

# Visible green upconversion luminescence of $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped $\text{CaWO}_4$ phosphor and effects of $\text{Yb}^{3+}$ concentration

Hyun Cho, Jung-Il Lee\* and Jeong Ho Ryu\*<sup>†</sup>

*Department of Nanomechatronics and Engineering, Pusan National University, Miryang 627-706, Korea*

*\*Department of Materials Science and Engineering, Korea National University of Transportation, Chungju 380-702, Korea*

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**Abstract** The upconversion (UC) luminescence of  $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  co-doped  $\text{CaWO}_4$  phosphors and effects of  $\text{Yb}^{3+}$  concentration are investigated in detail. Single crystallized  $\text{CaWO}_4:\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  phosphor can be obtained, co-doped up to 35.0/5.0/30.0 mol% ( $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$ ) by solid-state reaction. Under 980 nm excitation,  $\text{CaWO}_4:\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  phosphor exhibited strong green UC emissions visible to the naked eye at 530 and 550 nm induced by the intra 4f transitions of  $\text{Er}^{3+}$  ( $^4\text{H}_{11/2}, ^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ ). The optimum doping concentrations of  $\text{Yb}^{3+}$  that would result in the highest UC luminescence were determined, and a possible UC mechanism that depends on the pumping power is discussed in detail.

**Key words**  $\text{CaWO}_4:\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$ , Upconversion, Luminescence

## 1. Introduction

Over the past several decades, upconversion (UC) luminescence in rare earth (RE) ions doped phosphor materials has been extensively studied since its discovery in the 1960s [1]. Potential applications include solar cells, novel display technologies and, more recently, biophysics. The UC phosphors could indeed be used as probes for imaging of individual molecules in biological cells [2, 3]. Fluorescence imaging using near infrared (NIR) excitation is expected to have a major impact in biomedical imaging [4, 5]. The application of UC phosphor is also being considered in the photovoltaic industry to develop high-efficient solar cells [6].

Both of the above applications require, however, the development of more efficient and highly stable UC phosphors with low excitation density thresholds. Up to now, most of the RE doped UC phosphors have been halides such as  $\text{NaYF}_4$  [7]. However, they have very poor physicochemical stabilities, which make their applications difficult in industrial fields. Therefore, it is important to search for stable oxide host materials with high UC efficiency.

Tungstate represents an important family of oxide materials that can be applied in various fields, such as

photoluminescence, microwave, optical fibers, and scintillating materials [8]. Among them, calcium tungstate ( $\text{CaWO}_4$ ) has high density ( $6.1 \text{ g/cm}^3$ ), high irradiation damage resistance and relatively low phonon threshold energy compared to the other oxide materials [9]. The  $\text{W}^{6+}$  ions in  $\text{CaWO}_4$  matrices have strong polarization because of their large electric charge and small radius; this strong polarization consequently decreases symmetries and enhances the Stark energy splitting of the RE ion in the crystal field [10]. We already reported effects of  $\text{Li}^+$  and  $\text{Er}^{3+}$  concentration in  $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  co-doped  $\text{CaWO}_4$  [11, 12]. In this work,  $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  co-doped  $\text{CaWO}_4$  UC phosphors were synthesized with various  $\text{Yb}^{3+}$  concentrations by solid-state reaction. Their structural and UC luminescent properties were investigated, and effects of  $\text{Yb}^{3+}$  concentrations on UC luminescence were discussed according to the UC mechanism.

## 2. Experimental

$\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  co-doped  $\text{CaWO}_4$  ( $\text{CaWO}_4:\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$ ) phosphor samples were prepared by the traditional solid-state reaction method. The starting materials were  $\text{CaCO}_3$  (Kojundo Chemical, 99.99 %),  $\text{WO}_3$  (Kojundo Chemical, 99.99 %),  $\text{Li}_2\text{CO}_3$  (Kojundo Chemical, 99.99 %),  $\text{Er}_2\text{O}_3$  (Shinetsu Chemical, 99.99 %) and  $\text{Yb}_2\text{O}_3$  (Shinetsu Chemical, 99.99 %). The molar ratios of the cations were as follows:  $(1 - 2x - 2y)\text{Ca}^{2+} + x\text{Yb}^{3+} + y\text{Er}^{3+} +$

<sup>†</sup>Corresponding author  
Tel: +82-43-841-5384  
Fax: +82-43-841-5380  
E-mail: jhryu@ut.ac.kr

$(x+y)\text{Li}^+ + \text{W}^{6+}$ ,  $x = 0.000, 0.025, 0.050, 0.075, 0.100, 0.150, 0.200, 0.300$  and  $y = 0.050$ . In this work, the  $\text{Er}^{3+}$  concentration was fixed at 5.0 mol% [12] to investigate the effects of  $\text{Yb}^{3+}$  concentration ranging from 0 to 30 mol% on UC luminescence. The charge discrepancy of  $\text{Ca}^{2+}$  with  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  could be compensated by  $\text{Li}^+$  co-doping. Based on the above chemical formula, the starting powders with the designed stoichiometric quantities were ball-milled for 2 hrs, and then were calcined at  $1000^\circ\text{C}$  for 2 hrs in air. The crystalline phases of the calcined powders samples were identified by X-ray powder diffraction (XRD), operating at 40 kV using  $\text{Cu-K}\alpha$  radiation ( $\lambda = 1.5406 \text{ \AA}$ ). The UC luminescence spectra were recorded using a spectrophotometer at room temperature. A 980 nm laser diode with maximum 100 mW output was used as the excitation source. The pumping power dependence of UC emission was calculated using irradiation power from 20 to 110 mW (SPEX, 1404p, France).

### 3. Results and Discussion

Fig. 1(a) shows phase identification of the  $\text{CaWO}_4 : \text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  samples with various  $\text{Li}^+/\text{Yb}^{3+}$  concentrations calcined at  $1000^\circ\text{C}$  for 2 hrs. The prominent peaks corresponded well to the scheelite-type  $\text{CaWO}_4$  phase (JCPDS # 41-1431) at all  $\text{Li}^+/\text{Yb}^{3+}$  concentrations. No impurities or secondary phases could be identified from the XRD patterns in the limit of XRD resolution, thus suggesting that single crystallized  $\text{CaWO}_4 : \text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  with various  $\text{Li}^+/\text{Yb}^{3+}$  concentrations up to 35.0/30.0 mol% can be obtained by solid-state reaction. Based on the effective ionic radii of the cations with different coordination numbers (CN) [13] and large charge difference between  $\text{Ca}^{2+}$  ion and  $\text{W}^{6+}$  ion, it can be expected that  $\text{Li}^+$ ,  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  [ $r(\text{Li}^+) = 0.92 \text{ \AA}$ ,  $r(\text{Er}^{3+}) = 1.004 \text{ \AA}$ ,  $r(\text{Yb}^{3+}) = 0.985 \text{ \AA}$ , when CN = 8] are preferably substituted into the  $\text{Ca}^{2+}$  sites [ $r(\text{Ca}^{2+}) = 1.12 \text{ \AA}$ , when CN = 8] instead of the  $\text{W}^{6+}$  sites [ $r(\text{W}^{6+}) = 0.66 \text{ \AA}$ , when CN = 4]. Note, that when the  $\text{Ca}^{2+}$  ions are substituted by the  $\text{Li}^+$ ,  $\text{Er}^{3+}$  or  $\text{Yb}^{3+}$  ions with a smaller ionic radius than that of  $\text{Ca}^{2+}$ , the corresponding lattice constant becomes smaller. In Fig. 1(b), the (112) and (103) diffraction peaks shift to higher  $2\theta$  angle, indicating the decrease of the lattice constants when  $\text{Li}^+/\text{Yb}^{3+}$  ions are substituted into the  $\text{Ca}^{2+}$  ion sites.

Fig. 2 shows the UC luminescent spectra of the prepared  $\text{CaWO}_4 : \text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  phosphors with various  $\text{Li}^+/\text{Yb}^{3+}$  concentrations from 0.050/0.000 to 35.0/30.0 mol%

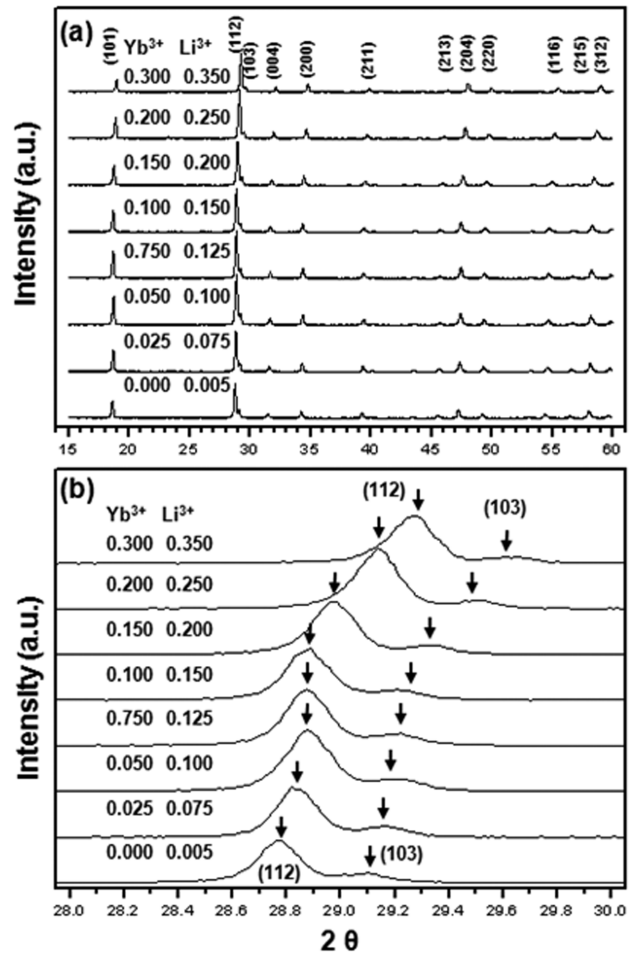


Fig. 1. (a) XRD patterns of  $\text{CaWO}_4 : \text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  samples with various  $\text{Li}^+/\text{Yb}^{3+}$  concentrations calcined at  $1000^\circ\text{C}$  for 2 hrs. (b) The enlarged XRD patterns near  $2\theta = 29^\circ$  for (112) and (103) peaks.

under 980 nm laser excitation. The UC luminescent spectra consist of three regions: (1) intense green emission between 515 to 540 nm assigned to  $^4\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2}$  transitions ( $G_1$ ), (2) green emission between 540 nm and 560 nm assigned to  $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$  transitions ( $G_2$ ) and (3) the relatively weak red emission between 650 and 680 nm assigned to  $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$  transitions of  $\text{Er}^{3+}$  ions [11, 12].

The intensity of the UC emission was enhanced by the doping of the sensitizer  $\text{Yb}^{3+}$ . When the  $\text{Yb}^{3+}$  ions are doped, green emissions increase because the  $\text{Yb}^{3+}$  ions absorb light of 980 nm wavelength, effectively. The relative integral intensities of the  $G_1$  and  $G_2$  increase approximately 12 and 7 times, respectively, when the  $\text{Yb}^{3+}$  concentration is 20.0 mol%. These results show that the  $\text{Yb}^{3+}$  ion plays a role in the energy transfer process. The intensities of green UC emission ( $G_1$ ) increased with increasing  $\text{Li}^+/\text{Yb}^{3+}$  concentration and maximized in the 25.0/20.0 mol% sample. Thus, we confirmed that optimum  $\text{Li}^+/\text{Yb}^{3+}$  doping concentration for strongest green

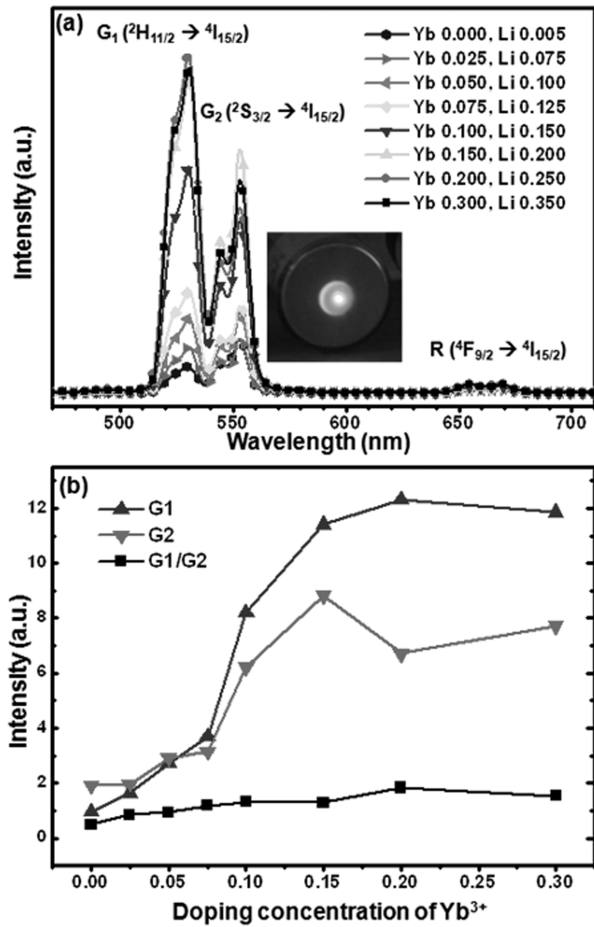


Fig. 2. UC luminescence spectra of  $\text{CaWO}_4:\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  samples with  $\text{Li}^+/\text{Yb}^{3+}$  concentrations excited at 980 nm. The inset photograph shows strong green emission for the sample with  $\text{Li}^+/\text{Yb}^{3+}$  concentration of 25.0/20.0 mol%, as observed by the naked eye, excited by a 980 nm laser diode.

emission was 25.0/20.0 mol% with  $\text{Er}^{3+}$  doping concentration fixed at 5.0 mol%. The 25.0/5.0/20.0 mol% ( $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$ ) co-doped  $\text{CaWO}_4$  sample emitted the strongest green light visible by the naked eye when excited by a 980 nm laser diode of 100 mW, as shown in the inset of Fig. 2. The green emission ratio ( $G_1/G_2$ ) was almost unchanged, which indicated that the populating probability of  $\text{Er}^{3+}$  from  $^4\text{F}_{7/2}$  to  $^4\text{H}_{11/2}$  or  $^4\text{S}_{3/2}$  levels remained stable with increase of  $\text{Yb}^{3+}$  concentration.

Fig. 3(a) shows the green and red UC luminescent intensities of the 25.0/5.0/20.0 mol% ( $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$ ) co-doped  $\text{CaWO}_4$  sample plotted on a logarithmic scale as a function of pump power. In UC processes, the UC emission intensity  $I_{\text{UC}}$  is proportional to the  $n$  value of the irradiation pumping power  $P$ , that is  $I_{\text{UC}} \propto P^n$ , where  $n$  is the number of pumping photons required to produce UC emission,  $I_{\text{UC}}$  is the luminescent intensity, and  $P$  is the laser pumping power [12]. The calculated  $n$  values were 1.63, 1.71, 1.61, and 1.72 for green emissions

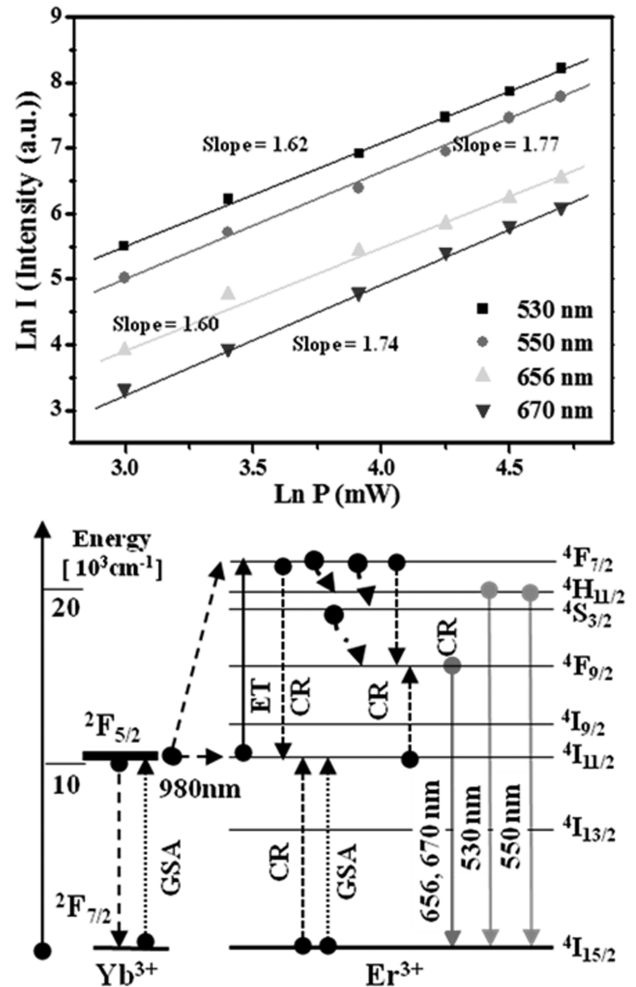


Fig. 3. (a) Pumping power dependence of UC emission of 25.0/5.0/20.0 mol% ( $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$ ) co-doped  $\text{CaWO}_4$  sample under working currents from 20 to 110 mW at 530, 550, 655 and 670 nm. (b) A simplified energy level diagram of  $\text{Er}^{3+}$  with  $\text{Yb}^{3+}$  ions and the dominant UC mechanisms in  $\text{CaWO}_4:\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  phosphor [14].

at 530 and 550 nm and for red emissions at 656 and 670 nm, respectively. These results indicated that a two-photon UC process was assigned to the green and red emissions in the  $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  co-doped  $\text{CaWO}_4$ .

The UC emission mechanism and population processes for the green ( $^4\text{H}_{11/2}$ ,  $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ ) and red ( $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$ ) UC luminescence in the  $\text{CaWO}_4:\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  phosphor system are illustrated in Fig. 3(b) [14]. Under 980 nm excitation,  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  ions were initially excited from the ground state to the excited state through the ground state absorptions (GSA) process ( $\text{Er}^{3+}: ^4\text{I}_{15/2} \rightarrow ^4\text{I}_{11/2}$ ,  $\text{Yb}^{3+}: ^2\text{F}_{7/2} \rightarrow ^2\text{F}_{5/2}$ ) and the sensitized energy transfer upconversion (S-ETU) process of  $^2\text{F}_{5/2}(\text{Yb}^{3+}) + ^4\text{I}_{11/2}(\text{Er}^{3+}) \rightarrow ^2\text{F}_{7/2}(\text{Yb}^{3+}) + ^4\text{F}_{7/2}(\text{Er}^{3+})$ , which were responsible for the population at  $^4\text{H}_{11/2}$  level in  $\text{Er}^{3+}$ , respectively. For the green emissions, the energy transition

from  $^4\text{I}_{11/2}$  level to  $^4\text{F}_{7/2}$  level of  $\text{Er}^{3+}$  involved into three possible processes as follows [15, 16]:

- (1) ESA:  $^4\text{I}_{11/2} + \text{a photon (980 nm)} \rightarrow ^4\text{F}_{7/2}$
- (2) Sensitized ETU (S-ETU):  $^2\text{F}_{5/2}(\text{Yb}^{3+}) + ^4\text{I}_{11/2}(\text{Er}^{3+}) \rightarrow ^2\text{F}_{7/2}(\text{Yb}^{3+}) + ^4\text{F}_{7/2}(\text{Er}^{3+})$
- (3) ETU:  $^4\text{I}_{11/2}(\text{Er}^{3+}) + ^4\text{I}_{11/2}(\text{Er}^{3+}) \rightarrow ^4\text{F}_{7/2}(\text{Er}^{3+}) + ^4\text{I}_{15/2}(\text{Er}^{3+})$

These three possible processes can populate electrons to the  $^4\text{F}_{7/2}$  level from the  $^4\text{I}_{11/2}$  level in  $\text{Er}^{3+}$ , and then the  $^4\text{F}_{7/2}$  level relaxes rapidly and non-radiatively to the following lower levels at  $^4\text{H}_{11/2}$  and  $^4\text{S}_{3/2}$  in  $\text{Er}^{3+}$ . As a result, the above mentioned processes can produce green emissions in the spectral lines near 530 and 550 nm. The UC emission was dominated by strong green emissions at 530 nm ( $^4\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2}$ ) and 550 nm ( $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ ). For the red emission,  $^4\text{F}_{9/2}$  level was generated by non-radiative relaxation from  $^4\text{S}_{3/2}$  to  $^4\text{F}_{9/2}$  level and by the cross relaxation  $^4\text{F}_{7/2} + ^4\text{I}_{11/2} \rightarrow ^4\text{F}_{9/2} + ^4\text{F}_{9/2}$  transition. Finally,  $^4\text{F}_{9/2}$  level relaxed radiatively to the ground state at  $^4\text{I}_{15/2}$  level and released red emission at 655 and 670 nm.

#### 4. Conclusion

In summary, single crystallized  $\text{CaWO}_4 : \text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  phosphor was synthesized, co-doped up to 35.0/5.0/30.0 mol% ( $\text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$ ) by solid-state reaction. Under 980 nm excitation,  $\text{CaWO}_4 : \text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  phosphors exhibited bright green UC luminescence visible to naked eyes at 530 and 550 nm. The optimum doping concentration of  $\text{Yb}^{3+}$  for highest green UC luminescence was 20.0 mol%. Moreover, a two-photon process was responsible for both UC luminescence of green and red emission. It is concluded that  $\text{CaWO}_4 : \text{Li}^+/\text{Er}^{3+}/\text{Yb}^{3+}$  phosphors can be a promising candidate for meeting the requirements of biomedical or solar cell applications.

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