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## SYNTHESIS AND LUMINESCENCE PROPERTIES OF $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$ PHOSPHOR FOR SOLID STATE LIGHTING

A novel method to prepare  $\text{Eu}^{2+}$  doped chlorapatite phosphor  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$  useful for solid state lighting has been given in this paper. The phosphor was synthesized by the Pechini (citrate gel) method which turned out to be more efficient than the conventional high temperature solid state reaction. The results of the photoluminescence (PL) investigation revealed that it was possible to efficiently excite the phosphor by a UV-visible light from 220 to 430 nm; the phosphor exhibited a bright blue emission at the wavelength  $\lambda_{em} = 456$  nm for the excitation wavelength  $\lambda_{ex} = 350$  nm of near-ultraviolet light. The developed phosphor emits in blue and, hence, could provide one of the three (RGB) primary color components in a phosphor-converted LED-producing white light.

SOLID STATE LIGHTING, PECHINI (CITRATE GEL) METHOD, BLUE PHOSPHOR, PHOTOLUMINESCENCE.

### 1. Introduction

White-light emitting diodes (W-LEDs) are one of the most promising eco- friendly light sources due to their low energy consumption [1]. W-LEDs offer benefits in terms of reliability, energy saving, and safety and therefore have drawn much attention in recent years [2, 3]. To increase the efficiency of W-LEDs, special attention has recently been paid to the development of new phosphors with good luminescence properties that can be excited in the long-UV range (300 – 420 nm). Blue phosphors are an important part in those new phosphors. Recently, W-LEDs have been used in many applications due to the developments in GaN-based chips and phosphor technology. The most popular products in the market are obtained by the combination of a blue-emitting phosphor ( $\text{YAG}:\text{Ce}^{3+}$ ), which suffer from the low color rendering index(CRI) and high color temperature  $T_c$  (usually above 5500 K). These drawbacks can be overcome by the use of triband W-LED, utilizing RGB (red, green and blue) tricolor phosphor coatings on the near ultraviolet (near-UV) LED chip. Blue phosphor  $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$  (BAM: $\text{Eu}^{2+}$ ) has been intensively studied [4, 5]. However,

BAM: $\text{Eu}^{2+}$  has two major drawbacks: thermal degradation and UV damage, which lead to a color shift and loss of brightness [6, 7]. Apatite phosphors, which are naturally occurring materials, have recently been used for field-emission displays (FEDs) and would be suitable for white LEDs in the near future because of their low price, environmental friendliness, thermal stability and good photoluminescence properties [8]. W.N. Wang, et al. [8] reported synthesis of a chloroapatite blue phosphor  $(\text{Ca},\text{Mg})_5(\text{PO}_4)_3\text{Cl}:\text{Eu}$  with high quantum efficiency using a spray pyrolysis method. The color of the present W-LED depends completely on phosphors because the eyes are not sensitive to the UV output from the W-LED. The market share of the three-band W-LEDs based on near-UV chips has been steadily increasing.  $\text{Eu}^{2+}$  ions doped alkaline earth halophosphates are efficient blue-emitting phosphors used for triband W-LEDs. The hosts have been paid more attention in many studies because of their high quantum efficiencies and the excellent physical and chemical stabilities [9, 10]. At the time they show very interesting physical, and, in particular, optical properties [11, 12]. Several solid solutions of alkaline earth halophosphates like  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$ ,  $\text{Sr}_5(\text{PO}_4)_3\text{Cl}$  and  $\text{Ba}_5(\text{PO}_4)_3\text{Cl}$

are known [13]. The substitution of  $\text{Eu}^{2+}$  for  $\text{Ca}^{2+}$  is facilitated by the similarity in ionic radii. These phosphors are normally synthesized by solid state reaction which requires very high temperature and it is time consuming also. This prompted us to go for alternative method for the synthesis of such phosphors which would be easy, needs low temperature and less time consuming than solid state reaction.

The present work reports for the first time the synthesis of  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  phosphor via the Pechini (citrate gel) method and the investigation of its photoluminescent properties.

## 2. Experimental

For synthesis of  $\text{Eu}^{2+}$  activated chlorapatite phosphor  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$  stoichiometric amount of the precursors  $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ ,  $\text{Eu}_2\text{O}_3$  converted to  $\text{Eu}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ ,  $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$  and  $(\text{NH}_4)_2\text{H}_2\text{PO}_4$  were taken in a china clay basins and dried in a desiccator. All the dried precursors were then finely milled and mixed together. Stoichiometric amount of Citric monohydrated and Ethylene glycol along with 2 drops of Glacial acetic acid were added to

dried precursors and stirred continuously.

On slow heating up to  $140^\circ\text{C}$  for  $\sim 1$  h, the solution boils with the evolution of pale yellowish brown fumes and the process of gelation started. The mixture was then allowed to cool leading to a thick pale yellow gel. The gel was further heated slowly up to  $350^\circ\text{C}$  in air. The polymerization took place and a pale yellow resin/foam was formed and was pyrolysed into stunning black foam at  $450^\circ\text{C}$ , which started burning at  $600^\circ\text{C}$ . The complete pyrolysis took place at  $750^\circ\text{C}$  for 2 h. The white powder so obtained was slowly reduced first at  $600^\circ\text{C}$  for 1 h and then at  $970^\circ\text{C}$  for 3 h in presence of charcoal in order to reduce the trivalent activator to divalent state. Thus white crystalline  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  phosphor was prepared.

## 3. Results and discussion

**XRD-Studies.** X-ray diffraction (XRD) pattern of as prepared  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  phosphor obtained using Rikagu Meniflex II X-ray diffractometer is shown in Fig. 1. The XRD pattern of calcium apatite suggests the formation of a crystalline  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$

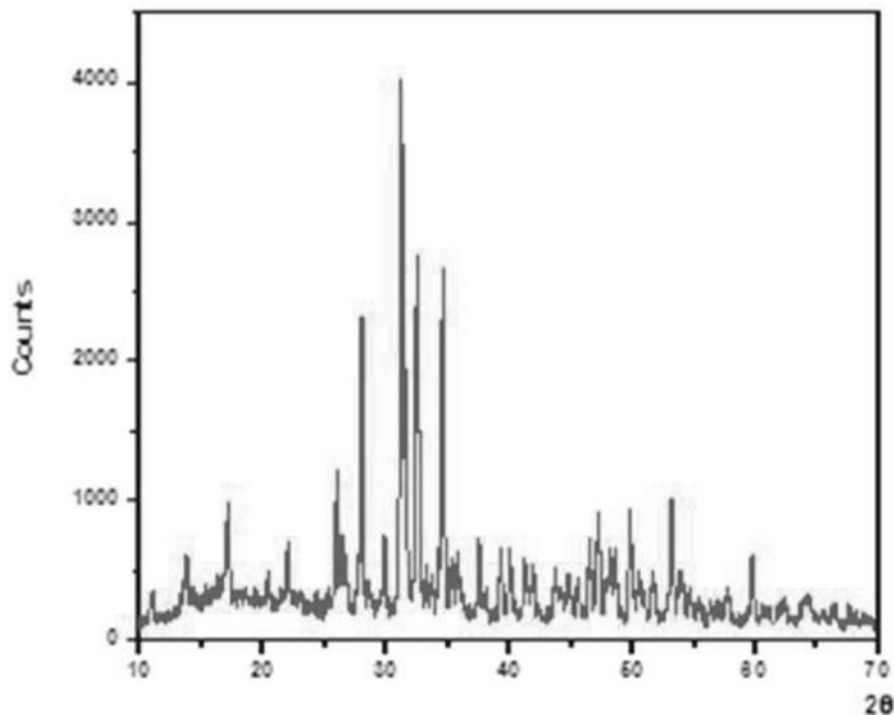


Fig. 1. X-ray diffraction pattern of  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  phosphor

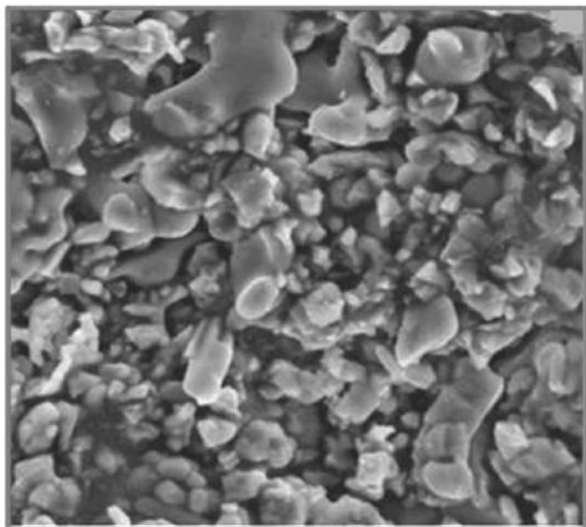


Fig. 2. Scanning electron microscope image of as-prepared  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  phosphor

matrix. The results of the XRD analysis indicate that almost all diffraction peaks can be indexed to a pure hexagonal  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$  in JCPDS file with file No. JCPDS 33-0271.

**Surface Morphology.** The phosphor surface morphology was investigated using a Hitachi S-520 scanning electron microscope (SEM). Fig. 2 presents the SEM image of as prepared  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  phosphor. It can be seen that the particles have some irregular shape and the particle size lies in the range from 5 to 10  $\mu\text{m}$ .

**Photoluminescence (PL) study.** PL measurements were performed at room temperature, using a Hitachi F-7000 Spectrofluorimeter equipped with a 450 W xenon lamp, in the range from 200 to 700 nm, with spectral width of 2.5 nm. Spectra were corrected using Rhodamine B standard by following the procedure prescribed by Hitachi. Prepared phosphors for W-LED meet the basic requirement that exhibits a bright emission under the excitation of near-UV light. Thus, the excitation and emission spectra of the prepared phosphors  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  were studied in order to assess their potential to be used for near-UV LED based W-LEDs. The photoluminescence (PL) and photoluminescence excitation (PLE)

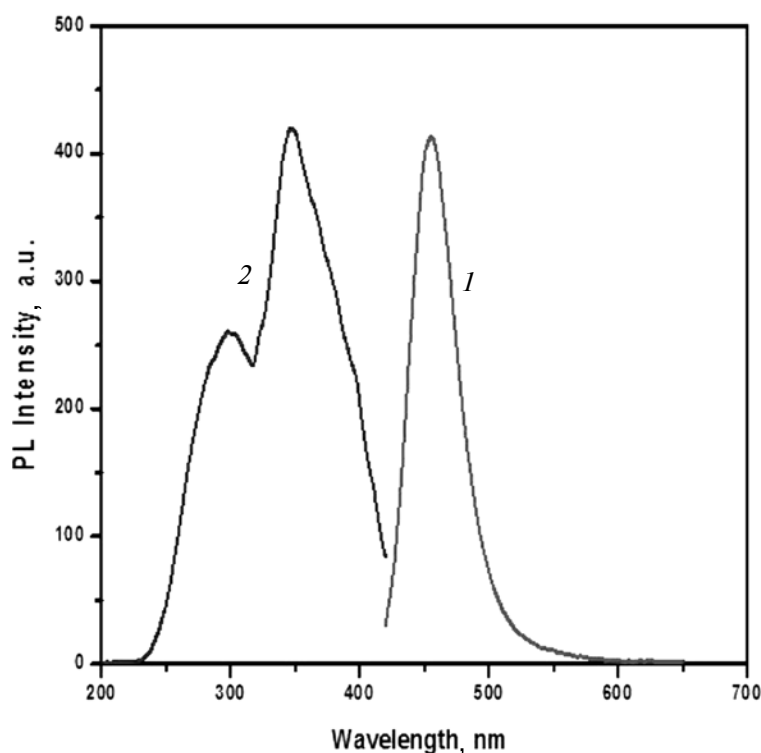


Fig. 3. Photoluminescence emission (1) and excitation (2) spectra of  $\text{Eu}^{2+}$  activated  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$  phosphor;  $\lambda_{em} = 456 \text{ nm}$ ,  $\lambda_{ex} = 350 \text{ nm}$

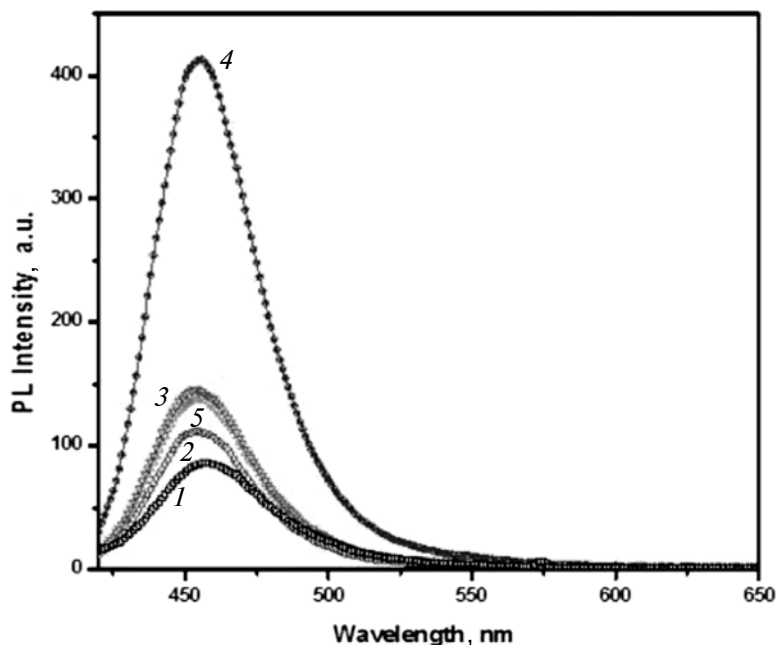


Fig. 4. Photoluminescence emission spectrum of  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$  with different concentration of  $\text{Eu}^{2+}$ , mol: 0.001 (1), 0.002 (2), 0.005 (3), 0.010 (4), 0.020 (5)

spectra of phosphor prepared are shown in Fig. 3. There are two broad bands in the PLE ( $\lambda_{em} = 456 \text{ nm}$ ) spectra of phosphors, which are due to the transition from  $^8S_{7/2}$  ( $4f^7$ ) ground state of  $\text{Eu}^{2+}$  to the  $4f^65d^1$  excited state. The weaker band is located at about 299 nm, and the stronger one is located at around 350 nm with shoulders at 386 nm, which matches well with the emission of commercially available near-UV LED chips. The bright blue emission band with peak at about 456 nm is observed in the PL ( $\lambda_{ex} = 350 \text{ nm}$ ) spectra of this phosphors, which could be attributed to the typical  $4f^65d^1$  ( $t_{2g}$ ) –  $4f^7$  ( $^8S_{7/2}$ ) transition of  $\text{Eu}^{2+}$  [14].

The concentration of the activator has an impact on the performance of a phosphor. Therefore, it is important to determine the composition of the  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  phosphor with optimal PL emission intensity. A series of  $\text{Ca}_{5-x}(\text{PO}_4)_3\text{Cl} : x\text{Eu}^{2+}$  phosphors with various  $\text{Eu}^{2+}$  content  $x$  was prepared and studied for the effect of activator concentration. The emission spectra of  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$  phosphor ( $\lambda_{ex} = 350 \text{ nm}$ ) with different activator concentration are shown in Fig. 4. No obvious changes were observed for all the samples in our experimental wavelength range,

except the fact that the emission intensity of phosphor increases with the increase in  $\text{Eu}^{2+}$  concentration and reaches the maximum at  $x = 0.01$  then concentration quenching occurs as the concentration of  $\text{Eu}^{2+}$  increased above 1 %. This type of quenching may be attributed to the fact that energy transfer between two identical ions occurs because the average distance between the activator ions becomes short enough for the energy to migrate and for the killers to reach [15].

**CIE color coordinates.** Fig. 5 shows color coordinates CIE (Commission internationale de l'éclairage) 1931 as (0.1551, 0.0849) for  $\text{Ca}_5(\text{PO}_4)_3\text{Cl} : 0.01 \text{Eu}^{2+}$  where as the commercial blue phosphor  $\text{BaMgAl}_{10}\text{O}_{17} : \text{Eu}^{2+}$  (BAM: $\text{Eu}^{2+}$ ) has color coordinates as (0.1417, 0.1072) thus showing better purity of  $\text{Ca}_5(\text{PO}_4)_3\text{Cl} : 0.01 \text{Eu}^{2+}$  as compared to BAM: $\text{Eu}^{2+}$  phosphor. Moreover, the color coordinates of the above synthesized phosphor are nearer to those for blue color suggested by the color system EBUPAL/ESCAM, RGBs Blue as well as Adobe blue (0.15, 0.06). Thus the synthesized phosphor is a potential candidate for blue emitting phosphor for solid state lighting using near-UV based W-LEDs.

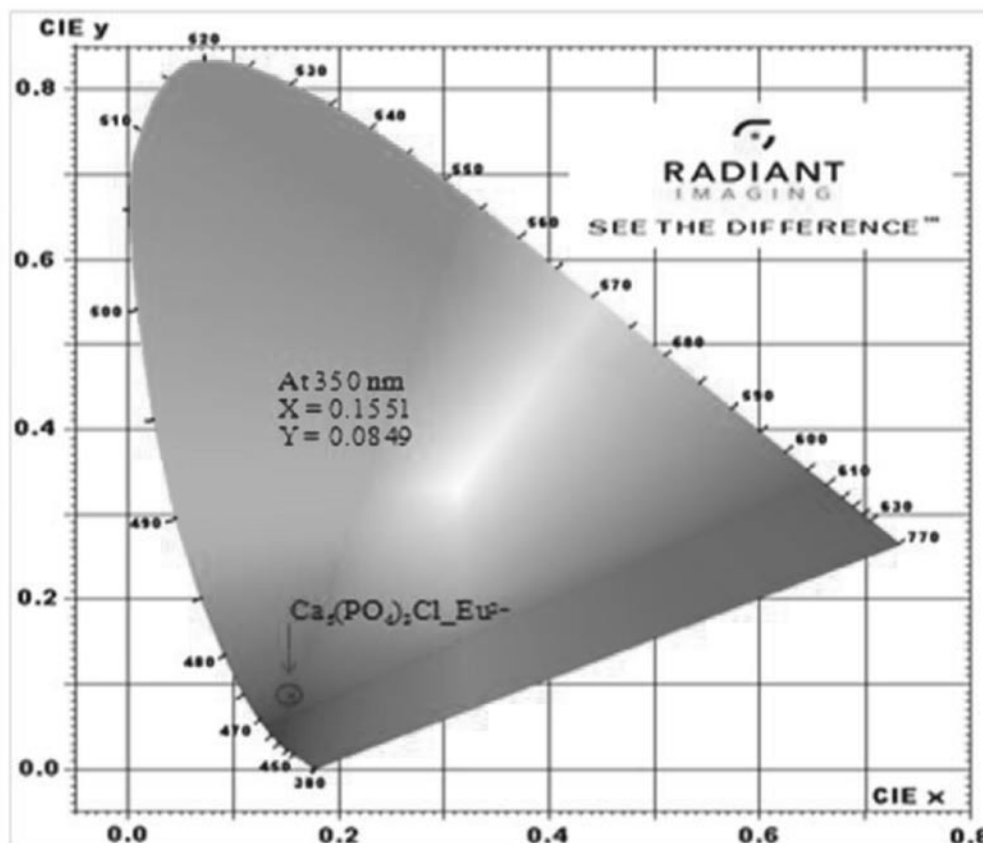


Fig. 5. CIE chromaticity coordinates of  $\text{Ca}_5(\text{PO}_4)_3\text{Cl} : 0.01\text{Eu}^{2+}$  phosphor

#### 4. Conclusions

For the first time  $\text{Eu}^{2+}$  doped chlorapatite phosphor  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$  was synthesized by novel Pechini (citrate gel) method. Photoluminescence measurements showed that  $\text{Eu}^{2+}$  doped chlorapatite phosphor  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$  synthesized by this method exhibits intensive blue wide-band emission with maximum intensity at 456 nm under near-UV excitation. Both blue and white LEDs can be fabricated by pre-coating the above synthesized phosphors onto 395 nm-emitting InGaN chips. Moreover, the strong absorption of phosphor in the range of 300 nm to 410 nm makes this  $\text{Eu}^{2+}$ -activated

chlorapatite phosphor a potential candidate as a blue component (one of the three primary color components) for fabrication near-UV based phosphor converted white LEDs.

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### **Гейм Д.Н., Ингале Н.Б., Оманвар Ш.К. СИНТЕЗ И ЛЮМИНЕСЦЕНТНЫЕ СВОЙСТВА СОЕДИНЕНИЯ $\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$ , ПЕРСПЕКТИВНОГО ДЛЯ СОЗДАНИЯ ТВЕРДОТЕЛЬНОГО ИСТОЧНИКА ОСВЕЩЕНИЯ.**

В статье представлен новый метод приготовления люминофора на основе хлорapatита  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$ , активированного  $\text{Eu}^{2+}$ , который можно применять как твердотельный источник освещения. Люминофор был синтезирован методом Печини (цитратный метод), который оказался более эффективным, чем традиционный метод высокотемпературной твердотельной реакции. Изучение люминофора показало, что его фотолюминесценцию можно возбуждать источником света в диапазоне 220 – 430 нм, что вызывает ярко-синее свечение на длине волны  $\lambda_{em} = 456$  нм (длина волны возбуждения  $\lambda_{ex} = 350$  нм лежит в ближней УФ-области). Предлагаемый люминофор испускает синий цвет и, следовательно, может служить одним из трех исходных цветовых компонентов (RGB – красный, зеленый, синий) светодиода, дающего белый свет.

ТВЕРДОТЕЛЬНОЙ ИСТОЧНИК ОСВЕЩЕНИЯ, МЕТОД ПЕЧИНИ (ЦИТРАТНЫЙ МЕТОД), СИНИЙ ЛЮМИНОФОР, ФОТОЛЮМИНЕСЦЕНЦИЯ.



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