Energy transfer and unusual decay behaviour of BaCa$_2$Si$_3$O$_9$:Eu$^{2+}$,Mn$^{2+}$ phosphor†

Matthias Müller and Thomas Jüstel*

In this work the photoluminescence (PL) of BaCa$_2$Si$_3$O$_9$:Eu$^{2+}$,Mn$^{2+}$ and the energy transfer (ET) between Eu$^{2+}$ and Mn$^{2+}$ were examined. A series of powder samples with various Mn$^{2+}$ concentrations were prepared by high temperature solid state route. Phase purity was investigated using X-ray powder diffractometry. Emission and excitation spectra as well as diffuse reflectance spectra were recorded to elucidate the PL properties of co-doped BaCa$_2$Si$_3$O$_9$:Eu$^{2+}$,Mn$^{2+}$. Furthermore, fluorescence lifetime measurements were performed. PL and lifetime measurements were carried out from 100 to 800 K and 100 to 500 K, respectively. Moreover, external quantum efficiencies were determined and colour points were calculated. It turned out that ET from Eu$^{2+}$ to Mn$^{2+}$ is of a resonant type and occurs via dipole–quadrupole interactions. Temperature dependent PL measurements indicate high temperature stability of emission intensity in BaCa$_2$Si$_3$O$_9$:Eu$^{2+}$,Mn$^{2+}$. Finally, it was found that fluorescence lifetimes of Eu$^{2+}$ BaCa$_2$Si$_3$O$_9$ show an unusual increase with increasing temperature.

1. Introduction

Even though the invention of bright blue light emitting diodes (LEDs) by Nakamura et al. nearly dates back a quarter of a century, LEDs still have a vast impact on advances in lighting technology.1 Meanwhile, LEDs have replaced more and more conventional light sources such as incandescent and discharge lamps. This is because of the fact that LEDs provide many benefits compared to thermal and gas discharge light sources, such as longer lifetimes, higher wall plug efficiency and higher colour rendering.2 Nowadays, most of the commercially available white light emitting LEDs comprise a blue emitting (In,GaN) chip pumping a green-yellow emitting phosphor, e.g. (Y,Gd)$_3$Al$_5$O$_{12}$:Ce$^{3+}$. This setup provides a high luminous efficacy due to emission in the green spectral range. Unfortunately, these lamps suffer from high colour temperature and low colour rendering index due to the lack of emission in the red spectral range.3 Therefore, these light sources are unpopular for domestic lighting. To overcome these drawbacks, one approach is to use a phosphor blend comprising a blue, green, and red phosphor, which is excited by an ultraviolet emitting LED. Using this concept, cold and warm white emitting LEDs with excellent colour points can be realized.4 However, these packages undergo a loss in blue emission due to re-absorption by the green and red phosphors. For this reason, many research groups are developing single phase white emitting phosphors to convert UV radiation into white light.5

One approach to realize a white emitting phosphor is to use the ion couple Eu$^{2+}$ and Mn$^{2+}$.6 The broad emission bands in the blue and red spectral range of Eu$^{2+}$ and Mn$^{2+}$ in many host structures complement each other to white light due to additive colour mixing. Furthermore, Eu$^{2+}$ usually exhibits a broad excitation band in the UV range due to the spin and parity allowed [Xe]4f$^7$–[Xe]4f$^6$5d$^1$ interconfigurational electric-dipole transition. Therefore, Eu$^{2+}$ is well appropriated for pumping by UV LEDs. In addition the blue emission band of Eu$^{2+}$ is also suitable for sensitizing the spin and parity forbidden [Ar]3d$^5$–[Ar]3d$^5$ excitation transitions of Mn$^{2+}$ via energy transfer (ET). To investigate the photoluminescence (PL) properties as well as the ET from Eu$^{2+}$ to Mn$^{2+}$, a series of co-doped BaCa$_2$Si$_3$O$_9$:Eu$^{2+}$,Mn$^{2+}$ samples with various Mn$^{2+}$ concentrations were synthesized. BaCa$_2$Si$_3$O$_9$ was described for the first time in the work of Eskola in 1922.7 Later on, in 1965 Alfors et al. investigated the mineral walstromite.8 Based on their results on optical properties and X-ray powder diffraction data they stated that BaCa$_2$Si$_3$O$_9$ is identical to walstromite. Glasser et al. reported on the crystal structure of synthetic BaCa$_2$Si$_3$O$_9$ using photographic X-ray diffraction data in 1968.8 The crystal structure derived from a single crystal analysis of BaCa$_2$Si$_3$O$_9$ was firstly published by Barkley et al. in 2011.10

Shortly afterwards, Yao et al. presented the first report on the
blue emission of Eu²⁺ doped BaCa₂Si₃O₉. Moreover, Gaft et al. published an article concerning the luminescence of natural walstromite in 2013.

BaCa₂Si₃O₉ crystallizes triclinically in the space group P1. The structure of triclinic BaCa₂Si₃O₉ is built up of layers consisting of alternating Si₂O₆ rings. Between these layers Ba and Ca atoms are incorporated. BaCa₂Si₃O₉ comprises two non-equivalent Ca sites, namely Ca1 and Ca2. The Ca1 site is coordinated by 8 oxygen atoms with a mean distance of 2.545 Å. The Ca2 site is surrounded by 6 oxygen atoms with an average bond length of 2.370 Å. The Ba atoms are 8-fold coordinated with an average distance of 2.841 Å. The ionic radii of Ca for 8 and 6-fold coordination are 1.12 and 0.96 Å. Ba²⁺ in 8-fold coordination has an ionic radius of 1.42 Å. The ionic radii of Mn²⁺ and Eu²⁺ for 8 and 6-fold coordination are 0.96 and 0.83 Å as well as 1.25 and 1.17 Å, respectively. Based on the ionic radii, it can be assumed that the Mn²⁺ ions tend to occupy the Ca sites whereas the Eu²⁺ ions tend to occupy the Ba²⁺ sites as well as the 8-fold coordinated Ca²⁺ sites.

2. Experimental

Preparation

Ba₀.₉₉Eu₀.₀₁(Ca₁₋ₓMnₓ)₂Si₃O₉ samples were synthesized via conventional high temperature solid state reaction. High purity starting materials BaCO₃ (Alfa Aesar, 99.8%), CaCO₃ (Merck KGaA, Reag. Ph. Eur.), SiO₂ (Merck KGaA, Ph. Eur.), Eu₂O₃ (Treibacher Industrie AG, 99.99%) and MnC₂O₄·2H₂O (Dr Paul Lohmann, chem. pure) were weighed in stoichiometric amounts. 1 wt% H₂BO₃ (Merck KGaA, Ph. Eur.) was added as a flux. Subsequently, the educts were ground in an agate mortar. After drying at ambient temperature, the obtained powder blends were heated at 1000 °C for 2 h in air to decompose the carbonates. Afterwards the samples were ground and finally calcined in alumina boats at 1200 °C for 12 h in reducing forming gas flow (Westfalen, 5% H₂, 95% N₂). After calcination, hard sinters with a slightly yellow body colour were obtained which were subsequently ground to a fine powder.

Characterization

Phase purity was investigated using X-ray powder diffractometry (XRD). XRD patterns were recorded on a Rigaku MiniFlex II diffractometer working in Bragg–Brentano geometry using Cu Kα radiation. Step width and integration time were 0.02 and 1 s, respectively.

PL spectra and photoluminescence excitation (PLE) spectra were recorded on an Edinburgh Instruments FSL900 spectrometer equipped with a Xe arc lamp (450 W) and a cooled (−20 °C) single-photon counting photomultiplier (Hamamatsu R2658P). PL spectra were corrected by using a correction file obtained from a tungsten incandescent lamp certified by the National Physical Laboratory, UK.

For photoluminescence decay (PLD) measurements on Eu²⁺, the spectrometer was equipped with a picosecond pulsed laser (5 mW, pulse width = 76.6 ps, λ_em = 375 nm). For PLD measurements on Mn²⁺ a microsecond pulsed Xe lamp (100 W, pulse width = 1 µs) was attached to the spectrometer.

For temperature dependent measurements the spectrometer was equipped with a cryostat (Oxford Instruments). Liquid nitrogen was used as a cooling agent. Temperature stabilization time was 60 s and tolerance was set to ±3 K.

Diffuse reflectance (DR) spectra were recorded on an Edinburgh Instruments FS900 spectrometer equipped with a Xe arc lamp (450 W), a cooled (−20 °C) single-photon counting photomultiplier (Hamamatsu R928) as well as a Teflon-coated integration sphere. BaSO₄ (99.998%, Sigma-Aldrich) was used as a reflectance standard.

External quantum efficiencies η_ext were determined using the approach of Kawamura et al. To this end, PL spectra of the sample as well as of the excitation source were recorded in the integration sphere. From this, η_ext can be calculated by the following equation:

\[
\eta_{\text{ext}} = \frac{\int I_{\text{em}}(\lambda)d\lambda}{\int I_{\text{ex}}(\lambda)d\lambda - \int I_{\text{exc}}(\lambda)d\lambda}
\]

where \( I_{\text{em}}(\lambda) \) is the emission intensity of the sample, \( I_{\text{ex}}(\lambda) \) and \( I_{\text{exc}}(\lambda) \) are the intensities of the excitation source in the absence and presence of the sample.

3. Results and discussion

Collected XRD patterns of doped and also of undoped BaCa₂Si₃O₉ samples as well as the ICDD reference cards of BaCa₂Si₃O₉ and SiO₂ are presented in Fig. 1. The XRD patterns indicate the formation of the triclinic BaCa₂Si₃O₉ phase. Furthermore, with increasing doping concentrations of Eu²⁺ and Mn²⁺, no change in the host structure can be observed. However, samples with \( x > 0.1 \) show an additional reflex at about 25.9° which can be assigned to SiO₂. This proves the successful synthesis of the investigated BaCa₂Si₃O₉:Eu²⁺,Mn²⁺ phosphors with a Mn²⁺ concentration up to \( x = 0.1 \).

Fig. 2 shows DR spectra of undoped BaCa₂Si₃O₉ host material and also of Ba₀.₉₉Eu₀.₀₁Ca₂Si₃O₉ and Ba(Ca₀.₉₅Mn₀.₀₅)₂Si₃O₉. Undoped BaCa₂Si₃O₉ exhibits high reflectance between 250 and 800 nm. Thus, undoped BaCa₂Si₃O₉ possess a white body colour. The DR spectrum of Ba₀.₉₉Eu₀.₀₁Ca₂Si₃O₉ shows a broad absorption band between 250 and 450 nm due to the allowed [Xe]4f⁹⁷-[Xe]4f⁸⁵d⁵⁺-transition of Eu²⁺. Because of the absorption band in the blue range of the electromagnetic spectrum, Ba₀.₉₉Eu₀.₀₁Si₃O₉ exhibits a slightly yellow body colour. The DR spectrum of Ba(Ca₀.₉₅Mn₀.₀₅)₂Si₃O₉ shows absorption in the UV region between 250 and 350 nm which can be tentatively assigned to a Mn²⁺ charge transfer transition.

The PLE spectrum as well as the PL spectrum of Ba₀.₉₉Eu₀.₀₁Ca₂Si₃O₉ is depicted in Fig. 3a. The PL spectrum was recorded monitoring the 460 nm emission of Eu²⁺ and exhibits a broad band consisting of various unresolved bands.
This band is due to excitation from the [Xe]4f7 ground state to the [Xe]5d 1 multiplet of Eu 2+. The PL spectrum of Ba0.99Eu0.01Ca2Si3O9 (λex = 320 nm) shows an emission band peaking at about 444 nm with FWHM of 47 nm (2333 cm⁻¹). This emission originates from relaxation of the excited [Xe]5d 1 state to the [Xe]4f7 ground state. Further, Ba0.99Eu0.01Ca2Si3O9 possesses an emission band in the red region of the spectrum. The PLE spectrum of this emission is shown as a dotted line. Fig. 3b illustrates the PLE and PL spectra of Ba(Ca0.95Mn0.05)2Si3O9. Monitoring the 590 nm emission of Mn2+, the PLE spectrum of Ba(Ca0.95Mn0.05)2Si3O9 shows various bands centred at 326, 348, 359, 405, 432, and 510 nm. These peaks can be assigned to transitions from the 6A1(6S) ground state to 4T1(4G), 4E(4D), 4T2(4D), 4E(4G)A1(4G), 4T2(4G), and 4T1(4G), respectively. The PL spectrum of Ba(Ca0.95Mn0.05)2Si3O9 was recorded under an excitation wavelength of λex = 405 nm and exhibits a broad band with a maximum at about 594 nm resulting from a transition from the 4T1(4G) excited state to the 6A1(6S) ground state. This observation is in accordance with the results given by Gaft et al. regarding Mn2+ emission in natural walsstromite.12 In addition, the Mn2+ emission band comprises a tailing to the red range of the visible spectrum indicating emission from different crystallographic sites. PLE as well as PL spectra of co-doped Ba0.99Eu0.01(Ca0.95Mn0.05)2Si3O9 were depicted in Fig. 3c. The PL spectrum of Ba0.99Eu0.01(Ca0.95Mn0.05)2Si3O9 shows two bands peaking at about 445 and 590 nm which can be assigned to electronic transitions of Eu2+ ([Xe]5d 1 to [Xe]4f7) and Mn2+ (4T1(4G) to 6A1(6S)), respectively. PLE spectra of Ba0.99Eu0.01(Ca0.95Mn0.05)2Si3O9 were recorded, monitoring the 460 nm emission of Eu2+ as well as the 590 nm emission of Mn2+. These PLE spectra appear similar to the PLE of singly
doped Ba$_{0.99}$Eu$_{0.01}$Ca$_2$Si$_3$O$_9$ monitoring the blue emission of Eu$^{2+}$. This observation strongly implies the occurrence of ET from Eu$^{2+}$ to Mn$^{2+}$.

Fig. 4 illustrates the PL spectra of the synthesized Ba$_{0.99}$Eu$_{0.01}$(Ca$_{1-x}$Mn$_x$)$_2$Si$_3$O$_9$ series with $x = 0, 0.005, 0.010, 0.015, 0.020, 0.050, 0.100, 0.150,$ and $0.200$. As can be concluded from the spectra, with increasing Mn$^{2+}$ concentration the PL intensity of Eu$^{2+}$ decreases. This behaviour reflects the assumption provided above regarding ET from Eu$^{2+}$ to Mn$^{2+}$. The inset in Fig. 4 depicts the relative PL intensities of Eu$^{2+}$ and Mn$^{2+}$. It was found that the PL intensity of Mn$^{2+}$ increases continuously up to a Mn$^{2+}$ concentration of $x = 0.15$ where a saturation effect begins. Concentration quenching of the Mn$^{2+}$ emission was not observed for the synthesized samples.

Furthermore, PLD measurements were performed monitoring the Eu$^{2+}$ emission to investigate the ET from Eu$^{2+}$ to Mn$^{2+}$ in more detail. Fluorescence lifetimes $\tau$ of Ba$_{0.99}$Eu$_{0.01}$(Ca$_{1-x}$Mn$_x$)$_2$Si$_3$O$_9$ samples with increasing Mn$^{2+}$ content were determined, monitoring the 445 nm emission of Eu$^{2+}$ under an excitation wavelength of $\lambda_{\text{ex}} = 375$ nm. Fig. 5 illustrates the obtained PLD curves. The PLD curves can be best fitted with a bi-exponential function applying the following equation:

$$I = A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}}$$ (2)

Here, $I$ is the luminescence intensity, $A_1$ and $A_2$ are parameters and $t$ is the time. The terms $\tau_1$ and $\tau_2$ are the partial lifetimes for the exponential components. The bi-exponential shape of the PLD curves originates from two different emitting centres and suggests Eu$^{2+}$ emission from two distinct crystallographic sites. This is thoroughly possible since BaCa$_2$Si$_3$O$_9$ provides two different Ca sites and one Ba site, as mentioned above. This assumption is backed by PLD measurements monitoring the emission at 415 and 495 nm which yield different luminescence lifetimes ($\tau$ at 415 nm = 602 ns, $\tau$ at 415 nm = 702 ns) (Fig. S1 in the ESI†). The average luminescence lifetimes $\tau$ of Eu$^{2+}$ in BaCa$_2$(Si$_3$O$_9$):Eu$^{2+}$,Mn$^{2+}$ can be derived using the above mentioned parameters and the following equation:

$$\tau = \frac{A_1 \tau_1^2 + A_2 \tau_2^2}{A_1 \tau_1 + A_2 \tau_2}$$ (3)

Emission fractions $\text{frac}_1$ and $\text{frac}_2$, partial lifetimes $\tau_1$, and $\tau_2$ and also the calculated average lifetimes are summarized in Table 1. The results show a decreasing lifetime $\tau$ of Eu$^{2+}$ with increasing Mn$^{2+}$ concentration. Since ET processes are usually faster than radiative transitions, this circumstance clearly indicates the occurrence of an ET from Eu$^{2+}$ to Mn$^{2+}$. The ET efficiency $\eta_T$ can be calculated using following equation:

$$\eta_T = 1 - \frac{\tau_5}{\tau_{50}}$$ (4)

In this equation $\tau_5$ and $\tau_{50}$ are the average lifetimes of Eu$^{2+}$ in the presence and absence of Mn$^{2+}$. The inset of Fig. 5 illustrates the calculated values for $\eta_T$ for the investigated BaCa$_2$Si$_3$O$_9$:Eu$^{2+}$,Mn$^{2+}$ samples as a function of the Mn$^{2+}$ content. This shows that the ET efficiency $\eta_T$ continuously.

Table 1. Fluorescence lifetimes $\tau$ as well as partial lifetimes $\tau_1$ and $\tau_2$ and the emission fractions $\text{frac}_1$ and $\text{frac}_2$ of Eu$^{2+}$ in Ba$_{0.99}$Eu$_{0.01}$(Ca$_{1-x}$Mn$_x$)$_2$Si$_3$O$_9$

<table>
<thead>
<tr>
<th>Sample (x)</th>
<th>$\text{frac}_1$ (%)</th>
<th>$\tau_1$ (ns)</th>
<th>$\text{frac}_2$ (%)</th>
<th>$\tau_2$ (ns)</th>
<th>$\tau$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>13</td>
<td>212</td>
<td>87</td>
<td>698</td>
<td>634</td>
</tr>
<tr>
<td>0.005</td>
<td>14</td>
<td>208</td>
<td>86</td>
<td>697</td>
<td>629</td>
</tr>
<tr>
<td>0.010</td>
<td>13</td>
<td>206</td>
<td>87</td>
<td>690</td>
<td>625</td>
</tr>
<tr>
<td>0.015</td>
<td>13</td>
<td>206</td>
<td>87</td>
<td>693</td>
<td>630</td>
</tr>
<tr>
<td>0.020</td>
<td>12</td>
<td>204</td>
<td>88</td>
<td>687</td>
<td>628</td>
</tr>
<tr>
<td>0.050</td>
<td>13</td>
<td>201</td>
<td>87</td>
<td>680</td>
<td>617</td>
</tr>
<tr>
<td>0.100</td>
<td>13</td>
<td>193</td>
<td>87</td>
<td>673</td>
<td>609</td>
</tr>
<tr>
<td>0.150</td>
<td>15</td>
<td>175</td>
<td>85</td>
<td>636</td>
<td>569</td>
</tr>
<tr>
<td>0.200</td>
<td>16</td>
<td>176</td>
<td>84</td>
<td>629</td>
<td>555</td>
</tr>
</tbody>
</table>
increases with increasing Mn$^{2+}$ content. For the highest Mn$^{2+}$ concentration with $x = 0.20$, $\eta_T$ amounts to 12% whereas the PL intensity of Eu$^{2+}$ decreases around 70%. Due to faster competitive ET processes, e.g. migration to defect sites, a significant amount of emission energy is lost before it can be transferred to the Mn$^{2+}$ ions. This behaviour increases with increasing Mn$^{2+}$ concentration.

The average distance between Eu$^{2+}$ and Mn$^{2+}$ ($R_{\text{Eu-Mn}}$) in the host material at which ET occurs can be estimated by applying the following formula published by Blasse:$^{17}$

$$R_{\text{Ce-Mn}} = \frac{2}{3} \left( \frac{3V}{4\pi x N} \right)^{\frac{1}{3}}$$  \hspace{1cm} (5)

Here, $V$ is the volume of the unit cell, $x$ the concentration of Eu$^{2+}$ and Mn$^{2+}$ in the host, and $N$ is the number of available sites for the dopants in the unit cell. For BaCa$_2$Si$_3$O$_9$, $V$ and $N$ are 396.01 Å$^3$ and 6, respectively. Using this equation for $x = 0.005$, 0.010, 0.015, 0.020, 0.050, 0.100, 0.150, and 0.200, ($R_{\text{Eu-Mn}}$) is calculated to be 20.3, 18.5, 17.1, 16.1, 10.5, 12.8, 10.5, and 8.4 Å, respectively. The Mn$^{2+}$ concentration where the Eu$^{2+}$ PL intensity is one-half of that in the sample without Mn$^{2+}$ is called critical concentration $x_c$. Plugging in $x_c$ into formula (5), the critical distance $R_c$ can be derived. $R_c$ is defined as the distance where the probability of ET from sensitizer to activator equals the probability of radiative transition in the sensitizer. For Ba$_{0.99}$Eu$_{0.01}$(Ca$_{1-x}$Mn$_x$)$_2$Si$_3$O$_9$, $x_c$ was determined to be 0.134. From this, $R_c$ is calculated to be 9.6 Å.

To elucidate the characteristics of the ET process in Ba$_{0.99}$Eu$_{0.01}$(Ca$_{1-x}$Mn$_x$)$_2$Si$_3$O$_9$, the obtained decay curves were analysed by applying the Inokuti–Hirayama model. Assuming a uniform distribution of Eu$^{2+}$ and Mn$^{2+}$ in the host structure, and neglecting further energy migration processes besides the ET from Eu$^{2+}$ to Mn$^{2+}$, the time-dependent course of the PL intensity of Eu$^{2+}$ can be described by following equation:$^{18}$

$$I(t) = I_0 \times e^{-\frac{t}{\tau_0}} - \alpha \left( \frac{t}{\tau_0} \right)^{\frac{1}{3}}$$  \hspace{1cm} (6)

In this equation, $t$ is the time, $I(t)$ is the PL intensity after excitation, $I_0$ is the PL intensity at $t = 0$, $\tau_0$ is the intrinsic luminescence lifetime of the sensitizer in the absence of the activator, $\alpha$ is a parameter for the probability of ET. $S$ is related to the electronic multipole character of the ET. $S = 6$, 8, and 10 corresponds to dipole–dipole, dipole–quadrupole, and quadrupole–quadrupole interactions, respectively. Modifying eqn (6) leads to following relation:

$$\ln \left[ -\ln \left( \frac{I(t)}{I_0} \right) \right] = \ln \left( \frac{t}{\tau_0} \right)^{\frac{1}{3}}$$  \hspace{1cm} (7)

Plotting the PLD curves using this relation yields a straight line with a slope equal to 1/$S$. The obtained curves for the measured Ba$_{0.99}$Eu$_{0.01}$(Ca$_{1-x}$Mn$_x$)$_2$Si$_3$O$_9$ samples with $x = 0.005, 0.010, 0.015, 0.020, 0.050, 0.100, 0.150$, and 0.200 are depicted in Fig. 6. The calculated $S$ values are roughly coincident with the theoretical value of $S = 8$. This result suggests dipole–quadrupole interactions as the dominant mechanism of ET from Eu$^{2+}$ to Mn$^{2+}$ in co-doped BaCa$_2$Si$_3$O$_9$:Eu$^{2+}$,Mn$^{2+}$.

This finding is quite reasonable since the electronic [Xe]4f$^7$–[Xe]4f$^6$5d$^1$-transition in Eu$^{2+}$ is allowed whereas the electronic [Ar]3d$^5$–[Ar]3d$^3$-transition in Mn$^{2+}$ is forbidden. Therefore, the critical distance $R_c$ for ET from Eu$^{2+}$ to Mn$^{2+}$ can be calculated using the spectral overlap method:$^{17,19}$

$$R_c = 0.63 \times 10^{28} \int \frac{f^{2}Q_{A}^{2}Q_{M}^{2}}{f^{2}dE} \int F_{S}(E)F_{A}(E)dE$$  \hspace{1cm} (8)

In this formula $f_{\lambda} = 10^{-10}$ and $f_{\lambda} = 10^{-7}$ are the oscillator strengths of dipole and quadrupole electronic absorption transitions, respectively, for Mn$^{2+}$. The absorption cross section $Q_{A}$ of Mn$^{2+}$ can be expressed using the relationship $Q_{A} = 4.8 \times 10^{-12}f_{\lambda}$ derived by Blasse. $\lambda$ is the emission wavelength of Eu$^{2+}$. $E$ is the energy of maximal spectral overlap. From this, the critical distance $R_c$ is calculated to be 8.9 Å. This value is in accordance with the one calculated using Blasse’s approach (9.6 Å).

To investigate the temperature dependence of the PL of co-doped Ba$_{0.99}$Eu$_{0.01}$(Ca$_{0.90}$Mn$_{0.10}$)$_2$Si$_3$O$_9$, PL spectra were recorded from 100 to 800 K. The obtained PL spectra are depicted in Fig. 7. The spectra demonstrate that with increasing temperature PL intensity of Eu$^{2+}$ and Mn$^{2+}$ decreases due to thermal quenching. The inset of Fig. 7 illustrates the normalized PL integrals versus their temperature. From this, activation energy $E_A$ for thermal quenching can generally be
estimated by fitting the data points by a Fermi–Dirac distribution:

$$I(T) = \frac{I_0}{1 + B \times e^{\frac{E_A}{kT}}}$$  \hspace{2cm} (9)

In this equation, \(I(T)\) is the luminescence intensity at a certain temperature and \(I_0\) is the luminescence intensity at zero Kelvin. \(B\) is the quenching frequency factor, \(T\) is the temperature and \(k\) is the Boltzmann constant. However, due to an additional turning point, the present data points cannot be fitted by ordinary Fermi–Dirac distribution. Therefore, eqn (9) is expanded to a sum of two weighed Fermi–Dirac distributions:

$$I(T) = A \frac{I_{0,a}}{1 + B \times e^{\frac{E_{A,a}}{kT}}} + (1 - A) \frac{I_{0,b}}{1 + B \times e^{\frac{E_{A,b}}{kT}}}$$  \hspace{2cm} (10)

Here, \(I_{0,a}\) and \(I_{0,b}\) are the PL intensities at zero Kelvin. \(A\) describes the fraction of the first term. From this, \(E_{A,a}\) and \(E_{A,b}\) were determined to be about 0.07 and 0.84 eV, respectively. Plugging in the values for \(E_{A,a}\) and \(E_{A,b}\) in eqn (11) yields \(T_{1/2,a}\) and \(T_{1/2,b}\):

$$T_{1/2} = -\frac{E_A}{k \times \ln\left(\frac{1}{2}\right)}$$  \hspace{2cm} (11)

\(T_{1/2}\) is the temperature at which PL intensity of a luminescent centre is decreased to one-half of its maximum. For Ba_{0.99}Eu_{0.01}(Ca_{0.90}Mn_{0.10})_2Si_3O_9, \(T_{1/2,a}\) and \(T_{1/2,b}\) were calculated to be 242 and 666 K, respectively. The PL intensities originating from Eu^{2+} and Mn^{2+} were plotted separately (Fig. S2 and S3 in the ESI†). From that it can be seen that the bi-sigmoidal temperature behaviour strongly decreases if investigating the PL intensities of Eu^{2+} solely. Due to overlapping of the red emission band the bi-sigmoidal shape does not vanish completely. To examine the origin of this double sigmoidal quenching behaviour, PL of singly doped Ba_{0.99}Eu_{0.01}Si_3O_9 was measured in the temperature range from 100 to 800 K as well (Fig. S4 in the ESI†). At low temperatures an additional emission band extending from about 600 to 750 nm arises. PLD measurements of this emission band revealed a fluorescence lifetime of about 945 ns (Fig. S5 in the ESI†). This value matches well with the decay time of Eu^{2+}. Furthermore, the obtained PLD curve shows mono-exponential decay behaviour, indicating emission from one particular crystallographic site. These Eu^{2+} ions presumably occupy the 6-fold coordinated Ca2 sites in BaCa_2Si_3O_9. On this small site, the crystal field splitting of the d-orbitals of Eu^{2+} is rather high because of which the lower edge of the [Xe]5d multiplet is moved towards the ground state. Due to relatively low emission energies in the red spectral range and consequently strong multi-phonon relaxation as well as large Stokes shift, this emission exhibits a lower quenching temperature. Furthermore, with increasing temperature a blue shift of Mn^{2+} emission can be observed. This behaviour is due to an increasing average distance between the Mn^{2+} ions and their oxygen ligands with increasing temperatures. As a consequence, the crystal field splitting of the 3d orbitals of Mn^{2+} decreases resulting in a shift of the \(^{4}T_{1}(^{5}G) \rightarrow ^{6}A_{1}(^{5}S)\) transition to higher energies.20

To obtain more detailed information regarding the temperature dependent behaviour of Ba_{0.99}Eu_{0.01}(Ca_{0.90}Mn_{0.10})_2Si_3O_9, PLD measurements were performed from 100 to 500 K. Fig. 8 depicts the PLD curves of Ba_{0.99}Eu_{0.01}(Ca_{0.90}Mn_{0.10})_2Si_3O_9 monitoring the 445 nm emission of Eu^{2+}. The curves can be best fitted with a bi-exponential function, suggesting Eu^{2+} emission from two distinct crystallographic sites as mentioned previously. The derived fluorescence lifetimes are presented in Table 2 and show an unusual increase with increasing temperatures. This phenomenon was only reported by a few authors and is still uncommon.21,22 According to Meijerink and Blasse, this behaviour is presumably caused by thermal population of
higher energetic 4f-6d states. Excited states in Eu$^{2+}$ can either be (spin) octets or sextets. The sextet states are at higher energies than the octet states according to Hund’s rule. With increasing temperature the higher energetic sextet states will be populated. For these states, transition to the $8S_7/2$ ground state is spin-forbidden resulting in lower decay rates and thus longer fluorescence lifetimes.\(^{22}\) Fluorescence lifetimes of Mn$^{2+}$ emission in dependency of temperature were measured, too. The obtained PLD curves are depicted in Fig. 9 and can be well fitted with a bi-exponential function. This result is consistent with the assumption made above that Mn$^{2+}$ is located on two different crystallographic sites. The calculated average lifetimes of Mn$^{2+}$ are summarized in Table 2. With increasing temperature, Mn$^{2+}$ fluorescence lifetimes decrease continuously due to an increase in non-radiative relaxation to the ground state. Therefore, it can be concluded that thermal quenching of emission in BaCa$_{2}$Si$_{3}$O$_{9}$:Eu$^{2+}$,Mn$^{2+}$ is primarily caused by Mn$^{2+}$ ions. As deduced from PLD curves of Mn$^{2+}$ emission as well as from ionic radii of Ba$^{2+}$, Ca$^{2+}$ and Mn$^{2+}$, it can be concluded that Mn$^{2+}$ ions preferably occupy the two Ca sites in BaCa$_{2}$Si$_{3}$O$_{9}$. Since the ionic radii of 6- and 8-fold co-ordinated Mn$^{2+}$ are smaller compared to those of Ca$^{2+}$, the excited states of Mn$^{2+}$ can strongly be polarized. This leads to an increase in the equilibrium distance between Mn$^{2+}$ and its oxygen ligands and therefore to a shift of the ground and excited state parabolas in the configurational coordinate diagram. Further, the crossing point of the parabolas is shifted to lower energy, and thus to a lower activation energy for thermal quenching.

To investigate the PL efficiency of the Ba$_{0.99}$Eu$_{0.01}$–(Ca$_{1-x}$Mn$_{x}$)$_{2}$Si$_{3}$O$_{9}$ samples, external quantum efficiencies $\eta_{\text{ext}}$ were measured as mentioned above. To the best of our understanding, external quantum efficiency $\eta_{\text{ext}}$ is defined as:

$$\eta_{\text{ext}} = \frac{N_{\text{emission}}}{N_{\text{absorption}}}$$  \(12\)

where $N_{\text{emission}}$ is the number of photons emitted by the phosphor and $N_{\text{absorption}}$ is the number of photons absorbed by the phosphor. The resulting quantum efficiencies $\eta_{\text{ext}}$ are summarized in Table 3. For the investigated samples $\eta_{\text{ext}}$ is around 30%. The low quantum efficiency of BaCa$_{2}$Si$_{3}$O$_{9}$:Eu$^{2+}$,Mn$^{2+}$ can be ascribed to the overlap of the blue emission band and the excitation band of the red emission of Eu$^{2+}$. Due to ET from the blue Eu$^{2+}$ site to the red Eu$^{2+}$ site which is thermally quenched, $\eta_{\text{ext}}$ decreases.

According to the relevant PL spectra, Commission International de l’Eclairage 1931 (CIE) chromaticity coordinates were calculated. Fig. 10 depicts the CIE chromaticity diagram.
Table 3  External quantum efficiencies $\eta_{ext}$ and CIE colour coordinates of $\text{Ba}_{0.99}\text{Eu}_{0.01}(\text{Ca}_{1-x}\text{Mn}_x)\text{Si}_3\text{O}_9$

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\eta_{ext}$</th>
<th>CIE ($x$/$y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 0.000$</td>
<td>0.31</td>
<td>(0.151</td>
</tr>
<tr>
<td>$x = 0.005$</td>
<td>0.31</td>
<td>(0.163</td>
</tr>
<tr>
<td>$x = 0.010$</td>
<td>0.30</td>
<td>(0.170</td>
</tr>
<tr>
<td>$x = 0.015$</td>
<td>0.31</td>
<td>(0.182</td>
</tr>
<tr>
<td>$x = 0.020$</td>
<td>0.32</td>
<td>(0.190</td>
</tr>
<tr>
<td>$x = 0.050$</td>
<td>0.34</td>
<td>(0.224</td>
</tr>
<tr>
<td>$x = 0.100$</td>
<td>0.36</td>
<td>(0.260</td>
</tr>
<tr>
<td>$x = 0.150$</td>
<td>0.26</td>
<td>(0.325</td>
</tr>
<tr>
<td>$x = 0.200$</td>
<td>0.30</td>
<td>(0.354</td>
</tr>
</tbody>
</table>

4. Conclusions

A series of $\text{Ba}_{0.99}\text{Sr}_0.01\text{Eu}^{2+}\text{Mn}^{2+}$ powder samples with various Mn$^{2+}$ concentrations was prepared via high temperature solid state synthesis. Excited by UV radiation, $\text{Ba}_{0.99}\text{Sr}_0.01\text{Eu}^{2+}\text{Mn}^{2+}$ shows two emission bands located at about 444 and 594 nm originating from Eu$^{2+}$ and Mn$^{2+}$, respectively. It turned out that Eu$^{2+}$ ions in $\text{Ba}_{0.99}\text{Sr}_0.01\text{Eu}^{2+}\text{Mn}^{2+}$ occupy the 8-fold coordinated Ba and Ca1 sites as well as the 6-fold coordinated Ca2 sites. Mn$^{2+}$ ions tend to occupy both Ca sites. These results are confirmed by PLD measurements. The highest PL intensity of Mn$^{2+}$ was found at a Mn$^{2+}$ concentration of $x = 0.15$. It was further demonstrated that ET from Eu$^{2+}$ to Mn$^{2+}$ in $\text{Ba}_{0.99}\text{Sr}_0.01\text{Eu}^{2+}\text{Mn}^{2+}$ is of resonant type and occurs via dipole-quadrupole interaction. The critical distance $R_c$ between Eu$^{2+}$ and Mn$^{2+}$ was derived by using Blasse’s concentration quenching method as well as the spectral overlap method and was calculated to be 9.6 and 8.9 Å, respectively. Temperature dependent PL measurements prove a “double” sigmoidal decrease of the PL intensity of Eu$^{2+}$. Therefore, $\text{Ba}_{0.99}\text{Sr}_0.01\text{Eu}^{2+}\text{Mn}^{2+}$ has two $T_{1/2}$ values, $T_{1/2,a}$ and $T_{1/2,b}$, which were calculated to be 242 and 666 K, respectively. In addition to that, PLD measurements revealed an unusual increase of Eu$^{2+}$ fluorescence lifetime, which presumably originates from thermal population of higher excited energy levels. Temperature dependent PLD measurements on the Mn$^{2+}$ emission suggest that thermal quenching in $\text{Ba}_{0.99}\text{Sr}_0.01\text{Eu}^{2+}\text{Mn}^{2+}$ is primarily caused by Mn$^{2+}$ ions. CIE 1931 colour points can be tuned from the blue to the magenta colour range.

Acknowledgements

The authors are grateful to Merck KGaA Darmstadt, Germany, for generous financial support.

Notes and references