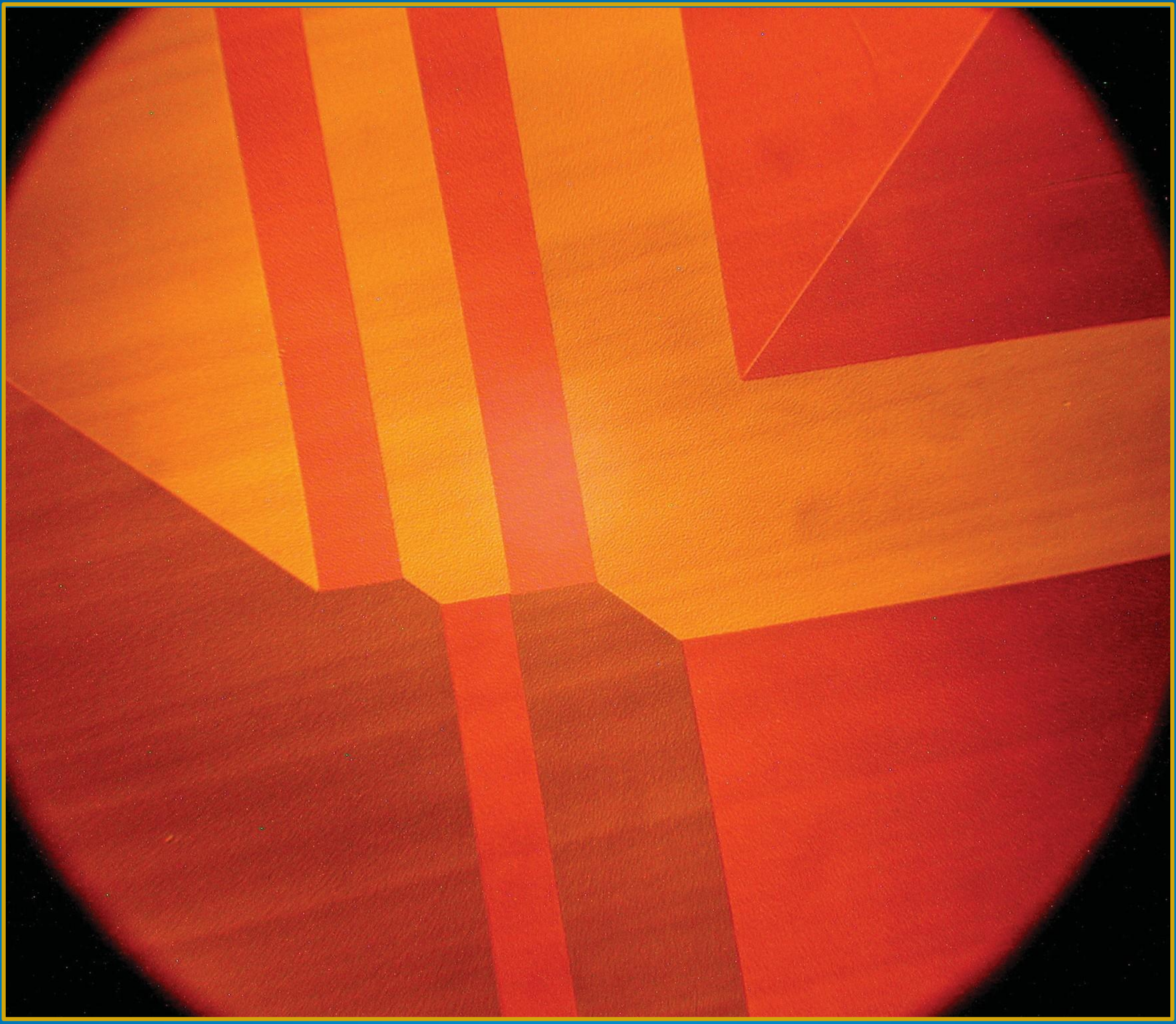

Optics and Photonics

Transformative Research Opportunities in the Mathematical and Physical Sciences

Mathematical and Physical Sciences Advisory Committee

July 2014

National Science Foundation

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Contents

EXECUTIVE SUMMARY

REPORT OF THE OPTICS AND PHOTONICS SUBCOMMITTEE OF THE MPS ADVISORY COMMITTEE: SCIENCE OPPORTUNTIES IN OPTICS AND PHOTONICS

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Optics and Photonics is a unified intellectual discipline with a history dating back to the earliest development of mankind's scientific thought. It is based on rigorous theories of electromagnetism, extended where appropriate to quantum electrodynamics, combined with understanding of light-matter interactions in materials. At the same time, the field of optics and photonics is almost without parallel in terms of the breadth of its impact on other fields of science and its impact on a broad range of technologies. Despite the long history of optics and photonics, it is also a field that has undergone and is undergoing a dramatic expansion in its impact. This growth is driven by continued scientific and technological breakthroughs: from unprecedented control of single photons to pulses of electromagnetic radiation of continually increasing intensity and decreasing duration to new coherent sources of x-ray radiation.

Against this backdrop, further interest in examining optics and photonics was sparked by the recent report of the National Research Council entitled *Optics and Photonics: Essential Technologies for Our Nation* and the recently released report *Building a Brighter Future with Optics and Photonics* issued by the Committee on Science of the National Science and Technology Council. In response, a subcommittee of the Advisory Committee of Mathematics and Physical Sciences Directorate of the National Science Foundation was formed. The subcommittee was charged (*Appendix 1*) to consider the capabilities, capacity and potential for advancing optics and photonics science, and opportunities that may arise, including the development of new experimental tools, materials and models, as well as the scientific and education mission of the NSF. The subcommittee was asked to identify basic research opportunities as well as the need, if any, for investments in the development of research infrastructure to support optics and photonics.

The Optics and Photonics subcommittee assembled to address these issues consisted of researchers covering the broad range of areas where optics and photonics play a critical role in the disciplines represented by the MPS Directorate. The members are listed in *Appendix 2*.

The work of the subcommittee was conducted primarily through a series of online workshops and discussions. Prof. Emily Carter of Princeton University served as the liaison to the MPSAC, with staff support from Dr. Clark V. Cooper at the NSF.

A summary of priority research areas, with an emphasis on critical needs for research investments, is presented in this document. The subcommittee is unanimously of the opinion that recent breakthroughs and unmet needs in critical areas of optics and photonics provide the opportunity for disproportionate returns on investments, returns that will have an impact on a broad range of fundamental scientific research, while at the same time laying the foundations for major technological advances. The committee also noted the intense international commitment to investments in optics in photonics throughout the world. The European Photonics 21 initiative is one example of such a large-scale program in this arena, but major investments in Asia can also be easily identified.

The subcommittee identified the following research areas as deserving particularly high priority of additional resources. These areas were chosen not only based on their great inherent intellectual merit within the discipline of optics and photonics, but also because of the impact research in these areas will have in advancing a far broader range of science and technology.

1. *Plasmonics and nanophotonics: controlling optical fields and propagation on the nanoscale*

2. *Coherent electromagnetic fields: attosecond time scales and x-ray photon energies*

3. *Optomechanical interactions: from single-molecule mechanics to macroscopic quantum states*

4. *Seeing beyond the diffraction limit and new imaging modalities*

5. *Creating and controlling quantum coherence with light*

6. *Controlling molecules with light and light with molecules*

7. *Observing the universe: optics and photonics for astronomy and astrophysics*

REPORT OF THE OPTICS AND PHOTONICS SUBCOMMITTEE OF THE MPS ADVISORY COMMITTEE: SCIENCE OPPORTUNTIES IN OPTICS AND PHOTONICS

The following seven research areas were identified as deserving particularly high priority of additional resources. The areas were chosen not only based on their great inherent intellectual merit within the discipline of optics and photonics, but also because of the impact that advances in these areas will have on a far broader range of science and technology, as is described below in the discussion of each theme. It is the committee's strong view that investments in these areas will have a disproportionate return across a broad range of disciplines beyond optics and photonics.

(1) Plasmonics and nanophotonics: controlling optical fields and propagation on the nanoscale

A remarkable frontier of optics and photonics over the past several years has concerned the ability to control light fields on a spatial scale far smaller than the wavelength of light, which lies in the range of 500 nm in the visible range. This field has been driven by advances in electronics and nanoscience that allow the precise sculpting of materials with precision down to the nanometer level. At the same time, theoretical advances in understanding new types of light-matter interaction in meta-materials and photonic crystals have also played an indispensable role in advancing the field.

We stress that the length scale from a few nanometers to a few dozen nanometers that can be accessed and controlled with plasmonic and nanophotonics allow access to an extraordinarily rich regime for new science, as well as technologies that spring from it. This is the current size of transistors in modern integrated circuits. Viruses and pathogens are often on this scale. Aerosol chemistry in the atmosphere takes place on sub-micron particles. Composite materials, surface catalysis, interstellar dust, all have important features determined by nanometer regions. Yet, because this is below the wavelength of visible radiation, science has lacked many of the tools it needs to interrogate this regime.

Recent advances in the ability to control light fields and light propagation in nanoscale structures has already yielded remarkable results, with impact on diverse fields of science and technology. Representative examples include strong localized enhancement of electromagnetic fields in properly constructed metallic structures, which has led to the detection of individual molecules by the weak Raman scattering process and to near-field microscopy techniques that achieve spatial resolution below 1/20th of the wavelength of light. The ability to tune the resonant behavior in metallic nanostructures has also led to a new class of optically active materials for diverse applications in sensing and medicine.

Photonic crystals, which transpose the concept of a band gap for propagating electronic states in a crystalline solid to the optical domain, can now be constructed to precisely control the propagation and, through the introduction of defect states, the localization of light fields. Photonic crystal cavities yield, through high degree of field localization and their high-Q factors, very large enhancements in the electromagnetic field. This has allowed, for example, for the possibility of strong nonlinear response driven by a single photon and, correspondingly, strong nonlinear interactions between individual photons. Also building on advances in semiconductor fabrication techniques, other types of ultrahigh-Q resonators have been constructed, such as ring resonators. These structures not only provide new avenues for optical signal processing in communication systems, but fundamental building blocks for ultrasensitive sensors and platforms to explore optomechanical interactions.

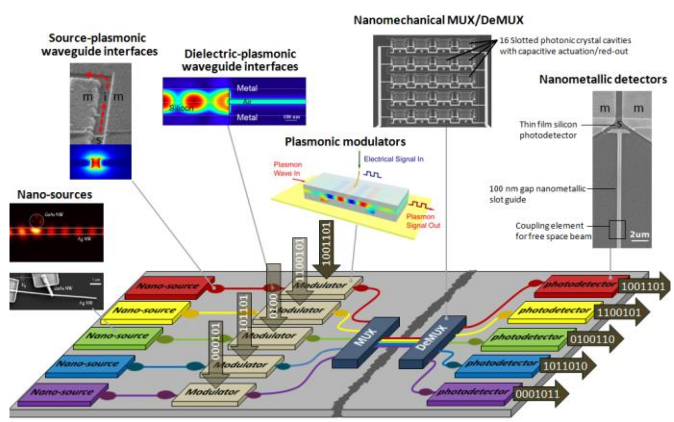

Figure 1. Illustration of possible integration of several novel nanophotonic devices, based on photonic crystals and plasmonic response, for high performance communications application. [M. Brongersma, private communication]

A further major recent advance in this arena has been the development of the class of optical meta- materials. Optical meta-materials are constructed from sub-wavelength sized structures to yield a material with an effective response resembling that of a conventional homogeneous material, but able to access optical properties that are not normally exhibited by real materials. In particular, optical meta-materials provide access to a regime with negative dielectric permittivity and negative magnetic permeability, leading to a response characterized by a negative refractive index. Such materials have been created for long wavelength radiation and have demonstrated key theoretical predictions. Recent advances have pushed the range of negative refractive index to the visible spectral range.

It is the view of the subcommittee that plasmonics and nanophotonics is a critical frontier research area of optics and photonics. Although there have been remarkable advances over the past years, the field continues to address very fundamental issues in the control and propagation of light fields on the nanoscale, provides major research challenges, and will enable scientific advances in diverse fields, as well as important new technologies. Impact is anticipated in information technology, high- resolution imaging, chemical sensing and photocatalysis, biology, and medicine.

Some of the key gaps and opportunities for the research program that were identified include: (1) the integration of advances in nanophotonics (based on dielectric materials) with progress in plasmonics and meta-materials (based largely on metallic materials); (2) the systematic development of nanophotonics and plasmonics in the quantum optics regime; (3) the development of new tunable plasmonic materials, such as graphene and conductive oxides, that will expand the possibilities for plasmonics, while allowing integration with CMOS technology; (4) photonics at high frequencies, in the vacuum ultraviolet spectrum and beyond.

In addition to the extremely high potential that fundamental research in these areas provides for new technologies, investments in nanophotonics and plasmonics are timely because recent developments, including both theory and nanofabrication, now enable deeply subwavelength nanophotonics. Furthermore, meta-materials and plasmonics-based nanophotonics are the basis of a disruptive technology that will have a dramatic impact on information technology, communications, and other applications.

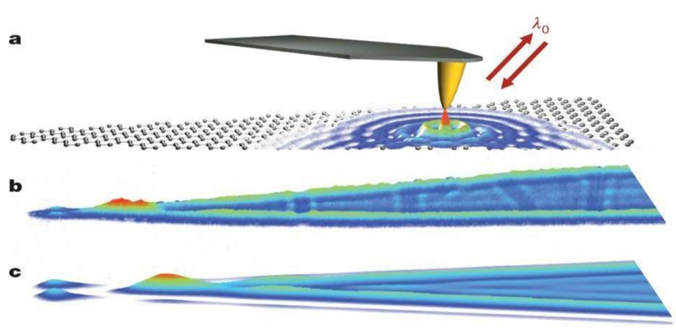

Figure 2. Generating and probing highly confined plasmons on a graphene surface using a plasmonic excitation of an appropriately shaped metal tip. The graphene plasmon is tunable by carrier density and localized to less than 1/100 of the free-space wavelength of the light. [After J. Chen et al., Nature 487, 77 (2012)]

(2) Coherent electromagnetic fields: attosecond time scales and x-ray photon energies

Arguably the single most important driving factor in the advance of optics and photonics over the past half century has been the impact of the laser in providing coherent electromagnetic radiation over an increasingly wide spectral range. At the same time, the impact of the expanding spectral range has been enhanced by remarkable advances in the ability to control frequency, on the one side, and the time structure of the radiation, on the other. Frequency control with sub-Hertz precision not only enabled breakthroughs in cold atoms and fundamental tests of the laws of physics, but also advances in time standards. Temporal control at the femtosecond level, not only permitted dramatic new insights into the dynamics of materials and nonequilbrium properties, but also allowed the development of the fiber-optic communication backbone of the modern economy. Recently, through the development of frequency combs based on modelocked lasers, ultra-high frequency precision and ultrashort laser pulses have been united.

At the present moment, we are at the threshold of a new set of dramatic advances in our ability to generate and control coherent electromagnetic radiation. In this case, the new frontier is the x-ray spectral range, with the concomitant ability to produce attosecond (10-18 s) and sub-attosecond pulses. The field is being propelled by two disruptive technologies: x-ray free electron lasers (XFEL) and high-harmonic generation from femtosecond lasers. The former was first demonstrated within the past few years by the LCLS light source at SLAC National Accelerator Laboratory and is now being implemented at facilities around the world. The LCLS XFEL not only provides short pulses, but brilliance 109 higher than synchrotron sources. The latter is being pursued in laboratories of leading research groups here and abroad. While the capabilities, range of applications, and experimental scale of these two approaches differ strongly, both of these methods offer exceptional scientific opportunities to study high-field, short-wavelength physics, and to explore a myriad of new scientific opportunities afforded by their capabilities.

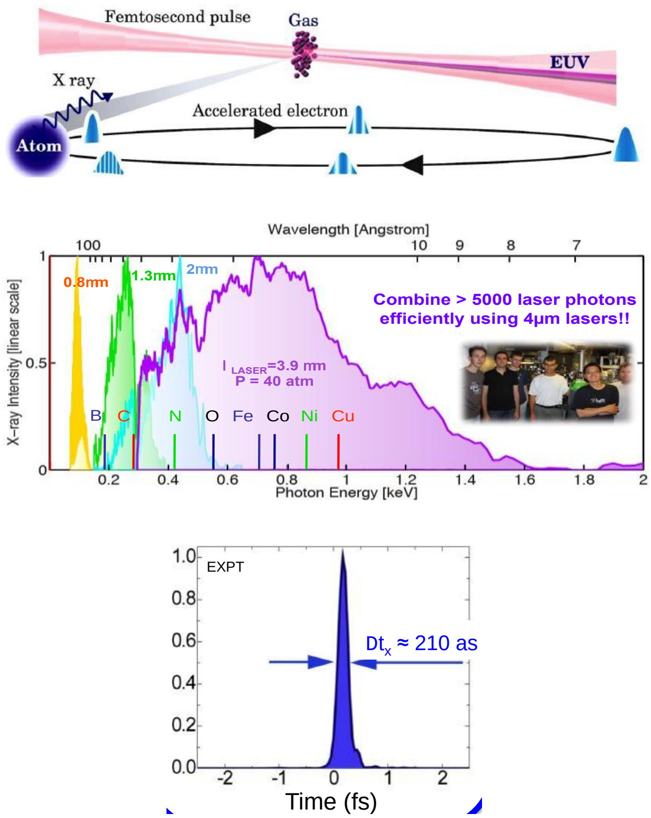

Figure 3. Schematic representation of high-harmonic generation (HHG) process during a single optical cycle of an ultrashort laser pulse (top). Spectrum of radiation produced for excitation with femtosecond laser pulses of various wavelengths (bottom) and correlation trace showing attosecond (as) pulse duration (middle). [After T. Popmintchev et al., Science 336, 1287 (2012)]

The new capabilities provided by these sources include the ability perform ultrafast time-resolved spectroscopy in fundamentally new ways. It now becomes possible to follow charge flow and bond rearrangement through the powerful tool of atomic core-level spectroscopy with ultrafast time resolution; to perform angularly-resolved photoemission spectroscopy with femtosecond resolution from a broad class of materials; and, with the availability of hard x-rays, to time-resolve structural changes in materials on an ultrafast time scale. By materials, we should stress that we understand solids, but atoms, molecules in condensed, liquid, and vapor phase. Further, the high-intensity and ultrashort duration of pulses from x-ray free electron lasers opens the possibility of performing structural analysis by diffraction from nanoscale samples and perhaps from individual molecules. This latter development is of the greatest importance for structural biology, since it obviates the need for crystallization of samples and relies on the enhanced flux that can be utilized in an ultrafast diffraction measurement.

In addition, convenient sources of x-rays will facilitate new imaging modalities that rely on their ability to penetrate thick objects, to image small features in three dimensions, and to exploit elemental and chemical specificity.

The above capabilities, extending from the extreme ultraviolet upwards in photon energy, will have a profound effect on addressing fundamental problems in materials science, in correlated electron physics, in reaction and chemical dynamics, and in biology. Examples of problems that have already begun to be addressed by these techniques include studies of heat flow on the nanoscale in which ballistic and diffusive modes could be distinguished; real-time studies of bond-breaking at surfaces in which a new weakly bound precursor state was found; ultrafast studies of magnetization and chemical dynamics; and a determination of the precise time to photoemit an electron from a solid.

Underpinning advances in the applications of new coherent sources of x-rays has been the science of the interaction of ultra-intense radiation with matter, whether in the harmonic generation process, in the shaping and control of attosecond pulses, pumping new x-ray laser sources, or in efforts to obtain x-ray diffraction patterns of molecules before they undergo change in the intense x-ray field. This arena of research represents, in many respects, the foundation of attosecond science. It is a field in which both theory and experiment play critical roles, not only vital scientifically, but essential for the continued advancement of new coherent sources and their application to a wide range of problems.

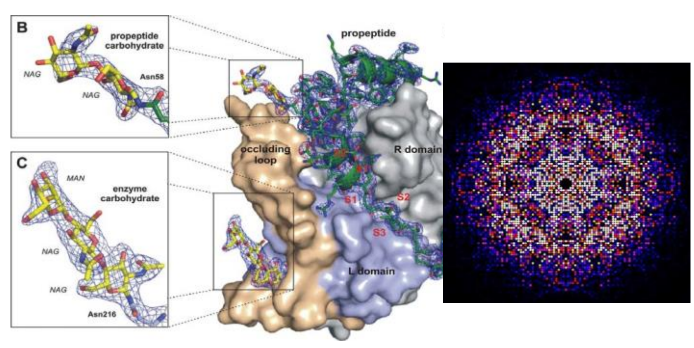

Figure 4. New structural analysis on an enzyme related to sleeping sickness by means of x-ray diffraction with pulses from the LCLS XFEL. This demonstrates the "diffract before destroy" principle. [After L. Redecke et al., Science 339, 227 (2013)]

In short, panoply of new opportunities is unfolding for extending precision coherent and time-resolved spectroscopy into the x-ray spectral region with impact on multiple scientific disciplines. Funding for this research area is low compared with that in many other countries and there is a pressing need of investment to remain at the forefront of this rapidly evolving field.

(3) Optomechanical interactions: from single-molecule mechanics to macroscopic quantum states

The transfer of momentum from light fields to matter with mass has led to dramatic advances in various fields of research. This interaction, for resonant systems, lies at the heart of laser cooling techniques that have permitted the creation of Bose-Einstein condensates from gas-phase atoms and extensive exploration of the properties of these systems. Progress in these fields continues rapidly, with the development of techniques to produce ultracold molecules now becoming available and the controlled use of condensates permitting a new approach to examine the behavior of ideal quantum systems through development of quantum simulators.

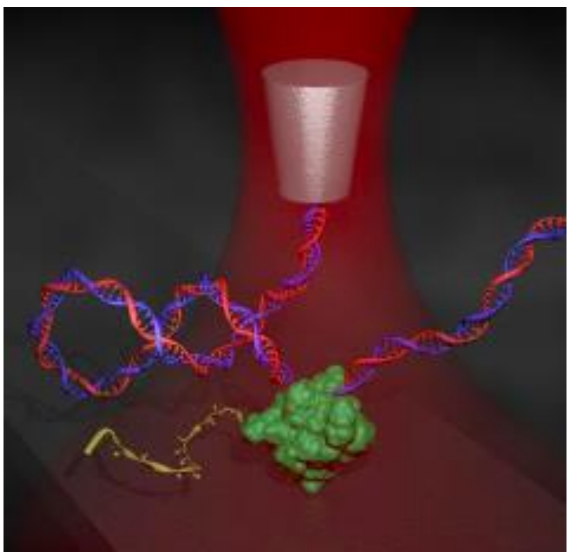

Figure 5. Optical fields with orbital angular momentum can be used to apply precisely controlled torque to dielectric particles. By coupling molecules to this particle, one can extend previous investigations of the influence of force on individual molecules to examine the influence of torque. This allows, for example, the study of DNA transcription under torsion, as illustrated schematically in the figure. [After J. Ma et al., Science 340, 1580-3 (2013) and A. Ju, Cornell Chronicle, June 27, 2013]

In the case of non-resonant interactions, laser light allows precise manipulation on the nanoscale. The concept of using radiation forces to control small dielectric particles has developed into a method for sensitive probing of the mechanical properties of individual molecules and other refined measurements of the response of materials in the nanoscale. In particular, this method of "laser tweezers" has emerged as an important tool within the life sciences for probing individual molecules and sub-cellular structure with heretofore-unattainable precision. This research field remains one where innovation in optics and photonics is driving new scientific advances. Recent examples include advances in ultrahigh resolution optical traps and the use of orbital angular momentum to convey precise amounts of torque individual to molecules, as shown in *Figure 5*.

Another important arena of advance has been the combination of single molecule spectroscopy with controlled mechanical manipulation of molecules. This allows one to determine the influence of force through precise spectroscopic signatures from the molecules, for example, through changes in resonant energy transfer between chromophores (*Figure 6*).

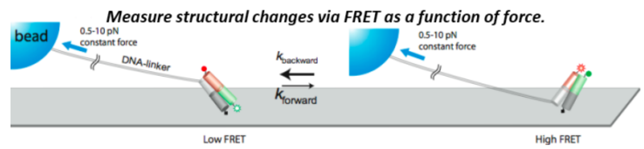

Figure 6. Combination of the "laser tweezers" technique to apply precise forces to individual molecules with a readout of the consequences of the force using single molecule spectroscopy by FRET (fluorescence resonant energy transfer). [After S. Hohng et al., Science 318, 279 (2007)]

The field of optomechanics has also been developing rapidly in a different direction where quantum mechanics plays a crucial role for the nature of both the light and mechanical vibrations. This fascinating new field of quantum optomechanics benefits from and informs diverse fields, including atomic, molecular and optical physics (e.g., ultracold science), quantum optics, low-temperature physics, condensed-matter physics, nanoscience, and quantum information science. In particular, the recent advances rely on progress in quantum optics and atomic physics for exquisite control of light-matter interactions; for understanding of the mechanical effects of light and the associated routes to laser cooling; for the use of nonclassical light fields to exceed the standard quantum limit of measurements; and for understanding of quantum noise and decoherence. Nanoscience and technology have provided us with the tools to make a wide variety of ultrasensitive micro and nanomechanical devices, structures with high-Q resonance and strong light-matter interaction, and to characterize these structures with spatial resolution down to the atomic level. These latter advances mirror other breakthroughs in the use of mechanical sensing to measure properties on the atomic scale with extreme precision, including single electron spin detection via magnetic resonance, attometer scale displacement sensing, zeptonewton scale force sensing, and yoctogram scale mass sensing.

The central focus of research in quantum optomechanics has been the study of the interaction of light with mechanical vibrations through the use of high-Q resonant structures. In addition to achieving a deep understanding of the different coupling regimes, researchers have been able to apply a method analogous to side-band cooling of trapped ions that was developed within the atomic, molecular and optical physics community to cool the vibrations. In this approach, enhancement by an optical resonance causes the rate of anti-Stokes Raman scattering processes to exceed that of Stokes Raman scattering. In this fashion, the light field carries off energy from the vibration, leading to a laser-cooling process. This method has now reached a major milestone in achieving cooling to the quantum limit of an average mode occupancy below one vibrational quantum. While this situation is easily achieved in molecular systems with vibrational frequencies in the mid- or far-infrared, reaching the quantum limit with macroscopic vibrations represents an entirely new regime, one where quantum mechanics interfaces more naturally with the macroscopic world. Relying on such fundamental light-matter interactions allows these phenomena to be investigated for mechanical resonances over an enormous range of masses and frequencies, as indicated in the figure. Indeed, the underlying light-matter interactions are relevant for determining underlying properties for the sensing of displacement in gravitational wave detection in the Laser Interferometer Gravitational-wave Observatory (LIGO) facility.

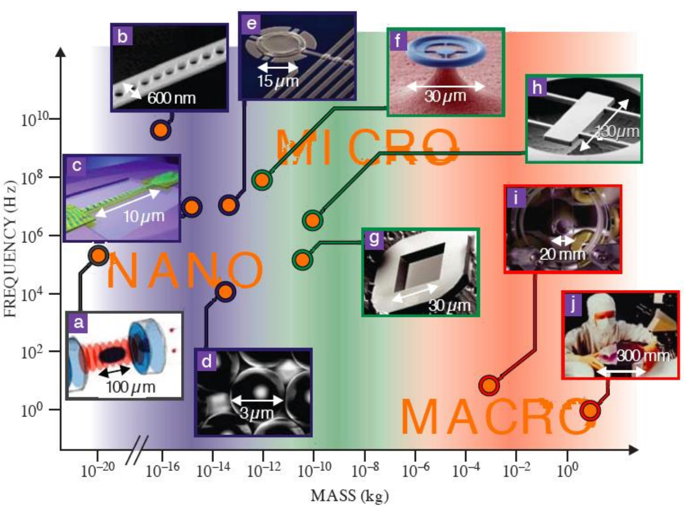

Figure 7. Cavity optomechanics investigations are currently being pursued on systems from individual atoms to macroscopic masses, covering more than 20 orders of magnitude in mass and 10 orders of magnitude in frequency [After M. Aspelmeyer et al., Physics Today 65(7), 29 (2012)]

The potential from successful research in this field is exceptional. It will permit tests of quantum theory at unprecedented size and mass scales, improve measurement capabilities beyond the standard quantum limit for fundamental physics measurements, establish spatial quantum superpositions of massive objects to probe theories of decoherence, and provide insight into the transition from quantum to classical behavior.

(4) Seeing beyond the diffraction limit and new imaging modalities

In terms of breadth of impact for science and technology, the optical microscope has perhaps been one of the most significant tools provided by optics and photonics. The impact has been and remains particularly pronounced not only in the physical sciences, but also in the life sciences. A fundamental restriction of conventional optical microscopy is that defined by the diffraction limit, imposed by the wave character of light focused or imaged in the far field. Given the flexibility of application of optical microscopy and the tremendous information content contained in spectroscopic signatures, there is enormous potential for techniques that can significantly extend the spatial resolution of optical microscopy. Several distinct advances have now created a revolution in optical microscopy that is having profound impact on a wide range of scientific disciplines and constitutes an area where additional research on the underlying methodologies is likely to have a disproportionate impact.

Advances in super-resolution microscopy have come from several distinct approaches, each of which opens distinctive new possibilities. One class of super-resolution microscopy is based on exquisite control of light fields in the near-field, where the restrictions of conventional light propagation are lifted. These schemes can involve either the localization of light sources or localization of scattering of light. While the first active research in such near-field optical microscopy dates back to the last century, the field is currently being strongly driven by the interaction with the advances in plasmonic control of light described above. This is leading to the extension of near-field techniques across the spectral range, into the far-infrared, for example; to precise polarization control; to advances in the quantitative interpretation of data; to combination with ultrafast optics; and further improvements in resolution and sensitivity.

A second major class of advance in microscopy has involved nonlinear interaction with materials. Of particular note has been the method of stimulated emission depletion (STED) microscopy in which a super-resolution fluorescence image is achieved by selectively deactivating fluorescence away from the center of the spot. This has yielded resolution below 100 nm and, in some cases, even below 10 nm. The method, although involving the complexity of nonlinear optics, does not require any near-field control and thus has all of the flexibility of traditional far-field imaging techniques. As such, it is widely applicable to problems in the life sciences. Nonlinear spectroscopy methods are also having a profound impact through their application to vibrational spectroscopy. The Raman process probes vibrational transitions through purely optical beams, rather than infrared radiation that would be needed for direct vibrational transitions. Thus, with respect to the infrared wavelength, higher resolution can be readily achieved. Key difficulties for Raman microscopy, however, involve sensitivity and background issues. Advances in nonlinear microscopy based on coherent anti-Stokes Raman scattering (CARS) and stimulated Raman scattering are showing excellent progress in overcoming these limitations for many applications.

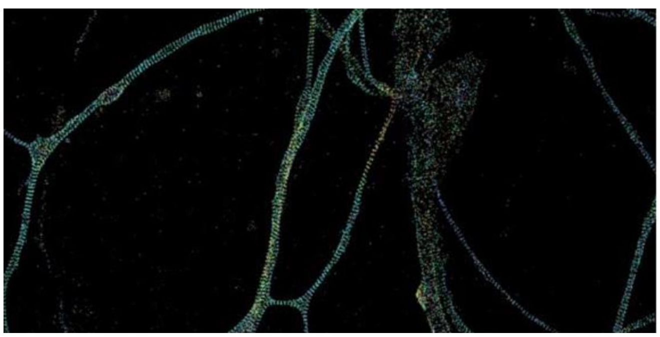

Figure 8. Structure of periodic rings in neurons revealed by super-resolution STORM microscopy. [After K. Xu et al., Science 339, 452 (2013)]

A further class of super-resolution microscopy designated by STORM (Stochastic Optical Reconstruction Microscopy) or PALM (Photo Activated Localization Microscopy) operates on yet another principal of image reconstruction. The underlying insight is that the position of a single isolated emitter can be determined by far-field optics to a precision far superior to the wavelength of light, simply by carefully measuring the scattering intensity as a focused laser beam is scanned over the emitter. The STORM/PALM techniques use this principle together with the selective activation of individual chromophores to obtain remarkably high-resolution images in biological systems. The revolutionary impact of these capabilities is illustrated in the figure showing previously unknown periodic structure of neurons revealed by STORM microscopy.

A further area of great importance for different disciplines, including notably neuroscience, involves advances in imaging in highly scattering media. Although light can propagate through centimeters of tissue, the strong scattering processes cause rapid degradation in imaging capabilities. Although this is a remains a very challenging problem, fundamental research in optics and photonics provides valuable approaches and significant recent advances, including the use of adaptive optics, the application of novel imaging geometries, and advanced analysis of wave propagation effects in scattering media to deconvolute increasingly sophisticated experimental data.

The high impact of this collection of imaging techniques on other areas of science, including forefront areas such as neuroscience, motivates research in the underlying optics and photonics principles and implementation. Such research is in itself strongly cross disciplinary, requiring advanced instrumentation, fundamentals of linear and nonlinear wave propagation, and mathematical modeling for data analysis.

(5) Creating and controlling quantum coherence with light

Coherence is one of the most fundamental and ubiquitous aspects of quantum mechanics and also the central aspect of novel many-body behavior in quantum solids and of new schemes for quantum computing. In this context, the ever advancing degree of control that lasers provide over electromagnetic radiation is one of the most powerful experimental tools available. The relevant coherence may be simply in the form of extremely monochromatic radiation of precisely controlled frequency, as is available from cw lasers and frequency combs of modelocked lasers, or it may arise from precise control of the waveform of ultrashort laser pulses, including specification of the carrier envelope phase.

The coherence of the laser radiation gives it a central role in investigation of very diverse physical phenomena, from precisely controlled impurity states in solids to atomic condensates to controlled molecular processes to correlated photon states. Here we highlight some of the forefront activities and opportunities.

In the realm of gas phase atoms, the creation of cold atoms and Bose-Einstein condensates was a spectacular triumph of the use of lasers to control matter. Recent research has emphasized systems that go beyond the homogeneous mean-field physics of a simple condensate. In particular, the use of optical lattices, combined with single atom detection, has permitted the exploration of materials with designer Hamiltonians to explore Bose Hubbard models, strongly correlated systems, Anderson localization and diffusion and artificial gauge fields.

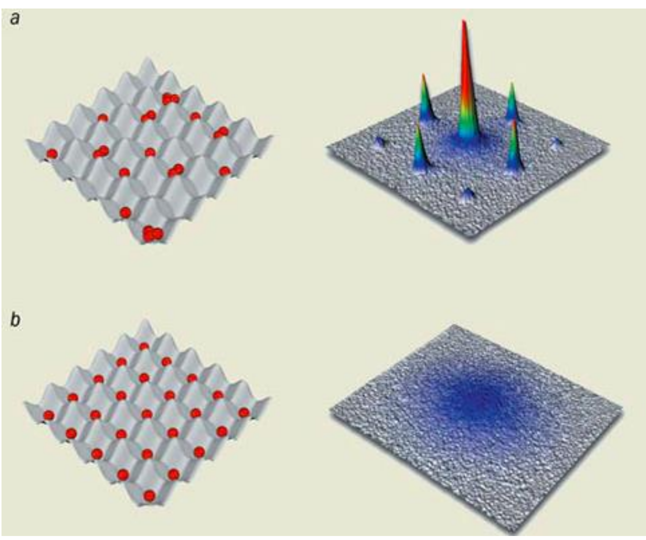

Figure 9. Optical lattices created by interfering laser beams permit precise tuning of interactions between atoms, allowing the creation of new states of matter and quantum simulators. [After I. Bloch, Nature Phys. 1, 23 (2005)]

In solids, simple quantum systems can be constructed using quantum dot structures, in which electrons are strongly confined spatially and mimic the behavior of electrons in atoms. These material systems have provided a basis for exploring fundamental aspects of quantum coherence and building controlled interactions between individual quantum systems. Just as in atoms, the spin of electrons in quantum dots can be accessed optically because of the influence of spin orbit interactions and level shifts in external magnetic fields. Frequency and time-resolved optical spectroscopy have provided a wealth of information about spin lifetimes and dephasing pathways, including coupling to nuclear spins, which provides a major channel for dephasing.

Recently, nitrogen-vacancy (NV) defect centers in diamond have been demonstrated as exceptional quantum systems for optical control. They are photostable and operate as single photon sources at room temperature. Most importantly they have long spin coherence times and can be optically read out at room temperature. Research has demonstrated the possibility of preparing, manipulating, and reading out the spin state of individual electrons at NV centers by purely optical means. In addition to their potential for creating interacting spin systems, the very long coherence times renders these materials excellent for sensors of magnetic fields, strain, and other perturbations. Recent advances have also shown the attractive features of color centers in SiC crystals.

For molecular systems, controlling quantum coherence between states under photoexcitation can influence reaction channels. Even in large photoexcited molecules this topic has been a subject of great recent interest because of research indicating the role of quantum coherence in steps in photosynthetic systems, including the role of quantum entanglement of excitations in a photosynthetic light-harvesting protein.

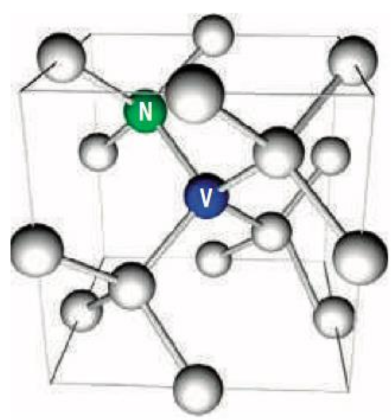

Figure 10. NV centers in diamond provide a solid-state material system with convenience optical access to a quantum system having long spin coherence times. In isotopically pure carbon, spin coherence times of a fraction of a second have been observed at room temperature. [After T. Gaebel et al., Nature Phys. 2, 408 (2006)]

Finally, the coherence of laser light provides a means of producing strongly entangled photons through the nonlinear response of second-order nonlinear material. These sources are providing the basis for tests of the fundamental properties of quantum mechanics.

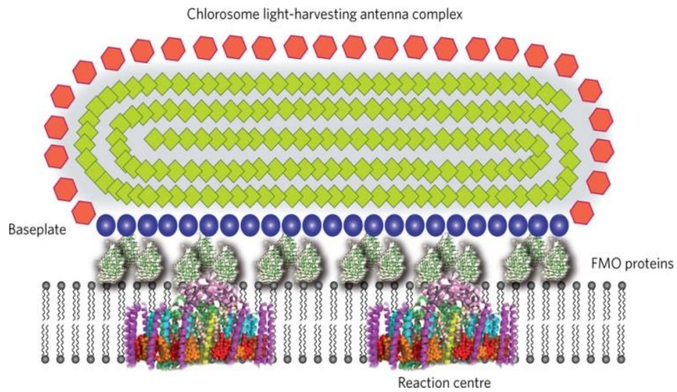

Figure 11. Photosystem in which energy is collected in a light harvesting complex and transferred to the reaction center. Recent research indicates the role of coherence and quantum entanglement in the energy transfer process. [After G. D. Scholes, Nature Phys. 6, 402 (2010)]

Underlying these diverse physical phenomena and their important implications are the ability to produce, control, and monitor coherence through refined control of light fields and the fundamental understanding of light matter interactions. These topics are critical research areas that lie at the core of optics and photonics research.

(6) Controlling molecules with light and light with molecules

The study of photoinduced changes in molecules is a central research topic in chemistry and lies at the heart of critical industrial processes such as the modification of photoresists by photopolymerization, as well the production of new molecules through the photosynthesis process.

A topic of great current interest that interfaces photochemistry with nanoscience as well as the theme of optomechanics described above is the notion of photodriven molecular machines. Recent research has demonstrated the possibility of mechanical motion of molecules through cyclic steps in analogy to mechanical motors. A significant recent advance has been the development of systems in which unidirectional rotational motion is achieved using the chiral molecules, as illustrated in the figure. Optical control methods based on shaping of the characteristics of the driving light field can enhance the efficiency of the process through steps involving excitation with a chirped pulse, a pump step, and a dump step.

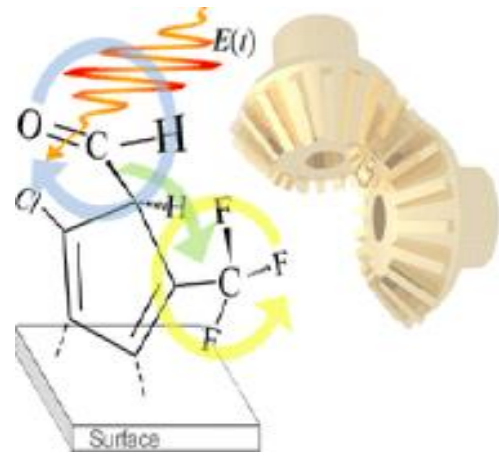

Figure 12. Photodriven unidirectional rotation has been demonstrated in molecular motor based on chiral molecules. [After M. Yamaki et al., Phys. Chem. Chem. Phys. 11, 1662 (2009)]

Progress in developing such molecular machines requires advances in laser and pulse shaping capabilities, along with theoretical advances in devising the optimal excitation strategy. The payoff is an enhanced understanding of fundamental processes that are relevant to many areas of science, from biology to nanoscience.

Within the context of optics and photonics, molecular systems also offer a research opportunity for the development of materials that interact with light to achieve important technological outcomes. These include the production of photovoltaic power, the shaping of materials in two and three dimensions, and the optoelectronic control of light and generation of new frequencies through nonlinear optics. The advantages of organic materials over inorganic systems include great design flexibility, low cost, and the potential for outstanding performance in terms of speed and efficiency.

An example of the possibilities is shown by the use of two-photon excitation to achieve three-dimensional patterning of materials. The figure shows the use of a molecular system with optimized two-photon absorption to induce photopolymerization as a means of obtaining precise 3D patterning of materials.

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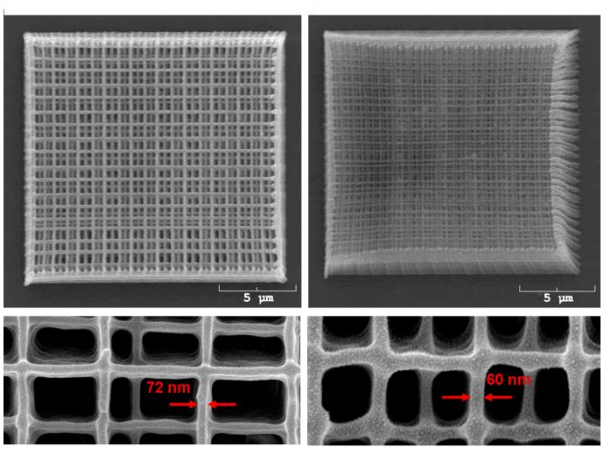


Figure 13. Production of a 3D woodpile photonic crystal structure using photopolymerization with a 532 nm laser. The nonlinearity enhances resolution and also permits 3D patterning. The structure can be tuned by the laser power, as shown in structures (a) and (b). [After W. Haske et al., Opt. Express 15, 3426 (2007)]

Understanding and enhancement of the nonlinear response of molecules will also benefit the development of materials with second-order nonlinear response (for second-harmonic generation and electro-optic switching) and the third-order response, which can be used for all optical pulse switching and optical pulse limiting, as well as for two-photon absorption. This research area draws on advances in molecular synthesis, theory and computation, as well as improved laser sources, such as low cost femtosecond lasers, to enhance the range of applications.

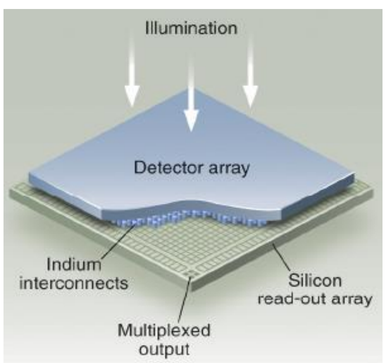
This area is timely for research investment because of its centrality to chemistry, but also its strong connection to advances in other areas. In particular, developments in plasmonics provide renewed impetus for the development of nonlinear materials that can be easily integrated with nanostructures. Understanding of nonlinear material response, the development of improved chromophores, and study of light matter interaction is also essential for advanced imaging schemes, such as those discussed above, and critical for progress in brain imagining and other major problems in the life sciences.

(7) Observing the universe: optics and photonics for astronomy and astrophysics

Optics and photonics techniques and technology have been and remain the central methods for probing the universe around us. As such, advances in optics and photonics play an indispensible role in these fundamental science areas. In addition to the optical design of observatories on the ground and in space, imaging detectors are a crucial part of recording optical signals with high precision and sensitivity. Here, we highlight critical research issues that will not only strongly benefit astronomy and astrophysics with respect to detector development, but also relate to fundamental advances in optics and photonics that have the potential for impact in fields ranging from communications to environmental sensing.

We describe two areas of particular importance and impact: building on advances in CMOS technology to produce high-performance hybrid detectors and new approaches for detection in the far-infrared/THz spectral range.

Image sensor technologies in the visible and IR spectral ranges are complex systems that optimize and trade off many desired features, including quantum efficiency, sensitivity as a function of wavelength, linearity and dynamic range, dark current noise characteristics, integration time and readout speed, pixel number and size, and electronic interfacing. Based on the enormous ongoing investment in large-scale integration in silicon CMOS technology within the commercial sector, detectors based on this technology are continually expanding in importance. In the context of high-performance detectors for diverse astronomy and astrophysics applications, a crucial set of technologies involves hybrid imaging sensors in which the detector array is fabricated in the optimal material system (Si, HgCdTe, III-V semiconductors and quantum wells, etc.) and fused with a silicon read-out integrated circuit (CMOS ROIC). This approach can be applied with pixel counts exceeding 100 megapixels, without sacrificing flexibility in the choice of detector material.



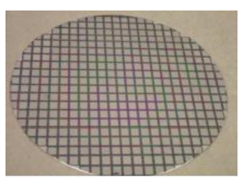


Figure 14. Arrangement of a hybrid CMOS imaging sensor. This design provides the optimized read-out integrated circuit in CMOS technology with the choice of most suitable detector material for the specific application. The image to the right shows a wafer-to-wafer hybridization with 150 M interconnections. [After J. W. Beletic et al., SPIE Proc. 7021, H1 (2008)]

An important recent development is the use of backside illuminated CMOS (BI CMOS) detectors. This approach combines the best of CCDs and CMOS sensors leading to very low noise, very low dark current, and radiation hardness. Combined with wafer-to-wafer bonding, this will produce a large class of high-performance imaging sensors for space and other applications. The technology is currently being pursued much more aggressively outside the United States than domestically.

The THz and mm-wave spectral range has traditionally been difficult to access, despite its interest and importance in terms of spectroscopy. For example, the cosmic microwave background lies in this spectral range. The recent report of the observation of the B-mode polarization pattern in background radiation, providing a signature of cosmic inflation shortly after the big bang, was the result of precision measurements in which high signal-to-noise was essential.

Spectroscopic capabilities in this important spectral range have been advancing through several distinct experimental approaches. From the perspective of laboratory experiments in this spectral range, an important advance from the optics and photonics community has been the use of ultrafast spectroscopy to generate and detect controlled THz waveforms using the time resolution inherent in femtosecond laser pulses, which are coupled to THz electric fields by photoconductivity or optical rectification and electro-optic sampling. In the context of observational astronomy and sensing, however, passive detectors with high sensitivity are needed. Here, we highlight recent progress in ultrahigh speed electronics as offering possibilities for advances in spectroscopy in the THz region. Because of large investments in high-speed electronics, integrated circuits operating in the range of many hundreds of GHz are now available. This provides significant new opportunities for spectroscopy in ranges approaching the THz through the development of optimized devices for this purpose. This research is particularly timely because it offers a substantial expansion of the available spectral range, while capitalizing on progress in devices developed for high-speed electronics applications.

Complementing these approaches have been dramatic developments in detection of single photons at long wavelengths using new advances in superconducting transition edge bolometric detectors and superconducting nanowire detectors. This represents a frontier that can enhance not only measurement sensitivity for astrophysics and other applications, but can also extend quantum optics into a new spectral range.

APPENDIX 1. CHARGE TO THE OPTICS AND PHOTONICS SUBCOMMITTEE OF THE MPS ADVISORY COMMITTEE

A newly-formed subcommittee of the MPS Advisory Committee is charged with advising MPS on its role, vision, and scientific and educational program of work in support of Optics and Photonics basic research. In developing this advice, the subcommittee should be cognizant of the current NSF investments in optics and photonics research and education, the most recent NRC report described above (and its recommendations to the NSF), as well as other background material from the optics and photonics research community.

The subcommittee should consider the capabilities, capacity, potential for advancing optics and photonics science, and opportunities that may arise including the development of new experimental tools, materials, and models, as well as the scientific and education mission of the NSF. The subcommittee is asked, at a minimum, to address the adequacy of the current MPS portfolio in optics and photonics, and to identify a set of basic research grand challenges that would enable new technological advances. In addition, the subcommittee should identify basic research opportunities as well as the need, if any, for investments in the development of research infrastructure to support optics and photonics. Lastly, the report should also address education-related research efforts needed to support the professional development of the next generation of the U.S. optics and photonics workforce.

APPENDIX 2. MEMBERSHIP OF THE OPTICS AND PHOTONICS SUBCOMMITTEE OF THE MPS ADVISORY COMMITTEE

David Awschalom
Liew Family Professor in Molecular Engineering, University of Chicago

James Beletic
Vice President, Space and Astronomy, Teledyne Scientific and Imaging Corporation

Philip Bucksbaum
Marguerite Blake Wilbur Professor in Natural Science, Stanford University

Taekjip Ha
Professor of Physics, University of Illinois Urbana-Champaign

Tony Heinz (Chair)
David Rickey Professor of Physics and Electrical Engineering, Columbia University

William L. Kath
Professor of Engineering Sciences and Applied Mathematics, Northwestern University

Seth Marder
Professor of Chemistry and Biochemistry, Georgia Institute of Technology

Pierre Meystre
Regents Professor of Physics and Optical Science, University of Arizona

Margaret Murnane
Distinguished Professor, Department of Physics, University of Colorado

Vladimir Shalaev
Burnett Professor of Electrical Engineering and Biomedical Engineering, Purdue University

Roseanne Sension
Professor of Chemistry and Physics, University of Michigan