

Red persistent luminescence in $\text{MgGa}_2\text{O}_4:\text{Cr}^{3+}$; New phosphor for *in vivo* imaging

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Abstract. A new red emitting long-lasting phosphorescence (LLP) material useful as biomarker for small animal *in vivo* imaging is presented. X-ray irradiated $\text{MgGa}_2\text{O}_4:\text{Cr}^{3+}$ is shown to be a suitable persistent phosphor emitting in the range 650 nm to 770 nm. *In vivo* re-excitation of its persistent luminescence is also possible with 580 nm excitation. $\text{MgGa}_2\text{O}_4:\text{Cr}^{3+}$ has almost 44% cationic site inversion. Cr^{3+} ion occupies octahedral site resulting in a broad emission peaking at 707 nm corresponding to $\text{Cr}^{3+} \ ^2\text{E}(^2\text{G}) \rightarrow ^4\text{A}_2(^4\text{F})$ transition. LLP is most intense for the compound with nominal Mg deficiency which also has the highest cation inversion. It is proposed that structural defects occurring due to cation inversion are responsible for LLP.

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Persistent luminescent materials are those which emit light usually in the visible range for hours after their exposure to radiation is stopped. The delay in emission is caused by the presence of defect levels in the forbidden gap. Irradiation of the material, with UV or X-rays for instance, creates free electrons and holes which get trapped in these defect levels. When the difference in energy between the trapping levels and the host bands is close to the room temperature energy, a slow detrapping of charges due to thermal excitation can prolong the emission. Thermal energy available at room temperature actuates the detrapping of electron (or hole) which radiatively recombines with a hole (or electron) more deeply trapped at or around a luminescent center [1]. There has been a growing interest in long-lasting phosphors because of their excellent properties and widespread applications like night vision, medical diagnostics, temperature sensors, etc. [2, 3, 4].

Long-lasting phosphors with red or near-infrared emission are fast emerging as probes for *in vivo* small animal optical imaging after the first demonstration of the technique in 2007 [3]. In this method, the specially designed LLP nanoparticles, which are able to circulate in the blood vessels of small animals, are used as luminescent biomarkers. Making use of red persistent luminescence for optical imaging presents numerous advantages over conventional fluorescence techniques. The biomarkers are irradiated before injection into the animal body (*ex vivo*) making the exposure of animal to high energy radiations unnecessary. Since the nanoparticles are irradiated outside the animal body and the emission is in the biological optical window (650 nm to 900 nm), autofluorescence of living tissues is prevented thus improving the signal to noise ratio.

Recently, ZnGa₂O₄:Cr³⁺ (ZGO) has been discovered to serve this application with enhanced LLP properties [5]. The relatively simple, normal spinel structure of ZnGa₂O₄ adds to its advantage. In continuation of our work in finding new materials exhibiting LLP property with emission in the biological optical window, we report here a new material, MgGa₂O₄:Cr³⁺ (MGO) exhibiting LLP with high brightness and suitable for *in vivo* imaging. The host MgGa₂O₄, like ZnGa₂O₄ is a wide band gap semiconductor with $E_g \sim 4.74$ eV [6], favoring the formation of localized energy levels by incorporation of dopants like transition metal ions. It also belongs to cubic space group $Fd\bar{3}m$ with cell parameter $a = 8.2891$ Å [7]. However, magnesium gallate favors a partially inverse spinel structure unlike the near normal spinel structure of ZnGa₂O₄ [7]. Cr³⁺ ions are expected to occupy Ga³⁺ octahedral sites and present energy levels well described by a Tanabe-Sugano diagram for d³ electronic configuration in octahedral crystal field [8]. In this letter, apart from reporting LLP in MgGa₂O₄:Cr³⁺, we show that the structural inversion is one of the key factors in controlling LLP property in these spinel hosts.

Solid state method was employed to synthesize MgGa₂O₄:Cr³⁺ powders from its constituent metal oxides MgO (Sigma Aldrich 99.995% pure), Ga₂O₃ (Sigma Aldrich 99.99% pure) and CrO₃ (SRL 99% pure), with 0.5 mol% Cr doped for Ga. Calculated amounts of powders were thoroughly mixed, pelletized and sintered in air at 1300°C for 6 hours. Annealed pellets were crushed into fine powders for further characterizations.

The compounds were prepared by mixing three different molar ratios for cations to form an AB₂O₄ compound (A=Mg, B=Ga+Cr) with A/B = 0.5 (noted s-MGO for stoichiometric MGO), A/B = 0.495 (d-MGO for 1% Mg deficient MGO) and A/B = 0.505 (e-MGO for 1% Mg excess MGO). The main reason for this was the observation in ZnGa₂O₄:Cr³⁺ that varying the cation ratio during synthesis has an effect on inversion degree and therefore on LLP properties [5].

X-ray diffraction (XRD) patterns were recorded on Rigaku X-ray diffractometer using Cu K α radiation in 2θ range 20°-80°. Photoluminescence (PL) at room temperature (RT) was recorded on Varian Cary Eclipse spectrofluorimeter in the range 200nm-800nm with xenon lamp as excitation source. PL spectra at 10K were measured on powder pellets glued on the cold finger of a cryostat. Excitation was provided by an Optical Parametric Oscillator (OPO) pumped by the third harmonic of a YAG:Nd pulsed laser. Emission was collected via an optical fiber using a Scientific Pixis 100i CCD camera coupled to monochromator with 1200 grooves/mm grating. LLP was measured on 180 mg powder packed in 1 cm diameter sample holder. Luminescence was detected via an optical fiber using Scientific Pixis 100 CCD camera cooled at -65°C coupled with an Acton SpectraPro 2150i spectrometer for spectral analysis. Prior to this, the samples were irradiated with either X-rays (Mo-tube, 20mA-50kV) for 15 minutes or 580 nm wavelength of the OPO laser for 30 minutes.

XRD patterns of all three samples indicate formation of cubic spinel phase. Rietveld refinement was carried out for all the three patterns with cations occupying tetrahedral 8a positions (site symmetry: T_d) and octahedral 16d positions (site symmetry: D_{3d}) [9]. Parameters like lattice constant, cationic site occupancy along with scale factor, background, instrumental parameters etc., totaling 18 were varied in fitting. The resultant fit along with residual pattern for one of the compounds (d-MGO) is presented in FIG. 1. Presence of negligible (~1%) amount of un-reacted MgO was detected in all three compounds. In a normal spinel structure, divalent Mg²⁺ cations occupy tetrahedral A sites and trivalent Ga³⁺ cations occupy octahedral B sites. Partially inverted spinel structure results when some of the Mg²⁺ ions occupy B sites and the same number of Ga³⁺ ions occupy A sites. The refinement of cationic site occupancy confirmed the nearly inverse spinel structure of the compounds with Mg occupancy in octahedral site around 44% in agreement with Millard et al [7]. The occupancy was found to be 44.4(3)% for s-MGO, 45.2(3)% for d-MGO and 43.9(5)% for e-MGO indicating that, with increase in Mg content, cationic site inversion decreases.

PL excitation spectra presented in FIG. 2 consist of host band gap excitation peaking at 230 nm and three broad absorption bands around 270 nm, 420 nm and 585 nm belonging to ⁴A₂(⁴F) → ⁴T₁(⁴P), ⁴A₂(⁴F) → ⁴T₁(⁴F) and ⁴A₂(⁴F) → ⁴T₂(⁴F) Cr³⁺ d-d transitions respectively [10, 11]. The emission spectra of all three compounds are nearly overlapping with each other comprising of only three distinguishable crests at 707 nm, 715 nm and 727 nm (represented by arrows in FIG. 2) and a shoulder peak at 662 nm. The emission lines at 707 nm and 715 nm result from the ²E(²G) → ⁴A₂(⁴F) transition [12] of Cr³⁺ in a regular octahedral environment (R lines) and/or Cr³⁺ in

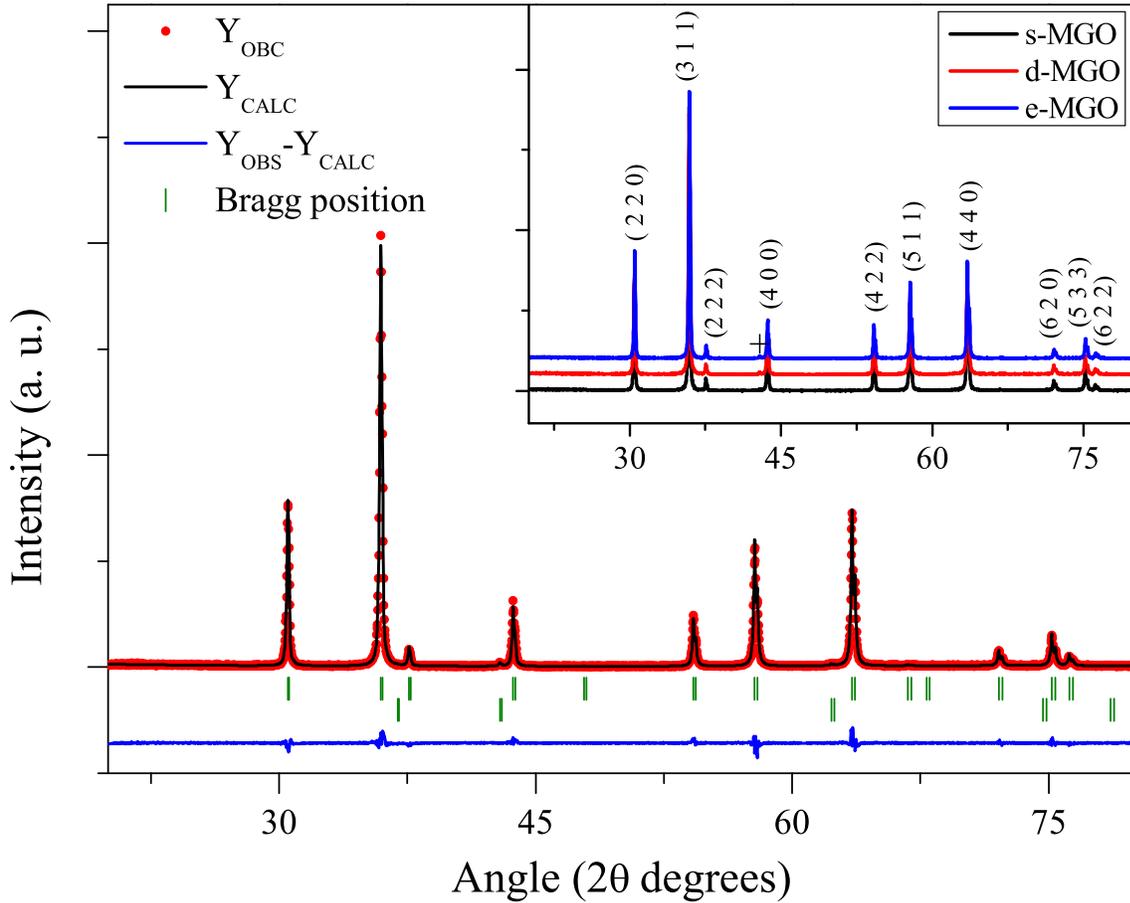


Figure 1. Rietveld refined XRD pattern of d-MGO indicating formation of spinel phase with minor ($\sim 1\%$) MgO impurity (marked with + in the inset). Inset shows XRD patterns of s-MGO and e-MGO along with d-MGO.

distorted octahedral environments (N lines). The relatively high degree of cation site inversion in MGO suggests they may be more likely due to latter.

A comparison of excitation and emission spectra of Cr³⁺ ion in MGO with that in ZGO matrix (FIG. 2) indicates a red shift for the excitation and emission lines observed in MGO. This shows that the crystal field experienced by Cr³⁺ ion in MGO is weaker than the corresponding crystal field in ZGO. The ligand field splitting term Δ_o/B has been determined by calculating the ratio of excitation frequencies and matching them with the ratio of length of the lines representing the transitions in the Tanabe-Sugano diagram [13]. For the two excitation peaks in MGO, $\lambda_1 = 585$ nm ($\nu_1 = 17094$ cm⁻¹) and $\lambda_2 = 420$ nm ($\nu_2 = 23810$ cm⁻¹), the ratio ν_2/ν_1 was found to be 1.393. Locating these ratios onto d³ Tanabe-Sugano diagram as shown in FIG. 3, the Δ_o/B for MGO was approximately obtained to be 25.6. A similar calculation for Cr doped ZGO based on parameters reported in Ref. [5] yielded a value of Δ_o/B equal to 27.8. These values confirm the weaker crystal field around Cr³⁺ ion in MGO as compared to that in ZGO

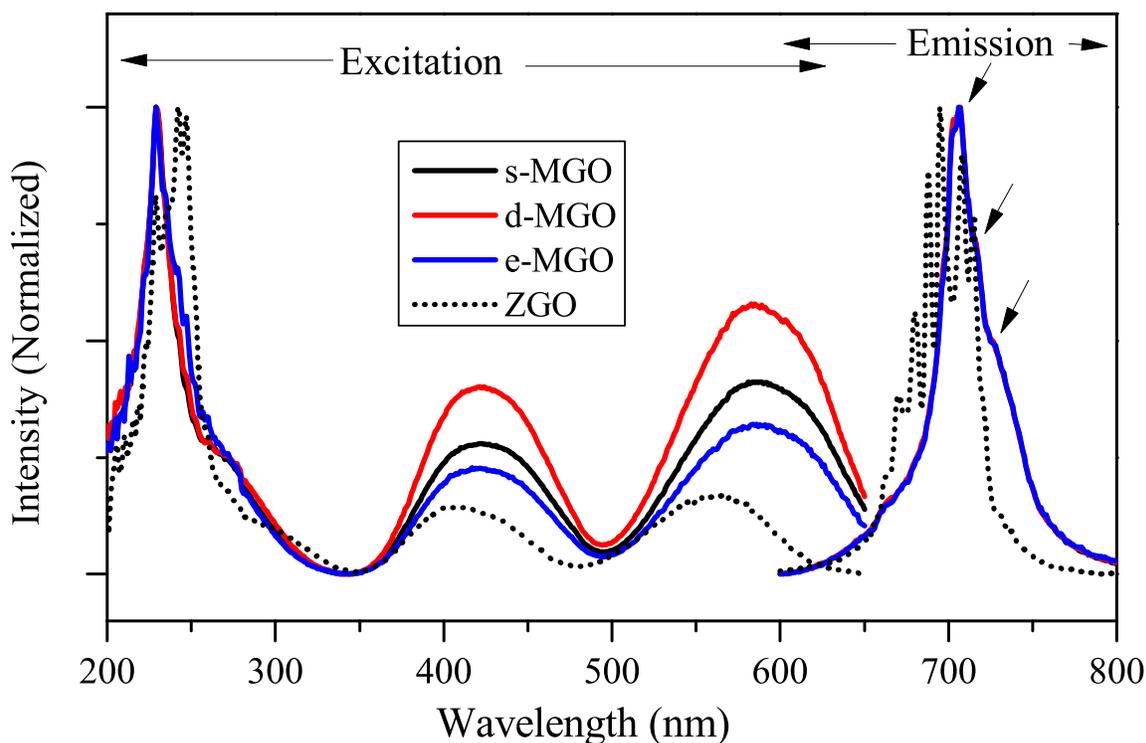


Figure 2. PL excitation spectra of the emission at 707 nm, and emission spectra excited at 230 nm. Dotted lines represent excitation spectra of the emission at 695 nm and emission spectra excited at 245 nm for Zn_{0.99}Ga_{1.99}Cr_{0.01}O₄ (noted as ZGO).

compound in agreement with the high degree of cation inversion. The broadening of the emission bands for MGO relative to ZGO can also be explained by the structural disorder induced by site inversion in MGO.

To further understand the emission spectra in detail, excited optical luminescence (EOL) spectra were recorded at 10K under various excitation wavelengths (460 nm-EOL, 420 nm-EOL, 380 nm-EOL) and are presented in FIG. 4. Emission spectra measured upon these three distinct excitation wavelengths (380 nm, 420 nm and 460 nm), reveal fine structures composed of up to six lines which have independent intensity variation as a function of excitation wavelength. This indicates that different emitting centers contribute to the total luminescence. For instance, the line at 707 nm (line 4 in FIG. 4) appears as the most intense line in spectrum recorded with 380 nm excitation while the maximum shifts to 715 nm (line 6 in FIG. 4) under longer excitation wavelength (420 nm). Therefore the six lines marked in FIG. 4 are attributed to distinct zero phonon lines revealing up to six different surroundings for trivalent chromium ions in MGO. This can be expected due to the partial inverse structure of the spinel host.

At RT, in the UV excited spectrum (230 nm-EOL), the same lines as the ones reported in low temperature spectra can be recognized though they appear broader due to thermal agitation (FIG. 4). X-ray excited optical luminescence (X-EOL) spectrum (FIG. 4) also appears similar although it presents weaker resolution as larger slit widths

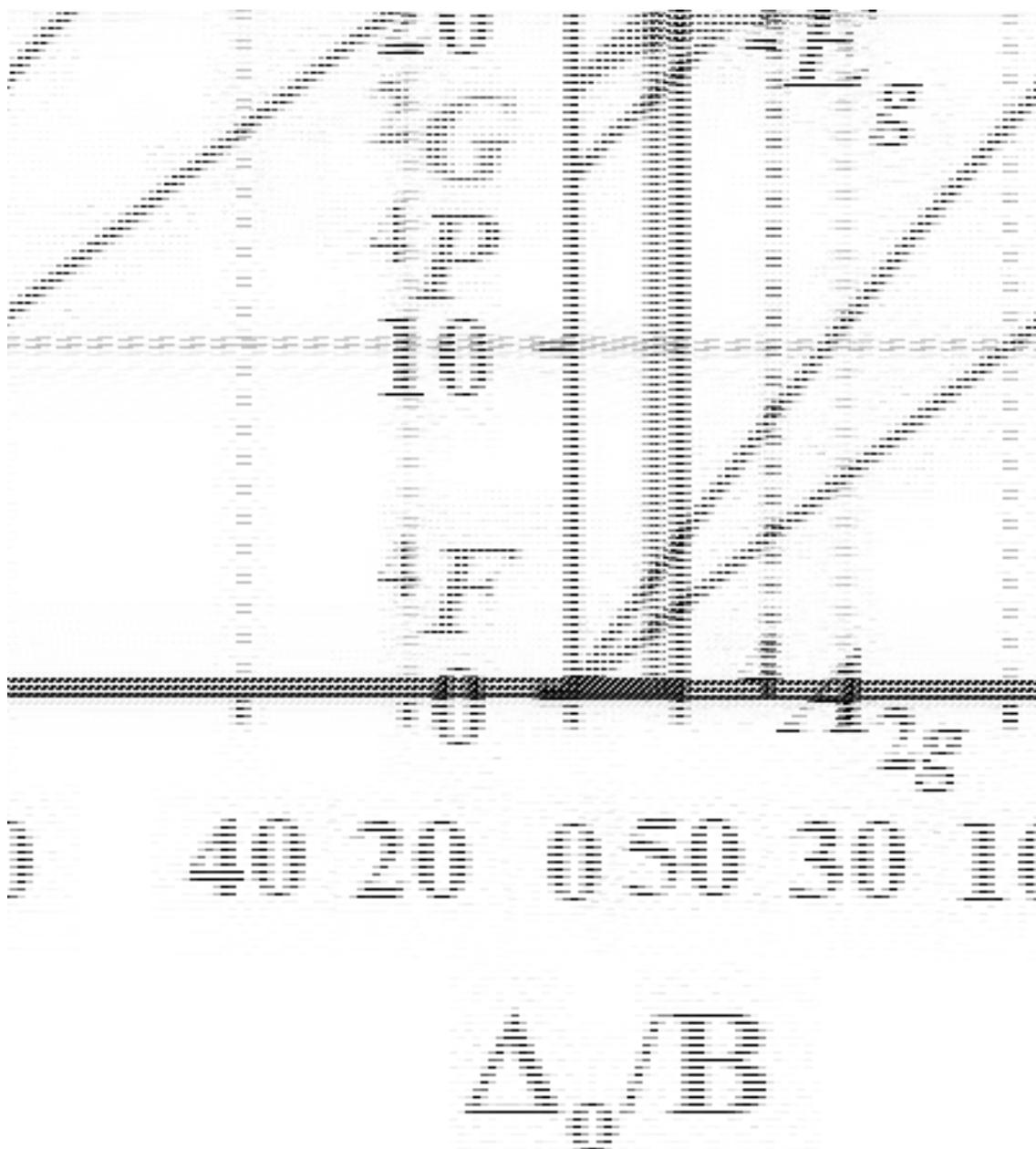


Figure 3. d^3 Tanabe-Sugano diagram for Cr^{3+} ion in octahedral environment. Solid arrows correspond to Cr^{3+} d-d transitions in MGO and dotted arrows correspond to transitions in ZGO.

were used. X-EOL is the luminescence emitted by the material under shining X-rays while X-LLP spectrum is recorded with excitation source turned off. It can be seen that the X-LLP spectrum is identical to the X-EOL spectrum, i.e. with dominant emission around 712 nm which could be originating from distorted Cr^{3+} ions present in MGO. In ZGO, LLP was shown to arise mainly from the N2 lines of distorted Cr^{3+} ions while PL

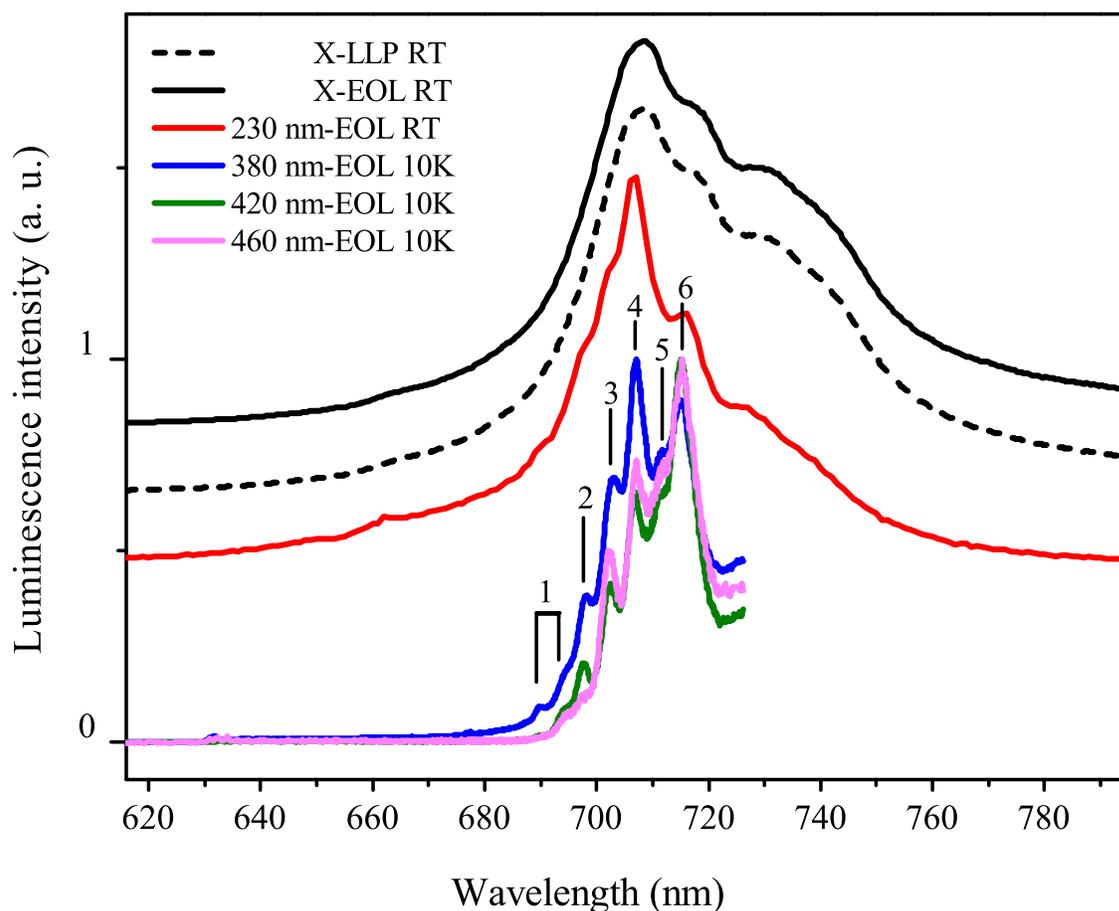


Figure 4. Comparison of luminescence spectra of d-MGO under various excitations (X-ray or UV-visible). X-LLP = X-ray excited long-lasting phosphorescence spectrum obtained 5 s after the end of a 15 minutes long X-ray excitation. X-EOL = X-ray excited optical luminescence.

spectra showed dominant R line emission [5]. In addition, RT spectra shows shoulder like features at 662 nm, 727 nm (also seen in PL spectra FIG. 2) and a broad band emission around 740 nm. The peak at 662 nm, present in RT spectra and absent in 10K spectra may correspond to Anti-Stokes phonon side band (PSB) of the R lines. The longer wavelength 727 nm peak and the broad hump around 740 nm result from the ${}^4T_2({}^4A) \rightarrow {}^4A_2({}^4F)$ transition of Cr³⁺ ions in intermediate crystal field [10].

X-ray excited LLP decay curves of these compounds presented in FIG. 5(a) show that d-MGO sample gives most intense LLP followed by s-MGO and e-MGO. It is interesting to observe that the same trend is also followed in the cation site inversion. Such a direct relation between cation site inversion and LLP property indicates that structural defects resulting from cationic inversion may be responsible for LLP in the MGO series. Furthermore, these three compounds display much better LLP than the original compound Ca_{0.2}Zn_{0.9}Mg_{0.9}Si₂O₆:Eu²⁺, Dy³⁺, Mn²⁺ (CZMSO) used to patent

the optical imaging technique [14] discussed in Ref. [3]. The inset of FIG. 5(a) presents LLP decay curves obtained for excitation with 580 nm laser. Significant LLP signal is visible even after 20 minutes. This is interesting from the application point of view since it enables the re-excitation of the biomarkers inside the animal body [15]. LLP is obtained with this harmless orange excitation in MGO as well as ZGO compounds mainly due to the presence of ${}^4A_2({}^4F) \rightarrow {}^4T_2({}^4F)$ excitation band of Cr³⁺ around 580 nm. Such a possibility does not exist for CZMSO compound as it does not have any excitation band beyond 450 nm [3]. Also, the comparatively simpler structure of MgGa₂O₄:Cr³⁺ than the silicate may add another advantage in terms of easy elucidation of LLP mechanism. Although MGO shows less LLP intensity than ZGO, its mean fluorescence wavelength is red-shifted from 701 nm (ZGO) to 726 nm (MGO)(FIG. 5(b)). Further, the emission spectrum of MGO is broader than that in ZGO. These are certain advantages as the optical absorption of biological tissues steeply decreases with increasing wavelength in the range 600-760 nm [16].

X-ray Rietveld refinement confirmed the nearly inverse character of the spinel structure of Cr doped MgGa₂O₄ compounds and showed that inversion could be slightly increased by varying the Mg/(Ga+Cr) nominal ratio towards Mg deficiency. MGO was shown to present enhanced LLP brightness and red shifted emission spectrum compared to the silicate reference CZMSO used to demonstrate the technique of *in vivo* imaging using LLP probes. Similarly to ZGO, long-lasting phosphorescence in MGO could also be observed with 580 nm excitation, making *in vivo* re-excitation of the MGO probe possible. Although MGO was shown to present about 7 times less intense LLP than ZGO at wavelength of respective emission maximum, its mean fluorescence wavelength was red shifted by 25nm inside the optical transparency window of biological tissues. This could make MGO a better LLP probe than ZGO in conditions of real *in vivo* imaging. The increase in inversion of the spinel structure was found to be favorable for the LLP intensity showing once again a relation between antisite defects and LLP phenomenon in ZGO-like spinels. In conclusion, we have developed a new red long lasting phosphor MgGa₂O₄:Cr³⁺, which could be used as an efficient probe for *in vivo* small animal optical imaging.

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References

- [1] McKeever S W S 1985 *Thermoluminescence of Solids* (UK: Cambridge University press)
- [2] Pan Z, Lu Y Y and Liu F 2012 Sunlight-activated long-persistent luminescence in the near-infrared from Cr³⁺-doped zinc gallogermanates *Nat. Mater.* **11** 58

- [3] Chermont Q L M D, Chanéac C, Seguin J, Pellé F, Maîtrejean S, Jolivet J P, Gourier D, Bessodes M and Scherman D 2007 Nanoprobes with near-infrared persistent luminescence for *in vivo* imaging *PNAS* **104** 9266
- [4] Aizawa H, Katsumata T, Takahashi J, Matsunaga K, Komuro S, Morikawa T and Toba E 2002 Fiber-optic thermometer using afterglow phosphorescence from long duration phosphor *Electrochem. Solid-State Let.* **5** H17
- [5] Bessière A, Jacquart S, Priolkar K, Lecointre A, Viana B and Gourier D 2011 ZnGa₂O₄:Cr³⁺: a new red long-lasting phosphor with high brightness *Optics Express* **19** 10131
- [6] Liu Z, Hu P, Jing X and Wang L 2009 Luminescence of native defects in MgGa₂O₄ *J. Electrochem. Soc.* **156** H43
- [7] Millard R L, Peterson R C and Swainson I P 2000 Synthetic MgGa₂O₄-Mg₂GeO₄ spinel solid solution and β -Mg₃Ga₂GeO₈: chemistry, crystal structures, cation ordering, and comparison to Mg₂GeO₄ olivine *Phys. Chem. Minerals* **27** 179
- [8] Tanabe Y and Sugano S 1954 On the absorption spectra of complex ions II *J. Phys. Soc. Japan* **9** 766
- [9] Hahn Th (Editor) 2005 *International Tables for Crystallographic Volume A: Space-group symmetry* (US: Springer Publishing)
- [10] Sosman L P, Fonseca R J M D, Tavares Jr. A D, Barthem R B and Arbitta T 2007 New spectroscopic results of trivalent chromium in magnesium gallate *J. Phys. Chem. Solids* **68** 22
- [11] Silva M A F M D, Pedro S D S and Sosman L P 2010 Cr³⁺ impurity concentration and excitation dependences of magnesium gallate spinel photoluminescent data *J. Alloys Compd.* **492** 282
- [12] Zhang WX, Wang YH, Li HL, Wang XS and Zhao H 2013 Structure and luminescence properties of MgGa₂O₄:Cr³⁺ with Zn substituted for Mg *Spectroscopy and Spectral Analysis* **33** 31
- [13] House J E 2008 *Inorganic Chemistry* (Elsevier: Academic press) p 673
- [14] Chermont Q L M D, Scherman D, Bessodes M, Pellé F, Maîtrejean S, Jolivet J P, Chanéac C and Gourier D 30/10/2006 Nanoparticules à luminescence persistante pour leur utilisation en tant qu'agent de diagnostique destiné à l'imagerie optique *in vivo* *CNRS patent* internat. ext. WOEP06067950, WO2007048856
- [15] Maldiney T, Richard C, Scherman D, Gourier D, Viana B and Bessière A 30/01/2013 Nanoparticules à luminescence persistante excitables *in situ* pour imagerie optique *in vivo*, imagerie multimodale optique-IRM *in vivo*, et la théranostique *Patent PCT N° PCT/EP2013/051727*
- [16] Weissleder R and Ntziachristos V 2003 Shedding light onto live molecular targets *Nat. Med.* **9** 123

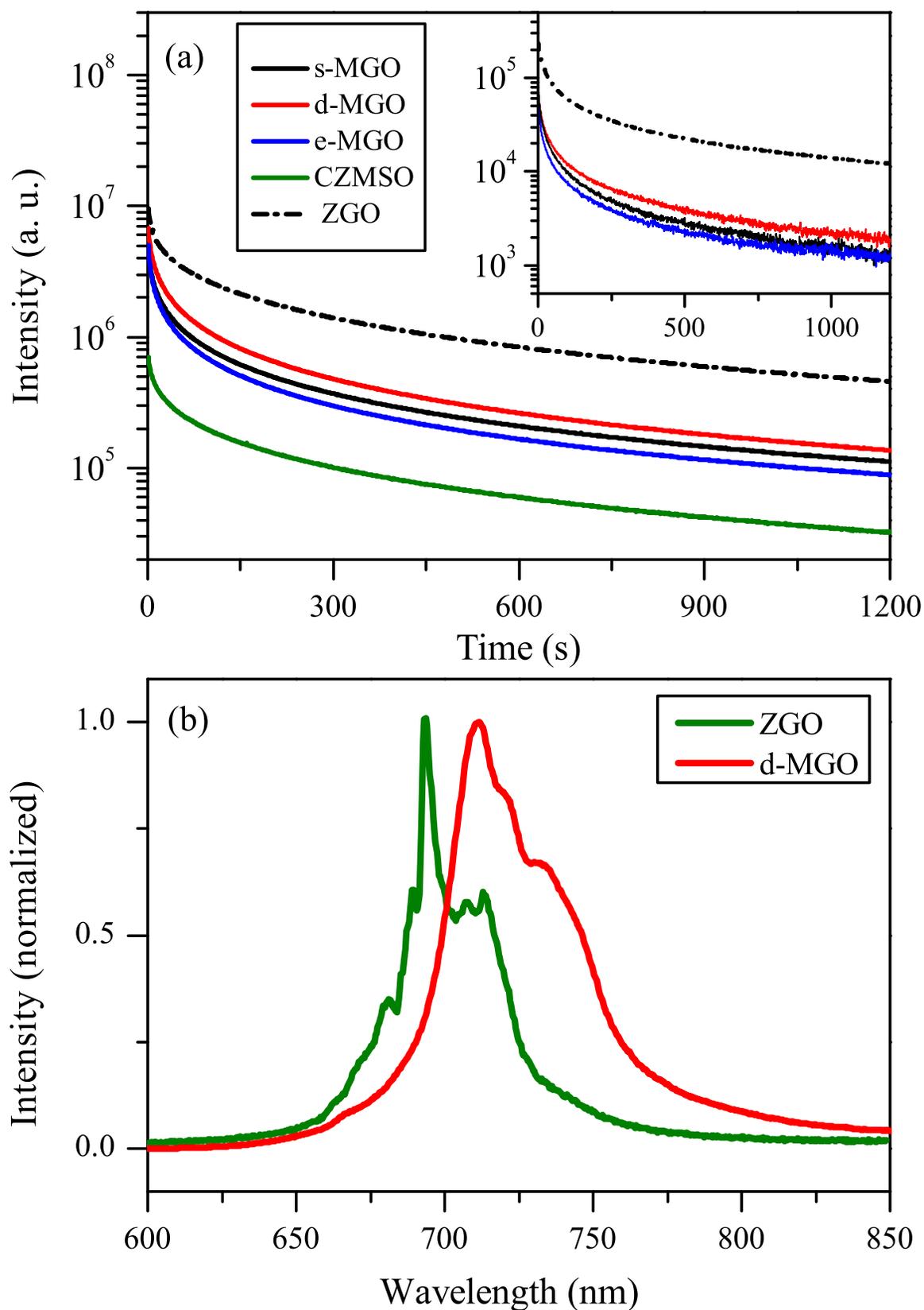


Figure 5. (a) LLP decay curves of MGO (full lines) and ZGO (dotted line) after 15 minutes X-ray irradiation (main figure) and 30 minutes 580 nm laser irradiation (inset), (b) X-LLP emission spectra obtained 5 s after the end of 15 minutes long X-ray excitation. Concentration of Cr³⁺ in ZGO is 0.5 mol% and the concentration of luminescent ion Mn²⁺ in CZMSO is 2.5 mol%.