wavelength, FWHM, color purity and thermal activation energy, it can be found that the performance of  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  is at an advantage.

### 3.4 Applications in white LED backlight display

The wide excitation, narrow emission, and excellent thermal stability make  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  a potential candidate for backlight display applications. A white LED was fabricated with  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  and the commercial green and red phosphor on an UV (370 nm) chip under a voltage of 3.2 V and current of 5 mA, whose EL spectrum and photograph are shown in Fig. 5(b). It can be seen a warm LED with low CCT = 3401 K, CRI = 95.5, and CIE color coordinate of (0.3447, 0.3682) has been obtained. For a comparison, the EL spectrum and photograph of the commercial blue phosphor  $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$  combined with UV (370 nm) chip are given in Fig. S5.† It is noticeable that the CCT of LED with  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  (3401 K) is lower than that of  $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$  (5064 K), CRI up to 95.5% and CIE color coordinate of (0.4165, 0.4074) had more application potential. The color gamut of our white LED device can cover the color space of 75% NTSC in CIE 1931 (as shown in Fig. 5(a)), which belongs to the broad gamut category. All these

results indicate that  $\text{KSS}_{0.6}\text{C}_{0.4}\text{S}:0.07\text{Bi}^{3+}$  is a promising narrow-band blue phosphor for display backlight.

## 4. Conclusions

A series of blue narrow-band phosphors  $\text{KScSr}_{1-y}\text{Ca}_y\text{Si}_2\text{O}_7:0.07\text{Bi}^{3+}$  were obtained by introducing  $\text{Ca}^{2+}$  ions into  $\text{KScSrSi}_2\text{O}_7:\text{Bi}^{3+}$ . With  $\text{Ca}^{2+}$  concentration increasing, the original crystal field environment changed, which lead to the migration of  $\text{Bi}^{3+}$  from K site to Sr site. Consequently, the main emission peak wavelength changed from 410 nm to 455 nm, and the luminescence color turned from purple to blue. Importantly, the distortion of the polyhedron in the crystal was reduced, the rigidity of the crystal structure was increased, and the symmetry was improved. As a result, under the excitation of 370 nm,  $\text{KScSr}_{0.6}\text{Ca}_{0.4}\text{Si}_2\text{O}_7:0.07\text{Bi}^{3+}$  phosphor presented a blue narrow band emission with a FWHM of 40 nm, and the color purity increased from the original 78% to 88%. And moreover, the LED device using  $\text{KScSr}_{0.6}\text{Ca}_{0.4}\text{Si}_2\text{O}_7:0.07\text{Bi}^{3+}$  phosphor performs a low CCT of 3401 K and a  $R_a$  of 95.5. The results demonstrate that the blue narrow-band phosphor  $\text{KScSr}_{0.6}\text{Ca}_{0.4}\text{Si}_2\text{O}_7:0.07\text{Bi}^{3+}$  has a bright prospect for application in LEDs.

## Conflicts of interest

The authors declare that they have no conflicts of interest.

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