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Optical Thermometry by Monitoring Dual Emissions from YVO₄ and Eu³⁺ in YVO₄:Eu³⁺ Nanoparticles

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ABSTRACT

Contactless optical thermometry is successfully applied for accurate local temperature sensing in many scientific and technological areas. Majority of optical thermometers utilize a ratiometric approach between thermally coupled levels. Such sensors have an inherent limitation of relative thermal sensitivity linked to the maximal energy gap between these levels, which can make them useless for some important applications. Here we report simple dual-center YVO₄:Eu³⁺ thermometers that do not have this limitation. Thermal sensing using YVO₄:Eu³⁺ nanoparticles is based on monitoring luminescence intensity ratio between YVO₄ host emission and Eu³⁺ luminescence lines. By taking advantage of the different temperature behavior of the aforementioned emission bands, contactless sensing was demonstrated within 123–423 K range. High thermometric performances including sub-degree temperature resolution (up to 0.2 K) and relative thermal sensitivity (up to 1.4 % K⁻¹) at room temperature reveal the good potential of YVO₄:Eu³⁺ phosphors for thermometry and lay a foundation for the future development of dual-center probes.

KEYWORDS: dual-center thermometry, luminescence, Eu³⁺, YVO₄, lifetime

INTRODUCTION

During last years rare earth doped phosphors have been intensively utilized in various applications from light sources and displays to catalysts and biological labels.¹⁻⁴ Recently, much attention was attracted to contactless luminescence thermometry as a new method allowing to define temperature with submicron spatial and sub-degree thermal resolution.⁵⁻⁸ The development of highly sensitive nanothermometers is of high demand in a variety of fields involving nanoelectronics, integrated photonic devices, microfluidics, and nanomedicine.⁹⁻¹¹ To date, luminescence thermometry is provided through monitoring of particular steady-state or kinetics temperature-sensitive parameter, namely luminescence intensity (or intensity ratio), bandwidth, line position, lifetime or polarization.^{12,13}

Most frequently luminescence sensing is based on ratiometric approach since this method is self-referencing and stable toward material quantity, excitation power fluctuations and detector sensitivity.¹¹ Ratiometric sensing usually utilize the analysis of luminescence intensities ratio (LIR) between thermally coupled levels. However, the use of thermally coupled levels for temperature sensing imposes a fundamental limitation on the relative thermal sensitivity ($S_r = \Delta E/kT^2$), as these levels should have the energy gap (ΔE) not larger than 2000 cm^{-1} to minimize decoupling process. This limitation can be overcome if LIR would be calculated between emission bands attributed to different active centers.¹⁴ Dual-center thermometers have been developed on the base of hybrid materials (metal-organic frameworks with lanthanides,^{15,16} $\text{NaGdF}_4:\text{Nd}^{3+}$ and PbS/CdS/ZnS quantum dots in a single-encapsulated nanoparticle¹⁷, $\text{Zn}_{0.99}\text{Mn}_{0.01}\text{Se/ZnCdSe}$ system¹⁸, nanodiamond-Eu/Tb hybrid material¹⁹), inorganic samples containing two rare earths²⁰⁻²² or rare earth – transition metal ions.²³⁻²⁵

Another strategy to design a dual-center thermal sensor is utilizing hosts with temperature-dependent intrinsic luminescence. It is sufficient to dope such a host with single rare earth or transition metal ions to provide ratiometric thermometry. This approach was successfully realized by several scientific groups. Zhang et al. reported $\text{Ca}_5\text{Mg}_4\text{V}_6\text{O}_{24}:\text{Eu}^{3+}$ powders for

thermal sensing within 298–473 K range with thermal sensitivity about 0.5 % K⁻¹.²⁶ CaNb₂O₆:Eu³⁺ and CaNb₂O₆:Eu³⁺,Bi³⁺ phosphors showed high thermal sensitivity of 1.8 and 3.8 % K⁻¹, respectively.²⁷ Noteworthy, the reported thermometers have a quite complex host composition, which makes synthesis more difficult. Moreover, the possible spatial resolution of these thermometers is limited by their particle size (several microns).

Here, we suggest simple single-doped YVO₄:Eu³⁺ nanoparticles (NPs) as dual-center phosphor for thermal sensing with high spatial and thermal resolution. The first emission center of studied phosphors is YVO₄ host, which displays a broad emission band in the blue spectral region, while the second one is Eu³⁺ ions which demonstrate a typical red luminescence. Different nature of emission centers and presence of temperature dependent energy transfer between host and Eu³⁺ makes YVO₄:Eu³⁺ NPs a promising candidate for dual-center thermometry. Effect of doping concentration and choice of Eu³⁺ transition for LIR calculation on thermometric parameters of synthesized samples was studied. Radiative and nonradiative decay rates defining Eu³⁺ emission intensity were calculated within 123–573 K range. Thermometric performances were explored by determining relative thermal sensitivity, temperature resolution, and repeatability.

EXPERIMENTAL

We prepared YVO₄:Eu³⁺ 0.01 at.% and YVO₄:Eu³⁺ 0.1 at.% NPs using the modified Pechini method described in our earlier works (Figure 1).^{28–30} The reagents were metal oxides, concentrated nitric acid to produce metal nitrates, citric acid to form a citrate complex of metals and ethylene glycol for the etherification reaction, which leads to the formation of the polymer gel. The Pechini method allowed synthesizing amorphous oxide particles after gel pyrolysis at 500 °C for 1 hour. The modified Pechini technique includes an additional stage of powder heat treatment in an inert salt melt. The temperature of this additional heat treatment was selected taking into account two limiting factors. On the one hand, temperature must be lower than the oxide melting point. On the other hand, temperature must be higher than the melting point of the

salt so that the aggregate state of the reaction environment is liquid. The amorphous oxide precursor was annealed in the potassium chloride melt at 950 °C for 1.5 hours. This synthesis temperature and duration of calcination time were earlier experimentally selected and optimized.³¹ The additional stage suggested by the authors allows obtaining crystalline particles with weak agglomeration. This positively affects the luminescence properties of the material. The substance obtained after cooling consists of product particles distributed in a solid chloride matrix. YVO₄:Eu³⁺ particles were easily separated from chlorides by washing in distilled water three times and dried for further research.

Figure 1. Scheme of YVO₄:Eu³⁺ nanoparticles synthesis using modified Pechini technique.

Rigaku «Miniflex II» diffractometer measured powder X-ray diffraction of synthesized samples. SUPRA 40VP WDS scanning electron microscope (SEM) was used to obtain micrograph images. Steady-state and kinetics luminescence properties at different temperatures were studied with Fluorolog-3 spectrometer. Linkam THMS 600 heating stage with a resolution of 0.1 °C

were used to control temperature. Steady-state temperature regime was obtained by a 5 min waiting time before each measurement.

RESULTS AND DISCUSSION

Figure 2a presents XRD patterns of the studied $\text{YVO}_4:\text{Eu}^{3+}$ samples with the standard card of tetragonal YVO_4 . All peaks of synthesized samples match with the tetragonal phase without any impurity lines found. Substitution of Y^{3+} by Eu^{3+} ions did not affect diffraction line positions due to small Eu^{3+} doping concentration in both powders. Figure 2b shows scanning microscopy image of $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% sample. Powder consists of well-faced NPs with an average size of about 60–70 nm. The obtained photo reveals weak agglomeration of NPs synthesized using the modified Pechini method. Figure S1 displays SEM image and particle size distribution of Sm^{3+} -doped YVO_4 NPs obtained at the same synthesis conditions.

Figure 2. a) XRD pattern of $\text{YVO}_4:\text{Eu}^{3+}$ samples with different concentrations; b) SEM image of $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% powder.

Figures 3a and 3b show emission spectra of $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% nanopowders measured at different temperatures upon $\lambda_{\text{ex}} = 300$ nm. This wavelength was chosen based on the measured excitation spectra (Figure S2). Excitation radiation is absorbed by

YVO₄ host with subsequent host emission or energy transfer to Eu³⁺ ions.^{32,33} Emission spectra include a broad band centered at 455 nm assigned to YVO₄ host luminescence and series of narrow peaks corresponding to transitions from metastable ⁵D₀ level to lower-lying ⁷F_J levels of Eu³⁺ ions (J = 1–4): ⁵D₀–⁷F₁ (594 nm), ⁵D₀–⁷F₂ (619 nm), ⁵D₀–⁷F₃ (648 nm), and ⁵D₀–⁷F₄ (698 nm).³⁴ It should be noted that YVO₄:Eu³⁺ 0.01 at.% displayed also transitions originated from higher excited Eu³⁺ levels such as ⁵D₂–⁷F₁ (475 nm), ⁵D₂–⁷F₂ (483 nm), ⁵D₁–⁷F₁ (538 nm), ⁵D₁–⁷F₂ (553 nm), and ⁵D₁–⁷F₃ (573 nm). Excitation and emission spectra of undoped YVO₄ NPs displaying broad bands centered at 300 and 455 nm respectively are presented in Figure S3.

Figure 3. Emission spectra of a) YVO₄:Eu³⁺ 0.01 at.% and b) YVO₄:Eu³⁺ 0.1 at.% NPs at different temperatures ($\lambda_{\text{ex}} = 300$ nm).

One can see that temperature increase led to the monotonic decrease of host intensity, whereas temperature dependence of Eu³⁺ emission intensity was more complex (Figure S4 and S5). Taking into account this fact, we suggested utilizing LIR between the host band and Eu³⁺ lines as a temperature-dependent parameter. Since LIR is calculated from the same measurement, the ratiometric approach is more robust toward systematic errors compared to temperature readout based on a single emission band intensity.²⁴ LIRs between YVO₄ band and the three most intense Eu³⁺ emission lines: LIR₁ (host/⁵D₀–⁷F₁), LIR₂ (host/⁵D₀–⁷F₂), and LIR₃ (host/⁵D₀–⁷F₄) were calculated. All calculated LIRs demonstrated a monotonic increase along with 1/T growth

(temperature decrease) for both $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% samples (Figure 4a, 4b, S6 and S7). The experimental data were approximated with the following function:

$$\text{LIR} = \frac{I_{\text{host}}}{I_{\text{Eu}}} = A + Be^{-C/T} \quad (1)$$

where A, B and C are temperature-independent constants and T is the absolute temperature. Eq. (1) should be regarded as phenomenological fitting. Noteworthy, $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% phosphors can be used for thermal sensing within 123–423 K and 123–323 K temperature ranges, respectively. A narrower temperature range in the latter case is explained by higher thermal quenching of host emission due to higher energy transfer efficiency to Eu^{3+} ions. The thermal quenching of YVO_4 emission for samples with different Eu^{3+} doping concentration is clearly seen in Figure 3.

To estimate phosphors' performances as possible thermal sensors, the thermometric characteristics should be calculated and compared with thermometers reported earlier. The relative thermal sensitivity ($S_r = \frac{1}{\text{LIR}} \frac{d\text{LIR}}{dT}$) is one the most important parameter, which serves for comparison between different thermometers irrespective of their nature (mechanical, electrical, optical). Figure 4c and 4d show S_r temperature evolution for $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% samples. The relative thermal sensitivities were calculated based on different LIRs (LIR_1 , LIR_2 and LIR_3). It can be seen that temperature increase results in a decline in S_r values. Choice of particular LIR slightly affects thermal sensitivity in the physiological temperature range, while a significant difference was observed only at lower temperatures. The obtained S_r values were found to be 1.17 and 1.40 % K^{-1} at 298 K for $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% nanothermometers, respectively. These values are comparable with sensitivities of ratiometric Eu^{3+} -doped thermometers utilizing thermoequilibrium between two ground energy levels: 1.23 % K^{-1} ($\text{YVO}_4:\text{Eu}^{3+}$),³⁵ 1 % K^{-1} ($\text{Y}_2\text{O}_3:\text{Eu}^{3+}$),³⁶ 0.9 % K^{-1} (Eu^{3+} -doped alumino-phosphate glass),³⁷ and 1.14 % K^{-1} ($\text{Ca}_3\text{Sc}_2\text{Si}_3\text{O}_{12}:\text{Eu}^{3+}$).³⁸

Figure 4. Temperature evolution of luminescence intensity ratio LIR_1 for a) $YVO_4:Eu^{3+}$ 0.01 at.% and b) $YVO_4:Eu^{3+}$ 0.1 at.% thermometers between 123–423 K and 123–323 K, respectively; relative thermal sensitivities of c) $YVO_4:Eu^{3+}$ 0.01 at.% and d) $YVO_4:Eu^{3+}$ 0.1 at.% samples.

Temperature resolution (ΔT) defines how accurate temperature measurement could be done utilizing a particular thermometer. Our earlier research has demonstrated that ΔT value can be obtained via different experimental methods: from the temperature calibration curve, from the measurement of emission spectra series at the same temperature or from the monitoring of sample's cooling down.³⁹ Here, ΔT was calculated using the first technique according to the following formula: $\Delta T = \frac{1}{S_r} \frac{\delta LIR}{LIR}$, where $\delta LIR/LIR$ is the temperature relative uncertainty obtained as a dispersion of three repeated measurements. The obtained ΔT values (at $T = 298$ K)

for $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% nanothermometers are listed in Table 1. One can see that $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% sample provides more accurate temperature determination, while LIR_3 is the best ratiometric parameter allowing sub-degree sensing.

Table 1. Relative thermal sensitivity (S_r) and temperature resolution (ΔT) of $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% nanothermometers at $T = 298$ K.

Thermometer	Sensing parameter	S_r (% K^{-1})	ΔT (K)
$\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.%	LIR_1	1.17	1.0
	LIR_2	1.19	0.4
	LIR_3	1.20	0.2
$\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.%	LIR_1	1.40	2.1
	LIR_2	1.44	2.0
	LIR_3	1.38	0.5

To compare the studied optical thermometers with the dual-emitting ratiometric temperature sensors reported earlier, their thermometric performances are listed in Table 2. It can be noted that not all papers provide temperature resolution, which makes comparison difficult. The highest thermal sensitivity of $5.4 \% \text{ K}^{-1}$ was obtained for $\text{LiTaO}_3:0.001\text{Ti}^{4+}/0.02\text{Eu}^{3+}$ phosphors, whereas Eu^{3+} -doped YVO_4 thermometers demonstrated average sensitivity. Among host/ Ln^{3+} ratiometric sensors, $\text{YVO}_4:\text{Eu}^{3+}$ samples have the simplest composition.

Table 2. Thermometric performances of dual-emitting ratiometric optical thermometers at room temperature.

Material	S_r (% K^{-1})	ΔT (K)	Ref.
$\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.%	1.20	0.2	This work
$\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.%	1.38	0.5	

$\text{LiTaO}_3:0.001\text{Ti}^{4+}/0.02\text{Eu}^{3+}$	5.4	0.14	40
$\text{Ca}_8\text{BaCe}(\text{PO}_4)_7:0.05\text{Mn}^{2+}$	0.4	—	41
$\text{Li}_5\text{Zn}_8\text{Al}_5\text{Ge}_9\text{O}_{36}:0.025\text{Mn}^{2+}$	3.3	0.01	42
$\text{Sr}_2\text{MgAl}_{22}\text{O}_{36}:0.02\text{Cr}^{3+}$	1.7	—	43
$\text{YAlO}_3:\text{Yb}^{3+}/\text{Ho}^{3+}/\text{Mn}^{4+}$	0.2	—	44
$\text{Ca}_5\text{Mg}_4\text{V}_6\text{O}_{24}:\text{Eu}^{3+}$ 15%	0.5	—	26
$\text{LiCa}_3\text{MgV}_3\text{O}_{12}:0.01\text{Eu}^{3+}$	1.6	—	45

Repeatability referring to the variation when repeating measurements made under identical conditions assesses the precision of a thermometric system.⁴⁶ The repeatability of $\text{YVO}_4:\text{Eu}^{3+}$ thermometers was tested in consecutive heating-cooling cycles when the temperature was changed within 223–323 K (Figure 5). Temperature measurements were performed via two independent methods: luminescence thermometry and thermocouple. Luminescence thermal sensing was performed using all studied LIRs. $\text{YVO}_4:\text{Eu}^{3+}$ samples demonstrated good repeatability because temperatures obtained using optical thermometry matched well with the temperature of heater determined with thermocouple and repeated from cycle to cycle.

Figure 5. Thermal heating-cooling cycles of a) $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and b) $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% nanoparticles. Temperature was determined using all suggested LIRs.

To study temperature effect on luminescence kinetics of $\text{YVO}_4:\text{Eu}^{3+}$ phosphors, we recorded luminescence decay curves at different temperatures (123–573 K) (Figure 6a and 6c). Luminescence intensity of the most intense $^5\text{D}_0\text{--}^7\text{F}_2$ transition (619 nm) was monitored upon $\lambda_{\text{ex}} = 300$ nm excitation. All obtained experimental data displayed single exponential behavior and were fitted with $I = I_0 \cdot e^{-\frac{t}{\tau}}$, where τ is the observed $^5\text{D}_0$ lifetime. Noteworthy, several data points at low temperatures (123 and 173 K) show the rise of emission intensity, which corresponds to an energy transfer from YVO_4 host to Eu^{3+} ions. The decay curves show that the growth of Eu^{3+} doping concentration and increase of temperature accelerate the decay. Figure 6b and 6d present temperature dependence of the observed lifetimes with error bars. Lifetimes did not demonstrate significant changes with temperature variation except the lowest temperature of 123 K. In this case lifetime cannot be utilized as a temperature-dependent parameter for thermal sensing.

To provide a more detailed analysis, we calculated the radiative and nonradiative decay rates at different temperatures using 4f–4f intensity theory.^{47,48} In this theory $^5\text{D}_0\text{--}^7\text{F}_1$ transition is used as an internal reference because of its magnetic dipole character.⁴⁹ Taking into account the nanoscale size of studied particles, one should use effective refractive index, n_{eff} , composed of refractive index of surrounding medium n_{med} ($n_{\text{med}} = 1.00$) and material ($n_{\text{YVO}_4} = 2.00$), instead of refractive index n_0 . The radiative decay rates $A_{0-\lambda}$ ($\lambda = 2, 4$) were calculated using the formula:

$$A_{0-\lambda} = A_{0-1} \frac{\nu_{0-1} I_{0-\lambda}}{\nu_{0-\lambda} I_{0-1}} \quad (2)$$

where $I_{0-\lambda}$ and $\nu_{0-\lambda}$ are the integral intensity and frequency of $^5\text{D}_0\text{--}^7\text{F}_\lambda$ transition. Sum of all the $A_{0-\lambda}$ values ($\lambda = 1, 2, 4$) equals to the total radiative decay rate, A_r . The nonradiative decay rate, A_{nr} , can be obtained as $A_{nr} = \frac{1}{\tau_f} - A_r$. The quantum efficiency of the $^5\text{D}_0$ level, η , was obtained from formula: $\eta = \frac{A_r}{A_r + A_{nr}}$. Table 3 lists the radiative and nonradiative decay rates and quantum efficiencies for $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% NPs.

One can see only a small influence of temperature on both radiative and nonradiative decay rates

except low temperatures. $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% phosphor has higher A_{nr} values compared with $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.%, while A_{r} shows closer values. Also, the quantum efficiency is practically independent of temperature.

Figure 6. Luminescence decay curves of a) $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and c) $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% samples ($\lambda_{\text{ex}} = 300$ nm; $\lambda_{\text{em}} = 619$ nm); temperature dependence of $^5\text{D}_0$ level lifetime for b) $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and d) $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% samples.

Table 3. Radiative (A_{r}) and nonradiative (A_{nr}) decay rates of the $^5\text{D}_0$ level and quantum efficiencies (η) of $\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.% and $\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.% nanoparticles at different temperatures.

Temperature (K)	$\text{YVO}_4:\text{Eu}^{3+}$ 0.01 at.%				$\text{YVO}_4:\text{Eu}^{3+}$ 0.1 at.%			
	τ_{obs}	$A_{\text{r}} (\text{s}^{-1})$	$A_{\text{nr}} (\text{s}^{-1})$	$\eta(\%)$	τ_{obs}	$A_{\text{r}} (\text{s}^{-1})$	$A_{\text{nr}} (\text{s}^{-1})$	$\eta(\%)$

	(ms)				(ms)			
123	0.82	490	730	40	0.70	690	740	48
173	0.66	640	870	43	0.61	770	880	46
223	0.63	700	880	44	0.59	820	870	48
273	0.64	760	810	48	0.59	800	900	47
298	0.65	780	770	50	0.59	850	850	50
323	0.66	790	730	52	0.58	870	860	50
373	0.65	800	730	52	0.59	840	850	50
423	0.65	810	740	52	0.59	840	860	50
473	0.65	810	740	52	0.59	880	820	52
523	0.65	800	730	52	0.59	860	840	51
573	0.65	780	750	51	0.58	860	860	50

CONCLUSIONS

Eu³⁺-doped YVO₄ NPs synthesized using the modified Pechini method were tested as non-contact ratiometric luminescence thermometers. YVO₄:Eu³⁺ 0.01 at.% and 0.1 at.% samples revealed tetragonal phase with no impurity and consisted of weak-agglomerated NPs of 60–70 nm. Emission spectra of YVO₄:Eu³⁺ phosphors displayed broad band corresponding to YVO₄ host with a series of characteristic sharp peaks assigned to ⁵D₀ – ⁷F_J transitions (J = 1–4). Temperature differently affected the emission intensities of host and Eu³⁺ ions, therefore, luminescence intensity ratio between them was utilized as a temperature dependent parameter for thermal sensing. Growth of Eu³⁺ doping concentration led to a narrowing of the temperature sensing range due to enhancement of energy transfer from host to Eu³⁺ ions. The best room temperature thermometric performance, namely S_r = 1.2–1.4 % K⁻¹ and ΔT = 0.2–0.5 K, was achieved by using LIR₃ (host/⁵D₀–⁷F₄). YVO₄:Eu³⁺ thermometers demonstrated good repeatability in consecutive heating-cooling cycles. The obtained results make Eu³⁺-doped YVO₄

nanothermometers promising candidates for accurate and stable contactless ratiometric temperature sensing. Temperature effect on emission lifetime, radiative and nonradiative decay rates within 123–573 K range was also studied. It was found that these parameters insignificantly changed except low temperatures.

SUPPORTING INFORMATION

The Supporting Information is available free of charge on the ACS Publications website at DOI: SEM image YVO₄:Sm³⁺ nanocrystalline powder prepared at the same synthesis conditions, excitation spectra of YVO₄:Eu³⁺ 0.01 at.% and 0.1 at.% NPs at room temperature ($\lambda_{\text{em}} = 619$ nm), excitation and emission spectra of undoped YVO₄ NPs at room temperature, temperature dependence of host and ⁵D₀–⁷F₂ transition, temperature behavior of different Eu³⁺ transitions emission intensity, temperature evolution of LIR₂ and LIR₃ for YVO₄:Eu³⁺ 0.01 at.% NPs between 123–423 K, temperature evolution of LIR₂ and LIR₃ for YVO₄:Eu³⁺ 0.1 at.% NPs between 123–323 K.

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Table of Contents

Dual-center luminescence $\text{YVO}_4:\text{Eu}^{3+}$ nanothermometer

$$\text{LIR} = \frac{I_{\text{YVO}_4}}{I_{\text{Eu}^{3+}}}$$

$$S_r = 1.2 \% \text{ K}^{-1}$$

$$\Delta T = 0.2 \text{ K}$$