Quantum cutting and tunable luminescence properties in $\text{Pr}^{3+}/\text{Sm}^{3+}$, Yb^{3+} co-doped SrMoO_4 powders

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ABSTRACT: Pr^{3+} , Yb^{3+} and Sm^{3+} , Yb^{3+} co-doped SrMoO_4 phosphors have been prepared via high temperature solid-state reaction method. The quantum cutting based on Sm^{3+} , Yb^{3+} couple results in a new emission band at 1000 nm and the quantum cutting based on Pr^{3+} , Yb^{3+} couple realizes a broad near-infrared emission of about 76 nm in full width at half maximum, centered at 1000 nm. Meanwhile the near infrared emission intensity for Sm^{3+} , Yb^{3+} and Pr^{3+} , Yb^{3+} co-doped SrMoO_4 phosphors have also been increased by 2.1 and 1.8 times, with 36.5% and 9.6% energy transfer efficiencies from Sm^{3+} to Yb^{3+} and Pr^{3+} to Yb^{3+} , respectively. The result provides a meaningful reference for designing broad-band near infrared phosphors or tunable near infrared laser materials.

1. INTRODUCTION

Quantum cutting (QC) can divide one high-energy photon into two or more low-energy photons, which makes the quantum efficiency of a luminescent material greater than 100% possible. QC has attracted much

attention of researchers since it was firstly observed in Pr^{3+} doped YF_3 phosphor [1, 2]. Now QC is regarded as a key approach to enhance the luminescent efficiency of phosphors.[3-7]. The $4f^N$ energy level structures of the rare earth ions and the interactions behind these provide a variety of possible ways for the realization of quantum cutting. Especially, QC phosphors based on Yb^{3+} , RE^{3+} ($\text{RE} = \text{Tb}, \text{Pr}, \text{Tm}, \text{Ho}$ and Ce) [6-13] couple has become a focus in recent years, owing to the special energy-level structure of Yb^{3+} ion. The Yb^{3+} ion has a single excited state (denoted by the term symbol $^2\text{F}_{5/2}$) $10,000\text{ cm}^{-1}$ above the $^2\text{F}_{7/2}$ ground state. The absence of other energy levels allows Yb^{3+} to exclusively “pick up” energy packages of $10,000\text{ cm}^{-1}$ from other co-doped lanthanide ions and emits photons at 1000 nm. Since the emission of Yb^{3+} at around 1000 nm matches well with the band gap of crystalline Si, QC phosphors based on Yb^{3+} , RE^{3+} is believed to be possibly applied in Si-based solar cells and NUV detectors. It is well known that the Pr^{3+} or Sm^{3+} doped phosphors can also give near infrared emission matching with Si-based optoelectronic devices under NUV or visible excitation. However, the luminescence efficiency for Pr^{3+} or Sm^{3+} doped phosphors is usually quite low. Considering the energy-level matching characteristics between $\text{Sm}^{3+}/\text{Pr}^{3+}$ and Yb^{3+} ions, the near infrared luminescence properties of Sm^{3+} and Pr^{3+} are also expected to be adjusted and improved by energy transfer

induced QC between the $\text{Sm}^{3+}/\text{Pr}^{3+}, \text{Yb}^{3+}$ couple.

On the other hand, recently the rare-earth ions activated alkaline earth metal tungstates and molybdates have attracted significant interests due to their attractive luminescence behavior and interesting structural properties for applications in ultra violet excited light-emitting diode (LED). The rare-earth ions activated alkaline earth metal tungstates and molybdates have scheelite-type tetragonal structure [14-17], belonging to the space group C_{4h}^6 ($I4_1/a$) [18-20]. Each of Mo or W atom is surrounded by four equivalent O atoms composing the $[\text{XO}_4]^{2-}$ ($\text{X} = \text{Mo}$ or W) tetrahedral configuration and each divalent metal shares corners with eight adjacent O atoms of $[\text{XO}_4]^{2-}$ tetrahedrons [21-23]. These special structure features of WO_4^{2-} and MoO_4^{2-} group in the phosphors lead to excellent thermal and hydrolytic stability of the phosphors. Moreover, these phosphors have strong absorption within the ultraviolet region and the energy absorbed can be transferred effectively to the doped rare earth ions[24]. In past years, therefore, the photoluminescence investigation of rare earth ions doped tungstates and molybdates was mainly focused on the ultraviolet to visible conversion for LED application, like Tb^{3+} , Tm^{3+} , Pr^{3+} , Sm^{3+} , Eu^{3+} doped SrMoO_4 , CaMoO_4 , SrWO_4 and CaWO_4 [25-31]. However, the near infrared conversion properties of rare earth ions doped tungstates and molybdates have received little attention.

In this work, therefore, Yb^{3+} , Pr^{3+} and Yb^{3+} , Sm^{3+} co-doped SrMoO_4 phosphors were synthesized. The tunable luminescence properties and the energy transfer induced QC mechanism have been discussed in detail.

2. EXPERIMENTAL

$\text{Sr}_{0.98-x}\text{MoO}_4$: 2% Sm^{3+} , x% Yb^{3+} , (x= 0, 0.3, 0.5, 1.0, 1.5, 2.0) and $\text{Sr}_{0.98-y}\text{MoO}_4$: 2% Pr^{3+} , y% Yb^{3+} , (y= 0, 0.5, 1.0, 1.5, 2.0) phosphors were synthesized through high temperature solid-state reaction technique. The starting materials were SrCO_3 , MoO_3 , Sm_2O_3 , Pr_6O_{11} and Yb_2O_3 (all materials are in analytical grade with purity of 99.99%). The raw materials were weighted according to the stoichiometric proportion, and an excess of 3 wt% of MoO_3 was added to the starting materials considering the influence of volatilization of MoO_3 . The reagents were mixed and ground thoroughly, and then the mixture were filled in corundum crucible and sintered for two times. After sintered at 800 °C for 3hr at air atmosphere, the intermediates were ground thoroughly and then sintered at 950 °C for another 3hr at air atmosphere. The finally obtained products were ground into powder with average size about 5 μm for measurement.

The crystalline phases of the phosphors were identified by a D/MAX 2500 X-ray diffract (XRD) meter using Cu tube with $\text{K}\alpha$ radiation of

0.15406nm in the 2θ range of $15^{\circ}\sim 85^{\circ}$. The excitation and emission spectra were obtained by a monochromator (Zolix Instrument, Omni- λ 320i) coupled with photomultiplier (PMTH-S1-CR131) and NIR sensitive detector (DInGaAs 2600-TE), which is equipped with a 150 W xenon lamp as the excitation source. The luminescence decay curves were measured by FLS920 (Edinburgh) spectrometer. All the measurements were performed at room temperature.

3. RESULTS AND DISCUSSION

Fig. 1 shows the XRD patterns of $\text{Sr}_{0.98-x}\text{MoO}_4: 2\%\text{Pr}^{3+}, x\%\text{Yb}^{3+}$, ($x= 0, 1.0, 2.0$) and $\text{Sr}_{0.98-y}\text{MoO}_4: 2\%\text{Sm}^{3+}, y\%\text{Yb}^{3+}$, ($y= 0, 1.0, 2.0$). All the peaks of the XRD pattern of $\text{Sr}_{0.98-x}\text{MoO}_4: 2\%(\text{Sm}^{3+} \text{ or } \text{Pr}^{3+}), x\%\text{Yb}^{3+}$ are in a good agreement with the JCPDS card #85-0586 for SrMoO_4 and there no obviously peaks of impurity phase have been observed, indicating that the doped Sm^{3+} , Pr^{3+} and Yb^{3+} ions have embedded into the crystal lattice and replaced sites of Sr^{2+} ions successfully.

Fig.1. XRD patterns of $\text{Sr}_{0.98-x}\text{MoO}_4: 2\%\text{Pr}^{3+}, x\%\text{Yb}^{3+}$, $\text{Sr}_{0.98-x}\text{MoO}_4: 2\%\text{Sm}^{3+}, x\%\text{Yb}^{3+}$ and the JCPDS card #85-0586 for SrMoO_4 .

The excitation spectra of Pr^{3+} single doped SrMoO_4 phosphors monitored at 647nm originating from the $\text{Pr}^{3+}: {}^3\text{P}_0 \rightarrow {}^3\text{F}_2$ transition and Sm^{3+} single doped SrMoO_4 monitored at 644 nm originating from the $\text{Sm}^{3+}: {}^4\text{G}_{5/2} \rightarrow {}^6\text{H}_{9/2}$ transition are shown in Fig.2, respectively. The excitation band of Pr^{3+} doped SrMoO_4 in the 435 -500 nm region is composed of the ${}^3\text{H}_4 \rightarrow {}^3\text{P}_J$ ($J = 0, 1, 2$) transitions, and the ${}^3\text{H}_4 \rightarrow {}^3\text{P}_2$ (455nm) transition is the strongest one among these transitions. In the Sm^{3+} doped SrMoO_4 , the excitation spectra are composed of several excitation bands ranging from 340 to 520 nm, and among them the strongest transition is ${}^6\text{H}_{5/2} \rightarrow {}^4\text{K}_{11/2}$

(405nm). The other excitation bands at 361nm, 375nm, 420nm, 460nm and 480nm can be ascribed to the ${}^6\text{H}_{5/2} \rightarrow {}^4\text{D}_{5/2}$, ${}^6\text{H}_{5/2} \rightarrow {}^4\text{D}_{3/2}$, ${}^6\text{H}_{5/2} \rightarrow {}^4\text{L}_{13/2}$, ${}^6\text{H}_{5/2} \rightarrow {}^4\text{I}_{13/2}$ and ${}^6\text{H}_{5/2} \rightarrow {}^4\text{I}_{11/2}$ transitions, respectively. The excitation band from 230nm to 320nm observed is the charge transfer band.

Fig.2 Excitation spectra of Pr^{3+} single doped SrMoO_4 phosphors monitored at 647nm (a) and Sm^{3+} single doped SrMoO_4 monitored at 644nm (b).

The measured visible and near infrared (NIR) emission spectra for the 2% Pr^{3+} , x% Yb^{3+} co-doped phosphors under excitation of 455 nm and 2% Sm^{3+} , x% Yb^{3+} co-doped under excitation of 405 nm phosphors are shown in Fig.3 and Fig.4, respectively.

From emission spectra in the visible region shown in Fig.3(a), we can see that the most intense emission band locates at around 647 nm, coming from the Pr^{3+} : ${}^3\text{P}_0 \rightarrow {}^3\text{F}_2$ transition in the Pr^{3+} , Yb^{3+} co-doped SrMoO_4 . The other emissions at 493, 528 and 620 nm are ascribed to the multiple

electronic transitions of Pr^{3+} : $^3\text{P}_0 \rightarrow ^3\text{H}_J$ ($J = 4, 5, 6$) and emissions at 605 and 685 nm are ascribed to transitions of Pr^{3+} : $^1\text{D}_2 \rightarrow ^3\text{H}_J$ ($J = 4, 5$), respectively. In Fig.3(b), all the visible emissions of Sm^{3+} , Yb^{3+} co-doped SrMoO_4 phosphors are originated from the $^4\text{G}_{5/2}$ level of Sm^{3+} , and in descending order of emission strength were 644nm, 600nm, 565nm and 685nm, ascribing to the transitions of Sm^{3+} : $^4\text{G}_{5/2} \rightarrow ^6\text{H}_J$ ($J = 9/2, 7/2, 5/2, 11/2$), respectively.

It is noted that the visible emission intensities of Pr^{3+} , Yb^{3+} and Sm^{3+} , Yb^{3+} co-doped SrMoO_4 phosphors decrease with the concentration of Yb^{3+} . The insets in Fig.3(a) and (b) further give the Pr^{3+} : $^3\text{P}_0 \rightarrow ^3\text{F}_2$ transition (644nm) and Sm^{3+} : $^4\text{G}_{5/2} \rightarrow ^6\text{H}_{9/2}$ transition (647nm) intensities as function of Yb^{3+} concentration, respectively. It suggests that the introduced Yb^{3+} ions quench the visible emissions of both Pr^{3+} and Sm^{3+} ions in SrMoO_4 .

Fig.3. Visible emission spectra of 2%Pr³⁺ single doped and 2%Pr³⁺, 1%Yb³⁺ co-doped SrMoO₄ (a) and 2%Sm³⁺ single doped and 2%Sm³⁺, 1%Yb³⁺ co-doped SrMoO₄ (b).

Inset shows the emission intensity tendency of the Pr³⁺: ³P₀→³F₂ (a) and Sm³⁺: ⁴G_{5/2}→⁶H_{9/2} (b) transition as function of Yb³⁺ concentration, the red line in the inset is a guide to the eyes.

The near infrared (NIR) emission spectra of the 2%Pr³⁺, x%Yb³⁺ doped and 2%Sm³⁺, x%Yb³⁺ doped SrMoO₄ phosphors are shown in Fig.4 (a) and (b), respectively. The near infrared emission peaks at 1040 nm in the Pr³⁺ single doped sample, assigned to the ¹G₄→³H₄ electronic transition of Pr³⁺. However, an emission at around 1000nm ascribed to the Yb³⁺: ²F_{5/2}→²F_{7/2} transition appears with the introduction of Yb³⁺ ions. As the Yb³⁺ concentration increases, the new emission band at 1000 nm goes up rapidly. This enhances the total emission intensity in the near infrared region. At Yb³⁺ concentration of 1%, the near infrared intensity in the region of 940-1100 nm increases by 1.8 times as compared with that of

the Pr^{3+} single doped sample. However, higher Yb^{3+} concentration will decrease the emission intensity due the concentration quenching. Interestingly, the spectral overlapping between the $\text{Yb}^{3+}: {}^2\text{F}_{5/2} \rightarrow {}^2\text{F}_{7/2}$ and $\text{Pr}^{3+}: {}^1\text{G}_4 \rightarrow {}^3\text{H}_4$ emission can broaden the bandwidth of the near infrared emission band whose peak locates at around 1000 nm. It is found that the 2% Pr^{3+} , 1% Yb^{3+} co-doped SrMoO_4 gives a broad near infrared band peaking at 1000 nm with full-width at half-maximum of 76 nm. The result can provide meaningful reference for designing broad-band near infrared phosphors or tunable near infrared laser materials.

In the Sm^{3+} single doped SrMoO_4 , the dominated emission in the near infrared region located at 940nm, originated from the $\text{Sm}^{3+}: {}^6\text{F}_{11/2} \rightarrow {}^6\text{H}_{5/2}$ transition. The other weaker emission at 700 nm, 890 nm and 1160 nm can also be observed, which are ascribed to ${}^4\text{G}_{5/2} \rightarrow {}^6\text{H}_{11/2}$, ${}^4\text{G}_{5/2} \rightarrow {}^6\text{F}_{5/2}$ and ${}^4\text{G}_{5/2} \rightarrow {}^6\text{F}_{9/2}$, respectively. With the concentration of Yb^{3+} ions increasing in the Sm^{3+} , Yb^{3+} co-doped sample, the intensities of the all emissions that originate from Sm^{3+} decrease, but the new emission band at around 1000nm ascribed to the $\text{Yb}^{3+}: {}^2\text{F}_{5/2} \rightarrow {}^2\text{F}_{7/2}$ transition increases, meaning that the emission intensities at 940 nm and 1000 nm can be conveniently adjusted by introducing Yb^{3+} ions of different concentration. The 1000 nm intensity reaches its maximum value at Yb^{3+} concentration of 1%, and then decreases at higher Yb^{3+} concentration. The near infrared intensity of

the 2%Sm³⁺, 1%Yb³⁺ co-doped SrMoO₄ in the region of 850-1100 nm increases by 2.1 times as compared with that of the Sm³⁺ single doped sample. Meanwhile the wavelength of the maximum emission peak shifts from 940 nm to 1000 nm. These results indicate that the introduced Yb³⁺ can not only adjust the spectral structure of the near infrared emission but also enhance its total intensity.

Fig.4. Near infrared (NIR) emission spectra of the 2%Pr³⁺, x%Yb³⁺ co-doped SrMoO₄ (a) and 2%Sm³⁺, x%Yb³⁺ co-doped SrMoO₄(b).

The Yb³⁺ concentration dependent luminescence properties in visible and near infrared regions suggest that the energy transfer (ET) processes from the Pr³⁺/ Sm³⁺ to Yb³⁺ ions take place in the Pr³⁺, Yb³⁺ and Sm³⁺, Yb³⁺ co-doped SrMoO₄ phosphors. The energy transfer induced quantum cutting has been witnessed in many Pr³⁺, Yb³⁺ co-doped phosphors [2, 32-34]. It is usually believed that there are two possible energy transitions from the Pr³⁺ to Yb³⁺ ions. They are cooperative energy transfer $^3P_0(\text{Pr}^{3+}) + 2^2F_{7/2}(\text{Yb}^{3+}) \rightarrow ^3H_4(\text{Pr}^{3+}) + 2^2F_{5/2}(\text{Yb}^{3+})$ and cross relaxation energy transfer $^3P_0(\text{Pr}^{3+}) + ^2F_{7/2}(\text{Yb}^{3+}) \rightarrow ^1G_4(\text{Pr}^{3+}) + ^2F_{5/2}(\text{Yb}^{3+})$ [2, 32-34]. Both ways can feed the Yb³⁺: $^2F_{5/2}$ level and depopulate the Pr³⁺: 3P_0 level, resulting in the enhancement of near infrared emission and the decrease of visible emission. In this case, the cross relaxation energy transfer from

Pr^{3+} to Yb^{3+} should be a more preferable way. This can be proved from emission spectra shown in Fig.4(a). Two NIR emission bands around 1000 and 1040 nm are observed in the Pr^{3+} , Yb^{3+} co-doped samples, which are derived from Yb^{3+} : $^2\text{F}_{5/2} \rightarrow ^2\text{F}_{7/2}$ and Pr^{3+} : $^1\text{G}_4 \rightarrow ^3\text{H}_4$ transitions respectively. Their emission intensities can be both enhanced with the addition Yb^{3+} ions and the Yb^{3+} -concentration dependent behaviors for the two emissions are also similar. This energy transfer induced quantum cutting broadens the bandwidth of emission at 1000 nm and enhances the near infrared luminescence intensity. The energy transfer mechanism excited by 455nm is described in **Fig.5(a)**.

In the Sm^{3+} , Yb^{3+} co-doped SrMoO_4 , the energy transfer quantum cutting between the Sm^{3+} , Yb^{3+} couple also occurs. In terms of the measured visible emission spectra in Fig.3(b) and the near infrared emission spectra in Fig.4(b), the energy transfer also decreases emissions of Sm^{3+} but increases the near infrared emission of Yb^{3+} . In these phosphors the visible emissions all originate from the $^4\text{G}_{5/2}$ level of Sm^{3+} to $^6\text{H}_J$ ($J = 5/2, 7/2, 9/2, 11/2$) level, respectively, no emission originated from levels beyond the $^4\text{G}_{5/2}$ level is observed. This means the non-radiative relaxation from $^4\text{K}_{11/2}$ to $^4\text{G}_{5/2}$ level is very rapid and efficient when Sm^{3+} is excited into its $^4\text{K}_{11/2}$ level by 405 nm light, so that the emission from the levels above $^4\text{G}_{5/2}$ is too weak to be observed. Therefore, it is deduced that the

most likely energy transfer from Sm^{3+} to Yb^{3+} ions is ${}^4\text{G}_{5/2}(\text{Sm}^{3+}) + {}^2\text{F}_{7/2}(\text{Yb}^{3+}) \rightarrow {}^6\text{F}_{7/2}(\text{Sm}^{3+}) + {}^2\text{F}_{5/2}(\text{Yb}^{3+})$, as shown in Fig.4(b). Obviously, the ${}^2\text{F}_{7/2}$ level of Yb^{3+} and ${}^6\text{F}_{7/2}$ level of Sm^{3+} will be both populated by this energy transfer QC. Thus the emissions from the ${}^2\text{F}_{7/2}$ level of Yb^{3+} and from the ${}^6\text{F}_{7/2}$ level of Sm^{3+} are expected in the Sm^{3+} , Yb^{3+} co-doped samples. However, only the 1000 nm Yb^{3+} emission is realized in the Sm^{3+} , Yb^{3+} co-doped SrMoO_4 . No emission from the ${}^6\text{F}_{7/2}$ level of Sm^{3+} is observed at any Yb^{3+} concentration. This can be ascribed to the dense level distribution and its small neighboring-level energy gap from the ${}^6\text{F}_{7/2}$ to ground states of Sm^{3+} . It leads to a very fast non-radiative decay of Sm^{3+} ions in ${}^6\text{F}_{7/2}$ state. Consequently the emission originated from the ${}^6\text{F}_{7/2}$ level is quite weak and hardly observed.

Fig.5. Schematic diagram of energy transfer mechanism between Pr^{3+} (Sm^{3+}), Yb^{3+} couple in SrMoO_4 .

To further understand the quantum cutting performed by energy transfer of Pr^{3+} , Yb^{3+} and Sm^{3+} , Yb^{3+} couples, the decay curves of Pr^{3+} : $^1\text{P}_0 \rightarrow ^3\text{F}_2$ emission at 647 nm and Sm^{3+} : $^4\text{G}_{5/2} \rightarrow ^6\text{H}_{9/2}$ emission at 644 nm have been measured, after the Pr^{3+} ions and Sm^{3+} ions are excited into their $^3\text{P}_1$ and $^4\text{I}_{11/2}$ levels by 472nm and 470nm light, respectively. The measured luminescence decay curves are shown in **Fig.6**.

Fig.6. Luminescence decay curves of Pr^{3+} : $^1\text{P}_0 \rightarrow ^3\text{F}_2$ emission (647nm) in Pr^{3+} , Yb^{3+} co-doped SrMoO_4 (a) and Sm^{3+} : $^4\text{G}_{5/2} \rightarrow ^6\text{H}_{9/2}$ transition (644 nm) in Sm^{3+} , Yb^{3+} co-doped SrMoO_4 (b).

The average lifetime (τ) and the energy transfer efficiency (η) can be calculated by using the following equations [35, 36]:

$$\tau = \frac{\int_0^\infty t I(t) dt}{\int_0^\infty I(t) dt} \quad (1)$$

$$\eta_{\text{Tx}} = 1 - \tau_{x\%} / \tau_0 \quad (2)$$

Here $I(t)$ is the time-dependent luminescence intensity. $\tau_{x\%}$ and τ_0 are the average lifetime of the corresponding state with x% Yb^{3+} and without Yb^{3+} doping, respectively. The calculated luminescence average lifetimes are given in Fig6. Both 647nm from Pr^{3+} : $^3\text{P}_0 \rightarrow ^3\text{F}_2$ transition and 644nm from Sm^{3+} : $^4\text{G}_{5/2} \rightarrow ^6\text{H}_{9/2}$ transition decrease monotonically with the increasing concentration of Yb^{3+} ions. The results give direct evidence that the energy transfers from Pr^{3+} to Yb^{3+} and Sm^{3+} to Yb^{3+} originate in the $^3\text{P}_0$ level of Pr^{3+} and $^4\text{G}_{5/2}$ level of Sm^{3+} , respectively.

Fig.7. Near infrared integral intensities of Pr^{3+} , Yb^{3+} and Sm^{3+} , Yb^{3+} codoped SrMoO_4 ,

and efficiency tendency of energy transfer from Pr^{3+} to Yb^{3+} and Sm^{3+} to Yb^{3+} ions when changing Yb^{3+} concentration, the lines in the inset is a guide to the eyes.

The Yb^{3+} concentration dependent quantum efficiency calculated with Eq.(2) and near infrared integral intensity are plotted in Fig.7. The Yb^{3+} emission intensity initially increases with the doping concentration increasing in both Pr^{3+} , Yb^{3+} and Sm^{3+} , Yb^{3+} co-doped samples, and then tends to decrease after reaching its maximal value, while the quantum cutting efficiency always increases with Yb^{3+} doping concentration increasing. This indicates that the concentration quenching caused by cross-relaxation among the doped ions results in the decrease of luminescence intensity at high Yb^{3+} concentration. The 2% Pr^{3+} , 1% Yb^{3+} and 2% Sm^{3+} , 1% Yb^{3+} co-doped SrMoO_4 phosphors give the strongest emissions in the near infrared region, in which the energy transfer efficiencies from Pr^{3+} to Yb^{3+} and Sm^{3+} to Yb^{3+} are 9.6% and 36.5 %, respectively.

4. CONCLUSION

In this work, Pr^{3+} , Yb^{3+} and Sm^{3+} , Yb^{3+} co-doped SrMoO_4 phosphors have been synthesized via traditional high temperature solid-state reaction method. These phosphors give efficient luminescence in near infrared region. QC performed by the ${}^3\text{P}_0(\text{Pr}^{3+}) + {}^2\text{F}_{7/2}(\text{Yb}^{3+}) \rightarrow {}^1\text{G}_4(\text{Pr}^{3+}) + {}^2\text{F}_{5/2}(\text{Yb}^{3+})$ and ${}^4\text{G}_{5/2}(\text{Sm}^{3+}) + {}^2\text{F}_{7/2}(\text{Yb}^{3+}) \rightarrow {}^6\text{F}_{7/2}(\text{Sm}^{3+}) + {}^2\text{F}_{5/2}(\text{Yb}^{3+})$

energy transfers has been observed in Pr^{3+} , Yb^{3+} and Sm^{3+} , Yb^{3+} co-doped SrMoO_4 phosphors respectively, which can intensify the near infrared emission intensity and adjust the spectra distribution. The work might provide useful reference for designing broad-band near infrared phosphors or tunable near infrared laser materials.

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REFERENCES

- [1] X. Wang, J. Zheng, Y. Xuan, X. Yan, Optics express, 21 (2013) 21596-21606.
- [2] L. Aarts, B.v.d. Ende, M.F. Reid, A. Meijerink, Physical Review B Condensed Matter, 81 (2010) 373-381.
- [3] X. Wang, X. Yan, Optics Letters, 36 (2011) 4353-4355.
- [4] d.E. Van, Bryan M., L. Aarts, A. Meijerink, Advanced Materials, 21 (2009) 3073-3077.
- [5] X. Huang, D. Chen, L. Lin, Z. Wang, Optik - International Journal for Light and Electron Optics, 125 (2014) 565-568.
- [6] W. Piper, Journal of Luminescence, 8 (1974) 344-348.
- [7] J.L. Sommerdijk, A. Bril, A.W.D. Jager, Journal of Luminescence, 9 (1974) 288-296.
- [8] X. Liu, S. Ye, Y. Qiao, G. Dong, B. Zhu, D. Chen, G. Lakshminarayana, J. Qiu, Applied Physics B, 96 (2009) 51-55.
- [9] K. Deng, T. Gong, L. Hu, X. Wei, Y. Chen, M. Yin, Optics Express, 19 (2011) 1749-1754.
- [10] YU D. C., HUANG X. Y, YE S., ZHANG Q. Y., Journal of Alloys & Compounds, 509 (2011) 9919-9923.
- [11] J.D. Chen, H. Guo, Z.Q. Li, H. Zhang, Y.X. Zhuang, J.D. Chen, H. Guo, Z.Q. Li, H. Zhang, Y.X. Zhuang, Optical Materials, 32 (2010) 998-1001.
- [12] L. Lin, H. Lin, Z. Wang, J. Chen, R. Huang, X. Rao, Z. Feng, Z. Zheng, Optical

Materials, 36 (2014) 1065-1069.

[13] X. Wang, C.S. Liu, T. Yu, X. Yan, Physical Chemistry Chemical Physics Pccp, 16 (2014) 13440-13446.

[14] L.S. Cavalcante, J.C. Sczancoski, R.L. Tranquilin, J.A. Varela, E. Longo, M.O. Orlandi, Particuology, 7 (2009) 353-362.

[15] J.C. Sczancoski, L.S. Cavalcante, M.R. Joya, J.A. Varela, P.S. Pizani, E. Longo, Chemical Engineering Journal, 140 (2008) 632-637.

[16] A. Phuruangrat, T. Thongtem, S. Thongtem, Journal of Alloys & Compounds, 481 (2009) 568-572.

[17] L.S. Cavalcante, J.C. Sczancoski, R.L. Tranquilin, M.R. Joya, P.S. Pizani, J.A. Varela, E. Longo, Journal of Physics & Chemistry of Solids, 69 (2008) 2674-2680.

[18] Lingna Sun, Qingrong Guo, Xinglong Wu, Shengjun Luo, Wanlong Pan, Kunlin Huang, Junfeng Lu, L. Ren, Minhua Cao, ‡ And, Changwen Hu, Journal of Physical Chemistry C, 111 (2007) 532-537.

[19] G. Jia, C. Tu, Z. You, J. Li, Z. Zhu, Y. Wang, B. Wu, Journal of Crystal Growth, 273 (2004) 220-225.

[20] M. Anicetesantos, F.C. Picon, M.T. Escote, E.R. Leite, P.S. Pizani, J.A. Varela, E. Longo, Applied Physics Letters, 88 (2006) 211913-211913-211913.

[21] A. Phuruangrat, T. Thongtem, S. Thongtem, Journal of Crystal Growth, 311 (2009) 4076-4081.

[22] A. Phuruangrat, T. Thongtem, S. Thongtem, Journal of Physics & Chemistry of Solids, 70 (2009) 955-959.

[23] N. Niu, P. Yang, W. Wang, F. He, S. Gai, D. Wang, J. Lin, Materials Research Bulletin, 46 (2011) 333-339.

[24] Z.H. Ju, R.P. Wei, J.X. Ma, C.R. Pang, W.S. Liu, Journal of Alloys & Compounds, 507 (2010) 133-136.

[25] P. Yang, L.I. Chunxia, W. Wang, Z. Quan, S. Gai, J. Lin, Journal of Solid State Chemistry, 182 (2009) 2510-2520.

[26] M.M. Haque, H.I. Lee, D.K. Kim, Journal of Alloys & Compounds, 481 (2009) 792-796.

[27] L. Zhou, J. Wei, J. Wu, F. Gong, L. Yi, J. Huang, Journal of Alloys and Compounds, 476 (2009) 390-392.

[28] F.B. Cao, Y.W. Tian, Y.J. Chen, L.J. Xiao, Q. Wu, Journal of Alloys & Compounds, 475 (2009) 387-390.

[29] X. Li, Z. Yang, L. Guan, J. Guo, Y. Wang, Q. Guo, Journal of Alloys & Compounds, 478 (2009) 684-686.

[30] C. Guo, F. Gao, L. Liang, B.C. Choi, J.-H. Jeong, Journal of Alloys and Compounds, 479 (2009) 607-612.

[31] J. Wan, L. Cheng, J. Sun, H. Zhong, X. Li, W. Lu, Y. Tian, H. Lin, B. Chen, Journal of Alloys and Compounds, 496 (2010) 331-334.

[32] Y. Katayama, S. Tanabe, Materials, 3 (2010) 2405-2411.

[33] E.V.D. Kolk, O.M.T. Kate, J.W. Wiegman, D. Biner, K.W. Krämer, Technovation,

33 (2011) 1024-1027.

[34] X. Zhou, G. Wang, K. Zhou, Q. Li, Optical Materials, 35 (2013) 600-603.

[35] H. Jing, C. Guo, G. Zhang, X. Su, Z. Yang, J.H. Jeong, J.mater.chem, 22 (2012) 13612-13618.

[36] P.I. Paulose, G. Jose, V. Thomas, N.V. Unnikrishnan, M.K.R. Warriar, Journal of Physics & Chemistry of Solids, 64 (2003) 841–846.