Nanostructured La_2O_3 : $\text{Yb}^{3+}/\text{Er}^{3+}$: Temperature Sensing, Optical Heating and Bio-imaging Application

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Abstract

Nanostructured $\text{Yb}^{3+}/\text{Er}^{3+}$ co-doped La_2O_3 with intense green-light emission has been successfully synthesized by solvothermal method with further calcination. The prepared La_2O_3 : Yb^{3+} , Er^{3+} are composed of approximate spherical nanoparticles with the size of about 50 nm. Optical temperature sensing performances depended on the thermally coupled levels of Er^{3+} are evaluated by analyzing temperature-dependent up-conversion luminescence (UCL) spectra, and the maximum sensitivity is 0.0040 K^{-1} at 315 K in the physiological working temperature range (295 K-315 K). Furthermore, the heating effect is also investigated, which causes the temperature of the samples to increase from 300 to 341 K with the variation of power density from 7.08 to 26.19 W/cm^2 . In addition, cell toxicity experiment shows that the La_2O_3 has low cell cytotoxicity, and the confocal images of samples in HeLa cells are also obtained. All the results indicate that the nanostructured La_2O_3 : $\text{Yb}^{3+}/\text{Er}^{3+}$ also may be used as fluorescent bio-imaging.

Keywords: Solvothermal synthesis; Optical temperature sensing; Optical heater; Bio-imaging

1. Introduction

Temperature is a crucial parameter in the process of industrial production and scientific investigation. On the one hand, controlling temperature is beneficial to improve the efficiency of production and reduce energy consumption and environmental pollution for industrial manufacture. On the other hand, in biological research and biological engineer, temperature changes even in the tiny range may affect the lifetime of live cell. For example, so many biological experiments have testified that tumor cells can be killed when their ambient temperature is higher than 40 °C in the hyperthermia therapy [1-3]. With exactly monitoring temperature, health cells around the tumor can not be damaged. Real-time and hypersensitized the method of temperature measurement has become an urgent requirement for some treatment and diagnosis of the disease.

In the current, temperature measurement methods are mainly consist of two categories: contact methods (namely resistance temperature detector, thermocouples and thermistors) and noncontact methods including infrared thermography [4]. Among them, contact methods are not applied on complicated environment such as strong electromagnetic noise and corrosive chemical experiment. And noncontact methods can overcome such disadvantages by detecting infrared lighted that is emitted from the hot materials. However, infrared thermography has two characterized limitation: (i) the property of materials decides accuracy of temperature

measurement. (ii) the infrared light is easily absorbed by water and glass in monitoring temperature, preventing their application in some research such as biomedicine [5,6]. Another fluorescence intensity ratio (FIR) technology as a kind of noncontact thermometry is gradually regarded as promising technology for optical temperature sensor. FIR technology monitoring temperature is based on the fluorescence intensity of the two thermally coupled of rare earth (RE) ions without the effect of spectrum losses and fluctuations, so it is free of low sensitivity and high environmental dependence [7-9]. Due to two thermally coupled levels $^2H_{11/2}$ and $^4S_{3/2}$, doping Er^{3+} ions have become a good choice for temperature-depended sensor. For the enhancement of absorption cross-section of 980 nm laser, Yb^{3+} ions are usually called as sensitizer and doped into fluorescent materials [10, 11]. Nanoparticle which is much smaller than normal materials has advantage in decreasing light scattering and enhancing spatial resolution [12, 13]. And then upconversion nanoparticles (UCNPs) which can be excited by 980 nm laser and emit visible light include higher photochemical stability, deeper penetration and minimal autofluorescence [14]. To sum up, UCNPs will play more and more important role in the temperature sensor, scientific research and bio-imaging.

In some oxide hosts, La_2O_3 has many advantages which include plentiful mineral resources, low costs and low phonon energy ($\sim 400\text{ cm}^{-1}$). So Er^{3+} - Yb^{3+} -doped La_2O_3 is a kind of valuable materials because of their high excitation efficiency, low toxicity, long luminescence lifetime and prominent stability [15]. Herein, the Yb^{3+} sensitized Er^{3+} doped La_2O_3 nanostructured materials are successfully synthesized by

solvothermal methods with further calcination. The FE-SEM images exhibit that the average diameter of particles is about 50 nm. The UCL excited by 980 nm diode laser have been investigated in $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped La_2O_3 nanostructured materials. The fluorescence intensity ratio (FIR) from $^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$ levels to $^4\text{I}_{15/2}$ of Er^{3+} are used to investigate the optical temperature sensing properties especially in the physiological working temperature range (295 K-315 K). Moreover, the heating effect by 980 nm laser which introduced the temperature of La_2O_3 to change from 300 K to 341 K with the power density in the range of 7.08-26.19 W/cm^2 could be used in biothermal treatment. Its cell cytotoxicity and cell imaging are also explored. All the experimental results indicate that the $\text{La}_2\text{O}_3: \text{Yb}^{3+}/\text{Er}^{3+}$ nanoparticle may be promising materials in the field of fluorescent bio-imaging, nanothermometry and photothermal therapy.

2. Experimental Procedure

2.1 Sample preparation

Materials. The $\text{Er}^{3+}-\text{Yb}^{3+}$ codoped La_2O_3 nanocrystalline phosphors were successfully synthesized by solvothermal method. All the chemicals were used without further purification and commercially available.

Synthesis of $\text{Er}^{3+}-\text{Yb}^{3+}$ codoped La_2O_3 . Rare earth nitrate (0.01 M $\text{Er}(\text{NO}_3)_3$ and 0.02 M $\text{Yb}(\text{NO}_3)_3$) stock solutions and $\text{La}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (99.9%) were used as the starting materials. In a typical procedure, 0.01 M $\text{Er}(\text{NO}_3)_3$, 0.02 M $\text{Yb}(\text{NO}_3)_3$, 2.1651g $\text{La}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ and 40 mL aqueous ammonia were added in Ethylene glycol solution to form a mixing solution. Then agitation for 2 h again, the

as-obtained mixing solution was poured into a Teflon bottle held in a stainless steel autoclave, sealed and kept at 200°C for 10 h. Then, the obtained precipitates were washed many times with ethanol. Subsequently, the precipitates were dried at 90°C for 12 h. Finally, the precursor was dried and calcined at 800°C for 2 h. In this way, the La₂O₃ nanoparticles were obtained.

2.2 Cell cytotoxicity assay

3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) proliferation assay was applied to measure cell viability. At first, the HeLa cells were seeded in 96-well microplate, and HeLa cells and La₂O₃: Er³⁺, Yb³⁺ with concentrations from 3.125 to 100 µg/mL in growth medium incubated for 24 hours at 37 °C and 5% CO₂. Then, 100 µL MTT (0.5 mg/mL in PBS solution) were added in each well to incubate again for 4 hours at 37°C. At last, removing growth medium and adding DMSO to each well, the microplate was placed at room for 2h.

2.3 Cell imaging

Firstly, the HeLa cells were cultured in Dulbecco minimum essential media (MEM-α) including 10% fetal bovine serum (FBS), 1% penicillin, and 1% amphotericin B. And then, HeLa cells were seeded in 35 mm culture dishes the day before experiment. In the process of experiment, the La₂O₃ nanocrystalline that was dispersed into aqueous solution were add to HeLa cells with incubating 24 hours at 37°C and 5% CO₂. Cellular imaging was got by confocal laser scanning microscope (Olympus, FV 1000) equipped with the Nuance GNIR CCD camera, 980 nm laser as pump source focused on the wells.

2.4 Characterization

The characterization of the structure and crystalline phase was recorded on a Rigaku-Dmax 2500 diffractometer at a scanning rate of 15 °/min in the 2 θ range from 10° to 80 using Cu K α radiation ($\lambda=0.15405$ nm). The field emission-scanning electron microscope (FE-SEM, XL30, Philips) examined morphology and size of the obtained samples. The Andor Shamrock SR-750 fluorescence spectrometer measured the UCL spectra. The signal of the samples were collected from 450 to 700 nm by A CCD detector combined with a monochromator. A 980 nm diode which was coupled to a fiber (the core diameter 200 μ m, numerical aperture 0.22) laser was used as the pump source. Andor SR-500i spectrometer (Andor Technology Co, Belfast, UK) was used to record the luminescence spectra by exciting the samples with 980 nm. The Yb³⁺/Er³⁺ co-doped La₂O₃ samples were loaded in an iron sample cell and the temperature of the sample increased from 313 to 573 K heated by resistive wire elements.

3. Results and Discussion

3.1 X-ray Diffraction Analysis and Morphology

XRD and FE-SEM. To explore the phase purity and crystal structure, the La₂O₃: xEr³⁺, yYb³⁺ have been measured by XRD. The diffraction peaks of all samples prepared in our experiments show similar results, the XRD patterns of La₂O₃: xEr³⁺, yYb³⁺ ((a) x = 1 mol%; y = 1%, 3%, 4 mol%; (b) y = 2 mol%; x = 1%, 5 mol%) are presented in Figure 1 as representative examples. The XRD patterns of the obtained samples are exactly in agreement with the standard characteristic peaks of La₂O₃

structure (JCPDS no. 05-0602). Among these diffraction peaks, the strongest peak can be observed to be placed near $2\theta = 30.15^\circ$. This diffraction peak corresponds to (101) plane. Other diffraction peaks are detected at $2\theta = 26.28^\circ, 29.29^\circ, 39.69^\circ, 46.25^\circ, 52.32^\circ, 55.70^\circ, 56.22^\circ$. The crystallite size of the sample has been calculated by Scherrer equation as follows [16]

$$D = \frac{0.9\lambda}{\beta \cos \theta}$$

where λ is the wavelength of the X-ray (1.5405 Å), β is the half-width after subtracting the instrumental broadening, θ is diffraction angle for the given peak, D is the crystallite size. The average crystallite size of $\text{La}_2\text{O}_3: \text{Er}^{3+}, \text{Yb}^{3+}$ nanocrystallines has been calculated and found to be 44 nm.

At the same time, the typical FE-SEM images of the La_2O_3 sample prepared by solvothermal synthesis are revealed in Figure 2. From Figure 2(a) and (b) in the scale of 500, 300 nm, it can be observed that the nanostructured La_2O_3 particle mostly crystallized in spherical form with the mean particles size of about 50 nm. On the whole, the crystallite size of La_2O_3 in the FE-SEM pictures accords with the results that are calculated by Scherrer equation.

3.2 UCL of $\text{La}_2\text{O}_3: \text{Er}^{3+}, \text{Yb}^{3+}$ nanocrystallines

Concentration dependence of UC spectrum. Under 980 nm excitation, Figure 3 illustrates the UC emission spectra of the $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped La_2O_3 nanocrystallines with further calcination at 800°C. The UC emission bands are observed around 530 nm ($^2\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2}$), 549 nm ($^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$) and 671 nm ($^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$). In Figure 3(a), the room-temperature UC emission intensities keep Yb^{3+} ions concentration at fixed

0.02mol, Er^{3+} concentrations vary from 0.005 to 0.05mol. At the same time, Figure 3(b) shows the concentrations of Yb^{3+} ions in the co-doped La_2O_3 nanocrystallines vary from 0.01 to 0.05mol, the Er^{3+} ions concentration is fixed at 0.01mol. As shown in Figure 3(a) and (b), it is observed that the spectral properties and UCL intensities rely on doping concentrations. As shown in Figure 3(a), it can be observed that optimum concentration for the green emissions is 0.01mol Er^{3+} , above 0.01mol Er^{3+} concentration, gradual quenching of emission occurred as a result of concentration quenching. Furthermore, the occurrence of concentration quenching may result from energy transfer between the nearest Er^{3+} and $\text{Yb}^{3+}/\text{Er}^{3+}$ ions. When the concentration of Er^{3+} is above 0.01mol, the distance between Er^{3+} and $\text{Yb}^{3+}/\text{Er}^{3+}$ ions will be reduced, which strengthens nonradiative relaxation and causes the decrease in UCL intensity [17]. The Figure 3(b) indicates the UCL intensities decrease extraordinarily with the increasing Yb^{3+} above 0.02mol. Therefore, the better luminous one of these La_2O_3 nanocrystallines is 0.01mol Er^{3+} and 0.02mol Yb^{3+} and studied its optical temperature sensing and optical heated properties, which will be discussed in the next part.

3.3 Energy Diagram and Pump Power Study

Mechanism of UC emission. In order to understand UC processes and UC mechanism, Figure 4 and 5 respectively display possible double logarithmic plots of the two green emission intensities for with different pump power P_{980} and possible UC process. In Figure 4, the relationship of the UCL intensity (I_{UC}) and the pump power (P_{pump}) can be expressed as

$$I_{UC} \propto (P_{pump})^n,$$

where n is the number of laser photons used to occupied the upper emission state, I_{UC} and P_{pump} represent respectively the UCL intensity and power [18-20]. It can be found that the slopes of the three fitted lines corresponding to 530, 549 and 672nm emission are 2.3, 1.9 and 1.8, respectively. Therefore, the n values reveal that green and red UC emission are two-photon process and two NIR excitation photons are absorbed to emit one green or red UC photon in the $\text{La}_2\text{O}_3: \text{Er}^{3+}/\text{Yb}^{3+}$ samples [21].

As shown in Figure 5, we can further understand UC luminance process. The Yb^{3+} ions at $^2\text{F}_{7/2}$ can be excited to $^2\text{F}_{5/2}$ under 980 nm lasers pumping. Then ET step occurs between Yb^{3+} and Er^{3+} ions, the $^4\text{I}_{11/2}$ level of Er^{3+} ions is populated. The $^4\text{I}_{11/2}$ level of Er^{3+} is excited to $^4\text{F}_{7/2}$ state by the ESA or ET. And multiphonon relaxation (MPR) occurs and jumps to the lower levels $^2\text{H}_{11/2}$ ($^4\text{S}_{3/2}$). The green emissions and red emissions are observed due to the radiative relaxation from the $^2\text{H}_{11/2}$ ($^4\text{S}_{3/2}$) and $^4\text{F}_{9/2}$ level to $^4\text{I}_{15/2}$ level of Er^{3+} [22, 23]. Among these bands, the intensities of red bands are more obvious than green emitting due to cross-relaxation (CR) and energy back transfer (EBT) which are also explained from Figure 5 between Er^{3+} and Yb^{3+} ions. The CR process from the excited state $^4\text{S}_{3/2}$ of Er^{3+} ($^4\text{S}_{3/2} \rightarrow ^4\text{I}_{13/2}$) to the ground state of Yb^{3+} ($^2\text{F}_{7/2} \rightarrow ^2\text{F}_{5/2}$) and sequential step is the EBT which is from the Yb^{3+} ($^2\text{F}_{5/2} \rightarrow ^2\text{F}_{7/2}$) to the Er^{3+} ($^4\text{I}_{13/2} \rightarrow ^4\text{F}_{9/2}$) with the increase of Yb^{3+} and Er^{3+} concentration, so the two processes are helpful to enhanced the population of $^4\text{F}_{9/2}$. In conclusion, The CR and EBT processes induced green emission weaker than red emission [24].

3.4 Temperature Sensing Behavior

The UCL properties which are related with temperature of $\text{La}_2\text{O}_3: \text{Er}^{3+}, \text{Yb}^{3+}$

nanocrystalline has been studied according to the different intensities ratio from two closely thermally coupled levels to regard potentials as optical temperature sensing. It can also be seen that the population obeyed Boltzmann distribution in the thermally coupled levels [23, 25]. Figure 6 exhibits the UC emission spectra of 0.01mol Er³⁺, 0.02mol Yb³⁺ codoped La₂O₃ nanocrystalline annealed at 800°C from 313 K to 573 K and the pump power is set up at 0.6 W. It can be found interestingly that the R increases clearly with the increase of temperature. In the thermalization process the ²H_{11/2} level can be populated effectively from ⁴S_{3/2}, therefore relative intensities between the two thermally coupled levels have changed. Subsequently, it is also observed that the R increase with increasing temperature. It is well known that the population of each energy level related with the emission intensities, so the R from two green emissions can be defined in this way [26-28].

$$R = \frac{N_2}{N_1} = \frac{I_{2j}}{I_{1j}} = \frac{g_2 \sigma_{2j} \omega_{2j}}{g_1 \sigma_{1j} \omega_{1j}} \exp\left[\frac{-\Delta E}{K_B T}\right] = B \exp\left[\frac{-\Delta E}{K_B T}\right] \quad (1)$$

Where

$$B = \frac{g_2 \sigma_{2j} \omega_{2j}}{g_1 \sigma_{1j} \omega_{1j}}$$

N, g, σ, ω represent ions, the degeneracy, the emission cross-section, the angular frequency of fluorescence two transitions. I_{2j} and I_{1j} are the intensities of the ²H_{11/2} → ⁴I_{15/2} (513nm-539nm) and ⁴S_{3/2} → ⁴I_{15/2} (539nm-574nm), respectively. ΔE is the energy difference between the ²H_{11/2} and ⁴S_{3/2} levels, k_B represents the Boltzmann constant and T shows the absolute temperature [27].

Figure 7(a) illustrates R (I_{530}/I_{549}) of green emission bands at 530 nm and 549 nm

and $1/T$ obey function relation ranging from 313 to 573 K. By linear fitting, the slope of the line is about 1183, which really gives the $\frac{-\Delta E}{k_B}$ value. According to the fitting parameter the calculated value of ΔE is 822.4 cm^{-1} . The Figure 7(b) exhibits the variation of R with different temperature, in which the R values increased from 0.34 to 1.84 from 313 K to 573 K. The calculated value of B was 14.44. Meanwhile, the accuracy of measured temperature which is an important value for temperature sensor can be estimated by the followed formula:

$$\Delta T = \Delta R \times \frac{K_B T^2}{R \Delta E} \quad (2)$$

Where the ΔT is the error in the measured temperature and the ΔR is varied with FIR. The error in measured temperature is obtained to be $\pm 0.23 \text{ K}$ that indicates the high accuracy of prepared samples for optical temperature sensing purposes [29].

The sensitivity is an important parameter in quantitatively ensuring an optical sensor and is defined as the rate of R varying with absolute temperature and can be expressed as [30]:

$$S = \frac{dR}{dT} = R \left[\frac{\Delta E}{K_B T^2} \right] = B \frac{\Delta E}{k_B T^2} \exp \left[\frac{-\Delta E}{K_B T} \right] \quad (3)$$

The sample of La_2O_3 : 0.01 mol Er^{3+} , 0.02 mol Yb^{3+} nanocrystalline according to curve exhibiting the variation of sensitivity with temperature from 313 to 573 K is showed in Figure 8. It can be obviously found that the maximum sensitivity is about 0.0066 K^{-1} at 573 K and keeps increasing with temperature in our experimental range, and the maximum sensitivity is 0.0040 K^{-1} at 315 K in the physiological working temperature range (295 K-315 K). The result shows that the La_2O_3 : 0.01mol Er^{3+} ,

0.02mol Yb³⁺ nanocrystalline can be regarded as potential temperature sensing materials.

3.5 Analysis of Optical Heater

In order to study the influence of the laser induced thermal effect, under different power excitation, the green emission spectra of samples and plot of the calculated R (I_{530}/I_{549}) were shown in Figure 9 and the calculated values were exhibited in Table 1. It can be seen that the value of R rises from 0.28 to 0.40 when the power density increases from 7.08 to 20.52 W/cm². In terms of the optical temperature sensing properties, R value can represent a particular temperature, so under different pump powers, the substrate temperature heated under the excitation of 980 nm laser can be written by following Eq. (4) which is rearranged from Eq. (1) [31]:

$$T = \left[\frac{1}{\ln B - \ln R} \right] \left[\frac{\Delta E}{K_B} \right] \quad (4)$$

Where all the terms have their usual implications as mentioned Eq. (1). The lattice temperature varies from 300 to 341 K with increasing of power density from 7.08 to 26.19 W/cm². According to above results, the generation of heat becomes prominent by non-radiative relaxation at pump power. In general, the charged mobile is induced by the laser electric field strongly inside the crystalline, and the obtained energy transfer to heat by electron-phonon coupling. Heat produced spreads away from the crystalline and causes an increase in temperature of the nearby volume. At the same time, the enhanced electron-phonon interaction also occurred and led to extra heating of crystalline in crystalline. With temperature enhance, the electron-phonon interaction increases [32, 33]. In summary, Yb³⁺/Er³⁺ co-doped La₂O₃ phosphors have

also great potential materials as an optical heater.

3.6 Cell cytotoxicity test and the UCL imaging of living cells in vitro

As we all know, cell toxicity determined whether the samples were suit for bio-imaging. The viability of HeLa cells with different concentration of La_2O_3 : 0.01mol Er^{3+} , 0.02mol Yb^{3+} was measured by MTT methods. The Figure 10 displays that the samples have a low cell toxicity to HeLa cells. Even at the most high dosage of $100\text{ }\mu\text{g/mL}$, cell viability is more than 80%. Under 980 nm excitation, Figure 11 shows confocal microscopy images of HeLa cells, green light emission is displayed in Figure 11(b). It can be observed from the overlay (Figure 11 (c)) of bright-field images (Figure 11 (a)) and confocal image that brightly luminescent are visible in the cells, which indicates that the luminescence comes from the HeLa cells and the La_2O_3 : $\text{Er}^{3+}/\text{Yb}^{3+}$ has been internalized into the cells [34]. On the whole, La_2O_3 : $\text{Er}^{3+}/\text{Yb}^{3+}$ has a low cell toxicity and may be regarded as bio-imaging materials.

4. Conclusion

The Yb^{3+} and Er^{3+} co-doped La_2O_3 nanocrystallines with different dopant concentrations are successfully prepared by solvothermal synthesis with further calcination. The XRD and FE-SEM indicate that the La_2O_3 : 0.01mol Er^{3+} , 0.02mol Yb^{3+} prepared by solvothermal synthesis methods is pure phase, and the average diameter of nanocrystallines is about 50 nm. Furthermore, the optimal green emission can be observed in La_2O_3 : 0.01mol Er^{3+} , 0.02mol Yb^{3+} under the 980 nm excitation. The R of the green bands is related with temperature to examine its temperature sensing behavior. The maximum sensitivity of the nanocrystalline with optimal

dopant concentration is 0.0066 K^{-1} at 573 K. Moreover, the heating effect is also investigated, and the temperature of sample increase from 300 to 341 K with an increase of power density from 7.08 to 26.19 W/cm^2 . The Er^{3+} and Yb^{3+} codoped La_2O_3 nanocrystallines has a low cell toxicity, and the confocal images of samples in HeLa cells are also obtained. The experimental results can help us to increase our understanding of the multifunctional La_2O_3 nanostructured materials and develop their future applications.

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Table Caption

Table 1. Calculated values of temperature at different pump power densities corresponding to different R values of $\text{La}_2\text{O}_3: \text{Er}^{3+}/\text{Yb}^{3+}$ phosphors.

Figure captions

Figure 1. The X-ray diffraction patterns of $\text{La}_2\text{O}_3: x\text{Er}^{3+}, y\text{Yb}^{3+}$ samples annealed at 800°C : (a) $x = 0.01\text{mol}$, $y = 0.01\text{mol}$; (b) $x = 0.01\text{mol}$, $y = 0.03\text{mol}$; (c) $x = 0.01\text{mol}$, $y = 0.04\text{mol}$; (d) $x = 0.01\text{mol}$, $y = 0.02\text{mol}$; (e) $x = 0.05\text{mol}$, $y = 0.02\text{mol}$. And reference date JCPDS 05-0602.

Figure 2. The FE-SEM images of $\text{La}_2\text{O}_3: \text{Yb}^{3+}, \text{Er}^{3+}$ nanocrystallines.

Figure 3. The UC luminescence spectra of $\text{La}_2\text{O}_3: x\text{Er}^{3+}, y\text{Yb}^{3+}$: (a) $y = 0.02\text{ mol}$; $x = 0.005, 0.01, 0.02, 0.03, 0.04, 0.05\text{ mol}$. and (b) $x = 0.01\text{ mol}$; $y = 0.01, 0.02, 0.03, 0.04, 0.05\text{ mol}$. Inset shows the variation of R/G (Red/Green) emission intensity ratio with the Yb^{3+} ions concentration.

Figure 4. The Pump power dependence of UC emission of $\text{La}_2\text{O}_3: 0.01\text{ Er}^{3+}, 0.02\text{ Yb}^{3+}$ nanocrystallines.

Figure 5. The energy level diagrams of $\text{Yb}^{3+}/\text{Er}^{3+}$ co-doped La_2O_3 under excitation of 980 nm and possible UC processes.

Figure 6. Temperature evolution of the Er^{3+} UC emission spectra excited by 980 nm laser for the $\text{La}_2\text{O}_3: 0.01\text{ Er}^{3+}, 0.02\text{ Yb}^{3+}$ nanocrystalline from 313 K to 573 K .

Figure 7. (a) The R (I_{530}/I_{549}) of Er^{3+} green UC emissions for the $^2\text{H}_{11/2}, ^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ transitions relative to the temperature range of $313\text{-}573\text{ K}$; (b) The monolog plot of

the R versus 1/T for the $\text{La}_2\text{O}_3: 0.01 \text{ Er}^{3+}, 0.02 \text{ Yb}^{3+}$ phosphor.

Figure 8. The sensor sensitivity $S = dR/dT$ as a function of the temperature for $\text{La}_2\text{O}_3:$

$0.01 \text{ Er}^{3+}, 0.02 \text{ Yb}^{3+}$. S_2 represents the value of experiment sensitivity.

Figure 9. The UCL spectra of the green bands $^2\text{H}_{11/2}/^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ of Er^{3+} with

different pump power for $\text{La}_2\text{O}_3: 0.01\text{Er}^{3+}, 0.02\text{Yb}^{3+}$. Inset: R as a function of laser

pump power.

Figure 10. Cell viability assessment with HeLa cells with different concentration of

La_2O_3 nanocrystalline.

Figure 11. (a) bright-field image of HeLa cells; (b) confocal image of HeLa cells after

incubation with $\text{Er}^{3+}/\text{Yb}^{3+} \text{ La}_2\text{O}_3$, collected at green (520 nm-570 nm) channels; (c)

the overlay of bright-field image and panels (b).

Table 1.

Power density (W/cm ²)	R	Temperature (K)
7.08	0.278	299
7.78	0.280	300
9.91	0.297	305
13.45	0.329	313
16.28	0.355	319
16.99	0.361	321
17.69	0.366	322
19.10	0.380	325
19.82	0.389	327
20.52	0.395	329

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11