Supporting Information: Efficient Optical Amplification in the Nanosecond Regime from Formamidinium Lead Iodide Nanocrystals

Paris Papagiorgis[†], *Andreas Manoli*[†], *Loredana Protesescu*[‡,#], *Charis Achilleos*[†], *Miltiadis Violaris*[†], *Konstantinos Nicolaides*[⊥], *Theodosis Trypiniotis*[⊥], *Maryna I. Bodnarchuk*[#], *Maksym V. Kovalenko*[‡,#], *Andreas Othonos*[ǁ] *and Grigorios Itskos*[†,]*

[†]Department of Physics, Experimental Condensed Matter Physics Laboratory, University of Cyprus, Nicosia 1678, Cyprus

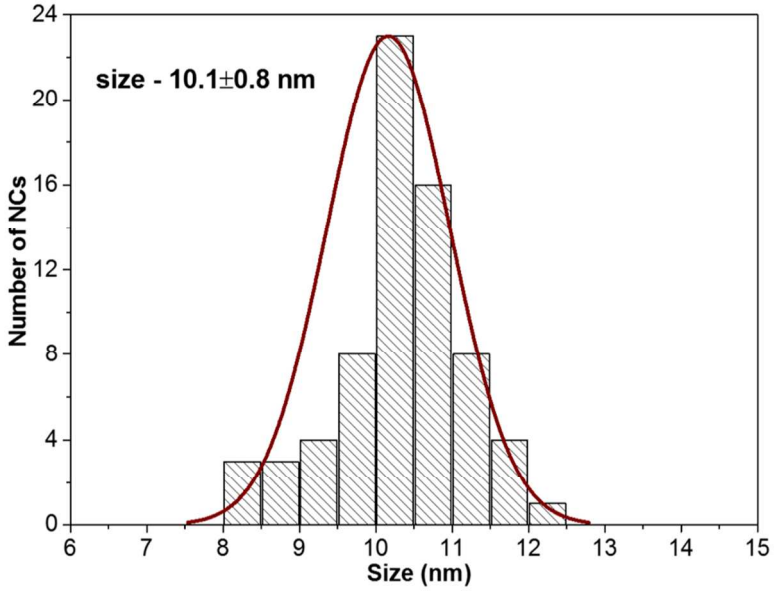
[‡]Institute of Inorganic Chemistry, Department of Chemistry and Applied Biosciences, ETH Zürich, CH-8093 Zürich, Switzerland

[#]Laboratory for Thin Films and Photovoltaics, Empa – Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland

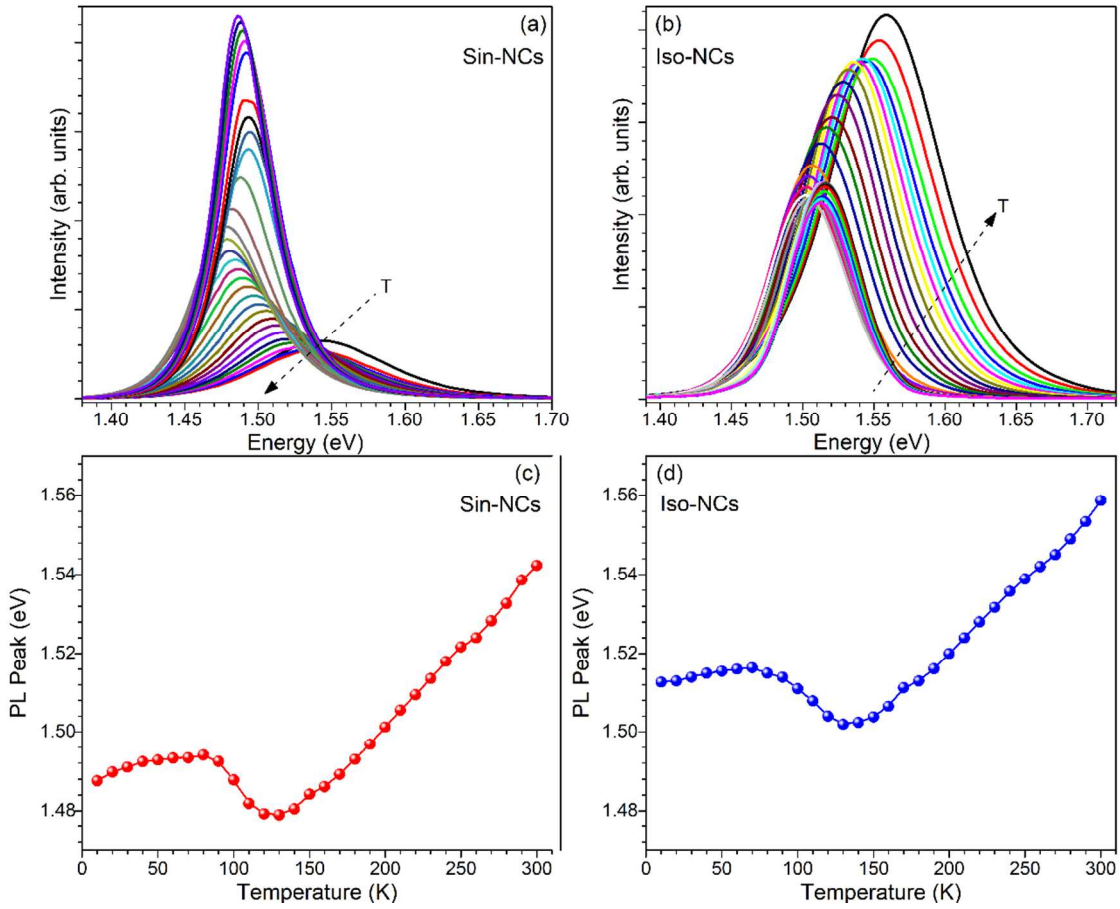
[⊥]Department of Physics, University of Cyprus, Nicosia 1678, Cyprus

[ǁ]Department of Physics, Laboratory of Ultrafast Science, University of Cyprus, Nicosia 1678, Cyprus

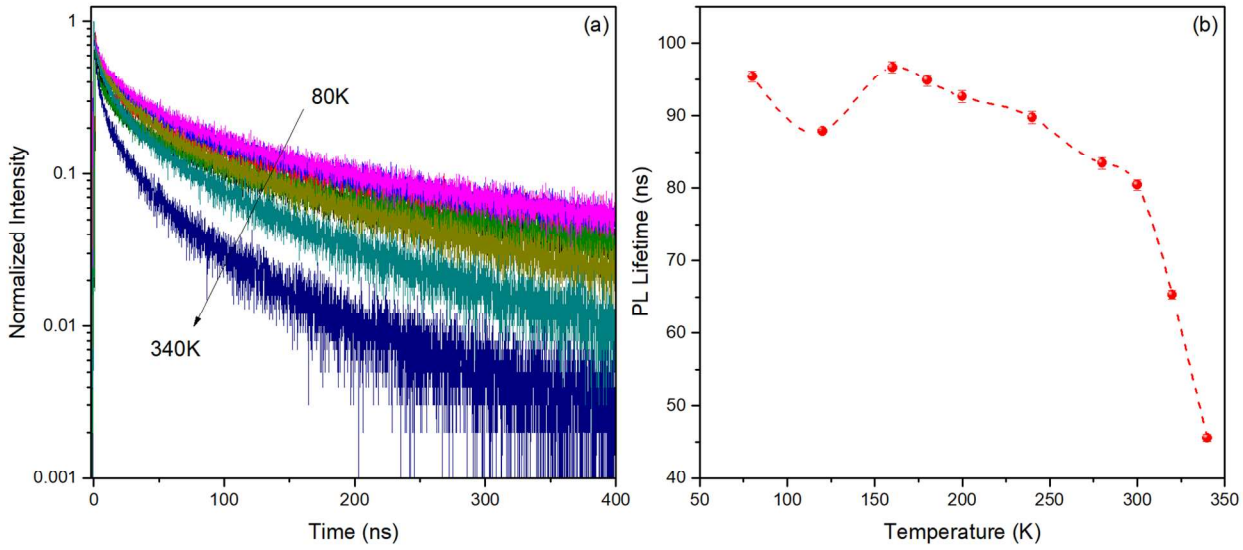
[*]itskos@ucy.ac.cy



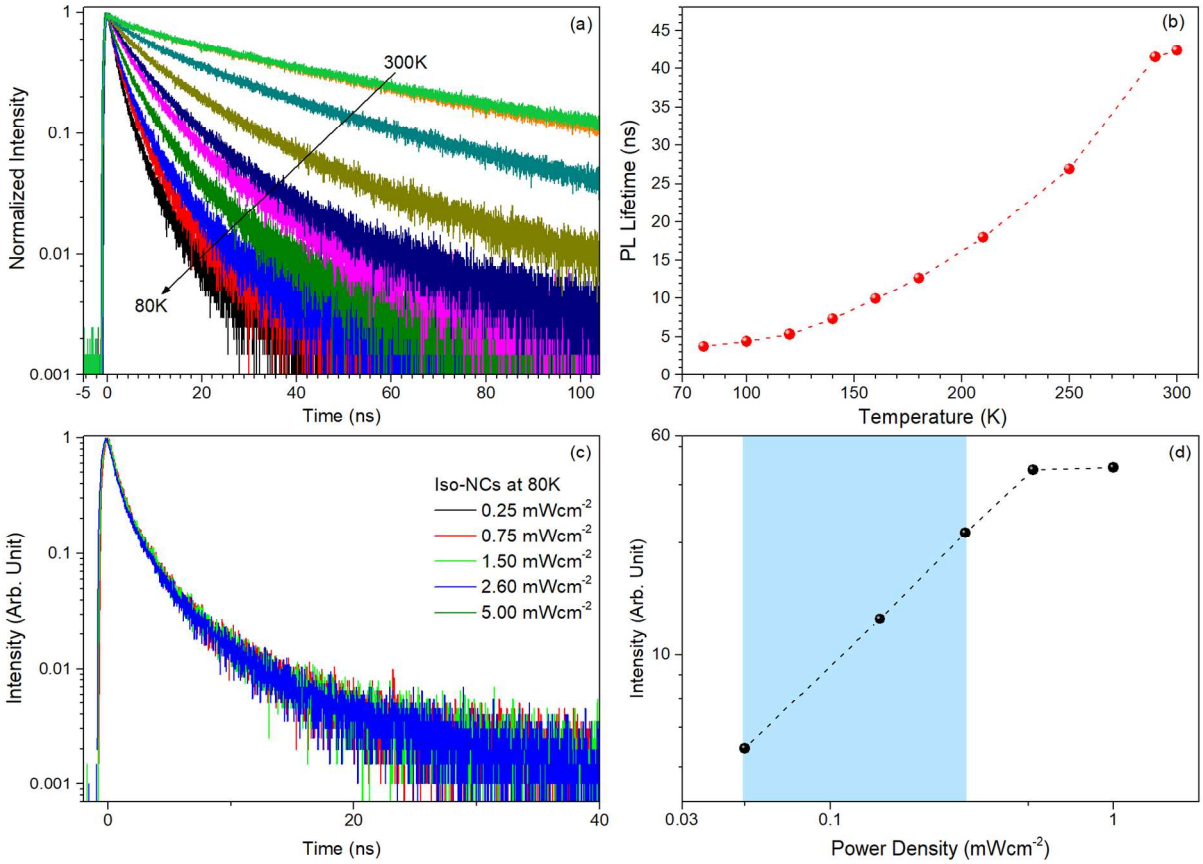
Supplementary Figure S1: $FAPbI_3$ nanocrystal size-histogram obtained from TEM measurements. The histogram is fitted by a Gaussian, yielding the mean size of the studied NCs equal to 10.1±0.8 nm.



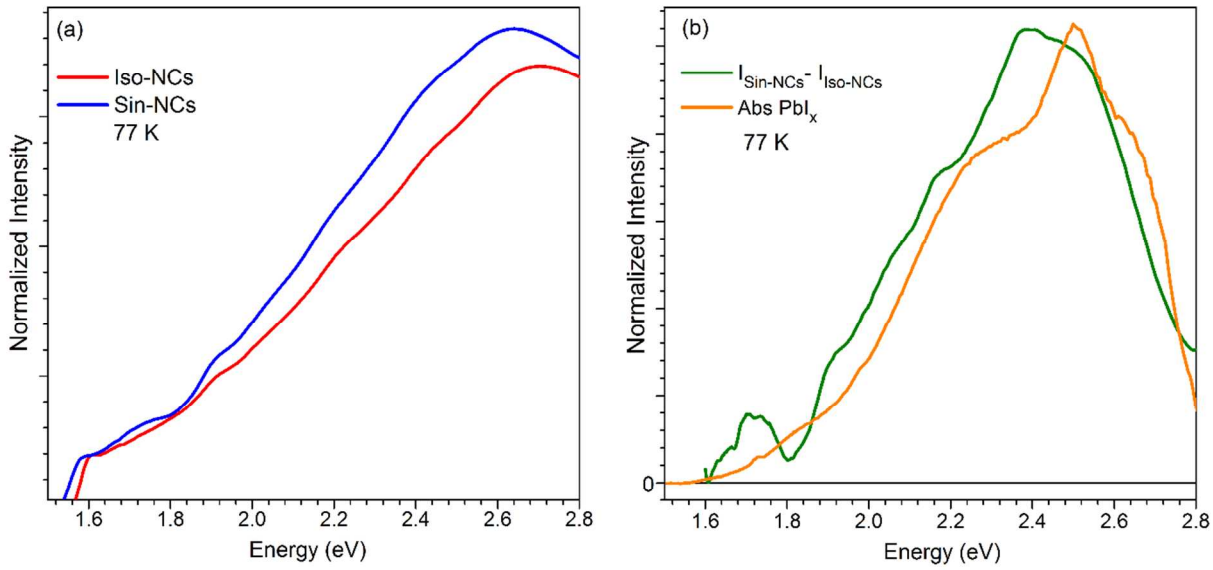
Supplementary Figure S2: Temperature dependent PL spectra from films containing **(a)** sintered $FAPbI_3$ NCs, **(b)** isolated $FAPbI_3$ NCs. The temperature evolution of the PL maximum for the films with **(c)** sintered NCs**, (d)** isolated NCs.



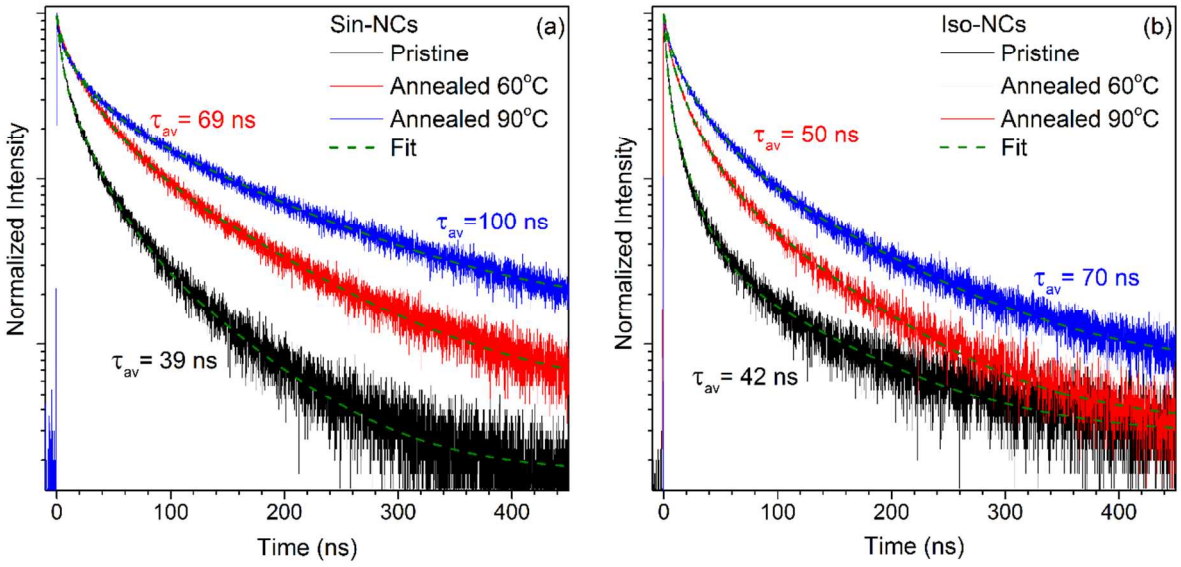
Supplementary Figure S3: (a) PL decays from a sin-NC film in the 80 to 340 K range. **(b)** Average PL lifetime versus temperature for the same film. The PL lifetime is extracted from double-exponential fits of the PL decays, as described in the Materials and Methods section of the main manuscript.



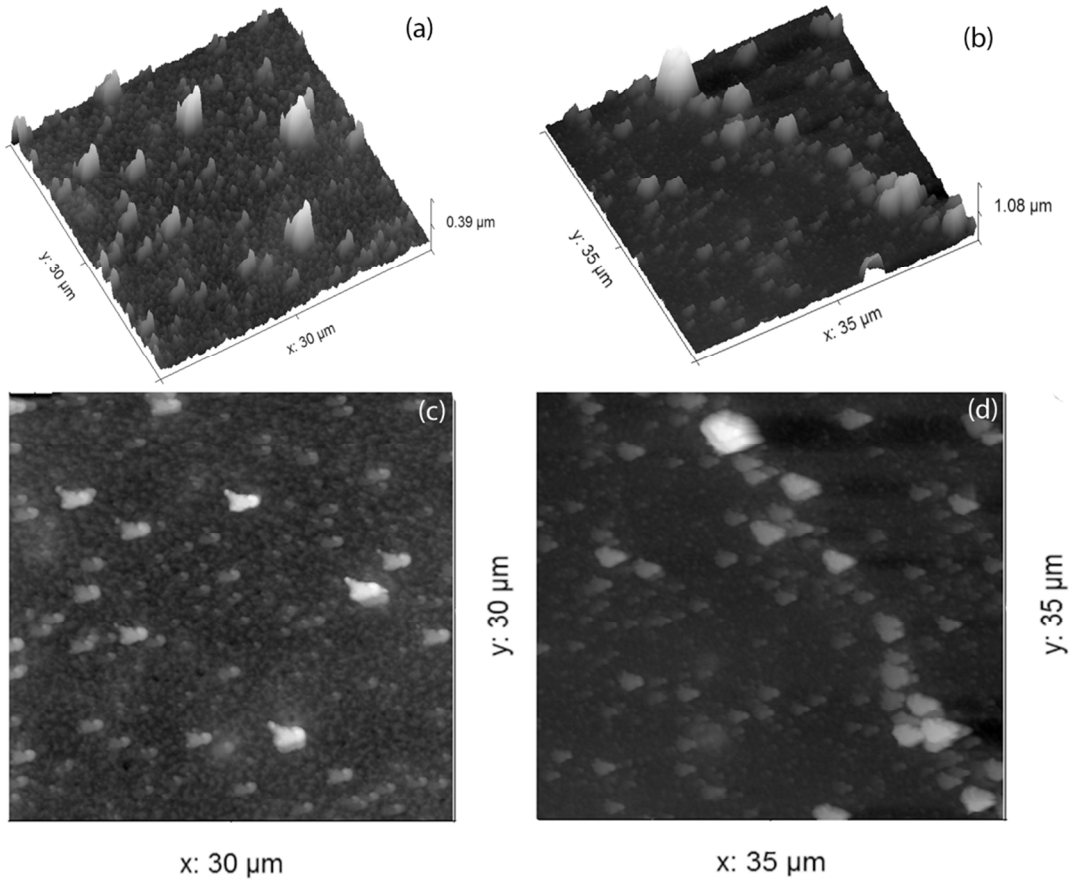
Supplementary Figure S4: (a) PL transients from a film containing intact NCs at different temperatures in the 80 to 300 K range. **(b)** Average PL lifetime versus temperature for the same film. The PL lifetime is extracted from double-exponential fits of the PL decays, as described in the Materials and Methods section of the main manuscript. **(c)** PL decays from an iso-NC film for various excitation fluences in the 0.25-5 mW cm^2 range. **(d)** The zero-delay PL intensity versus power density, from the same film, yielding a strictly linear growth across the excitation range (highlighted by blue color) used in our PL experiments.



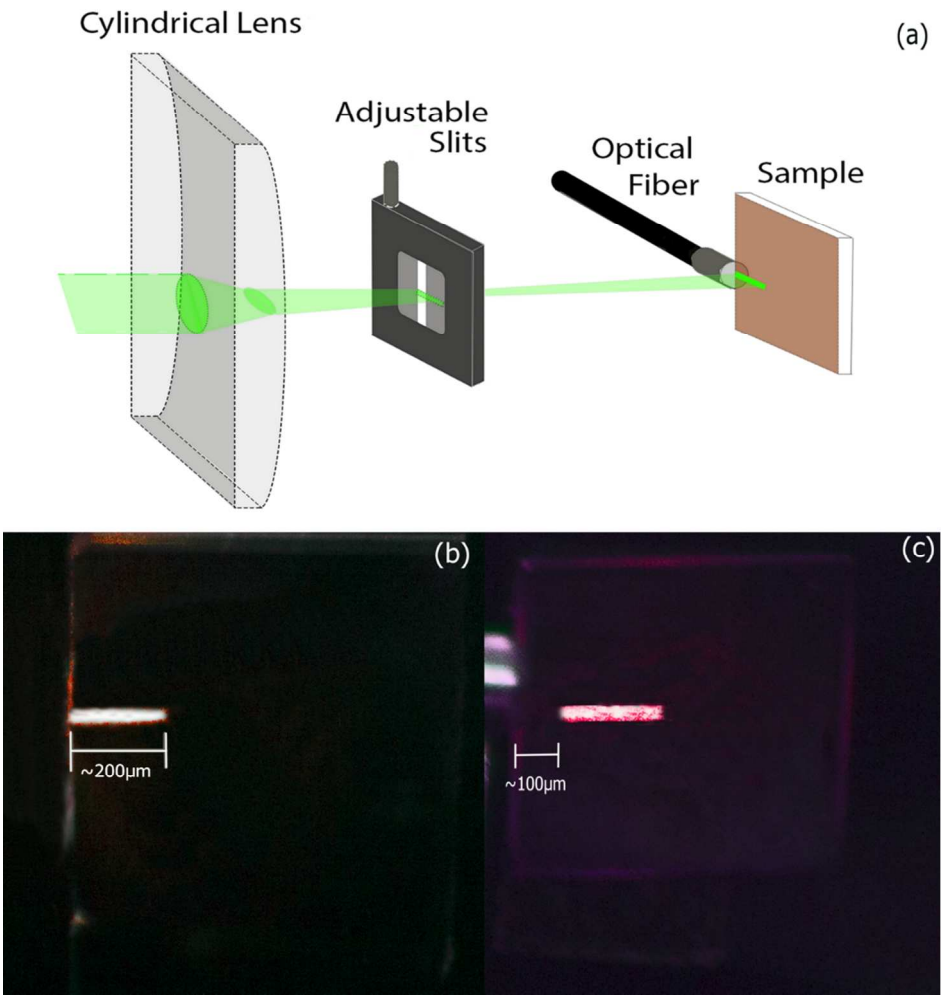
Supplementary Figure S5: (a) PLE spectra recorded at liquid nitrogen temperature (77 K) from films containing isolated and necked NCs. The partial loss of confinement in the later film is evident by the red-shift of the band-edge compared to that of the former film. **(b)** The difference of the PLE spectra of the two films i.e. excess of PLE signal in the sin-NC film, is compared with an appropriately normalized absorption spectrum obtained at 77 K from a film deposited out of a PbI_2 solution in MFA. In the dry state, the absorption of the PbI_2 exhibits a broad feature extended down to the near-infrared, which is attributed to the formation of various PbI_x plumbate complexes (1). The spectral resemblance between the absorption and PLE difference indicates that in the mildly purified iso-NC films, emission is weakly quenched compared to the emission of properly purified sin-NC films by absorbing PbI_x complexes formed during the colloidal synthesis.



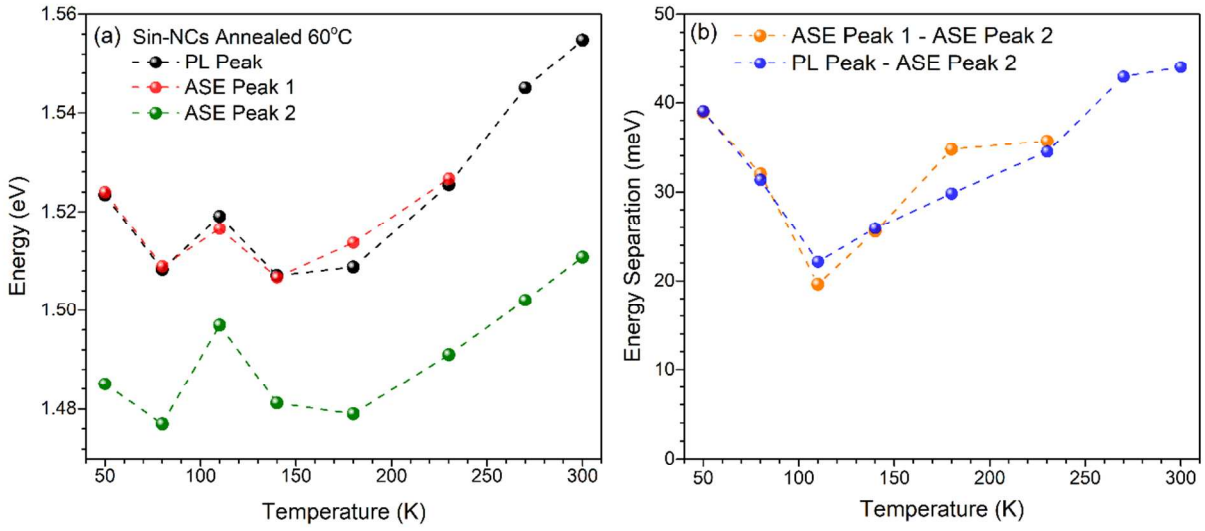
Supplementary Figure S6: The effect of gradual post-deposition thermal annealing on the photoluminescence decays from two films containing **(a)** Sintered NCs (Sin-NCs)**,** and **(b)** Isolated NCs (Iso-NCs).



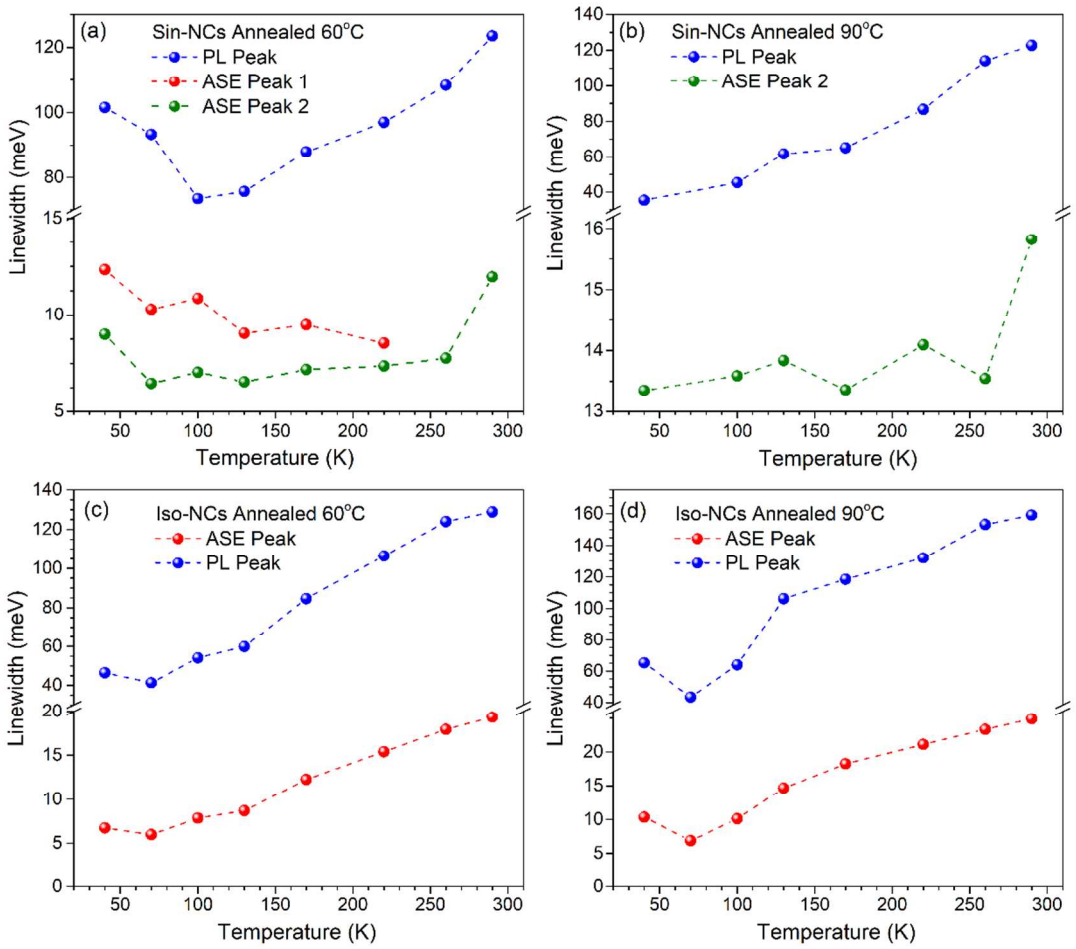
Supplementary Figure S7: AFM top view image from a sin-NC film **(a)** before and **(b)** after thermal treatment at 90^0 C for 30 min. AFM side view images of the same film **(c)** before and **(d)** after annealing.



Supplementary Figure S8: (a) Schematic of the variable stripe length (VSL) geometry used. Photographs of the ASE strip from a $FAPbI_3$ NC film, used for the experimental determination of **(b)** the net modal gain G, **(c)** the optical loss α.



Supplementary Figure S9: Temperature characteristics of the PL and ASE peaks in a sin-NC film that exhibits dual ASE. **(a)** PL and ASE peaks in the 40-300 K range, **(b)** Energy separation of the high energy ASE/PL peaks with the low energy ASE peak.



Supplementary Figure S10: The evolution of PL and ASE linewidths as a function of temperature for **(a,b)** a sin-NC and **(c,d)** an iso-NC film progressively annealed to 60° C and 90° C.

References

1. **Stamplecoskie K. G.; Manserab. J. S.; Kamat P. V.** Dual nature of the excited state in organic–inorganic lead halide perovskites. *Energy Environ. Sci.* **2015**, 8, 208-215.