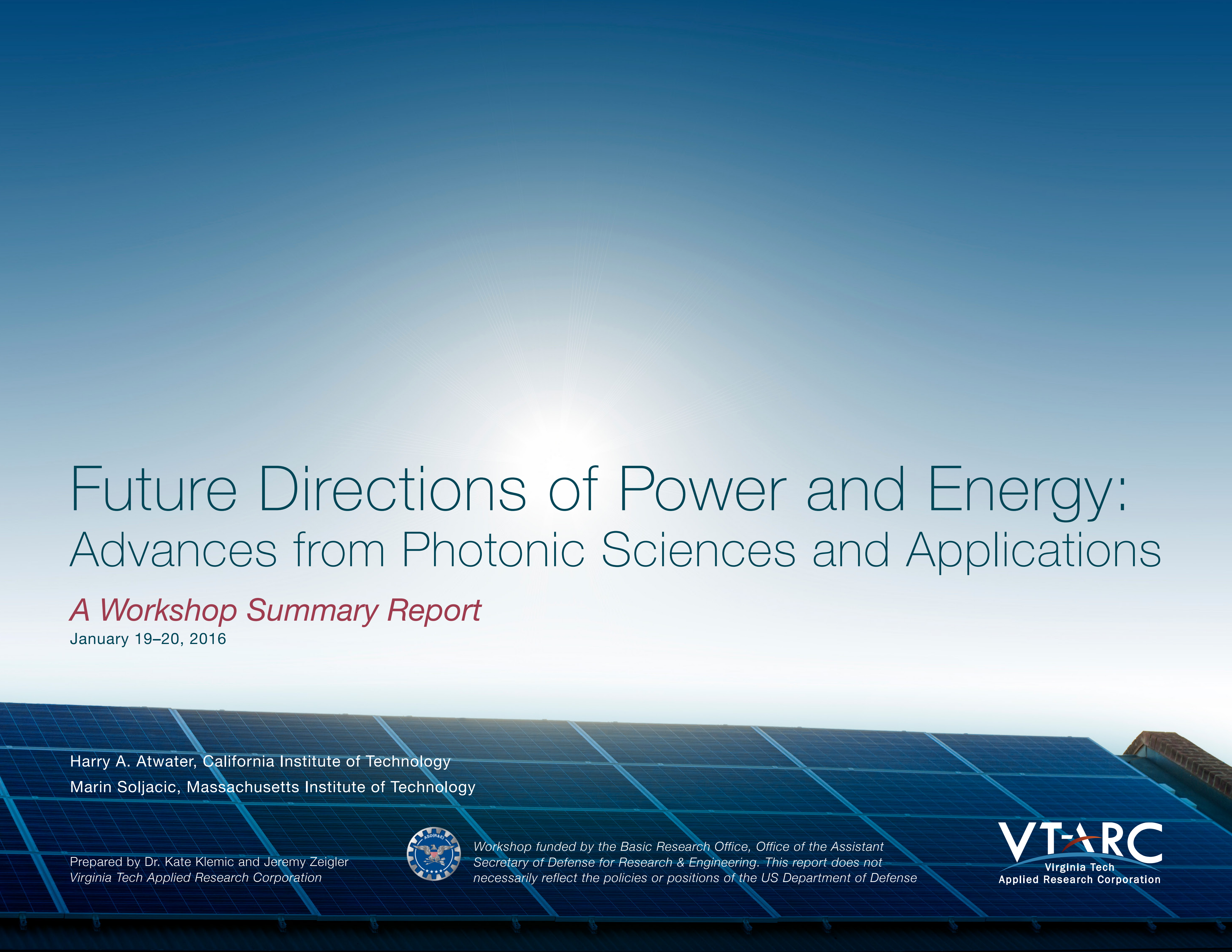

Future Directions of Power and Energy: Advances from Photonic Sciences and Applications

A Workshop Summary Report

January 19–20, 2016

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> Innovation is the key to the future, but basic research is the key to future innovation.
>
> *–Jerome Isaac Friedman,*
> *Nobel Prize Recipient (1990)*

Preface

Over the past century, science and technology has brought remarkable new capabilities to all sectors of the economy; from telecommunications, energy, and electronics to medicine, transportation and defense. Technologies that were fantasy decades ago, such as the internet and mobile devices, now inform the way we live, work, and interact with our environment. Key to this technological progress is the capacity of the global basic research community to create new knowledge and to develop new insights in science, technology, and engineering. Understanding the trajectories of this fundamental research, within the context of global challenges, empowers stakeholders to identify and seize potential opportunities.

The Future Directions Workshop series, sponsored by the Basic Research Office of the Office of the Assistant Secretary of Defense for Research and Engineering, seeks to examine emerging research and engineering areas that are most likely to transform future technology capabilities.

These workshops gather distinguished academic and industry researchers from the world's top research institutions to engage in an interactive dialogue about the promises and challenges of these emerging basic research areas and how they could impact future capabilities. Chaired by leaders in the field, these workshops encourage unfettered considerations of the prospects of fundamental science areas from the most talented minds in the research community.

Reports from the Future Direction Workshop series capture these discussions and therefore play a vital role in the discussion of basic research priorities. In each report, participants are challenged to address the following important questions:

- How might the research impact science and technology capabilities of the future?
- What is the possible trajectory of scientific achievement over the next 10–15 years?
- What are the most fundamental challenges to progress?

This report is the product of a workshop held January 19–20, 2016 at the Keck Conference Center at the California Institute of Technology, Pasadena, CA on Future Directions of Power and Energy: Advances from Photonic Sciences and Applications. It is intended as a resource to the S&T community including the broader federal funding community, federal laboratories, domestic industrial base, and academia.

Executive Summary

On January 19-20th, 2006, a workshop on *Future Directions of Power and Energy: Advances from Photonic Sciences and Applications* was held at the Keck Conference Center at the California Institute of Technology. The workshop gathered 30 distinguished academic and industry leaders in photonic science and technology to review recent and emerging research and to discuss how advances in optical phenomena, materials, and components and systems will impact power and energy technologies of the future. This report summarizes those discussions and presents the opportunities and challenges for photonic sciences, as well as the expected trajectory of research over the next 20 years.

Discussion was broadly divided into two areas: photonic devices and systems and the photonics materials that underly the devices and systems.

For photonic devices and systems, discussion focused on four key areas:

- Solar energy
- Control of thermal radiation
- High power lasers/optics
- Phased arrays and beamsteering

For solar energy, discussion began with a review of recent work on improved photovoltaic light management with highly luminescent, high radiative efficiency materials. This research has yielded new world records for photovoltaic conversion efficiency in single junction and multi-junction cells. In the future, conversion efficiencies are expected to go well beyond today's record efficiencies, as new photonic designs for high efficiency solar converters are developed and prototyped with new high radiative efficiency materials (e.g. perovskites and related materials). New fabrication methods are expected to enable photovoltaics with ultralight form factors for mobile power applications.

Photonic design principles that achieve comprehensive control of thermal radiation were discussed. These will enable control of the emission rate, spectral signature and direction of radiative emission. An important insight was that the cold (~3K) background temperature of deep space is a thermal reservoir that can be used for radiative cooling of objects below room temperature on earth, and to enable efficient power management in space technology applications.

The participants discussed the availability of high power, short-pulse (femtosecond) laser sources and noted that nonlinear optical materials have enabled lab-based optical systems to achieve attosecond-scale speed of optical pulses and high harmonic conversion for ultrashort pulse radiation sources in the extreme ultraviolet and X-ray wavelength regimes. These sources are expected to spur new science at photon energies comparable to those available at large synchrotrons but in more compact laboratory-scale form. Ultrafast pump-probe time-resolved spectroscopy in the ultraviolet and X-ray wavelength ranges are anticipated as well. Also, arrays of compact solid-state laser sources, architected as systems via optical power combining methods, offer the possibility of reliable and scalable high power laser systems.

The participants discussed the development of large phase-coherent arrays of optical and infrared frequency sources and modulators, with characteristics rivaling those of microwave frequency phased arrays. These phased arrays are expected to enable optical and infrared beam-forming and beam-steering arrays that can for example, serve as analogs to microwave radar systems at optical and infrared frequencies (LIDAR systems).

Underlying these advances in optical device and systems is a fast-moving wave of nanophotonic materials science and technology development.

The participants noted the advances and opportunities discussed for photonic materials science as:

- Nanophotonics
- Active media
- Artificial photonic materials
- New materials

They discussed recent progress in artificial photonic materials consisting of two- and three-dimensional arrays of wavelength- and subwavelength-scale plasmonic and dielectric elements. These include photonic crystals, metamaterials, and metasurfaces that enable control of virtually all of the important properties of reflected and transmitted light, including amplitude, phase, polarization and frequency. Progress has been spurred by the ability to design and rapidly prototype two-dimensional metasurfaces using planar lithographic printing methods borrowed from integrated electronics. In addition, sophisticated synthetic methods were discussed for architecting three-dimensional nanoscale materials, such as two-photon lithography.

Artificial photonic materials that enable control of incident and scattered light angle including angularly-selective photonic crystals and *photonic topological insulators*, were noted for the prospect of creating so-called optical diodes that permit light transmission in one direction but not in the opposite direction.

Lastly, the participants reviewed the potential of atomic-scale materials such as graphene, boron nitride and *transition metal dichalcogenides* for potential applications in telecommunications, sensing and cloaking devices. In addition to these, the participants expect the emergence of many previously unknown materials with exotic properties, as well as composite heterostructures composed of laminates of two-dimensional materials.

The participants discussed the challenges that limit progress in photonic science.

For photonic devices and systems, these challenges are the ability to:

1. Tailor photonic architectural designs to specific applications.
2. Fabricate arrays of nanophotonic elements that meet the potential of simulated structures.
3. Efficiently generate high harmonic radiation for true ultrafast ultraviolet and x-ray sources.

For photonic materials, the most important challenges include:

1. To develop low loss plasmonic materials.
2. To exploit the properties of ultrathin and 2-D materials at high efficiency.

The workshop participants were generally optimistic about the field of photonic sciences. They expect that continued research and investment to have a profound impact on both the science and technology of power and energy.

Introduction

Photonics is the highly interdisciplinary science of light and other forms of radiant energy. It encompasses the diverse fields of optics, physics, electrical engineering, chemistry, and material science. Photonics research examines new ways to generate and harness light for technologies related to energy production, sensing, communications, and information processing technologies.

Advances in photonic sciences are fueling progress in many areas of broad relevance to power and energy. Most notably, advances in photovoltaic materials have increased the use of solar energy and therefore reduced the need for fossil fuels. Rapid scientific progress in other areas of photonics also promise important impact, especially for low-power and mobile requirements. For example, chip-based lightwave systems that rely on nanophotonic designs are enabling lightwave systems with potential for bandwidth and information processing power significantly beyond those achievable by today's electronic systems, and scientific advances in nanophotonics are challenging the limits to optical mode volume, optical device switching energy and signal-to-noise constraints.

The Promise of Photonics Sciences for Power and Energy Applications

Solar energy is a key technology for future power and energy generation, for both large-scale terrestrial power generation and power generation in space. Currently, terrestrial solar power is intermittent and limited by the low capacity factor. New research aims to combine solar energy generation with compact and efficient storage into versatile, robust systems that provide dispatchable power. For space-based photovoltaics, breakthroughs are expected to improve efficiency and reduce mass. *Thermophotovoltaic* structures that combine non-solar thermal radiation sources with photovoltaic generation are another related area of opportunity for compact, efficient and dispatchable power generation. New photonic power generation schemes include optical rectification, thermoelectric and photo-thermoelectric phenomena and hot carrier excitation and transport.

Control of thermal radiation in terrestrial and space-based environments represents a challenge and opportunity for photonic sciences. New artificial materials originally envisioned for applications in near infrared communications in visible light waves processes may also have considerable applications in thermal management and infrared radiation control.

New **ultrafast optical systems** are enabling researchers to access strong fields to generate femtosecond to attosecond optical pulses with tailored properties and to utilize these pulses to explore physical phenomena in the time domain that have previously been inaccessible. Strong fields are also enabling generation of high harmonics to create ultrashort pulses of coherent radiation at frequencies spanning from infrared to extreme ultraviolet and X-ray frequencies. **Understanding strong field processes in materials at length scales down to the nanoscale may enable efficient and highly tailorable future high-power optical systems composed of very large numbers of nanoscale components.**

Manipulation and control of coherent radiation using photonic architectures can steer, scan or focus beams at RF frequencies. While approaches such as phased array technology are relatively mature at RF frequencies, their applications at shorter wave including terahertz, infrared, visible and X-ray frequencies is much less well developed, and are limited by lack of versatile materials and device concepts for phase and amplitude modulation.

New **artificial photonic materials** are enabling researchers to sculpt the flow of light and heat in matter. *Photonic crystals*, metamaterials and *metasurfaces* composed of plasmonic and dielectric elements enable optical index, dispersion and loss to be varied over a wide range of parameters. Such materials are composed of wavelength-scale and subwavelength scale assemblies of components, created via top-down and bottom-up assembly methods. New concepts emerging from condensed matter physics such as topological protection may enable control of light in modes that are robust with respect to scattering in materials.

Of considerable interest is the rapidly emerging field of **metasurfaces**, or flat optics composed of wavelength-scale to subwavelength active and passive antenna-like components. **Flat optical metasurfaces offer the potential for developing extremely compact optical components for power and energy applications.** These components can either emulate the function of existing three-dimensional optical components, separately or in combination, as well as lead to the creation of entirely new optical components that do not have analogs in conventional discrete or guided wave optical components.

These new frontiers for photonic sciences were discussed and debated at the recent Future Directions Workshop on Power and Energy held at the Keck Center at Caltech on January 19-20, 2016. This report summarizes those discussions, outlines the proposed opportunities and challenges with a research trajectory for the next 20 years.

Photonic Sciences Research

Advances, Opportunities, Challenges and Future Directions

This workshop gathered experts across the field of photonics sciences, from traditional disciplines like optics and semiconductor physics to emerging areas of nanophotonics and advanced materials. The participants categorized photonics research broadly as either photonic devices and systems science or photonic materials science. This section will examine the recent advances, future opportunities and challenges and the trajectory for each of these sciences. The research trajectory is described as near-term (5 years), mid-term (10 years) and long-term (20 years).

Photonic Devices and Systems Science

The topic of photonic devices and systems were divided into 4 application areas: Solar Energy, Thermal Radiation Control, High Power Lasers/Optics, Phased Arrays and Beamsteering:

Solar Energy

The participants expressed excitement about recent developments in flexible, lightweight and high efficiency photovoltaics and photoelectrochemical solar fuels devices that offer the potential for efficient, lightweight photovoltaics for mobile power. Until recently, high efficiency III-V solar cells such as those based on GaAs and InP were only available as devices fabricated on bulk substrates which are limited by their rigid, fragile and bulky form factor. Advances in *epitaxial liftoff* and thin film synthesis have allowed for high efficiency III-V solar cells on flexible substrates, greatly increasing their utility and reliability. This form factor has also led to important science and technology advances based on *photon recycling* in high radiative efficiency semiconductors (e.g., GaAs, GaInP) to achieve record photovoltaic open circuit voltages and efficiencies in thin film cells. Indeed, because of the consideration given to photon recycling and extraction principles in cell design, the performance of thin film cells now substantially exceeds those of the best on-wafer cells fabricated on bulk substrates. Advances in thin-film fabrication processes are expected in the next 5–10 years to realize thin film structures for other photovoltaic materials.

The greatest challenge for solar energy research is to improve the efficiency of solar energy conversion towards or above the theoretical limits for a given material (i.e. the Shockley-Queisser limit). As Figure 1 summarizes, most photovoltaic materials currently perform well below the SQ limit.

Fundamental research is progressing and new schemes have been proposed that should increase the efficiency and may even allow for efficiencies that exceed this limit, such as high efficiency multi-junction cells, spectral splitting cells, hot carrier *upconversion*, and non-reciprocal structures that couple light into solar cells. The participants also discussed recent advances in inorganic halide perovskite materials which have high radiative efficiency and low manufacturing costs.

The participants expect research within the next 10 years to develop new applications for solar devices cells, including direct heat-to-electricity conversion, cells to power the internet of things, and cells that work under low-light/room-light conditions. For example, new thermophotovoltaic devices have recently demonstrated conversion of the waste heat from a 1200 °C combustion-powered thermal engine to electricity with greater than 50% efficiency.

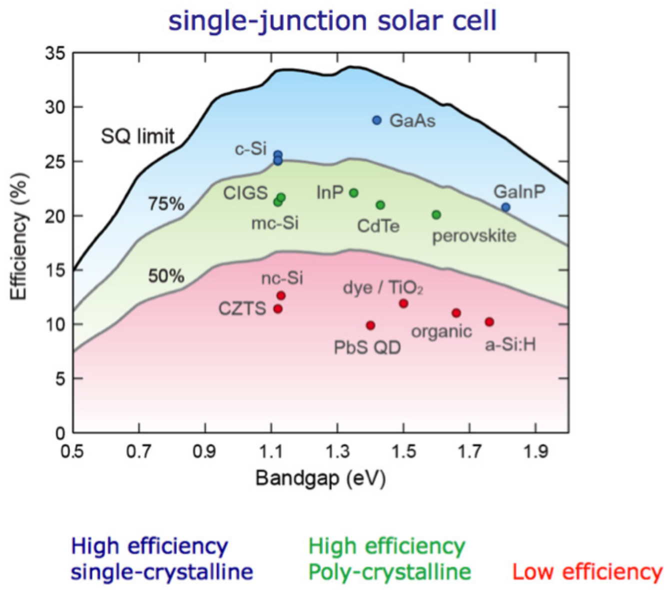

Figure 1: Efficiency of all the major photovoltaic material systems compared to the theoretical single junction (SQ) limit (dark line). Most materials are far from the theoretical limit, leaving much room for improvement *(Polman et al. Science, 352, 6283 (2016)*.

Thermal Radiation Control

The participants discussed recent progress in control of thermal radiation for applications ranging from energy (radiative cooling, ambient power harvesting, thermophotovoltaics, steam generation, solid state lighting), space (power generation out of thermal radiation with emphasis on weight and form factors, and ease of large-scale deployment), environment (water desalination and purification, thermally "smart" windows and roofs, forward-operating base thermal management), sensing (thermal radiation sources, compact spectroscopic thermal imagers, sources for chemical sensing) and defense (thermal signature management and obfuscation). Figure 2 illustrates examples of recent results that use novel photovoltaic devices that generate steam (left) or passively cool the air to 5 degrees below ambient (right).

The participants identified a number of technological and scientific advances needed to realize these technologies. **Near-term research aims to improve active control of thermal radiation with new devices that have highly tunable structures and new materials with desired temperature-dependent phase transitions.** Depending on application, such structures should be conformal, low-weight, flexible and expendable.

Of similar near-term relevance is the development of spectrally selective filters which would have an essential role in passive radiative cooling, thermophotovoltaics, high-temperature radiation tailoring, hyperspectral imaging, etc. A key challenge is developing capabilities for advanced photonic design and fabrication with tunable 2D materials and scalable 3D nano-printing techniques. To achieve this, it would be helpful to establish: a database of material properties in the relevant thermal wavelength ranges, design rules and foundry standards for fabrication, as well as standardized measurement capabilities.

Efforts to exploit the cold universe at 3K as a thermodynamic resource present a near-term technological challenge. One of the promising applications that this could enable is efficient passive radiative cooling of objects or buildings (e.g. a house or a forward-operating base). Pushing the boundary of this concept, one can envision thermally self-regulating structures, radiative cooling of the Earth, or laser cooling applied to the atmosphere.

In the mid-term, **an important scientific challenge will be to understand the fundamental science underlying thermal radiation from non-equilibrium systems, systems with gain, and nonlinear materials.** Fundamental questions that pertain to this include radiative thermal energy exchange in systems with multiple temperatures (such as hot electrons/cold phonons), violation of Kirchhoff's law (with potential application of such capabilities), and efforts to increase the low power density of thermal radiation in the far field.

Figure 2. (Left) Solar steam generation by heat localization *(Ghasemi et al. Nat. Comms 5, 4449 (2014))*. **(Right) Passive radiative cooling under direct sunlight** *(Raman et al. Nature, 515, 7528 (2014))*.

High Power Lasers/Optics

The workshop participants reviewed recent advances in laser and optics research that increase the power and extend the frequency range to extremely short pulses of light. Applications range from spectroscopy, communications, and sensing and detection, and military applications like laser weapons and mid-infrared (mid-IR) countermeasures.

They identified the challenges and opportunities as:

1. Compact, efficient, and cost-effective extended ultraviolet (EUV) and X-ray sources.
2. Reliable high-power pico-, femto-, and atto-second lasers.
3. High-power mid-IR and terahertz (THz) sources.
4. Nonlinear materials and engineered structures for high-power and high duty cycles that work from the mid-IR to the UV.

Of particular interest is the potential for high power lasers to be used as a *table-top X-ray* sources (Figure 3). Free electron X-ray sources are important for studies of the crystal, energy, and electronic structure of solid and living biological matter. This is the only reliable tools available for resolving individual proteins and viruses. Currently, X-ray free electron lasers (XFELS), such as the Stanford Linac Coherent Light Source (LCLS), are housed in large and expensive facilities. A tabletop X-ray source would reduce the energy, cost, and size and make these instruments more accessible to researchers. They could be as ubiquitous as electron microscopes.

One limiting factor to building table-top x-ray source is the need for new high-power and ultra-fast lasers that go beyond the femtosecond range and and operate in the attosecond range. These extremely short laser pulses are key to generating high-intensity and ultra-fast X-rays. Research to overcome these issues includes 1) [high harmonic generation]() (HHG) in ionized [plasmas]() 2) nanostructured [photocathodes]() driven by THz sources and 3) theoretical designs that use highly confined surface plasmons in graphene as the undulator for electrons (as opposed to a series of magnets in standard XFEL designs) (Figure 4).

Creating an X-ray source via high harmonic generation (HHG) in ionized plasmas is a promising technique because it provides a super-continuum of light that simultaneously streams UV to X-ray wavelengths, providing a very flexible light source. These new systems are driven by a femtosecond mid-IR laser into a high-pressure gas cell containing ionized gas. Current X-ray sources have reached 1.6 keV energy with modest efficiencies of 10^{-9}. Continued development of hollow photonic crystal fibers will enable this approach to go even further.

Hollow photonic crystal fibers engineered for high harmonic generation and frequency conversion especially for the UV range are of technological interest in the next five-year horizon (Figure 5). These photonic crystal fibers provide a long effective interaction length and a small mode area that substantially decrease laser-pumping thresholds for nonlinear optical effects. In the case of X-ray sources, these hollow fibers can contain a gas which acts as a gain medium and serves as a guide for the powerful and ultra-short laser beams necessary to drive the plasmas. Similarly, other photonic crystal structures may also offer frequency conversion via four-wave mixing, as well as sensing capabilities that could potentially be integrated into a chip.

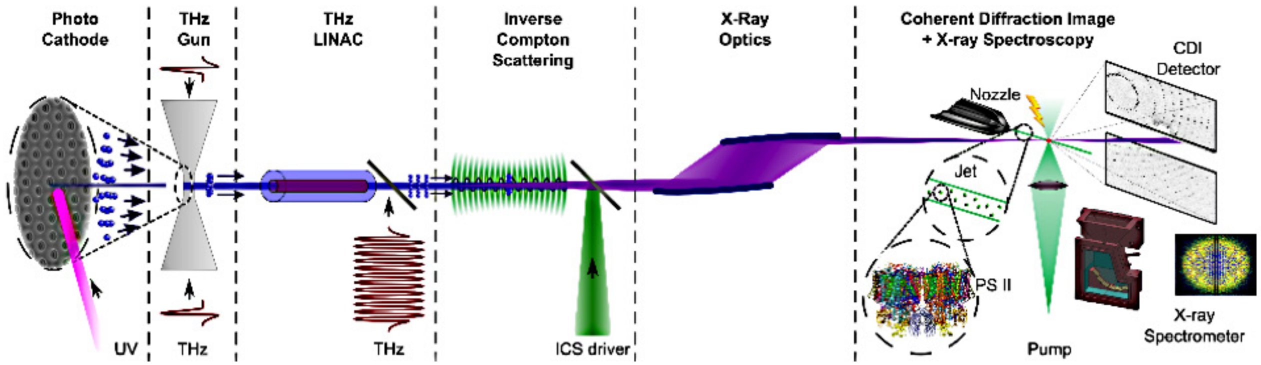

Figure 3. Design for a tabletop X-ray source with nanostructured photocathodes as a source of electrons. The system has intrinsic attosecond synchronization and requires only picosecond lasers at the 1J-level for kHz operation *(Nanni et al. Nature Comms. (2015))*.

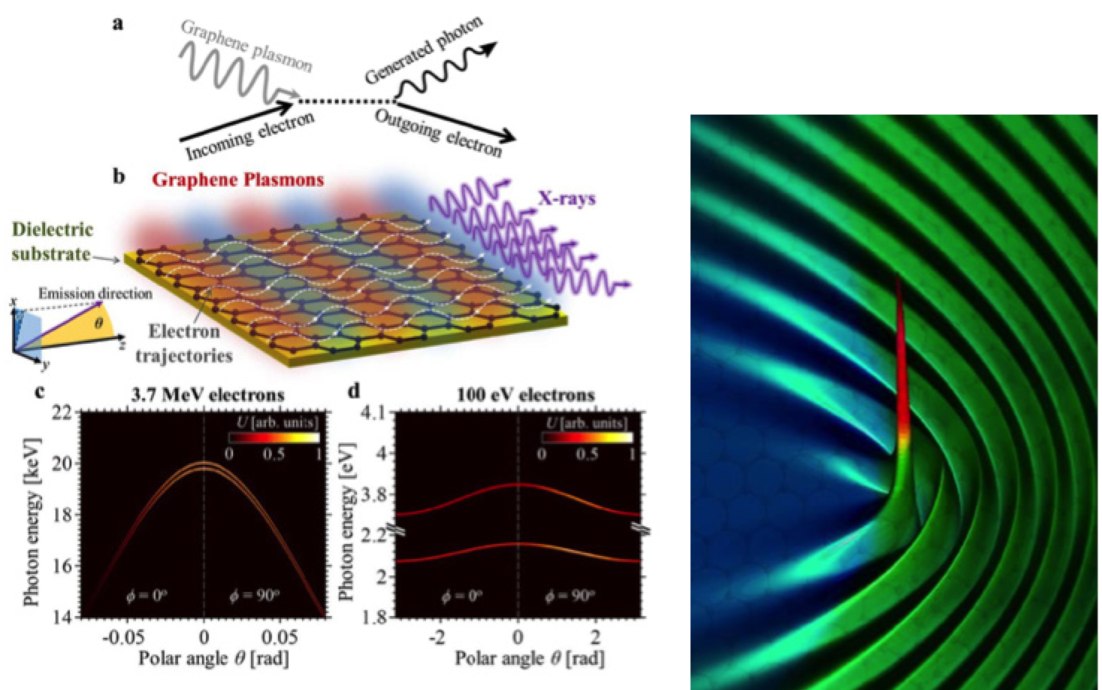

Figure 4. Theoretical design for a graphene plasmon-based free-electron IR to X-ray source. Surface plasmons undulate the electrons and replace the series of magnets in more traditional X-ray sources *(Wong et al. Nature Photonics, 46-52 (2016))*.

Nanostructured photocathodes can be used to make a compact source of electrons. To reach X-ray energies of 10 keV, the pitch and the size of these photocathodes will need to be reduced below 100nm. Continued development of nanofabrication techniques at a large-area scale and improved THz light sources will mark important steps for this approach. Improved nanofabrication techniques will not only benefit these THz sources but will also benefit any technology that requires nanoscale components.

The participants discussed research areas that will improve reliability, manufacturing robustness, and usability of high-power picosecond and femtosecond lasers. Within the next five years they expect that three primary types of lasers will be improved: fiber-lasers, thin disk lasers, and cryogenic lasers (each category has specific advantages). Fiber-lasers can generate higher continuous-wave production while having increased reliability, low jitter and noise, and a compact solid-state design. Attosecond lasers will take longer to meet the same reliability.

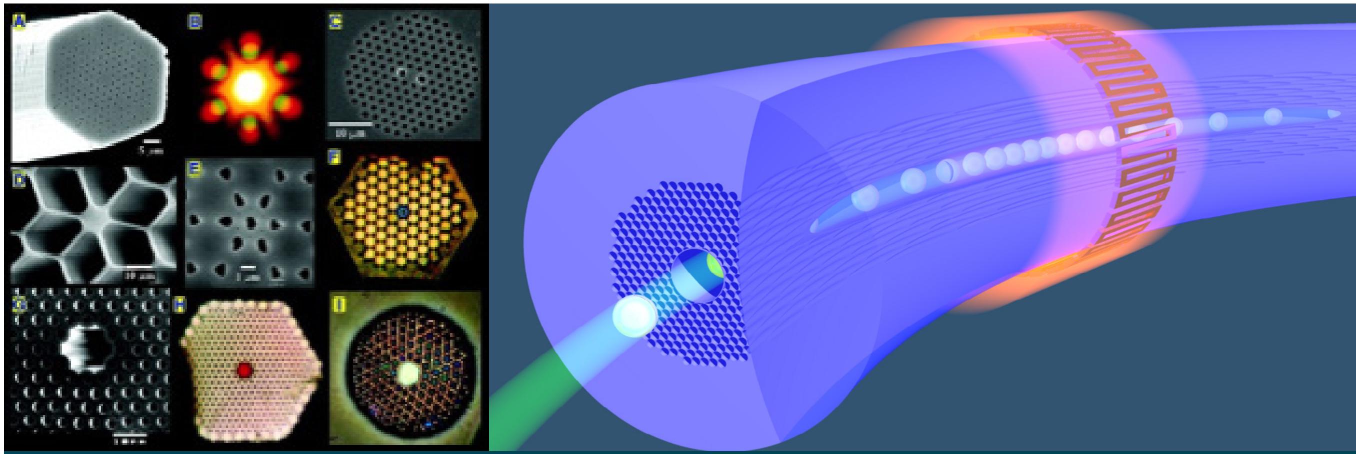

Figure 5. Photonic crystal hollow-core fibers that confine very large power densities, enhance nonlinear interactions, and improve phase matching *(Russell, Philip Science, 358-362 (2003))*. **An ionized gas that acts as the** *gain medium* **can be contained in the core** *(Dholakia et al. Physics 5, 76 (2012))*.

Another near term challenge is the improved production of *periodically poled lithium niobate* (PPLN) and other high-end nonlinear materials for high-power and high duty cycle lasers. The current technical challenge is to produce larger high-quality crystals. It will be necessary to promote significant infrastructure in the manufacturing of these and related nonlinear materials. Collaborations with national labs and industry may prove necessary to produce these important crystals. In addition to X-ray sources, improved PPLN will have broader impact in the telecommunication industry and may be used to generate polarization-entangled photon pairs for quantum key distribution.

The participants also discussed the need for optically driven high power THz sources for a wide-ranging sensing and detection applications. THz radiation can stimulate molecules and electrons in materials without ionizing the electrons off of atoms or molecules. Future technologies may include imaging human tissue without damage, non-invasively checking for defects in materials, and identifying explosives. Two promising approaches include (i) THz sources generated in solid-state nonlinear optical materials (mentioned above) and (ii) tailoring laser-driven plasma sources to produce broadband THz pulses. This research has a high scientific and technological priority for the next 5 to 10 years.

Lastly, with the progress of UV/EUV and X-ray sources, it will be necessary to extend artificial photonic structure concepts to UV/EUV and X-ray for beam manipulation. **This research will not only have a direct impact on high-power and ultra-fast light sources but will also open up new possibilities for industry to mass produce nanoscale optical and electronic devices.** This will require new materials and improved optical designs that will be of major scientific interest in the next twenty-year horizon.

Phased Arrays and beamsteering

Emerging trends in electromagnetic beam forming and its active steering by radio frequency (RF) and optical phased array systems is a topic that drew significant attention among the workshop attendees. Such systems form the backbone of high-power sources and lasers, Radars and light Radars (LIDARs) and are of immense importance for both military and civilian applications. Ultra-long distance communication, wireless power transfer, power-efficient multi-target high-speed identification and tracking, autonomous navigation, and directional electromagnetic weapons are just some of many prospective technologies that were outlined during the discussion.

In particular, **high priority trends emerging in this field that will offer significant technological advances for potential use in the next five to ten years include:**

1. Design of tiled large transmit/receive aperture optical phased arrays on a semiconductor chip for high-power and agile beam-steering, directional sources and light radars.

2. Design of RF and optical metasurface-based phased arrays with highly tunable subwavelength elements for generation of arbitrarily shaped RF and optical beam patterns at much lower cost and higher efficiency than modern active electronically steerable arrays (AESAs).
3. Design of compact, low-loss, optical true-time delay lines via coupling of photons with slow-wave excitations, such as phonons, for wideband RF photonics and optical phased arrays with zero squint.

Phased array antennas represent networks of radiating elements assembled together and acting coherently to form radiation pattern with desired parameters. Introducing phase difference between individual radiating elements enables control over beam shaping. Although beam steering with phased arrayed antennas has remained an active research area for decades (with the US taking a leading role in the field), a number of important recent developments that will drive progress were identified by the attendees.

In particular, novel guided-wave metasurface-based frequency-diverse static aperture devices without mechanical scanning or dynamic beam-forming elements have been proposed (Figure 6, left). Furthermore, **the use of liquid crystal TFTs as a substitute for power-hungry electronics was demonstrated for fast (sub-nanosecond), cost-effective (~$100) and low switching power beam steering.** These developments suggest pathways for conceptually new holographic imaging systems, arbitrary amplitude and/or phase pattern forming. Research in 5–10 year timeline will push these systems to higher operating frequencies and faster switching speeds than current liquid crystal devices, as well as allow for fully digital beam forming with high power capabilities—enabling technologies beyond modern AESAs utilized in, for example, state of the art aircraft such as the F-35.

Participants reviewed the remarkable progress made in the near infrared and visible frequency range. Several new concepts of novel chip-based arrays and components for tunable, conformal, gimbal-free beam steering and shaping have been suggested. Such systems open pathways for all-electronic low-coast ultrafast LIDARs and multi-target high-power high-directionality lasers. Specifically, with the help of an integrated photonics approach, 1ft semiconductor-based tiled optical phase arrays capable of large steering angles (~60 degrees) for 8 kW beam output were demonstrated; novel field-effect tunable metasurfaces comprised of subwavelength elements for phase and wavefront engineering at 1550 nm free-space wavelength were shown (Figure 6, right), and, finally, true-time chip-scale optical delay lines based on Brillouin photon-phonon coupling in 100 nm silicon membranes were discussed. **These developments in the near future (5–10 years) may provide support for much higher power beams and may enable next generation of optical phased arrays: miniaturized, low-size, power-efficient, broadband and ultra-fast.**

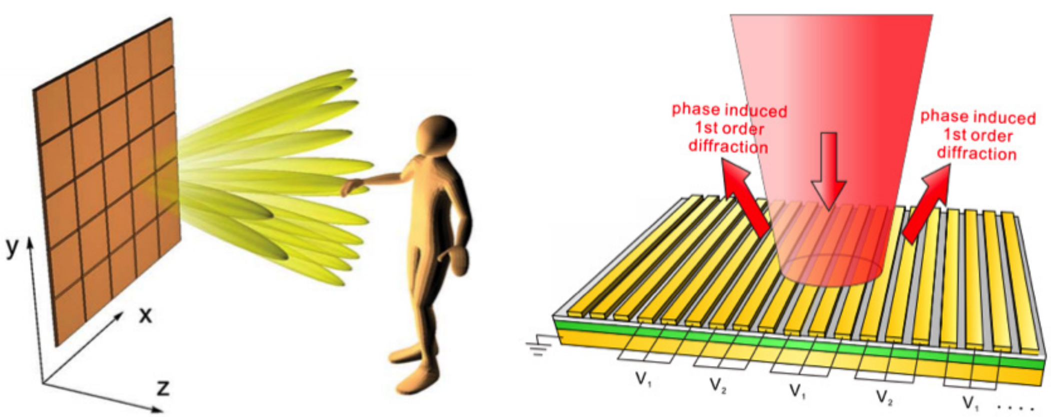

Figure 6. (Left) Metasurface based holographic imaging *(Hunt et al., J. Opt. Soc. Am. A 31, 2109 (2014))*. **A pseudorandom multi-frequency beam pattern formed by a metasurface allows for 3D spatial imaging of the target. (Right) Electric-field-effect tunable conformal optical phased array metasurface** *(Huang et al., arXiv 1511.09380 (2015))***—beam steering is due to electrically induced phase delay between the array elements.**

Technological progress in these areas will help perfect these emerging conformal optical phased arrays that will support developing techniques for side lobe suppression via spacing the array elements beyond the diffraction limit. It will also enable larger aperture (~10 m in diameter) low-loss arrays for high-power lasing, provide higher switching speed (~ 1 ms in 5–10 years and ~1 ns in 20 years, respectively) and enable wider steering angles (60–100 degrees). In the area of plasmonic reflect-array metasurfaces, it is expected that this will allow for lower loss systems (capable of supporting higher powers) and higher degree of tunability (full amplitude and 360 degree phase control).

The participants also outlined potential research directions that may push the boundaries of the field. These include the design of novel high-plasma frequency plasmonic materials based on effective electron mass engineering, which may create RF inspired components (e.g., diodes) at optical frequencies, the design of ultra-light and extra-large size RF phased arrays combined with photovoltaic elements that can be deployed into space for solar energy harvesting, and the extension of phased array systems to ultraviolet and X-ray frequencies.

Photonic Materials Science

Research in photonic materials science is fundamental to the development of the photonic devices and systems described above. Participants anticipate rapid development with continued research in these 4 areas: *Plasmonics*/Dielectric Nanophotonics, Active Media, Artificial Photonic Materials, and New Materials

Plasmonics/Dielectric Nanophotonics

The promise of the field of plasmonics is the ability to guide and localize light at the nanoscale. The strong interaction between free electrons in metals and electromagnetic waves has made metals the traditional material of choice for plasmonic structures. However, metals suffer from high losses at optical frequencies, necessitating the development of alternative materials and structures to perform similar functions in this frequency range. Pushing this notion to the limit, **workshop participants envision an extremely low loss plasmonic material with the ability to confine light at scales much smaller than the wavelength of light in free space**. While it is not yet clear how such a material will be realized, its usefulness cannot be overstated. As a near-term (5-year) scientific challenge, participants call for research in engineered materials with high plasma frequencies that work as electrical conductors at optical frequencies.

A key challenge is the development of plasmonic and dielectric metasurfaces and metamaterials for controlling light (Figure 7). Such devices, both large-area and compact, must enable spectral, angular, and scattering tunability. Active gain-loss metallic-dielectric composites may be used to attain directional emission or perfect absorption. Among other applications, this capability would be instrumental in energy conversion, particularly in enhancing absorption in photovoltaics and thermophotovoltaics.

Emerging 3D nano-printing methods (such as a Nanoscribe) offer a route for 3D photonic crystal band gap materials and unprecedented photonic control. **A key near- and mid-term technological challenge is extending these 3D fabrication capabilities to smaller scales and more materials, as well as integrating them with tunable 2D materials (where optical properties can be controlled by chemical doping or electrical bias).**

With the increase in computational capabilities, aperiodic, topology (computer) optimized structures are beginning to fundamentally alter the landscape of nanophotonic devices. Such numerical optimization tools have already enabled orders of magnitude greater figures of merit than conventional (hand-designed) structures—examples include structures for nonlinear efficient frequency conversion and wide-angle applications. A near-term scientific challenge is to leverage the power of machine learning and inverse design methods to enable plasmonic devices with superior performance, smaller size and novel functionality.

Plasmonic and dielectric metasurfaces and meta-materials are beginning to illustrate versatility for surface engineering, including selectively reflective/absorptive surfaces. Going forward, new device designs using cavities, sub-wavelength antennas, and engineered surfaces are needed. These devices should strongly enhance light emission and absorption of emerging optoelectronic materials, especially in the visible, near, and mid-IR regime, within the next 10 years.

Recent theoretical advances have shown that the effective mass of electrons can be tailored in semiconductors with certain artificial superlattices. Such systems can exhibit extremely strong electron response and very high conductivity. **A mid-term (10-year) scientific challenge is to investigate combined electronic and photonic dispersion engineering via artificial superlattices, towards realizing a new type of low-loss plasmonic material.**

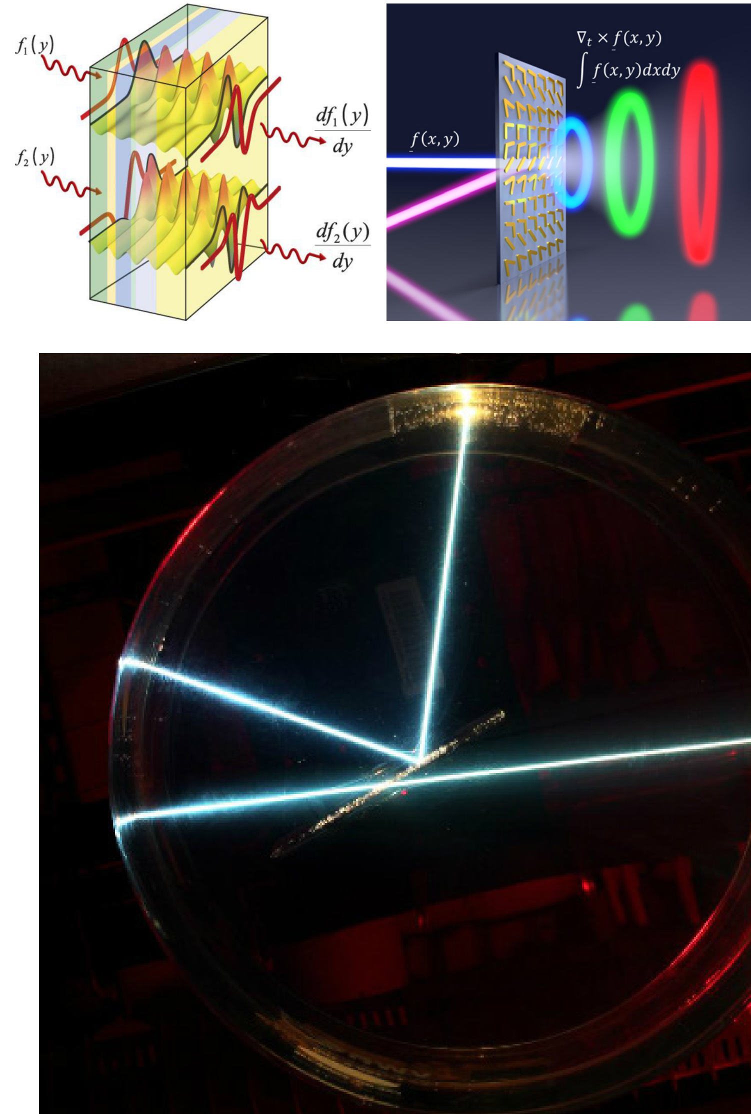

Figure 7. (Top, left) Metastructure *(A. Silva, F.Monticone, G. Castaldi, V. Galdi, A. Alu and N. Engheta, Science, 343, 160-163 (2014))* **and (top, right) Metasurface designed to perform mathematical operations on the input light profile** *(Koenderink et al. Science, 348, 6234 (2015))*. **(Bottom) Metamaterial structure demonstrating angular selectivity of light transmission** *(Shen et al. Science, 343, 6178 (2014))*.

Active Media: Nonlinear Optics, Spontaneous Emission, Gain, Optomechanics

During the workshop, significant attention was dedicated to novel directions in the field of active media. Active media is defined as a class of systems and materials that strongly interact with electromagnetic radiation, such as nonlinear materials, gain media, optomechanical systems and quantum systems (e.g., atoms and quantum dots). The areas where such systems and materials find their application are diverse, ranging from sensors and lasers to communication and computing. The applications of particular interest are high-power wavelength-agile terahertz and mid-infrared lasers (which may be used as weapons and mid-IR countermeasures), power-dependent metasurfaces with arbitrary spectral control for high-power laser damage protection, optically active coatings for environment-dependent fluorescent sensing, and novel paradigms for low-energy and fast optics-based image processing and computing. It is important to mention that the US is one of the leaders in the field.

Workshop participants outlined several emerging trends and areas of high priority in the field of nonlinear materials, gain, and frequency conversion for the next 10 years. Specifically, the following subareas have been identified as high priority: 1) extending the frequency conversion and gain to new wavelengths including mid-IR, terahertz (THz), vacuum ultraviolet (VUV) and X-ray for generation of high power and/or energy density beams and short pulses, 2) development of optically driven high power THz sources, and 3) manufacturing of large scale nonlinear optical materials for mid-IR to THz.

Recent developments have suggested that these goals are achievable with continued effort. In particular, very efficient mechanism of THz generation via optical rectification in cryogenically cooled periodically polled Lithium Niobate (LiNbO3) was discussed. As was the recent use of higher power pump lasers, to extend THz generation efficiency over 10%. Such a method offers a promising technology for compact, efficient, low-cost high output power THz and mid-IR lasers in the range of 0.3–30 THz.

New research will be focused on development of such nonlinear lasers that will enable new technologies in previously inaccessible frequency domains. **In a 5 year horizon, it is expected that with the use of high power (1kW) and/or high energy (1J) infrared lasers (1–2 micron) high power wavelength agile THz sources will be developed.** It is further anticipated that utilizing nonlinear materials with ultralow dispersion form THz to optical frequencies (such as ZnGeP, CdSiP), a phase-mismatch free ultra-broadband gain across THz and mid-IR may be realized. In a 10 year timeline, manufacturing larger scale nonlinear materials, for instance larger size LiNbO3 crystals, will enable kW output powers. **Within a 20 year horizon, it is expected that tunable kW far- and mid-IR lasers will be developed, enabling such technologies as solid-state kW-power THz phased arrays.** Near-term basic research in these directions may potentially extend the frequency conversion techniques to vacuum ultraviolet and X-ray frequencies.

Other high priority research directions for nonlinear optics research over the next 10 years include: developing reconfigurable nonlinear metasurfaces with arbitrary spectral control (power, wavelength, direction, polarization in transmission and reflection, wavefront control), accessing ultra-low power optical nonlinearities (down to single photon) in an integrable form and at room temperature, and optical signal processing at extremely low power and ultra-fast speeds.

Optical photonic circuits (Figure 8) have the potential to reduce the energy requirements by 1000x, from femtojoule energy per bit of information used in modern electronic systems to as little as an attojoule per bit. In addition, they would work at 100THz or greater speeds compared to current GHz frequencies. Different architectures have been proposed for large scale photonic networks, including a neuromorphic architecture that mimics the human brain's visual cortex. Research in this area will allow for better understanding of the system-level architecture in the presence of nonlinearities and will foster the development of chip-scale systems.

Ideas that push the boundaries of science and technology were also discussed. In particular, the

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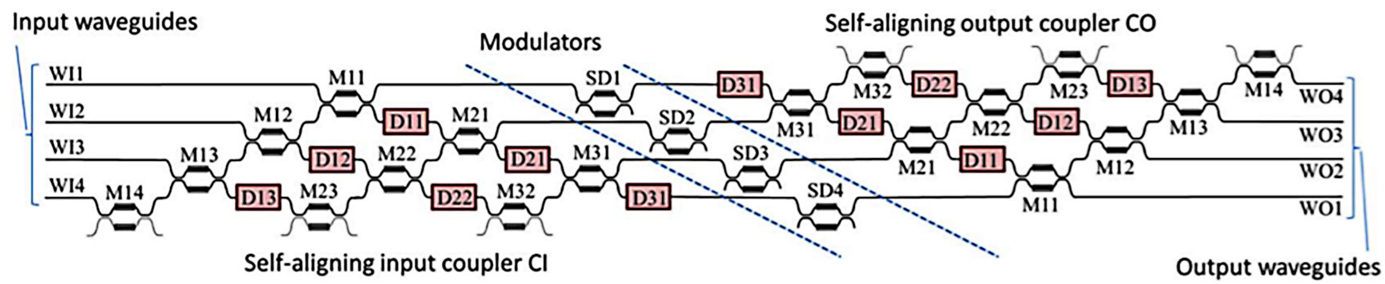

Figure 8. Very large scale integrated (VLSI) optics for optical signal processing *(D. A. B. Miller, Photon. Research 1, 1, (2013))*. **Introducing nonlinear elements into the system may enable conceptually new signal processing paradigms.**

extension of artificial photonic structure concepts to UV and X-ray was named a scientific challenge with a 20 year horizon; study of light coupling with matter excitations, such as phonons, polaritons, excitons was identified as an area of basic research that may enable novel opto-electronic systems; and, lastly, development of conformal coatings for large-area, passive, optical sensing and read-out via environment-dependent fluorescence or reflectance changes was mentioned as medium priority technology within a 10 year span.

Artificial Photonic Materials

Recent advances in nanofabrication and simulation of electromagnetic behavior at the nanoscale has led to the burgeoning field of artificial photonic materials. These are materials with engineered structure at the scale of the electromagnetic wavelength that perform functions not traditionally possible with conventional optics. Included in this topic are the fields of metamaterials, metasurfaces, photonic crystals, photonic *topological insulators*, etc.

The greatest advances are expected over the next 10 years with the development of reconfigurable metasurfaces that permit arbitrary spectral control (power, wavelength, direction, polarization in transmission and reflection, and wavefront control). For example, artificial photonic materials with arbitrary wavefront control could be used to modify the orbital angular momentum of light which would increase the amount of data carried by a single optical fiber. Combining nanoantennas with variations of active matrix technology could provide dynamic beam forming and wave forming apertures. If achieved in the optical regime, this could lead to novel display technologies. For example, if a display could detect the location of the viewer, it could only send the image in that direction rather than into the half space, greatly increasing its efficiency. The ability of a surface to dynamically change its reflectivity or absorptivity could lead to technologies such as passive displays without light emission elements, as well as dynamic camouflaging techniques.

Further development of spectrally and angularly selective filters could lead to many technological advances in the next 5–10 years. This includes passive radiative cooling by blocking radiation that would typically be absorbed while emitting thermal radiation into local transparency windows, selective thermal emission, such as incandescent bulb filters that recycle infrared radiation that is typically wasted, directionally and spectrally more efficient solid state LED lighting, blocking infrared light in compact cell phone cameras, and hyperspectral imaging. **For space applications, nearly every surface of a satellite or spacecraft could be covered with its own spectrally selective surface and/or have its own optical function.** This could aid in thermal control, navigation, and camouflaging. Additionally, ground and air vehicles could also benefit from spectrally selective surfaces custom designed for each surface and application.

The participants also discussed potential applications of photonic topological insulators that would benefit from further fundamental scientific research over the next 5–10 years. This includes dynamic low-loss non-passive modulation and topologically protected one-way optical propagation that could potentially lead to schemes that achieve -110dB optical isolation. An example of a photonic topological insulator waveguide is shown in Figure 9. Additionally, further investigation into schemes for achieving large area/volume single optical modes, such as photonic crystals with Weyl points where the number of optical states don't scale with size, could lead to the development of compact high powered lasers.

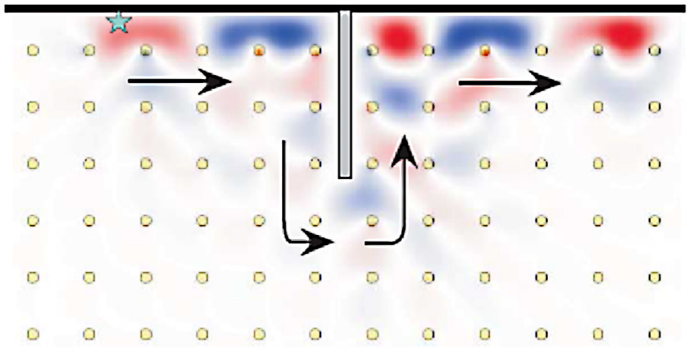

Figure 9. Topologically protected one-way waveguide in which electromagnetic radiation can maneuver around obstacles because backscattering is completely suppressed *(Wang et al. PRL 100 13905 (2008))*.

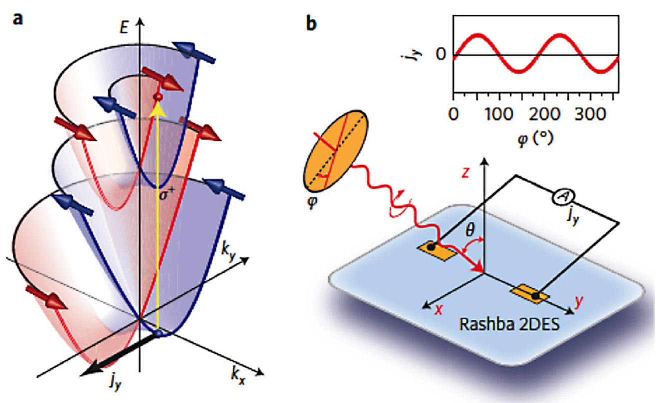

Figure 10. A non-uniform distribution of photo-excited carriers in k-space by circularly polarized light results in spin polarized photocurrent *(Yuan et al. Nature Nano., 851-857 (2014))*.

New Materials

The emergence of novel nanomaterials over the past decade has created new challenges and opportunities for low weight, highly efficient solar cells, low-power telecommunication, and improved sensing. **The participants discussed the need for new materials with highly tunable optical and electronic properties, improved understanding of growth and processing, and computational approaches to predicting and confirming material properties and proposed a trajectory of research to produce the next generation of highly efficient power and energy devices over next twenty years.**

Of particular interest is two-dimensional (2D) materials such as graphene, black phosphorus, and transition metal dichalcogenide (TMDC) monolayers such as molybdenum disulfide (MoS^2) that have highly tunable optical and electronic properties, topological insulators such as bismuth selenide (Bi^2Se^3) and bismuth telluride (Bi^2Te^3) for newly discovered electronic surface states that are robust against defects. The controlled absorption and emission of light and the subsequent spatial and frequency control of light in 2D materials will lead to promising telecommunication, sensing, and cloaking devices.

Advances over the past five years have discovered more exotic properties in 2D materials. Circularly polarized light has produced polarized photocurrents in tungsten diselenide (WSe^2) that depends on the degree of polarization of incident light and can be further modulated with an external electric field. The creation and electric control of spin photocurrents (Figure 10) can possibly extend the functionalities of spintronics into actual devices. Recently discovered Dirac surface states in Bi^2Se^3 prevent the backscattering of electrons from defects which enables more energy efficient devices. Lastly, coupling these spin waves to surface plasmons can give rise to a hybridized "spin-plasmon" that has enhanced lifetimes, thus, providing a possible solution for low losses in plasmonic devices that can concentrate light orders of magnitude below the diffraction limit and lead to ultra-compact optoelectronic devices.

The participants emphasized the need for improved growth and processing of III-V materials, perovskites, and 2D materials to meet the needs for the next generation of power and energy technologies. Several paths of research outlined include i) the ability to grow new nanomaterials, ii) low cost way to make high-quality films of known materials, and iii) determine processing to fabricate devices with high reproducibility. More specifically, it will be important to correlate the chemistry and resultant properties of nanomaterials, the grain growth kinetics and thermodynamics to produce desired films and nanostructures and the fundamental processes of formulation, processing, composition, materials properties, and device functionalities.

> "The emergence of novel nanomaterials over the past decade has created new challenges and opportunities for low weight, highly efficient solar cells..."

New materials for the next generation of solar devices include thin film III-V semiconductors and *organic–inorganic halide perovskites*. Thin film III-V semiconductors promise ultra-light and high-efficiency solar cells that will be important for mobile, space and military applications. **Organic–inorganic halide perovskites holds tremendous promise for both solar and optoelectronic devices with applications ranging from light emitting diodes and lasers to water splitting.** These materials offer high quantum yields and bandgaps at 1.7–1.8 eV that can be cheaply integrated with silicon to make highly efficient tandem cells. Over the past four years, perovskites have made dramatic gains in power conversion efficiencies from a couple percent to over 20%. However, they suffer from thermal instability, light-induced degradation, ion migration, phase instability, and no dark current. Future research in the fundamental electronic and optical properties will be necessary to examine the crystallographic structure and the chemistry of these materials.

The participants discussed the fundamental research necessary to passivate defects and activate dopants in these emerging materials (i.e. 2D materials, perovskites) if they are going to obtain properties such as nearly 100% *photoluminescence* quantum yields and higher carrier lifetimes for highly efficient devices. For instance, the chemical treatment of MoS^2 via organic superacids can passivate and repair surface defects, copper (Cu) atom intercalation into Bi^2Se^3 and Bi^2Te^3 and lithium (Li) ion intercalation into thin graphite (Figure 11) can dramatically change the electronic and optical properties of these materials. These treatments do not change the atomic structure of the material when studied with X-ray photoelectron spectroscopy, Raman spectroscopy, and scanning tunneling microscopy, but photoluminescence quantum yield can be enhanced over 95%, dramatically improving performance and increasing possible applications.

Equally as important as the experimental investigation of these materials, research over the next 10 years will focus on new computational methods to predict and confirm material properties from first-principles simulations. For example, calculations of the band structure and scattering rates of electrons via density function theory (DFT) combined with transport theory are required to understand the phonon conductivity and electron mobility in many emerging materials.

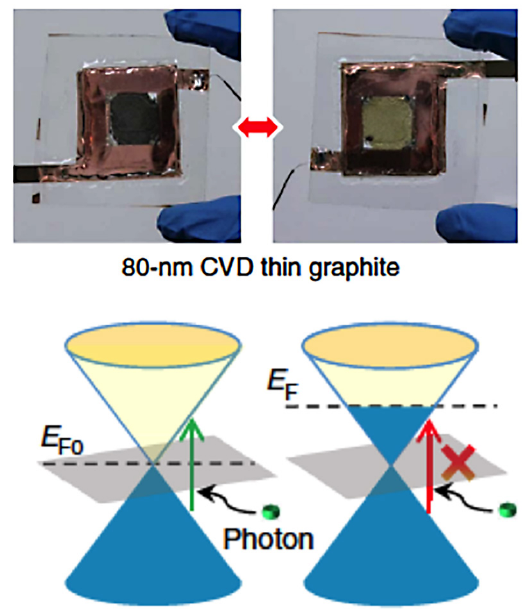

Figure 11. Intercalation of lithium ions in graphite changes the *fermi level* of the electrons and dramatically changes the optical transmission of the film *(Bao et al. Nature Comms. (2014))*.

Conclusion

Since the invention of the laser more than 50 years ago, photonic sciences has been a driving force for innovations that impact technologies across all sectors of modern life. Today, new photonic phenomena, materials and emerging device concepts are poised to propel photonic capabilities to levels at the extreme limits of space and time. Workshop participants expect that the technologies that emerge from this research will have broad impact on not only power and energy, but also communications, computing, medicine, and defense.

Most notable, they expect solar cells with higher efficiency and greater flexibility, new energy harvesting systems that integrate photovoltaics with electronic and thermal systems, small footprint heating and cooling systems that use active control of thermal radiation, and new optical systems with unprecedented manipulation and control of energy. Specific near-term impact discussed included ultra-long distance communication, wireless power transfer, power-efficient multi-target high-speed identification and tracking, autonomous navigation, directional electromagnetic weapons.

The workshop provided a unique opportunity for leading researchers in academia and industry to discuss and debate the frontiers of photonic sciences. They reviewed the state-of-the art in both science and technology and then outlined the future of the field for the next 20 years. They then asked, what emerging science and technology concepts and ideas are key to reaching those goals?

Among the many science and technology ideas reviewed in this report, the most notable include:

Emerging science ideas:

- Thermo-photovoltaics and photo-electrode materials
- Tailored thermal radiation in far-field and near-field energies
- Reconfigurable metasurfaces for arbitrary and dynamic manipulation of light
- Nanophotonic integrated, nonlinear optics for ultra-low power at room temperature
- Adaptive operation of nanophotonic devices, to compensate for varying conditions (temperature/solar exposure/ etc.)
- Novel mechanisms of assessing and controlling photon-electron interactions at surfaces and interfaces
- Entropy-centered analysis and design of optical systems and networks

Emerging technology ideas:

- Solar energy harvesting for solar water treatment and solar fuels (including low-power no-solar concentration technologies)
- Photonic materials and components for the extreme environment (e.g. compact and transparent thermal management solutions for large temperature gradient, turbid and corrosive medium, resistance of fracture and blast waves)
- Compact high power semiconductor lasers enabled by nanophotonics
- Compact x-ray lasers
- Compact THz sources at room temp at > 1W level at any (or broad) frequency
- Steering laser beams of large power (1W or larger) to an arbitrary direction in space
- LIDARs systems at faster than nanosecond speeds, with greater than 10,000x10,000 resolvable spots
- 3D nano-printing multi-material technologies for improved photonic control

Of the many research areas discussed, the highest priority was given to:

- Nanoplasmonics to squeeze light to smaller wavelength scales with loss comparable to dielectrics (preferable without amplification)
- Manipulation of optical angular momentum for light localization, multiplexing and channel capacity increase
- 2D-materials for use in plasmonics and nanophotonics
- Topological photonics to break time-symmetry at near-infrared and visible frequencies
- Angular selectivity with novel photonic crystals and photonic topological insulators
- Optical photonics circuits for high speed, low power computing (neuro-morphic and other)
- Modeling of photon-matter interactions with high fidelity multiphysics that captures charge transfer, heat transfer and phase change for length scales down to the atomic level

The participants were optimistic that continued research in these priority research areas will have substantial impacts on the future of science and technological progress in power and energy and beyond. They expect the pathway to applications will encompass both invention of entirely new and unforeseen photonics-based technologies, as well as greatly accelerated development of already-identified --but as-yet underdeveloped-- technologies.

Glossary

Phased array antennas – networks of radiating elements assembled together and acting coherently to form radiation pattern with desired parameters.

Electromagnetic metasurface – artificial sheet material with sub-wavelength thickness and subwavelength elements that allows electromagnetic radiation shaping on demand.

Plasmonics – field of optics studying light control and manipulation via its interaction with subwavelength metallic or similar structures.

Optical nonlinearity – class of effects in which properties of a medium are input beam power dependent.

Epitaxial liftoff – The process of removing a thin-film, epitaxially grown device from its growth substrate by etching away a sacrificial layer grown between the device and substrate.

Photon recycling – The efficient reabsorption of radiatively emitted photons within a solar cell that would otherwise be wasted via parasitic absorption or external escape.

Upconversion – The process of creating a high-energy photon from two or more lower energy photons.

Thermophotovoltaic – A device that converts thermal energy to electricity through the use of a photovoltaic, often also containing a thermal emitter with engineered emission characteristics.

Photonic topological insulator – An engineered electromagnetic material with carefully designed electromagnetic states allowing one-way propagation of photons, immune to disorder-induced backscattering.

Fermi level – the energy level of an electron such that at thermodynamic equilibrium the energy level would have a 50% probability of being occupied at any given time.

Organic–inorganic halide perovskite – a light-harvesting active material with the perovskite crystal structure and is most commonly composed of a hybrid organic-inorganic lead or tin halide-based material.

Photocathode – a negatively charged electrode that is made of a photosensitive material that when struck by a photon can emit an electron due to the photoelectric effect.

Photoluminescence – light emission from any form of matter after the absorption of photons. It is one of many forms of luminescence (light emission).

Topological insulator – a material that behaves as an insulator in its interior but whose surface contains conducting states, meaning that electrons can only move along the surface of the material. In general, topological order creates a ground state degeneracy that cannot be lifted by any local perturbations but rather depends on the topology of space.

Transition metal dichalcogenide – atomically thin semiconductors of the type MX2, with M being a transition metal atom (Mo, W, etc.) and X being a chalcogen atom (S, Se, or Te.). One layer of M atoms is sandwiched between two layers of X atoms.

Plasma – fundamental state of matter that can be created by heating a gas or subjecting it to a strong electromagnetic field. It can have a decreased or increased number of electrons, creating positive or negative charged particles.

Periodically poled lithium niobate (PPLN) – highly efficient medium for nonlinear wavelength conversion processes. PPLN can be used for frequency doubling, difference frequency generation, sum frequency generation, optical parametric oscillation.

High harmonic generation (HHG) – nonlinear process in a gas, plasma, or solid that is illuminated by an intense laser pulse and consequently emits several frequencies of light that are integer multiples of the original laser pulse.

Gain medium – material where an increased amplitude of light can be created via the stimulated emission of electronic or molecular transitions.

Photonic crystal – an artificial crystal structure (made out of a dielectric material) that can manipulate beams of light in the same way that ionic lattices in semiconductors control electrons.

Table-top X-ray – an X-ray source that can fit on top of a scientific table or in a room.

Appendix I:
Workshop Attendees

Harry Atwater, *http://solarfuelshub.org*
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Department of Applied Physics and Material Science
PhD (1987), Electrical Engineering, Massachusetts Institute of Technology

Harry Atwater is the Howard Hughes Professor of Applied Physics and Materials Science at the California Institute of Technology. He currently serves as Director for the Joint Center for Artificial Photosynthesis. He is the Editor-in-Chief for ACS Photonics, and is a Fellow of the Materials Research Society and a Member of the US National Academy of Engineering.

Atwater's scientific interests lie at the intersection of photonics and energy conversion. His group has created new high efficiency solar cell designs, and developed principles for light management in solar cells. Atwater is an early pioneer in nanophotonics and plasmonics; he gave the name to the field of plasmonics in 2001.

Dr. Atwater is an MRS Fellow and has been honored by awards, including election to the National Academy of Engineering in 2015; Fellowship from the Royal Netherlands Academy of Arts and Sciences in 2013; the ENI Award in Renewable and Nonconventional Energy in 2012; Green Photonics Award in Renewable Energy Generation, SPIE 2012; Popular Mechanics Breakthrough Award, 2010; MRS Kavli Lecturer in Nanoscience in 2010; Joop Los Fellowship from the Dutch Society for Fundamental Research on Matter in 2005; A.T. & T. Foundation Award, 1990; NSF Presidential Young Investigator Award, 1989; IBM Faculty Development Award, 1989-1990; Member, Bohmische Physical Society, 1990; and an IBM Postdoctoral Fellowship, 1987.

Ray Beausoleil, *http://www.labs.hpe.com/people/ray_beausoleil/*
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Hewlett Packard Labs
PhD (1986), Physics, Stanford University

Ray Beausoleil is a Hewlett Packard Enterprise (HPE) Senior Fellow in Fundamental Technologies at Hewlett Packard Labs, and a Consulting Professor of Applied Physics at Stanford University. At HPE, he leads the Large-Scale Integrated Photonics research group, and is responsible for research on the applications of optics at the micro/nanoscale to high-performance classical and quantum information processing. His current research projects include photonic interconnects for exascale computing, and low-power complex nanophotonic circuits. Ray received the Bachelor of Science with Honors in Physics from the California Institute of Technology in 1980; the Master of Science degree in Physics from Stanford University in 1984; and his Ph.D. in Physics from Stanford in 1986. In 1996, Ray became a member of the technical staff at HP Laboratories. He has published over 300 papers and conference proceedings and five book chapters. He has over 115 patents issued, and over three dozen pending. He is a Fellow of the American Physical Society, and the recipient of the 2016 APS Distinguished Lectureship on the Applications of Physics.

Peter Bermel, *http://web.ics.purdue.edu/~pbermel/research.html*
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Peter Bermel is an Assistant Professor in the Department of Electrical and Computer Engineering at Purdue University. He leads the Energy and Nanophotonics research group at Purdue University, and is also a PI for the Bay Area Photovoltaic Consortium.

His research focuses on improving the performance of photovoltaic, thermophotovoltaic, and nonlinear systems using the principles of nanophotonics, with particular focus on light trapping in photovoltaics, selective thermal emission in thermophotovoltaics, and photon recycling for photovoltaic, thermophotovoltaic, and lighting applications. Key enabling techniques for his work include electromagnetic and electronic theory, modeling, simulation, fabrication, and characterization. He is widely-published in both scientific peer-reviewed journals and publications geared towards the general public, and has been cited over 3600 times.

He is a recipient of an NSF CAREER award, a Purdue IMPACT Faculty Fellow, an NSF Graduate Research Fellow, a MIT Compton Fellow, and a Winston Churchill Foundation Scholar. He is also an Associate Editor for the OSA journal, Optics Express.

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PhD (1998), Materials Science, FOM Institute in Amsterdam

Mark Brongersma is a Professor in the Department of Materials Science and Engineering at Stanford University. He received his PhD in Materials Science from the FOM Institute in Amsterdam, The Netherlands, in 1998. From 1998-2001 he was a postdoctoral research fellow at the California Institute of Technology. During this time, he coined the term "Plasmonics" for a new device technology that exploits the unique optical properties of nanoscale metallic structures to route and manipulate light at the nanoscale.

His current research is directed towards the development and physical analysis of nanostructured materials that find application in nanoscale electronic and photonic devices. Brongersma received a National Science Foundation Career Award, the Walter J. Gores Award for Excellence in Teaching, the International Raymond and Beverly Sackler Prize in the Physical Sciences (Physics) for his work on plasmonics, and is a Fellow of the Optical Society of America, the SPIE, and the American Physical Society.

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Department of Mechanical Engineering
PhD (1993), Mechanical Engineering, University of California, Berkeley

Gang Chen is the Carl Richard Soderberg Professor of Power Engineering and Head of the Department of Mechanical Engineering at Massachusetts Institute of Technology (MIT). He is the director of the "Solid-State Solar-Thermal Energy Conversion Center (S3TEC Center)" - an Energy Frontier Research Center funded by the US Department of Energy.

His research interests center on nanoscale transport and energy conversion phenomena and mechanisms, and their applications in energy storage and conversion, and thermal management.

He is a recipient of a K.C. Wong Education Foundation fellowship and a John Simon Guggenheim Foundation fellowship. He received an NSF Young Investigator Award, an R&D 100 award, an ASME Heat Transfer Memorial Award, a Nukiyama Memorial Award by the Japan Heat Transfer Society, a World Technology Network Award in Energy, an Eringen Medal from the Society of Engineering Science, and the Capers and Marion McDonald Award for Excellences in Mentoring and Advising from MIT. He is a fellow of American Association for Advancement of Science, American Physical Society, and American Society of Mechanical Engineers. He is an academician of Academia Sinica and a member of the US National Academy of Engineering.

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Yi Cui is an Associate Professor in the Department of Materials Science and Engineering at Stanford University. He is an Associate Editor of Nano Letters. He is a co-director of the Bay Area Photovoltaic Consortium of the US Department of Energy.

His research is on nanomaterials design for energy and environment technology. He is a highly proliferate materials scientist and has published ~310 research papers, filed more than 40 patent applications and give ~300 plenary/keynote/invited talks. In 2014, he was ranked NO.1 in Materials Science by Thomson Reuters as "The World's Most Influential Scientific Minds".

He has received numerous awards including MRS Fellow (2016), MRS Kavli Distinguished Lectureship in Nanoscience (2015), Resonate Award for Sustainability (2015), Inaugural Nano Energy Award (2014), Blavatnik National Award Finalist (2014), Wilson Prize (2011), the Sloan Research Fellowship (2010), KAUST Investigator Award (2008), ONR Young Investigator Award (2008), MDV Innovators Award (2007), Technology Review World Top Young Innovator Award (2004). He has founded Amprius Inc. (2008) to commercialize the breakthrough high-energy battery technology and co-founded 4C Air Inc. (2015) to commercialize the PM2.5 filtration technology from his lab.

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Jennifer Dionne is an Assistant Professor in the Department of Materials Science and Engineering at Stanford University, as well as an affiliate professor of the Precourt Institute for Energy, Stanford Neurosciences Institute, and Bio-X.

Her research develops new optical materials and methods to directly visualize, probe, and control both biologically- and energy-relevant systems with nanometer-scale resolution. This research has led to demonstration of negative refraction at visible wavelengths, development of a subwavelength silicon electro-optic modulator, design of plasmonic optical tweezers for nano-specimen trapping, demonstration of a metamaterial fluid, and synthesis of high-efficiency and active upconverting materials. Most recently, Jen has developed in situ techniques to visualize chemical transformations and light-matter interactions with nanometer-scale spatial resolution.

She is the recipient of the Adolph Lomb Medal (2016), a Sloan Foundation Fellowship (2015), the Presidential Early Career Award for Scientists and Engineers (2014), and the inaugural Kavli Nanoscience Early Career Lectureship (2013). Further, her work has been recognized with an NSF CAREER Award (2012) and an AFOSR Young Investigator Award (2011). She was also named one of Technology Review's TR35 - 35 international innovators under 35 tackling important problems in transformative ways (2011). When not in the lab, Jen enjoys teaching three classes ("Materials Chemistry", "Optoelectronics", and "Science of the Impossible"), exploring the intersection of art and science, and cycling the latest century.

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Nader Engheta is the H. Nedwill Ramsey Professor at the University of Pennsylvania in Philadelphia, with affiliations in the Departments of Electrical and Systems Engineering, Materials Science and Engineering, Physics and Astronomy, and Bioengineering.

His current research activities span a broad range of areas including nanophotonics, metamaterials, nano-scale optics, graphene optics, imaging and sensing inspired by eyes of animal species, optical nanoengineering, microwave and optical antennas, and physics and engineering of fields and waves. He has co-edited (with R. W. Ziolkowski) the book entitled "Metamaterials: Physics and Engineering Explorations" by Wiley-IEEE Press, 2006. He was the Chair of the Gordon Research Conference on Plasmonics in June 2012.

He has received several awards for his research including the 2015 SPIE Gold Medal, the 2015 Fellow of National Academy of Inventors (NAI), the 2015 NSSEFF Award from DoD, the 2015 IEEE Antennas and Propagation Society Distinguished Achievement Award, the 2014 Balthasar van der Pol Gold Medal from the International Union of Radio Science (URSI), the 2013 Inaugural SINA Award in Engineering, the 2012 IEEE Electromagnetics Award, 2006 Scientific American Magazine 50 Leaders in Science and Technology, and IEEE Third Millennium Medal. He is a Fellow of six international scientific and technical societies, i.e., IEEE, OSA, APS, MRS, SPIE, and American Association for the Advancement of Science (AAAS). He has been selected to receive the Honorary Doctorate of Technology from Aalto University in Finland in October 2016.

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Shanhui Fan is a Professor in the Department of Electrical Engineering at Stanford University. His laboratory is part of Stanford's Center for Nanoscale Science and Engineering and the Ginzton lab an interdisciplinary research lab that investigates research that overlap between engineering and the sciences.

His research involves fundamental and applied studies in plasmonics, metamaterials, silicon photonics, photovoltaics, quantum optics and computational electromagnetics.

Dr. Fan is a Fellow of IEEE, SPIE, the Optical Society of America and The American Physical Society. He received the Adolf Lomb Medal from the Optical Society of America in 2007 and the National Academy of Sciences Award for Initiative in Research in 2007. He received the STMicroelectronics Faculty Scholar Award and is the recipient of the David and Lucile Packard Fellowship in Science and Engineering and an NSF Career Award.

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Franz X. Kaertner leads the Ultrafast Optics and X-rays Group with locations at MIT and Center for Free-Electron Laser Science at DESY, Hamburg, Germany.

His research interests include classical and quantum noise, few-cycle and ultralow jitter femtosecond lasers and its use in precision timing distribution, cryogenic lasers and optical parametric amplifiers for MID-IR and THz sources and its use in advanced accelerators and light sources, femtosecond laser frequency combs, integrated electronic photonic systems, compact x-ray sources and attosecond science. He is known for his work on phase noise analysis of oscillators, octave spanning lasers and dispersion compensating mirrors, few-cycle pulse generation, ultrafast optical techniques for femtosecond synchronization, attosecond timing jitter measurements and THz acceleration. He is a fellow of OSA and IEEE.

He has lead several successful research programs in the areas of frequency and timing metrology, femtosecond lasers, arbitrary optical waveform generation, high order harmonic generation, mid-IR sources, THz generation and acceleration and integrated electronic-photonic systems. In Hamburg, he is principal investigator in the Excellence Cluster: The Hamburg Center for Ultrafast Imaging. Jointly with collaborators from University of Hamburg, the Germany Electron-Synchrotron Facility (DESY) and Arizona State University, his team was awarded a prestigious Synergy Grant of the European Research Council, AXSIS: Frontiers in attosecond X-ray Science: Imaging and Spectroscopy to construct an FEL-like table-top attosecond X-ray source based on high energy, high power laser technology and THz acceleration.

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His research interests are in nanophotonics, quantum optics, and optomechanics for applications in precision measurement and quantum information science.

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Albert Polman is scientific group leader at the FOM Institute AMOLF in Amsterdam, the Netherlands, where he heads the Program "Light management in new photovoltaic materials". He is Professor of Photonic materials for photovoltaics at the University of Amsterdam. He was post-doctoral researcher at AT&T Bell Laboratories until 1991 and then became group leader at AMOLF, where he also served as director from 2006-2013. In 2003 he spent a sabbatical year at Caltech.

His research focuses on nanophotonics, with special emphasis on light management in solar cells and optical metamaterials. He has published over 280 papers that are cited over 20.000 times.

Polman is co-founder of Delmic BV, a startup company that commercializes a cathodoluminescence microscopy technique developed by Polman and his group. Polman is member of the Royal Netherlands Academy of Arts and Sciences (KNAW), Fellow of the Materials Research Society (MRS), and recipient of ERC Advanced Investigator Grants (2011, 2016), the ENI Renewable Energy Prize (2012), the Physica Prize of the Dutch Physical Society (2014), the Julius Springer Award for Applied Physics (2014) and the MRS Innovation in Materials Characterization Award (2014).

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Michelle Povinelli is an Associate Professor in the Ming Hsieh Department of Electrical Engineering at the University of Southern California.

Her research interests include nanophotonics, including photonic crystals, microresonators, nanowires, and metamaterials, for applications in energy, communications, and sensing. She has co-authored more than seventy journal articles, three book chapters, and three US Patents.

She is the recipient of an NSF CAREER Award, Army Research Office Young Investigator Award, Presidential Early Career Award for Scientists and Engineers (PECASE), and a TR35 Award for innovators under age 35 from MIT's Technology Review magazine. In 2006, she received the L'Oréal For Women in Science Postdoctoral Fellowship.

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Alejandro Rodriguez is an Assistant Professor of Electrical Engineering at Princeton University.

His research is in the areas of nanophotonics, nonlinear optics, and fluctuation electromagnetic phenomena. He has helped to develop some of the first methods for computing fluctuation interactions in complex environments and made significant contributions to the understanding of ways of tailoring thermal radiation and Casimir forces in nano-structured media.

Prof. Rodriguez was the recipient of an NSF Early Career Award, the Department of Energy Fredrick Howes Award in Computational Science, and was recently named a National Academy of Sciences Kavli Fellow as well as a World Economic Forum Global Shaper.

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Vlad Shalaev is the Bob and Anne Burnett Distinguished Professor of Electrical and Computer Engineering and Scientific Director for Nanophotonics in Birck Nanotechnology Center at Purdue University. He also holds appointments in the Departments of Physics and Biomedical Engineering.

His research focuses on nanophotonics, plasmonics, and optical metamaterials. He has authored three books, twenty-one book chapters and over 300 research publications.

He has received several awards for his research in the field of nanophotonics and metamaterials, including the Max Born Award of the Optical Society of America for his pioneering contributions to the field of optical metamaterials and the Willis E. Lamb Award for Laser Science and Quantum Optics. He is a Fellow of the IEEE, APS, SPIE, and OSA.

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Paul Sharps is the Chief Technology Officer at SolAero Technologies Corporation. He has been involved in the development of high efficiency, multi-junction solar cells for more than 25 years, for both space and terrestrial applications. Dr. Sharps has 18 patents and more than 100 conference proceedings and peer reviewed publications.

He is the recipient of the Irving Weinberg Award (2014), IEEE PVSC Napkin Award (2009), AVS/Russell Varian Award at Stanford (1990), ATT/Bell Labs Scholarship at Stanford (1986), John Bray Award at Purdue University for outstanding undergraduate (1977). He was the EMCORE principal investigator for 2008 R&D 100 award winner for "Inverted Metamorphic Multijunction (IMM) Solar Cell" with NREL, also Editor's Choice Award.

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Dr. David R. Smith is the Chair and James B. Duke Distinguished Professor of the Electrical and Computer Engineering Department at Duke University, where he also serves as Director for the Center for Metamaterial and Integrated Plasmonics. Dr. Smith is also the Founding Director of the Metamaterials Commercialization Center at Intellectual Ventures in Bellevue, Washington. He holds a secondary faculty appointment in the Physics Department at Duke University, is a Visiting Professor of Physics at Imperial College, London, an Adjunct Professor position at the University of California, San Diego (UCSD), and an Affiliate Professor position at the University of Washington, Seattle.

His research interests include the theory, simulation and characterization of unique electromagnetic structures, including photonic crystals, metamaterials and plasmonic nanostructures. Smith and his colleagues demonstrated the first left-handed (or negative index) metamaterial at microwave frequencies in 2000, and also demonstrated a metamaterial "invisibility cloak" in 2006.

He is the recipient of the Descartes Research Prize (2005), was selected as one of the "Scientific American 50 (2006) and was named a "Citation Laureate" by Thomson-Reuters ISI Web of Knowledge (2009). He is co-recipient of the McGroddy Prize for New Materials, awarded by the American Physical Society, for "the discovery of metamaterials" (2013). In 2014 and 2015, Dr. Smith again made the Reuters-ISI listing of "Highly Cited Researchers," in the area of Physics. Dr. Smith has recently been active in transitioning metamaterial concepts for commercialization, being a co-founder of Evolv Technology and advisor to Kymeta Corporation and Echodyne Corporation—all companies devoted to developing metamaterial products.

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Marin Soljačić is a Professor of Physics at Massachusetts Institute of Technology. He is also a founder of WiTricity Corporation (2007).

His main research interests are in electromagnetic phenomena, focusing on nanophotonics, nonlinear optics, and wireless power transfer. He is a coauthor of 180 scientific articles, more than 80 issued US patents, and he has been invited to give more than 100 invited talks at conferences and universities around the world.

He is the recipient of the Adolph Lomb medal from the Optical Society of America (2005), and the TR35 award of the Technology Review magazine (2006). In 2008, he was awarded a MacArthur fellowship "genius" grant. He is a correspondent member of the Croatian Academy of Engineering since 2009. In 2011 he became a Young Global Leader (YGL) of the World Economic Forum. In 2014, he was awarded Blavatnik National Award, as well as Invented Here! (Boston Patent Law Association).

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Luke Sweatlock leads the Nanophotonics & Plasmonics Laboratory at Northrop Grumman Aerospace Systems, and is a Visitor in Applied Physics and in the Resnick Sustainability Institute at Caltech.

His research interests include plasmonics, optics, and metasurface devices. His recent work includes the study of fundamental physics of light-matter interactions in functional nanomaterials, and of the potential for transformative applications in sensors, communications, photovoltaics, and thermal management enabled by engineered materials. He has worked extensively on the development of analytical and numerical methods, including electromagnetic techniques for plasmonics and efficient global optimization techniques for metamaterial design.

He is a founding principal investigator within Northrop Grumman's NG/NEXT fundamental research initiative, and received the Northrop Grumman Aerospace Systems Research & Technology Award in 2013.

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Kerry Vahala is the Ted and Ginger Jenkins Professor of Information Science and Technology and Professor of Applied Physics at the California Institute of Technology. He is also an Executive Officer in the Applied Physics and Materials Science Department.

His research group has created the highest Q-factor chip-based optical resonators and also launched many of the subjects of study in the field of optical microcavities.

Vahala has received an Alexander von Humboldt Award for his work on high-Q devices. He was also involved in the early effort to develop quantum-well lasers for optical communications and received the IEEE Sarnoff Award for his research on quantum-well laser dynamics. He is a fellow of the IEEE, the IEEE Photonics Society, and the Optical Society of America.

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Dr. Verghese recently became Head Engineer for Google's Self Driving Car project, developing optical sensors for autonomous vehicles. Previously he was Assistant Head of the Advanced Technology Division at MIT Lincoln Laboratory until April 2016. He has also worked in two startups, PhotonEx to develop 40 & 80 Gb/s optoelectronic modules for fiber-optic systems and WiTricity to commercialize short-range wireless power transmission. In his last role at Lincoln Laboratory, Dr. Verghese supported technology development for advanced systems and its transfer into industry.

His research interests include photon-counting imagers, millimeter-wave and THz devices, compound semiconductors, and components for laser radars and optical communications. He worked for 18 years at Lincoln Laboratory in technical and leadership roles on teams developing Mars Lasercom, ALIRT laser radar systems, and other related DoD programs to assist in the transition of APD technology into fielded systems.

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Zheng Wang is an Assistant Professor in the Department of Electrical & Computer Engineering of the University of Texas at Austin, and holds the Jack Kilby / Texas Instruments Endowed Faculty Fellowship in Computer Engineering.

His research pioneered topological photonic devices at microwave frequencies, and builds subwavelength optical and acoustic devices using periodic media and multimaterial fibers for signal processing, sensing and transduction applications. He has co-authored over 27 peer-reviewed journal articles and holds 2 US patents.

He is a member of IEEE, OSA, and MRS societies. In 2013, he was the Packard Fellow for Science and Engineering. In 2012, Dr Wang was selected as "One of the World's Top Young Innovators" by MIT Technology Review.

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Eli Yablonovitch is Professor of Electrical Engineering and Computer Science at the University of California, Berkeley, He is also Director of the NSF Center for Energy Efficient Electronics Science (E3S), a multi-University Center headquartered at the University of California, Berkeley. He founded Ethertronics Inc, which has shipped over one billion cellphone antennas.

He is regarded as a Father of the Photonic BandGap concept and his pioneering research in the field of optoelectronics and photonic band-gap research focuses on optoelectronics, high speed optical communications, high efficiency light-emitting diodes and nano-cavity lasers, and photonic crystals at optical and microwave frequencies. He introduced the 4(n squared) ("Yablonovitch Limit") light-trapping factor that is in worldwide use, for almost all commercial solar panels. Based on his mantra that "a great solar cell also needs to be a great LED", his startup company Alta Devices Inc. has, since 2011, held the world record for solar cell efficiency, now 28.8% at 1 sun. He introduced the idea that strained semiconductor lasers could have superior performance due to reduced valence band (hole) effective mass. With almost every human interaction with the internet, optical telecommunication occurs by strained semiconductor lasers.

He has been elected to the NAE, the NAS, and as Foreign Member, UK Royal Society. Among his honors is the Buckley Prize of the American Physical Society, and the Isaac Newton Medal of the UK Institute of Physics.

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Yang Yang is the Carol and Lawrence E. Tannas Jr. Chair Professor of Materials Science and Engineering at University of California, Los Angeles. Before he joined UCLA in 1997, he served on the research staff of UNIAX (now DuPont Display) in Santa Barbara from 1992 to 1996.

He research interest include organic electronics, organic/inorganic interface engineering, and the development and fabrication of related devices, such as photovoltaic cells, LEDs, and memory devices. His notable contributions to the field of organic photovoltaics (OPV) are enhanced understanding of polymer morphology and its influence on device performance; the invention of the inverted organic solar cell; the inverted tandem solar cell; and transparent OPV devices. He has published more than 300 papers.

Yang is the fellow of American Physical Society (2015); Materials Research Society (2015); Royal Society of Chemistry (2015); SPIE (2014) and the E-M Academy (2014). He was also recognized as 'World's most influential scientific minds" by Thomason Reuters, 2016. (Only 19 scientists selected).

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Xiang Zhang is Ernest S. Kuh Endowed Chaired Professor of Mechanical Engineering at the University of California Berkeley. He is also the Director of NSF Nano-scale Science and Engineering Center (NSEC), Director of the Materials Sciences Division at Lawrence Berkeley National Laboratory (LBNL), and is a member of the Kavli Energy Nano Science Institute.

His research focuses on nano-scale science and technology, materials physics, photonics and bio-technologies. He has published over 240 journal papers, including over 50 publications in Science, Nature series, PNAS and Physical Review Letters. He has given over 280 Keynote, Plenary and Invited talks at international conferences and institutions.

He is a recipient of the NSF CAREER Award (1997); SME Dell K. Allen Outstanding Young Manufacturing Engineer Award (1998) and ONR Young Investigator Award (1999). He is an elected member of US National Academy of Engineering (NAE), Academia Sinica (National Academy in Republic of China), and Fellow of five scientific societies: APS (The American Physical Society), OSA (The Optical Society of America), AAAS (The American Association for the Advancement of Science), SPIE (The International Society of Optical Engineering), and ASME (The American Society of Mechanical Engineers).

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Appendix II

Workshop Organization

The two-day workshop was organized to encourage lively discussion and debate and to maximize the interaction of the participants. The first day began with short, introductory presentations that framed the workshop goals. The remainder of time was spent in small group discussions. The participants split into groups of 6-8 experts to discuss key questions for their research area and then assembled as a group to discuss these findings.

The morning breakout session asked: What are the desired applications for advanced photonics?

1. Solar Energy
2. Thermal Radiation Control
3. High Power Lasers/Optics
4. Phased Arrays and Beamsteering: Radar and LIDAR

The afternoon breakout session asked: What novel science and materials need to be developed to enable the applications?

1. Plasmonics/Dielectric Nanophotonics
2. Active Media: Nonlinear Optics, Spontaneous Emission, Gain, Optomechanics
3. Artificial Photonic Materials: Metasurfaces/Metamaterials/Photonics
4. New Materials

The second day included "White-space" presentations on these topics:

- Outlook for Solar Photovoltaics
- High Power and Nonlinear Photonics in High Q Microcavities
- Metatronics and Metasurfaces "Over the Horizon"

That day ended with a final discussion about the key ideas that should be included in the report.