Ultraviolet Upconversion Emissions of Gd\textsuperscript{3+} Resulted in Enhanced Multi-photon Transitions of Tm\textsuperscript{3+} in Y\textsubscript{0.800-x-y}F\textsubscript{3}:Yb\textsuperscript{3+\textsubscript{0.200}}, Tm\textsuperscript{3+\textsubscript{x}}, Gd\textsuperscript{3+\textsubscript{y}} Nanocrystals

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Abstract: The upconversion emissions, which are attributed to the transitions of \( ^6I_J \) or \( ^6P_J \rightarrow ^8S_7/2 \) (Gd\textsuperscript{3+}), \( ^2H_6 \rightarrow ^1G_4 \) (Tm\textsuperscript{3+}), \( ^1D_2 \rightarrow ^1F_4 \) or \( ^3H_6 \) (Tm\textsuperscript{3+}), and \( ^1P_0 \) and \( ^1I_6 \) \( \rightarrow ^3F_4 \) or \( ^3H_6 \) (Tm\textsuperscript{3+}), respectively, have been investigated and assigned in the Y\textsubscript{0.800-x-y}F\textsubscript{3}:Yb\textsuperscript{3+\textsubscript{0.200}}, Tm\textsuperscript{3+\textsubscript{x}}, Gd\textsuperscript{3+\textsubscript{y}} nanocrystal samples by following an excitation at 980 nm. The lifetimes with Gd\textsuperscript{3+} and Tm\textsuperscript{3+} states imply that the effects of the nanocrystal dimension on the transition rates play a key role for the valid population of \( ^1I_6 \) (or \( ^3P_J \), \( ^1D_2 \), \( ^1G_4 \) state under 980 nm excitation, leading to ultraviolet-enhanced upconversion with Tm\textsuperscript{3+} and the energy-transfer processes from Yb\textsuperscript{3+} to Tm\textsuperscript{3+} to Gd\textsuperscript{3+} based on the energy-matching conditions. These experimental results have revealed that it would be potential to apply the fluoride nanomaterials doped by rare-earth ions for searching ultraviolet solid-state lasing materials.

Key words: energy transfer; nanocrystal; ultraviolet upconversion emission; rare-earth

1. Introduction

Frequency upconversion (UC) is an important process on optical generation from near infrared (NIR) to visible and to ultraviolet (UV) emission in rare-earth (Re)-doped materials. So, Re-doped UC materials have been widely explored because of their potential applications such as optical data storage, color displays, IR sensors, environmental monitoring, and so on\textsuperscript{[1-5]}. In particular, fluoride materials have wide applications in optics as windows, lenses, scintillation crystals\textsuperscript{[6]}, and also as host for Re ions has exhibited excellent frequency UC features and in past two decades, the UC properties of, such as Tm\textsuperscript{3+}, Er\textsuperscript{3+} and Ho\textsuperscript{3+} etc, have been investigated in depth (seeing [1]). However, UC emissions of Gd\textsuperscript{3+} have been rarely reported due to the large energy gap between the ground state \( ^8S_7/2 \) and the first excited state \( ^6P_{7/2} \) from Gd\textsuperscript{3+} served as host material ions though activator or sensitizer ions has been extensively exhibited and used \textsuperscript{[6-10]}. In recent years, the frequency UC phenomenon of Gd\textsuperscript{3+}, Er\textsuperscript{3+}, and Tm\textsuperscript{3+} has attracted much attention as a potential approach in searching for miniaturized short-wavelength solid-state lasers\textsuperscript{[11-13]}. In more recent

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years, Re-doped fluorides with various nanostructures have been purposefully prepared due to interesting optical properties, especially a series of luminescent nanomaterials based on NIR to UV UC processes of Tm$^{3+}$ and Gd$^{3+}$ have been depicted, moreover considerable efforts have been devoted to further improving the UC emission performances of these materials.$^{[14-16]}$

A previous investigation indicated that YF$_3$ was a good host material for NIR-to-visible UC emissions$^{[17]}$, so the article described how the orthorhombic nanocrystals of Y$_{0.800-x-y}$F$_3$: Yb$^{3+}$$_{0.200}$, Tm$^{3+}$$_x$, Gd$^{3+}$$_y$ were synthesized using a well-known hydrothermal method, the samples displayed bright blue light under 980 nm excitation after annealing. The purpose of this paper is to understand the enhanced UV emission phenomenon and the energy-transfer processes between Yb$^{3+}$-Tm$^{3+}$-Gd$^{3+}$ based on the energy matching conditions. After a brief analysis of UC emissions of Tm$^{3+}$ in Sec. 3.1, we will give a schematic energy-level diagram of Yb$^{3+}$ and Tm$^{3+}$ in Y$_{0.800-x}$F$_3$: Yb$_{0.020}$, Tm$_{y}$ nanocrystals annealed at 600 $^\circ$C, describing the upconverted multi-photon transition processes of Tm$^{3+}$ and the energy-transfer processes from Yb$^{3+}$ to Tm$^{3+}$ by following 980 nm excitation. It is identified that the enhanced UV UC emissions for Tm$^{3+}$ in the nanocrystals are originated from the effect of the nanodimension on its excited-state lifetimes. Consequently, an explicit energy-transfer cross-relaxation energy-transfer mechanism for the emissions of Gd$^{3+}$ based on frequency UC processes is suggested in section 3.2.

2. Experimental section

2.1 Synthesis and sample Preparation

The synthesis of Y$_{0.800-x,y}$F$_3$: Yb$^{3+}_{0.200}$, Tm$^{3+}_x$, Gd$^{3+}_y$ ($x=0.001, 0.002, 0.003, 0.005$; $y=0, 0.100, 0.200, 0.500$) nanocrystals was elaborated on a typical Y$_{0.595}$F$_3$: Yb$^{3+}_{0.200}$, Tm$^{3+}_{0.005}$, Gd$^{3+}_{0.200}$ nanocrystal preparation procedure. Firstly, the original materials were all analytical reagents, and
5.95 mmol Y₂O₃ (99.99%), 2 mmol Gd₂O₃ (99.99%), 2 mmol Yb₂O₃ (99.99%) and 0.05 mmol Tm₂O₃ (99.99%) were together dissolved in hydrochloric acid (HCl, 37%) at 60-70 °C to form clear solution (CS), then hydrofluoric acid (HF, 40%) was added dropwise into CS to obtain turbid solution while stirring with a magnetic force stirrer. After being continuously stirred for more than 0.5 h, the colloidal solution was achieved and transferred into two 50 mL Teflon-lined autoclaves in stainless steel kettle and treated at 130 °C for 12 h. After cooling to room temperature naturally, the upper clear solution was discarded and the remainder was isolated by centrifugation. The centrifugal remainder was washed with deionized water by centrifugation at least 3 times. After dried in vacuum at 60 °C for 6 h, the resulting white powder was obtained. However, the white powder had hardly UC emissions under 980-nm excitation. After annealing for 1 h under an Ar atmosphere at 600°C, the sample emitting bright blue luminescence and intense UV light was obtained under 980-nm-LD excitation.

2.2 Spectrum measurements

To observe the crystallization phase, XRD analysis was carried out with Rigaku RU-200b powder diffractometer using Ni-filtered CuKα radiation with λ=0.15406 nm. The size and the morphology were characterized by Hitachi S-4800 field-emission scanning-electron microscopy (FE-SEM). UC emission spectra were recorded with Hitachi F-4500 fluorescence spectrophotometer. The lifetime of Tm³⁺:¹D₂ state was taken with a Sunlite OPO from Continuum (Repeat frequency, 10 Hz; Pulse width, 6 ns), and Triax550 spectrometer from JY and TDS3052 oscillograph from Tektronix, respectively. All measurements were performed at room temperature.

3. Results and discussion

3.1 Enhanced near-violet upconversion emissions of Tm³⁺
Figure 1 shows upconverted emission spectra of Tm$^{3+}$ in $Y_{0.800-y}F_{3}:Yb_{0.200}^{3+}$, $Tm_x^{3+}$ nanocrystals. It can be noted that the strong UC emissions are observed in the UV region with increasing the $Tm^{3+}$-doped content though the blue luminescence peaks always exhibit in the all nanocrystal samples with $Y_{0.795-x}F_{3}:Yb_{0.020}^{3+}$, $Tm_{0.005}^{3+}$ as following the excitation at 980-nm laser diode (LD). What factor does result in the stronger UV emissions in the samples? Firstly, XRD pattern of the annealed $Y_{0.795}F_3$: $Yb_{0.020}^{3+}$, $Tm_{0.005}^{3+}$ nanocrystal sample was taken, as shown in the inset in Fig.1, which shows an orthorhombic YF$_3$ phase with the space group Pnma (62) comparing with the standard data of YF$_3$ crystal (JCPDS 74-0911).

![Figure 1](image_url)

**Fig. 1** Upconverted emission spectra of Tm$^{3+}$ in $Y_{0.800-y}F_{3}:Yb_{0.200}^{3+}$, $Tm_x^{3+}$ nanocrystals annealed at 600 °C, and the inset at the top right corner, XRD pattern and FE-SEM image of $Y_{0.795}F_3$: $Yb_{0.020}^{3+}$, $Tm_{0.005}^{3+}$ nanocrystals.

The right hand side of the inset exhibits the FE-SEM image of the sample. It is obvious that the samples are composed of getting together particles with an average size about 200 nm. Additionally, comparing the nanocrystal with the bulk sample with the same $Tm^{3+}$-doped content in Fig.2, there is no doubt that it is the nanodimension$^{[12,18-25]}$, but not the $Tm^{3+}$-doped content, plays an important role for the UC processes of populating $^1D_2$ and $^1I_6$ state. And further, the dependence of UC emission intensity on the $Tm^{3+}$-doped content is also viewed in Fig.3. The $^1G_4$ $\rightarrow^3H_6$ transition basically keeps unchanged, however, the $^1I_6 \rightarrow^3H_6$, $^1I_6 \rightarrow^3F_4$, $^1D_2 \rightarrow^3H_6$, and $^1D_2 \rightarrow^3F_4$ transition gradually becomes dominant with increasing the $Tm^{3+}$-content, respectively. It is conceivable that, in the nanocrystal samples, only the higher $Tm^{3+}$-doped content can make the...
population of the $^1I_6$ and $^1D_2$ state rise effectively.

**Fig. 2** Upconversed emission spectrum of $Y_{0.798}F_3:Yb_{0.020}^{3+}$, $Tm_{0.002}^{3+}$ nanocrystal annealed at 600 °C and $Y_{0.798}F_3:Yb_{0.020}^{3+}$, $Tm_{0.002}^{3+}$ bulk material, respectively.

**Fig. 3** Dependence of upconversed emission intensity on Tm$^{3+}$-doped content in $Y_{0.800-x}F_3:Yb_{0.020}^{3+}$, Tm$^{3+}$ (x=0.001, 0.002, 0.003, 0.005) nanocrystals, respectively.

As shown in Fig. 4, under the lower Tm$^{3+}$-doped content, populating the $^1G_4$ state need absorb three 980-nm photons, nevertheless the 4-photon and the 5-photon absorption processes are consonant with populating the $^1D_2$ and $^1I_6$ state because, as x=0.1, the interaction between Tm$^{3+}$ and Tm$^{3+}$ cannot be established, leading to the dominant $^1G_4\rightarrow^3H_6$ radiation transition based on the difference of the population efficiency at $^1G_4$, $^1D_2$ and $^1I_6$ state, respectively. With increasing the Tm$^{3+}$-doped content, the cross-relaxation processes become stronger due to smaller and smaller Tm$^{3+}$–Tm$^{3+}$ distance. Seeing the scheme in left-hand side of Fig. 4, by $^1G_4$ depopulating process with the $(^1G_4, ^3H_4)\rightarrow(^1D_2, ^3F_4)$ [26] or $(^3H_6, ^1G_4)\rightarrow(^1D_2, ^3F_4)$ [27] cross-relaxation process, the $^1D_2$ state is effectively populated, simultaneously $^1I_6$ level being populated, too, by means of resonantly absorbing a 980-nm photon. In this way, seeing Fig. 4 the cross-relaxation processes enable the $^1D_2$ state to be populated with the 3-photon process under 980-nm LD excitation which actually increases the population efficiency. In addition, the reasons why the $^1D_2$ state of Tm$^{3+}$ in
the higher Tm$^{3+}$-doped bulk sample is not able to be effectively populated would be the relatively shorter radiation lifetime of the $^1G_4$ state ($60-101$ μs with decreasing the Tm$^{3+}$-doped content in the bulk fluorides)$^{[28]}$, which suppresses the establishment with the $([^1G_4, ^3H_4]→[^1D_2, ^3F_4]$ or $[^1H_6, ^1G_4]→[^1D_2, ^3F_4]$ cross-relaxation process, resulting in an effective population at $^1G_4$ state being not able to be achieved all the while.

Fig.4 Level diagrams of Yb$^{3+}$ and Tm$^{3+}$ in Y$_{0.800-x}$F$_3$:Yb$_{0.020}$, Tm$_{0.002}$ nanocrystals annealed at 600 °C and schematic upconverted processes following 980 nm LD excitation. Schematic representation of the cross-relaxation processes populating the $^1D_2$ state with Tm$^{3+}$$^1$G$^4$, $^3H_4$→$^1D_2$, $^3F_4$) and $[^1H_6, ^1G_4]→[^1D_2, ^3F_4]$ in higher Tm$^{3+}$-doped nanocrystals.

3.2 Upconversion emissions of Gd$^{3+}$ following the excitation with 980 nm LD

As shown in the inset of Fig. 5, the XRD pattern of the annealed Y$_{0.595}$F$_3$:Yb$_{0.020}$, Tm$_{0.005}$, Gd$_{0.020}$ $^{3+}$ equally shows an orthorhombic YF$_3$ phase with the space group Pnma (62) comparing with the standard data of YF$_3$ crystal (JCPDS 74-0911) like the Y$_{0.798}$F$_3$:Yb$_{0.020}$, Tm$_{0.002}$ sample, and the FE-SEM image implies that the nanoparticles hold an average size less than 200 nm. The sample after annealing at 600 °C as shown in Fig.5 still displays bright blue luminescence (Due to $^1D_2→^3F_4$ and $^1G_4→^3H_6$ transition of Tm$^{3+}$) as following an excitation with 980 nm LD, in addition the enhanced UV emissions with Tm$^{3+}$ ($^3P_0$, $^1I_6→^3H_6$; $^3P_0$, $^1I_6→^3F_4$ and $^1D_2→^3H_6$) are also observed, in the same time the emissions of the both ranges in 270–281 nm and 300-320 nm coming from the $^6I_{J}→^8S_{7/2}$ and $^6P_{J}→^8S_{7/2}$ transitions of Gd$^{3+}$ are clearly obtained. Comparing Fig. 1 with Fig. 5, it is found that, for the two samples consisting of the equal Tm$^{3+}$-doped content, the
intensity of $^1I_6 \rightarrow ^3F_4$ radiation transition has the contrary changing trend. From Fig. 6, it is seen that, with increasing the Gd$^{3+}$-doped content, the Gd$^{3+}$ emissions have the enhancement phenomena and the $^1I_6 \rightarrow ^3H_6$ intensity of Tm$^{3+}$ decreases, too. Further considering the changing trend of Tm$^{3+}$ $^1I_6 \rightarrow ^3F_4$ radiation transition mentioned above, there is no denying that the shortened space between Gd$^{3+}$-Tm$^{3+}$ with increasing Gd$^{3+}$-doped content effectively improves the energy-transfer efficiency from Tm$^{3+}$ $^1I_6$ to Gd$^{3+}$ $^6I_J$ state.

Fig. 5 The upconversion emission spectrum in the both ranges of 270–281 nm and 300-320 nm comes from the $^6I_J \rightarrow ^8S_{7/2}$ and $^6P_J \rightarrow ^8S_{7/2}$ transitions of Gd$^{3+}$, respectively, in Y$_{0.595}$F$_3$: Yb$_{0.200}^{3+}$, Tm$_{0.005}^{3+}$, Gd$_{0.20}^{3+}$ nanocrystal and the inset at the top right corner, XRD pattern and FE-SEM image of the sample

To going a step further to explore the mechanism of the UC emissions in the nanocrystal samples, the temporal evolution of Tm$^{3+}$ and Gd$^{3+}$ luminescence in the nanocrystals is investigated and the lifetimes for the representative emissions (476 nm, 451 nm, 362 nm, 347 nm and 311 nm) from $^1G_4$ (Tm$^{3+}$), $^1D_2$ (Tm$^{3+}$) $^1I_6$ (Tm$^{3+}$) and $^6P_{7/2}$ (Gd$^{3+}$) are taken, and the decay curves can be fitted well with an exponential or biexponential function as $I = A_0 \exp(-t/\tau)$ and $I = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$, respectively. According to the best-fitted result as shown in Table 1, as $y = 0$, the time decay of the exponential processes is dominant due to the absence of an energy-transfer process from Tm$^{3+}$ to Gd$^{3+}$; as $y > 0$, the complex emission lifetimes are displayed. For $y=0.1$–0.5, the decay curves with Gd$^{3+}$ ($^6P_2 \rightarrow ^8S_{7/2}$) transition peaked at 311 nm can always be fitted well with a biexponential function implying that there must be two different luminescence centers, one of which is achieved by the energy transfer from $^1I_6$ to $^6I_J$ state, the another is attributed to the non-radiation relaxation process from the Gd$^{3+}$ $^6D_J$ state populated by the
interaction between Yb$^{3+}$ and Gd$^{3+}$. For the lifetimes of Tm$^{3+}$ at $y>0$, seeing Table 1, the lower Gd$^{3+}$-doped content, such as $y=0.1$, enable the Tm$^{3+}$-Tm$^{3+}$-pairs-lone center to maintain mainly, thus nothing is more satisfactory than to use an exponential fitting, and with increasing $x$ to 0.5, there are the two luminescence lifetimes peaked at 347 nm, and the lifetime of the 362 nm emission become single exponential, which means an energy-back transfer from $^6D_1$ to $^3P_2$ state and the Tm$^{3+}$-Tm$^{3+}$-pair-lone center disappears due to a higher Gd$^{3+}$-doped content. As seen in Table 1, The two lifetimes at $y=0.2$ can fully prove that there must be the both the Tm$^{3+}$-Gd$^{3+}$-pairs and Tm$^{3+}$-Tm$^{3+}$-pairs luminescence centers under the medial Gd$^{3+}$-doped content. All the time, the single luminescence lifetimes peaked at 467-nm can indicate that the $^1G_4$ state is not concerned with the interaction processes between Tm$^{3+}$ and Gd$^{3+}$. In a word, comparing with the lifetime in bulk materials$^{[20, 21]}$ the $^6P_{7/2}$ state in the nanocrystals has a relatively short lifetime, which leads to accepting the migrated energy from Tm$^{3+}$ effectively, contrarily, $^1G_4$ and $^1D_2$ state shows a long that, respectively, which can ensure the valid population of the upper $^1I_6$ level in the nanocrystals.

So, it can be suggested that, by the effects of the nanodimension on the lifetimes from the both Tm$^{3+}$ and Gd$^{3+}$ excited states, the enhanced UC UV emissions of Tm$^{3+}$ is induced, promoting the energy-transfer processes from Yb$^{3+}$ to Tm$^{3+}$ to Gd$^{3+}$ and resulting in the emissions of Gd$^{3+}$.

<table>
<thead>
<tr>
<th>Peak value nm</th>
<th>Table 1. Luminescence lifetimes of Gd$^{3+}$ and Tm$^{3+}$ states in Y$<em>{0.795}$Yb$</em>{0.2}$Tm$_{0.005}$GdyF$_3$ (y = 0, 0.1, 0.2, 0.5) nanocrystals</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>311(Gd$^{3+}$:P$<em>{1}^{6}S</em>{7/2}$)</td>
<td>$A_1=0.860 \quad \tau_1=7808$</td>
<td>$A_1=0.967 \quad \tau_1=604$</td>
<td>$A_1=0.549 \quad \tau_1=1745$</td>
<td></td>
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</tr>
<tr>
<td>347(Tm$^{3+}$:1$F_{5}$)</td>
<td>141</td>
<td>179</td>
<td>3519</td>
<td>651</td>
<td></td>
</tr>
<tr>
<td>362(Tm$^{3+}$:D$<em>{2}^{3}H</em>{6}$)</td>
<td>184</td>
<td>255</td>
<td>395</td>
<td>1042</td>
<td></td>
</tr>
<tr>
<td>451(Tm$^{3+}$:D$<em>{2}^{3}F</em>{4}$)</td>
<td>$A_1=0.893 \quad \tau_1=477$</td>
<td>$A_2=0.099 \quad \tau_2=1333$</td>
<td></td>
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<tr>
<td>476(Tm$^{3+}$:G$<em>{2}^{3}H</em>{6}$)</td>
<td>555</td>
<td>615</td>
<td>668</td>
<td></td>
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</tr>
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</table>

To visually describe the energy-transfer processes from Yb$^{3+}$ to Tm$^{3+}$ to Gd$^{3+}$ very well, an
energy-level schemes of Gd\(^{3+}\), Yb\(^{3+}\), Tm\(^{3+}\) and the processes of UC excitation and emissions are set up, as shown in Fig. 7. From Fig. 7, it is apparent that, following the excitation with 980 nm, the five-photon processes is necessary to populate the \(^3P_2\) or \(^1I_6\) level of Tm\(^{3+}\), and so it is sure that population of \(^6I_j\) and \(^6P_j\) levels of Gd\(^{3+}\) in the samples is achieved by the energy-transfer processes from \((^3P_2, ^1I_6)\) to \((^6I_j, ^6P_j)\) levels, that is, the efficient UC emissions of Gd\(^{3+}\) strongly depends on the population of \(^1I_6\) state. It is sure that the lifetime \(^1G_4\) and \(^1D_2\) state plays a uniquely important role in the efficient energy transfer processes. In fact, the nanocrystal radii is greater than the half wavelengths of the both \(^1D_2\rightarrow^3F_4\) and \(^1G_4\rightarrow^3H_6\) radiation transitions, which makes the transition rates decrease rapidly\(^{[23]}\), leading to more efficient population at \(^1D_2\), \(^1I_6\) and \(^6I_J\) level, respectively. The obtained emission spectra are a direct proof of the validity for the explanation. The both nanocrystal dimension and Tm\(^{3+}\)-doped content have valuable effects on the upconversion emissions of Gd\(^{3+}\). With the increasing Tm\(^{3+}\) content, the distance between Tm\(^{3+}\)–Tm\(^{3+}\) shortens more and more, making Tm\(^{3+}\)–Tm\(^{3+}\) interaction stronger, cross-relaxation process becomes much easier, spontaneously Tm\(^{3+}\)–Gd\(^{3+}\) distance becomes shorter and energy transfer from Tm\(^{3+}\) \(^1I_6\) to Gd\(^{3+}\) \(^6I_J\) state occurs easily, too, assuring the cross-relaxation and energy-transfer processes more effective, which results in the UV emission enhancement of Tm\(^{3+}\) and the upconversion emission of Gd\(^{3+}\).

![Fig. 6 Upconverted emission spectra of Gd\(^{3+}\) from Y\(_{0.795}\)\(_{0.200}\)\(_{0.500}\)\(_{0.100}\) F\(_3\):Yb\(_{0.200}\)\(_{0.500}\)\(_{0.100}\)\(_{0.500}\) nanocrystals annealed at 600 °C](image-url)
Fig. 7  Energy-level diagrams of Gd$^{3+}$, Yb$^{3+}$ and Tm$^{3+}$ and schematic processes of energy transfer from Yb$^{3+}$ to Tm$^{3+}$ to Gd$^{3+}$, cross relaxation, upconversion transitions and emissions

4. Conclusions

The experiments show that the $Y_{0.800-x}F_{3}:Yb_{0.200}^{3+}, Tm_{x}^{3+}$ and $Y_{0.745}F_{3}: Yb_{0.200}^{3+}, Tm_{0.005}^{3+}$, Gd$_{0.050}^{3+}$ nanocrystal samples can be synthesized by a hydrothermal method. The nanodimension may make the lifetimes of Tm$^{3+}$ excited states become longer, resulting in the increase of the multiphoton UC transition efficiency and the intense UV-UC emissions as following 980-nm-LD excitation in the nanodimension samples. Based on the spectroscopic analysis for the nanocrystal samples, the enhanced mechanism of the multiphoton UC transitions are suggested as following the near-infrared-980-nm-LD excitation in the nanocrystal samples. The experimental results could provide a novel approach for searching for efficient NIR-to-UV short-wavelength emission materials. Therefore, it is possible that the nanocrystal materials could be applied to fabricate miniaturized UV-lasing solid-state devices with the UC processes.

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