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All the co-authors participated in the elaboration of this work, however some dedicated more time to some specific activities, which we describe below:

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- supervision - K, Pavani
- project administration - M.P.F. Graça, Antonio S.B. Sombra
- funding acquisition - M.J. Soares, Antonio S.B. Sombra

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Analogy of different optical temperature sensing techniques in $LaNbO_4:Er^{3+}/Yb^{3+}$ phosphor

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ABSTRACT

Three of the possible approaches to optical temperature sensing of a thermographic phosphor were formally compared in upconversion (UC) of Er^{3+} and Yb^{3+} doped lanthanum orthoniobate (LNO) phosphor. The three approaches used in the study were namely fluorescence intensity ratio (FIR) of thermally coupled levels (TCL), Valley to Peak ratio (VPR) and the ratio of non-thermally coupled levels (NTCL), respectively. The TCLs in the study were the ratio of intensities of $^2H_{11/2}\rightarrow {}^4I_{15/2}$ and $^4S_{3/2}\rightarrow{}^4I_{15/2}$ UC transitions of Er^{3+} ion. VPR method was verified within $^2H_{9/2} \rightarrow {}^4I_{15/2}$ transition of Er^{3+} UC. The other ratios of transitions which are not fit in TCL were investigated through NTCL technique. Ratios of several sets of transitions namely $^4S_{3/2}\rightarrow{}^4I_{15/2}/{}^2H_{9/2}\rightarrow{}^4I_{15/2}$, $^4S_{3/2}\rightarrow{}^4I_{15/2}/{}^2I_{9/2}\rightarrow{}^4I_{15/2}$, $^4S_{3/2}\rightarrow{}^4I_{15/2}/{}^4F_{9/2}\rightarrow{}^4I_{15/2}$, $^4F_{7/2}\rightarrow{}^4I_{15/2}/{}^2H_{11/2}\rightarrow{}^4I_{15/2}$, $^2H_{11/2}\rightarrow{}^4I_{15/2}/{}^4I_{9/2}\rightarrow{}^4I_{15/2}$ and $^2H_{11/2}\rightarrow{}^4I_{15/2}/{}^2G_{11/2}$ were considered for NTCL technique. Moreover, the effect of temperature in the emission color was analyzed and a change from yellow (0.3310; 0.5990) to green (0.2590; 0.6740) was observed when the temperature rise has been increased from 10 to 300 K. Results obtained indicate that the LNO:Er^{3+}/Yb^{3+} phosphor could be employed in optical thermometry and this phosphor would be a candidate with high potential as sensor operating from low to room temperature using TCL, VPR and / or NTCL methods. The most prominent sensing technique in the case of LNO:Er/Yb material among the three techniques is found to be NTCL with the high relative sensitivity of 1.19 % K^{-1} at 300 K.

KEYWORDS: $LaNbO_4$: Er^{3+}/Yb^{3+}; Optical temperature sensing; Upconversion; Fluorescence intensity ratio

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1. INTRODUCTION

Upconversion (UC) ceramics based on rare earth (RE) dopants present applications in different areas such as solar cells, environment, solid-state lighting devices, medicine, thermometry, and others [1–4]. REs are highly used in luminescence applications because of their narrow emission and excitation bands with long lifetimes, originated from f-f electronic transitions [5,6].

Recently, optical thermometry based on UC luminescence has been extensively studied because of its exceptional advantages, such as large-scale imaging, contactless measurement, and others. Optical thermometry / measuring temperature using light-based phenomenon could be done in many different ways. Different methods are based on different temporal character of the emission such as whether it is excited by a steady-state, time-resolved, frequency domain source based on emission intensity, band position, bandwidth, spectral shape, dual-excited single emission band, emission decay time, emission rise time, phase angle, time-resolved single emission, polarization, polarization lifetime etc [7]. Though there are different methods for optical thermometry, steady-state excitation-based methods play a phenomenal role because of the easiness of experimental determination of the signal and cost-related issues [7]. Among the steady-state excitation methods, fluorescence intensity ratio (FIR) using thermally coupled levels (TCL), valley to peak ratio (VPR), the ratio of non-thermally coupled levels (NTCL) are a few of the methods which play a prominent role in optical thermometry.

In the FIR of TCL technique, two levels are considered to be thermally coupled when they have an energy difference between 200 and 2000 cm^{-1} [8,9]. In this method, the excitation of ions to a lower level makes the higher level of the TCL populated based on Boltzmann's distribution law [10]. As the distribution of emission from these two levels is relative to the working temperature, a ratio of population distribution between the TCL determines the ratio of the emission intensities. For this method to be implemented in any ion, the availability of a couple of energy levels with a difference of energy between 200 and 2000 cm^{-1} is necessary. Moreover, if the lower level of TCL is metastable with a longer lifetime, it would fetch for the thermometry measurements.

NTCL technique on the other hand, considers two levels, which are thermally not coupled. Any two emission peaks of active ion/ions whose initial emitting levels' energy difference is more than 2000 cm^{-1} could be used in this technique unless they are to be detected by different detectors in different regions. As different emitting levels have different emission cross-sections at different temperatures, this method cannot rely on

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any particular law and suitable empirical formulas are being used for internal temperature detection of the material [11].

Regarding the VPR technique, according to Zhou et al. [12], the technique could be realized with three conditions fulfilled. Firstly, the presence of a double-peak spectrum. Secondly, the profile of this spectrum must accord well with the Lorentzian profile throughout the temperature range of an experiment. Finally, the line-widths of two emission peaks in this double-peak must enlarge / broaden homogeneously within this temperature range.

Each of the above-mentioned thermographic techniques requires certain requirements, which are uncommon in many of the substances, and for that reason; the analysis of different methodologies for a single phosphor is not widely explored in the literature. It could be better to compare possible different techniques of temperature sensing in a single substance, say for example a ceramic / phosphor and conclude the best useful technique. For this purpose, in this work lanthanum ortho-niobate ($LaNbO_4$) ceramic with RE ions as dopants have been chosen. Due to the host's ability to facilitate the replacement of La^{3+} ion by any other rare-earth ions (Er^{3+}/Yb^{3+}) for UC resulting in a spectrum convenient for experimental comparison of the three aforementioned thermometry techniques [13–16].

Previously, we had reported Er^{3+}/Yb^{3+} co-doped $LaNbO_4$ phosphors prepared by high-temperature solid-state reaction method and exhibited UV, blue, green, red and IR emissions with the near infrared (NIR, 980 nm) excitation [17]. In the present article, we compare the optical temperature sensing properties of LNO:Er^{3+}/Yb^{3+} with three different solid-state thermometry techniques namely FIRs of TCL, VPR and NTCL, respectively.

2. EXPERIMENTAL SECTION

Analytical grade oxides La_2O_3 (99.99%, Aldrich), Nb_2O_5 (99.9%, Aldrich), Er_2O_3 (99.9%, Aldrich), and Yb_2O_3 (99.9%, Aldrich) were used in the synthesis of LNO:1.0%Er^{3+}10%Yb^{3+} phosphor by the solid-state reaction method. The synthesis conditions employed for material preparation are described in our previous work [17]. The structural analysis of the materials was performed by X-ray diffraction (XRD) using an XPert Pro MPD (Panalytical) diffractometer with Cu-Kα radiation.

The UC luminescence spectra were recorded as a function of temperature in the range of 14 – 300 K using an integrated system consisting of an RLTMDL – 980 – 1W model diode laser and a Spex 1702/1704 spectrometer, equipped with a cryostat and

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vacuum pump, with a resolution of ≤ 0.05 nm. Labview software was employed to process and obtain the data in the temperature range analyzed.

3. RESULTS AND DISCUSSION

Structural characterization of the Er^{3+}–Yb^{3+} co-doped $LaNbO_4$ phosphors (X-ray diffraction (XRD), Scanning electron microscopy and Raman spectroscopy) as well as temperature- and power-dependent UC mechanism were previously published [17]. The published information of XRD, SEM, partial energy level diagram, temperature dependent UC has been presented in Fig. 1 for verification. However, this phosphor was not evaluated regarding its potential application as an optical sensor. As to explore the feasibility of the present host for its thermographic nature, the three possible approaches were investigated and compared in this work to evaluate the sensing ability of $LaNbO_4$:1.0%Er^{3+}10.0%Yb^{3+} (LNO:Er/Yb) phosphor which was with the best optical UC characteristics among the other rare-earth concentrations in our previous work.

3.1. FIR technique using TCL:

One of the prominent and most obvious thermometry methods is the TCL technique. In the TCL thermometry method, the intensity of fluorescence originating from two thermally coupled levels of an active ion (in this case Er^{3+} ion) is measured. The population of the TCL follows Boltzmann's population distribution with respect to temperature, the FIR could be expressed by the following equation, [18–20]:

$$\mathrm{FIR(TCL)} = \frac{\mathrm{I}_2}{\mathrm{I}_1} = \mathrm{A}\exp\left(-\frac{\Delta\mathrm{E}_f}{\mathrm{k_B T}}\right) + \mathrm{B} \qquad (1)$$

where I_2 is the intensity of the emission from the higher excited state, I_1 is the intensity of the emission from the lower excited state. A is the fitting constant, B is an overlap of the luminescence peaks, ΔE_f is the energy gap between the two thermally coupled levels analyzed, k_B is the Boltzmann constant, and T is the absolute temperature. The FIR is a continuously decreasing function of temperature and its value depends only on ΔE_f.

In optical thermometry, sensitivity is a parameter of great importance. To understand the rate of change in the FIR with respect to the temperature and to compare among different materials, the Absolute (S_a) and relative (S_r) sensitivities play vital roles and are expressed according to eqs. (2) and (3), respectively

$$\mathrm{S_a} = \frac{\mathrm{dFIR}}{\mathrm{dT}} = \frac{\mathrm{A}\,\Delta\mathrm{E}_f}{\mathrm{k_B T^2}}\exp\left(-\frac{\Delta\mathrm{E}_f}{\mathrm{k_B T}}\right) \qquad (2)$$

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$$\mathrm{S_r} = \frac{1}{\mathrm{FIR}}\frac{\mathrm{dFIR}}{\mathrm{dT}} = \frac{\Delta \mathrm{E}_f}{\mathrm{k_B T^2}} \qquad (3)$$

where, ΔE_f is the fitting energy difference between the thermally coupled levels and the error with respect to experimental energy difference (ΔE_m) gives an insite of its agreement with the experimental values. The error (goodness of fit) δ, can be expressed as [21]:

$$\delta = \frac{|\Delta E_\mathrm{f} - \Delta E_\mathrm{m}|}{\Delta \mathrm{E_m}} \qquad (4)$$

In Er^{3+} ions, since the energy difference between $^2H_{11/2}$ and $^4S_{3/2}$ levels is less than 2000 cm^{-1}, they are considered as thermally coupled and their population distribution is governed by Boltzmann's law. The intensities of $^2H_{11/2}\rightarrow{}^4I_{15/2}$ and $^4S_{11/2}\rightarrow{}^4I_{15/2}$ transitions with respect to temperature were presented in Fig. 2(a), where the intensity of $^4S_{11/2}\rightarrow{}^4I_{15/2}$ transition peaked at 550 nm, decreases with the increase of temperature while that of $^2H_{11/2}\rightarrow{}^4I_{15/2}$ transition increases with temperature due to an increase of excited population in $^2H_{11/2}$ with temperature according to Boltzmann's law. Fig. 2(b) presents the ln(FIR(I_{528}/I_{550})) as a function of 1/T, which is linear in nature, with ΔE_f = 468.67 cm^{-1} for the thermally coupled levels $^2H_{11/2}$ and $^4S_{3/2}$ from 70 K. The intensity ratio of transitions $^2H_{11/2}\rightarrow{}^4I_{15/2}$ and $^4S_{11/2}\rightarrow{}^4I_{15/2}$ which is FIR(TCL) or FIR(I_{528}/I_{550}) thus calculated has been fit according to Eq. (1). The results obtained are shown in Fig. 2(c) and it is observed that the FIR(I_{528}/I_{550}) increases exponentially with temperature. The experimental value of the energy difference, ΔE_m between the levels $^2H_{11/2}$ and $^4S_{3/2}$ is found to be ~ 758 cm^{-1} [22]. For the LNO:Er/Yb phosphor, the goodness of the fit δ represented by Eq. 4 is found to be 0.36 for FIR(I_{528}/I_{550}) demonstrating that the energy transfer between TCL and other levels is not neglected and the population of TCL at high temperature is induced by the routes of Boltzmann's distribution which is an important characteristic for optical temperature sensing [23,24].

Fig. 2(d) shows absolute (S_a) and relative (S_r) sensitivities of LNO:Er/Yb phosphor found according to Eqs. (2) and (3), respectively. The value of S_a increases with the increase of temperature, while that of S_r decreases exponentially with temperature, respectively. S_r can be expressed by $674.35/T^2$ and at 300 K, the S_r value is found to be 0.749 % K^{-1} for FIR(I_{528}/I_{550}) [24–26]. To compare with any other sensing material, S_r value could be adopted. Table 1 compares the S_r values of some of the reported phosphor materials with that of LNO:Er/Yb. From Table 1, it is quite evident that LNO:Er/Yb is having very good sensitivity when compared to many of the phosphors. Some of the hosts

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are rare earth oxides, heavy metal oxides and even fluorides which have low S_r values at 300 K than LNO:Er/Yb phosphor.

3.2. FIR technique using VPR:

The second method that can be used for temperature measurement is the valley to peak intensity ratio (VPR) which is calculated with the ratio between the valley formed by fluorescence peaks overlap and the peak fluorescence intensity. This method is little explored in the literature than TCL as it is based on the fulfillment of certain conditions before it can be used as described in the introduction part [41,42].

Fig. 3(a) shows the temperature dependent UC emission spectra of LNO:Er/Yb within the region 402 to 405.5 nm. This region of emission belongs to the transition $^2H_{9/2} \rightarrow {}^4I_{15/2}$. The UC emission peak however ranges from 402 to 416 nm as shown in Fig. 1(d). As the VPR changing phenomenon is observed only in the region 402 to 405.5 nm, the other part has been discarded in the spectrum. All spectra were normalized to the emission intensity at 404.5 nm. After a careful analysis of the bands, it is possible to verify that the emission could reach the requirements demanded by the VPR method. Fig. 3(b) shows a behavior monotonic of the VPR with temperature indicating that this analysis can be employed for the band and valley duo. The relationship between the VPR of $I_{403.55}/I_{404.5}$ and temperature can be fitted by a linear function as follows:

$$\mathrm{VPR} = \mathrm{a}\,(\mathrm{T} - T_0) + b \qquad (5)$$

where a represents the slope of the linear curve, b is a constant and T_0 is the initial temperature. Relative sensitivity (S_r) using VPR can be written as,

$$S_r = \frac{1}{VPR}\frac{d(VPR)}{dT} \qquad (6)$$

From the fitting of the VPR data (Fig. 3(c)) with Eq. 5, the fitting parameters obtained were $a=6.76\times10^{-4}$, $b=0.2508$ and $T_0=97.46$. These parameters were used to fit the profile of S_r with respect to temperature using Eq. 6 for the analysed VPR and are shown in Fig. 3(d). S_r (VPR) values were observed to be decreasing with respect to the rise in temperature. Table 2 presents different S_r values of the reported materials using VPR method. It could be inferred that the relative sensitivity of the LNO:Er/Yb phosphor with other phosphors is not so substantial, but the method by itself has some impact while determining the temperature and the S_r value of the LNO:Er/Yb phosphor at 300 K is comparable to that of Er^{3+} doped $CaWO_4$ phosphor [42].

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3.3. FIR technique using NTCL:

In the analysis of a material as an optical temperature sensor, it is important to investigate different aspects and the ratio of NTCLs is an important technique by the fact that they often show greater sensitivity than the ratio of TCLs [45–47]. If two emission states possess an energy gap greater than 2000 cm^{-1}, then they could be assumed as NTCL where the Boltzmann's distribution law is negligible and often allows higher values of S_r for FIR. In this case, Boltzmann's distribution law cannot be implemented while calculating the temperature and intensity relation. Since the traditional FIR of TCL is not appropriate for NTCL, the experimental FIR can be well fit by following an empirical formula expressed below [48]

$$FIR(NTCL) = \frac{1}{A+Be^{(-C/T)}} \quad (7)$$

where A, B and C are constants. Figs. 4 (a-d) present the intensities of different UC peaks, their ratio in the case of NTCL, S_a and S_r with respect to change in temperature. The temperature sensitivities S_a and S_r, the key parameters in the performance of thermometers were determined using the below equations

$$S_a = \left|\frac{dFIR(NTCL)}{dT}\right| \quad (8)$$

$$S_r = \left|\frac{dFIR(NTCL)}{dT}\right| \frac{1}{NTCL} \quad (9)$$

To elucidate this method, we have chosen different sets of emission levels (peaks) pertaining to the combination of transitions $^4S_{3/2}\rightarrow{}^4I_{15/2}/{}^2H_{9/2}\rightarrow{}^4I_{15/2}$, $^4S_{3/2}\rightarrow{}^4I_{15/2}/{}^2I_{9/2}\rightarrow{}^4I_{15/2}$, $^4S_{3/2}\rightarrow{}^4I_{15/2}/{}^4F_{9/2}\rightarrow{}^4I_{15/2}$, $^4F_{7/2}\rightarrow{}^4I_{15/2}/{}^2H_{11/2}\rightarrow{}^4I_{15/2}$, $^2H_{11/2}\rightarrow{}^4I_{15/2}/{}^4I_{9/2}\rightarrow{}^4I_{15/2}$ and $^2H_{11/2}\rightarrow{}^4I_{15/2}/{}^2G_{11/2}\rightarrow{}^4I_{15/2}$ and for ease of representation, the ratios of intensities were assigned using their peak wavelengths as I_{550}/I_{412}, I_{550}/I_{800}, I_{550}/I_{660}, I_{470}/I_{528}, I_{528}/I_{800} and I_{528}/I_{382}, respectively. Different transitions have different trends in intensities with respect to temperature. Fig. 4(a) shows the trend of each of the UC peaks considered in the NTCL method. The three-photon UC bands peaked at 382, 412 and 470 nm have exponential decrease due to the exponential increase of phonons in the matrix when the temperature increases. Regarding the two photon based UC emission, it was observed that the transition at 528 nm increases exponentially with the temperature that could be explained by thermal stimulation of the photons between the levels $^2H_{11/2}$ and $^4S_{3/2}$ due to the low energy difference between these states [49,50]. The other two-photon UC transitions at 550, 660, 800 and 855 nm increase from 14 to 90 K and then decrease exponentially. FIRs of many NTCLs were evaluated for the phosphor and the values were represented in Fig. 4(b). As can be observed, ratios demonstrated an

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increase with the increase of sample temperature. The experimental ratios can be well fitted using Eq. 7 with an exception to FIR (I_{550}/I_{800}).

From the data of FIR and using Eq. 7, S_a and S_r using Eq. 8 and 9 were obtained for NTCL and the results obtained are presented in the Figs. 4 (c) and (d), respectively. S_r demonstrates exponentially decreasing behavior with temperature, with exception of the ratios I_{550}/I_{412} and I_{550}/I_{800} that presented an initial increase and then a decreasing trend. Table 3 presents the FIR fitting parameters A, B and C along with S_r at 300K obtained for different NTCLs in this work. Of all the FIR evaluated for NTCLs, the ratio I_{528}/I_{800} presented the highest relative sensitivity (S_r = 1.19 % K^{-1} at 300 K).

Results demonstrated that all emissions from LNO:Er/Yb phosphor could be employed for the application of optical sensing of temperature using any of the three sensing techniques. In our investigation, it could be inferred that the FIR techniques namely TCL, VPR and NTCL techniques have their maximum sensitivities as 0.749, 0.175 and 1.19 % K^{-1} at 300 K. Hence, in the present work NTCL has been regarded as the best technique with a highest relative sensitivity when compared to others in LNO host. The S_r values of NTCL when compared with other hosts, also presented in Table 4, and LNO has the maximum value listed in the table.

3.4: CIE changes in UC with temperature:

To evaluate the effect of temperature in the emission color of the LNO:Er/Yb, the Commission Internationale de l'Eclairage (CIE) coordinates were calculated and the corresponding results are shown in the CIE 1931 coordinates diagram in Fig. 5. It can be seen that the emission color changed from pale green (0.331; 0.599) to dark green (0.259; 0.674) as the temperature increases from 14 to 300 K. This fact could be justified by the decrease of blue and red emission intensities while increase of the green emission with peak position at 528 nm (as demonstrated in [17]).

4. CONCLUSION

In conclusion, the optical temperature sensing properties of LNO:1.0%Er^{3+}10%Yb^{3+} phosphor were investigated through the fluorescence intensity ratio (FIR) using TCL, VPR and NTCL techniques, respectively. While using TCL method, the S_r value at 300 K is found to be 0.43 % K^{-1} for FIR(I_{528}/I_{550}). LNO:Er/Yb is having very good sensitivity when compared to many of the phosphors using TCL method. While the S_r of VPR ($I_{403.55}/ I_{404.5}$) has been determined to be 0.175 % K^{-1} at 300 K, which is a value lower than other oxides but the method has been proved to be effective with the LNO phosphor system with Er/Yb as dopants for upconversion. Regarding the NTCL method, of all the ratios chosen for NTCL, FIR (I_{528}/I_{800}) showed maximum S_r at 300 K as 1.19 % K^{-1} and it dominates the other two techniques in the study. This sensitivity value is greater than that presented by many materials already published in the literature.

Moreover, the S_r values of FIR using NTCL were maximum in the present host material. The change of CIE coordinates with temperature was observed with a change in emission colour as well. It has been noted that emission colour changed from pale green (0.331; 0.599) to dark green (0.259; 0.674) when the temperature increased from 14 to 300 K. Results obtained demonstrate that the LNO:Er/Yb system would be a potential candidate for developing novel optical temperature sensors operating at low to room temperatures.

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Tables:

Table 1: Relative sensitivities (S_r) using FIR of thermally coupled levels (TCL) of different RE doped UC phosphors at 300 K.

Material	**S_r (% K^{-1})**	**Reference**
$Gd_2O_3:Er^{3+}/Yb^{3+}$	0.39	[27]
$NaYF_4:Er^{3+}/Yb^{3+}/Gd^{3+}/Nd^{3+}$	0.26	[28]
$NaYF_4:Er^{3+}/Yb^{3+}$	0.29	[29]
$TeO_2–WO_3:Er^{3+}/Yb^{3+}$	0.28	[30]
$NaGdF_4:Er^{3+}/Yb^{3+}$	0.37	[31]
$CaMoO_4:Ho^{3+}/Yb^{3+}/Mg^{3+}$	0.66	[32]
$CaWO_4:Ho^{3+}/Yb^{3+}$	0.50	[33]
$La_2CaZnO_5:Er^{3+}/Ho^{3+}/Yb^{3+}$	0.625	[34]
$ZnWO_4:Er^{3+}/Yb^{3+}$	0.875	[35]
$La_2(WO_4)_3:Er^{3+}/Yb^{3+}$	1.132	[36]
$SrWO_4:Er^{3+}/Yb^{3+}$	0.965	[37]
$NaY(WO_4)_2:Er^{3+}/Yb^{3+}$	1.16	[38]
$CaWO_4:Er^{3+}/Yb^{3+}$	1.01	[39]
$Ca_2MgWO_6:Er^{3+}/Yb^{3+}$	0.93	[40]
LNO:1.0Er^{3+}10.0Yb^{3+}	0.749	Present work

Table 2: S_r values based on VPR different phosphor materials at 300 K.

Material	**S_r (% K^{-1})**	**Reference**
$CaWO_4:Er^{3+}$	0.20	[42]
$SrMoO_4$:Er/Yb	0.375	[43]
$ZrO_2:Eu^{3+}$	1.8	[44]
LNO:Er/Yb	0.175	Present work

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Table 3: FIR fitting parameters A, B and C and relative sensitivity (S_r) at 300 K for different NTCLs.

FIR	**A**	**B**	**C**	**RMS**	**S_r (% K^{-1})**
550 / 412	0.30	-0.33	88.47	0.9956	0.41
550 / 800	0.16	-0.14	53.58	0.9685	0.16
550 / 660	-18.81	18.76	-2.79	0.9721	0.47
470 / 528	0.03	3.56×10^{-4}	-1074.80	0.9979	0.35
528 / 800	-0.11	0.040	-509.88	0.9955	1.19
528 / 382	0.03	3.29×10^{-4}	-1197.06	0.9962	0.50

Table 4: Comparison of S_r values of different materials using FIR(NTCL) at 300 K.

Material	**S_r (% K^{-1})**	**Reference**
$Gd_2(WO_4)_3$:Ho^{3+}/Tm^{3+}/Yb^{3+}	0.817	[48]
YF_3: 20% Yb^{3+}, 0.5% Tm^{3+}	~1	[51]
YTiYb:1Ho^{3+}/20Zn^{2+}	0.529	[52]
YTiYb:1Ho^{3+}/30Zn^{2+}	0.634	[52]
GeO_2–PbO–PbF_2–YbF_3–ErF_3	1.0	[53]
Y_2O_3: 2%Yb^{3+}, 1%Er^{3+}	1.32	[47]
$Ca_4Y_{5.34}Si_4O_{24}$:1%Er^{3+},10%Yb^{3+}	1.1	[54]
$NaGdF_4$:2%Er^{3+}/18%Yb^{3+}/0.005Fe^{3+}	0.46	[55]
LNO:Er/Yb	1.19	Present work

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Figure captions:

Fig. 1: (a) X-ray diffraction of LNO host as well as LNO:Er/Yb phosphors, (b) SEM micrograph of LNO:Er/Yb, (c) partial energy level diagram representing NIR excitation and several UC emissions in LNO:Er/Yb, (d) temperature dependent UC in the region 350-500 nm representing 3 photon process and (e) temperature dependent UC in the region 500-870 nm representing 2 photon process, respectively.

Fig. 2: (a) Temperature dependent variation of intensities of peaks at 528 nm and 550 nm, (b) Ln(FIR) as a function of inverse of temperature, (c) FIR between 528 and 550 nm peaks and (d) absolute (S_a) and relative (S_r) sensitivities of LNO:Er/Yb phosphor as a function of temperature by TCL method.

Fig. 3: (a) Normalised UC emission spectra within the region 402 and 405.5 nm, (b) valley and peak intensities at 403.55 and 404.5 nm, (c) VPR values and (d) S_r values for LNO:Er^{3+}/Yb^{3+} phosphor as a function of temperature, respectively.

Fig. 4: (a) Integrated intensity of different UC bands, (b) FIR, (c) S_a and (d) S_r of different combinations of NTCL bands of LNO: Er/Yb UC as a function of temperature, respectively.

Fig. 5: CIE chromaticity coordinates as function of temperature from integrated intensity of LNO:Er^{3+}/Yb^{3+} phosphor upconversion upon 980 nm laser radiation.

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Highlights:

- Upconversion of $LaNbO_4$:Er^{3+}/Yb^{3+} being considered for temperature sensing
- Observation of three different fluorescence sensing techniques in single material
- Fluorescence Intensity Ratio (FIR) of all the three techniques estimated
- Non-thermally coupled levels being prominent compared to thermally coupled and valley to peak ratios

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Declaration of interests

- ✓ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Pavani Krishnapuram (corresponding author)
On behalf of all the authors

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