Upconversion thermometry incorporated optical fiber based temperature sensor

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Abstract

Research carried out has demonstrated an optical temperate sensor based on upconverting nanoparticles coated on the tip of optical fiber. The experimentally obtained variation in the integrated intensity ratio of thermally coupled fluorescence peaks with temperature corresponds well to the results seen from a theoretical model. This approach of using optical fiber-based upconversion has the potential to create very compact sensors for use in a wide variety of applications.

Introduction

- Upconversion using Nanoparticles (UCNPs) involves an inorganic crystalline host matrix doped with trivalent rare-earth ions.
- UCNPs' $4f^n$ electronic configuration is split due to electronic repulsion and spin-orbit coupling, thus giving rise to thermally-coupled levels (TCLs) with an energy separation in range of 200 cm^{-1} ≤ ΔE ≤ 2000 cm^{-1}
- The ratio of TCLs naturally provides an intensity-referenced signal, thus mitigating problems regularly associated with referenced dye and dual-emission wavelength probes.
- The use of an optical fiber approach for temperature sensing offers advantages including simpler design, high signal to noise ratio, immunity to electromagnetic interference.
- In this work, UCNPs has been synthesized and coated on the tip of multimode optical fiber to realize a compact, sensitive and versatile temperature sensing probe.

Methodology: key features

UCNPs synthesis ($NaYF_4$: (18%) Yb^{3+}, (2%) Er^{3+})

- Precursors : $YCl_3.6H_2O$; $YbCl_3.6H_2O$; $ErCl_3.6H_2O$, NaF
- Solvent: 1-Octadecene
- Surfactant: Oleic acid
- Process: Solvothermal decomposition method
- Colloidal Solution: Cyclohexane
- Mean diameter: ~ 56 nm
- Phase: Hexagon

UCNPs coating

- Suspended UCNPs were extracted from the colloidal solution by centrifugation, partially dried and coated on the tip of the 1000 μm optical fiber used.

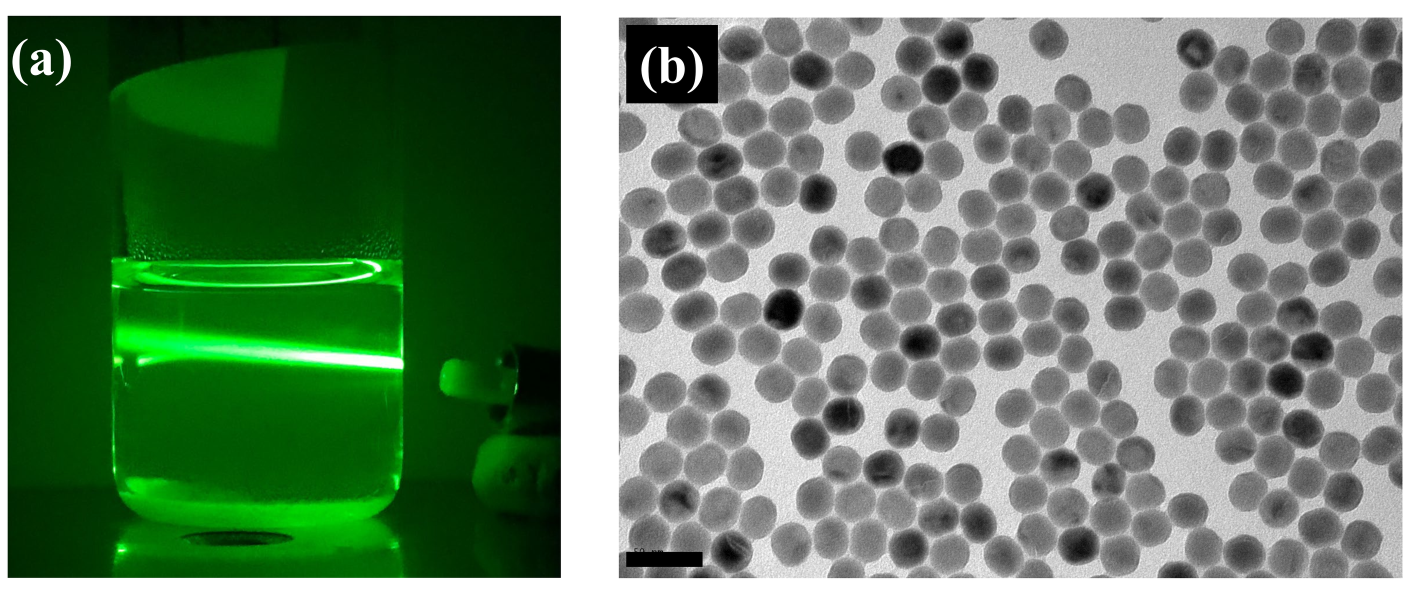

Figure 1: (a) Green fluorescence along the path of the 980 nm laser beam in the UCNPs colloidal solution. (b) TEM image of UCNPs. Scale bar shown in down-left corner = 50 nm

Experimental Setup

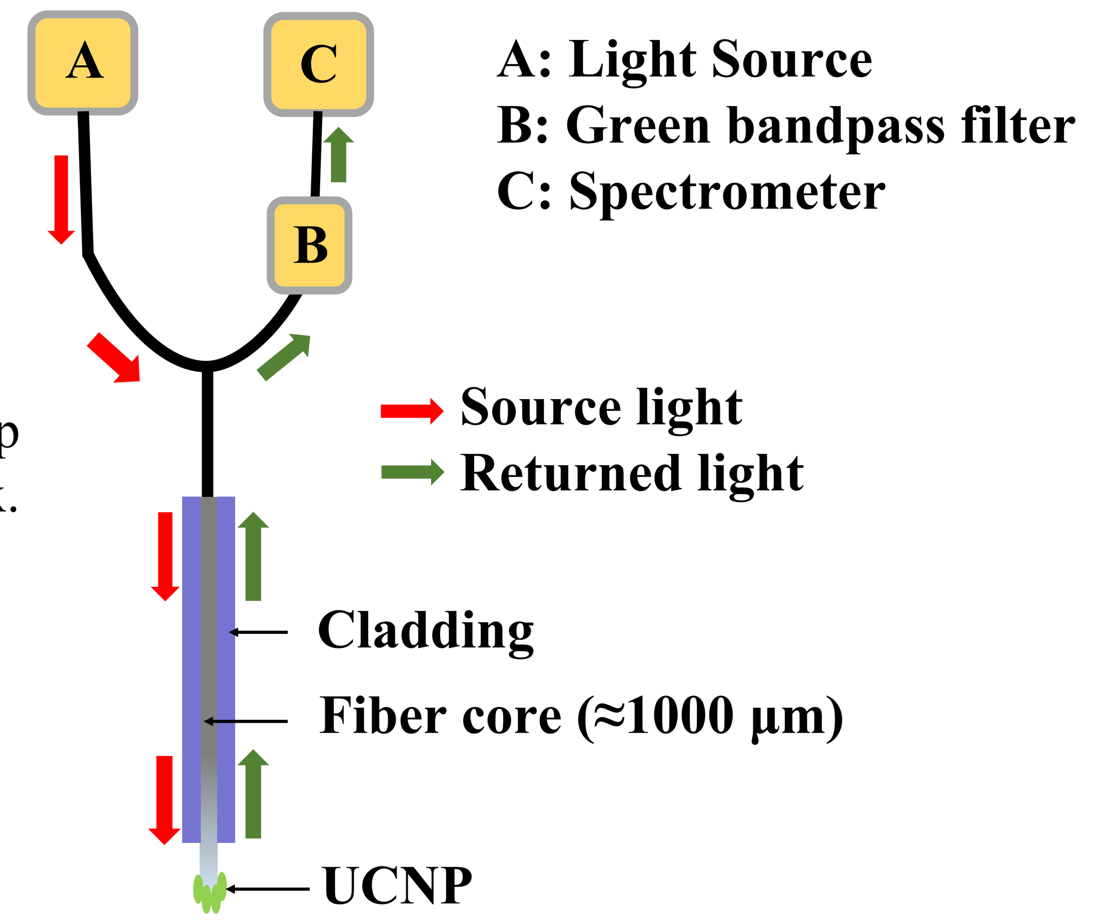

Figure 2: Schematic of the experimental setup used. Source "A" used: λ ≈ 976 nm; max. power ≈ 500 mW)

- The coated fiber was connected to 2x1 fiber coupler whose other two ends were connected to 980 nm laser source and mini-spectrometer.

Results & Discussions

- The effect of temperature on the green fluorescence of the Er^{3+} ions is shown in Fig. 3a.
- $^4S_{3/2}$ and $^2H_{11/2}$ energy levels are thermally coupled, thus the ratio of the integrated intensity of the $^2H_{11/2} \rightarrow {}^4I_{15/2}$ and the $^4S_{3/2} \rightarrow {}^4I_{15/2}$ transitions, shown as I_H and I_S respectively in Fig. 3a, is governed by Eq. 1.
- The experimental values of parameters used for plotting a graph based on Eq. 1 are given in Table 1 (these values have been obtained from the literature).
- The results of the experiment carried out and the predictions of the model used are plotted in Fig. 3b. They shows a good agreement, especially over the low temperature region where there is an overlap, as highlighted in the inset in Fig. 3b.

$$\text{Intensity Ratio}\left(\frac{I_H}{I_S}\right) = \frac{\beta \exp\left(-\frac{\Delta E}{kT}\right)}{1+\gamma\left[1-exp\left(-\frac{\hbar\omega}{kT}\right)\right]^{\left(-\frac{\Delta E}{\hbar\omega}\right)}} \quad (1)$$

Table 1: Value and description of various parameters of Eq. 1

Parameters	Value	Description
ℏω	360 cm^{-1}	Lattice vibration of $NaYF_4$ crystal
β	13	Ratio of radiative and non-radiative transition rate of $^4S_{3/2}$ -> $^4I_{15/2}$
γ	0.18	Ratio of radiative and non-radiative transition rate of $^2H_{11/2}$ -> $^4I_{15/2}$
ΔE	740 cm^{-1}	Energy separation between $^2H_{11/2}$ and $^4S_{3/2}$

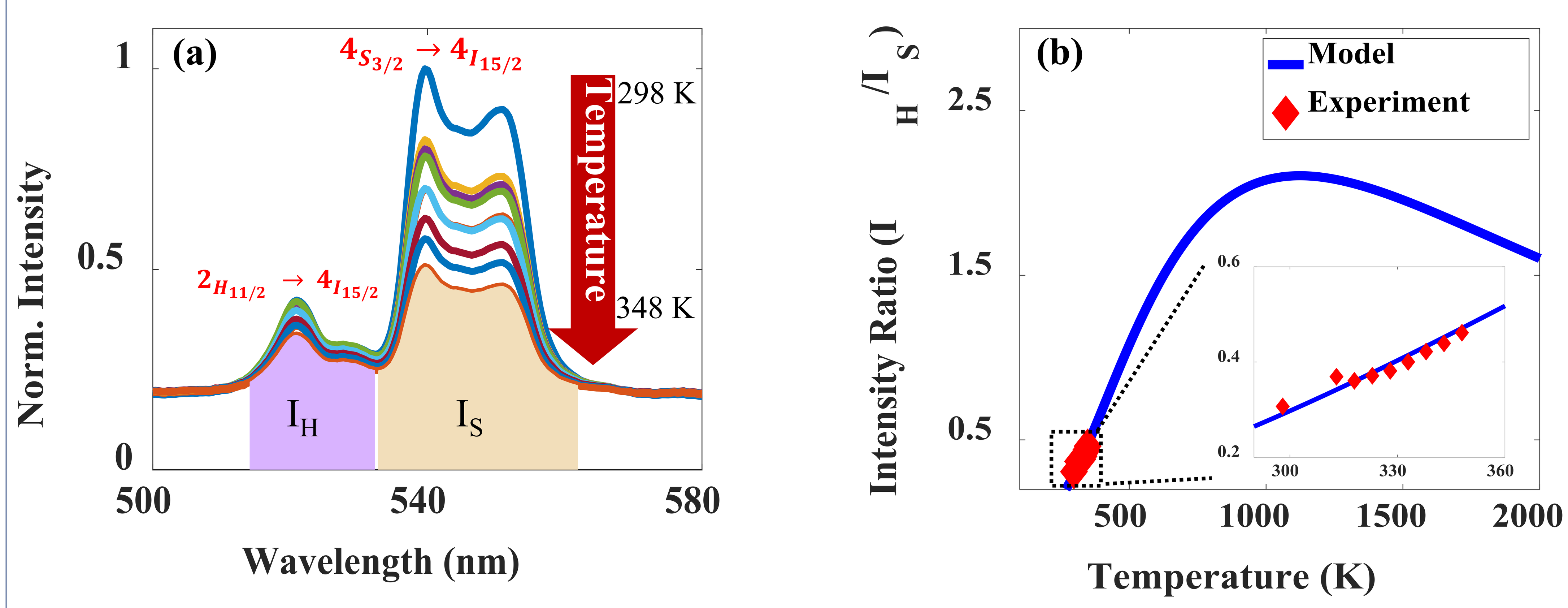

Figure 3: (a) Variation in the fluorescence spectrum of the UNCPs with temperature. All spectra are normalized to the intensity of the Er^{3+} emission at 540 nm and 298 K. (b) The modelled and experimental variation of the intensity ratio with temperature. Inset: Experimental data: 300 – 350K

Conclusions

- UCNPs have been successfully synthesized, coated on an optical fiber and demonstrate upconversion thermometry in a series of experimental measurements.
- The sensor calibration arising from the change in the integrated intensity ratio of the peak wavelengths at 520 nm and 550 nm agree well with theoretical model.
- This technique can be used to develop several different types of UCNP-based sensors with potential for use in several different applications.

Acknowledgements: Worshipful Company of Saddlers, George Daniels Educational Trust, the Royal Academy of Engineering, Erasmus Mundus Program.