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Water Stable 1D Hybrid Tin(II) Iodide Emits Broad Light with 36% Photoluminescence Quantum Efficiency

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ABSTRACT

The optical and light emission properties of tin and lead halide perovskites are remarkable because of the robust room temperature performance, broad wavelength tunability, high efficiency and good quenching-resistance to defects. These highly desirable attributes promise to transform current light emitting devices, phosphors and lasers. One disadvantage in most of these materials is the sensitivity to moisture. Here we report a new air-stable one-dimensional (1D) hybrid lead-free halide material (DAO)Sn₂I₆ (DAO: 1,8-octyldiammonium) that is resistant to water for more than 15h. The material exhibits a sharp optical absorption edge at 2.70 eV and a strong broad orange light emission centered at 634 nm, with a full width at half maximum (FWHM) of 142 nm (0.44 eV). The emission has a long photoluminescence (PL) lifetime of 582 ns, while the intensity is constant over a very broad temperature range (145-415 K) with a photoluminescence quantum yield (PLQY) of at least 20.3% at RT. Above 415 K the material undergoes a structural phase transition from monoclinic (*C2/c*) to orthorhombic (*Ibam*) accompanied by a red shift in the bandgap and a quench in the photoluminescence emission. Density functional theory calculations support the trend in the optical properties and the 1D electronic nature of the structure, where the calculated carrier effective masses along the inorganic chain are significantly lower than those perpendicular to the chain. Thin films of the compound readily fabricated from solutions exhibit the same optical properties, but with improved PLQY of 36%,

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3 for a 60 nm thick film, among the highest reported for lead-free low-dimensional 2D
4 and 1D perovskites and metal halides.
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7 INTRODUCTION

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9 Halide perovskites are a unique family of semiconductors¹⁻² that can be
10 efficiently exploited in a wide range of applications spanning from solid state solar
11 cells,³⁻⁴ γ -ray detectors,⁵ lasing,⁶ thermography⁷ and photocatalysis⁸ to LEDs.⁹⁻¹⁰ The
12 vast majority of these materials have the perovskite structure which is defined as one
13 featuring octahedral metal MX_6 centers where the octahedra connect to each other by
14 sharing only corners to form 3D, 2D, and 1D structures. The 3D halide perovskites are
15 formulated as AMX_3 ($A = CH_3NH_3^+$ (MA), $HC(NH_2)_2^+$ (FA), Cs^+ ; $M = Ge^{2+}$, Sn^{2+} , Pb^{2+} ;
16 $X = Cl^-$, Br^- , I^-).^{11,12} $A'_2A_{n-1}M_nX_{3n+1}$ formula describes 2D perovskites, where A' is a
17 monovalent or divalent ($A'A_{n-1}M_nX_{3n+1}$) organic cation acting as a spacer between the
18 perovskite layers and A is monovalent cation,¹³⁻¹⁴ while 1D materials (e.g.
19 $A'M_nX_{2n+1}$)¹⁵⁻¹⁶ and often 0D nanostructures are referred to as perovskites (e.g. AMX_3
20 quantum dots). If the MX_6 octahedra, however, are not connected by sharing corners,
21 the structures are not proper perovskites and can be referred to as perovskitoids.¹⁷
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32 A relatively recent and most prominent property of this class of materials is their
33 ability to chemically engineer and shape the light emission spectra (e.g. strong broad
34 light and white light emission),¹⁸⁻²⁰ color stability, and color rendering capability, either
35 as stand-alone semiconductor compounds in light emitting diodes (LEDs)²¹ or in
36 combination with a phosphor.²² Hybrid halide perovskites also offer the advantage of
37 solution processability,²³ fine tuning of optical properties,²⁴ high photoluminescence
38 quantum yield (PLQY) and composition of earth abundant chemical elements,²⁵ thus
39 lowering the cost and expanding the color gamut application range of the existing
40 technologies.²⁶
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47 A plethora of hybrid perovskite and metal halide candidate materials with
48 notable PLQY values have been reported towards this end: 2D compounds such as
49 (EDBE)-[$PbBr_4$] (EDBE: 2,2'-(ethylenedioxy)bis(ethylammonium) with 9% PLQY,²⁷
50 (2,6-dmpz)₃ Pb_2Br_{10} (2,6-dmpz: 2,6-dimethylpiper-azine) with 12% PLQY,²⁸ 1D
51 compounds such as (AD) Pb_2Cl_5 (AD: acridine) with 7.45% PLQY,²⁹ (AQ) $PbCl_4$ (AQ:
52 3-aminoquinoline) with 9% PLQY,³⁰ (TMEDA) Pb_2Br_6 (TMEDA:
53 N,N,N'-trimethylethylene-diammonium) with 10% PLQY,³¹ ($C_4N_2H_{14}$) $PbBr_4$ and
54 ($C_4N_2H_{14}$) $Pb_{0.987}Mn_{0.013}Br_4$ ($C_4N_2H_{14}$: N, N-dimethylethylenediamine) with 20% and
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3 28% PLQY respectively,³²⁻³³ (TDMP)PbBr₄ (TDMP: trans-2,5-dimethylpiperazine)
4 with 45% PLQY,³⁴ and 0D materials in single crystal form such as
5 (C₄N₂H₁₄Br)₄SnBr₃I₃ with 85% PLQY,³⁵ and (C₉NH₂₀)₂SbCl₅ with 95% PLQY.³⁶ In
6 the latter two cases the achieved PLQY values are comparable to those recorded for
7 CsPbX₃ (X: Br, I) perovskite quantum dots (QD),³⁷ which exhibit near-unity PLQY.³⁸⁻
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Two fundamental prerequisites for the commercial utilization of a new material are their composition of non-toxic elements (e.g. Sn²⁺) and their long-term environmental stability.⁴² Most of the reported hybrid materials with highly efficient light emission are based on Pb²⁺, and only few are stable under extreme conditions, such as [Pb₂Cl₂]²⁺[-O₂C(CH₂)₄CO₂⁻] which is water stable for 24h⁴³ and [N-methyl-dabconium]PbI₃ which is water stable for one month.⁴⁴

Nonetheless, there is significant interest in developing less toxic lead-free compounds. Progress in this regard includes (C₈NH₁₂)₄Bi_{0.57}Sb_{0.43}Br₇·H₂O (4.5% PLQY),⁴⁵ (PEA)₂SnI₄ (PEA: phenylethylamine, 6.4% PLQY as nanodisks),⁴⁶ (TEA)₂SnI₄ (TEA: thienylethylamine, 18.8% PLQY as nanodisks),⁴⁷ (C₁₈H₃₅NH₃)₂SnBr₄ (88% PLQY as colloidal suspension),⁴⁸ (C₅H₇N₂)₂ZnBr₄ (19% PLQY)⁴⁹, (Bmpip)₂SnI₄ (Bmpip: 1-butyl-1-methyl-piperidinium, 35% PLQY),⁵⁰ (C₄N₂H₁₄I)₄SnI₆ (75% PLQY),³⁶ Cs₃Cu₂I₅ (90% PLQY)⁵¹ and (C₉NH₂₀)₂SbCl₅ (95% PLQY).³⁶ In the majority of cases these materials have molecular 0D structures. Even though they can be efficient light emitters, generally there is limited information on their environmental stability, or how they perform well above room temperature.

Addressing the above concerns, we report here the synthesis of 1D (DAO)Sn₂I₆ (DAO: 1,8-octyldiammonium) compound with a new structure, which is water stable for more than 15h, and exhibits strong broad orange light emission at room temperature (RT) with 20.3% PLQY. To our knowledge, this PLQY value is among the highest for low dimensional (1D, 2D) metal halide broad light emitters in single crystal form (Table S1). The PL is characterized by a constant PL linewidth in the 175-415 K temperature range and a stable PL intensity in the 145-415 K range. Power dependent PL studies suggest that the origin of the broad light emission is ascribed to trap states. Films of (DAO)Sn₂I₆ can be made using a one-step (OS) solution deposition method based on this material's precursor components. The films maintained the crystal's excellent optical properties, and achieve an enhanced bright broad light emission with at least 36%

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3 PLQY.
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6 RESULTS AND DISCUSSION 7 8 9

10 Synthetic Aspects and Water Stability 11

12 High quality single crystals of (DAO)Sn₂I₆ were obtained by the reaction of an
13 off-stoichiometric amount of SnCl₂×2H₂O and 1,8-diamino octane (2:0.5) in hydrogen
14 iodide (HI) and hypophosphorous acid (H₃PO₂) solution (volume ratio 5:8). This
15 specific reagent ratio was used for the acquisition of large yellow single crystals (~0.2
16 cm). When equimolar reactants ratio (1:1) for Sn and DAO was tested instead, powder
17 size crystals were formed. The resulting (DAO)Sn₂I₆ crystals were filtered in air and
18 dried under vacuum. The presence of high amount of H₃PO₂ in the solution helps to
19 suppress Sn²⁺ oxidation and formation of orange SnI₄ crystals that can contaminate the
20 final product. Notably, (DAO)Sn₂I₆ can remain in its mother liquor for months without
21 formation of SnI₄.
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29 Powder X-ray diffraction (PXR) measurements verified the phase purity of
30 the as made single crystals, as the calculated PXR pattern from the single crystal
31 structure refinement matched exactly the experimentally recorded one (Figure 1a, b).
32 SEM studies revealed the uniform well faceted rectangular shape of the single crystals,
33 see Figure 1c. Remarkably, the resulting (DAO)Sn₂I₆ crystals are stable not only after
34 washing with water, but can also remain in liquid water for more than 15h without
35 structural decomposition as determined by PXR, Figure 1a, b. Given the well-known
36 extreme moisture sensitivity of Sn²⁺ based perovskite materials, the water stability of
37 (DAO)Sn₂I₆ is surprising. To illustrate this performance, we compared the stabilities of
38 the most air stable Pb based perovskites, such as the highly “hollow” 3D
39 (MA)_{0.56}(en)_{0.44}(Pb)_{0.692}(I)_{2.824} (en: ethylenediammonium),⁵² the 2D (HA)₂(MA)₃Pb₄I₁₃
40 (HA: hexylammonium) and also the pristine 3D MAPbI₃.⁵³ All these crystals
41 decomposed immediately upon contact with water to yellow PbI₂, whereas the
42 (DAO)Sn₂I₆ crystals remained intact for at least 15h (Figure 2). This exceptional water
43 stability is accompanied by a diminished crystal solubility (at least three times lower)
44 in common polar solvents such as dimethylformamide (DMF), dimethylacetamide
45 (DMA), N-methyl-2-pyrrolidone (NMP) and dimethylsulfoxide (DMSO) as compared
46 to higher dimensional hybrid halide perovskite analogues, such as 3D MAPbI₃⁵⁴ and
47 2D (NH₃C_mH_{2m}NH₃)(CH₃NH₃)_{n-1}Pb_nI_{3n+1}.⁵⁵
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3 X-Ray Photoelectron Spectroscopy (XPS) measurements performed on the
4 samples before and after the water treatment indicated no valence changes (using SnI₂
5 and SnI₄ crystals as standards), (Figure S1). Furthermore, the UV-VIS optical
6 absorption and Raman spectra of fresh crystals and crystals after water immersion were
7 unchanged (Figure 3, S2a). After 2 weeks of air exposure XPS measurements detected
8 surface oxidation of the Sn²⁺ into Sn⁴⁺ (Figure S1b) and crystal color change from
9 yellow to brown and black. However, this is limited to the surface of the crystals and
10 there is no underlying decomposition even after 90 days exposure in air, as concluded
11 by PXRD measurements (Figure S3). Thermogravimetric analysis (TGA)
12 measurements revealed that (DAO)Sn₂I₆ is thermally stable up to 558K, which is the
13 same temperature range as the 2D Pb based Ruddlesden-Popper perovskites⁵³ and about
14 25 K lower than the 3D MASnI₃ perovskites (Figure S4b).⁵² Differential scanning
15 calorimetry (DSC) measurements followed by PXRD indicate the presence of a phase
16 transition, expressed as an endothermic peak at 425K (Figure S4a). We therefore,
17 investigated the crystal structure over a wide range of temperature to elucidate the
18 distinguishing features of the phase changes and look for other phase transitions, as
19 described below.

20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 **Structural properties**

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36 Single crystal XRD analysis revealed that the material crystallizes in the
37 monoclinic centrosymmetric *C2/c* space group at room temperature. There is one
38 crystallographically independent Sn²⁺ cation and four I⁻ ions which through the
39 presence of an inversion centre and a glide plane generate a 1D inorganic chain along
40 the crystallographic *c*-axis. The chain consists of corner sharing [SnI₅]³⁻ moieties
41 (Figure 4a). The Sn²⁺ cations are coordinated by five I⁻ ions and exhibit a distorted
42 square pyramidal geometry. The structure consists of an unprecedented 1D double
43 inorganic chain based on corner sharing square pyramidal [SnI₅]³⁻ moieties, which are
44 separated and charge balanced by 1,8-octyldiammonium cations. Each square
45 pyramidal moiety is connected by the equatorial iodide atoms to four other [SnI₅]³⁻ units
46 at an angle (Sn-I(4)-Sn) of 114.638(11)° creating in this way a 1D double inorganic
47 ladder-like chain of opposite facing pyramids (Figure 4b). This geometry indicates that
48 the 5s² lone pair in the Sn²⁺ ions is stereochemically active with its expected location
49 being on the opposite side of the axial Sn-I bonds. In the square pyramidal [SnI₅]³⁻
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moiety the axial Sn-I(3) distance is 2.8948(3) Å while the equatorial distances range from 3.0890(3) Å to 3.3116(3) Å, for Sn-I(4) and Sn-I(2) respectively.

Among the inorganic chains, propagating along the crystallographic *c*-axis reside two opposite phasing, double protonated organic (DAO) molecules charge balancing the structure. The linkers are staggered along the axis direction, while the terminal ammonium groups on the alternating organic molecules are pointing along the *b*-axis towards opposite chains. The planes of the linkers are separated by 2.5 Å, while the distance among the N-H hydrogens and the bridging equatorial I(2) anions of the [SnI₅]³⁻ pyramids is 2.87 Å, signalling moderate hydrogen bond interactions (Figure S6).⁵⁶

Phase transition. The (DAO)Sn₂I₆ exhibits a temperature dependent phase transition from monoclinic to orthorhombic as determined by PXRD and single crystal XRD studies. Scanning the range of 80K to 500K we observed one clear phase transition between 410K-440K and verified the compound is stable up to at least 500K. From 80K to 410K there is a shift of the PXRD pattern to lower 2θ values, indicative of lattice thermal expansion. The solved and refined single crystal structure at 100K was found to be the same as the RT one (Table 1). From 410K to 500K, however, a structural phase transformation is evidenced by the disappearance of the (111) diffraction peak of the monoclinic phase and the appearance of the (121) peak of the orthorhombic phase (Figure S5). When the temperature reaches 440K the structure increases in symmetry, adopting the orthorhombic centrosymmetric *Ibam* space group, based on single crystal XRD measurements (Figure 5, Table 1). This phase transition is accompanied by a change in color from yellow to dark red and a gradual increase in the unit cell volume from 2369.30(15) Å³ to 2476.9(2) Å³ representing a ~4.5% expansion (Table 1). This large expansion is coupled to the relaxation of the structure, as the inorganic chain becomes less distorted at high temperature (HT), as evidenced by the opposite equatorial Sn-I(1)-Sn and Sn-I(4)-Sn angles changing from 101.108(8)° and 114.638(11)° at room temperature (RT), to 98.94(3)° and 139.38(5)° at HT respectively. The asymmetry of the distorted [SnI₅]³⁻ pyramid at RT as compared to the less distorted HT phase, is also clear by the change in the equatorial Sn-I bond lengths. In the RT phase they reside at distances of Sn-I(4), Sn-I(1) and Sn-I(2) 3.0890(3) Å, 3.2896(3) Å and 3.3116(3) Å respectively, while at HT, the corresponding values are 3.1783(7) Å and 3.2050(8) Å, for Sn-I(2) and Sn-I(3) respectively. These parameters

clearly depict the higher distortion of the pyramids of the RT phase, which have a direct effect on the optical properties, as there is crystal colour change from yellow to red.

The organic cations at HT are also relaxed, shifting from the bent RT configuration, to an almost linear one, stretching across two neighboring inorganic chains. The corresponding distance among the N-H hydrogens and the axial I(1) anions of the $[\text{SnI}_5]^{3-}$ pyramids is 2.93 Å. This is a significant difference between the HT and RT structures, as in the first case the two ammonium groups are facing the same inorganic chain, whereas at HT, the two ammonium groups charge balance opposite inorganic chains across the *a*-axis (Figure S7). In this case the ammonium groups lay closer to the axial iodide ions and not to the equatorial as it observed in the RT phase.

Electronic structure calculations

Density functional theory (DFT) calculations provide insight about the electronic structure and the semiconductor properties of $(\text{DAO})\text{Sn}_2\text{I}_6$ at room temperature (298 K, *C2/c*) and high temperature (440 K, *Ibam*). The electronic band structure at RT, exhibits bands with strong energy dispersion in the $[\text{Sn}_2\text{I}_6]$ chain direction and low dispersions in perpendicular directions, reflecting the 1D character of the crystals (Figure 6). The conduction band minimum (CBM) is located at the Γ point of the Brillouin zone (BZ), while the valence band maximum (VBM) is found, at the edge of BZ (M point) giving rise to an indirect bandgap of 2.215 eV. The computed band gap is a little bit lower than the experimental determined one at 2.70 eV, which is expected from the chosen level of theory (see Supporting Information). The valence band maximum (VBM) consists mostly of I(5p) orbitals with a contribution from Sn(5s) lone pair states, while CBM consists mostly of Sn(5p) orbitals (Figure S8a, S10a). For the less distorted HT phase, the band gap remains indirect in nature, the CBM being located at the X point of the BZ, and the VBM at the G_0 point, exhibiting again an indirect bandgap of 2.149 eV at this level of computation. The calculations therefore do predict a red shift of the band gap consistently with crystal color change from yellow to red for the HT phase (Figure 6b). Partial densities of states do not exhibit strong difference between the two phases (Figure S8). The main contrast is found in the contributions of the outer (I_{out} , axial) and inner (I_{in} , equatorial) iodide atoms of the inorganic chain to the VBM and CBM at both temperatures (Figure S9). At RT the I_{out} peak is shifted in comparison to the I_{in} peak, indicating more localized states, while at HT the contributions of I_{in} and I_{out} exhibit a better overlap. This could be ascribed to the

stronger interaction of the axial iodide atoms with the ammonium groups at RT, through moderate hydrogen bonding. The distance among the N-H hydrogens and the bridging equatorial I(2) anions of the $[\text{SnI}_5]^{3-}$ pyramids is 2.87 Å at RT (see above) while at HT it shifts to 3.50 Å, signalling weaker interaction.

An important parameter for the evaluation of the charge transport properties in a semiconductor material, is the carrier effective masses.⁵⁷ In (DAO) Sn_2I_6 due to the reduced dimensionality of the framework, we calculated these parameters along the inorganic chain and perpendicular to the chain. For the RT phase, the values are $m_{e,\parallel}^* = 0.32m_0$ and $m_{h,\parallel}^* = 0.72m_0$ for electrons and holes respectively along the 1D inorganic chain, while these values exhibit a strong anisotropy perpendicular to the chain, $m_{e,\perp}^* = 2.72m_0$ and $m_{h,\perp}^* = 2.86m_0$. These results clearly suggest that there is negligible electronic coupling between neighbouring inorganic chains. The effective masses of 1D (DAO) Sn_2I_6 m_e^* and m_h^* along the inorganic chain are slightly larger than those reported for the 3D MASnI_3 and 2D (BA) SnI_4 (BA: butylammonium) compounds, $m_e^* = 0.13m_0$, $m_h^* = 0.28m_0$ ⁵⁸ and $m_e^* = 0.13m_0$, $m_h^* = 0.15m_0$ ⁵⁹ respectively.

For the HT phase, DFT calculations yield lower masses $m_{e,\parallel}^* = 0.09m_0$, $m_{h,\parallel}^* = 0.33m_0$ and $m_{e,\perp}^* = 1.18m_0$, $m_{h,\perp}^* = 6.23m_0$ along the 1D inorganic chain and perpendicular to the chain respectively. This significant difference between the two phases is clearly connected to the much less distorted nature of the HT phase, where the increased Sn-I orbital overlap leads to broader bands and better charge transport properties. This trend was also observed for the 3D MAPbI_3 analogs, where lowering of the crystal symmetry from the cubic undistorted phase to the distorted tetragonal phase, lead to a reduction of the Pb-I orbital overlap and higher carrier effective masses.⁶⁰

Optical absorption and photoluminescence

UV-VIS absorption spectra of (DAO) Sn_2I_6 reveal a sharp absorption edge at 2.70 eV for both the pristine and the water treated sample (Figure 3, S2a). The RT Raman spectra of the fresh and water treated sample were also identical (Figure S2b). The spectra are dominated by sharp vibrational peaks, which are characteristic of low-dimensional non-perovskite metal halide materials,²⁸ in contrast to the broad spectral features that are observed for 3D perovskites.⁶¹ Comparing the spectra for (DAO) Sn_2I_6 to those of the 1D compound $(\text{CH}_3)_3\text{SSnI}_3$, we can ascribe the peaks at lower

wavenumbers (15-100 cm^{-1}) to the bending of the I-Sn-I bonds, whereas the peaks at higher wavenumbers (100-200 cm^{-1}) derive from the stretching of the Sn-I bonds.⁶²⁻⁶³ Notably the vibration peaks of (DAO) Sn_2I_6 at RT, are much sharper than those of $(\text{CH}_3)_3\text{SSnI}_3$, depicting the higher rigidity of the (DAO) Sn_2I_6 structure.

Upon excitation of the as made crystals with a 400 nm beam (DAO) Sn_2I_6 exhibits a broad strong emission centered at 634 nm with a large full width at half maximum (FWHM) of 142 nm (0.44 eV). The PL maximum has a large energy shift of 174 nm (0.75 eV) (Figure 7a). This behavior is typical for broad light emitter materials,⁶⁴ however, its origin depends on a number of structural parameters (dimensionality,⁶⁵ composition,⁶⁶ presence of defects⁶⁷), and is unique for each compound.⁶⁸⁻⁶⁹ The strong broad light emission of (DAO) Sn_2I_6 gave a PLQY of 20.3% (Figure S11), while the PL peak position and FWHM is the same regardless of excitation power (Figure S12). This PLQY value is the among the highest recorded for 1D metal halides, and a record value for lead free 1D broad light emitter materials in single crystal form.⁷⁰

The corresponding CIE (International Commission on Illumination) chromaticity coordinates are (0.55, 0.42), with a much larger contribution from the red region of the spectrum as compared to pure white light, which has chromaticity coordinates of (0.33, 0.33). This gives the emission from (DAO) Sn_2I_6 a correlated color temperature (CCT) of 1822 K (warm orange light), and a color-rendering index (CRI) value of 75, meaning that this material is suitable for outdoor lighting (Figure 8b). CIE coordinates and CCT values were calculated using the ColorCalculator by OSRAM Sylvania, Inc. CRI index quantifies how accurately illuminated colors are reproduced; for indoor lighting values above 80 are required.⁷¹

Photoemission yield spectroscopy in air (PYSA) measurements provided insight into the electronic band alignment of the synthesized perovskite materials.⁷² The position of the valence band maxima (VBM) was determined through PYSA measurements, while the conduction band minima (CBM) was determined by subtracting the corresponding optical band gap values from the measured VBM energies. The recorded values for the pristine crystals, the water treated ones as well as the 3D MASnI_3 are presented in Figure S13. The VBM of the pristine material lays a little deeper in energy than the water treated one, which could be an indication of the surface degradation of the water treated sample. Furthermore, the fact that the pristine material has higher ionization energy than MASnI_3 , is consistent with the higher air

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3 stability of (DAO)Sn₂I₆, considering that MASnI₃ is stable in air for a few minutes
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8 **Origin of PL emission**

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10 In order to verify whether the emission is a bulk property and does not originate
11 from surface defects, the large single crystals were grounded and the PL spectra were
12 recorded, showing no difference in PL intensity (Figure S14), suggesting that the PL is
13 indeed a bulk property. To gain insight into the mechanism of the broad emission,
14 variable-temperature PL measurements were performed from 5 to 295K. With
15 decreasing temperature there is a small gradual red shift of the PL peak from 631 nm
16 (295K) position to 655 nm (145K), while at 115K a big red shift to 745 nm is observed
17 (Figure 7b). This could be ascribed to an unidentified phase transition close/below
18 100K (Figure 5). The FWHM of the peaks gradually shrinks, from 142 nm to 135 nm
19 from 295K to 175K (Figure S15b). Below this temperature the PL emission becomes
20 significantly broader, exhibiting FWHM values ranging from 198 to 180 nm, for 145K
21 to 5K respectively (Figure S15b).
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31 The measured average decay lifetime at RT is 582 ns using multi-exponential
32 fitting of the emission decay curve (Figure 7c), showing three components with decay
33 constants of 0.7, 187 and 935 ns. At 77 K the lifetime shows a single exponential decay
34 with decay constant of 968 ns, comparable with the long decay component at RT (Table
35 S14). The magnitude of the PL lifetime in (DAO)Sn₂I₆ may be ascribed to a trap
36 assisted emission mechanism (see below).⁷⁴ Notably, at RT the recorded lifetime is
37 much longer than those in QDs (Quantum dots) materials, with values of few ns,³⁸ 1D
38 strong light emitting metal halide materials, such as C₄N₂H₁₄PbBr₄ with recorded
39 values of few tens of ns,³² C₅H₁₆N₂Pb₂Br₆ with a lifetime of about one hundred ns,³¹
40 and 1D fully inorganic white light emitters such as CsCu₂I₃, with values below one
41 hundred ns.⁷⁵
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50 We also measured the dependence of PL intensity as a function of excitation
51 power density and found that it does not follow a linear trend (for various temperatures),
52 as it saturates at high power flux. This suggests that the source of emission stems from
53 permanent defects and not self-trapped excitons (STEs) (Figure 7d).⁷⁶⁻⁷⁷ Correcting the
54 PL spectra by the excitation intensity, we observe that the PL quenches at higher
55 excitation power (Figure S16), which is a typical behavior for radiative trap-assisted
56 recombination.^{74, 78-79} In the latter case, emission is observed when a photogenerated
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charge is trapped in a midgap state and combines with a counter charge before it relaxes back to the ground state via a nonradiative pathway.⁸⁰

To evaluate the robustness of the PL emission at higher temperatures, variable temperature measurements were carried out up to 575 K (high temperature range) (Figure S17). Remarkably, the (DAO)Sn₂I₆ emission exhibits not only a constant PL linewidth in the temperature range of 175-415 K but a sustainable PL intensity over the broad range of 145-415 K (Figure S15a). Interestingly, above 415K the PL quenches (Figure S17). This is in accordance with the recorded phase transition (Figure S5) from the distorted monoclinic phase (*C2/c*) at 410 K, to the less distorted orthorhombic phase (*Ibam*) at 440 K (Figure 5). It is possible that under this structural configuration, and heat treatment of the material, any emitting defect is suppressed or changed in character. Similarly, although the structural and electronic properties are unaffected by the water treatment (based on PXRD, UV-VIS and Raman measurements), the PL emission is quenched. This is in alignment with the assignment of PL to permanent defects that can be modified without perturbing the bulk material's properties.

The PL emission spectra are intact, both in terms of emission wavelength and shape until the temperature of the phase transition is reached (Figure S18). The PL stability within the RT phase limit is further supported by the determined CIE chromaticity coordinates of (0.53, 0.45) at 415 K, and the color-rendering index (CRI) value of 73, which are very close to the RT recorded values of (0.55, 0.42) and 75 respectively, verifying the excellent high temperature emission performance of the material. This finding is important because an LED operating temperature can be as high as 425K.⁸¹⁻⁸²

Film deposition

A highly attractive feature of (DAO)Sn₂I₆ is its ability to deposit uniform high-quality thin films. Because of the moderate solubility (see above) of the crystals in a variety of polar solvents, we used precursor salts instead. Freshly prepared octylenediammonium diiodide (DAO-I₂) (see S.I.) and SnI₂ were dissolved in DMF, in an off stoichiometric ratio (DAO-I₂: SnI₂ = 1:1), and spin coated, using a one-step (OS) deposition method (see S.I.) giving rise to a colorless film which upon UV illumination exhibited strong orange light emission (Figure 8c). If a stoichiometric ratio (DAO-I₂: SnI₂ = 1:2) is used instead, a red film is formed, which can be ascribed to the formation of the 2D Ruddlesden-Popper (DAO)SnI₄ compound. This can be verified by

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3 comparing the PXRD patterns of the reported Pb analogue (DAO)PbI₄⁵⁵ and the
4 corresponding film (Figure S19).
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6 Atomic force microscopy (AFM) measurements revealed that a uniform, 60 nm
7 thin film was formed, with a surface roughness RMS value of 9.8 nm (Figure S20).
8 PXRD measurements shed light on the film composition, which consists of an (110)
9 oriented (DAO)Sn₂I₆ major crystalline phase (Figure S21). There is also a small
10 diffraction peak present at 6.6° 2θ, which is not predicted from the calculated pattern,
11 nor from unreacted precursor species (Figure S22) and may be an indication of the
12 formation of a different minor phase. Nonetheless, the film's optical absorption,
13 emission and the PLE spectra (Figures 9, S23-24) are very similar to those of the single
14 crystals. This verifies that the origin of the PL emission is the same in both the film and
15 the crystals. The thin films, however, exhibited a much improved PLQY of 36% (Table
16 2). The enhanced PLQY value is further supported by the significantly longer PL decay
17 average lifetime at RT which was determined to be 1114 ns by multi-exponential fitting
18 (Figure S25). The decay components are similar to those of the crystals but with much
19 larger portion of the photons emitted from the longer decay route (see table S14),
20 similar to the dynamics at 77K. The slower decay seems to indicate a more efficient
21 transfer of the excitons to the lower energy states. Furthermore, the corresponding CIE
22 chromaticity coordinates of (0.59, 0.40) (Figure 8d), are very close to the bulk crystals
23 recorded ones of (0.55, 0.42), while the calculated color-rendering index (CRI) value
24 is 74, rendering this film a competent light emitter as the single crystals (CRI value 75).
25 PYSAs measurements demonstrated the corresponding CBM and VBM energy levels
26 with values of 2.73(5) eV and 5.43(5) eV respectively. These results lay the path for
27 the further optimization of film assembly and PL performance for future device
28 explorations.
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48 CONCLUSIONS

49 The new 1D Sn based metal halide compound (DAO)Sn₂I₆ is stable in contact
50 with water for 15h, posing as a record stability for a Sn(II) based metal halide material,
51 while exhibiting highly efficient broad light emission with PLQY of 20.3%, in single
52 crystal form. Equally important is that the material maintains this emission performance
53 over a wide temperature range, and up to 415 K, surpassing the operating temperature
54 of an LED. Furthermore, at RT the PL lifetime is very long (582 ns) thus allowing for
55 efficient carrier recombination. Thin films can be fabricated exhibiting the same
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3 emission properties (CRI values and CIE coordinates) as the bulk crystals but with an
4 improved PLQY value of 36%, for a 60 nm thick film. The origin of the strong emission
5 is ascribed to the existence of permanent defects. The (DAO)Sn₂I₆ stands out not only
6 as an auspicious environmentally friendly and stable potential LED semiconductor
7 candidate, but also as a photocatalyst, based on its high PL lifetime values and water
8 stability. These results demonstrate the versatile nature of perovskitoid hybrid halide
9 materials, laying the path for the design of next generation of water stable lead-free
10 semiconductors.
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19 ASSOCIATED CONTENT

20 Supporting Information

21 Materials and methods, synthetic details, additional supplementary figures and tables
22 about material characterization, X-ray diffraction measurements, photoluminescence
23 measurements, XPS measurements, AFM measurements, thermogravimetric analysis
24 and PYSA measurements.
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30 This material is available free of charge via the Internet at <http://pubs.acs.org>.

31 X-ray crystallographic data for (DAO)Sn₂I₆-100K

32 X-ray crystallographic data for (DAO)Sn₂I₆-293K

33 X-ray crystallographic data for (DAO)Sn₂I₆-440K
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53 Notes

54 The authors declare no competing financial interest.
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Figures

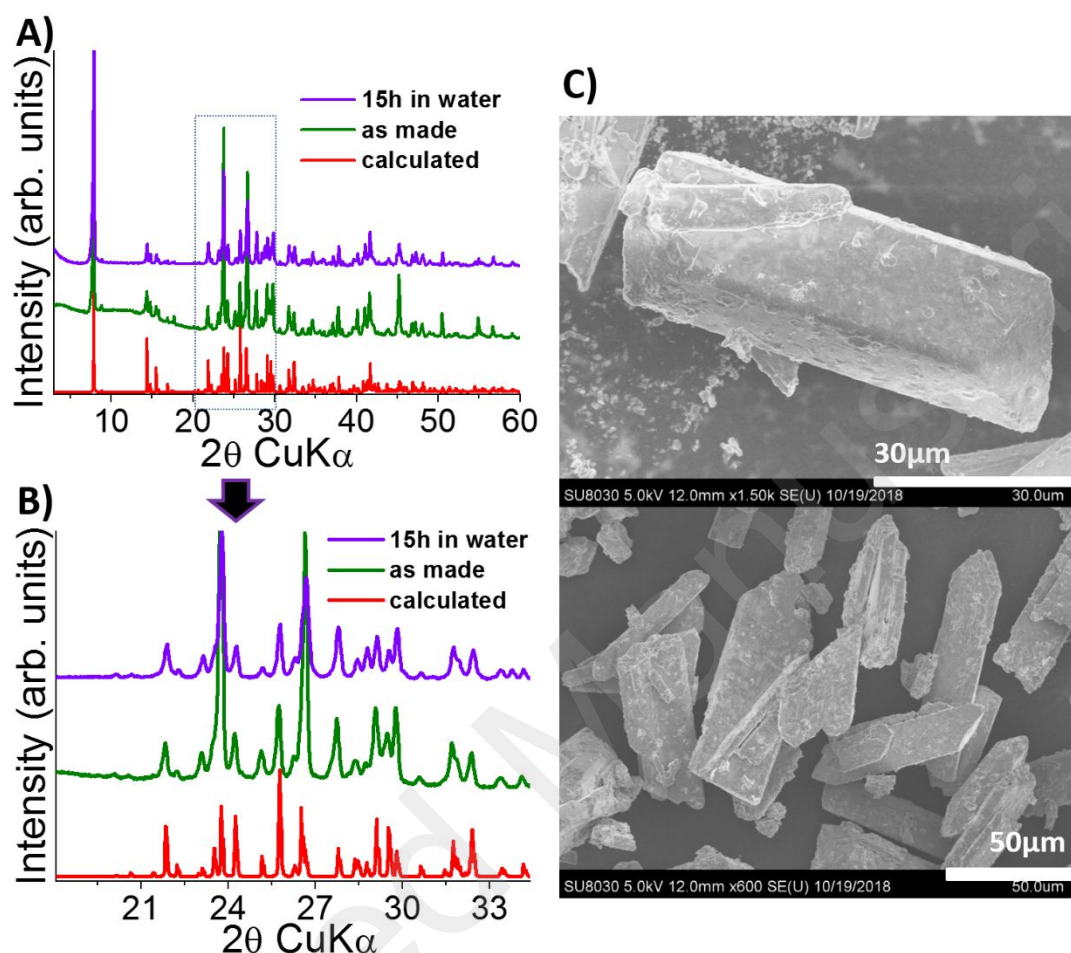


Figure 1. A) Comparison of the PXRD patterns for the as made (DAO) Sn_2I_6 crystals and the water treated ones, to the calculated pattern based from the solved single crystal structure and B) zoom into the highlighted area of the PXRD patterns from 20° to 34° 2θ verifying the high crystallinity and phase purity of the water treated sample. C) Representative SEM images of the as made (DAO) Sn_2I_6 single crystals.

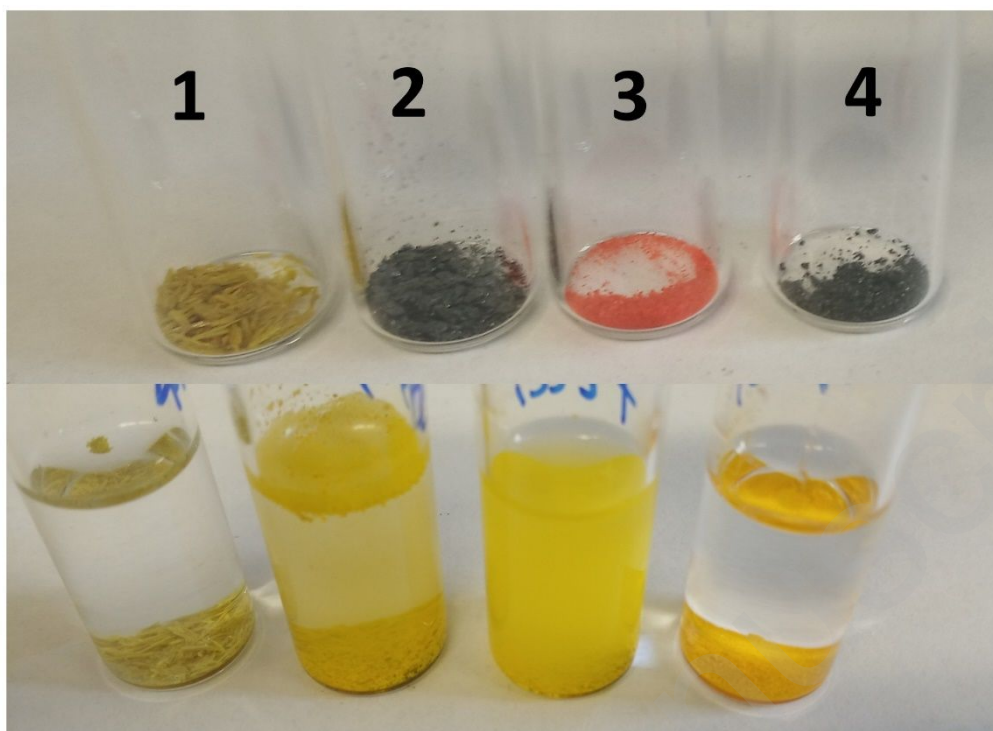


Figure 2. Water stability test. Top: Single crystals of $(\text{DAO})\text{Sn}_2\text{I}_6$ (1) along with some of the most stable in air Pb based perovskites, such as the 2D $(\text{HA})_2(\text{MA})_3\text{Pb}_4\text{I}_{13}$ (2) the highly “hollow” 3D $(\text{MA})_{0.56}(\text{en})_{0.44}(\text{Pb})_{0.692}(\text{I})_{2.824}$ (3), and the pristine 3D MAPbI_3 (4) for comparison. Bottom: The corresponding crystals immersed in water. Compounds (2), (3) and (4) decomposed immediately, while (1) is structurally intact even after 15 hours.

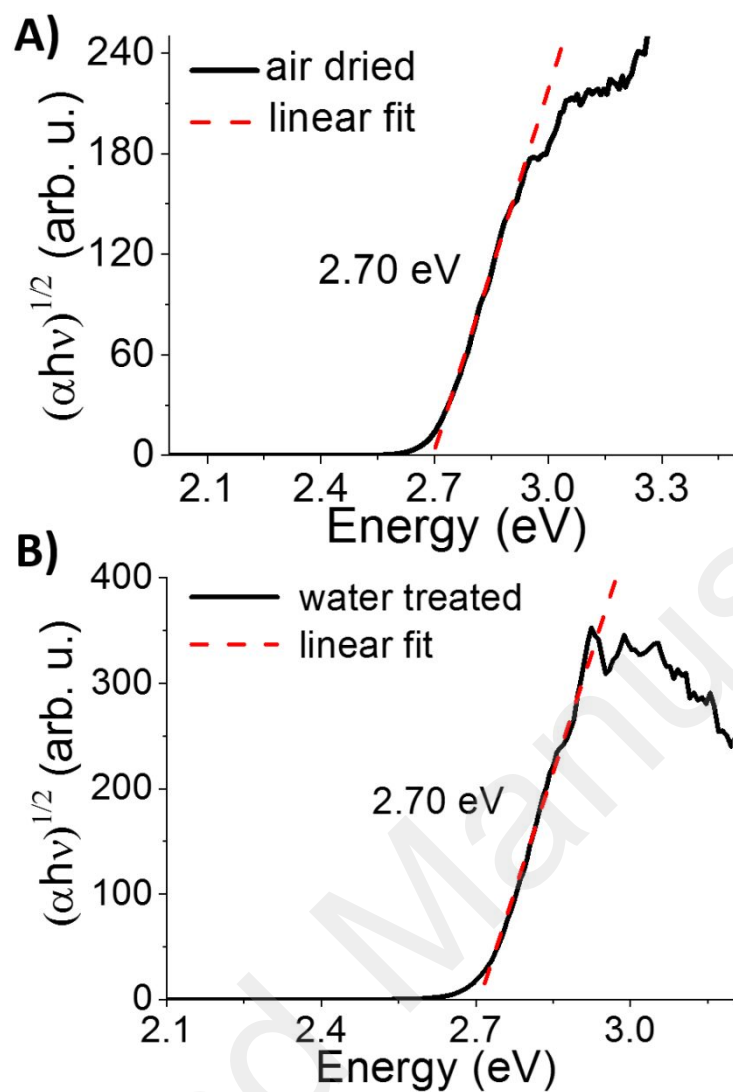


Figure 3. Tauc plot and determined band gap for (A) the fresh crystals and (B) the water treated ones.

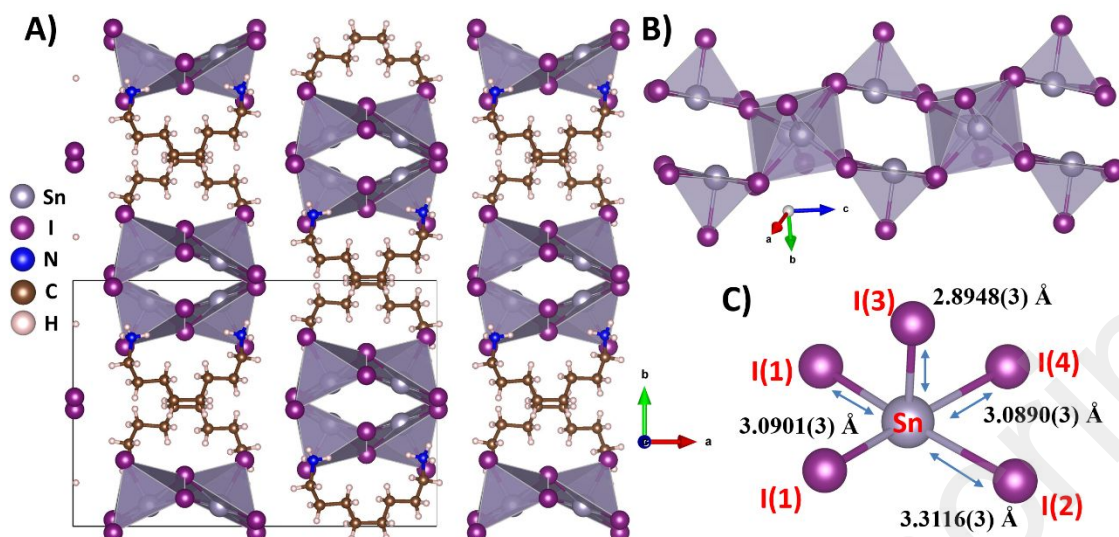


Figure 4. A) Part of the 1D structure of (DAO)Sn₂I₆ at RT, looking down the *c*-axis. B) Representation of the 1D double inorganic chain based on [SnI₅]³⁻ moieties. C) The distorted square pyramidal geometry of the Sn²⁺ cations of the inorganic chain, along with the corresponding Sn-I bond lengths and atom numbers.

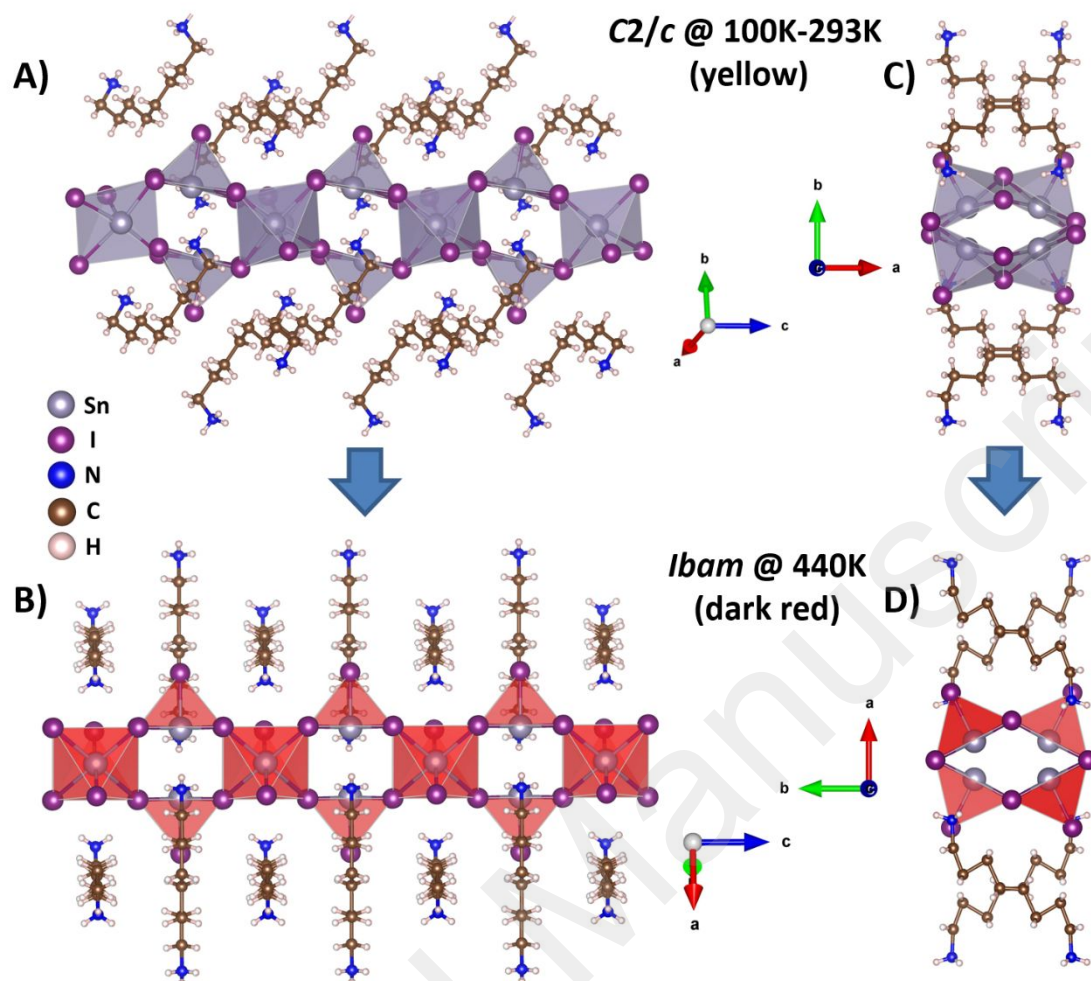


Figure 5. The recorded temperature dependent phase transition of $(DAO)Sn_2I_6$. A) The yellow crystals crystallize at the monoclinic $C2/c$ space group at 293K, B) while at 440K the structure exhibits a profound phase transition to the orthorhombic phase ($Ibam$ space group) accompanied by less distorted, highly oriented organic and inorganic parts and a crystal color change from yellow to dark red. C) Part of the RT and D) HT structures viewing along c -axis.

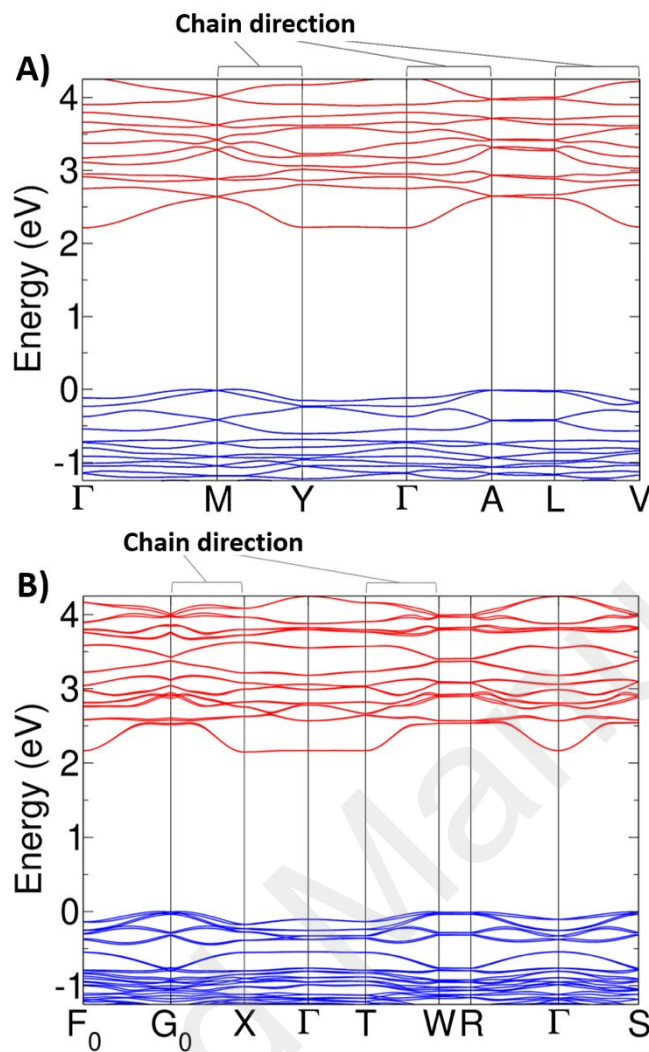


Figure 6. Electronic band structures for A) RT yellow crystals of (DAO)Sn₂I₆ and as well as for B) the high temperature red crystals.

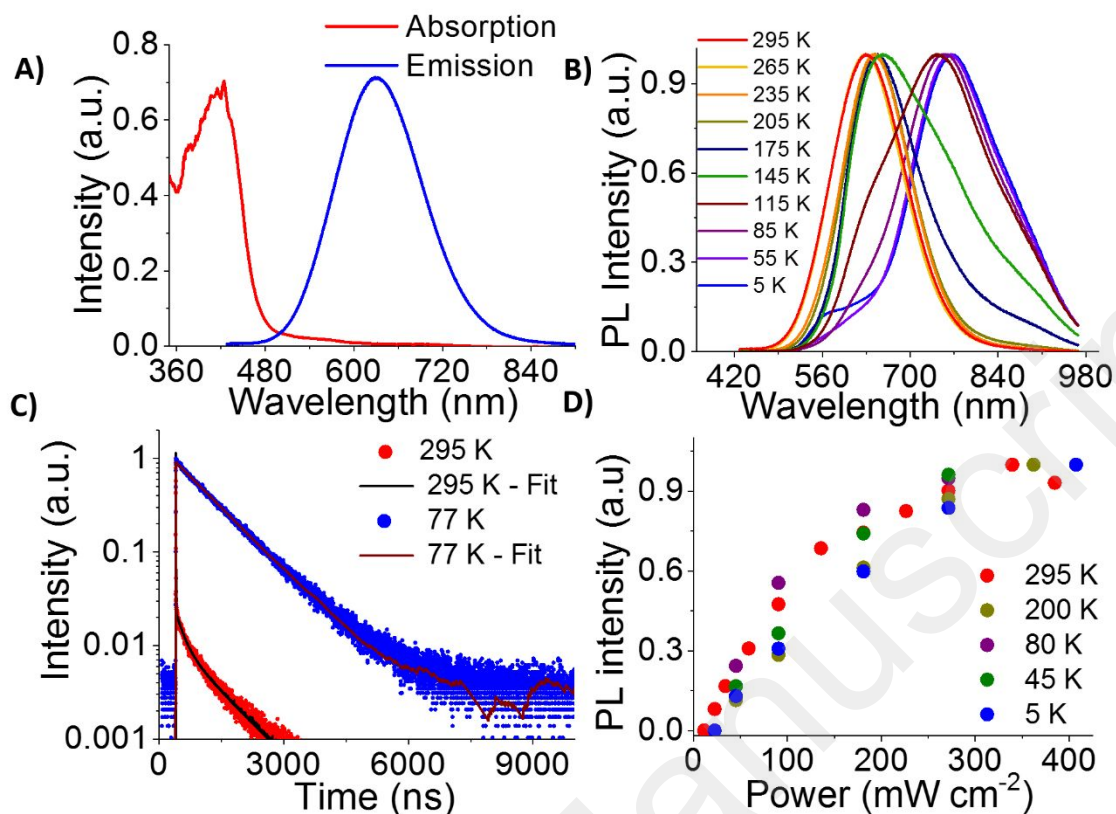


Figure 7. A) The recorded absorption and emission spectra of compound (DAO)Sn₂I₆, B) temperature dependent PL measurements from 295K to 5K, C) Time-resolved photoluminescence decay at 77K and 295K, D) Emission intensity versus excitation power at various temperatures, revealing the saturation of PL intensity with increasing power.

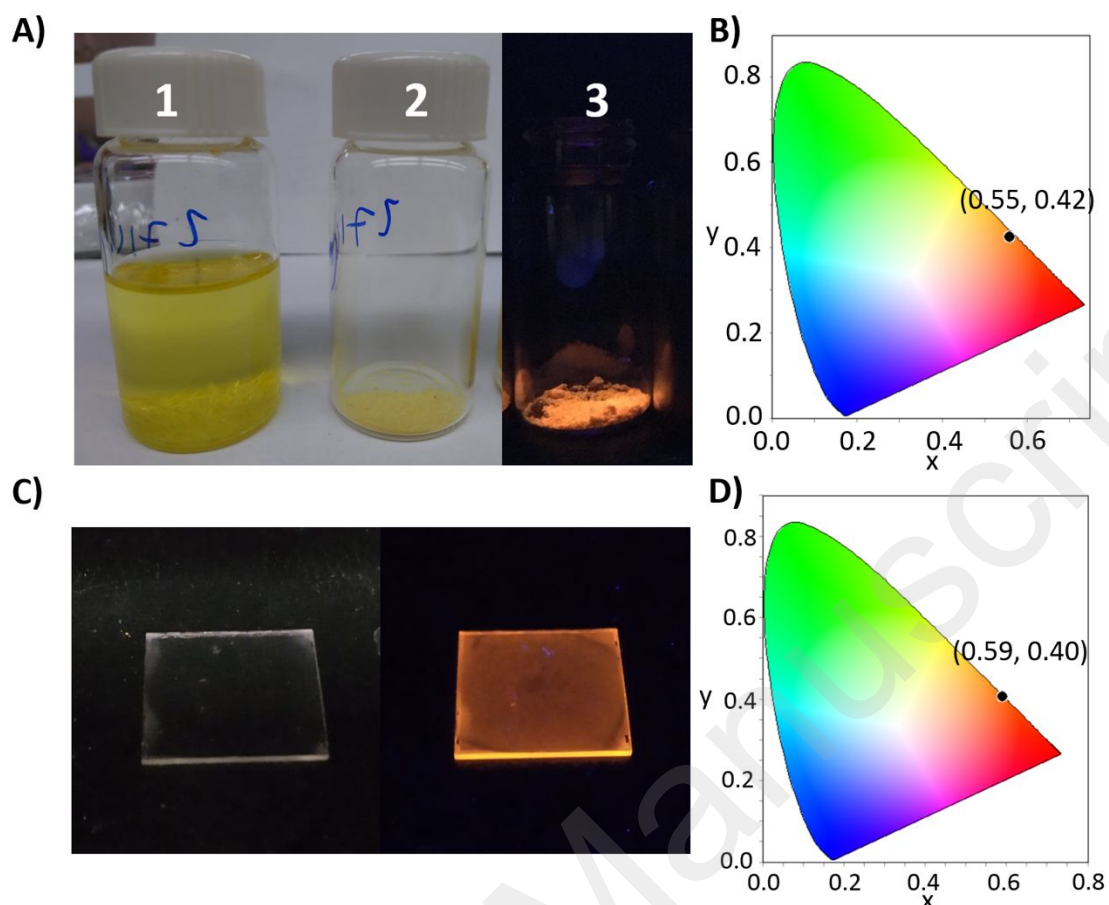


Figure 8. A) Photographs of (1) as made single crystals in the mother liquor of hydrogen iodide and hypophosphorous acid, (2) dried crystals under ambient light, and (3) and under UV light. B) CIE chromaticity coordinates for (DAO)Sn₂I₆. C) Photographs of fabricated thin film under ambient light and under UV light. D) CIE chromaticity coordinates for the thin film emission.

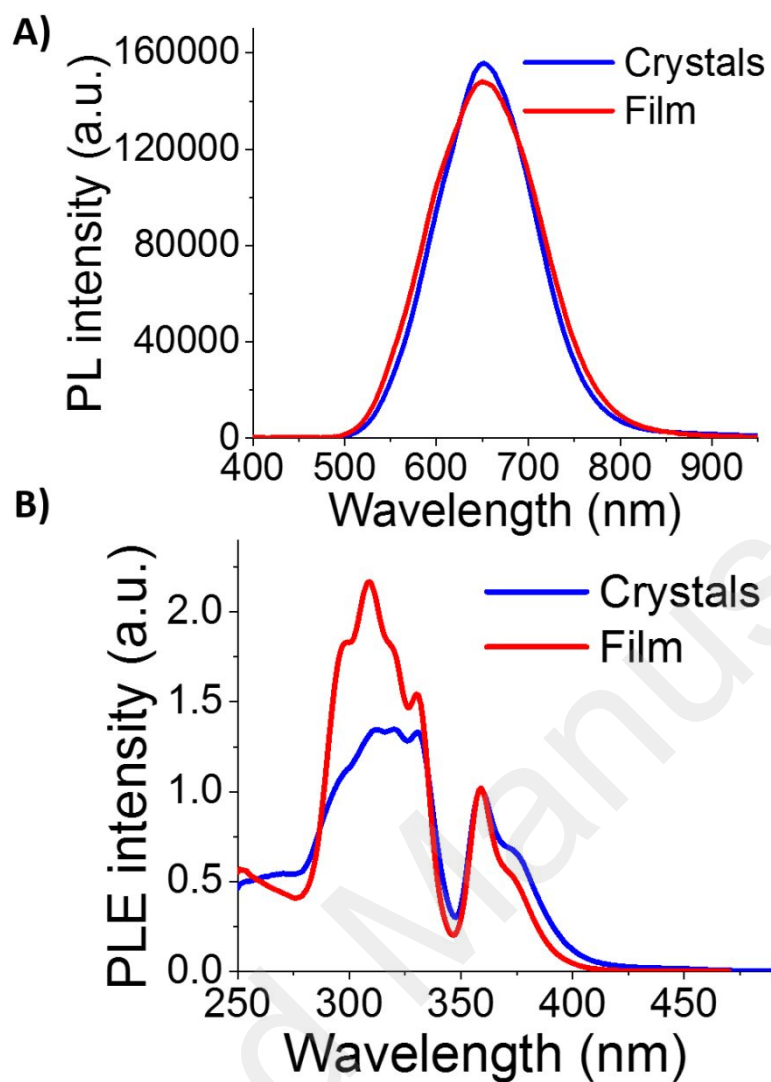


Figure 9. Comparison of (A) PL emission spectra and (B) PLE spectra for (DAO)Sn₂I₆ single crystals and thin film.

Table 1. Crystal and Structure Refinement Data for (DAO)Sn₂I₆ at 100K, 293K and 440K.

Temperature	100K	293K	440K
Crystal system	monoclinic	monoclinic	orthorhombic
Space group	<i>C2/c</i>	<i>C2/c</i>	<i>Ibam</i>
Unit cell dimensions	a = 21.0227(12) Å, α = 90° b = 13.4267(8) Å, β = 108.8167(19)° c = 8.6803(5) Å, γ = 90°	a = 21.1574(8) Å, α = 90° b = 13.5267(5) Å, β = 108.8895(17)° c = 8.7500(3) Å, γ = 90°	a = 13.7210(3) Å, α = 90° b = 20.3857(6) Å, β = 90° c = 8.8553(8) Å, γ = 90°
Volume	2319.2(2) Å ³	2369.30(15) Å ³	2476.9(2) Å ³
Z	4	4	4
Density (calculated)	3.2796 g/cm ³	3.2103 g/cm ³	3.0708 g/cm ³
Independent reflections	4230 [R _{int} = 0.0395]	5392 [R _{int} = 0.0378]	1304 [R _{int} = 0.0294]
Completeness to θ = 29.33°	98%	98%	99%
Data / restraints / parameters	4230 / 0 / 58	5392 / 0 / 58	1304 / 3 / 38
Goodness-of-fit	1.42	1.35	2.82
Final R indices [I > 2σ(I)]	R _{obs} = 0.0171, wR _{obs} = 0.0516	R _{obs} = 0.0287, wR _{obs} = 0.0718	R _{obs} = 0.0472, wR _{obs} = 0.1194
R indices [all data]	R _{all} = 0.0177, wR _{all} = 0.0519	R _{all} = 0.0380, wR _{all} = 0.0764	R _{all} = 0.0662, wR _{all} = 0.1249
Largest diff. peak and hole	0.61 and -0.61 e·Å ⁻³	0.99 and -0.64 e·Å ⁻³	0.86 and -0.48 e·Å ⁻³

$$R = \frac{\sum ||F_o| - |F_c||}{\sum |F_o|}, wR = \left(\frac{\sum [w(|F_o|^2 - |F_c|^2)^2]}{\sum [w(|F_o|^4)]} \right)^{1/2} \text{ and } w = 1/(\sigma^2(I) + 0.0004I^2)$$

Table 2. Photophysical properties of the bulk crystals and the assembled thin film of the (DAO)Sn₂I₆ compound. (τ_{av} is the average PL lifetime).

(DAO)Sn ₂ I ₆	T(K)	PLQY (%)	τ_{av} (ns)	FWHM (nm)	CRI	CCT (K)	CIE
Crystals	298K	20.3	582	142	75	1822	(0.55,0.42)
Film	298K	36	1114	145	74	1529	(0.59,0.40)

Table of Contents Graphic

