Supporting information

Excellent cryogenic optical thermometry of green up-conversion in Ho^{3+}-doped perovskite $Na_{0.5}Bi_{0.5}TiO_3$ ceramics

Yuzhen Wang[1], Yanan Wang[1,3], Chaoyang Ma[2,*], Zhe Feng[1], Chuandong Zuo[1], Wanggui Ye[1], Chong Zhao[1], Yanbin Li[1], Zicheng Wen[2,4], Zhiquan Cao[5], Zhijun Cao[6], Xiaofei Shen[2], Chong Wang[2], Yingkui Li[2], Xuanyi Yuan[1], Yongge Cao[2,4,*]

[1] Department of Physics, Renmin University of China, Beijing, 100872, China

[2] Songshan Lake Materials Laboratory, Dongguan, Guangdong, 523808, China

[3] Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

[4] Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

[5] New York University, New York, NY 10003, USA

[6] University of Virginia, Charlottesville, VA 22904, USA

* Corresponding authors: machaoyang@sslab.org.cn

caoyongge@sslab.org.cn

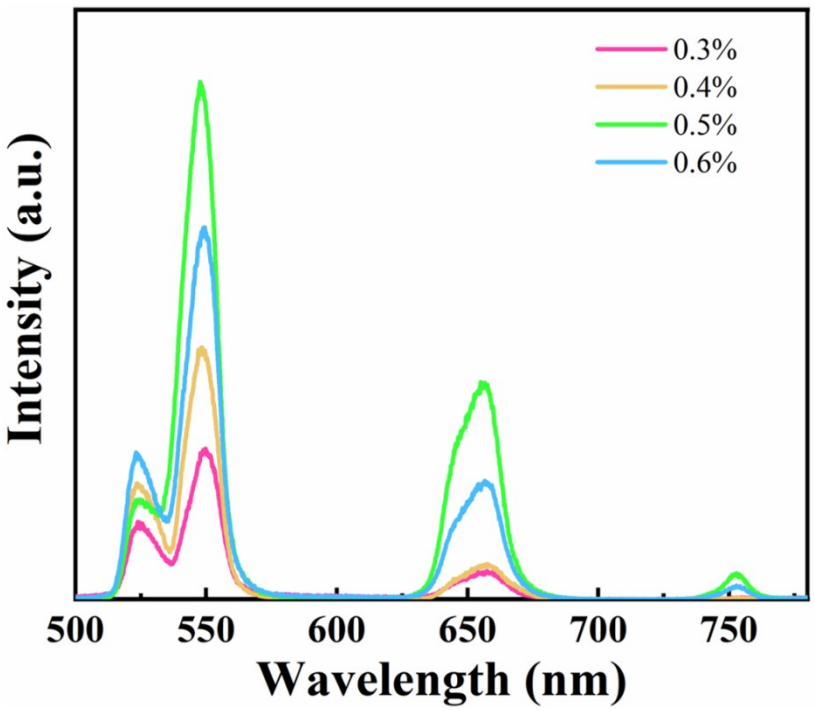

Fig. S1 UCPL of $Na_{0.5}Bi_{0.5}TiO_3$: *x* at% Ho (*x*=0.3, 0.4, 0.5, 0.6) samples.

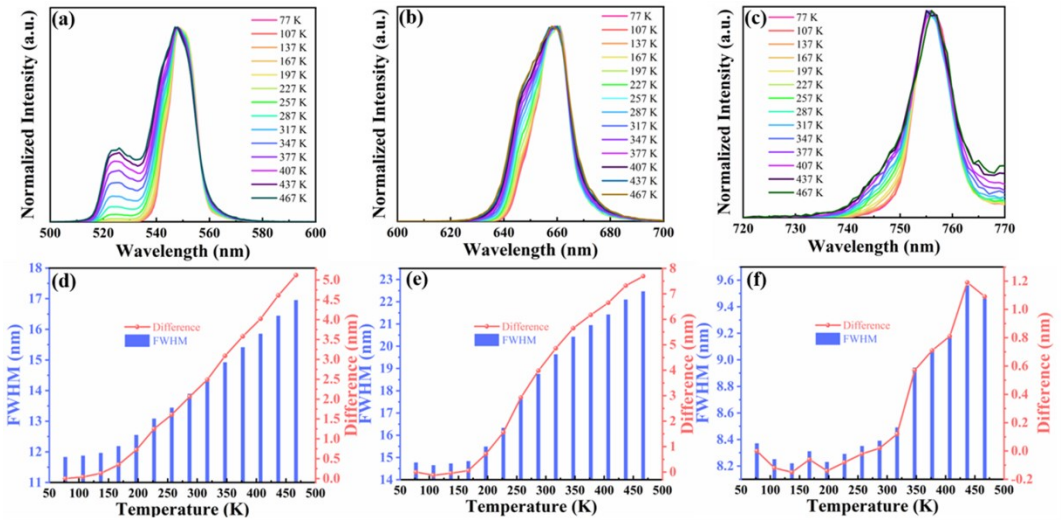

Fig. S2 Normalized up-conversion emission at (a) 548 nm, (b) 654 nm and (c) 753 nm for Ho^{3+} single-doped NBT: Ho sample under various temperatures. The temperature-dependent FWHM and its difference based on 77 K for emission at (d) 548 nm, (e) 654 nm and (f) 753 nm.

As we can see, all the emission peaks generally become widening along with temperature increasing on the whole. This can be interpreted by using Boltzmann distribution (F. Wang, et al. RSC Advances **7**, (2017) 27422.):

$$FWHM(T) = W_0 \times \sqrt{\coth\frac{h\nu}{2kT}}$$

$$W_0 = \sqrt{8\ln 2} \times h\nu \times \sqrt{s}$$

where W_0 is the FWHM at 0 K, $h\nu$ is the vibrational phonon energy. s and k are Huang-Rhys parameter and the Boltzmann constant, respectively. As the temperature rises, the electron phonon interaction is enhanced and the excited electrons extend to higher energy levels, thus increasing the transition of electrons from different energy levels, and resulting in the increase of FWHM.

Table S1 The energy gaps of $^5F_4$ and $^5S_2$ levels of Ho^{3+}-doped different host materials.

Chemical composition	Wavelength	ΔE(cm^{-1})	Ref
$Ca_x(LiHo)_{x/2}Bi_4Ti_4O_{15}(0\leq x\leq 1.0)$	530 nm /545 nm		27
$(K_{0.47}Na_{0.47}Li_{0.06})(Nb_{0.94}Bi0_{.06})O_3$:0.5Ho	526 nm /552 nm	613	28
$(K_{0.47}Na_{0.47}Li_{0.06})(Nb_{0.94}Bi0_{.06})O_3$:1.0Ho	526 nm /552 nm	650	

$0.9(K_{0.5}Na_{0.5})NbO_3$-$0.1SrTiO_3$:0.005Ho	523 nm /551 nm	846.63	29
$0.9(K_{0.5}Na_{0.5})NbO_3$-$0.1SrTiO_3$:0.01Ho	523 nm /551 nm	776.56	
ZrO_2:Ho	540 nm /550 nm		30
$BaTiO_3$-$Na_{0.5}Ho_{0.5}TiO_3$	523 nm /553 nm	933.83	41
$Na_{0.5}Bi_{0.5}TiO_3$:0.005Ho	**525 nm /548 nm**	**1023.74**	**This work**