

Research Article

Synthesis of Luminescent Ink from Europium-Doped Y_2O_3 Dispersed in Polyvinyl Alcohol Solution

Astuti, Mikrajuddin Abdullah, and Khairurrijal

Department of Physics, Bandung Institute of Technology, Jl. Ganeca 10, Bandung 40132, Indonesia

Correspondence should be addressed to Mikrajuddin Abdullah, din@fi.itb.ac.id

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Luminescent ink from europium-doped Y_2O_3 ($Y_2O_3:Eu$) has been synthesized by two steps method: first, synthesis of luminescent powder of $Y_2O_3:Eu$ by simple heating of metallic nitrates in a polymer solution and second, dispersing the powder in a polyvinyl alcohol (PVA) solution. The stability of the ink (luminescent colloid) was strongly affected by mixing process of the powder and the solution. Mixing process must be performed for a long time (about 8 hours) at above room temperature to product stable colloids. We observed that mixing at 30–40°C resulted in a stable and highly dispersed colloid. The writing test was performed on a white paper to show the potential use of the colloid for making security codes.

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1. Introduction

Rare earth ions have long been used for producing phosphor materials. Doping appropriate host matrix (usually oxide) with these ions products sharp and intense emission under UV excitation [1]. Researchers have succeeded to produce many kinds of rare earth-doped oxide phosphors emitting various colors. To date, they succeeded to produce blue phosphor of $(Zn,Mg)O:Zn$, green phosphor of $ZnGa_2O_4:Mn$, red phosphor of $Y_2O_3:Eu$ and $CrTiO_3:Pr$ [2, 3], red phosphor of $SrTiO_3:Pr,M$ ($M = Al$ or Ga) [4], and yellow-green phosphor of $(Y,Gd)Al_5O_{12}:Ce$ [5, 6].

Red phosphor of Y_2O_3 doped with trivalent ions such as Eu has particularly attracted considerable interest in terms of high chemical durability and thermal stability [7]. This phosphor has been widely used in CRT displays. Under ultraviolet excitation, this phosphor emits strong luminescence at wavelength of 612 nm corresponding to $^3D_0 \rightarrow ^7F_2$ transition in Eu^{3+} ions. Many kinds of methods have been proposed to synthesize Y_2O_3 -based phosphors such as sol-gel method [8], chemical vapor deposition [9], combustion synthesis [10] coprecipitation [11], spray pyrolysis [12], simple heating of precursors in a polymer solution [13], hydrothermal [14–16], and bicontinuous cubic phase [17, 18].

In recent years, there are also interests in production of nanometer-sized oxide phosphors. Bhargava et al. reported that doped phosphors yield high luminescence efficiency at nanoscale size [19], although it is generally confirmed that in micrometer sizes range, the sizes of most practical phosphors, the luminescence efficiency of impurity ion-doped materials decreases with the crystal size because of a large contribution of the surface to the nonradiative decay. However, micrometer- to submicrometer-sized phosphors particles are sometimes preferred in specific applications such as for practical CRT, plasma display panel, or high radiation energy detection (such as to make films for X-ray detection) applications [5]. Therefore, both nanometer- and micrometer-sized phosphors are still important in the current technology since they meet different applications.

In the past few years, several papers have been devoted to the development of luminescent inks using phosphor materials. This ink is potential for detecting any counterfeiting, alteration, and unauthorized trading. This ink is useful for security ink applications, which are a highly effective and cost-efficient method of protection valuable documents and products against fraud. Luminescent ink also meets applications in optoelectronic such as for development of light emitting devices. Luminescent inks can be adapted to inkjet printing technology for printing security documents.

Inkjet printing process reveals a number of advantageous such as precise material deposition on paper or substrate at well-defined position, low material consumption, and less material wastage [20]. Luminescent inks are nothing but luminescent colloids. It generally contains luminescent particles dispersed in suitable liquid. There are many reports on the production of luminescent colloids, and many of these colloids are based on semiconductor nanoparticles. However, applications of such colloids currently suffer from additional issues, such as harmful solids (e.g., CdSe, CdTe), harmful solvents or additives (e.g., long-chained phosphanes, amines, sulfides) [21]. Exploring safer colloids for luminescent inks becomes very challenging. One potential approach is to make colloid using oxide phosphors as luminescent entities.

To date, there are few reports on production of oxide phosphor-based luminescent colloid. For example, colloid luminescence of $\text{LaPO}_4\text{:Ce,Tb}$ and $\text{LaPO}_4\text{:Eu}$ in ionic liquid synthesized by a microwave-induced method was reported by Bühler and Feldmann. [21]. Other kinds of luminescent colloids were also reported such as colloidal silicon nanocrystals prepared by nanoseconds laser fragmentation and laser ablation in water [22] and colloidal silicon nanoparticles prepared by etching silica with hydrogen fluoride in cyclohexane [23, 24].

To the best our knowledge, no attempt has been made to synthesize stable $\text{Y}_2\text{O}_3\text{:Eu}$ colloid for luminescent ink applications. This situation could be due to the difficulty in dispersing the prepared $\text{Y}_2\text{O}_3\text{:Eu}$ in precise liquid or difficulty in production of $\text{Y}_2\text{O}_3\text{:Eu}$ particles insitu in liquid media. The aim of this work is to produce stable colloid of $\text{Y}_2\text{O}_3\text{:Eu}$ emitting red luminescence. Initially, $\text{Y}_2\text{O}_3\text{:Eu}$ particles were synthesized using a polymer complex processing method [13]. This method is promising for producing oxide particles in the submicrometer down to the several tens of nanometers [5, 6, 13, 25–28]. The entire process is very quick, and a large amount of particle products can be obtained in less than an hour. Secondly we attempt to produce luminescent colloid using the prepared phosphor particles.

2. Experiments

2.1. Preparation of $\text{Y}_2\text{O}_3\text{:Eu}$ Particles. In this study, red phosphor of $\text{Y}_2\text{O}_3\text{:Eu}$ was prepared by using a simple heating of the corresponding nitrous metals in a polymer liquid. Yttrium nitrate hexahydrate, $\text{Y}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (Kanto Chemicals, Japan) and europium nitrate hexahydrate, $\text{Eu}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (Kanto Chemicals, Japan) were dissolved in 100 mL distilled water. The total mass of two precursors was fixed at 2.0 g. However the molar fraction of Eu/Y was varied from 3% to 7% mol/mol. This range of molar fraction is located at around the optimum doping level of europium-doped yttrium oxide reported previously to obtain the highest photoluminescence (PL) intensity [12, 13]. At higher doping level, the PL intensity decreases with doping concentration due to concentration quenching mechanism [29, 30]. After completely dissolution of two nitrous metals, 8 g of polyethylene glycol (PEG, $\text{H}(\text{OCH}_2\text{CH}_2)_n\text{OH}$, Wako Pure Chemicals, Japan) with n between 300 000–500 000 was

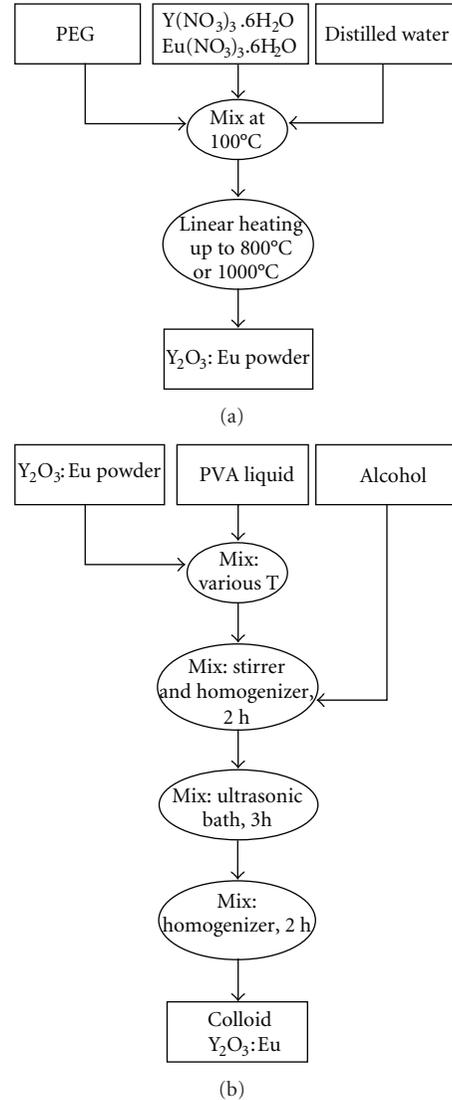


FIGURE 1: (a) Schematic diagram of production of $\text{Y}_2\text{O}_3\text{:Eu}$ powder by a simple heating in a polymer liquid, and (b) schematic diagram for production of stable luminescent colloid of $\text{Y}_2\text{O}_3\text{:Eu}$ particles dispersed in PVA solution.

added into the solution and then stirred with heating at 100 °C for 2 hours. The product was then put in an alumina crucible and heated in a furnace under atmospheric air. The temperature was increased linearly up to 800 °C for 30 minutes or 1000 °C for 45 minutes and then naturally cooled just after arriving the heating temperature peak. The procedure of synthesis of the powder is schematically shown in Figure 1(a).

2.2. Preparation of $\text{Y}_2\text{O}_3\text{:Eu}$ Colloid. Initially PVA, $(\text{CH}_2\text{CHOH})_n$, (Bratachem, Indonesia) with average n of 22000 was dissolved in distilled water at molar concentration of 5%. After PVA dissolved completely, 0.15 g of $\text{Y}_2\text{O}_3\text{:Eu}$ powder was put into the solution, followed by stirring at various heating temperatures for 1 hour. 10 mL

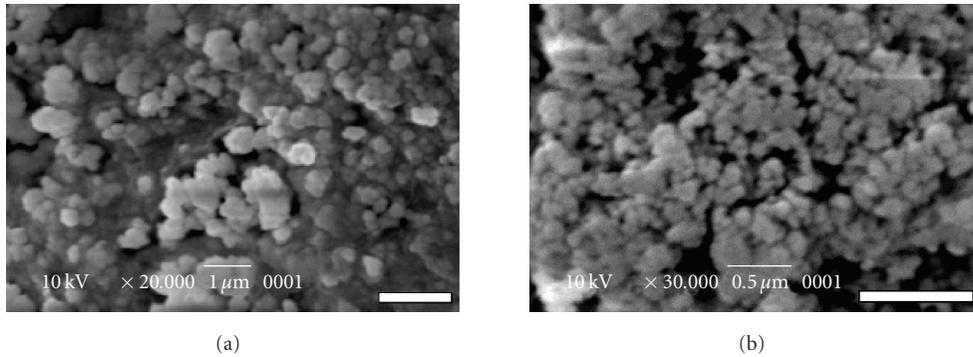


FIGURE 2: SEM images of samples prepared at different heating temperature peaks: (a) 800 °C and (b) 1000 °C. The lengths of the scale bars are 1 μm .

alcohol (70%, Bratachem, Indonesia) was then added into the mixture, and mixing using a mechanic stirrer and a homogenizer (ultraturrax T10, IKA, Germany, set at speed level of 4) was performed for 2 hours, followed by mixing using an ultrasonic bath for about 3 hours. Finally, the mixture was additionally mixed using a homogenizer for 2 hours. Figure 1(b) is the experiment procedures for making colloid. We have tried three temperatures of mixing, that is, room temperature, 30–40 °C, and 50–60 °C.

The morphology of samples was characterized using a scanning electron microscopy (SEM, JEOL JSM-6360LA) instrument, luminescence spectra were detected by a spectrophotometer Shimadzu RF-5301 PC instrument, fourier transform infra red spectrum was detected using a Shimadzu IRPrestige-21 FTIR spectroscope, and X-ray diffraction patterns were measured using a Phillips PW 1710 X-ray diffractometer ($\text{CuK}\alpha$, $\lambda = 0,154 \text{ nm}$).

3. Results and Discussion

Figure 2 shows SEM images of $\text{Y}_2\text{O}_3:\text{Eu}$ powders prepared at different peak temperatures: (a) 800 °C and (b) 1000 °C. It is likely seen that grain sizes of samples prepared at these two-peak temperatures could not be distinguished. This similarity was most probably due to the fact that the heating time was relatively short for the production of two samples, that is, around 30 minutes. Commonly, change in morphology through a heating process would be observed in prolonged heating time at higher temperatures, such as found in a sintering process. Typical grain sizes in all samples were between 40 and 100 nm. This size range is suitable for use as solid entities in inkjet material. This size range could produce stable ink, in term of free of agglomeration process (kinetically stable). Furthermore, using particles of less than 100 nm in diameter, we could generate fine printing results, such as line thickness of down to 1 μm [20].

At present, we produced luminescent ink using powder made at a heating temperature peak of 1000 °C. Based on many reports, the luminescence intensity of powder prepared at higher temperatures is stronger than that of samples prepared at lower temperatures [12].

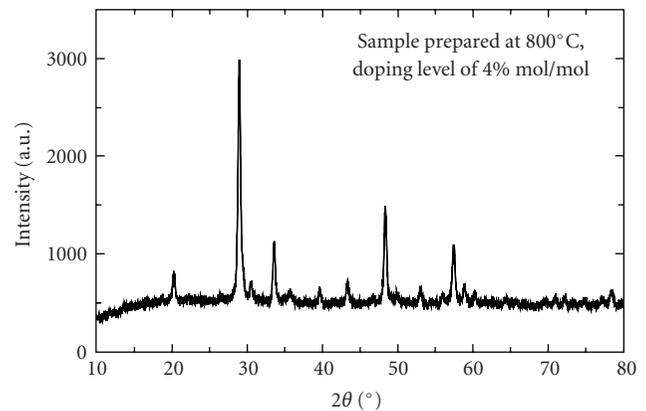


FIGURE 3: XRD patterns of samples prepared at heating temperature of 800 °C and doping level of 4% mol/mol.

Effects of synthesis parameters on the crystallinity and luminescence intensity of $\text{Y}_2\text{O}_3:\text{Eu}$ have been investigated in our previous work [13]. In this paper we do not focus on these points. What we shall explore now is how to make stable colloids using $\text{Y}_2\text{O}_3:\text{Eu}$ particles prepared by heating of precursors in a polymer solution. The XRD patterns of a single sample that was prepared at heating temperature of 800 °C shown here just for proving the particles we have made are really $\text{Y}_2\text{O}_3:\text{Eu}$. The XRD patterns as shown in Figure 3 are the same as that reported previously [13]. It clearly shows the presence of Y_2O_3 peaks.

The most important goal in the production of stable luminescent inks from $\text{Y}_2\text{O}_3:\text{Eu}$ powder is to find the most suitable liquid and the most appropriate route to produce stable colloid. Different liquids and routes result in different colloids in terms of property and stability or even a stable colloid are never obtained. We remarked that PVA solution is suitable liquid for the production of colloid. At present experiment, without heating process during mixing the $\text{Y}_2\text{O}_3:\text{Eu}$ powder and liquid, we never found stable colloid. Figure 4(a) is the colloid prepared by mixing without heating. The particles progressively precipitated at the bottom of container soon after stopping the mixing

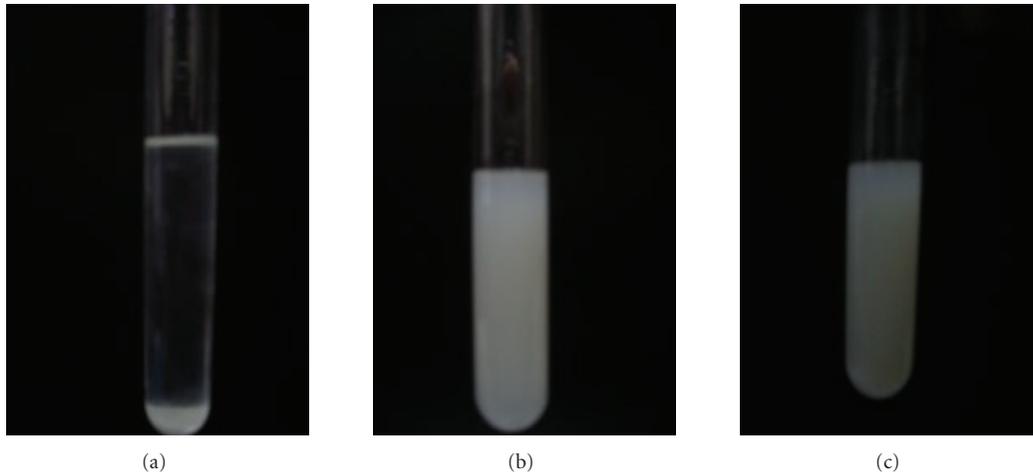


FIGURE 4: Colloid of $Y_2O_3:Eu$ prepared at different heating temperatures: (a) without heating (room temperature), (b) heating temperature of 30–40 °C, and (c) heating temperature of 50–60 °C.

process. In contrary, when heating was given during stirring, we found homogeneous dispersion of particles in liquid phase. Figure 4(b) is colloid that was mixed with heating at temperature of 30–40 °C, and Figure 4(c) is that prepared at mixing temperature of 50–60 °C. We also identified an increase of colloid stability when using higher PVA molarity. It must be noted that all colloids in Figures 4(a)–4(c) have been treated similarly, except they were only different in mixing temperature.

It is clear that heating during mixing of $Y_2O_3:Eu$ powder with PVA solution is absolutely needed to produce stable colloid. This observation might be ascribed to several factors: firstly, a possible increase in solubility of PVA at higher temperature so that particles of $Y_2O_3:Eu$ homogeneously dispersed between polymer chains; secondly, a possible increase in adsorption of polymer chain on the particle surface at elevated temperature. These two factors can overcome the particles from agglomeration as well as can maintain the particles, especially small particles, to remain in the liquid phase. But, more comprehensive investigations are still required to prove these assumptions.

At the beginning, just after stopping the stirring process, we found slightly precipitation occurred even at a colloid prepared by heating during stirring. The precipitants contained large granulars. After completely precipitation of large granulars for a few days, the remained mixture was stable up to four months. This colloid that contains particles of smaller sizes has achieved the kinetic stability. The fraction of particles remained in the colloid was determined by weighting the precipitated particles. Initially, we used 0.15 g of particles to make colloid. After reaching a stable condition for a few months, the mass of the precipitated particles was around 0.027 g. Therefore, the mass fraction of particles remained in the stable colloid compared to the initial mass of particles used to make colloid was about 82%, or the concentration of the particles in the stable colloid was 0.123 g/10 mL.

To prove the existence, smaller particles remained in the colloid after removing the precipitants, we recorded again

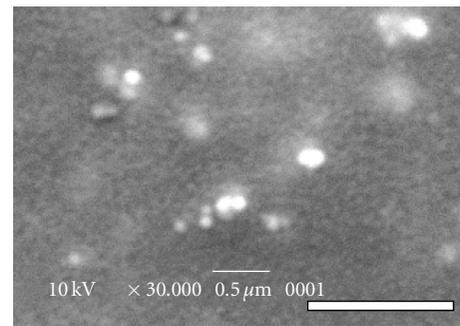


FIGURE 5: SEM images of particles in stable colloid. The length of the scale bar is 1 μ m.

the SEM picture of those particles. A drop of colloid was put on an SEM substrate and dried for several minutes. We were difficult to get a sharp SEM image for particles in colloid since the SEM substrate was likely covered by a PVA layer. We could only notify indication of the existence of smaller and separated particles in the stable colloid, as shown in Figure 5. Polymer in the colloid played a role as separator between particles as well as stabilizer in the colloid. This is not surprising because PVA has been frequently used as particle stabilizer in chemical synthesis of metal colloid. The PVA can prevent agglomeration and precipitation of the particles. The PVA has been well known as a good stabilizer for small particles such as CdS [31].

Intensive mixing of the powder with PVA liquid with a homogenizer might have broken connected particles in the original powder and dispersed the particles homogeneously in the liquid phase. Larger and unbroken particles precipitated at the bottom of the container, and the remained particles formed stable colloid.

FTIR spectra of four months old colloid made from $Y_2O_3:Eu$ that was synthesized at the heating temperature peak of 1000 °C are shown in Figure 6(a). A broad peak (A) at around 3346 cm^{-1} is originated from O-H stretching

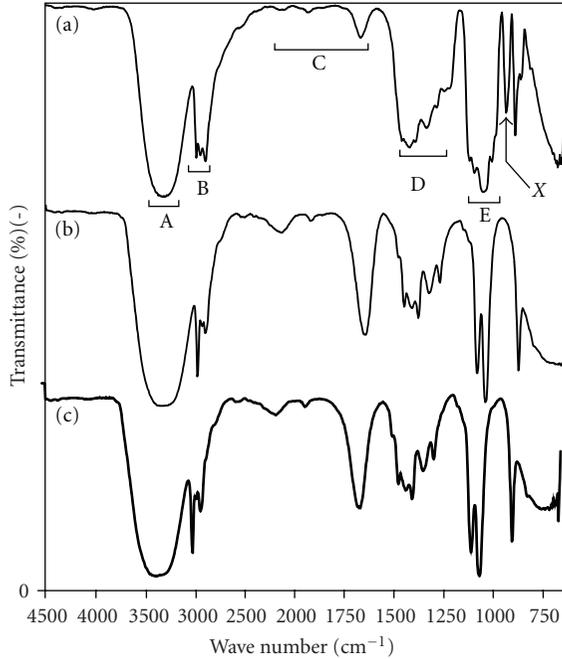


FIGURE 6: (a) FTIR spectrum of stable colloid from $Y_2O_3:Eu$ particles in a PVA solution, (b) FTIR spectrum of a PVA solution without $Y_2O_3:Eu$ particles, and (c) FTIR spectrum of colloid from $Y_2O_3:Eu$ particles in a glycerin solution.

in hydroxyl groups. Both PVA and alcohol contain hydroxyl groups. C-H stretching, (B), was observed at around $2980-2840\text{ cm}^{-1}$. Overtone or combination band (C) located in the range $2000-1667\text{ cm}^{-1}$ [32]. Absorption at around $1400-1213\text{ cm}^{-1}$ (D) might originated from C-H bend and C-C stretching. C-O stretching (E) was observed at around 1023 cm^{-1} . We were unable to detect any stretching in oxide material such as Y-O stretching at around 562 cm^{-1} and 464 cm^{-1} [33] due to limitation of the range of measurement in our equipment. The absorption peaks resulted by bonding of metal ions usually appear at short wave numbers [34].

As comparison, we also observed the FTIR spectrum of PVA solution (without $Y_2O_3:Eu$ powder) as shown in Figure 6(b). In general, the absorption peaks are very similar. Typical peaks originated from PVA, alcohol, and water are clearly observed as observed in Figure 6(a). The difference is only on the presence of a peak labeled by X in Figure 6(a) at 923.90 cm^{-1} , which was absent in PVA liquid. We assumed that this peak is originated from bonding of PVA chain with the surface of $Y_2O_3:Eu$ particles. To conform this assumption, we have also made another colloid by dispersed $Y_2O_3:Eu$ particles in a solution of glycerin. The type of bondings in glycerin is similar to that in PVA. The infrared spectrum of this colloid, as shown in Figure 6(c), is similar with Figure 6(a). The absorption peak at 923.90 cm^{-1} was not observed, proving that this absorption peak is truly originated from interaction between PVA chain and the surface of $Y_2O_3:Eu$. Furthermore, when $Y_2O_3:Eu$ particles was dispersed in a mixture of PVA and

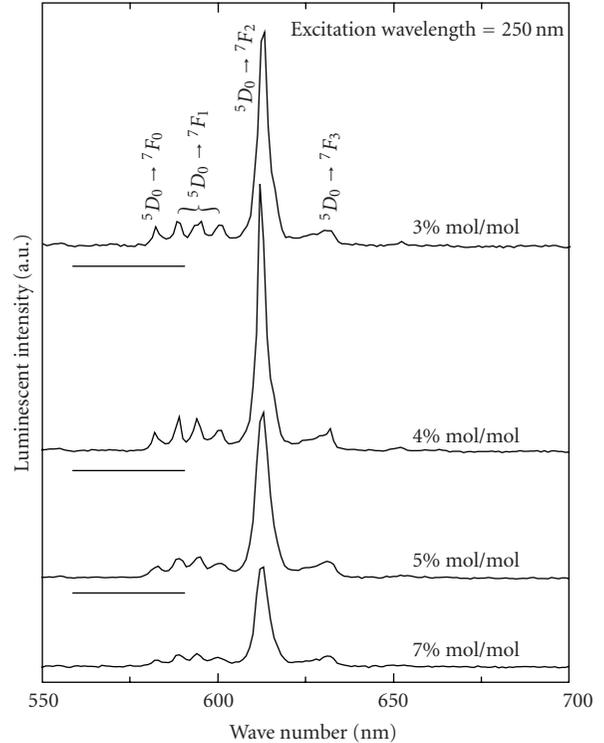


FIGURE 7: Photoluminescence spectra of $Y_2O_3:Eu$ powder prepared at heating temperature of $1000\text{ }^\circ\text{C}$ containing different Eu concentrations: (top to bottom) 3% mol/mol, 4% mol/mol, 5% mol/mol, and 7% mol/mol. In measurements, the samples were excited using a UV of 250 nm in wavelength.

glycerin solutions, peak at 923.90 cm^{-1} became slightly weaker. The peak still occurs because of the presence of PVA and $Y_2O_3:Eu$ particles. The weakness was caused by the presence of glycerin which acted to reduce the chance of bonding between PVA and the surface of $Y_2O_3:Eu$ particles.

It is still not clear what type of bonding resulting the X peak. If we consider that it is originated from some kinds of bonding between atoms in Y_2O_3 and atoms in PVA, the possible bonding combinations are O-O, O-C, and O-H, where the left side atom comes from Y_2O_3 , and the right side atoms come from PVA. Other combinations like Y-O, Y-C, and Y-H are likely impossible because they would produce short wavelength peaks. For example, Y-O bonding results absorption at around 562 cm^{-1} and 464 cm^{-1} [33]. In three possible bondings, that is, O-O, O-C, and O-H, the O-C bonding (stretching) has resulted absorption at around 1023 cm^{-1} , and O-H bonding has resulted absorption 3346 cm^{-1} . Therefore, it is likely that the X peak is originated from O-O bonding between O atom from Y_2O_3 surface and O atom from PVA. This assumption is supported by the location of this peak at slightly lower energy compared to peak from O-C bonding. It is because the reduced mass of O-O bonding is slightly larger than the reduced mass of C-O. The reduced mass of O-O is $\mu_{o-o} \approx (16 \times 16)/(16 + 16) = 8\text{ amu}$, and the reduced mass of O-C is

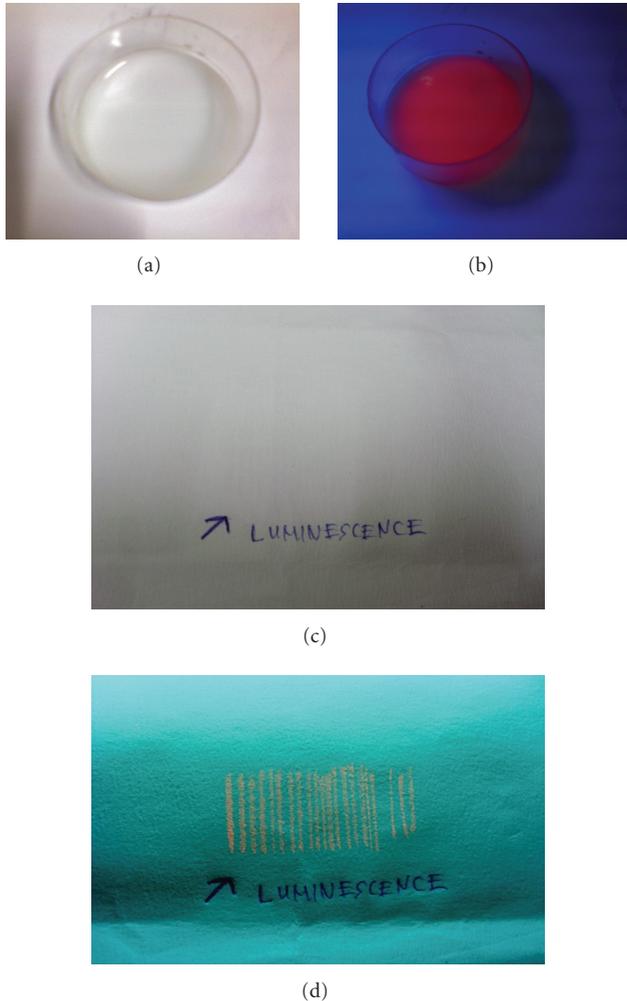


FIGURE 8: Stable colloid of $Y_2O_3:Eu$ without UV illumination (a) and when illuminated with UV of wavelength 254 nm (b). Example of writing result using stable luminescent colloid: (c) without illumination with UV and (d) under UV illumination.

$\mu_{o-c} \approx (16 \times 12)(16 + 12) = 6.9 \text{amu}$. Since the wave number is proportional to the inverse square of the reduced mass, we can approximate the location of O-O absorption at around $\omega_{o-o} \approx \omega_{c-o} \sqrt{\mu_{c-o} \mu_{o-o}}$. Using $\omega_{c-o} = 1023 \text{cm}^{-1}$, we obtain $\omega_{o-o} \approx 947 \text{cm}^{-1}$, for example, very close to the location of peak X at 923.90cm^{-1} .

This suggestion might be compared to the bonding of OH group on the surface of SiO_2 (oxide like Y_2O_3). OH functional group will be adsorbed on the surface of free SiO_2 surface, and it is likely that the bonding between O on the surface of SiO_2 and O on the OH group happens.

The photoluminescence spectra of samples prepared at heating temperature peak of 1000°C with different dopant concentrations: $Eu/Y = 3\% \text{ mol/mol}$, $4\% \text{ mol/mol}$, $5\% \text{ mol/mol}$, and $7\% \text{ mol/mol}$ are shown in Figure 7. In order to make a precise comparison of the PL intensities produced by all samples, the powder was put in a small metallic cup and then pressed under the same pressure to obtain

the same powder density. Measurement was performed in a reflection mode. The excitation was performed using an ultraviolet laser of 250 nm. The peaks at around 600 nm are originated from electron transition in Eu^{3+} ion from 5D_0 state to 7F_J states, with $J = 0, 1, 2, 3, 4, \text{ and } 6$. The strongest peak at 612 nm is originated from 5D_0 to 7F_2 transition. It is clear from Figure 7 that the PL intensity initially increases with increasing in the fraction of Eu and then decreases at higher fraction of Eu. The highest intensity was observed at Eu concentration of $4\% \text{ mol/mol}$. This is the reason why in the development of colloid we used samples that contained $4\% \text{ mol/mol}$ of Eu.

Figure 8(a) is the picture of colloid that has been kept for four months without UV illumination, and Figure 8(b) is the same colloid under UV irradiation. The red luminescent emitted by the colloid is still stable after storing for four months, indicating that the stably existence of particles in the colloid. The appearance color is also homogeneous, indicating the particles are dispersed homogeneously. The occurrence of red luminescent colloid over a long period of time proved that the particles did not have a tendency to agglomerate and precipitate and thus indicating the effectiveness of PVA capping.

Example of writing result using the prepared colloid is shown in Figures 8(c) and 8(d). Several parallel lines was written on a white paper using colloid prepared at $30\text{--}40^\circ\text{C}$ mixing temperature. After drying process, we did not read any mark on the paper without UV illumination. The mark became clearly seen when illuminated using a UV source of wavelength around 254 nm. This picture proved the potential use of the colloid for making security codes such as that found in bank notes, saving books, invisible barcodes, and other security documents. This ink is also potential for development of optoelectronic devices such as for production of plane-shaped luminescent displays, optical sensor, repeater in optical transmission, and by inkjet printing technology, for which very definitive sizes and shapes can be obtained.

4. Conclusions

We have been able to produce stable luminescent ink from powder of $Y_2O_3:Eu$ powder dispersed in PVA solution. $Y_2O_3:Eu$ played a role as luminescent centers in the ink which emitted strong red luminescence under UV illumination. The key factor determining the ability of production of stable colloid is mixing process of the powder with PVA solution. The mixing must be performed at prolonged time (around eight hours) at temperatures above the room temperature. Mixing temperature of $30\text{--}40^\circ\text{C}$ seemed to be the optimum temperature of mixing. Test of the function of the ink as material for making security codes was performed on a white paper at which the codes can only be read under UV illumination. This ink (luminescent colloid) can also meet several applications in optoelectronics such as for production of light emitting devices, light sensor, and luminescent displays in a very definitive sizes and shapes.

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References

- [1] M. Abdullah, C. Panatarani, T.-O. Kim, and K. Okuyama, "Nanostructured ZnO/Y₂O₃:Eu for use as fillers in luminescent polymer electrolyte composites," *Journal of Alloys and Compounds*, vol. 377, no. 1-2, pp. 298–305, 2004.
- [2] S. S. Chadha, D. W. Smith, A. Vecht, and C. S. Gibbons, in *Proceedings of the SID International Symposium: Digest of Technical Papers*, vol. 51, p. 1, Santa Ana, Calif, USA, May 1994.
- [3] S. H. Cho, J. S. Yoo, and J. D. Lee, "Synthesis and low-voltage characteristics of CaTiO₃:Pr luminescent powders," *Journal of the Electrochemical Society*, vol. 143, no. 10, pp. L231–L234, 1996.
- [4] S. Itoh, H. Toki, K. Tamura, and F. Kataoka, "A new red-emitting phosphor, SrTiO₃:Pr³⁺, for low-voltage electron excitation," *Japanese Journal of Applied Physics*, vol. 38, no. 11, pp. 6387–6391, 1999.
- [5] M. Abdullah, K. Okuyama, I. W. Lenggoro, and S. Taya, "A polymer solution process for synthesis of (Y,Gd)₃Al₅O₁₂:Ce phosphor particles," *Journal of Non-Crystalline Solids*, vol. 351, no. 8-9, pp. 697–704, 2005.
- [6] M. Abdullah and Khairurrijal, "Derivation of scherrer relation using an approach in basic physics course," *Jurnal Nanosains & Nanoteknologi*, vol. 1, no. 1, p. 79, 2008.
- [7] D. Matsuura, "Red, green, and blue upconversion luminescence of trivalent-rare-earth ion-doped Y₂O₃ nanocrystals," *Applied Physics Letters*, vol. 81, no. 24, pp. 4526–4528, 2002.
- [8] Y. L. Soo, S. W. Huang, Z. H. Ming, et al., "X-ray excited luminescence and local structures in Tb-doped Y₂O₃ nanocrystals," *Journal of Applied Physics*, vol. 83, no. 10, pp. 5404–5409, 1998.
- [9] R. Schmechel, M. Kennedy, H. von Seggern, et al., "Luminescence properties of nanocrystalline Y₂O₃:Eu³⁺ in different host materials," *Journal of Applied Physics*, vol. 89, no. 3, pp. 1679–1686, 2001.
- [10] T. Ye, Z. Guiwen, Z. Weiping, and X. Shangda, "Combustion synthesis and photoluminescence of nanocrystalline Y₂O₃:Eu phosphors," *Materials Research Bulletin*, vol. 32, no. 5, pp. 501–506, 1997.
- [11] T. Igarashi, M. Ihara, T. Kusunoki, K. Ohno, T. Isobe, and M. Senna, "Relationship between optical properties and crystallinity of nanometer Y₂O₃:Eu phosphor," *Applied Physics Letters*, vol. 76, no. 12, pp. 1549–1551, 2000.
- [12] Y. C. Kang, S. B. Park, I. W. Lenggoro, and K. Okuyama, "Preparation of nonaggregated Y₂O₃:Eu phosphor particles by spray pyrolysis method," *Journal of Materials Research*, vol. 14, no. 6, pp. 2611–2615, 1999.
- [13] M. Abdullah, I. W. Lenggoro, B. Xia, and K. Okuyama, "Novel processing for softly agglomerated luminescent Y₂O₃:Eu³⁺ nanoparticles using polymeric precursors," *Journal of the Ceramic Society of Japan*, vol. 113, no. 1313, pp. 97–100, 2005.
- [14] X. Guo, Y. Wang, and J. Zhang, "Synthesis multivariuous morphologies and sizes of YBO₃:Eu³⁺ phosphors and clarification of the crystal structure of YBO₃," *Journal of Crystal Growth*, vol. 311, no. 8, pp. 2409–2417, 2009.
- [15] J. L. Ferraru, A. M. Pires, and M. R. Davolos, "The effect of Eu³⁺ concentration on the Y₂O₃ host lattice obtained from citrate precursors," *Materials Chemistry and Physics*, vol. 113, no. 2-3, pp. 587–590, 2009.
- [16] L. Qianshu, F. Caihong, J. Qingze, G. Lin, L. Chenmin, and B. X. Hui, "Shape-controlled synthesis of yttria nanocrystals under hydrothermal conditions," *Physica Status Solidi a*, vol. 201, no. 14, pp. 3055–3059, 2004.
- [17] W.-C. Chien, "Synthesis of Y₂O₃:Eu phosphors by bicontinuous cubic phase process," *Journal of Crystal Growth*, vol. 290, no. 2, pp. 554–559, 2006.
- [18] W.-C. Chien and Y.-Y. Yu, "Preparation of Y₂O₃:Ce³⁺ phosphors by homogeneous precipitation inside bicontinuous cubic phase," *Materials Letters*, vol. 62, no. 26, pp. 4217–4219, 2008.
- [19] R. N. Bhargava, D. Gallagher, X. Hong, and A. Nurmikko, "Optical properties of manganese-doped nanocrystals of ZnS," *Physical Review Letters*, vol. 72, no. 3, pp. 416–419, 1994.
- [20] G. Mauthner, K. Landfester, A. Köck, et al., "Inkjet printed surface cell light-emitting devices from a water-based polymer dispersion," *Organic Electronics*, vol. 9, no. 2, pp. 164–170, 2008.
- [21] G. Bühler and C. Feldmann, "Transparent luminescent layers via ionic liquid-based approach to LaPO₄:RE (RE = Ce, Tb, Eu) dispersions," *Applied Physics A*, vol. 87, no. 4, pp. 631–636, 2007.
- [22] V. Svrcek, D. Mariotti, R. Hailstone, H. Fujiwara, and M. Kondo, "Luminescent colloidal silicon nanocrystals prepared by nanoseconds laser fragmentation and laser ablation in water," in *Proceedings of the Materials Research Society Symposium*, vol. 1066, pp. 437–442, San Francisco, Calif, USA, March 2008, paper no. 1066-A18-10.
- [23] A. Fojtik, M. Giersig, and A. Henglein, "Formation of nanometer-size silicon particles in laser induced plasma in SiH₄," *Berichte der Bunsen-Gesellschaft Physical Chemistry, Chemical Physics*, vol. 97, no. 11, p. 1493, 1993.
- [24] A. Fojtik and A. Henglein, "Luminescent colloidal silicon particles," *Chemical Physics Letters*, vol. 221, no. 5-6, pp. 363–367, 1994.
- [25] O. A. Lopez, J. McKittrick, and L. E. Shea, "Fluorescence properties of polycrystalline Tm³⁺-activated Y₃Al₅O₁₂ and Tm³⁺-Li⁺ co-activated Y₃Al₅O₁₂ in the visible and near IR ranges," *Journal of Luminescence*, vol. 71, no. 1, pp. 1–11, 1997.
- [26] S. Yamamoto, M. Kakihana, and S. Kato, "Polymer complex solution route to the low-temperature synthesis of tetragonal Zr_{0.88}Ce_{0.12}O₂ with a reduced amount of organic substance," *Journal of Alloys and Compounds*, vol. 297, no. 1-2, pp. 81–86, 2000.
- [27] P. Duran, F. Capel, D. Gutierrez, J. Tartaj, and C. Moure, "A study of V-shaped PTC behaviour of Sr_{0.4}Pb_{0.6}TiO₃ ceramics," *Journal of the European Ceramic Society*, vol. 22, no. 7, pp. 1171–1175, 2002.
- [28] J. C. Ray, R. K. Pati, and P. Pramanik, "Chemical synthesis of nanocrystalline zirconia by a novel polymer matrix-based precursor solution method using triethanolamine," *Materials Letters*, vol. 48, no. 2, pp. 74–80, 2001.
- [29] S. Shionoya and W. M. Yen, *Phosphor Handbook*, CRC Press, Boca Raton, Fla, USA, 1998.
- [30] G. Blasse and B. C. Grabmaier, *Luminescent Materials*, Springer, New York, NY, USA, 1994.
- [31] A. Pucci, M. Boccia, F. Galembeck, C. A. de Paula Leite, N. Tirelli, and G. Ruggeri, "Luminescent nanocomposites containing CdS nanoparticles dispersed into vinyl alcohol based polymers," *Reactive and Functional Polymers*, vol. 68, no. 7, pp. 1144–1151, 2008.

- [32] R. M. Silverstein, G. L. Bassler, and T. C. Morrill, *Spectrometric Identification of Organic Compounds*, John Wiley & Sons, New York, NY, USA, 1991.
- [33] G. Yao, L. Su, X. Xu, and J. Xu, "Eu:Y₂O₃ nano-phosphor prepared by novel energy-saving solution combustion method," *Journal of Alloys and Compounds*, vol. 462, no. 1-2, pp. 381–385, 2008.
- [34] K. Nakamoto, *Infrared and Raman Spectra of Inorganic and Coordination Compounds*, John Wiley & Sons, New York, NY, USA, 4th edition, 1986.



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