Electronic Supplementary information

White upconversion luminescence power and efficiency in Yb^{3+}-, Er^{3+}- and Tm^{3+}-doped $BaIn_6Y_2O_{13}$

Jiao Zhang[a], Yanmin Yang[a]*, Chao Mi[a], Yanzhou Liu[a], Fang Yu[a], Xiaohong Li[a], Yaohua Mai[a]*

[a] *College Hebei Key Lab of Optic-electronic Information and Materials, College of Physics Science and Technology, Hebei University, Baoding 071002, PR China*

E-mail: mihuyym@163.com .and yaohuamai@163.cm

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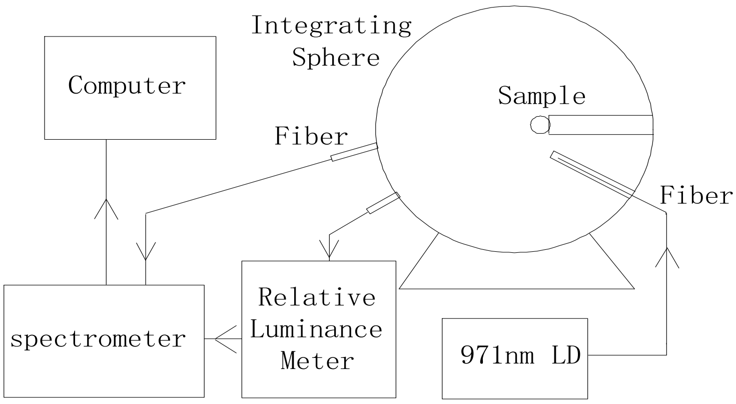


Fig.S1 Schematic of the experimental setup for UC efficiency measurements.

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_{max}=3W. 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:

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

where P_s is the power density, P_{LD} and S_{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_{unabs} 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):

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

Where η_O is the absolute efficiency, η_{UC} is the extremum efficiency, γ_{ab} is the absorption rate.

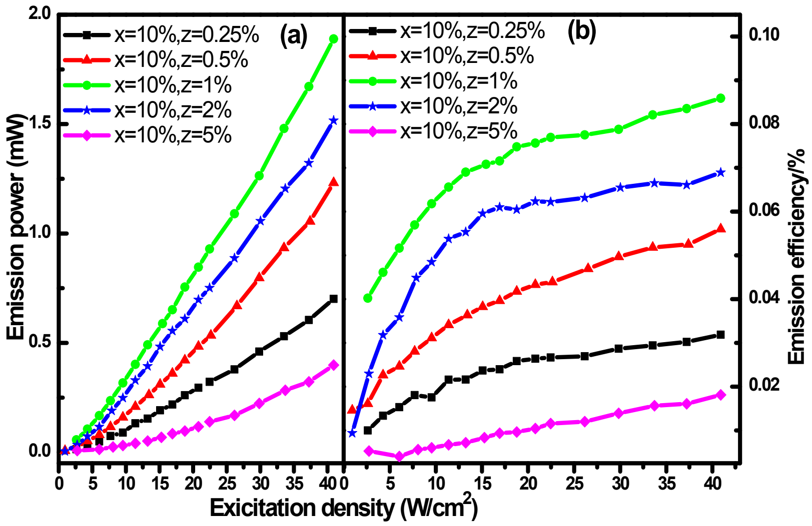


Fig.S2 (a) The emission powers of $BaIn_6Y_2O_{13}$:xYb^{3+}, zTm^{3+} phosphors under different excitation densities. (b) The relationship between the absolute efficiencies and excitation densities of $BaIn_6Y_2O_{13}$:xYb^{3+}, zTm^{3+}.

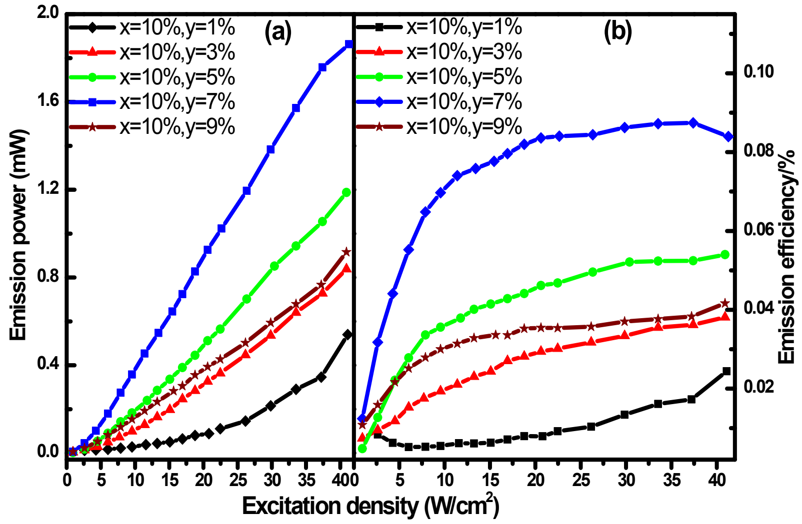
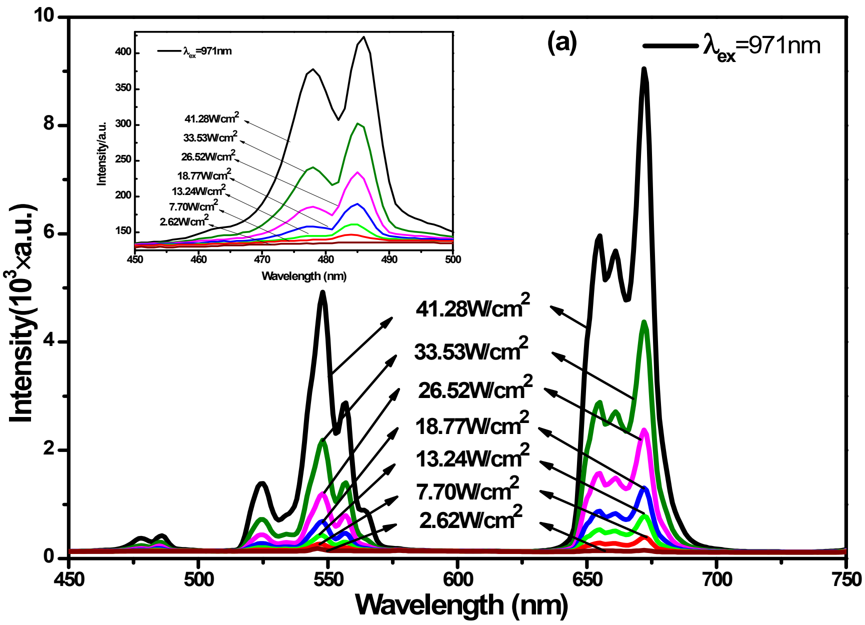


Fig.S3 (a) The emission powers of $BaIn_6Y_2O_{13}$:xYb^{3+}, yEr^{3+} phosphors under different excitation densities. (b) The relationship between the absolute efficiencies and excitation densities of $BaIn_6Y_2O_{13}$:xYb^{3+}, yEr^{3+}.



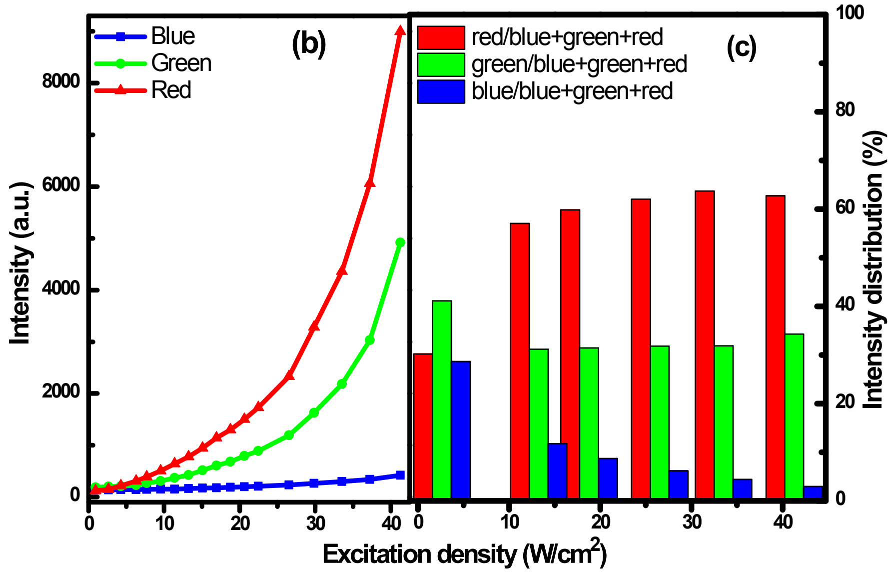
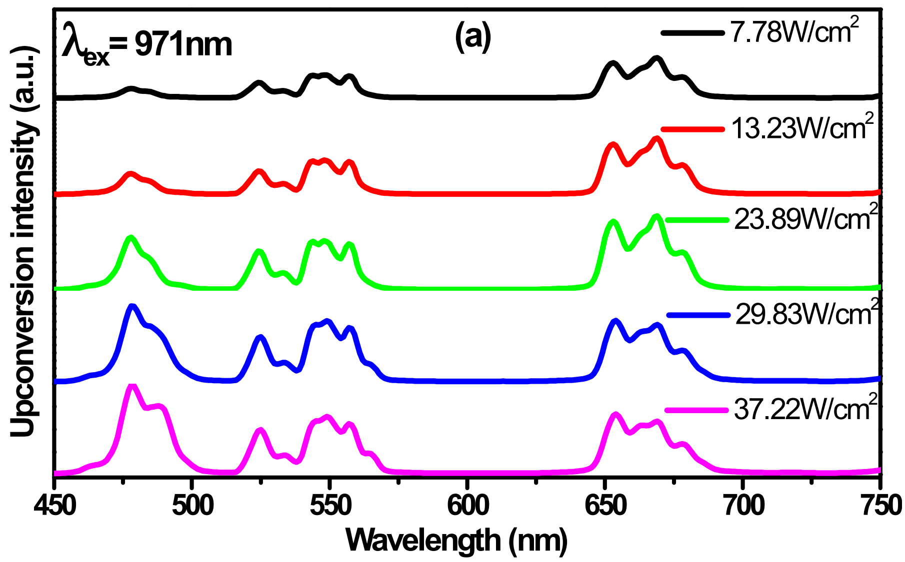


Fig.S4. The UC emission spectra (a), emission intensity(b) of I_R, I_G and I_B , Intensity distributions and (c) of $I_R/I_{(B+G+R)}$, $I_G/I_{(B+G+R)}$ and $I_B/I_{(B+G+R)}$ of white emitting $BaIn_6Y_2O_{13}$: 10% Yb^{3+}, 1% Er^{3+}, 1% Tm^{3+} for different excitation densities (1:2.62 w/cm^2, 2: 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.



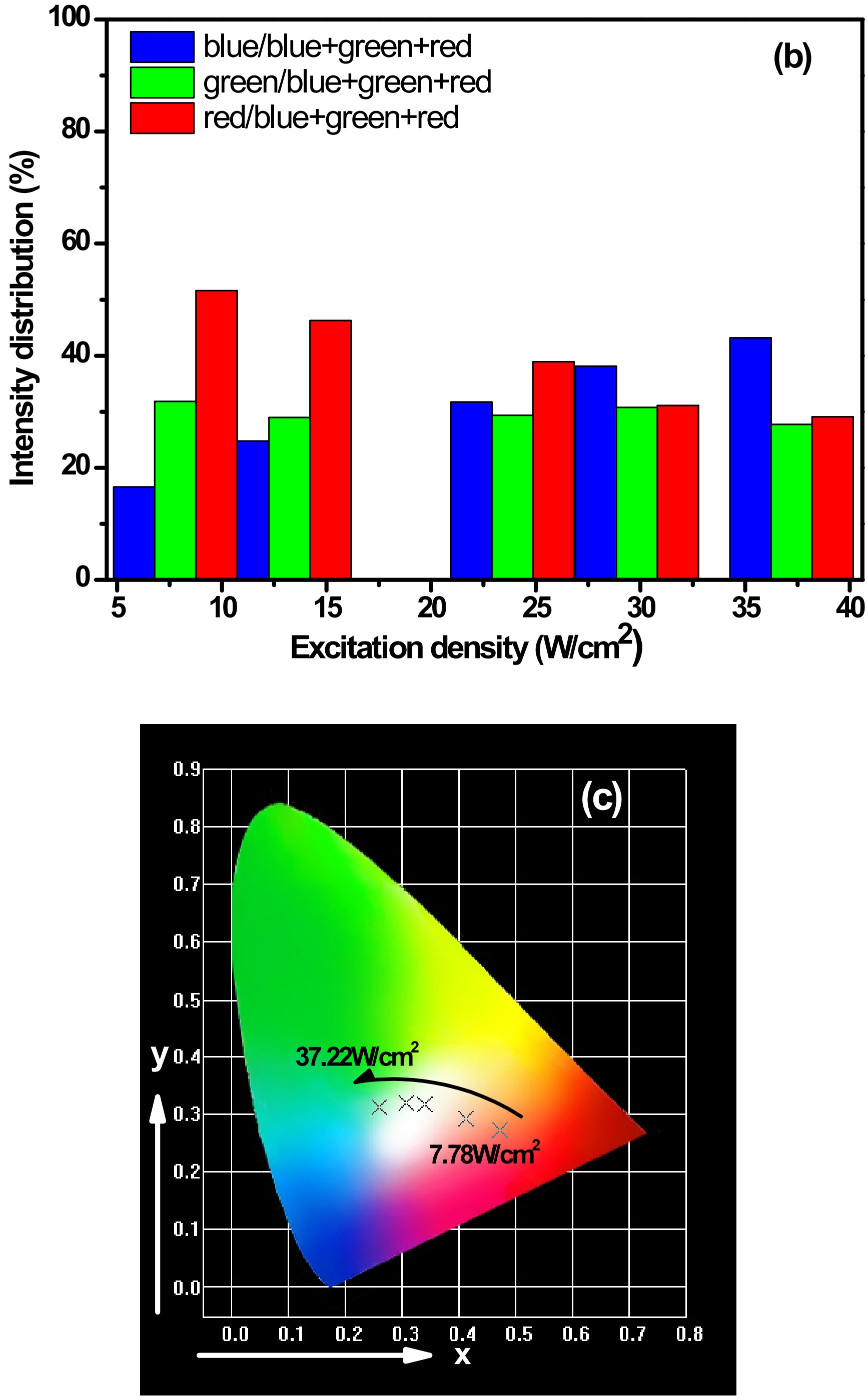


Fig.S5 The UCL spectra (a), Intensity distributions (b) of $I_R/I_{(B+G+R)}$, $I_G/I_{(B+G+R)}$ and $I_B/I_{(B+G+R)}$ and CIE chromaticity diagram (c) of white emitting $BaIn_6Y_2O_{13}$: 10%Yb^{3+},0.5% Er^{3+}, 1%Tm^{3+} for different excitation densities (1:7.78 w/cm^2, 2:13.23 w/cm^2, 3:23.89 w/cm^2, 4:29.83 w/cm^2, 5: 37.22 w/cm^2) under 971 nm excitation.

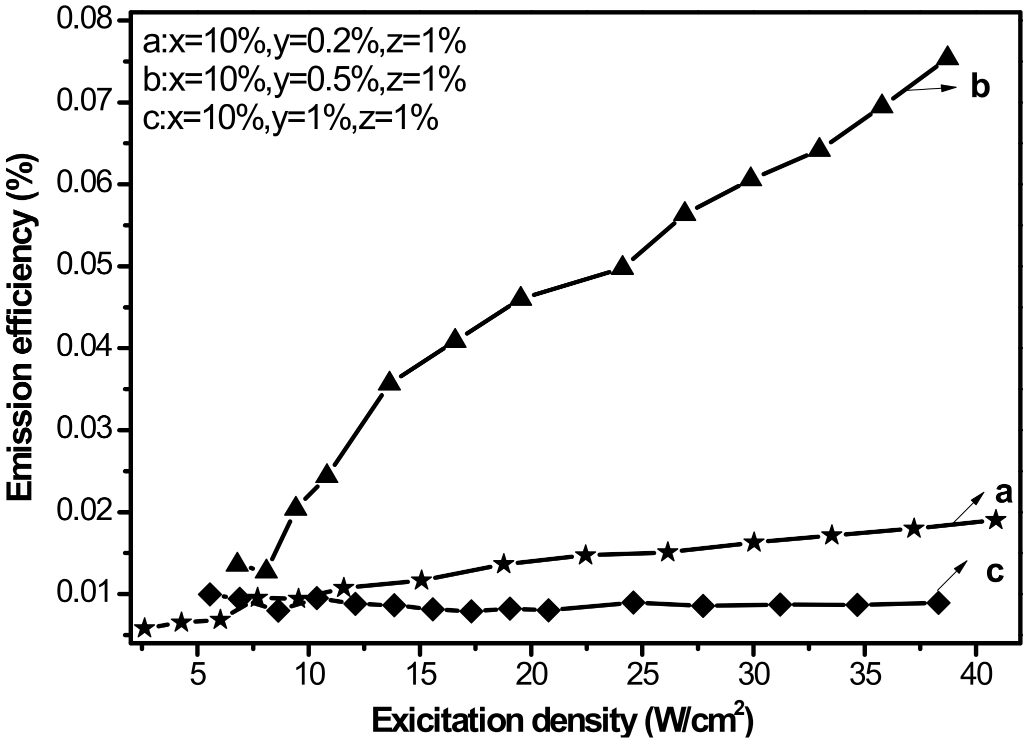


Fig.S6 The relationship between the absolute efficiency and excitation density of the tri-doped materials: $BaIn_6Y_2O_{13}$: xYb^{3+}, yEr^{3+}, zTm^{3+}.

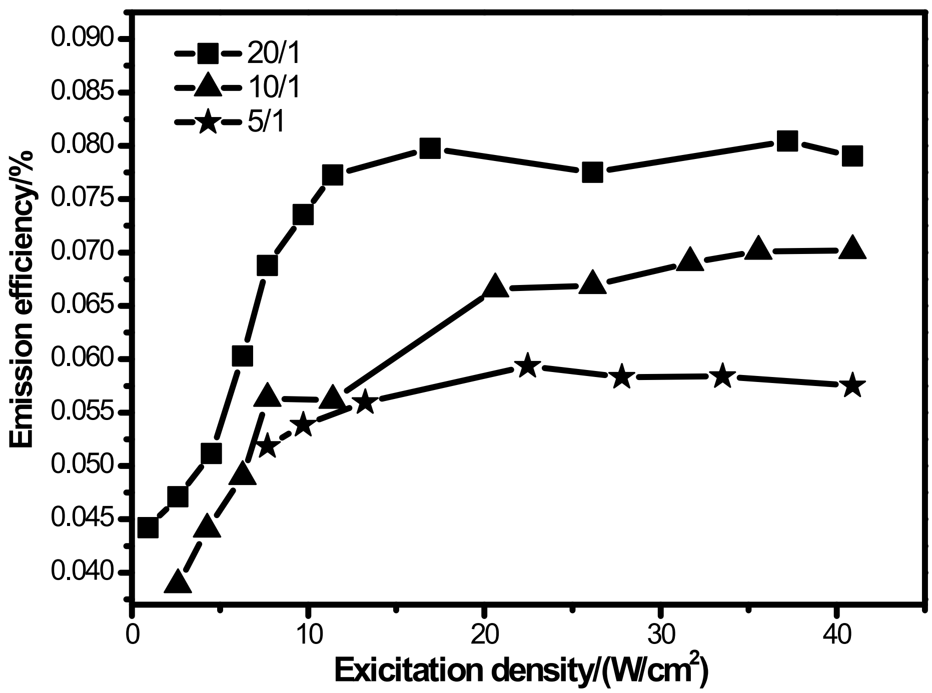


Fig.S7 The relationship between the absolute efficiency and excitation density of the Biphasic materials: $BaIn_6Y_2O_{13}$:Yb^{3+}, Tm^{3+} (m_1) + $BaIn_6Y_2O_{13}$:Yb^{3+}, Er^{3+} (m_2), the m_1/m_2 is equal to 20/1, 10/1 and 5/1, respectively.

Samples	Tri-doped $BaIn_6Y_2O_{13}$:Yb^{3+}, Er^{3+}, Tm^{3+}			The biphasic materials (m_1/m_2)		
	10%,0.2%,1%	**10%,0.5%,1%**	**10%,1%,1%**	**5/1**	**10/1**	**20/1**
η_O /%	0.02	0.05	0.009	0.05	0.07	0.08
γ_{ab} /%	20.4	20.7	18.8	22.3	26.4	21.2
η_{UC} /%	0.10	0.24	0.05	0.22	0.27	0.38

Table S1. The UC absolute efficiency, absorption rate and extremum efficiency of the tri-doped and biphasic $BaIn_6Y_2O_{13}$ samples.

Host [ref]	Dopants	Excitation conditions	CIE color coord	η UC(%)
$Lu_3Ga_5O_{12}$ nanocrystals[14]	Yb^{3+} Er^{3+} Tm^{3+}	980nm cw laser (down to 34 mW/mm^2)	x = 0.270 y = 0.338	0.1
Y_2O_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_3nanocrystals[40]	Yb^{3+} Er^{3+} Tm^{3+}	976nm pulsed laser(2 ps, 15 nJ, $2W/mm^2$)	x = 0.310 y = 0.359	
Y_2BaZnO_5 phosphors[12]	Yb^{3+} Er^{3+} Tm^{3+}	977nm cw laser (down to 25 mW/mm^2)	x = 0.299 y = 0.298	0.3
	biphasic	977nm cw laser (down to 90 mW/mm^2)	x = 0.306 y = 0.313	
$BaIn_6Y_2O_{13}$ 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.

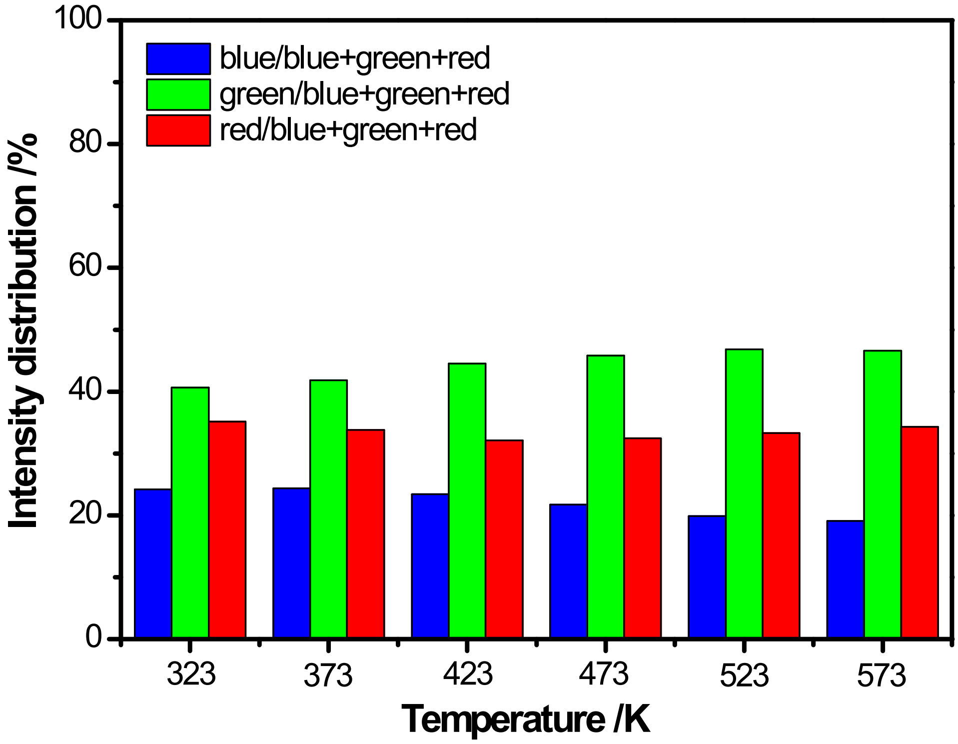


Fig.S8 Intensity distributions of $I_B/I_{(B+G+R)}$, $I_G/I_{(B+G+R)}$ and $I_R/I_{(B+G+R)}$ in the $BaIn_6Y_2O_{13}$ Yb^{3+}(10%), Er^{3+}(0.2%), Tm^{3+}(1%) phosphors on increasing the measured temperature.

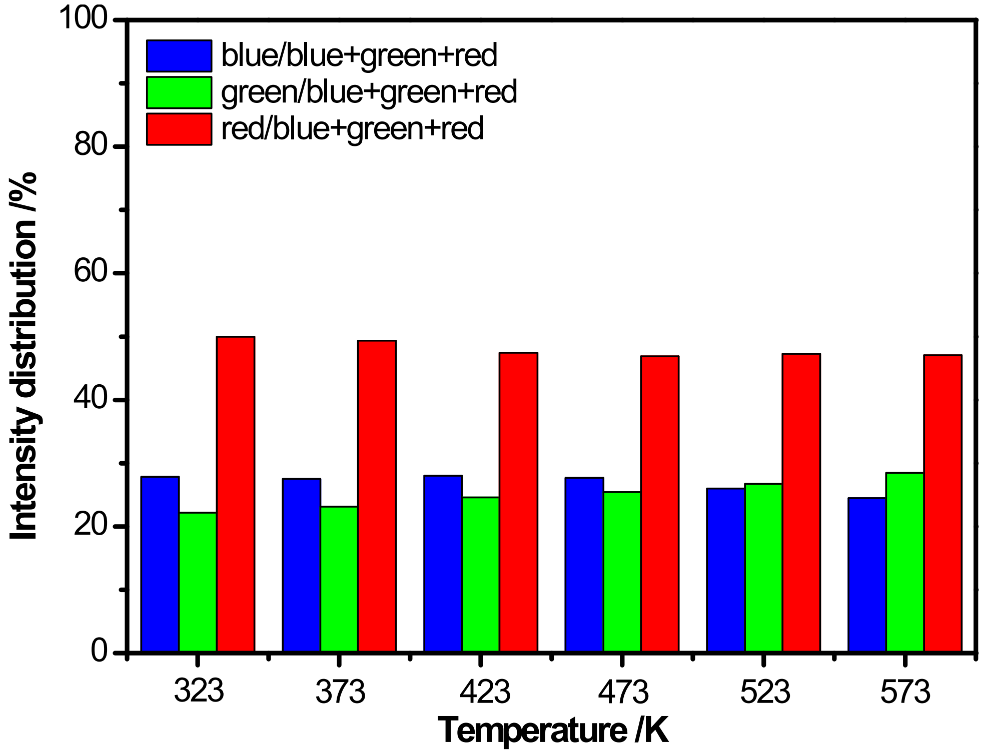


Fig.S9 Intensity distributions of $I_B/I_{(B+G+R)}$, $I_G/I_{(B+G+R)}$ and $I_R/I_{(B+G+R)}$ in the $BaIn_6Y_2O_{13}$:Yb^{3+} (10%), Tm^{3+} (1%) (90.9% w/w) + $BaIn_6Y_2O_{13}$:Yb^{3+} (10%), Er^{3+} (5%) (9.1% w/w) powders on increasing the measured temperature.