Electronic Supplementary information

White upconversion luminescence power and efficiency in 
Yb$^{3+}$-, Er$^{3+}$- and Tm$^{3+}$-doped BaIn$_6$Y$_2$O$_{13}$


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Fig.S1 Schematic of the experimental setup for UC efficiency measurements.

The setup used to acquire the emitted visible light power for the phosphors is pictured in Fig.1. The excitation source used for UC was a 971 nm controlled temperature CW semiconductor diode laser with $P_{\text{max}}=3\text{W}$. The diode was coupled to a fiber (the core diameter 200 μm, numerical aperture 0.22). The power density was calculated based on the divergence of laser light (45°) and distance between the sample and laser (1mm). The laser spot radius was equal to the distance between the sample and laser multiplied by 0.22 (manufacturer provided), so the power density can be expressed as:

$$P_s = \frac{P_{\text{LD}}}{S_{\text{ex}}} = \frac{P_{\text{LD}}}{\pi R^2} \times \sin 45° \quad (1)$$

where $P_s$ is the power density, $P_{\text{LD}}$ and $S_{\text{ex}}$ are the emitted power of LD and excitation area, respectively, and $R$ is the laser spot radius.

The copper sample holder in the middle of the integrating sphere was excited by LD. After multiple reflections of the integrating sphere, the emitted UC light was collected using an optical
fiber then analyzed with a spectrometer (380-800nm) and a relative luminance meter. The excitation powers $P_{LD}$ under different currents were measured by LP-3A power meter (Physcience Opto-Electronics Co., Beijing, China). After initial alignment of the setup, efficiency was obtained in two steps. For the first measurement, the copper sample holder in the integrating sphere was left empty (no sample inside), and the laser spectrum was obtained by a spectrometer. From this step, we got the integrated intensity ($I_{inc}$ integrated over the 950-1000 nm). For the second measurement, the copper sample holder in the integrating sphere was filled with sample. From this step, we got the UC emission power ($P_{em}$ integrated over the 380-800 nm) and integrated intensity ($I_{inc}$ integrated over the 950-1000 nm). Finally, the UC efficiency was calculated as the ratio of the luminescence power emitted by sample over the power absorbed in the infrared (950-1000 nm range):

$$\eta_O = \frac{P_{em}}{P_{LD}} \quad (2) \quad \gamma_{ab} = \frac{I_{inc} - I_{unabs}}{I_{inc}} \quad (3) \quad \eta_{UC} = \frac{P_{em}}{P_{abs}} = \frac{P_{em}}{P_{LD}} \frac{I_{inc} - I_{unabs}}{I_{inc}} = \frac{\eta_O}{\gamma_{ab}} \quad (4)$$

Where $\eta_O$ is the absolute efficiency, $\eta_{UC}$ is the extremum efficiency, $\gamma_{ab}$ is the absorption rate.

![Fig.S2](image_url) (a) The emission powers of BaIn$_6$Y$_2$O$_{13}$:xYb$^{3+}$, zTm$^{3+}$ phosphors under different excitation densities. (b) The relationship between the absolute efficiencies and excitation densities of BaIn$_6$Y$_2$O$_{13}$:xYb$^{3+}$, zTm$^{3+}$. 
Fig. S3 (a) The emission powers of BaIn$_6$Y$_2$O$_{13}$:xYb$^{3+}$, yEr$^{3+}$ phosphors under different excitation densities. (b) The relationship between the absolute efficiencies and excitation densities of BaIn$_6$Y$_2$O$_{13}$:xYb$^{3+}$, yEr$^{3+}$. The emission powers are plotted against the excitation density (W/cm$^2$) for different values of x and y. The efficiencies are also shown for the same excitation densities. The inset in (a) shows the excitation spectra for different concentrations of Yb$^{3+}$ and Er$^{3+}$. The inset in (b) shows the emission spectra for different excitation densities.
Fig. S4. The UC emission spectra (a), emission intensity(b) of $I_R$, $I_G$ and $I_B$, Intensity distributions and (c) of $I_R/I_{B+G+R}$, $I_G/I_{B+G+R}$ and $I_B/I_{B+G+R}$ of white emitting BaIn$_6$Y$_2$O$_{13}$: 10% Yb$^{3+}$, 1% Er$^{3+}$, 1% Tm$^{3+}$ for different excitation densities (1: 2.62 w/cm$^2$, 2: 7.70 w/cm$^2$, 3: 13.24 w/cm$^2$, 4: 18.77 w/cm$^2$, 5: 26.52 w/cm$^2$, 6: 33.53 w/cm$^2$, 7: 41.28 w/cm$^2$) under 971 nm excitation.
Fig.S5 The UCL spectra (a), Intensity distributions (b) of $I_B/I_{(B+G+R)}$, $I_G/I_{(B+G+R)}$ and $I_B/I_{(B+G+R)}$ and CIE chromaticity diagram (c) of white emitting BaIn$_6$Y$_2$O$_{13}$: 10%Yb$^{3+}$,0.5% Er$^{3+}$, 1%Tm$^{3+}$ for different excitation densities (1:7.78 w/cm$^2$, 2:13.23 w/cm$^2$, 3:23.89 w/cm$^2$, 4:29.83 w/cm$^2$, 5: 37.22 w/cm$^2$) under 971 nm excitation.
Fig. S6 The relationship between the absolute efficiency and excitation density of the tri-doped materials: 
$\text{BaIn}_6\text{Y}_2\text{O}_{13}:x\text{Yb}^{3+}, y\text{Er}^{3+}, z\text{Tm}^{3+}$.

Fig. S7 The relationship between the absolute efficiency and excitation density of the Biphasic materials: 
$\text{BaIn}_6\text{Y}_2\text{O}_{13}:\text{Yb}^{3+}, \text{Tm}^{3+} (m_1) + \text{BaIn}_6\text{Y}_2\text{O}_{13}:\text{Yb}^{3+}, \text{Er}^{3+} (m_2)$, the $m_1/m_2$ is equal to 20/1, 10/1 and 5/1, respectively.
Tri-doped BaIn$_6$Y$_2$O$_{13}$:Yb$^{3+}$, Er$^{3+}$, Tm$^{3+}$

The biphasic materials (m$_1$/m$_2$)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Tri-doped BaIn$_6$Y$<em>2$O$</em>{13}$:Yb$^{3+}$, Er$^{3+}$, Tm$^{3+}$</th>
<th>The biphasic materials (m$_1$/m$_2$)</th>
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<tbody>
<tr>
<td></td>
<td>10%,0.2%,1%</td>
<td>10%,0.5%,1%</td>
</tr>
<tr>
<td></td>
<td>10%,1%,1%</td>
<td>5/1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10/1</td>
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<td>0.27</td>
<td>0.38</td>
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Table S1. The UC absolute efficiency, absorption rate and extremum efficiency of the tri-doped and biphasic BaIn$_6$Y$_2$O$_{13}$ samples.

<table>
<thead>
<tr>
<th>Host</th>
<th>Dopants</th>
<th>Excitation conditions</th>
<th>CIE color coord</th>
<th>$\eta_{UC}$ (%)</th>
</tr>
</thead>
</table>
| Lu$_2$Ga$_5$O$_{12}$ nanocrystals$^{14}$ | Yb$^{3+}$ Er$^{3+}$ Tm$^{3+}$ | 980 nm cw laser (down to 34 mW/mm$^2$) | x = 0.270  
y = 0.338 | 0.1             |
| Y$_2$O$_3$ nanocrystals$^{32}$ | Yb$^{3+}$ Er$^{3+}$ Tm$^{3+}$ | 976 nm cw laser (down to 100 mW/mm$^2$) | x = 0.320  
y = 0.340 |                 |
| Transparent oxy-fluoride glass ceramic embedded with YF$_3$ nanocrystals$^{10}$ | Yb$^{3+}$ Er$^{3+}$ Tm$^{3+}$ | 976 nm pulsed laser (2 ps, 15 nJ, 2 W/mm$^2$) | x = 0.310  
y = 0.359 |                 |
| Y$_2$BaZnO$_5$ phosphors$^{12}$ | Yb$^{3+}$ Er$^{3+}$ Tm$^{3+}$ | 977 nm cw laser (down to 25 mW/mm$^2$) | x = 0.299  
y = 0.298 | 0.3             |
|                         | biphasic                 | 977 nm cw laser (down to 90 mW/mm$^2$) | x = 0.306  
y = 0.313 |                 |
| BaIn$_6$Y$_2$O$_{13}$ phosphors | Yb$^{3+}$ Er$^{3+}$ Tm$^{3+}$ | 971 nm cw laser (down to 22.46 W/cm$^2$) | x = 0.335  
y = 0.336 | 0.24            |
|                         | biphasic                 | 971 nm cw laser (down to 26.12 W/cm$^2$) | x = 0.330  
y = 0.313 | 0.38            |

Table S2. Compositions, excitation conditions, color coordinates and UC efficiencies of white light emitting materials reported in the literature.
Fig.S8 Intensity distributions of $I_B/I_{(B+G+R)}$, $I_G/I_{(B+G+R)}$ and $I_R/I_{(B+G+R)}$ in the $\text{BaIn}_6\text{Y}_2\text{O}_{13}$:Yb$^{3+}$ (10%), Er$^{3+}$ (0.2%), Tm$^{3+}$ (1%) phosphors on increasing the measured temperature.

Fig.S9 Intensity distributions of $I_B/I_{(B+G+R)}$, $I_G/I_{(B+G+R)}$ and $I_R/I_{(B+G+R)}$ in the $\text{BaIn}_6\text{Y}_2\text{O}_{13}$:Yb$^{3+}$ (10%), Tm$^{3+}$ (1%) (90.9% w/w) + $\text{BaIn}_6\text{Y}_2\text{O}_{13}$:Yb$^{3+}$ (10%), Er$^{3+}$ (5%) (9.1% w/w) powders on increasing the measured temperature.