Electronic Supplementary Information

Low power density 980 nm-driven ultrabright red-emitting upconversion nanoparticles via synergetic Yb\(^{3+}/\)Tm\(^{3+}\) cascade-sensitization

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Fig. S1 TEM images: (A) NaErF\(_4\):Yb(98%); (B) NaErF\(_4\):Yb(85%); (C) NaErF\(_4\):Yb(60%). (D-F): Corresponding NaErF\(_4\):Yb@NaLuF\(_4\) core/shell structured UCNPs.
Fig. S2 Powder X-ray diffraction patterns: (A) NaErF₄:Yb(98, 85, 70, 60%), NaErF₄:Yb(98%)@NaLuF₄ (~2.5 nm), NaErF₄:Yb/Tm(19/1%) and standard β-NaYF₄ (JCPDS 16-0334); (B) NaLuF₄ coated NaErF₄:Tm(0.5%) and NaErF₄:Yb/Tm(69/1%) with different shell thickness. Fast Fourier transform (C) and high angle annular dark field scanning transmission electron microscopy (D) images of the as-prepared β-NaErF₄:Tm(0.5%)@NaLuF₄, supporting the formation of core/shell structured β-UCNPs.

Fig. S3 Decay curves of \(^{4}S_{3/2}(Er^{3+})\) at 540 nm for core/shell structured NaErF₄:Yb(70%)@NaLuF₄ with different shell thickness (~2.5 nm, ~4 nm) under excitation at 980 nm.
**Fig. S4** TEM images: (A) NaErF₄:Yb/Tm(89/1%); (B) NaErF₄:Yb/Tm(79/1%); (C) NaErF₄:Yb/Tm(69/1%); (D) NaErF₄:Yb/Tm(59/1%); (E) NaErF₄:Yb/Tm(19/1%); (F) NaErF₄:Tm(0.5%). Corresponding NaErF₄:Yb/Tm@NaLuF₄ (G-K) and NaErF₄:Tm(0.5%)@NaLuF₄ (L) core/shell structured UCNPs.

**Fig. S5** TEM images: (A) NaYbF₄:Tm(1%) and (B) NaYbF₄:Tm(1%)@NaLuF₄ UCNPs. (C) Upconversion emission spectrum of NaYbF₄:Tm(1%)@NaLuF₄ UCNPs under excitation at 980 nm (0.2 W cm⁻²).

**Fig. S6** Power dependence characteristics of Er³⁺ emissions at 540 and 654 nm in NaYF₄:Yb/Er(20/2%)@NaLuF₄ under excitation at 980 nm.
**Fig. S7** TEM images: (A-B) NaErF₄:Yb/Tm(69/1%) with ~4 nm and ~6 nm NaLuF₄ shell. (C-D) NaErF₄:Tm(0.5%) with ~4 nm and ~6 nm NaLuF₄ shell.

**Fig. S8** Upconversion emission spectra of NaErF₄:Tm(0.5%) with 6 nm NaLuF₄ shell under 980 nm excitation.

**Fig. S9** Experimental setup for the *in vitro* penetration simulation model.
Fig. S10  Upconversion emission spectra of NaLuF$_4$ coated NaErF$_4$:Yb (98%) and NaYF$_4$:Yb/Er(20/2%) UCNPs.