Polymer Microfibers Incorporated with Silver Nanoparticles: a New Platform for Optical Sensing

Muhammad Khuram Shahzad¹, Yundong Zhang¹*, Adil Raza², Muhammad Ikram³, Kaiyue Qi¹, Muhammad Usman Khan¹, Muhammad Jehanzaib Aslam¹ and Abdulaziz Alhazaa⁴,⁵*

Abstract
The enhanced sensitivity of up-conversion luminescence is imperative for the application of up-conversion nanoparticles (UCNPs). In this study, microfibers were fabricated after co-doping UCNPs with polymethylmethacrylate (PMMA) and silver (Ag) solutions. Transmission losses and sensitivities of UCNPs (tetrogonal-LiYF₄:Yb³⁺/Er³⁺) in the presence and absence of Ag were investigated. Sensitivity of up-conversion luminescence with Ag (LiYF₄:Yb³⁺/Er³⁺/Ag) is 0.0095 K⁻¹ and reduced to (LiYF₄:Yb³⁺/Er³⁺) 0.0065 K⁻¹ without Ag at 303 K under laser source (980 nm). The UCNPs microfibers with Ag showed lower transmission losses and higher sensitivity than without Ag and could serve as promising candidate for optical applications. This is the first observation of Ag-doped microfiber via facile method.

Keywords: Microfibers, Up-conversion luminescence, Er³⁺, Ag, Transmission losses, Sensitivity

Background
Up-conversion nanoparticles (UCNPs) after co-doping with lanthanides ions have drawn much attention due to application in imaging, laser materials, display technologies, and solar cells [1–3]. The low fluorescence emission efficiency of UCNPs can be caused by the small absorption coefficients of lanthanide ions. The nanoscale dispersion of metal nanoparticles in polymeric and inorganic substrates has triggered a great interest in novel physical, chemical, and biologic properties of the nanocomposite materials [4]. For potential applications of the further miniaturization of electronic components, optical detectors, chemical and biochemical sensors, and devices are exciting possibilities with metal nanoparticles. Additionally, the semiconductors have been used as sensitizers for widening absorption range, such as CdSe, CdS, PbS, WO₃, and Cu₂O [5, 6]. Among these semiconductors, Cu₂O is an interesting candidate due to its narrow band gap of ~ 2.1 eV, non-toxicity, low cost and abundance but heterostructure of Cu₂O/ZnO is a promising material structure. It leads to a functional integration, novel interface effect’s properties of Cu₂O and ZnO material [7]. On the other hand, UCNPs depicts superior properties relative to semiconductor quantum dots for instance the absence of autofluorescence tissue penetrability near-infrared laser excitation, non-blinking, and high chemical stability [8]. The synthesis of lanthanide-doped materials with spherical nanoparticles and nanorods has been studied by many research groups [9]. The issue of UCNPs oxidation occurs at high temperature significantly which reduced their applications. To avoid oxidation, core/shell structure overcomes oxidation whereas SiO₂ shell grows around nanocrystals. Nanocrystal integration on chip as microstructure light detector is difficult. Therefore, microtubes, quantum dot-doped nanofibers, and dye-doped polymer nanowires have been employed in microstructural optoelectronics technology after successful investigation [10]. Correspondingly, nanowires, microtubes, and nanofibers have been fabricated and utilized to discuss the thermal sensing behavior by different research groups [11, 12].
However, metal nanoparticles (MNPs) have been considered to enhance UCNPs efficiency. Different strategies including chemical modification, crystal structure, and local field adjustment of metal have been proposed to improve the efficiency and sensitivity [13]. Investigations on rare earth ion-doped luminescence materials for luminescence enhancement of metal nanostructure such as Er$^{3+}$/Yb$^{3+}$ co-doped bismuth-germinate glasses containing Ag nanoparticles and Er$^{3+}$/Yb$^{3+}$ co-doped β-NaLuF$_4$ nanocrystals which are spin-coated over gold NPs have been reported with inconsistent results and high sensitivity [14]. Moreover, aggregation-induced emission (AIE) is a distinctive fluorescence phenomenon which suggested that few dyes can emit stronger fluorescence in their solid state than in dispersion solution [15–17]. Different mechanism including J-aggregate formation, conformational planarization, and twisted intramolecular charge transfer for the AIE phenomenon has been previously proposed by researchers [18–22]. Besides, materials with AIE characteristics have attracted more research attention for potential application in various field organic light-emitting diode, chemosensing, and bioimaging [23–27]. Especially, the preparation of AIE-active fluorescent organic nanoparticles has attracted attention recently. These materials containing AIE dyes could emit strong luminescence in physiological solution which effectively conquers the aggregation-caused quenching effect of fluorescent organic nanoparticles based on typical organic dyes [28, 29]. Although many strategies for the preparation of AIE-active fluorescent organic nanoparticles have been developed, the preparation of AIE-active through facile and effective multicomponent reaction (MCR) has received rare attention due to mismatch with experimental data [30–34]. So, the unique AIE properties of dyes showed very promising for the fabrication of ultra-bright luminescent polymeric nanoparticles [35, 36].

In maximum experimental study, powder samples were used to perform the spectral measurements that increased the concerns regarding the influence of aggregation inter-reflection. Therefore, it is necessary to establish a facile and simple strategy to overcome the abovementioned drawbacks. Thus, Ag nanoparticles after co-doping with UCNPs and PMMA solution were used in microfibers to enhance the luminescence. However, no results have been described focusing on Ag co-doped UCNPs to microfibers (UCNPs-MF).

Herein, we present a facile method to prepare microfibers from UCNPs/PMMA with and without Ag solutions. Especially, the photoluminescence properties of Ag and absence of Ag co-doped microfibers are studied at various excitation point of microfibers. Moreover, UC luminescence characteristics of a microfiber is investigated by exciting 980 nm diode laser source at different temperature for the purpose of temperature sensing. The dependence of the integrated FIR on temperature is obtained and the experimental data can be fitted well with an exponential function. Thus, a single microfiber having transitions 2H11/2→4I15/2 and 4S3/2→4I15/2 levels at 522 and 541 nm is used to calculate the thermal sensitivities.

Experimental and Method Section

Materials

The silver (Ag) powder, chloroform, cyclohexane, NaOH, NH$_4$F, and ethanol were purchased from Shanghai Chemical Company, China. These chemicals were of analytic grade and used without further purification.

Preparation of Tetrogonal-LiYF$_4$:Yb$^{3+}$/Er$^{3+}$ Nanoparticles

UCNP (tetrogonal-LiYF$_4$:Yb$^{3+}$/Er$^{3+}$) was prepared using thermal decomposition technique. The three-necked flasks of 100 mL were used which contain rare earth ions $\text{LnCl}_3$ (Ln=Lu, Yb, Er) having a molar ratio of 78:22:1, respectively. The solution includes 15 mL 1-octadecene (ODE) and 6 mL oleic acid (OA). The mixture was heated up to 150°C to obtain a pellicud solution and cooled up to room temperature after eliminating oxygen and residual water. Four millimoles of Na$_2$CO$_3$ and 2.5 mmol of NaOH were added slowly into a flask containing 10 mL solution of methanol. To confirm, fluoride was dissolved entirely by stirring process up to 30 min after that prepared solution was heated at 300°C at a rate of 50°C/min for 1 h under argon atmosphere. The precipitates were separated at the rate of 4000 rpm and cooled down to room temperature, washed with ethanol, and dried at 60°C for 12 h.

Fabrication of Ag Co-doped Fibers

In a typical fabrication process, 0.003 g of Ag, 0.005 g of tetrogonal-LiYF$_4$:22%Yb$^{3+}$/1%Er$^{3+}$, and 0.6 g of PMMA were mixed separately in 15 mL, 12 mL, and 18 mL of cyclohexane ($C_{16}H_{32}$) and chloroform (CHCl$_3$) solution, respectively. Afterwards, the mixture of PMMA gradually dispensed into Ag and UCNP solutions and stirred for 30 min until a transparent solution was obtained. A fiber probe with a tip several microns in size was fabricated using the flame-heated drawing technique. After the mixed solution was dropped on the glass substrate, a fiber probe was then dipped into the mixed solution and withdrawn rapidly to fabricate the microfibers. The microfibers were then drawn and cut into small pieces, as shown in Fig. 1.

Spectra Measurement

Figure 2 demonstrates the experimental setup, to study the thermal and optical properties of microfibers. The microfibers were illuminated using an excitation source of
980 nm after depositing on a glass substrate. In order to measure the transmission losses of microfibers, ×20 objective (NA = 0.4) was used. The charge-coupled device (CCD, ACTON) camera was applied to obtain emission spectra of a microfiber, and ocean optics spectrometer was used to record the spectra for temperature-sensing measurement. The excitation of microfibers having different diameter was demonstrated with 980 nm laser source under 0.998 mW laser power to study microscopic thermal properties.

Results and Discussion

Structure and Transmission Properties

Phase purity and crystal structure of UCNPs were studied by applying X-ray diffraction (XRD, Rigaku Miniflex II) technique. The observed XRD peak patterns (Fig. 3a) are well indexed and in agreement with JCPDS card # 17-0874. Fig. 3(b) displays scanning electron microscopy (SEM, NOva Nano-SEM 650) images of a microfiber. One of the SEM image could be clearly seen (see the inset) which suggests that a microfiber has a uniform diameter, together with a smooth surface. For better resolution, we used transmission electron microscopy (TEM, Tecnai G2F30) and energy-dispersive X-ray analysis (EDS, Tecnai G2F30) to investigate individual Ag co-doped microfibers. Figure 3(c, d) shows TEM and EDS images, respectively, which confirm the strong evidence of uniform dispersion of Ag co-doped nanoparticles in a single microfiber.

Furthermore, X-ray photoelectron spectroscopy (XPS, Thermofisher Escalab 250Xi) was used to determine the successful incorporation of rare earth ions and Ag ions into the LiYF₄ host material as shown in Fig. 4a–f. The XPS survey spectrum (Fig. 4a) shows the presence of Li, Y, F, Yb, Er, and Ag elements, and the peak at 55.25 eV can be assigned to the binding energy of Li 1s (Fig. 4b). The peaks observed at 158.08 eV (Fig. 4c) can be assigned to the Y 3d. The peak at 684.08 eV is attributed to the binding energy of F 1s (Fig. 4d). The Yb 4d and Er 4d peaks (Fig. 4e) can be observed at 186.08 and 164.08 eV, respectively. The peak located at 359.08 eV is related to the binding energy of Ag 3d. This confirms the successful tridoping of Ag ions in LiYF₄:Yb³⁺/Er³⁺ nanoparticles [37].

Figure 5a shows Fourier transform infrared ray (FTIR, Nicolet50 NTA449F3) spectra of LiYF₄:Yb³⁺/Er³⁺/Ag
Fig. 3 Characterization process of LiYF₄:Yb³⁺/Er³⁺ and Ag co-doped microfibers. a XRD of LiYF₄:Yb³⁺/Er³⁺. b SEM of Ag co-doped microfiber. c TEM of Ag co-doped microfiber. d EDS of Ag co-doped microfiber.

Fig. 4 XPS a survey, b Li 1s, c Y 3d, d F 1s, e Yb and Er 4d, and f Ag 3d spectra of LiYF₄:Yb³⁺/Er³⁺ NPs doped with Ag.
nanoparticles in the region 400–4000 cm⁻¹. The studies were carried out in order to ascertain the purity and nature of nanoparticles. The peaks observed at 3452 cm⁻¹ are may be due to O-H stretching and deformation. The bands at 2925 and 2848 cm⁻¹ are associated to the asymmetric (υas) and symmetric (υs) stretching vibration of methylene (−CH₂) in the long alkyl of oleate molecule, respectively. The bands at 1566 and 1469 cm⁻¹ can be assigned to the asymmetric (υas) and symmetric (υs) stretching vibration of the carboxylic group, respectively. The spectra contain a peak at 1740 cm⁻¹ due to C=O stretching vibration. The peak located at 1383 cm⁻¹ corresponds to the C-H deformation vibration. The spectra also contain a peak at 910 and 669 cm⁻¹ which is due to asymmetric stretching vibration and Ag-O deformation vibrations. It implies that FTIR results are in accordance with literature values [38].

To better understand the formation mechanism of Ag-doped microfibers, the thermal gravimetric analysis (TGA, NETZSCH) was conducted under a dry airflow from 293–393 K temperature. It is observed in Fig. 5b that a microfiber shows roughly two degradation steps. The first weight loss below 333 K could be attributed to loss of absorbed moisture/with the evaporation of trapped solvent (H₂O or CHCl₃) which is independent of sample composition. In graph, second weight loss happens from 333 K to 393 K which clearly represents the polymeric degradation process. Hence, Ag co-doped microfibers are polymer-based fibers which cannot stand with the temperature above 332 K [4].

![FTIR spectra of LiYF₄:Er³⁺/Yb³⁺/Ag](image1)

![TGA spectra LiYF₄:Er³⁺/Yb³⁺/Ag](image2)

**Fig. 5** a FTIR spectra of LiYF₄:Er³⁺/Yb³⁺/Ag. b TGA spectra LiYF₄:Er³⁺/Yb³⁺/Ag

![Photoluminescence images with different diameter of microfibers.](image3)

**Fig. 6** Photoluminescence images with different diameter of microfibers. a–c Luminescence of Ag microfiber under dark background. d–f Excitation without Ag microfiber under black background.
In order to investigate individual optical properties of Ag-doped and undoped microfibers, laser light (980 nm) was employed from standard optical fiber to expose microfibers at oblique angles with respect to microfibers along axis. Figure 6a shows Ag co-doped microfiber (diameter ~ 6 μm) which was vertically excited under dark background with 980 nm and appeared that light spread in whole fiber because of Ag co-doped nanoparticles served as light transmitter. Conversely, Fig. 6d depicts without Ag co-doped microfiber (diameter ~ 6.5 μm) which was excited under dark background at top position with 980 nm laser source. It suggests that light cannot transmit equally in fiber due to high self-absorption and Rayleigh scattering phenomena. A microfiber (diameter ~ 6 μm) containing Ag co-doped NPs shows high green light emission than undoped Ag (diameter ~ 6.5 μm) having the same excitation of laser source under dark field. It is observe that bright end spots with no cluster having optical waveguides intend Ag co-doped microfiber absorbs near IR light and conduct alike toward end points. Moreover, Fig. 6b and c indicate that the Ag co-doped fibers having different diameters (~15.55 and ~9.15 μm) were excited at five different positions and exhibited green light emissions toward end points. Conversely, 980 nm laser source was applied to excite microfibers (without Ag NPs) at different five position having different diameters (~11.89 and 14.57 μm) which are shown in Fig. 6e–f, indicating less green light emission toward end points. The photoluminescence (PL) intensity of excited points against end spots was performed to elaborate the wave-guiding performance of microfibers (with and without Ag NPs) quantitatively [39]. We used adobe photoshop to convert spot images from RGB to gray styles, these gray values were evaluated by using MATLAB to characterize the corresponding intensities. After normalizing end points of photoluminescence intensities toward excited points, decay curves dependent of light propagation distance were obtained.

![Fig. 7 a, b Fitting lines between photoluminescence (PL) intensity and guiding distance of different diameter of microfibers with Ag co-doped under different excitation point. c–d Fitting lines between photoluminescence (PL) intensity and guiding distance of different diameter of microfibers without Ag co-doped under different excitation point](image-url)
The transmission losses were measured using equation [40]:

\[
\frac{I_{\text{endpoint}}}{I_{O}} = \exp(-\alpha d)
\]  

(1)

Here, Eq. (1) shows that excited spots distance increases which results exponentially decrease of photoluminescence intensity. The relationship between photoluminescence intensity as a function of guiding distance of fibers (\(\sim 15.55\) and \(\sim 9.15 \mu m\)) with Ag NPs is shown in Fig. 7a, b. The emitted spectra were collected at five positions along the axis of microfibers which specifies the transmission of laser light with transmission loss coefficients \(\alpha = 108.94 \text{ cm}^{-1}\) and \(91.05 \text{ cm}^{-1}\). Conversely, Fig. 7c, d demonstrates the transmission loss coefficients of microfibers (without Ag NPs) having a diameter of 11.89 and 14.57 \(\mu m\) are about 231.72 and 274.84 \(\text{cm}^{-1}\), respectively. It is noteworthy that when the light is guided through Ag co-doped microfibers, it maintains small mode areas along the entire length of fiber. It enables strong interaction between light and Ag nanoparticles in cascade and leading to light transfer with high efficiency relative to microfibers without Ag. Ag co-doped nanoparticles have highly efficient photon to plasmon conversion in wave-guiding microfibers and facilitated enhanced light matter interactions within a highly localized area [41]. It accelerates opportunities for developing Ag-based photonic components and devices having high compactness, low optical power consumption, and reduced sizes. It is noted that simultaneous multiphoton excitation has been widely applied in fluorescent optical microscopy to show increased resolution and decreased specimen autofluorescence, as well as increased imaging depth. However, the low NIR absorption cross-section of multiphoton labels requires this technique to subject to the use of high-peak power ultrashort-pulsed laser. Principally distinct from simultaneous multiphoton process in dyes and QDs, which involves the use of a virtual energy level, photon up-conversion in UCNPs relies on the sequential absorption of low energy photons through the use of ladder-like energy levels of lanthanide doping ions. This quantum mechanical difference makes UCNP orders of magnitude more efficient than multiphoton process, allowing excitation with a low-cost continuous-wave laser diode at low-energy irradiance, typically as low as \(\sim 10^{-1} \text{ W/cm}^2\) [42]. The microfibers (UCNPs/PMMA/Ag) possess favorable transmission properties. Thus, the proposed microfibers (UCNPs/PMMA/Ag) have advantages of easy fabrication, low cost, strong plasticity, and unique optical properties of UCNPs such as large anti-stokes shift and abundant emission bands, further supporting their applications based on optical signal transmission, sensors, and optical components. Consequently, our estimated results of wave-guiding performances show well agreement with reported work [43, 44].

Energy Levels and Thermal Effects

To elaborate the energy level diagram of UCNPs (Yb\(^{3+}/\)Er\(^{3+}\)), two dominant green emission bands around 522 and 541 and a red emission band centered at \(\sim 660 \text{ nm}\) were observed. These observed emission lines are originated from \(2\text{H}_{11/2} \rightarrow 4\text{I}_{15/2}\), \(4\text{S}_{3/2} \rightarrow 4\text{F}_{9/2}\), and \(4\text{S}_{3/2} \rightarrow 4\text{I}_{15/2}\) of Er\(^{3+}\) ions, respectively. Energy levels \(2\text{H}_{11/2}\) and \(4\text{S}_{3/2}\) are populated by two photon processes. For population system of Yb\(^{3+}/\)Er\(^{3+}\) ions, Yb\(^{3+}\) ions are excited by the pumping photons to populate consecutive three levels of Er\(^{3+}\) ions which are demonstrated as \(4\text{I}_{11/2}\), \(4\text{F}_{9/2}\), and \(2\text{H}_{11/2}\) levels. It is observed that the population of \(2\text{H}_{11/2}\) is obtained from given process \(4\text{I}_{15/2} \rightarrow 4\text{I}_{11/2}\) (Er\(^{3+}\)); \(2\text{H}_{11/2} \rightarrow 2\text{H}_{11/2}\) (Er\(^{3+}\)) levels. This phenomenon is caused by temperature excitation between thermally coupled levels. Therefore, the populations of \(2\text{H}_{11/2}\) and \(4\text{S}_{3/2}\) satisfy the Boltzmann statistics resulting in variation of population rates of \(2\text{H}_{11/2} \rightarrow 4\text{I}_{15/2}\) and \(4\text{S}_{3/2} \rightarrow 4\text{I}_{15/2}\) levels [45]. The mechanism of up-conversion process in Er\(^{3+}/\)Yb\(^{3+}\) is illustrated in Fig. 8.

The Ag co-doped UCNPs in fibers showed spectra with 980 nm laser source. The up-conversion (UC) luminescence is suitable for temperature-sensing applications. Therefore, Figs. 9a and 10a depicted the emission spectra of Ag and without Ag co-doped NPs which ranged from 400 to 750 nm under fiber laser excitation source, and spectra were collected with an average increment of 5 °C in temperature regime (303–348 K). Interestingly, by increasing temperature, the emission intensities were decreased significantly, therefore using 0.998 mW laser powers to avoid from thermal effects, clearly indicating the temperature-dependent behavior. While UCNPs-MF was heated in the temperature domain of 348–303 K, all photoluminescence was restored to original position whereas intensities showed significant reduction upon increasing the temperature. Therefore, this significant reduction in intensity is attributed to the escalation of variety of relative intensity corresponding to several multiphonon relaxation
rates to diverse multiphonon relaxation rate. The luminescent intensity is significantly increased by introducing Ag in a microfiber under same experimental condition. Typically, heat energy is generated by laser light near irradiated area whose temperature is measured by applying thermal sensors, to estimate temperature of irradiated point with great accuracy. Fluorescence intensity ratio technique is a versatile technique widely used for temperature estimation. We discussed Ag and without Ag co-doped fibers upon temperature fluctuation; populations of $^{2}\text{H}_{11/2}$ and $^{4}\text{S}_{3/2}$ followed the Boltzmann distribution which resulted in variable population rates of $^{2}\text{H}_{11/2} \rightarrow ^{4}\text{I}_{15/2}$ and $^{4}\text{S}_{3/2} \rightarrow ^{4}\text{I}_{15/2}$. Temperature sensing can be calculated using intensity ratio between $^{2}\text{H}_{11/2} \rightarrow ^{4}\text{I}_{15/2}$ and $^{4}\text{S}_{3/2} \rightarrow ^{4}\text{I}_{15/2}$ transitions. Fluorescence intensity ratio (FIR) method can be expressed from the following equation [46]:

$$\text{FIR} = \frac{I_{522\text{nm}}}{I_{541\text{nm}}} = C \exp \left( \frac{-\Delta E}{kT} \right)$$

(2)

Here, $I_{522\text{nm}}$ and $I_{541\text{nm}}$ are the relative intensities, $C$ is the proportionality constant, $\Delta E$ is the energy gap between 522 and 540 nm, $T$ is the absolute temperature, and $k$ is the Boltzmann constant. Moreover, Figs. 9b and 10b display the variation of FIR with temperature; Eq. (2) determined that observed experimental data have a good linear fitting relationship. It is worth to investigate another key parameter that is the thermal-sensing mechanism of Ag- and without Ag-doped microfiber. Therefore, sensitivity ($S_a$) can be written as follows [47]:

$$S_a = \frac{\text{FIR}}{dT} = \text{FIR} \left( \frac{\Delta E}{kT^2} \right)$$

(3)

Here, $S_a$ is the absolute sensitivity of Ag and without Ag co-doped microfibers. The curves are exhibited in Figs. 9c and 10c, but digital values (FIR, $\Delta E$, and $k$) for Ag and without Ag are obtained by fitted curves presented in Figs. 9b and 10b. Maximum sensor sensitivities for LiYF$_4$:Yb$^{3+}$/Er$^{3+}$ and LiYF$_4$:Yb$^{3+}$/Er$^{3+}$/Ag demonstrated to be 0.0065 and 0.0095 K$^{-1}$ at 303 K, respectively. The optical temperature sensor’s sensitivities in different host materials are listed in Table 1. Although other sensitivities have a higher value as compared to without Ag UCNPs, LiYF$_4$:Yb$^{3+}$/Er$^{3+}$/Ag is superior to host materials.

This may be linked to the highest sensitivity among other host materials, as displayed in Table 1. Furthermore, we observed that sensitivity of LiYF$_4$:Yb$^{3+}$/Er$^{3+}$/Ag at 303 K is also higher than LiYF$_4$:Yb$^{3+}$/Er$^{3+}$/Ag manifested to a highly efficient photon to plasmon conversion of Ag nanoparticles in microfibers. The Ag co-doped microfibers are intrinsically immune to photobleaching which
provided high stability dopant for optical sensing. It suggests that Ag co-doped fibers due to significant sensing properties are suitable for temperature recognition. As a result, the utilization of Ag nanoparticles in a microfiber is beneficial to increase the luminescence and to tailor thermal sensing properties, suggesting a promising sensitive temperature sensor.

Conclusions

In summary, tetragonal-LiYF₄:Yb³⁺/Er³⁺ were prepared via thermal decomposition method and fibers were fabricated after co-doping PMMA solution with Ag and UCNPs. Successful Ag incorporation in UCNPs was supported through SEM, TEM, EDS, XPS, FTIR, and TGA analysis. The Ag co-doped polymer microfibers with a wave-guiding excitation approach and demonstrated potential use in thermal sensor were investigated. The intensity-dependent temperature sensitivity of Ag microfiber (0.0095 K⁻¹) at 303 K, proposing Ag-doped microfibers are potential candidates for upgrading intensity-based temperature sensitivity at room temperature, which opens up new opportunities for developing compact photonic and plasmonic devices with low optical power. In the development of a newly employed method of microfibers with specified properties, significant improvements in up-conversion enhancement may be possible, leading to a more efficient up-converter, thereby enabling many of the technological applications of these materials.

Abbreviations

JCPSD: Joint committee on powder diffraction standards; CCD: Charge-coupled device; UCNPs-MF: Up-conversion nanoparticles microfibers; UC: Up-conversion; PL: Photoluminescence; Ln³⁺: Trivalent lanthanide ions; LiYF₄:Er³⁺/Yb³⁺; 1%Er³⁺/22%Yb³⁺; LiYF₄:Er³⁺/Yb³⁺/Ag: 1%Er³⁺/22%Yb³⁺/0.003g; RE: Rare earth ions; XRD: X-ray diffraction; TEM: Transmission electron microscope; SEM: Scanning electron microscope; EDS: Energy dispersive X-ray spectroscopy; XPS: X-ray photoelectron spectroscopy; FTIR: Fourier transform infrared rays; TGA: Thermal gravimetric analysis; FIR: Fluorescence intensity ratio; AE: Energy difference; SA: Absolute sensitivity

Acknowledgements

We acknowledge the characterization contribution of Engr. Muhammad Zeeshan Farooq from the Department of Material Science and Engineering, Harbin Institute of Technology, China, and the hard work of each member in our group. The authors do not have any kind of funding for this study.

Authors’ Contributions

MKS and AR performed the whole experiments and wrote the manuscript. YZ provided the novel idea to carry out the experiment. AA participated in the analyzes of the results and discussion of this study. MI, KQ, MUK, and MJA revised the manuscript and corrected the English. All authors read and approved the final manuscript.

Availability of Data and Materials

All data are fully available without restriction.

Competing Interests

The authors declare that they have no competing interests.

Author details

1National Key Laboratory of Tunable Laser Technology, Institute of Opto-Electronics, Department of Electronic Science and Technology, Harbin Institute of Technology (HIT), Harbin 150080, People’s Republic of China. 2College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, 29 Yudaao Street, Nanjing 210016, People’s Republic of China. 3Solar Cell Applications Research Lab, Department of Physics, Government College University, Lahore, Punjab 54000, Pakistan. 4Research Chair for Tribology, Surface, and Interface Sciences, Department of Physics and Astronomy, College of Science, King Saud University, Riyadh, Saudi Arabia. 5King Abdullah Institute for Nanotechnology, King Saud University, Riyadh, Saudi Arabia.

Received: 8 April 2019 Accepted: 28 July 2019
Published online: 08 August 2019

References

1. Elizabeth D, Lambertus H, John R, Roger M (1996) A three-color, solid-state, three-dimensional display. Sci 276:1185–1189
2. Yi G, Lu H, Zhao S, Ge Y, Yang W, Chen D, Guo L-H (2004) Synthesis, characterization and biological application of size-controlled nanocrystalline NaYF₄:Yb:Er infrared-to-visible up-conversion phosphors. Nano Lett 4:2191–2196
3. Jian Y, Yuexue L, Duanting Y, Hancheng Z, Chunguang L, Changshan X, Li M, Xiaojun W (2016) A vacuum-annealing strategy for improving near-infrared super long persistent luminescence in Cu²⁺ doped zinc gallogermanate nanoparticles for bio-imaging. Dalton Trans 45:1364–1372
4. Xin W, Huiqing F, Pengrong R, Huawa Y, Jin L (2012) A simple route to disperse silver nanoparticles on the surface of silica nanofibers with excellent photocatalytic properties. Mater Res Bull 47(7):1734–1739
5. Xinwei Z, Huiping F, Huiying T, Mingang Z, Xiaoyan Y (2012) Chemical bath deposition of Cu₂O quantum dots onto ZnO nanorod arrays for application in photovoltaic devices. RSC Adv 5(30):23401–23409
6. Xiaohu R, Huiqing F, Chao W, Jianguang M, Hua L, Mingchang Z, Shenlui H, Weijia W (2018) Wind energy harvester based on coaxial rotary freestanding triboelectric nanogenerators for self-powered water splitting. Nano energy 50:562–570

Table 1 The sensitivity values of optical temperature sensors in different host materials

| Materials     | Temperature (K) | Transitions                                | Intensity-dependent temperature sensitivity (K⁻¹) | Ref.          |
|---------------|----------------|--------------------------------------------|-----------------------------------------------|--------------|
| Er:Mo:Yb₂TiO₅ | 295–973        | ^6H₁₁/₂→^4S₃/₂                                            | 0.0048 (467)                                  | [48]         |
| Er:Bi₃NdWO₁₅  | 175–550        | ^6H₁₁/₂→^4S₃/₂                                            | 0.0037 (385)                                  | [49]         |
| Er:Yb:NdF₄   | 303–363        | ^6H₁₁/₂→^4S₃/₂                                            | 0.0031 (303)                                  | [50]         |
| Er:Yb:CaWO₄  | 303–873        | ^4I₁₅/₂→^2H₉/₂, ^4I₁₃/₂→^1H₅/₂, ^4I₁₃/₂→^1H₅/₂, ^4I₁₅/₂→^1H₅/₂ | 0.0073 (873)                                  | [51]         |
| Er:Yb:La₂O₃  | 303–600        | ^6H₁₁/₂→^4S₃/₂                                            | 0.0091 (303)                                  | [52]         |
| NaLuF₄:Yb:Er/Tm | 120–300      | ^6H₁₁/₂→^4S₃/₂                                            | 0.0019 (300)                                  | [53]         |
| LiYF₄:Yb:Er/Ag | 303–348      | ^6H₁₁/₂→^4S₃/₂                                            | 0.0095 (303)                                  | This work    |
with hyper branched polymers based on supramolecular chemistry and their potential for drug delivery. J. Colloid Interface Sci 513:198–204
29. Hongye H, Meiyling L, Qing W, Ruming J, Daizhuang X, Qiang H, Yuanqing W, Fengjie D, Xiangyang Z, Yen W (2018) Facile fabrication of luminescent hyaluronic acid with aggregation-induced emission through formation of dynamic bonds and their theranostic applications. Mater Sci Eng C 91:201–207
30. Ruming J, Han L, Meiyling L, Jianwen T, Qing H, Hongye H, Yuanqing W, Xianyang C, Xiangyang Z, Yen W (2017) A facile one-pot mannich reaction for the construction of fluorescent polymer nanoparticles with aggregation-induced emission feature and their biological imaging. Mater Sci Eng C 81:416–421
31. Ruming J, Meiyling L, Cong L, Qiang H, Hongye H, Qing W, Yuanqing W, Xianyang C, Xiao Y, Yen W (2017) Facile fabrication of luminescent polymer nanoparticles containing dynamic linkages via a one-pot multicomponent reaction: synthesis, aggregation-induced emission and biological imaging. Mater Sci Eng C 80:708–714
32. Qian YC, Ruming J, Meiyling L, Qing W, Daizhuang X, Tian J, Hongye H, Yuanqing W, Xianyang C, Xiao Y, Qiang H, Yen W (2017) Microwave-assisted multicomponent reactions for rapid synthesis of AIE-active fluorescent polymer nanoparticles by post-polymerization method. Mater Sci Eng C 80:578–583
33. Qian YC, Ruming J, Meiyling L, Qing W, Dazhuang X, Tian J-W, Hongye H, Yuanqing W, Xiao Y, Yen W (2017) Preparation of AIE-active fluorescent polymer nanoparticles through a catalyst-free thiolene click reaction for biomedical applications. Mater Sci Eng C 80:411–416
34. Jian WT, Ruming J, Peng G, Dazhuang X, Liucheng M, Guanjian Z, Meiyling L, Fengjie D, Xiangyang Z, Yen W (2017) Synthesis and cell imaging applications of amphiphilic AIE-active poly (amino acid). Mater Sci Eng C 79:563–569
35. Yanzhu L, Liucheng M, Xinhua L, Meiyling L, Daizhuang X, Ruming J, Fengjie D, Yongxiu L, Xianyang C, Yen W (2017) Direct encapsulation of AIE-active dye with β cyclodextrin terminated polymers: self-assembly and biomedical imaging. Mater Sci Eng C 78:862–867
36. Parthiban R, Prakash C, Seog WR, Jinkwon K (2013) Enhanced upconversion luminescence in NaGdF4:Er3+ nanoparticles by Fe3+ doping and their application in bioimaging. Nanoscale 5:7811–7817
37. Singh N-D, Lab N-A-C, Mohan M-R, Ahmad R (2012) FTIR studies on silver (methylacrylate) nanocomposites via in-situ polymerization technique. Int J Electrochem Sci 7:5596–5603
38. Niu N, Yang P, He F, Zhang X, Bai S, Li C, Lin J (2012) Tunable multicolor and white bright emission of one dimensional NaLuF4:Yb3+, (Ln= Er, Tm, Ho, Er/Tm, Tm/Ho) microstructure. J Mater Chem 22:10889–10899
39. Beer (1852) Bestimmung der absorption des rothen lichts in farbigen mediern. Ann. Phys. 68:78–88
40. Wang P, Zheng L, Xia Y, Tong L, Xu X, Ying Y (2012) Polymer nanofibers embedded with aligned gold nanorods: a new platform for plasmonic studies and optical sensing. Nano Lett 12:3145–3150
41. Heer S, Kompe K, Gudel H-U, Haase M (2004) Highly efficient multicolour upconversion emission in transparent colloids of lanthanide-doped NaYF4 nanocrystals. Adv Mater 16:2102–2105
42. Muhammad K-S, Yundong Z, Lugui C, Lu L, Mehwish K-B, Hanyang L (2018) Dispensing upconversion nanocrystals in PMMA microfiber: a novel methodology for temperature sensing. RSC Adv 8:19362–19368
43. Jiang S, Zeng P, Xiao L-Q, Tian S-F, Guo H, Chen Y-H, Duan C-K, Yi M (2014) Optical thermometry based on up-converted luminescence in transparent glass ceramics containing NaYF4:Er3+/Er3+ nanocrystals. J Alloys Compd 619:538–541
44. Chengqi E, Yanyan B, Lan M, Xiaohong Y (2017) Tm3+ Modified optical temperature behavior of transparent Er3+-doped hexagonal NaGdF4 glass ceramics. Nanoscale Res Lett 12:427
45. Muhammad K-S, Yundong Z, Muhammad U-K, Xiao S, Lu L, Hanyang L (2018) Upconversion thermometer through novel PMMA fiber containing nanocrystals. Opt Mater Express 8:332796–332804
46. Zheng H, Chen B-J, Yu H-Q, Zhang J-S, Sun J-S, Li X-P, Sun M, Tian B, Zhong H, Fu S-B, Hua R-N, Xia H-P (2014) Temperature sensing and optical heating
in Er\textsuperscript{3+} single-doped and Er\textsuperscript{3+}/Yb\textsuperscript{3+} codoped NaY(WO\textsubscript{4})\textsubscript{2} particles. RSC Adv 4:47556–47563

48. Dong B, Cao B, He Y, Liu Z, Li Z, Feng Z (2012) Temperature sensing and in vivo imaging by molybdenum sensitized visible upconversion luminescence of rare earth oxides. Adv Mater 24:1987–1993

49. Zou H, Wang X, Hu Y, Zhu X, Sui Y, Song Z (2014) Optical temperature sensing by upconversion luminescence of Er doped Bi\textsubscript{5}TiNbWO\textsubscript{15} ferroelectric materials. AIP Adv 4:127157

50. Muhammad K-S, Yundong Z, Muhammad U-K, Harse S, Muhammad I (2019) Optical thermometry probe via fiber containing β-NaLuF\textsubscript{4}:Yb\textsuperscript{3+}/Er\textsuperscript{3+}/Tm\textsuperscript{3+}. Curr Appl Phys 19:739–744

51. Xu W, Zhang Z, Cao W (2012) Excellent optical thermometry based on short wavelength upconversion emissions in Er\textsuperscript{3+}/Yb\textsuperscript{3+} codoped CaWO\textsubscript{4}. Opt Lett 37:4865–4867

52. Dey R, Rai V-K (2014) Yb\textsuperscript{3+} sensitized Er\textsuperscript{3+} doped La\textsubscript{2}O\textsubscript{3} phosphor in temperature sensors and display devices. Dalton Trans 43:111–118

53. Aihua Z, Feng S, Yingdong H, Feifei S, Dandan J, Xueqin W (2018) Simultaneous size adjustment and upconversion luminescence enhancement of β-NaLuF\textsubscript{4}:Yb\textsuperscript{3+}/Er\textsuperscript{3+}/Tm\textsuperscript{3+} microcrystals by introducing Ca\textsuperscript{2+} for temperature sensing. CrystEngComm 20:2029–2035

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.