ACS Applied Materials and Interfaces 2021 vol.13 N46, pages 54874-54883

Harvesting Sub-bandgap Photons via Upconversion for Perovskite Solar Cells

Singh R., Madirov E., Busko D., Hossain I.M., Konyushkin V.A., Nakladov A.N., Kuznetsov S.V., Farooq A., Gharibzadeh S., Paetzold U.W., Richards B.S., Turshatov A.
Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

Abstract

Lanthanide-based upconversion (UC) allows harvesting sub-bandgap near-infrared photons in photovoltaics. In this work, we investigate UC in perovskite solar cells by implementing UC single crystal BaF2:Yb3+, Er3+ at the rear of the solar cell. Upon illumination with high-intensity sub-bandgap photons at 980 nm, the BaF2:Yb3+, Er3+ crystal emits upconverted photons in the spectral range between 520 and 700 nm. When tested under terrestrial sunlight representing one sun above the perovskite's bandgap and sub-bandgap illumination at 980 nm, upconverted photons contribute a 0.38 mA/cm2 enhancement in the short-circuit current density at lower intensity. The current enhancement scales non-linearly with the incident intensity of sub-bandgap illumination, and at higher intensity, 2.09 mA/cm2 enhancement in current was observed. Hence, our study shows that using a fluoride single crystal like BaF2:Yb3+, Er3+ for UC is a suitable method to extend the response of perovskite solar cells to near-infrared illumination at 980 nm with a subsequent enhancement in current for very high incident intensity.

http://dx.doi.org/10.1021/acsami.1c13477

Keywords

BaF crystal 2, lanthanide, perovskite solar cells, sub-bandgap transmission loss, upconversion

References

[1] NREL Best Research-Cell Efficiency Chart. https://www.nrel.gov/pv/cell-efficiency.html (accessed Sept 29, 2021).

[2] Green, M. A. Third Generation Photovoltaics: Advanced Solar Energy Conversion; Springer: Berlin Heidelberg, 2003.

[3] Green, M. A. Third Generation Photovoltaics: Ultra-High Conversion Efficiency at Low Cost. Prog. Photovolt. 2001, 9, 123-135, 10.1002/pip.360

[4] Green, M.; Dunlop, E.; Hohl-Ebinger, J.; Yoshita, M.; Kopidakis, N.; Hao, X. Solar Cell Efficiency Tables (Version 57). Prog. Photovolt. 2021, 29, 3-15, 10.1002/pip.3371

[5] Al-Ashouri, A.; Köhnen, E.; Li, B.; Magomedov, A.; Hempel, H.; Caprioglio, P.; Márquez, J. A.; Vilches, A. B. M.; Kasparavicius, E.; Smith, J. A.; Phung, N.; Menzel, D.; Grischek, M.; Kegelmann, L.; Skroblin, D.; Gollwitzer, C.; Malinauskas, T.; Jošt, M.; Matič, G.; Rech, B.; Schlatmann, R.; Topič, M.; Korte, L.; Abate, A.; Stannowski, B.; Neher, D.; Stolterfoht, M.; Unold, T.; Getautis, V.; Albrecht, S. Monolithic Perovskite/Silicon Tandem Solar Cell with >29% Efficiency by Enhanced Hole Extraction. Science 2020, 370, 1300-1309, 10.1126/science.abd4016

[6] Sofia, S. E.; Wang, H.; Bruno, A.; Cruz-Campa, J. L.; Buonassisi, T.; Peters, I. M. Roadmap for Cost-Effective, Commercially-Viable Perovskite Silicon Tandems for the Current and Future PV Market. Sustainable Energy Fuels 2020, 4, 852-862, 10.1039/C9SE00948E

[7] Brown, A. S.; Green, M. A. Limiting Efficiency for Current-Constrained Two-Terminal Tandem Cell Stacks. Prog. Photovolt. 2002, 10, 299-307, 10.1002/pip.425

[8] Jacobs, D. A.; Langenhorst, M.; Sahli, F.; Richards, B. S.; White, T. P.; Ballif, C.; Catchpole, K. R.; Paetzold, U. W. Light Management: A Key Concept in High-Efficiency Perovskite/Silicon Tandem Photovoltaics. J. Phys. Chem. Lett. 2019, 3159-3170, 10.1021/acs.jpclett.8b03721

[9] Trupke, T.; Green, M. A.; Würfel, P. Improving Solar Cell Efficiencies by Down-Conversion of High-Energy Photons. J. Appl. Phys. 2002, 92, 1668-1674, 10.1063/1.1492021

[10] Shalav, A.; Richards, B. S.; Green, M. A. Luminescent Layers for Enhanced Silicon Solar Cell Performance: Up-Conversion. Sol. Energy Mater. Sol. Cells 2007, 91, 829-842, 10.1016/j.solmat.2007.02.007

[11] Richards, B. S. Luminescent Layers for Enhanced Silicon Solar Cell Performance: Down-Conversion. Sol. Energy Mater. Sol. Cells 2006, 90, 1189-1207, 10.1016/j.solmat.2005.07.001

[12] Kroupa, D. M.; Roh, J. Y.; Milstein, T. J.; Creutz, S. E.; Gamelin, D. R. Quantum-Cutting Ytterbium-Doped CsPb(ClBr)Perovskite Thin Films with Photoluminescence Quantum Yields over 190%. ACS Energy Lett. 2018, 3, 2390-2395, 10.1021/acsenergylett.8b01528

[13] Trupke, T.; Green, M. A.; Würfel, P. Improving Solar Cell Efficiencies by Up-Conversion of Sub-Band-Gap Light. J. Appl. Phys. 2002, 92, 4117-4122, 10.1063/1.1505677

[14] Richards, B. S. Enhancing the Performance of Silicon Solar Cells via the Application of Passive Luminescence Conversion Layers. Sol. Energy Mater. Sol. Cells 2006, 90, 2329-2337, 10.1016/j.solmat.2006.03.035

[15] Gibart, P.; Auzel, F.; Guillaume, J. C.; Zahraman, K. Below Band-Gap IR Response of Substrate-Free GaAs Solar Cells Using Two-Photon up-Conversion. Jpn. J. Appl. Phys. 1996, 35, 4401-4402, 10.1143/JJAP.35.4401

[16] Shalav, A.; Richards, B. S.; Trupke, T.; Krämer, K. W.; Güdel, H. U. Application of NaYF: Erup-Converting Phosphors for Enhanced near-Infrared Silicon Solar Cell Response. Appl. Phys. Lett. 2005, 86, 013505 10.1063/1.1844592

[17] Fischer, S.; Ivaturi, A.; Jakob, P.; Krämer, K. W.; Martin-Rodriguez, R.; Meijerink, A.; Richards, B.; Goldschmidt, J. C. Upconversion Solar Cell Measurements under Real Sunlight. Opt. Mater. 2018, 84, 389-395, 10.1016/j.optmat.2018.05.072

[18] Deng, X.; Zhang, C.; Zheng, J.; Zhou, X.; Yu, M.; Chen, X.; Huang, S. Highly Bright Li(Gd,Y)F:Yb,Er Upconverting Nanocrystals Incorporated Hole Transport Layer for Efficient Perovskite Solar Cells. Appl. Surf. Sci. 2019, 485, 332-341, 10.1016/j.apsusc.2019.04.226

[19] Lai, X.; Li, X.; Lv, X.; Zheng, Y.-Z.; Meng, F.; Tao, X. Broadband Dye-Sensitized Upconverting Nanocrystals Enabled near-Infrared Planar Perovskite Solar Cells. J. Power Sources 2017, 372, 125-133, 10.1016/j.jpowsour.2017.10.067

[20] Schoenauer Sebag, M.; Hu, Z.; De Oliveira Lima, K.; Xiang, H.; Gredin, P.; Mortier, M.; Billot, L.; Aigouy, L.; Chen, Z. Microscopic Evidence of Upconversion-Induced Near-Infrared Light Harvest in Hybrid Perovskite Solar Cells. ACS Appl. Energy Mater. 2018, 1, 3537-3543, 10.1021/acsaem.8b00518

[21] Monguzzi, A.; Mezyk, J.; Scotognella, F.; Tubino, R.; Meinardi, F. Upconversion-Induced Fluorescence in Multicomponent Systems: Steady-State Excitation Power Threshold. Phys. Rev. B 2008, 78, 195112, 10.1103/PhysRevB.78.195112

[22] Baluschev, S.; Miteva, T.; Yakutkin, V.; Nelles, G.; Yasuda, A.; Wegner, G. Up-Conversion Fluorescence: Noncoherent Excitation by Sunlight. Phys. Rev. Lett. 2006, 97, 143903, 10.1103/PhysRevLett.97.143903

[23] Kinoshita, M.; Sasaki, Y.; Amemori, S.; Harada, N.; Hu, Z.; Liu, Z.; Ono, L. K.; Qi, Y.; Yanai, N.; Kimizuka, N. Photon Upconverting Solid Films with Improved Efficiency for Endowing Perovskite Solar Cells with Near-Infrared Sensitivity. ChemPhotoChem 2020, 4, 5271-5278, 10.1002/cptc.202000143

[24] Boyer, J. C.; van Veggel, F. C. J. M. Absolute Quantum Yield Measurements of Colloidal NaYF: Er, YbUpconverting Nanoparticles. Nanoscale 2010, 2, 1417-1419, 10.1039/c0nr00253d

[25] Saleta Reig, D.; Grauel, B.; Konyushkin, V. A.; Nakladov, A. N.; Fedorov, P. P.; Busko, D.; Howard, I. A.; Richards, B. S.; Resch-Genger, U.; Kuznetsov, S. V.; Turshatov, A.; Würth, C. Upconversion Properties of SrF:Yb,ErSingle Crystals. J. Mater. Chem. C 2020, 8, 4093-4101, 10.1039/C9TC06591A

[26] Chen, X.; Xu, W.; Song, H.; Chen, C.; Xia, H.; Zhu, Y.; Zhou, D.; Cui, S.; Dai, Q.; Zhang, J. Highly Efficient LiYF:Yb, ErUpconversion Single Crystal under Solar Cell Spectrum Excitation and Photovoltaic Application. ACS Appl. Mater. Interfaces 2016, 8, 9071-9079, 10.1021/acsami.5b12528

[27] Kaiser, M.; Würth, C.; Kraft, M.; Hyppänen, I.; Soukka, T.; Resch-Genger, U. Power-Dependent Upconversion Quantum Yield of NaYF:Yb,ErNano-and Micrometer-Sized Particles-Measurements and Simulations. Nanoscale 2017, 9, 10051-10058, 10.1039/C7NR02449E

[28] Yang, S.; Xia, H.; Jiang, Y.; Zhang, J.; Shi, Y.; Gu, X.; Zhang, J.; Zhang, Y.; Jiang, H.; Chen, B. TmDoped α-NaYFSingle Crystal for 2 mm Laser Application. J. Alloys Compd. 2015, 643, 1-6, 10.1016/j.jallcom.2015.04.112

[29] Cassanho, A.; Knowles, D.; Jenssen, H. P. Optical Properties of Nd:NaYFand Ho:NaYF. Tunable Solid State Lasers 1989, 139-145, 10.1364/ASSL.1989.CC7

[30] Madirov, E. I.; Konyushkin, V. A.; Nakladov, A. N.; Fedorov, P. P.; Bergfeldt, T.; Busko, D.; Howard, I. A.; Richards, B. S.; Kuznetsov, S. V.; Turshatov, A. An Up-Conversion Luminophore with High Quantum Yield and Brightness Based on BaF:Yb,ErSingle Crystals. J. Mater. Chem. C 2021, 9, 3493-3503, 10.1039/D1TC00104C

[31] Richman, I. Longitudinal Optical Phonons in CaF, SrF, and BaF. J. Chem. Phys. 2004, 41, 2836, 10.1063/1.1726360

[32] Khenkin, M. V.; Katz, E. A.; Abate, A.; Bardizza, G.; Berry, J. J.; Brabec, C.; Brunetti, F.; Bulović, V.; Burlingame, Q.; Di Carlo, A.; Cheacharoen, R.; Cheng, Y. B.; Colsmann, A.; Cros, S.; Domanski, K.; Dusza, M.; Fell, C. J.; Forrest, S. R.; Galagan, Y.; Di Girolamo, D.; Grätzel, M.; Hagfeldt, A.; von Hauff, E.; Hoppe, H.; Kettle, J.; Köbler, H.; Leite, M. S.; Liu, S.; Loo, Y. L.; Luther, J. M.; Ma, C. Q.; Madsen, M.; Manceau, M.; Matheron, M.; McGehee, M.; Meitzner, R.; Nazeeruddin, M. K.; Nogueira, A. F.; Odabaşl, Ç.; Osherov, A.; Park, N. G.; Reese, M. O.; De Rossi, F.; Saliba, M.; Schubert, U. S.; Snaith, H. J.; Stranks, S. D.; Tress, W.; Troshin, P. A.; Turkovic, V.; Veenstra, S.; Visoly-Fisher, I.; Walsh, A.; Watson, T.; Xie, H.; Yldlrlm, R.; Zakeeruddin, S. M.; Zhu, K.; Lira-Cantu, M. Consensus Statement for Stability Assessment and Reporting for Perovskite Photovoltaics Based on ISOS Procedures. Nat. Energy 2020, 5, 35-49, 10.1038/s41560-019-0529-5

[33] Joseph, R. E.; Jiménez, C.; Hudry, D.; Gao, G.; Busko, D.; Biner, D.; Turshatov, A.; Krämer, K.; Richards, B. S.; Howard, I. A. Critical Power Density: A Metric to Compare the Excitation Power Density Dependence of Photon Upconversion in Different Inorganic Host Materials. J. Phys. Chem. A 2019, 123, 6799-6811, 10.1021/acs.jpca.9b03851

[34] Stöhr, M.; Roth, K.; Jähne, B. Measurement of 3D Pore-Scale Flow in Index-Matched Porous Media. Exp. Fluids 2003, 35, 159-166, 10.1007/s00348-003-0641-x

[35] Malitson, I. H. Refractive Properties of Barium Fluoride. J. Opt. Soc. Am. 1964, 54, 628, 10.1364/JOSA.54.000628

[36] Ghazy, A.; Safdar, M.; Lastusaari, M.; Aho, A.; Tukiainen, A.; Savin, H.; Guina, M.; Karppinen, M. Luminescent (Er,Ho)OThin Films by ALD to Enhance the Performance of Silicon Solar Cells. Sol. Energy Mater. Sol. Cells 2021, 219, 110787, 10.1016/j.solmat.2020.110787

[37] Menyuk, N.; Dwight, K.; Pierce, J. W. NaYF: Yb,Er-an Efficient Upconversion Phosphor. Appl. Phys. Lett. 1972, 21, 159-161, 10.1063/1.1654325

[38] Suyver, J. F.; Grimm, J.; Krämer, K. W.; Güdel, H. U. Highly Efficient Near-Infrared to Visible up-Conversion Process in NaYF:Er,Yb. J. Lumin. 2005, 114, 53-59, 10.1016/j.jlumin.2004.11.012

[39] Schultes, M.; Helder, T.; Ahlswede, E.; Aygüler, M. F.; Jackson, P.; Paetel, S.; Schwenzer, J. A.; Hossain, I. M.; Paetzold, U. W.; Powalla, M. Sputtered Transparent Electrodes (IO:H and IZO) with Low Parasitic Near-Infrared Absorption for Perovskite-Cu(In,Ga)SeTandem Solar Cells. ACS Appl. Energy Mater. 2019, 2, 7823-7831, 10.1021/acsaem.9b01224

[40] Gharibzadeh, S.; Abdollahi Nejand, B.; Jakoby, M.; Abzieher, T.; Hauschild, D.; Moghadamzadeh, S.; Schwenzer, J. A.; Brenner, P.; Schmager, R.; Haghighirad, A. A.; Weinhardt, L.; Lemmer, U.; Richards, B. S.; Howard, I. A.; Paetzold, U. W. Record Open-Circuit Voltage Wide-Bandgap Perovskite Solar Cells Utilizing 2D/3D Perovskite Heterostructure. Adv. Energy Mater. 2019, 9, 1803699, 10.1002/aenm.201803699

[41] Masi, S.; Gualdrón-Reyes, A. F.; Mora-Seró, I. Stabilization of Black Perovskite Phase in FAPbIand CsPbI. ACS Energy Lett. 2020, 5, 1974-1985, 10.1021/acsenergylett.0c00801

[42] Ma, F.; Li, J.; Li, W.; Lin, N.; Wang, L.; Qiao, J. Stable α/δPhase Junction of Formamidinium Lead Iodide Perovskites for Enhanced near-Infrared Emission. Chem. Sci. 2017, 8, 800-805, 10.1039/C6SC03542F

[43] Binek, A.; Hanusch, F. C.; Docampo, P.; Bein, T. Stabilization of the Trigonal High-Temperature Phase of Formamidinium Lead Iodide. J. Phys. Chem. Lett. 2015, 6, 1249-1253, 10.1021/acs.jpclett.5b00380

[44] Li, Z.; Yang, M.; Park, J.-S.; Wei, S.-H.; Berry, J.-J.; Zhu, K. Stabilizing Perovskite Structures by Tuning Tolerance Factor: Formation of Formamidinium and Cesium Lead Iodide Solid-State Alloys. Chem. Mater. 2016, 28, 284-292, 10.1021/acs.chemmater.5b04107

[45] Conings, B.; Drijkoningen, J.; Gauquelin, N.; Babayigit, A.; D'Haen, J.; D'Olieslaeger, L.; Ethirajan, A.; Verbeeck, J.; Manca, J.; Mosconi, E.; De Angelis, F.; Boyen, H.-G. Intrinsic Thermal Instability of Methylammonium Lead Trihalide Perovskite. Adv. Energy Mater. 2015, 5, 1500477, 10.1002/aenm.201500477

[46] Leijtens, T.; Prasanna, R.; Bush, K. A.; Eperon, G. E.; Raiford, J. A.; Gold-Parker, A.; Wolf, E. J.; Swifter, S. A.; Boyd, C. C.; Wang, H.-P.; Toney, M. F.; Bent, S. F.; Mcgehee, M. D. Tin-Lead Halide Perovskites with Improved Thermal and Air Stability for Efficient All-Perovskite Tandem Solar Cells. Sustainable Energy Fuels 2018, 2, 2450-2459, 10.1039/C8SE00314A

[47] Zheng, X.; Chen, B.; Yang, M.; Wu, C.; Orler, B.; Moore, R. B.; Zhu, K.; Priya, S. The Controlling Mechanism for Potential Loss in CHNHPbBrHybrid Solar Cells. ACS Energy Lett. 2016, 1, 424-430, 10.1021/acsenergylett.6b00215

[48] Shao, S.; Liu, J.; Fang, H.-H.; Qiu, L.; ten Brink, G. H.; Hummelen, J. C.; Koster, L. J. A.; Loi, M. A. Efficient Perovskite Solar Cells over a Broad Temperature Window: The Role of the Charge Carrier Extraction. Adv. Energy Mater. 2017, 7, 1701305, 10.1002/aenm.201701305

[49] Cao, R.; Xu, F.; Zhu, J.; Ge, S.; Wang, W.; Xu, H.; Xu, R.; Wu, Y.; Ma, Z.; Hong, F.; Jiang, Z. Unveiling the Low-Temperature Pseudodegradation of Photovoltaic Performance in Planar Perovskite Solar Cell by Optoelectronic Observation. Adv. Energy Mater. 2016, 6, 1600814, 10.1002/aenm.201600814

[50] Labram, J. G.; Fabini, D. H.; Perry, E. E.; Lehner, A. J.; Wang, H.; Glaudell, A. M.; Wu, G.; Evans, H.; Buck, D.; Cotta, R.; Echegoyen, L.; Wudl, F.; Seshadri, R.; Chabinyc, M. L. Temperature-Dependent Polarization in Field-Effect Transport and Photovoltaic Measurements of Methylammonium Lead Iodide. J. Phys. Chem. Lett. 2015, 6, 3565-3571, 10.1021/acs.jpclett.5b01669

[51] Meloni, S.; Moehl, T.; Tress, W.; Franckevičius, M.; Saliba, M.; Lee, Y. H.; Gao, P.; Nazeeruddin, M. K.; Zakeeruddin, S. M.; Rothlisberger, U.; Graetzel, M. Ionic Polarization-Induced Current-Voltage Hysteresis in CHNHPbXPerovskite Solar Cells. Nat. Commun. 2016, 7, 1-19, 10.1038/ncomms10334

[52] Kim, S.; Bae, S.; Lee, S.-W.; Cho, K.; Lee, K. D.; Kim, H.; Park, S.; Kwon, G.; Ahn, S.-W.; Lee, H.-M.; Kang, Y.; Lee, H.-S.; Kim, D. Relationship between Ion Migration and Interfacial Degradation of CHNHPbIPerovskite Solar Cells under Thermal Conditions. Sci. Rep. 2017, 1, 1200, 10.1038/s41598-017-00866-6

[53] Green, M. A. General Temperature Dependence of Solar Cell Performance and Implications for Device Modelling. Prog. Photovolt. 2003, 11, 333-340, 10.1002/pip.496

[54] Singh, P.; Ravindra, N. M. Temperature Dependence of Solar Cell Performance-an Analysis. Sol. Energy Mater. Sol. Cells 2012, 101, 36-45, 10.1016/j.solmat.2012.02.019

[55] Bartesaghi, D.; del Carmen Pérez, I.; Kniepert, J.; Roland, S.; Turbiez, M.; Neher, D.; Koster, L. J. A. Competition between Recombination and Extraction of Free Charges Determines the Fill Factor of Organic Solar Cells. Nat. Commun. 2015, 6, 7083, 10.1038/ncomms8083

[56] Arnaoutakis, G. E.; Marques-Hueso, J.; Ivaturi, A.; Fischer, S.; Goldschmidt, J. C.; Krämer, K. W.; Richards, B. S. Enhanced Energy Conversion of Up-Conversion Solar Cells by the Integration of Compound Parabolic Concentrating Optics. Sol. Energy Mater. Sol. Cells 2015, 140, 217-223, 10.1016/j.solmat.2015.04.020

[57] Liang, L.; Teh, D. B. L.; Dinh, N.-D.; Chen, W.; Chen, Q.; Wu, Y.; Chowdhury, S.; Yamanaka, A.; Sum, T. C.; Chen, C.-H.; Thakor, N. V.; All, A. H.; Liu, X. Upconversion Amplification through Dielectric Superlensing Modulation. Nat. Commun. 2019, 10, 1391, 10.1038/s41467-019-09345-0

[58] Goldschmidt, J. C. Novel Solar Cell Concepts, University of Konstanz, 2009.

[59] Kuznetsov, S. V.; Alexandrov, A. A.; Fedorov, P. P. Optical Fluoride Nanoceramics. Inorg. Mater. 2021, 57, 555-578, 10.1134/S0020168521060078

[60] Richards, B. S.; Hudry, D.; Busko, D.; Turshatov, A.; Howard, I. A. Photon Upconversion for Photovoltaics and Photocatalysis: A Critical Review. Chem. Rev. 2021, 121, 9165-9195, 10.1021/acs.chemrev.1c00034

[61] Hofmann, C. L. M.; Fischer, S.; Eriksen, E. H.; Bläsi, B.; Reitz, C.; Yazicioglu, D.; Howard, I. A.; Richards, B. S.; Goldschmidt, J. C. Experimental Validation of a Modeling Framework for Upconversion Enhancement in 1D-Photonic Crystals. Nat. Commun. 2021, 12, 104, 10.1038/s41467-020-20305-x

[62] Das, A.; Mao, C.; Cho, S.; Kim, K.; Park, W. Over 1000-Fold Enhancement of Upconversion Luminescence Using Water-Dispersible Metal-Insulator-Metal Nanostructures. Nat. Commun. 2018, 9, 4828, 10.1038/s41467-01--07284-w

[63] Liu, Q.; Liu, H.; Li, D.; Qiao, W.; Chen, G.; Ågren, H. Microlens Array Enhanced Upconversion Luminescence at Low Excitation Irradiance. Nanoscale 2019, 11, 14070-14078, 10.1039/C9NR03105G