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# A simple, low-cost, highly efficient optical thermometry based on down-conversion green fluorescence of $Er^{3+}$:$SrGdGa_3O_7$ crystal

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ABSTRACT

We have developed a simple, low-cost and highly efficient optical temperature sensor based on intensity ratio of down-conversion green fluorescence of $Er^{3+}$ ions doped in $SrGdGa_3O_7$ single crystal. The sensor consists simply of a 384 nm light emitting diode, two narrow-band interference filters, two Si-photocells and two multimeters, without use of a monochromator or spectrometer or focusing lens. It has a simple, compact structure and is low-cost. The experimental results show that the device displays highly efficient sensing performance with good signal-to-noise ratio and high thermal resolution and temperature sensitivity, which has a value of $(5.5\text{-}102.1) \times 10^{-3}\,K^{-1}$ in the considered temperature range of 100–430 K. In addition, the experiments were repeated using a spectrometer and consistent results are obtained.
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## 1. Introduction

Recently, optical temperature sensing based on fluorescence intensity ratio (FIR) technique draws increasing attention [1–30], primarily due to their high electrical passiveness, negligible electromagnetic interference, wide dynamic range and multiplexing capabilities. Such sensor is promising for temperature sensing in some peculiar systems, such as electromagnetically and/or thermally harsh environments, some industrial processes which work under non-standard conditions and need a temperature sensor capable of controlling and monitoring these processes.

The FIR technique is based on the comparison of the fluorescence intensities of two temperature-dependent emissions from two closely spaced energy levels to a lower state of rare-earth ($RE^{3+}$) ion. It can reduce the influence of different factors such as measuring conditions, resolution and time exposure. Among the $RE^{3+}$ ions $Er^{3+}$, $Pr^{3+}$, $Yb^{3+}$, $Nd^{3+}$ [28–30], the $Er^{3+}$ is particularly suitable for this technique as its $^4S_{3/2}$ and $^2H_{11/2}$ states are closely spaced with an energy gap of $\sim$800 $cm^{-1}$, and are hence easily thermalized, resulting in the temperature-sensitive emission intensities of the $^4S_{3/2} \rightarrow {}^4I_{15/2}$ (550 nm) and $^2H_{11/2} \rightarrow {}^4I_{15/2}$ (530 nm) transitions. Moreover, the two transitions have relatively high radiative efficiencies and fluorescent intensities.

$Er^{3+}$-doped $SrGdGa_3O_7$ single-crystal, which was previously studied more as a laser material [31–37], displays some attractive features, such as highly disordered structure, lower cut-off phonon energy ($\sim$680 $cm^{-1}$[31]), longer lifetime of the $^4I_{11/2}$ (980 nm) manifold [31,34,35] and higher heat conductivity. These features imply that the crystal should display strong green fluorescence and high temperature sensitivity, which are two crucial performance specifications for a sensor. This prediction is verified by present work. In words, the $Er^{3+}$-doped $SrGdGa_3O_7$ crystal is a promising material for optical temperature sensing on the basis of thermal effect of FIR of the 530 and 550 nm green fluorescence.

In principle, the 530 and 550 nm green fluorescence of $Er^{3+}$ can be obtained by using a commercial UV-blue or near-infrared laser diode (LD) or light emitting diode (LED) as an excitation source. One can use the upconversion process to excite the green emissions and this is the case in the most of previous studies.ty

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- For the upconversion process, a commercially available 980 nm laser diode is the preferred excitation source. As an alternative, one can also utilize the down-conversion process [12–15] to excite the green fluorescence. To achieve that, one can choose various commercial UV-blue sources. From the viewpoint of device implementation, the excitation by the down-conversion process is more promising than that by the upconversion process because the upconversion process requires two excitation photons while the down-conversion process needs just only one excitation photon to populate one $Er^{3+}$ to the excited state. In the previous down-conversion studies, researchers have chosen either the 488 nm coherent radiation from an argon laser [12,13] or the 380 nm incoherent light from a xenon lamp [14,15] as the excitation source. Moreover, these studies focused on the temperature characteristics by the aid of a spectrometer. All of these studies are not practical from the viewpoint of device implementation, which requires that the device has simple structure, small size, low cost, large signal-to-noise and high sensitivity. In this work, we design and develop an optical thermometric sensor based on intensity ratio of down-conversion green fluorescence of $Er^{3+}$-doped $SrGdGa_3O_7$ single crystal from the viewpoint of practical device implementation. The sensor is implemented by a very cheap 384 nm LED ($1.5 only), two narrow-band interference filters, two Si-photocells and two multimeters. The device has the merits of simple structure, low cost and high efficiency of good signal-to-noise ratio and high temperature sensitivity.

## 2. Experiment

$SrGdGa_3O_7$ single crystal belongs to the crystal series of $ABC_3O_7$, where A = Ca, Sr, Ba; B = La, Gd; and C = Ga, Al. The $ABC_3O_7$ crystals belong to the tetragonal system and has a Melilite structure with a space group $P\bar{4}2_1m$ and lattice constants $a = 8.06$ Å and $c = 5.34$ Å. The $Er^{3+}$-doped $SrGdGa_3O_7$ single crystal used in this work was grown by conventional Czochralski method. A detailed description for crystal growth, structure and crystalline phase has been given in Refs. [31,38].

The $Er^{3+}$ concentration in the studied crystal was determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) with an accuracy of ± 10%. It has a value of 5.8 at%, which is equivalent to $3.5 \times 10^{20}$ ions/$cm^3$. The choice for the $Er^{3+}$ concentration considers two factors. In one hand, too low $Er^{3+}$ concentration results in too weak fluorescence signal. On the other hand, too high doping concentration increases the probability of re-absorption process, which may seriously affect the spectral profile (the phenomenon was studied more for the 1.5 μm ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) transition in the past, and was recently observed for the $^2H_{11/2} \rightarrow {}^4I_{15/2}$ transition [12]). In addition, heavy doping also affects the optical quality of the crystal. Here we adopt a compromised concentration of ~ 6 at%. A crystal plate with optically polished surfaces was used in this work. It has a dimension size $X \times Y \times Z = 22\ mm \times 3.58\ mm \times 14\ mm$. The four-fold axis of the crystal is along the direction of Z.

Fig. 1 depicts the schematic of the sensor we developed. The $Er^{3+}$-doped $SrGdGa_3O_7$ crystal plate, which acts as the sensing element, is spliced to a thermo-electrically ceramic plate. Light emitted from a 3 W (electric power, not the output optical power) 384 nm LED is incident onto the side-face along the direction parallel to the Z crystallographic axis of the crystal (see Fig. 1), without use of a focusing lens. The distance from the LED to the sensing crystal is ~5 mm. As demonstrated below, such a distance ensures a weak thermal effect (on the $Er^{3+}$ emissions) arising from that the excitation light heats the sample (the intensity of the 384 nm excitation light is estimated as ~ $10^3\ W/m^2$ at the crystal surface). In the case of without use of a focusing lens, the fluorescence was detected by two identical Si-photocells. To avoid that the residual excitation light enters the detector and hence affects the results, the sensitive faces of both photocells are not parallel to but form an angle of ~20° relative to the crystal surface, and are back on to the excitation light as shown in Fig. 1. Two narrow-band interference filter optical films with a sensitive area of $6 \times 6\ mm^2$ were placed in front of the photocells. One works for the 530 nm and another for the 550 nm fluorescence. The photocells and filters were placed as soon as possible near the sensing crystal to collect and detect more fluorescence. The nearest distance from the detector to the crystal surface is ~3 mm. To ensure that the two photocells are placed in two equivalent positions to cover both 530 and 550 nm wavelengths, we let the two photocells simultaneously detect either the 530 or the 550 nm signal at room temperature and adjust the position of one photocell. The two photocells should be at the equivalent positions when they have the same 530 or 550 nm outputs. Two multimeters were employed to measure the photovoltaic signal outputs of the 530 and 550 nm fluorescence. The temperature characteristics of the 530 and 550 nm green emissions of $Er^{3+}$-doped $SrGdGa_3O_7$ single crystal were characterized. The sensing crystal was heated through the thermo-electrically ceramic plate. The sample temperature was measured by an infrared thermometer with an

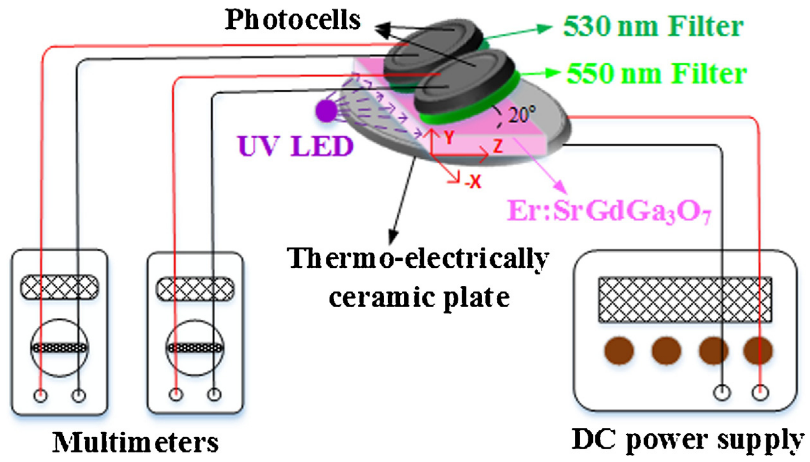

**Fig. 1.** Structure schematic of the temperature sensor developed.

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