# EFRC: LIGHT-MATERIAL INTERACTIONS IN ENERGY CONVERSION (LMI)

UPDATED: AUGUST 2016

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| **AWARDS:** $15.4M (August 2009 – July 2014); $15.2M (August 2014 – July 2018) | |
| **WEBSITES:** http://science.energy.gov/bes/efrc/centers/lmi/; http://lmi.caltech.edu/ | |
| **TEAM:** **California Institute of Technology (lead)**: Ralph Nuzzo (Director), Harry Atwater, Andrei Faraon, Nate Lewis, Austin Minnich; **Harvard University**: Jennifer Lewis; **Lawrence Berkeley National Laboratory**: Paul Alivisatos, Eli Yablonovitch, Xiang Zhang; **Stanford University**: Mark Brongersma, Jennifer Dionne, Shanhui Fan; **University of Illinois, Urbana-Champaign**: Paul Braun, Ralph Nuzzo, John Rogers | |

## SCIENTIFIC MISSION AND APPROACH

The LMI EFRC is a national resource for fundamental optical principles and phenomena relevant to solar energy conversion, and for design of new photonic materials and structures used for energy conversion. The overarching goal is to tailor the morphology, complex dielectric structure, and electronic properties of matter so as to sculpt the flow of sunlight and heat, enabling light conversion to electrical energy with unprecedented efficiency. Applying these photonic principles could enable record photovoltaic conversion efficiency and utilization of the entire visible and infrared solar resource. The Center is organized scientifically into four multi-institutional research groups (RGs).

**RG1 New Light Management Mechanisms**: Exploring new mechanisms and metaphotonic structures for controlling and usefully mediating light-material interactions along with predictive mathematical methods for their inverse design.

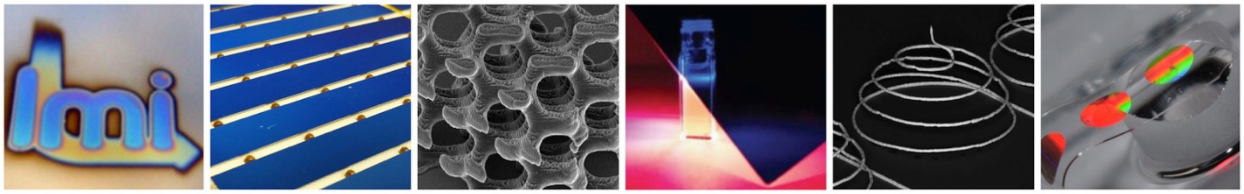
**RG2 Solar Spectrum Control and Conversion**: Designing photonic principles and fully integrated structures delivering unprecedented capabilities for control and conversion of the solar spectrum to greatly enhance photovoltaic efficiency.

**RG3 Thermal Photon Harvesting**: Establishing fundamental principles for the utilization and control of thermal photonics, and discovering new structures and materials that enable efficient and useful forms of energy conversion.

**RG4 Programmable Assembly of Photonic and Electronic Architectures**: Developing powerful new methods for programmable assembly of photonic, electronic, and optoelectronic architectures that yield both materials and device specific elements of enhanced performance.

## SELECTED SCIENTIFIC ACCOMPLISHMENTS

- Discovered new principles of photon emission to maximize photovoltaic conversion efficiencies, providing the foundations of current world record single, dual, and quadruple-junction solar cells.
- Designed photonic crystals with record performance, demonstrating the first optoelectronically active 3D photonic crystal LED and selective thermal emitters with unprecedented stability.
- Advanced quantum dot materials and new principles of photonic design enabling luminescent solar concentrators with record concentration ratios and levels of performance.
- Developed assembly schemes and interface materials for quadruple junction, four terminal solar cells with efficiencies of 44% at concentrations of 1000 suns.
- Developed light-driven material synthesis processes that enable energy conversion materials to develop their own complex architectures in response to illumination conditions.
- Established mathematical methods that enable the design and optimization of photonic structures for light-trapping, spectrum-splitting, and control of near-field thermal emission.



*LMI research, from left: refractive index design via porous Si etching; concentrating photovoltaics capturing diffuse and direct irradiance; gyroid photonic crystal fabricated by two-photon lithography; photonic mirror and quantum dot design for luminescent solar concentrators; printed conductive Ag microstructures; conformal metafilm of Si nanoposts.*

## IMPACT

- **Alta Devices**, co-founded by Atwater and Yablonovitch in 2007, has utilized LMI scientific insights about photon recycling in thin GaAs solar cells to achieve three successive world record open circuit voltages and efficiencies for 1 Sun solar cell conversion efficiency. http://altadevices.com/
- **Electroninks Inc.**, co-founded by J. Lewis in 2013, is commercializing reactive silver ink for printed electronics as well as a low-cost roller ball pen filled with conductive silver particle ink, known as Circuit Scribe, for STEM and the DIY/maker communities. The core technology stems from LMI research developing conductive inks. They launched Circuit Scribe using Kickstarter in November 2013 raising $670,000; and shipped their first products in July 2014. http://electroninks.com/
- **MC10**, co-founded by Rogers in 2008, is commercializing stretchable, wearable electronics. LMI work on microcell fabrication and assembly is being explored by MC10. https://mc10inc.com/
- **Semprius**, co-founded by Rogers and Nuzzo in 2005, is an innovator in high concentration photovoltaic solar modules. LMI's emerging ideas in stacking, multijunction cells and full spectrum utilization are of direct potential significance to the ultrahigh concentration technology platform that currently serves as the basis for Semprius' commercial modules. http://semprius.com/
- **Voxel8**, co-founded by J. Lewis, uses core technology from LMI research on conductive ink development and 3D printed batteries. This VC-backed venture has raised $14.5M since its inception in Fall 2014, and has grown to more than 25 full-time employees. Voxel8 shipped its first commercial product, a desktop 3D electronics printer in May 2016. http://www.voxel8.co/
- LMI research accomplishments have been the basis for more than $11M in follow-on funding from DOE, including four ARPA-E awards:
    - *Optics for full-Spectrum, Ultrahigh Efficiency Solar Conversion* (**PI's**: Harry Atwater, Paul Braun, Eli Yablonovitch) at **$2.4M** from March 2013 to September 2016
    - *Micro-optical Tandem Luminescent Solar Concentrator* (**PI's**: Ralph Nuzzo, Paul Alivisatos and Harry Atwater) at **$3.0M** from February 2016 to February 2019
    - *Micro-Scale Ultra-High Efficiency CPV/Diffuse Hybrid Arrays Using Transfer Printing* (**PI**: John Rogers) at **$2.9M** from January 2016 to December 2018
    - *Wide-Angle Planar Microtracking Microcell Concentrating Photovoltaics* (**PI's**: Noel Giebink, John Rogers) at **$2.9M** from January 2016 to December 2018

## PUBLICATIONS AND INTELLECTUAL PROPERTY

As of May 2016, LMI had published 143 peer-reviewed publications cited over 6,600 times and filed 28 disclosures, 24 US patent applications, and 13 foreign patent applications. One patent has been issued and five patent applications licensed. The top three most highly cited papers are:

- Liu, M. *et al.* A graphene-based broadband optical modulator. *Nature* **474**, 64-67, doi:10.1038/nature10067 (2011). [**953 citations**]
- Kelzenberg, M. *et al.* Enhanced absorption and carrier collection in Si wire arrays for photovoltaic applications. *Nature Materials* **9**, 239-244, doi:10.1038/NMAT2635 (2010). [**781 citations**]
- Aydin, K. *et al*. Broadband polarization-independent resonant light absorption using ultrathin plasmonic super absorbers. *Nature Communications* **2**, doi:10.1038/ncomms1528 (2011). [**501 citations**]