1. Introduction

In recent years, white lighting-emitting diodes (LEDs) have attracted much attention because of their applications in liquid crystal displays and solid-state lighting.\(^1\)\(^2\) The presently-commercialized white LEDs, fabricated by combining a blue-emitting LED chip with the yellow-emitting garnet phosphor (\(Y_2Al_5O_{12}:Ce^{3+}\)) have played an important role in solid-state lighting in recent years.\(^3\) They are characterized by cool white light with Commission Internationale de l’Eclairage (CIE) chromaticity coordinates of \((0.292, 0.325)\), a correlated color temperature (CCT) of 7756 K, and poor color rendering indices (CRI) of \((0.292, 0.325)\), 2705 K, and 89.7 was realized via energy transfer between \(Eu^{2+}\) and \(Mn^{2+}\). The energy transfer was demonstrated to be a resonant type dipole–quadrupole mechanism. Moreover, the obtained LED device exhibits an excellent color-rendering index \((R_\alpha = 97)\) at a correlated color temperature of 5651 K with the CIE coordinates \((0.3290, 0.3410)\).

Two series of novel phosphors of green-yellow emitting \(Ca_{8-x}Sr_xMgGd(PO_4)_7:Eu^{2+},Mn^{2+}\) and yellow-orange emitting \(Sr_yMgGd(PO_4)_7:Eu^{2+},yMn^{2+}\) were successfully synthesized by a solid-state reaction. The crystal structures, photoluminescence (PL), PL excitation (PLE) spectra and decay times were investigated in detail. Upon excitation at 350 nm, the \(Ca_{4}Sr_{4}MgGd(PO_4)_7:Eu^{2+}\) phosphor showed strong green emission centered at 513 nm, and the \(Sr_{y}MgGd(PO_4)_7:Eu^{2+}\) phosphor showed strong yellow emission centered at 513 nm and 593 nm, and \(Sr_{y}MgGd(PO_4)_7:Eu^{2+},yMn^{2+}\) showed strong orange emission centered at 510 nm and 616 nm. In addition, a standard warm white-light emitting single-phased phosphor of \(Sr_yMgGd(PO_4)_7:Eu^{2+},yMn^{2+}\) with chromaticity coordinates \((x, y)\), correlated color temperature (CCT) and Commission Internationale de l’Eclairage (CIE) coordinates of \((0.4497, 0.3929)\), 2705 K, and 89.7 were realized via energy transfer between \(Eu^{2+}\) and \(Mn^{2+}\). The energy transfer was demonstrated to be a resonant type dipole–quadrupole mechanism. Moreover, the obtained LED device exhibits an excellent color-rendering index \((R_\alpha = 97)\) at a correlated color temperature of 5651 K with the CIE coordinates \((0.3290, 0.3410)\).
2. Experimental section

2.1 Materials and synthesis

Polycrystalline phosphors with composition of Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$ and Sr$_{7.98}$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$,$y$Mn$^{2+}$ described in this work were prepared with a high-temperature solid-state reaction. Briefly, the constituent raw materials SrCO$_3$ (A. R., 99.9%), CaCO$_3$ (A. R., 99.9%), MgO (A. R., 99%), Gd$_2$O$_3$ (A. R., 99.99%), MnCO$_3$ (A. R., 99.9%), NH$_4$H$_2$PO$_4$ (A. R., 99%), and Eu$_2$O$_3$ (A. R., 99.99%) were weighed according to the stoichiometric ratio. Individual batches of 10 g were weighted according to the designed stoichiometry and mixed homogeneously with the same mass of absolute ethyl alcohol as the dispersant. A planetary ball-milling process, the obtained homogeneous slurry was placed in a Petri dish and dried in an oven. Then, the dried mixtures were put into a crucible with a lid and heated in a tubular furnace at 1250°C for 6 hours under a reducing atmosphere of 5% H$_2$/95% N$_2$. When cooled down to room temperature, the prepared phosphors were crushed and ground for subsequent measurements.

2.2 Characterization

All crystal structure compositions were checked for phase formation by using powder X-ray diffraction (XRD) analysis with a Rigaku X-ray diffractometer (Tokyo, Japan) with a graphite monochromator using Cu Kα radiation ($\lambda = 1.54056$ Å), over the angular range 10 < 2θ < 80, operating at 40 kV and 40 mA. XRD Rietveld profile refinements of the structural models and textural analysis were performed with the use of TOPAS 4.2 software. The photoluminescence (PL) and photoluminescence excitation (PLE) spectra of the samples were analyzed by using a Hitachi F-7000 spectrophotometer (Tokyo, Japan) with a 150 W Xe lamp. The luminescence decay curve was obtained from a Lecroy Wave Runner 6100 digital oscilloscope (1 GHz) using a tunable laser (pulse width = 4 ns; gate = 50 ns) as the excitation source (Continuum Sunlite OPO). Optical properties such as luminescence spectra, correlated color temperature (CCT), color-rendering index, and the Commission International de l’Eclairage (CIE) color coordinates of the initial mixed phosphors and the white LEDs fabricated were characterized using a DARSA PRO 5100 PL system (PSI Trading Co. Ltd, Korea) and evaluated under a forward bias current of 60 mA at room temperature.

3. Results and discussion

3.1 Phase identification and crystal structure

Fig. 1(a) depicts powder XRD profiles of Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_7$:Eu$^{2+}$ ($x = 0, 1, 2, 3, 4, 5, 6, 7, and 8$) samples along with the standard data Ca$_8$MgGd(PO$_4$)$_7$ (JCPDS card no. 50-1766). From Fig. 1, we can clearly find that all the diffraction peaks of the samples can be well indexed to the standard data of Ca$_8$MgGd(PO$_4$)$_7$, which proves that the phase of Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_7$:Eu$^{2+}$ samples is pure. Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_7$:Eu$^{2+}$ are isostructural with Ca$_8$MgGd(PO$_4$)$_7$ and the doping of Eu$^{2+}$ ions does not cause significant impurities to the crystal structure. Fig. 1(b) shows the zoomed powder XRD profiles in the range of 29–32 degree, which exhibits the linear shift of peaks with the Ca replaced the Sr in Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_7$:Eu$^{2+}$ samples.

The lattice parameters from Rietveld refinements using TOPAS 4.2 are displayed in Fig. 2. The lattice parameters and...
cell volumes show a linear dependence on $x$, as can be anticipated from Vegard’s law.\textsuperscript{13} Moreover, the substitution is accompanied by an increase of $a$, $c$, and $V$. The corresponding equations of the cell parameters as a function of chemical composition, $x$, are presented in Fig. 2 and can be explained by the difference in ionic radii between the substituted and substituting ions. It can be seen that both the lattice constants and primitive volume increase linearly when $x$ increases in Ca$_8$–Sr$_x$MgGd(PO$_4$)$_7$, which could be ascribed to the smaller ionic radius of Ca$^{2+}$ ions (1.00 Å, 1.12 Å, and 1.18 Å when corresponding number is 6, 8, and 9, respectively) compared to that of Sr$^{2+}$ ions (1.18 Å, 1.26 Å, and 1.31 Å when corresponding number is 6, 8, and 9, respectively).

To get the detailed crystal structure information on the obtained samples, we carried out Rietveld refinement of Sr$_8$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$ sample with the single crystal structure data of Sr$_9$MgH(PO$_4$)$_7$ (ICSD no. 5113) as the initial model. Fig. 3 shows the observed (crosses) and calculated (red dots) XRD patterns together with their difference (blue) for the refinement of Sr$_8$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$ sample. The refinement results reveal that Sr$_8$MgGd(PO$_4$)$_7$ has the trigonal structure with the space group of $R\bar{3}m$, cell parameters of $a = b = 10.569$ Å, $c = 19.57$ Å, and cell volume of $V = 1893.22$ Å$^3$. And the refinement finally converged to $GOF = 2.37$, $R_p = 7.7\%$, and $R_{wp} = 11.09\%$ (Table 1), which again demonstrates that Sr$_8$MgGd(PO$_4$)$_7$ is isotypic with Sr$_9$MgH(PO$_4$)$_7$ and Eu$^{2+}$ ions have been doped into the host lattice successfully.

The crystal structure model of Sr$_8$MgGd(PO$_4$)$_7$ is depicted in Fig. 4. In the unit cell of Sr$_8$MgGd(PO$_4$)$_7$, there are three Sr crystallographic sites (Sr1, Sr2, and Sr3), two Mg sites (Mg1 and Mg2) and two P sites (P1 and P2). The coordinated polyhedrons of Sr1, Sr2 and Sr3 are also shown in Fig. 4.

### 3.2 Photoluminescence properties of Ca$_8$–Sr$_x$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$ doped phosphors

Fig. 5 shows PLE spectra of Ca$_8$–Sr$_x$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$ ($x = 0, 1, 2, 3, 4, 5, 6, 7, 8$). The excitation spectra monitored at 510 nm consist of broad bands ranging from 220–500 nm with a maximum at ~350 nm, which are assigned to 4$f^7$–4$f^5$5$d^1$ transitions.

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**Table 1** Rietveld refinement and crystallographic data of Sr$_8$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$ sample

| Formula   | Sr$_8$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$ |
|-----------|----------------------------------------|
| Space group | $R\bar{3}m$ (no. 166), trigonal |
| $a$ (Å)   | 10.569                                  |
| $c$ (Å)   | 19.57                                   |
| $\alpha$ (deg) | 90                                    |
| $\gamma$ (deg) | 120                                   |
| $V$ (Å$^3$) | 1893.22                                 |
| $R_p$ (%)   | 7.7                                    |
| $R_{wp}$ (%) | 11.09                                  |
| $GOF$       | 2.37                                   |

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RSC Adv., 2017, 7, 19223–19230 | 19225
transition of Eu$^{2+}$ ions. The PLE spectra nearly cover the region from UV to blue. Moreover, the PL spectra, as shown in Fig. 6, are measured and studied to further analyze the Eu$^{3+}$ emitting centers in Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_2$:0.02Eu$^{2+}$. The luminous intensity of Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_2$:0.02Eu$^{2+}$ is rather low when $x \leq 2$ for the difference between radius of Ca$^{2+}$ (1 Å when corresponding number is 6) and that of Eu$^{2+}$ (1.17 Å when corresponding number is 6) is very large. Then the luminous intensity increased with more Sr$^{2+}$ replacing Ca$^{2+}$. The radius of Sr$^{2+}$ (1.18 Å when corresponding number is 6) is very similar to the radius of Eu$^{2+}$, which leads the Eu$^{2+}$ is easier to replace Sr$^{2+}$ than Ca$^{2+}$. Interestingly, the two emission bands turn to one emission bands at green light region when $x = 4$, namely, Ca$_4$Sr$_4$MgGd(PO$_4$)$_2$:0.02Eu$^{2+}$. Form Fig. 2, it is known that both the lattices constants and primitive volume increase linearly when $x$ increases in Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_2$ which could be ascribed to the larger ionic radius of Sr$^{2+}$ ions compared to that of Ca$^{2+}$ ions. Eu$^{2+}$ ions are easier to replace Sr$^{2+}$ rather than Ca$^{2+}$ because of their similar ionic radius. In Ca$_4$MgGd(PO$_4$)$_2$ host, Eu$^{3+}$ is very difficult to replace Ca$^{2+}$, leading the weak emission intensity. Sr$^{2+}$ makes the crystal lattice larger when Ca$^{2+}$ is replaced by Sr$^{2+}$, which leading that Eu$^{2+}$ can be easily doped into host, then the emission intensity increased. However, Eu$^{2+}$ has the tendency to replace the Sr$^{2+}$ which has similar ion radius in different Sr sites. So there are significant spectral variations when Ca$^{2+}$ is substituted by Sr$^{2+}$. When Sr$^{2+}$ continues to replace Ca$^{2+}$, the green emission band turns back into two emission bands, covered with green and yellow regions. The insets show the photographs of phosphors excited by 365 nm excitation. From Fig. 7(a), fitted curve (red dashed line) and deconvoluted Gaussian components (red, green, blue and cyan dashed lines) of Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_2$:0.02Eu$^{2+}$ ($x = 0, 1, 2, 3, 4, 5, 6, 7, 8$).
Ca$_{8-x}$Sr$_x$MgGd(PO$_4$)$_3$;0.02Eu$^{2+}$ (λ$_{ex}$ = 350 nm) are shown in detail. It can be seen that there are three deconvoluted Gaussian peaks of Eu$^{2+}$ corresponding to three types of Sr$^{2+}$/Ca$^{2+}$ sites in all samples. Peak 1 has a red shift before $x = 4$, while peak 2 and peak 3 have a blue shift before $x = 4$ with the increase replacement of Sr$^{2+}$, which is shown in Fig. 7(b). However, the emission peak position would not change when $x > 4$, which means the luminescence of Eu$^{2+}$ no longer depends strongly on the change of crystal field, even though the lattice parameters still increase. As depicted in Fig. 7(c), the luminous intensity increased and reached maximum at $x = 4$, and then decreased. After $x = 6$, the luminous intensity increased again and reached maximum at $x = 8$, that is Sr$_8$MgGd(PO$_4$)$_3$;0.02Eu$^{2+}$.

3.3 Energy transfer properties in Sr$_8$MgGd(PO$_4$)$_3$:Eu$^{2+}$,Mn$^{2+}$ phosphors

The PLE spectra (Fig. 8.) increase the intensity with increasing the concentration of doping Mn$^{2+}$ ions when monitored at 600 nm. The broad excitation bands covered from 220 nm to 470 nm. Under the excitation of 350 nm, both the emission of Eu$^{2+}$ and Mn$^{2+}$ can be observed in the PL spectrum of the co-doped samples as shown in Fig. 9. The emission intensity for Eu$^{2+}$ decreases with increasing Mn$^{2+}$ concentration, whereas the emission intensity for Mn$^{2+}$ increases with increasing the concentration. The insets show photographs of phosphors excited by 365 nm excitation. The color turns from yellow to orange-yellow with the increasing Mn$^{2+}$ concentration. There is a concentration quenching about Mn$^{2+}$ 616 nm emission peak when $y > 0.25$ in Sr$_8$MgGd(PO$_4$)$_3$;0.02Eu$^{2+}$,yMn$^{2+}$.

In order to well understand the energy transfer process, we measured the PL decay curves and then calculated the lifetimes as well as energy-transfer efficiencies. Fig. 10 shows the PL decay curves of the Eu$^{2+}$ ions in Sr$_8$MgGd(PO$_4$)$_3$:Eu$^{2+}$,yMn$^{2+}$, which were measured with excitation at 350 nm and monitored at 510 nm. One can see that the decay curve of the singly Eu$^{2+}$ doped Sr$_8$MgGd(PO$_4$)$_3$:Eu$^{2+}$ sample can be well fitted into a single-exponential function with a decay time of 1.161 μs. This is the radiative decay time of the Eu$^{2+}$ ions. For the Eu$^{2+}$ and Mn$^{2+}$ codoped samples, the doping of the Mn$^{2+}$ ions significantly modifies the fluorescent dynamics of the Eu$^{2+}$ ions. The results reveal that the fluorescence decays deviate slightly from a single exponential rule, indicating the presence of a non-radiative process. The effective lifetime is defined as

$$\tau = \frac{\int_0^\infty t I(t)dt}{\int_0^\infty I(t)dt}$$

On the basis of eqn (1), the effective lifetime values were calculated to be 1.160, 1.157, 1.151, 1.135, 1.111, 1.078, and 1.021 μs for Sr$_8$MgGd(PO$_4$)$_3$:Eu$^{2+}$,yMn$^{2+}$ with $y = 0.02, 0.04, 0.08, 0.12, 0.16, 0.2,$ and 0.25, respectively. It can be seen that the decay lifetime of the Eu$^{2+}$ ions decreases monotonically with an increase in the Mn$^{2+}$ doping concentration, which strongly supports energy transfer from the Eu$^{2+}$ to Mn$^{2+}$ ions.

Based on the following equation, the energy transfer efficiency ($\eta_T$) from Eu$^{2+}$ to Mn$^{2+}$ can be evaluated:

$$\eta_T = 1 - \frac{\tau_e}{\tau_{so}}$$

where $\tau_e$ and $\tau_{so}$ are the decay time of the Eu$^{2+}$ ions in the absence and presence of Mn$^{2+}$ ions.

The results are shown in Fig. 11. It can be observed that the $\eta_T$ increases gradually with the increase of the Mn$^{2+}$ doping concentration and finally reaches to 0.12 for $y = 0.25$.  

Fig. 8 PLE spectra of Sr$_8$MgGd(PO$_4$)$_3$:Eu$^{2+}$,yMn$^{2+}$ ($y = 0, 0.02, 0.04, 0.08, 0.12, 0.16, 0.2, 0.25$). The insets show photographs of phosphors excited by 365 nm excitation.

Fig. 9 PL spectra of Sr$_8$MgGd(PO$_4$)$_3$:0.02Eu$^{2+}$,yMn$^{2+}$ ($y = 0, 0.02, 0.04, 0.08, 0.12, 0.16, 0.2, 0.25$). The insets show photographs of phosphors excited by 365 nm excitation.

Fig. 10 PL decay curves of Eu$^{2+}$ in Sr$_8$MgGd(PO$_4$)$_3$:Eu$^{2+}$,yMn$^{2+}$ (excited at 350 nm and monitored at 510 nm).
According to Dexter’s theory, non-radiative energy transfer between sensitizer and activator ions can occur by exchange interaction, or multipolar interactions. The following formula will be fitted linearly if exchange interaction works:

$$\ln \frac{\eta_{so}}{\eta_{s}} \propto C$$  \hspace{1cm} (3)

where $C$ is the total concentration of Eu$^{2+}$ and Mn$^{2+}$ ions, $\eta_{so}$ and $\eta_{s}$ are the luminescence quantum efficiencies of Eu$^{2+}$ in the absence and presence of Mn$^{2+}$, respectively. The value of $\eta_{so}/\eta_{s}$ can be approximately estimated from the related decay time’s ratio $\tau_{so}/\tau_{s}$. Thus, eqn (3) can be represented by the following equation:

$$\ln \frac{\tau_{so}}{\tau_{s}} \propto C$$  \hspace{1cm} (4)

As shown in Fig. 12(a), linear relation is not well obtained via exchange interaction ($R^2 = 0.858$). Therefore, the energy of Eu$^{2+}$ is transferred to Mn$^{2+}$ by multiple–multiple interaction. For multipolar interactions, the following relation can be obtained:

$$\frac{\eta_{so}}{\eta_{s}} \propto C^{a/3}$$  \hspace{1cm} (5)

As mentioned above, eqn (5) can be also represented by the following equation:

$$\frac{\tau_{so}}{\tau_{s}} \propto C^{a/3}$$  \hspace{1cm} (6)

where $a = 6, 8$ and $10$ is corresponding to dipole–dipole, dipole–quadrupole and quadrupole–quadrupole interactions, respectively. In Fig. 12(b)–(d), it can be observed that a well fitted linear relation was obtained when $a = 8$, which indicates that the dominant interaction mechanism for energy transfer from Eu$^{2+}$ to Mn$^{2+}$ in Sr$_8$MgGd(PO$_4$)$_7$ is dipole–quadrupole interaction.

### 3.4 Temperature-dependent emission spectra, LED lamp fabrication and EL spectrum

To demonstrate the potential application of Ca$_8$Sr$_x$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$ and Sr$_8$MgGd(PO$_4$)$_7$:0.02Eu$^{2+}$:$y$Mn$^{2+}$ phosphor, as shown in Fig. 13, temperature-dependent integrated PL intensity of the phosphors have been obtained. These three types of
phosphors have similar thermal stabilities. There is around 50% intensity attenuation when temperature is 100 °C. The internal quantum efficiency of Sr₄Ca₄Gd(PO₄)₇:0.02Eu²⁺, Sr₈Gd(PO₄)₇:0.02Eu²⁺ and Sr₄Gd(PO₄)₇:0.02Eu²⁺,0.25Mn²⁺ phosphors is 20.6%, 30.2% and 17.8%. As Fig. 14(a) shows, phosphor-converted LED was fabricated by combining a 365 nm UV-chip and driven by a forward-bias current of 60 mA. Point B, G, Y, O and R represent Sr₅(PO₄)₃Cl:0.02Eu²⁺ blue phosphor, Ca₄Sr₄MgGd(PO₄)₇:0.02Eu²⁺ green phosphor, Sr₈MgGd(PO₄)₇:0.02Eu²⁺,0.25Mn²⁺ red phosphor, Sr₅MgGd(PO₄)₇:0.02Eu²⁺ yellow phosphor, Sr₈MgGd(PO₄)₇:0.02Eu²⁺,0.25Mn²⁺ orange phosphor and Sr₆Al₄O₁₅:0.01Mn⁴⁺ red phosphor, respectively. All the possible that mixed kinds of phosphors are contained in the area of dashed triangle. BGR (or BYR) represents the mixture composed of Sr₅(PO₄)₃Cl:0.02Eu²⁺ blue phosphor, Sr₆Al₄O₁₅:0.01Mn⁴⁺ red phosphor and Ca₄Sr₄MgGd(PO₄)₇:0.02Eu²⁺ green phosphor (or Sr₈MgGd(PO₄)₇:0.02Eu²⁺ yellow phosphor). A standard warm white-light emitting single-phased phosphor of Sr₆MgGd(PO₄)₇:Eu²⁺,Mn²⁺ (point O) with chromaticity coordinates (x, y), correlated color temperature (CCT) and Commission Internationale de l’Eclairage (CIE) coordinates of (0.4497, 0.3929), 2705 K, 89.7) is realized via energy transfer between Eu²⁺ and Mn²⁺. The insets show photographs of the LED lamp packages driven by 60 mA current. Fig. 14(b) and (c) show the electroluminescence (EL) spectra of the lamps. Three emission bands can be clearly seen in Fig. 14(b): 450 nm, attributable to Sr₅(PO₄)₃Cl:0.02Eu²⁺ blue phosphor, the 510 and 668 nm, attributable to the Ca₄Sr₄MgGd(PO₄)₇:0.02Eu²⁺ green phosphor and Sr₆Al₄O₁₅:0.01Mn⁴⁺ red phosphor, respectively. CRI value of BGR is 94.1 and CCT is 7556 K. Four emission bands can be clearly seen in Fig. 14(c), 450 nm, attributable to Sr₈MgGd(PO₄)₇:0.02Eu²⁺ yellow phosphor, Sr₆Al₄O₁₅:0.01Mn⁴⁺ red phosphor, respectively. CRI value of BYR reach up to 97 and CCT is 5651 K. The luminous efficiency of BGR, BYR and O LED prototype under 60 mA are 23.67 lm W⁻¹, 24.03 lm W⁻¹ and 24.28 lm W⁻¹, respectively.

The CIE chromaticity diagram, CIE chromaticity coordinates, CCT, and Rₐ were listed in Table 2. The results obtained for the LED package demonstrated that
Table 2  CIE chromaticity coordinates, CCT, and $R_a$ for marked points

| Point | Components | $(x, y)$ | CCT (K) | $R_a$ |
|-------|------------|---------|---------|-------|
| B     | Sr$_5$(PO$_4$)$_3$:Cl:0.02Eu$^{2+}$ | (0.1641, 0.0994) | —       | 18.3  |
| G     | Ca$_3$Sr$_2$MgGd[PO$_4$]:0.02Eu$^{2+}$ | (0.3492, 0.4599) | 5125    | 72.0  |
| Y     | Sr$_6$MgGd[PO$_4$]:0.02Eu$^{2+}$ | (0.3972, 0.4535) | 4808    | 82.0  |
| O     | Sr$_6$MgGd[PO$_4$]:0.02Eu$^{2+}$,0.25Mn$^{2+}$ | (0.4947, 0.3929) | 2705    | 89.7  |
| R     | Sr$_3$Al$_2$O$_3$:0.01Mn$^{4+}$ | (0.6252, 0.2859) | 1001    | 20.6  |
| BY    | B + Y     | (0.3316, 0.3719) | 5541    | 90.3  |
| BO    | B + O     | (0.4155, 0.3548) | 2949    | 84.9  |
| BGR   | B + G + R | (0.2966, 0.3213) | 7556    | 94.1  |
| BYR   | B + Y + R | (0.3290, 0.3410) | 5651    | 97.0  |

Cas$_{1-x}$Sr$_{x}$MgGd[PO$_4$]:0.02Eu$^{2+}$ has potential applications in the full-spectrum white-light NUV LEDs with excellent CRIs.

## 4. Conclusions

In summary, we have synthesized two series of novel phosphors of Cas$_{1-x}$Sr$_{x}$MgGd[PO$_4$]:Eu$^{2+}$ and Sr$_6$MgGd[PO$_4$]:Eu$^{2+}$, Mn$^{2+}$ by the high temperature solid-state reaction. A warm white-light emitting single-phased phosphor of Sr$_8$MgGd(PO$_4$)$_7$:Eu$^{2+}$, Mn$^{2+}$ with chromaticity coordinates $(x, y)$, correlated color temperature (CCT) and Commission Internationale de l’Eclairage (CIE) chromaticity coordinates $(x, y, y')$, realized via energy transfer between Eu$^{2+}$ and Mn$^{2+}$. The energy transfer was demonstrated to be a resonant type dipole–quadrupole mechanism. A white LED with $R_a = 97$ (or $R_a = 94.1$) was successfully fabricated by coating Sr$_6$MgGd[PO$_4$]:Eu$^{2+}$ (or Ca$_3$Sr$_2$MgGd[PO$_4$]:Eu$^{2+}$) with a blend of Sr$_5$(PO$_4$)$_3$:Cl:Eu$^{2+}$ blue and Sr$_3$Al$_2$O$_3$:Mn$^{4+}$ red phosphor onto a near UV 365 nm chip.

## Acknowledgements

This work was financially supported by the programs of National Natural Science Foundation of China (No. 51272282 & 51302311), and significant achievement transformation project of colleges and universities of the Central in Beijing (ZD20141000201), supported by Beijing Municipal Education Commission.

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