1. Introduction

As the basic parameter of thermodynamics, temperature measurement plays a vital role in scientific research, industrial production and medicine. In recent years, much attention has been paid to non-contact temperature sensors based on rare earth (RE) ion activated luminescent materials. Some UC luminescent materials with doping of RE ions have been studied for temperature sensors. The FIR technology based on the measurement of the temperature-dependent FIR from two excited state energy levels of activators represents an accurate temperature measuring method, because the FIR from the thermally coupled levels (TCLs) of RE ions is independent of the excitation intensity fluctuations, external disturbance and spectrum losses. Thus, reasonable measurement accuracy and sensitivity could be obtained with this method. The variation of FIR is generally caused by a thermally induced population redistribution among the TCLs. And some RE ions have already been explored for designing FIR thermometry, such as Er3+, Tb3+, Ho3+, and more. The sensitivity is an important role of a temperature sensing device. The absolute sensitivity is defined as the rate of change of FIR with change in temperature relative to FIR. Generally, a larger energy gap between the TCLs benefits the enhancement of sensitivity. However, the largest energy mismatches between those TCLs cannot exceed 2000 cm⁻¹, so it is difficult for the further improvement of sensitivity. There is an urgent need to design a new temperature measurement method to obtain high detecting sensitivity. Recently, a new kind of strategy has been proposed to solve the above drawback, which is based on FIR between the non-TCLs of the activators. The FIR derived from non-TCLs is also related to temperature. Compared with the FIR technique based on the TCLs, the FIR technique based on the non-TCLs is no longer limited by the energy gap. The Er3+ and Ho3+ ions also have non-TCLs pairs in addition to TCLs. So further investigation on temperature sensing properties of Er3+ and Ho3+ ions based on the FIR technology (TCLs and non-TCLs) is necessary.

Besides activators, temperature sensing properties of UC luminescent materials are also decided by host material. Among various hosts, tungstates have obtained much attention because of their brilliant physical and chemical stability, low phonon threshold energy, and high density. The Ln3+ ions also have high doped concentration in tungstates host. So the activators can emit intense and stable fluorescence even at high temperature. SrWO4 belongs to a body-centered tetragonal molecular system with scheelite crystal structure where WO4²⁻ molecular ions are loosely bound to Sr²⁺ cations. It has been reported that SrWO4 is an ideal host for optical temperature sensing materials. Recently, the temperature sensing properties of Ln³⁺ doped tungstates also have been studied. Pandey et al. report that the Er³⁺–Yb³⁺ co-doped SrWO4 phosphor is a good optical temperature sensing material, and its maximum absolute sensitivity reaches 0.01498 K⁻¹. The high sensitivity of Tm³⁺/Yb³⁺ co-doped SrWO4 phosphor for optical thermometry is synthesized by Song et al., and when the temperature is 323 K, the absolute sensitivity reaches a maximum of 0.00617 K⁻¹. For Sm³⁺ doped SrWO4 phosphor and Nd³⁺/Yb³⁺ co-doped...
SrWO4 phosphor, they also have good temperature sensing performance.\textsuperscript{14,16} Note that, the SrWO4 material is more suitable to be a UC fluorescence host for designing optical temperature sensor. However, as far as we know, the SrWO\textsubscript{4}:Yb\textsuperscript{3+}/Ho\textsuperscript{3+} phosphor for optical thermometry has not been investigated. There are even fewer reports on its optical thermometry using FIR technique based on the non-TCLs.

In this paper, the SrWO\textsubscript{4}:Yb\textsuperscript{3+}/RE\textsuperscript{3+}(RE = Er, Ho) phosphors are synthesized by a high temperature solid state reaction. The UC luminescence performances and temperature sensing properties are investigated under 980 nm excitation. The experimental results illustrate that the temperature sensitivity of our phosphors are better than the most reported Ho\textsuperscript{3+}(Er\textsuperscript{3+}) experimental results. The UC luminescence performances and temperature sensing are synthesized by a high temperature solid state reaction. The SrWO\textsubscript{4} doped Ho\textsuperscript{3+}(Er\textsuperscript{3+}) ions materials are optical temperature sensing material with good application value.

2. Experimental

2.1 Synthesis of the phosphor

The samples are designed according to the molar composition of Sr\textsubscript{1-x-y}Yb\textsubscript{x}Ho\textsubscript{y}O\textsubscript{21}WO\textsubscript{4} (x = 0, 1%, 2%, 3%, 4%, 6%, 10%) and Sr\textsubscript{1-y-x}Yb\textsubscript{x}Er\textsubscript{y}O\textsubscript{21}WO\textsubscript{4} (y = 0, 1%, 2%, 3%, 4%), and synthesized by solid-state reaction method. High-purity SrCO\textsubscript{3} (99%), WO\textsubscript{3} (99.8%), Yb\textsubscript{2}O\textsubscript{3} (99.99%), and Er\textsubscript{2}O\textsubscript{3} (99.99%) are purchased from Aladdin Chemical Reagent Co. Ltd (China). The raw materials are weighed by molar ratio and mixed together. The mixtures thoroughly are ground in a mortar of agate for 60 minutes. The ground mixture is transferred to a crucible ceramics and then heated it in a muffle furnace. First, the temperature rises to 900 °C by 10 °C min \textsuperscript{-1}. The samples are kept at 900 °C for 4 h. Next, temperature is increased by 5 °C min \textsuperscript{-1} to 1100 °C and kept for 6 h. Finally the SrWO\textsubscript{4}:Ho\textsuperscript{3+}/Yb\textsuperscript{3+} and SrWO\textsubscript{4}:Er\textsuperscript{3+}/Yb\textsuperscript{3+} phosphors are obtained.

2.2 Measurement and characterization

The structural formation of the phosphors has been measured using an X-ray diffraction (Rigaku D/Max-2500) in the range of 15° to 80° (2θ), and its radiation source is Cu K\textalpha ray of λ = 0.15406 nm. For morphology and size of the phosphors, the field emission scanning electron microscope (FE-SEM, JEOL JEM-6700F) is used to perform. The UC emission spectra are recorded using the Zolix Omni-A500 spectrometer under a 980 nm laser (MDL-III-980-2W, China) excitation. The samples are heated using an Orient KOJI TAP-02 high temperature thermometer, among a temperature range of 303 to 573 K, with a temperature control accuracy of 0.1 °C.

3. Result and discussion

3.1 Structural characterization

Fig. 1(a) shows the XRD patterns of the SrWO\textsubscript{4}:Ho\textsuperscript{3+}/Yb\textsuperscript{3+} phosphors. It can be seen that the diffraction peaks of the samples are very consistent with the standard card of SrWO\textsubscript{4} (JCPDS no. 08-0490). The sharp and strong diffraction peaks show that the synthesized samples are crystallized well. It also means that Sr\textsuperscript{3+} in the SrWO\textsubscript{4} lattice is substituted by Ho\textsuperscript{3+} and Yb\textsuperscript{3+} ions. The XRD patterns of the SrWO\textsubscript{4}:Er\textsuperscript{3+}/Yb\textsuperscript{3+} samples are shown in Fig. 1(b). The main diffraction peaks of samples are also consistent with the standard card of SrWO\textsubscript{4} (JCPDS no. 08-0490). But an extra weak peak at 29.3° appears in SrWO\textsubscript{4}:1%Er\textsuperscript{3+}, x%Yb\textsuperscript{3+}(x = 2, 3, 4) samples, which may be induced by the minor unreacted component of Yb\textsubscript{2}O\textsubscript{3}. Once the concentration of the Yb\textsuperscript{3+} ions is over 2%, a part of the Yb\textsuperscript{3+} ions will not be added in the lattice. In addition, the peak at 30° moves to a high angle direction with the concentration of Yb\textsuperscript{3+} ions increasing (see the illustration in Fig. 1(b)), which is attributed to the shrinkage of the crystal lattice caused by the doped Er\textsuperscript{3+} and Yb\textsuperscript{3+} ions substituting the Sr\textsuperscript{2+} sites. The ionic radius of Er\textsuperscript{3+}, Yb\textsuperscript{3+} and Sr\textsuperscript{2+} (Er\textsuperscript{3+}: 0.89 Å, Yb\textsuperscript{3+}: 0.86 Å and Sr\textsuperscript{2+}: 1.12 Å) are different, so the crystal lattice will produce deformation. The SEM images of SrWO\textsubscript{4}:Ho\textsuperscript{3+}y(1-y)/Yb\textsuperscript{3+} phosphor are shown in Fig. 2. It indicates that the size of the prepared phosphor is almost uniform.

3.2 Upconversion emission properties

Fig. 3(a) shows the UC emission spectrum of SrWO\textsubscript{4}:1%Ho\textsuperscript{3+}/2%Yb\textsuperscript{3+} phosphor from 500 to 800 nm under 980 nm excitation. Three characteristic emission bands are presented that the strong green emission (~540 nm) belongs to the radiative
transition from the $^5S_2/5F_4$ to $^5I_8$, the red emission ($\sim 663$ nm) belongs to the radiative transition from $^5F_4$ to $^5I_8$ and the weak near infrared emission ($\sim 756$ nm) corresponds to $^5F_4/5I_7$ energy level transition of Ho$^{3+}$ ions. Fig. 3(b) shows the UC emission spectra of SrWO$_4$:1%Ho$^{3+}$/x%Yb$^{3+}$ ($x = 0, 1, 2, 3, 4, 6, 10$). It is seen that, the intensities of all the UC emission peaks reach maximum values at $x = 2$. But they decrease if the Yb$^{3+}$ concentration is further increased up to 2%. The Yb$^{3+}$ ion is a high-efficiency sensitizer for Ho$^{3+}$ ion because it has larger absorption cross-sectional area at the near infrared. With increasing the Yb$^{3+}$ ions concentration to 2%, the energy transfer process from Yb$^{3+}$ to Ho$^{3+}$ can be enhanced, resulting in higher UC emission intensity. However, with the further enhancement of the Yb$^{3+}$ concentrations, the distance between the doping ions decreases with the increase of Yb$^{3+}$ concentration. It induces more intense interaction among adjacent Yb$^{3+}$ ions, which cause concentration quenching.

In order to explicate the possible UC emission process of the SrWO$_4$:Ho$^{3+}$/Yb$^{3+}$ sample, the dependence relation of the UC emission intensity via pump power is measured. The relationship between UC emission intensity and pumping power can be described by the following eqn (1):

$$I \propto P^n$$

(1)

where $I$ is the UC emission intensity, $P$ is the pumping power and $n$ is the photon numbers which correspond to populate the upper emitting levels. Fig. 3(c) shows the log–log plot of intensity versus pump power and the slopes of the fitted lines of SrWO$_4$:1%Ho$^{3+}$/2%Yb$^{3+}$ sample. It can be seen that $n$ values are 1.21, 1.24 and 2.27 for green ($\sim 540$ nm), red ($\sim 663$ nm), and near-infrared ($\sim 756$ nm) emissions. It indicates that these UC emission processes are related to the two-photon processes. The energy level diagrams of Ho$^{3+}$/Yb$^{3+}$ ions and possible UC emission processes are shown in Fig. 3(d).

Under 980 nm excitation, the Yb$^{3+}$ ion are excited from the ground state $^2F_{7/2}$ to the excited state $^2F_{5/2}$ by ground state absorption (GSA) process. Ho$^{3+}$ ions are excited to the excited state levels mainly through the energy transfer (ET) process from Yb$^{3+}$ to Ho$^{3+}$. Through ET1 ($^2F_{5/2}$ (Yb$^{3+}$) + $^5I_8$ (Ho$^{3+}$) $\rightarrow ^2F_{7/2}$ (Yb$^{3+}$) + $^5I_6$ (Ho$^{3+}$)), the Ho$^{3+}$ ions are excited from the $^5I_8$ to the $^5I_6$ state. Some Ho$^{3+}$ ions at $^5I_8$ state can nonradiatively (NR) relax to the $^5I_7$ state, and then populate the $^5F_5$ state by excited state absorption (ESA) from $^5I_7$ to $^5F_5$. Ho$^{3+}$ ions at $^5I_6$ state can continue to be excited into the $^5S_2$, $^5F_4$ coupling state by ET2 ($^2F_{5/2}$ (Yb$^{3+}$) + $^5I_6$ (Ho$^{3+}$) $\rightarrow ^2F_{7/2}$ (Yb$^{3+}$) + $^5S_2$, $^5F_4$ (Ho$^{3+}$)). Subsequently, the Ho$^{3+}$ ions at the $^5S_2$, $^5F_4$ coupling state will relax to the $^5F_5$ state by NR relaxation, and then a part of the Ho$^{3+}$ ions at the $^5F_5$ state are transferred to the $^5I_8$ state, concurrently red light of 663 nm is emitted. The $^5S_2$, $^5F_4$ coupling state relax to the $^5I_8$ and $^5I_7$ states, resulting in high

![Fig. 2](image_url) SEM images of SrWO$_4$: (a) 1%Ho$^{3+}$/2%Yb$^{3+}$ phosphor. (b) 1%Er$^{3+}$/1%Yb$^{3+}$ phosphor.

![Fig. 3](image_url) (a). The emission spectrum of SrWO$_4$:1%Ho$^{3+}$/2%Yb$^{3+}$ phosphor from 500 to 800 nm under exciting at 980 nm. (b). The UC emission spectra of SrWO$_4$:1%Ho$^{3+}$/x%Yb$^{3+}$ ($x = 0, 1, 2, 3, 4, 6, 10$). (c). Log–log diagram of excitation power density and UC emission intensity. (d). The energy level diagrams of Ho$^{3+}$/Yb$^{3+}$ ions and possible UC emission processes.
intensity green light (~540 nm) and low intensity red light (~756 nm), respectively.

The UC emission spectrum of SrWO₄:1%Er³⁺/1%Yb³⁺ phosphor is shown in Fig. 4(a). Two UC emission bands are exhibited, the strong green and the weak red emission, which can be attributed to the radiative transitions from \(^{2}H_{11/2} \rightarrow {^{4}I_{15/2}}\) and \(^{4}I_{9/2} \rightarrow {^{4}I_{15/2}}\) of the Er³⁺ ions, respectively. Fig. 4(b) shows the UC emission spectra of SrWO₄:1%Er³⁺/x%Yb³⁺ (x = 0, 1, 2, 3, 4). It can be found that the intensities of two emission bands first increase and then decrease with increasing Yb³⁺ concentrations, and reach a maximum at x = 1. Once the concentration of Yb³⁺ is over 1%, the UC emission intensities rapidly decline. This is mainly attributed to the transfer efficiency from Yb³⁺ to Er³⁺ ion decrease due to the limit of the Yb³⁺ that can be stabilized into the matrix. As demonstrated by the extra peaks in the XRD patterns, when the concentration of Yb³⁺ ions is over 2%, a part of the Yb³⁺ ions will not be added in the lattice.

The dependence relationship of the UC emission intensities of SrWO₄:Er³⁺/Yb³⁺ on pump power are shown in Fig. 4(c). For the emission ~528 nm, 550 nm and 654 nm, the slopes of the fitting experiment data are 1.70, 1.16 and 1.13, which is near 2. It indicates that all emission processes are related to the two-photon processes. Fig. 4(d) shows the energy level diagrams of Er³⁺/Yb³⁺ ions and possible UC emission processes.

3.3 Optical temperature-sensing properties

For investigating the optical temperature sensing characteristics of SrWO₄:Ho³⁺/Yb³⁺ phosphor, the emission spectra of the SrWO₄:Ho³⁺/Yb³⁺ sample are measured at different temperature. As shown in Fig. 5(a), it can be seen that the UC emission intensities of all emission band decrease with the temperature increasing. The possible reason is thermal quenching effect. But the decreasing rate of the different emission band is different. Fig. 5(b) shows the UC emission intensity variation of 540 nm \((^{5}S_{2}, \rightarrow {^{5}I_{6}})\) and 756 nm \((^{5}S_{2}, \rightarrow {^{5}I_{2}})\) with temperature increasing. It is clearly observed that the UC emission intensity at 756 nm drops much more slowly than that at 540 nm with the temperature increasing. By considering the
thermalization between $^5S_2$ and $^5F_4$ levels, the FIR of the UC emission from ($^5F_4$, $^5S_2$) / $^5I_8$ and ($^5F_4$, $^5S_2$) / $^5I_7$ transitions can be analyzed by using a four-level system, which was introduced by González-Pérez et al. as shown in Fig. 5(c). The $^5S_2$, $^5F_4$, $^5I_7$ and $^5I_8$ levels form a four-level system. The emission intensity is proportional to the population of each energy level and the population of the excited state relates to the temperature. So the FIR can be expressed by the following eqn (2).$^{24}$

$$\frac{\text{FIR}_1}{I_{756 \text{ nm}}} = \frac{I_{540 \text{ nm}}}{C_1 + C_2 \exp \left( -\Delta E/kT \right)}$$

where $C_1$, $C_2$, $C_3$ and $C_4$ are constants about spontaneous emission rate, energy level degeneracy and emission energy. $\Delta E$ is the energy gap of the $^5S_2$ and $^5F_4$, $k$ is the Boltzmann constant, and $T$ is the absolute temperature. It can be seen in Fig. 5(d), the FIR of the $I_{756 \text{ nm}}/I_{540 \text{ nm}}$ regularly changes with the temperature increasing. It shows a nonlinear variation of FIR value at the temperature range 303 to 573 K. The eqn (2) is used to well fit the data, the $C_1$, $C_2$, $C_3$, $C_4$ and $\Delta E$ are 0.15, /% 0.3, 2.98, /% 6.1 and 429.15 cm$^{-1}$, respectively.

In the experiment, absolute sensitivity ($S_a$) is a non-negligible evaluation index of temperature, which indicates the absolute change of FIR in unit temperature, as shown in eqn (3).

$$S_a = \frac{1}{\text{FIR}} \frac{d\text{FIR}}{dT}$$

Relative sensitivity ($S_r$) is also an important parameter that can be described as:

$$S_r = \frac{1}{\text{FIR}} \frac{d\text{FIR}}{dT}$$

$S_a$ and $S_r$ of the sample are shown in Fig. 5(e) and (f), which are fitted by eqn (3) and (4). The $S_a$ increases with the temperature enhancement, reaching a maximum of 0.0017 K$^{-1}$ at 573 K. While the maximum value of $S_r$ is 1.27% K$^{-1}$ at 573 K.

Fig. 6(a) shows that the emission intensities of the green and red band vary with temperature increasing. It can see that the intensity of red emission decreases more slowly than that of green emission. The energy levels $^5S_2$, $^5F_4$ and $^5F_5$ energy levels are far apart, and the particle population at the two energy levels do not follow the Boltzmann-type distribution. The $^5S_2$, $^5F_4$ and $^5F_5$ belong to non-TCLs. So the traditional FIR analysis method based on TCLs is not appropriate for the non-TCLs system. In the previous report, the relation of the non-TCLs FIR and temperature can be fitted by eqn (5).$^{26}$

$$\frac{\text{FIR}_2}{I_{540 \text{ nm}}} = \frac{I_{663 \text{ nm}}}{a + bT + cT^2}$$

Fig. 6(b) shows that the original data for the $I_{540 \text{ nm}}/I_{663 \text{ nm}}$ as a function of the temperature fitting with the eqn (5). Consequently the FIR based on $^5S_2$, $^5F_4$, $^5F_5$ (Ho$^{3+}$) shows the significant temperature dependence and well fits the eqn (5). The curve of $S_a$ and $S_r$ by calculation and fitting are shown in Fig. 6(c) and (d). The $S_a$ goes down with the increasing of temperature. The maximum $S_a$ is 0.0158 K$^{-1}$ at 303 K. While the $S_r$ reaches a maximum of 0.41% K$^{-1}$ at 393 K. The above analysis of the sensitivity of SrWO$_4$:Ho$^{3+}$/
Yb$^{3+}$ based on the TCLs and the non-TCLs shows that the sample has high sensitivity and it has certain application value in optical temperature measurement.

Besides, the Er$^{3+}$–Yb$^{3+}$ co-doped SrWO$_4$ phosphor has also been studied for its sensing properties. As shown in Fig. 7(a), the UC emission spectra of green light in the different temperature are recorded. The UC luminescence intensities of 528 nm and 550 nm (generated by $^2H_{11/2} ightarrow ^4I_{15/2}$ and $^4S_{3/2} ightarrow ^4I_{15/2}$) vary differently with the change of temperature. At 313 K, the intensity of the two emission bands is almost equal, with the

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**Fig. 6** (a) The emission intensity of SrWO$_4$:1%Ho$^{3+}$/2%Yb$^{3+}$ phosphor center at red (663 nm) and green (540 nm) changes with temperature. (b) The FIR ($I_{540\text{ nm}}/I_{663\text{ nm}}$). (c) the absolute sensitivity and (d) the relative sensitivity of SrWO$_4$:Ho$^{3+}$/Yb$^{3+}$ phosphor as a function of temperature.

**Fig. 7** (a) Temperature-dependent green UC emission spectra of 1%Er$^{3+}$/1%Yb$^{3+}$ co-doped SrWO$_4$ phosphor at 313–573 K. (b) dependence of FIR for $I_{528\text{ nm}}/I_{550\text{ nm}}$ on absolute temperature. (c and d) The variation of absolute sensitivity and the relative sensitivity for SrWO$_4$:1%Er$^{3+}$/1% Yb$^{3+}$ phosphor with temperature between 313 K and 573 K.
temperature increasing, the luminescence intensity of the 528 nm emission band is gradually increased within 313–433 K, and that of the 550 nm emission band gradually decreases. Then, in the range of 433–573 K, as the temperature increasing, the intensities of two bands also decrease because of the non-radiative relaxation enhancement. But the luminescence intensity of the 550 nm emission band decreases faster than that of 528 nm emission band. When the temperature increases, the electrons at $4S_{3/2}$ state are excited. The transition from $4S_{3/2}$ to $2H_{11/2}$ occurs. It indicates that the $2H_{11/2}$ and $4S_{3/2}$ states of Er$^{3+}$ can be regarded as TCLs, and the electrons population at $2H_{11/2}$ and the $4S_{3/2}$ states follows the Boltzmann distribution. The FIR of TCLs can be expressed by the eqn (6): 
\[
\text{FIR} = \frac{I_{528 \text{ nm}}}{I_{550 \text{ nm}}} = C \exp \left( \frac{\Delta E}{kT} \right)
\]

The changing of FIR of $I_{528 \text{ nm}}/I_{550 \text{ nm}}$ with temperature is displayed in Fig. 7(b), which is fitted by eqn (6). According to the fitting curve of the experimental data, the calculated C value is 24.29 and $\Delta E/k$ is 1012.9, so the $\Delta E$ between $2H_{11/2}$ and $4S_{3/2}$ states is 703.7 cm$^{-1}$, which is very close to the experiment value of 758 cm$^{-1}$, the latter is obtained from the UC emission spectrum. Fig. 7(c) shows the $S_a$ of SrWO$_4$:1%Er$^{3+}$/1%Yb$^{3+}$ phosphor. The $S_a$ of the phosphor increases at first and then decreases, reaching a maximum of 0.013 K$^{-1}$ at 513 K. In Fig. 7(d) the $S_r$ also is calculated, and the $S_r$ reaches a maximum of 1.03% K$^{-1}$ at 313 K.

In addition, thermal resolution ($\Delta T$) is also a key parameter, which can be defined as:
\[
\Delta T = \frac{\Delta \text{FIR}}{S_r} = \frac{\Delta \text{FIR}}{S_a}
\]

where $\Delta \text{FIR}$ is the uncertainty of FIR, $S_r$ is the relative sensitivity, and $S_a$ is the absolute sensitivity. The $\Delta \text{FIR}$ can be calculated by the following equation.
\[
\Delta \text{FIR} = \frac{\sum |FIR_i - \text{FIR}|}{n}
\]

Table 1 Comparison of the maximum sensitivity of Ho$^{3+}$(Er$^{3+}$)/Yb$^{3+}$ doped in different material

| Materials          | Energy level | $S_r$ (K$^{-1}$) | $S_a$ (K$^{-1}$) | Reference |
|--------------------|--------------|-----------------|-----------------|-----------|
| Bi$_2$SiO$_5$:Yb$^{3+}$/Tm$^{3+}$ | $^3F_{4/2}$/$^5G_4$ | 1.95% (300 K) | 0.0168 (300 K) | 7         |
| NaGdF$_4$:Er$^{3+}$/Yb$^{3+}$   | $^3H_{11/2}$/$^5S_{3/2}$ | 1.29% (303 K) | 0.0382 (363 K) | 28        |
| LaF$_3$:Er$^{3+}$/Yb$^{3+}$    | $^3H_{11/2}$/$^5S_{3/2}$ | 844/T$^{-2}$ (150 K) | 0.0025 (400 K) | 29        |
| Y$_2$O$_3$:Ho$^{3+}$/Yb$^{3+}$/Zn$^{3+}$ | $^3F_{2}$/K$_6$ | 1067.76/T$^{-2}$ (299 K) | 0.003 (673 K) | 30        |
| NaLa(MnO$_4$)$_2$:Sm$^{3+}$/Tb$^{3+}$ | $^5G_{7/2}$/D$_{4/2}$ | 1.93 (498 K) | 0.119 (263 K) | 31        |
| Ba$_2$Y$_2$Si$_2$O$_8$:Ho$^{3+}$/Yb$^{3+}$ | $^3F_2$/S$_{2,4}$/P$_4$ | 0.49% (298 K) | 0.023 (298–448 K) | 32        |
| Ba$_2$Y$_2$Si$_2$O$_8$:Er$^{3+}$/Yb$^{3+}$ | $^3P_2$/2$^1H_{11/2}$ | 0.78% (298 K) | 0.091 (298 K) | 32        |
| LaAlO$_3$:Er$^{3+}$/Yb$^{3+}$ | $^3H_{11/2}$/$^5S_{3/2}$ | 575.27/T$^{-2}$ (281 K) | 0.0032 (281 K) | 33        |
| NaY(WO$_4$)$_2$:Er$^{3+}$/Yb$^{3+}$ | $^3H_{11/2}$/$^5S_{3/2}$ | 1043.12/T$^{-2}$ (133 K) | 0.0112 (515 K) | 34        |
| SrWO$_4$:Er$^{3+}$/Yb$^{3+}$ | $^3H_{11/2}$/$^5S_{3/2}$ | 1.03% (313 K) | 0.013 (513 K) | This work |
| SrWO$_4$:Ho$^{3+}$/Yb$^{3+}$ | $^5S_2$/P$_{6}$ | 1.27% (573 K) | 0.0017 (573 K) | This work |
| SrWO$_4$:Ho$^{3+}$/Yb$^{3+}$ | $^5S_2$/P$_{6}$ | 0.41% (393 K) | 0.0158 (303 K) | This work |
of $\Delta$FIR and $\Delta T$ are presented among the range of 303–573 K in Fig. 8(a) and (b), respectively. It can be seen that the $\Delta$FIR of SrWO4:Ho3+/Yb3+ is lower than that of SrWO4:Er3+/Yb3+. At 303 K, the $\Delta T$ of SrWO4:Ho3+/Yb3+ and SrWO4:Er3+/Yb3+ have the minimum values of 0.72 K and 1.14 K, respectively. The values of $\Delta T$ become increasingly with the temperature enhancement. Therefore, the samples have better accuracy at lower temperature.

In order to correctly evaluate experimental results, the other materials doped with different RE ions are compared in Table 1. It can clearly conclude that the sensitivity of our sample is higher than that of the most of samples in the table.

4. Conclusion

In conclusion, the SrWO4:Ho3+(Er3+)/Yb3+ phosphors are successfully prepared by solid state reaction method. The UC luminescence properties of SrWO4:Ho3+(Er3+)/Yb3+ samples are investigated under 980 nm excitation. Furthermore, the temperature sensing properties of the Ho3+:5S2/5F4 (TCLs), Er3+:4H11/2/4S5/2 (TCLs) and the Ho3+:5S2, 5F4/5F5 (non-TCLs) are investigated in the temperature range of 303–573 K. Specifically, the absolute sensitivity value reaches 0.0158 K$^{-1}$ at 303 K for Ho3+:5S2, 5F4/5F5 (non-TCLs) and the relative sensitivity value reaches 0.41% at 393 K, which is superior to most optical temperature sensing materials doped with RE3+ ions. It means that the SrWO4:Ho3+/Yb3+ can achieve higher absolute sensitivity by FIR of non-TCLs, as well as it has potential application in optical temperature sensors.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by Natural Science Foundation of China (Grant No: 61705077); Science Foundation of Jilin Province Education Department (JJKH20190853KJ); Project of Jilin Provincial Science and Technology Department (No: 20190300364SF, 20200403072SF); Project of Jilin Province Development and Reform Commission (2019C048-4, 2020C021-5).

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