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Afterglow-intensity-ratio-based temperature sensing using a persistent phosphor

A high-sensitivity afterglow thermometer is realized in persistent $Y_3AI_2Ga_3O_{12}$:Pr³⁺ phosphors, which have unique advantages including zero background fluorescence and zero extra heat.

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1. Introduction

Temperature is one of the most basic physical parameters, and its precise measurement plays a vital role in scientific research, industrial production, life sciences, *etc.*^{1–3} Conventional temperature-sensing techniques can be divided into two categories: contact type methods, which include resistance temperature detectors, thermocouples, and thermistors,⁴ and noncontact type methods, which include infrared thermal imaging, thermal reflection,⁵ Raman spectroscopy,⁶ and so on. In recent years, non-contact optical thermometers based on steady-state fluorescence for biological sensing,⁷ catalytic reactions⁸ and rapid monitoring of the temperature of a free fluid⁹ have gradually become an important branch of the thermometry

Afterglow-intensity-ratio-based temperature sensing using a persistent phosphor[†]

Chuan Liao, ம ab Feng Chen, C Hao Wu, ம a Huajun Wu, ம a Liangliang Zhang, ம a Guo-hui Pan, 🕩 a Feng Liu, 🕩 *C Xiao-jun Wang 🕩 *d and Jiahua Zhang 🕩 *ab

Fluorescence intensity ratio (FIR)-based temperature-sensing techniques have received widespread attention in recent decades. However, the excitation light inevitably results in stray light and extra heat that will affect the accuracy of the thermometry. These drawbacks can be overcome *via* a non-real-time photo-excitation scheme using a persistent phosphor that is named here the afterglow intensity ratio (AIR) technique. Only several studies of AIR thermometry have been carried out where the Boltzmann equilibrium mechanism is mainly applied for manipulating the AIR. Here, we report highly sensitive AIR thermometry based on a thermal quenching (TQ) mechanism using the $Y_3Al_2Ga_3O_{12}$:Pr³⁺ persistent phosphor, which can generate an intense afterglow that originates from the $4f^15d^1 \rightarrow 4f^2$ and ${}^3P_0 \rightarrow {}^3H_4$ emissions of Pr³⁺ after ultraviolet charging. The AIR of the two emissions shows a strong temperature dependence in the range of 30-170 °C, giving a maximum relative sensitivity of up to 4.12% °C⁻¹ at 170 °C. The necessary high temporal stability of the AIR for accurate temperature measurement is proved. The application of the AIR technique is demonstrated *via* water-temperature measurement, where the error in the measurement is only 0.1 °C. Finally, we study and predicated some other persistent phosphors that showing application potential for AIR thermometry.

technique due to their convenience, rapid response, high sensitivity, and high temperature and spatial resolution.¹⁰⁻¹² Optical thermometry uses phosphor as the sensing material to achieve changes in various optical parameters, such as the fluorescence intensity ratio (FIR),¹³ fluorescence lifetime,¹⁴ peak position,³ bandwidth,9 polarization anisotropy,11 and emission intensity15 in a real-time photo-excitation process at different temperatures. However, stray light in real-time photo-excitation is inevitable, and ultraviolet excitation light^{16,17} can simultaneously produce background fluorescence for some substances being measured (e.g., chemical fibers,¹⁸ proteins,¹⁹ and organic matter²⁰). An upconverting phosphor can avoid background fluorescence; however, it does produce a lot of heat to increase the temperature due to its low up-conversion efficiency.21-25 These drawbacks of realtime photo-excitation limit the accuracy of thermometry, and they can be overcome via a non-real-time photo-excitation scheme that uses a persistent phosphor, namely the afterglow intensity ratio (AIR) technique.

Afterglow, which is also known as persistent luminescence, is a light-emission phenomenon of a persistent phosphor that can store external excitation energy and then persistently emit light for minutes to hours after the removal of the excitation.^{26–30} The persistent phosphor for use in an AIR technique requires pre-irradiation for charging the irradiation energy that can be thermally released to produce afterglow with a temperature-dependent spectral distribution. Until now, only

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^a State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, 3888 Eastern South Lake Road, Changchun, 130033, China. E-mail: zhangjh@ciomp.ac.cn

^b Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing, 100049, China

^c Key Laboratory for UV-Emitting Materials and Technology of Ministry of Education, Northeast Normal University, Changchun, 130024, China. E-mail: fengliu@nenu.edu.cn

^d Department of Physics, Georgia Southern University, Statesboro, GA 30460, USA. E-mail: xwang@georgiasouthern.edu

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a few studies on AIR thermometry have been carried out,³¹⁻³⁴ and the Boltzmann equilibrium mechanism has mainly been employed for manipulating the AIR.

In this paper, we report highly sensitive AIR thermometry based on a thermal quenching (TQ) mechanism using the Pr³⁺doped Y₃Al₂Ga₃O₁₂ persistent phosphor, which can generate an intense afterglow that originates from the $4f^{1}5d^{1} \rightarrow 4f^{2}$ and ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ emissions of Pr^{3+} after ultraviolet charging. In addition, Y₃Al₂Ga₃O₁₂:Pr³⁺ can be also charged through twophoton blue-light up-conversion excitation. The AIR of the $4f^{1}5d^{1} \rightarrow 4f^{2}$ to ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ emissions is studied as a function of the temperature in the range of 30-170 °C after ultraviolet charging at the corresponding temperature. The highest relative sensitivity of 4.12% °C⁻¹ is achieved at 170 °C. The high temporal stability of the AIR in Y₃Al₂Ga₃O₁₂:Pr³⁺ is proved, showing its potential for accurate temperature measurement. The measurement of water temperature with an error of only 0.1 °C is carried out using the AIR method. Moreover, the temperature-dependent afterglow emission spectra are also realized for a wide variety of persistent phosphors, such as $Lu_2SiO_5:Pr^{3+}$, $Y_3Al_5O_{12}:Tb^{3+}, Eu^{3+}$, $ZnGa_2O_4:Cr^{3+}$, and SrA l_2O_4 :Eu²⁺,Dy³⁺, showing their application potential for AIR thermometry.

2. Experimental section

2.1 Materials and synthesis

Well-crystallized cubic phase $Y_{3-x}Pr_xAl_2Ga_3O_{12}$ (x = 0.0005–0.01) phosphors were synthesized via a high-temperature solid-state reaction. In this work, we focus on the Y_{2.999}Pr_{0.001}Al₂Ga₃O₁₂ phosphor that has a more intense $4f^{1}5d^{1} \rightarrow 4f^{2}$ transition. Stoichiometric amounts of Y2O3 (99.99%), Al2O3 (99.99%), Ga₂O₃ (99.99%), and Pr₆O₁₁ (99.999%) powders were mixed and ground, and 5 mol% H₃BO₃ was added as a flux. These mixtures were sintered in air at 1550 °C for 3 h to obtain the phosphors. The source powders, sintering atmospheres, temperatures and times of the other four persistent phosphors mentioned in this work are: Lu₂SiO₅:0.05%Pr³⁺, Lu₂O₃ (99.995%), SiO_2 (SP), and Pr_6O_{11} (99.999%) in air at 1350 $^\circ \rm C$ for 3 h; $Y_3Al_5O_{12}$:0.2%Tb³⁺, 0.1%Eu³⁺, Y_2O_3 (99.995%), Al_2O_3 (99.99%), Tb_4O_7 (99.999%), and Eu_2O_3 (99.99%) in CO at 1550 °C for 5 h; ZnGa₂O₄:1%Cr³⁺, ZnO (99.5%), Ga₂O₃ (99.99%), and Cr_2O_3 (99.95%) in air at 1300 °C for 4 h; and SrAl₂O₄:1%Eu²⁺,2%Dy³⁺, SrCO₃ (AR), Al₂O₃ (99.99%), Eu₂O₃ (99.99%), and Dy_2O_3 (99.95%) in CO at 1300 °C for 1 h.

2.2 Characterization and measurements

The monochromatic light from a built-in xenon arc lamp (XBO-450W-OFR, OSRAM; as included in the spectrofluorometer, FluoroLog-3, Horiba) was used as the charging source for obtaining the afterglow excitation spectrum. A pulsed laser (SureLite II Nd:YAG laser, Continuum) with a tunable wavelength from an optical parametric oscillator was used as the charging source for obtaining the afterglow up-conversion charging (UCC) excitation spectrum. A 450 nm blue laser diode

(LSR455CP-FC-12W and LSR-PS-FA, Lasever Inc) was used for the UCC of the Y₃Al₂Ga₃O₁₂:Pr³⁺ phosphor. The afterglow emission spectra were record using a charge-coupled device (CCD) spectrometer (QEPro, Ocean Optics; optical fiber diameter, 600 µm; spectrometer slit, 100 µm; integration time, 5 s). An external heating/cooling stage (THMS-600, Linkam, UK) was used for variable temperature experiments. The afterglow decay curves were recorded using an FLS920 spectrometer (Edinburgh Instruments, UK). Before each measurement, the phosphor was heat-treated at 500 °C to empty all the traps. Thermoluminescence (TL) glow curves were obtained using an SL08-L TL reader (Rongfan Science and Technology Co. Ltd, Guangzhou, China). The heating rate was $4 \, {}^{\circ}\mathrm{C} \, \mathrm{s}^{-1}$. Before measurement of the TL glow curves and afterglow emission spectra, the samples were charged using a 254 nm mercury lamp (ZF-2, Anting Shanghai, China) for 10 min. The AIR calibration experiment of the Y₃Al₂Ga₃O₁₂:Pr³⁺ phosphor disk in water (depth, 5.5 cm) was performed using a constanttemperature heater (BII-3, Sile Shanghai, China) and a CCD spectrometer (see Fig. S7, ESI⁺ for details).

3. Results and discussion

3.1 Charging path of Y₃Al₂Ga₃O₁₂:Pr³⁺

The Y₃Al₂Ga₃O₁₂:Pr³⁺ phosphor can be charged using conventional one-photon ultraviolet excitation to produce afterglow emission,³⁵ as schematically illustrated in the inset of Fig. 1(a). The afterglow excitation spectrum was recorded after irradiation with monochromatic light from a filtered xenon arc lamp (see Fig. 1(a) and Fig. S1, ESI†). The excitation spectrum shows an ultraviolet band in the range of 220–320 nm (from 32 000 to 47 000 cm⁻¹). To gain insight into the distribution of traps in Y₃Al₂Ga₃O₁₂:Pr³⁺, the TL glow curve was measured after 254 nm charging, as shown in Fig. 1(b). The phosphor exhibits strong afterglow emission in the temperature range of 30–250 °C, which consists of two distinct peaks at 80 °C and 175 °C. As a result, the afterglow emission of Y₃Al₂Ga₃O₁₂:Pr³⁺ has the potential to be used for temperature sensing in this temperature range.

When a laser is used as the visible-light excitation source instead of a xenon arc lamp, up-conversion charging (UCC) excitation in the 4f²–4f² absorption region becomes pronounced, as shown in Fig. S2, ESI.† The UCC excitation spectrum shows some blue peaks at 450, 459, 473 and 487 nm, which correspond to the intermediate levels ${}^{3}P_{2}$, ${}^{1}I_{6}$, ${}^{3}P_{1}$ and ${}^{3}P_{0}$, respectively, of Pr³⁺. The up-converted afterglow exhibits a near quadratic dependence of the integrated TL intensity (*I*) on the blue laser excitation power density (*P*), $I \propto P^{1.73}$, indicating the occurrence of UCC (see Fig. S3, ESI[†]).^{36–39}

3.2 Temperature-dependent afterglow spectra

The afterglow emission spectra at various temperatures (30– 170 °C) in Y₃Al₂Ga₃O₁₂:Pr³⁺ charged using 254 nm ultraviolet light were measured (see Fig. S4, ESI[†]), and the spectra for 30, 100 and 170 °C are selected as examples shown in Fig. 2(a) for further study. The afterglow emission spectra show characteristic emissions of Pr³⁺ containing 4f¹5d¹ \rightarrow 4f² (³H_{4.5.6} and ³F_{2.3.4})

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Fig. 1 (a) Conventional afterglow excitation spectrum of the $Y_3Al_2Ga_3O_{12}$: Pr^{3+} phosphor. The inset shows the schematic illustration for ultraviolet charging. (b) TL glow curve for the 487 nm ($^{3}P_0 \rightarrow {}^{3}H_4$) emission of the $Y_3Al_2Ga_3O_{12}$: Pr^{3+} phosphor recorded after ceasing the 254 nm radiation.

bands in the 280–450 nm range and a ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ line at 487 nm. In Fig. 2(a) the intensity of the ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ emission line is normalized. It is apparent that the intensity of the $4f^{1}5d^{1} \rightarrow 4f^{2}$ emission bands with a peak maximum at 300 nm decreases markedly with increasing temperature from 30 °C to 170 °C (see also Fig. S4, ESI† for more details). This is due to the TQ relaxation of the $4f^{1}5d^{1}$ state to the ${}^{3}P_{0}$ state, as observed in Pr^{3+} -doped phosphors.^{40–43} As a result, the AIR of the $4f^{1}5d^{1}$ emission bands to the ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ emission line of $Y_{3}Al_{2}Ga_{3}O_{12}$: Pr^{3+} is applicable for temperature sensing.

A time-independent AIR is necessary for accurate temperature sensing. The afterglow decay curves monitored at 300 nm for the $4f^15d^1 \rightarrow 4f^2$ emission and that at 487 nm for the ${}^3P_0 \rightarrow {}^3H_4$ emission are depicted together in Fig. 2(b) for comparison. Indeed, the two decay curves satisfy the identical decay function at a fixed temperature, indicating a stable AIR with time. With a normalized the initial intensity, the afterglow emission band and line decay along the same trajectory for a fixed temperature over a time longer than 500 s (see Fig. S5, ESI†). The temporally stable AIR is well understood based on the afterglow mechanism illustrated in

Fig. 2(c), where the AIR is determined *via* the rate of TQ relaxation from the $4f^{1}5d^{1}$ state to the ${}^{3}P_{0}$ state and TQ is only temperature dependent, as analyzed in the next section.

3.3 AIR-based optical thermometry using the Y₃Al₂Ga₃O₁₂:Pr³⁺ phosphor

Here, the AIR is defined as the integrated intensity ratio of the $4f^{1}5d^{1} \rightarrow 4f^{2}$ emission (I_{1} , 280–450 nm) to the ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ emission (I_{2} , 480–490 nm). The ${}^{3}P_{0}$ state is populated mainly from TQ relaxation, as shown in Fig. S6, ESI.† From Fig. 2(a) and Fig. S4 ESI,† the temperature dependence of the AIR, I_{1}/I_{2} , is obtained and depicted in Fig. 3(a). The AIR can be well fitted using the following equation (see eqn (S3), ESI†) that is deduced using eqn (S1) and (S2) based on the TQ model

$$AIR(T) = \frac{AIR_0}{1 + \alpha \exp\left[-\frac{\Delta E_{TQ}}{k_B(T + 273)}\right]}$$
(1)

where AIR₀ is the value of the AIR in the limit of $T \rightarrow -273 \text{ °C}, \alpha$ is a constant, ΔE_{TQ} (eV) is the activation energy, and k_{B} (eV K⁻¹)



Fig. 2 (a) Normalized afterglow emission spectra of $Y_3Al_2Ga_3O_{12}$: Pr^{3+} after ceasing the 254 nm irradiation at different temperatures. (b) Afterglow decay curves of the phosphor monitored at 300 nm ($4f^15d^1 \rightarrow 4f^2$) and 487 nm ($^3P_0 \rightarrow {}^3H_4$) after irradiation at 254 nm at different temperatures. (c) Schematic illustration of the afterglow process of the phosphor.

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Fig. 3 (a) AIR (I_1/I_2) of the $Y_3Al_2Ga_3O_{12}$: Pr^{3+} phosphor as a function of temperature, and the fitting line. (b) AIR of the phosphor at different times after ceasing the 254 nm excitation at different temperatures. (c) Absolute sensitivity (S_a) and relative sensitivity (S_r) versus temperature. (d) Temperature uncertainty (δT) in the temperature range from 30 to 170 °C at different times after ceasing the excitation.

is the Boltzmann constant. The fitting line is in good agreement with the experimental data, and the fitting parameters are listed in Table S1, ESI.† The monotonicity of the AIR function ensures a one-to-one correspondence between the AIR and the temperature. To examine the temporal stability of the AIRs, the afterglow emission spectra were recorded at 5, 10, 15, 20 and 25 s after 254 nm ultraviolet charging. The corresponding AIR (I_1/I_2) was calculated and plotted in Fig. 3(b). Obviously, the AIR remains unchanged with time at a fixed temperature.

Based on the AIR curve shown in Fig. 3(a), the absolute sensitivity (S_a) and the relative sensitivity (S_r) are calculated using the following equations:^{1,44}

$$S_{\rm a} = \left| \frac{\rm d(AIR)}{\rm dT} \right| \tag{2}$$

$$S_{\rm r} = \frac{1}{\rm AIR} \left| \frac{\rm d(AIR)}{\rm dT} \right| \times 100\% \tag{3}$$

The calculated S_a and S_r values are plotted as a function of temperature in Fig. 3(c). It can be clearly observed that S_a and S_r show a trend of monotonically decreasing and increasing, respectively. The maximal absolute sensitivity is 0.192 °C⁻¹, which occurs at 30 °C. The relative sensitivities increase from 1.62 to 4.12% °C⁻¹ with an increase in temperature from 30 to

170 °C. The maximal relative sensitivity, $S_{r max}$, of 4.12% °C⁻¹ is among the highest reported relative sensitivities for FIR- and AIR-based optical thermometry sensors, as listed in Table 1.

Besides the sensitivity, the temperature uncertainty δT , also known as the temperature resolution, is another important parameter for evaluating the performance of a thermometer. It describes the smallest temperature change that a thermometer can resolve in practice, as described using the following equation^{2,55}

$$\delta T = \frac{1}{S_{\rm r}} \frac{\delta {\rm AIR}}{{\rm AIR}} = \frac{1}{S_{\rm r}} \sqrt{\left(\frac{\delta I_1}{I_1}\right)^2 + \left(\frac{\delta I_2}{I_2}\right)^2}$$
(4)

where δ AIR/AIR is the relative error of the experimental system, and $\delta I_i/I_i$ (i = 1 and 2) can be estimated using the signal-to-noise ratio of the experimental system. Since the afterglow intensity decays with time, we calculated δT values for different delay times and different temperatures, as shown in Fig. 3(d). On the one hand, the δT values gradually increase with an increase of the delay time, because the weakening of the afterglow intensity reduces the signal-to-noise ratio. On the other hand, the δT values first decrease and then increase with the increase in temperature, which is attributed to the combined effect of thermally induced afterglow enhancement (see Fig. 1(b)) and emission quenching at higher temperatures (see Fig. 2(a)). The

Table 1 Maximal relative sensitivity (S_{rmax} at a given T_s value) and temperature range (T range) of the used FIR- and AIR-based optical thermometry sensors in previous reports

Host	Dopant ion	Method	$S_{ m rmax}$ (% $^{\circ} m C^{-1}$)	$T_{\rm s}$ (°C)	T-range (°C)	Ref.
$NaGd(MoO_4)_2$	Tb^{3+}, Pr^{3+}	FIR	2.05	130	30 to 210	12
m-ZrO ₂	Ti^{4+}, Eu^{3+}	FIR	3.84	140	30 to 140	17
Ba ₃ Y ₄ O ₉	Er^{3+} , Yb^{3+}	FIR	0.37	-130	-190 to 290	24
Sr_2GeO_4	Pr^{3+}	FIR	9.0	-251	-256 to 327	40
$CaSc_2O_4$	Pr^{3+}	FIR	2.49	117	-73 to 217	42
BaTiO ₃	Ho^{3+}, Yb^{3+}	FIR	2.78	146	25 to 305	45
SrLu ₂ O ₄	Ce ³⁺	FIR	2.28	10	-123 to 27	46
CaMoO ₄	Ho^{3+}, Yb^{3+}	FIR	0.66	80	30 to 270	47
YAlO ₃	Nd^{3+}	FIR	1.83	20	20 to 338	48
LaF ₃	Nd^{3+}	FIR	~ 0.08	10	10 to 60	49
Bi2SiO5@SiO2	Nd^{3+}	FIR	~ 1.6	7	-13 to 427	50
Bi4Si3O13@SiO2	Nd^{3+}	FIR	~ 1.5	7	-13 to 427	50
Bi2SiO5@SiO2	Yb^{3+} , Tm^{3+}	FIR	~ 2.6	-13	-13 to 527	51
Bi ₂ Ga ₄ O ₉	Cr^{3+}	FIR	2.74	-193	-193 to 177	52
ZnGa ₂ O ₄	Cr^{3+}	FIR	~ 3.75	-3	-3 to 427	53
Bi ₂ Al ₄ O ₉	Cr^{3+}	FIR	~ 1.4	-173	-173 to 327	54
$Sr_4Al_{14}O_{25}$	$Eu^{2+}, Cr^{3+}, Nd^{3+}$	AIR	0.75	10	10 to 60	31
$SrAl_2O_4$	Eu^{2+} , Dy^{3+} , Tb^{3+}	AIR	\sim 7.0	-73	-213 to -33	32
NaYF ₄	Pr^{3+}	AIR	0.65	30	30 to 210	33
NaYF ₄	Er^{3^+}	AIR	1.06	30	30 to 150	34
$Y_3Al_2Ga_3O_{12}$	Pr^{3+}	AIR	4.12	170	30 to 170	This work

 δT of our thermometer is limited within 0.108–2.359 °C for the temperature range of 30–170 °C at 5 s after 254 nm ultraviolet charging, which can ensure an adequate reliability for low-temperature regions ($\delta T < 1$ °C).

intensity in a medium is described *via* the Lambert law, which is given as 56

$$I(x) = I_0 \exp(-\beta x) \tag{5}$$

Since the afterglow intensity always decreases with time, the increase in δT values with the measurement time delay is an inherent limitation of AIR-based temperature-sensing methods. In addition, the temperature-sensing range of the method is also limited by the trap distribution. However, these limitations are expected to be better resolved through the development of new persistent phosphors and optimization of existing persistent phosphors.

As an example, we demonstrate the non-contact temperature measurement of hot water using the afterglow emission spectrum of the $Y_3Al_2Ga_3O_{12}$:Pr³⁺ phosphor disk. Notably, the relationship between the propagation distance and the light

where I(x) and I_0 are light intensity after and before absorption, respectively, *x* is the propagation distance of the light, and β is a wavelength-dependent constant. Obviously, the spectral distribution will change due to different propagation distances in the medium. Therefore, we calibrated the AIR (I_1/I_2) of the Y₃Al₂Ga₃O₁₂:Pr³⁺ phosphor disk in water at a depth of 5.5 cm (see Fig. S7, ESI[†] for details), and calculated the AIR (I_1/I_2) as a function of temperature (see Fig. 4(c) and Fig. S8, ESI[†]). For comparison, Fig. 4(a) illustrates the setup for the simultaneous measurement of the hot water temperature using a contact thermocouple thermometer and our AIR method. The afterglow emission spectrum is measured in the dark after 254 nm



Fig. 4 (a) Demonstration of measuring the temperature of hot water. A $Y_3Al_2Ga_3O_{12}$: Pr^{3+} phosphor disk was placed at the bottom of a cup filled with hot water (depth, 5.5 cm). A contact thermocouple thermometer and a CCD spectrometer were used to record the hot water temperature and afterglow emission spectra, respectively. (b) Afterglow emission spectrum of the phosphor disk in water. (c) Plot of the values calculated from (b) as AIR (I_1/I_2) versus temperature to obtain the temperature of the hot water. For the calibration experiment in water see Fig. S7, ESI.†

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ultraviolet charging, as shown in Fig. 4(b). After calculation the AIR indicates that the water temperature is 57.1 $^{\circ}$ C (see Fig. 4(c)), which is close to the temperature of 57.0 $^{\circ}$ C measured using the contact thermocouple thermometer.

3.4 Other persistent phosphors for temperature sensing

Besides the $Y_3Al_2Ga_3O_{12}$:Pr³⁺ phosphor, we examined a variety of persistent phosphors for afterglow-based optical thermometry. The normalized afterglow emission spectra of Lu₂SiO₅:Pr³⁺, $Y_3Al_5O_{12}$:Tb³⁺,Eu³⁺, ZnGa₂O₄:Cr³⁺, and SrAl₂O₄:Eu²⁺,Dy³⁺ were studied at different temperatures, as shown in Fig. S9–S12, ESI,† respectively. Obviously, Lu₂SiO₅:Pr³⁺ and $Y_3Al_5O_{12}$:Tb³⁺, Eu³⁺ can be used as AIR-based thermometers. In addition, the bandwidth of the afterglow emission of ZnGa₂O₄:Cr³⁺ and the peak position of the afterglow emission of SrAl₂O₄:Eu²⁺,Dy³⁺ show temperature dependence and they may act as temperature-sensing parameters. Moreover, many persistent phosphors have been reported, but the behavior of the afterglow emission spectra have been less studied at various temperatures. It is expected that more persistent phosphors could be developed for AIR-based temperature sensing.

4. Conclusion

In summary, we realized optical temperature sensing in the range of 30-170 °C using an AIR method in the Y₃Al₂Ga₃O₁₂:Pr³⁺ persistent phosphor after ultraviolet charging. The AIR of the $4f^{1}5d^{1} \rightarrow 4f^{2}$ emission to the ${}^{3}P_{0} \rightarrow {}^{3}H_{4}$ emission of Pr^{3+} shows strong temperature dependence and offers quite a high relative sensitivity of 4.12% °C⁻¹ at 170 °C. Meanwhile, the AIRs remain unchanged with time, enabling the accurate measurement of temperature. Our AIR method was applied to the measurement of water temperature with an error of only 0.1 °C. It is expected that AIR temperature sensing after blue laser UCC could be feasible in for the $Y_3Al_2Ga_3O_{12}$:Pr³⁺ persistent phosphor. Moreover, the temperature-dependent afterglow emission spectra were also obtained for a wide variety of persistent phosphors, such $Lu_2SiO_5:Pr^{3+}$, $Y_3Al_5O_{12}:Tb^{3+}$, Eu^{3+} , $ZnGa_2O_4:Cr^{3+}$, as and $SrAl_2O_4{:}Eu^{2+}{,}Dy^{3+}{,}$ demonstrating their application potential for AIR thermometry.

Conflicts of interest

There are no conflicts to declare.

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