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14. ABSTRACT

See Attachment

15. SUBJECT TERMS

Capitalizing on Optical Science Trends and Challenges for Future Research

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Report Title

Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research

ABSTRACT

See Attachment

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

NATIONAL MATERIALS and MANUFACTURING BOARD (NMMB)

Harnessing Light:
Capitalizing on Optical Science Trends and Challenges for Future Research

Final Progress Report: September 27, 2010 – December 31, 2012

This is an Interim Progress Reporting for Proposal Number: 58809-EL, Agreement Number: W911NF-10-1-0488, which is due on March 31, 2013 for the period beginning September 27, 2010 and ending December 31, 2012.

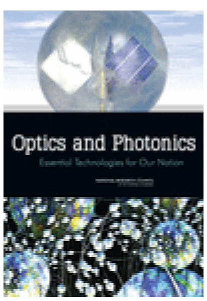
TO BE SUBMITTED Online at https://extranet.aro.army.mil/progress-reports/

This activity covers work performed under the following Contracts; DARPA-DSO, 09-DEPS-333-01, DARPA-MTO, 09-DEPS-333-03, NSF, 09-DEPS-333-02, NIST, 10-145-01, ARO, 10-145-02, DOE-EERE, 10-145-03 and DOE-BES, 10-145-04. Which supports the National Research Council (NRC) Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research, for the period beginning September 27, 2010 and ending December 31, 2012.

ACTIVITIES and FINDINGS

The committee has during the earlier period finalized their work on the report. The report did undergo review and initial editorial processing. The NRC released a pre-publication report on August 13. A final report is now available on:

http://www.nap.edu/catalog.php?record_id=13491



The major research and education activities of the project are:

From an educational perspective this grant has not directly generated any educational activities similar to a traditional grant. However, the study director Erik Svedberg has been able to practice his skills in running a national academies committee. From a research perspective the grant has generated a report with recommendations to the government (see point 2). These recommendations can be seen as the "outcome" of this work. The work itself is the meetings where the committee convened to hear presenters and to discuss the status of optics and photonics as well as writing the report. These activities were meeting on the following dates:

Harnessing Light: - 02/23/2011
Harnessing Light: - 04/07/2011
Harnessing Light: - 06/14/2011
Harnessing Light: - 08/23/2011
Harnessing Light: - 10/04/2011
Harnessing Light: - 02/13/2012

The speakers that gave official input to the research activity were:

Eugene Arthurs, SPIE,
John Dexheimer, First Analysis,
Ed Dowski, Ascentia Imaging,
Julie Eng, Finisar,
Michael Gerhold, United States Army,
Larry Goldberg, National Science Foundation,
Matthew Goodman, Defense Advanced Research Projects Agency,
Linda Horton, Department of Energy,
Kristina Johnson, Consultant,
Christian Jörgens, German Embassy,
Bikash Koley, Google,
Prem Kumar, CLEO,
Minh Le, Department of Energy,
Donn Lee, Facebook,
Robert Leheny, Institute for Defense Analyses,
Frederick J. Leonberger, Eovation Advisors, LLC,
Tingye Li, AT&T Consultant,
Aydogan Ozcan, University of California, Los Angeles,
Mario Paniccia, INTEL,
Kent Rochford, National Institute of Standards and Technology,
Joseph Schmitt, Cardiovascular Division, St. Jude Medical,
Jag Shah, Defense Advanced Research Projects Agency,
Bruce J. Tromberg, University of California, Irvine,
Usha Varshney, National Science Foundation,
Paul Wehrenberg, Consultant,

The major findings resulting from these activities are:

As stated above, from a research perspective the grant has generated a report with recommendations to the government, these recommendations can be seen as the "outcome" of this work and they are:

Key Recommendation: The committee recommends that the federal government develop an integrated R&D “national photonics initiative” in photonics (like the

National Nanotechnology Initiative (NNI)) that seeks to conceptualize and manage photonics R&D spending (and, possibly related investments) as a portfolio.

Key Recommendation: The committee recommends that the "National Photonics Initiative" spearhead a collaborative effort to improve the collection and reporting of R&D and economic data on this sector, including the development of a set of NAICS codes that cover photonics, the collection of data on employment, output, and privately funded R&D in photonics, and reporting of federal photonics-related R&D investment for all federal agencies and programs.

Key Recommendation: The U.S. government, and private industry in combination with academia, need to invent technologies for the next factor of 100 cost-effective capacity increase in Long Haul, Metro and Local Area Optical Networks.

Key Recommendation: The U.S. government, and specifically DOD, should strive towards harmonizing optics with silicon-based electronics to provide a new, readily accessible and usable, integrated electronics and optics platform.

Key Recommendation: The U.S. government and private industry should position the U.S. as a leader in the global data center business.

Key Recommendation: The United States defense and intelligence agencies should fund the development of optical technologies to support future optical systems capable of wide area surveillance, exquisite long-range object identification, high-bandwidth free-space laser communication, speed of light laser strike, and defense against both missile seekers and ballistic missiles.

Key Recommendation: The DOE should develop a plan for grid parity across the U.S. by 2020.

Key Recommendation: DOE should strongly encourage development of highly efficient LEDs for general purpose lighting and other applications.

Key Recommendation: New approaches, or dramatic improvements in existing methods and instruments, should be developed by industry and academia to provide increased sensitivity and specificity for detecting antibodies, enzymes and important cell phenotypes.

Key Recommendation: The United States should aggressively develop additive manufacturing technology and implementation.

Key Recommendation: The U.S. government, in concert with industry and academia, should develop soft x-ray lasers and imaging for lithography and 3D manufacturing.

Key Recommendation: The United States should develop the technology for generating light beams with pre-arranged photonic structure.

The opportunities for training, development and mentoring provided by this project are:

During this project a former 2012 Mirzayan fellow from the Academies, Maria Dahlberg, was hired temporarily to participate in the later phase of the project. She was mentored by senior staff officer Erik Svedberg. This generated an opportunity for a young scientist to see the process and to participate in the finalization of a report as well as the initial dissemination of it.

The outreach activities this project has undertaken are:

Several Town halls were held where the public were informed about the committee and its statement of task, then the public had an opportunity to comment and participate in a discussion of the statement of task for this committee. These were held at regular meetings in the optics and photonics community as indicated below.
Town hall DSS - 04/27/2011 http://spie.org/x6765.xml
Town Hall CLEO - 05/04/2011 http://www.cleoconference.org/
Town Hall at SPIE Optics + Photonics 2011 - 08/22/2011
http://spie.org/x30491.xml

SPIE Optics and Photonics 8/12-8/16 San Diego
http://spie.org/x30491.xml
Frontiers in Optics: The 96th OSA Annual Meeting and Exhibit (FiO) 10/14-10/18 Rochester, New York http://www.frontiersinoptics.com/

Publication & Products

Published as a result of this work are:

- Journal publications

To date no journal publications have been generated.

- Books or other non-periodical, one-time publications

The report itself, ISBN-10: 0-309-26377-8 (280 pages) at The National Academy Press

And the booklet: Harnessing Light, for Americas Technological Future. (14 pages)

The booklet has been distributed this far in the following way:

600 to SPIE meeting, Plus SPIE made a booklet and numerous videos based on this. Plus made 7,000 one-page summaries for distribution to every conference attendee. http://spie.org/x88993.xml
500 for distribution at the OSA (The Optical Society) Annual Meeting Oct 14-18, 2102, Rochester, NY
50 to Lawrence Goldberg of the National Science Foundation, Arlington, VA
50-ish to an OSA meeting at Stanford University
50-Steven Chu, DOE, speaking at a combination discussion about Harnessing Light
20 to the BEMA meeting held Oct 1-2, 2012

Web sites or other Internet sites created are:

The Academies have the report available at:
http://www.nap.edu/catalog.php?record_id=13491

And also: http://sites.nationalacademies.org/DEPS/NMMB/DEPS_060361

Other specific products (databases, physical collections, educational aids, software, instruments, or the like) developed are:

The following tweets have been made to the followers of the National Academy's informing them about different activities:

NASciences Oct 16, 1:37pm via HootSuite
In the news - RT @opticalsociety: On #FiO12 show floor today - Town Hall discussion on NRC optics & photonics rept: ow.ly/ewx5e
NASciences Sep 17, 9:30am via HootSuite
RT @Photonics_com: 'The Promise of #Optics and #Photonics' Presented on Capitol Hill - photonics.com/wa51857
NASciences Sep 14, 10:26am via HootSuite
Members of optics & photonics communty spoke at Capitol Hill about NRC's rept: ow.ly/dIvte , download it here: ow.ly/dIvwV
NASciences Aug 29, 8:10am via HootSuite
RT @OSAPublicPolicy: Miss our webcast last wk on the #optics and #photonics report? No problem, you can watch online! ow.ly/diuvm
NASciences Aug 22, 9:24am via HootSuite
Here's the video of the launch event for NRC's Optics and Photonics ow.ly/d9jIa - report is free to download: ow.ly/d9jMO
NASciences Aug 21, 11:05am via HootSuite
RT @opticalsociety: Join us for webcast today at 10am PDT - about the landmark @NASciences rept on #optics & #photonics ow.ly/d5WfV
NASciences Aug 20, 12:25pm via HootSuite
Thanks, @SPIEtweets! SPIE commends new NRC report Optics and Photonics: ow.ly/d61Gi , download it for free: ow.ly/d61JG
NASciences Aug 13, 12:28pm via HootSuite

OSA's G. Quarles: "Rept will serve as a vital tool to make the case for investments in optical science & technology" ow.ly/cW75T
NASciences Aug 13, 11:30am via HootSuite
Study Director Erik Svedberg on the NRC Optics and Photonics report: ow.ly/cVP7P
NASciences Aug 13, 11:20am via HootSuite
Comm. cochair Paul McManamon on the #Optics and #Photonics study: ow.ly/cVOpm, download here: ow.ly/cVON2
NASciences Aug 02, 9:15am via HootSuite
John Dexheimer on possible impacts of forthcoming NRC report #Optics and #Photonics ow.ly/cGBd5 @SPIEtweets

Contributions

1. the principal discipline(s) of the project;

   We believe that ultimately this work will affect all parts of society that has any connection to Optical Science. It has for some time been known that the scientists and the professional societies that deal with optics and photonics felt a keen need for the National Academies to provide an authoritative vision of the field's future. Since the field is, indeed, a key enabling technology that will help drive significant economic growth, a study should attempt to make recommendations that can be used to help policy-makers and decision makers capitalize on optics and photonics.

   other disciplines of science or engineering;

   Other disciplines will be affected by the recommendations in this study since optics and photonics is an enabling technology underpinning many modern disciplines. The final report has many examples of this.

2. the development of human resources;

   We believe the report will have a profound effect on the areas where the report touches upon different aspects of society. These are:

   The National Economy,
   Communications, Information Processing, And Data Storage,
   Defense and National Security,
   Energy,
   Health and Medicine,
   Advanced Manufacturing,
   Advanced Photonic Measurements and Applications,
   Strategic Materials For Optics, and
   Displays

3. the physical, institutional, or information resources that form the infrastructure for research and education;

> The committee recommends that the federal government develop an integrated initiative in photonics (similar in many respects to the National Nanotechnology Initiative) that seeks to bring together academic, industrial, and government researchers, managers, and policy makers to develop a more integrated approach to managing industrial and government photonics R&D spending and related investments.
> This recommendation is based on the committee's judgment that the photonics field is experiencing rapid technical progress and rapidly expanding applications that span a growing range of technologies, markets, and industries. Indeed, in spite of the maturity of some of the constituent elements of photonics (e.g., optics), the committee believes that the field as a whole is likely to experience a period of growth in opportunities and applications that more nearly resembles what might be expected of a vibrantly young technology. But the sheer breadth of these applications and technologies has impeded the formulation by both government and industry of coherent strategies for technology development and deployment.
> A national photonics initiative would identify critical technical priorities for long-term federal R&D funding. In addition to offering a basis for coordinating federal spending across agencies, such an initiative could provide matching funds for industry-led research consortia (of users, producers, and material and equipment suppliers) focused on specific applications, such as those described in the report. In light of near-term pressures to limit the growth of or even reduce federal R&D spending, the committee believes that a coordinated initiative in photonics is especially important.

Conference Proceedings

No direct conference proceedings have been produced but several videos have been generated such as:

http://spie.org/app/spietv/default.aspx?video=1503249561001
http://spie.org/x86585.xml Paul MacManamon video on HL II

Front matter and summary of final report

COMMITTEE ON HARNESSING LIGHT: CAPITALIZING ON OPTICAL SCIENCE TRENDS AND CHALLENGES FOR FUTURE RESEARCH

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CAREY CHEN, Christine Mirzayan Science and Technology Policy Fellow, STEP (October through December 2011)

[1] NAE, National Academy of Engineering.
[2] NAS, National Academy of Sciences.
[3] STEP, Board on Science, Technology, and Economic Policy.

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RICKY D. WASHINGTON, Executive Assistant
HEATHER LOZOWSKI, Financial Associate
MARIA L. DAHLBERG, Program Associate
LAURA TOTH, Program Assistant (Until February 2012)

[4] NAE, National Academy of Engineering.

PREFACE

The National Research Council (NRC) undertook the writing of a study on optics and photonics in 1988 (*Photonics: Maintaining Competitiveness in the Information Era*)[5] and then again in 1998 (*Harnessing Light: Optical Science and Engineering for the 21st Century*).[6] Now, after 14 years of dramatic technical advances and economic impact, there is need for another study to help guide the nation's strategic thinking in this area. Since 1998 many other countries have developed their own strategic documents and organizations in the area of optics and photonics, and many have cited the U.S. NRC's 1998 *Harnessing Light* study as instrumental in influencing their thinking. The present study, *Optics and Photonics: Essential Technologies for Our Nation*, discusses impacts of the broad field of optics and photonics and makes recommendations for actions and research of strategic benefit to the United States.

To conduct the study, the NRC established the Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research, which represents a diverse group of academic and corporate experts from across many disciplines critical to optical science and engineering, including materials science, communications, quantum optics, linear and nonlinear optical elements, semiconductor physics, device fabrication, biology, manufacturing, economic policy, and venture capital. The statement of task for this study (given in full in Appendix A) is as follows:

> 1. Review updates in the state of the science that have taken place since publication of the National Research Council report *Harnessing Light*;
> 2. Identify the technological opportunities that have arisen from recent advances in and potential applications of optical science and engineering;
> 3. Assess the current state of optical science and engineering in the United States and abroad, including trends in private and public research, market needs, examples of translating progress in photonics innovation into competitiveness advantage (including activities by small businesses), workforce needs, manufacturing infrastructure, and the impact of photonics on the national economy;
> 4. Prioritize a set of research grand-challenge questions to fill identified technological gaps in pursuit of national needs and national competitiveness;
> 5. Recommend actions for the development and maintenance of global leadership in the photonics-driven industry—including both near-term and long-range goals, likely participants, and responsible agents of change.

It became apparent from the outset that various funding agencies and professional societies that deal with optics and photonics felt a keen need for the NRC to provide an authoritative vision of the field's future. If the field is indeed a key enabling technology that will help drive significant economic growth, then such a study should attempt to make recommendations that can be used to help policy-makers and decision makers

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[5] National Research Council (NRC). 1988. *Photonics: Maintaining Competitiveness in the Information Era*, Washington, D.C.: National Academy Press.
[6] National Research Council (NRC). 1998. *Harnessing Light: Optical Science and Engineering for the 21st Century*. Washington, DC: The National Academies Press.

capitalize on optics and photonics. It was in this spirit that the committee conducted this study.

Several factors, including the following, made the committee's task a challenging one:

- The field of optics and photonics is extremely broad in terms of the technical science and engineering topics that it encompasses.
- The field impacts many different market segments, such as energy, medicine, defense, and communications, but as an enabling technology it is not always highlighted in available data about these areas.
- The field has expanded greatly beyond the United States, such that many other countries have invested heavily in research and development and manufacturing.

Additionally, the area of optics and photonics is typically subsumed as an enabling technology under the heading of other disciplines (e.g., electrical engineering, physics). Therefore, it was challenging to gather data specific to optics and photonics in terms of workforce and economic impact. For example, optics enables common DVD players, but is the economic impact to be gauged by the value of the whole DVD player or just the inexpensive yet high-performance laser that makes the whole system work properly? Similarly, how do we place a value on the fact that the society-transforming Internet could not have grown at such a fast pace, or achieved even close to its current level of performance, without low-loss optical fiber, which by itself is not particularly expensive? The committee grappled with many such questions.

In the course of the study, the committee observed that exciting progress has been made in the field and believes that the future holds much promise. A small anecdotal indication in the popular press of the breadth and depth of the field is that roughly 12 of the 50 best inventions of 2011 listed by *Time Magazine* had optics as a key technological part of the invention.[7]

Our entire community owes its sincerest gratitude to the generous sponsors of the study, which include the Army Research Office, the Defense Advanced Research Projects Agency, the Department of Energy, the National Institute of Standards and Technology, the National Research Council, the National Science Foundation, the Optical Society of America, and the International Society for Optics and Photonics (SPIE). Each sponsor was critical to enabling the study to proceed with the necessary resources, and key champion(s) in each of these organizations stepped forward at a crucial time to help out. We also wish to thank the many individuals who helped the committee accomplish its task, including the workshop speakers and study reviewers, and we are extremely grateful to have worked with outstanding committee members.

It was with a deep sense of appreciation that the committee was able to rely on the dedication, professionalism, insight, and good cheer of the NRC staff, primarily Dennis Chamot, Maria Dahlberg, Erik Svedberg, Laura Toth, and Ricky Washington. As the manager of the study, Erik has been a superb and tireless partner, whose keen perspective was invaluable. The committee also extends its thanks to Stephen Merrill, executive director of the National Academies' Board on Science, Technology, and Economic

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[7] Grossman, L., M. Thompson, J. Kluger, A. Park, B. Walsh, C. Suddath, E. Dodds, K. Webley, N. Rawlings, F. Sun, C. Brock-Abraham and N. Carbone. 2011. Top 50 Inventions. *Time*.

Policy, for engaging his staff during the latter part of this study, especially Paul Beaton, program officer, and Carey Chen, Christine Mirzayan Science and Technology Policy Fellow. In addition, the committee would like to thank Kathie Bailey-Mathae, Board Director of the Board on International Scientific Organizations, for critically helping with the preliminary groundwork leading up to the start of the study.

We sincerely hope that readers of this study find some perspectives that will help guide future actions, whether such readers are congressional staffers, funding agents, corporate chief technology officers, or high school students.

Paul McManamon and Alan E. Willner, *Co-Chairs*
Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

William B. Bridges [NAS/NAE], California Institute of Technology.
Elsa Garmire [NAE], California Institute of Technology.
James S. Harris [NAE], Stanford University.
Thomas S. Hartwick, Hughes Aircraft Company.
Eric G. Johnson, Clemson University
Stephen M. Lane, Lawrence Livermore National Laboratory.
E. Phillip Muntz [NAE], University of Southern California.
Thomas E. Romesser [NAE], Northrop Grumman Aerospace Systems.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Peter Banks [NAE], Red Planet Capital Partners. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee also thanks those who were guest speakers at its meetings and who added to the committee members' understanding of photonics and the issues surrounding it:

Eugene Arthurs, SPIE
John Dexheimer, First Analysis
Ed Dowski, Ascentia Imaging
Julie Eng, Finisar
Michael Gerhold, United States Army Research Office
Larry Goldberg, National Science Foundation
Matthew Goodman, Defense Advanced Research Projects Agency
Linda Horton, Department of Energy
Kristina Johnson, Consultant
Christian Jörgens, German Embassy
Bikash Koley, Google
Prem Kumar, CLEO

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Frederick J. Leonberger, Eovation Advisors, LLC
Tingye Li, AT&T Consultant
Aydogan Ozcan, University of California, Los Angeles
Mario Paniccia, INTEL
Kent Rochford, National Institute of Standards and Technology
Joseph Schmitt, Cardiovascular Division, St. Jude Medical
Jag Shah, Defense Advanced Research Projects Agency
Bruce J. Tromberg, University of California, Irvine
Usha Varshney, National Science Foundation
Paul Wehrenberg, Consultant

Summary

Optics and photonics technology is central to modern life. It enables the manufacture and inspection of all the integrated circuits in every electronic device in use.[8] It gives us displays on our smartphones and computing devices, optical fiber that carries the information in the Internet, advanced precision fabrication, and medical diagnostics tools. Technology offers the potential for even greater societal impact over the next few decades. Solar power generation and new efficient lighting could transform the energy landscape new optical capabilities will be essential to supporting the continued exponential growth of the Internet. Optics and photonics technology development and applications have substantially increased across the globe over the past several years. This is an encouraging trend for the world's economy and its people, while at the same time posing a challenge to U.S. leadership in these areas. As described in this study conducted by the National Research Council's (NRC's) Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research, it is critical that the United States to take advantage of these emerging optical technologies for creating new industries and generate job growth.

[8] For example, Photolithography is used to create most layers in the integrated circuits and cameras inspect the quality afterwards.

Each chapter addresses the developments that have taken place over the 15 years since the publication of the NRC report *Harnessing Light: Optical Science and Engineering for the 21st Century*[9], technological opportunities that have arisen since then, the state of the art in the United States and abroad, and recommendations for how to maintain U.S. global leadership.

It is the committee's hope that this study will help policy makers and leaders decide on courses of action that can advance the economy of the United States, provide visionary guidance and support of the future technology development of optics and photonics and of future applications, and ensure a leadership role for the United States in these areas. Although much is unknown in the course of pursuing basic optical science and its transition to engineering and ultimately to products, the rewards can be great. Researchers have achieved some dramatic feats. For example, optics and photonics now provide clocks which are so stable that they will slip less than 1 second in more than 100 million years. Although much more primitive clocks have enabled the incredibly useful Global Positioning System (GPS), it remains unclear how these new clock advances can be fully harnessed for the benefit of society. In many ways, this inability to see into the future might be analogous to the dawn of the laser in 1960, when many of the transforming applications of that extraordinary invention had not yet been contemplated. This is only one example of the magnitude of the impact that applications of technology innovation in optics and photonics t can produce.

GRAND CHALLENGE QUESTIONS TO FILL TECHNOLOGICAL GAPS

[9]National Research Council (NRC). 1998. *Harnessing Light: Optical Science and Engineering for the 21st Century*. Washington, DC: The National Academies Press.

To fill identified technological gaps in pursuit of national needs and national competitiveness, the committee developed five overarching grand challenge questions:

1. How can the U.S. optics and photonics community invent technologies for the next factor-of-100 cost-effective capacity increases in optical networks?

As mentioned in Chapter 3, it is not currently known how to achieve this goal, but the world has experienced a factor-of-100 cost-effective capacity increase every decade thus far, and user demand for this growth is anticipated to continue. Unfortunately, the mechanisms that have enabled the previous gains cannot sustain further increases at that high rate, and so the world will either see increases in capability stagnate or will have to invent new technologies.

2. How can the U.S. optics and photonics community develop a seamless integration of photonics and electronics components as a mainstream platform for low-cost fabrication and packaging of systems on a chip for communications, sensing, medical, energy, and defense applications?

In concert with the fifth grand challenge, achieving this grand challenge would make it possible to stay on a Moore's law-like path of exponential performance growth. The seamless integration of optics and photonics at the chip level has potential to significantly increase speed and capacity for many applications that are currently using only electronics, or are integrating electronics and photonics at a larger component level.

Chip-level integration will reduce weight and increase speed while reducing cost, thus opening up a large set of future possibilities as devices become further miniaturized.

3. How can the U.S. military develop the required optical technologies to support platforms capable of wide-area surveillance, object identification and improved image resolution, high-bandwidth free-space communication, laser strike, and defense against missiles?

Optics and photonics technologies used synergistically for a laser strike fighter or a high-altitude platform can provide comprehensive knowledge over an area, the communications links to download that information, an ability to strike targets at the speed of light, and the ability to robustly defend against missile attack. Clearly this technological opportunity could act as a focal point for several of the areas[10] in optics and photonics in which the U.S. must be a leader in order to maintain national security.

4. How can U.S. energy stakeholders achieve cost parity across the nation's electric grid for solar power versus new fossil-fuel-powered electric plants by the year 2020?

The impact on U.S. and world economies from being able to answer *yes* to this question would be substantial. Imagine what could be done with a renewable energy source, with minimum environmental impact, that is more cost-effective than nonrenewable alternatives. Although this is an ambitious goal, the committee poses it as

[10] This touches subjects such as camera development, high powered lasers, free space communication and many more.

a grand challenge question, something requiring an extra effort to achieve. Today, it is not known how to achieve this cost parity with current solar cell technologies.

5. How can the U.S. optics and photonics community develop optical sources and imaging tools to support an order of magnitude or more of increased resolution in manufacturing?

Meeting this grand challenge could facilitate a decrease in design rules for lithography, as well as the providing ability to do closed-loop, automated manufacturing of optical elements in three dimensions. Extreme ultraviolet (EUV) is a challenging technology to develop, but it is needed in order to meet future lithography needs. The next step beyond EUV is to move to soft x-rays. Also, the limitations in three-dimensional resolution on laser sintering for three-dimensional manufacturing is based on the wavelength of the lasers used. Shorter wavelengths will move the state of the art to allow more precise additive manufacturing that could eventually lead to three-dimensional printing of optical elements.

The committee believes that these five grand challenges are the top priorities in their respective application areas, and that because of their diverse nature, further prioritization amongst them is not advisable. These grand challenge questions are discussed in the main text immediately after the first key recommendation that supports the challenge and are drawn from the findings and recommendations throughout the report. They are discussed in the chapter in which they first appear, and occasionally also in succeeding chapters.

REPORT CONTENT AND KEY RECOMMENDATIONS

This report is primarily divided into chapters based on application areas with crosscutting chapters addressing the impact of photonics on the national economy, advanced manufacturing, and strategic materials. Following an introductory Chapter 1, Chapter 2 discusses the impacts of photonics technologies on the U.S. economy

Chapters 3 through 10 each cover a particular area of technological application. As mentioned the discussion of each application area typically begins with a review of updates in the state of the science that have taken place since the publication of the NRC's report, *Harnessing Light*, as well as the technological opportunities that have arisen from recent advances in and potential applications of optical science and engineering. Included are recommended actions for the development and maintenance of global leadership in the photonics-driven industry, including both near-term and long-range goals, likely participants, and responsible agents of change. As relevant to their respective topics, the chapters assess the current state of optical science and engineering in the United States and abroad, including trends in private and public research, market needs, examples of translating progress in photonics innovation into global competitive advantage (including activities by small businesses), workforce needs, manufacturing infrastructure, and the impact of photonics on the national economy.

Following is a chapter-by-chapter overview of the content of Chapters 2 through 10, including the key recommendations from each.

Chapter 2: Impact of photonics on the national economy

Chapter 2 considers the economic impact of optics and photonics on the nation and the world. This chapter uses a case study of lasers to discuss the conceptual challenges of developing estimates of the economic impact of photonics innovation. It also addresses the problems associated with using company-level data to provide indicators of the economic significance of the "photonics sector" within the U.S. economy. Additionally, this chapter discusses the ways in which the changing structure of the innovation process within photonics reflects broader shifts in the sources of innovation within the U.S. economy. The chapter also considers the results of recent experiments in public-private and inter-firm research and development collaboration in other high-technology areas for the photonics sector. Possibly the most important finding of the committee in this area is related to the pervasive nature of optics and photonics as an enabling technology.

Key Recommendation: The committee recommends that the federal government develop an integrated initiative in photonics (similar in many respects to the National Nanotechnology Initiative) that seeks to bring together academic, industrial, and government researchers, managers, and policy makers to develop a more integrated approach to managing industrial and government photonics R&D spending and related investments.

This recommendation is based on the committee's judgment that the photonics field is experiencing rapid technical progress and rapidly expanding applications that span a growing range of technologies, markets, and industries. Indeed, in spite of the maturity of some of the constituent elements of photonics (e.g., optics), the committee believes that the field as a whole is likely to experience a period of growth in opportunities and applications that more nearly resembles what might be expected of a vibrantly young technology. But the sheer breadth of these applications and technologies has impeded the formulation by both government and industry of coherent strategies for technology development and deployment.

A national photonics initiative would identify critical technical priorities for long-term federal R&D funding. In addition to offering a basis for coordinating federal spending across agencies, such an initiative could provide matching funds for industry-led research consortia (users, producers, material and equipment suppliers) focused on specific applications, such as those described in Chapter 3 of this report. In light of near-term pressures to limit the growth of or even reduce federal R&D spending, the committee believes that a coordinated initiative in photonics is especially important.

The committee also assesses as deplorable the state of data collection and analysis of photonics R&D spending, photonics employment, and sales. The development of better historical and current data collection and analysis is another task for which a national photonics initiative is well suited.

Key Recommendation: The committee recommends that the proposed national photonics initiative spearhead a collaborative effort to improve the collection and reporting of R&D and economic data on the optics and photonics sector, including the development of a set of North American Industry Classification System (NAICS) codes that cover photonics; the collection of data on employment, output, and privately funded R&D in photonics; and the reporting of federal photonics-related R&D investment for all federal agencies and programs.

It is essential that an initiative such as the proposed national photonics initiative be supported by coordinated measurement of the inputs and outputs in the sector such that national policy in the area can be informed by the technical and economic realities on the ground in the nation.

Chapter 3: Communications, Information Processing, and Data Storage

Chapter 3 considers communications, information processing, and data storage. The Internet's growth has fundamentally changed how business is done and how people interact. Photonics has been a key enabler allowing this communication revolution to occur. The committee anticipates that this revolution will continue, with additional demands driving significant increases in bandwidth and an even heavier reliance on the Internet. So far there has been a factor-of-100 increase in capacity each decade. However, there exists a technology wall inhibiting achievement of the next factor-of-100 growth.

Key Recommendation: The U.S. government, and private industry in combination with academia, need to invent technologies for the next factor-of-100 cost-effective capacity increase in long haul, metropolitan and local area optical networks.

The optics and photonics community needs to educate funding agencies, and information and entertainment providers, to the looming roadblock that will interfere with meeting the growing needs for network capacity and flexibility. There is a need to champion collaborative efforts, including consortia of companies, to find new technology–transmission, amplification, and off/on and switching–to carry and route at least another factor-of-100 capacity in information over the next 10 years.

Key Recommendation: The U.S. government, and specifically the Department of Defense, should strive toward harmonizing optics with silicon-based electronics to provide a new, readily accessible, and usable, integrated electronics and optics platform.

They should also support and sustain U.S. technology transition toward low-cost, high-volume circuits and systems that utilize the best of optics and electronics in order to enable integrated systems to seamlessly provide solutions in communications, information processing, biomedical, sensing, defense, and security applications. Government funding agencies, the DOD, and possibly a consortium of companies requiring these technologies should work together to implement this recommendation. This technology is one approach to assist in accomplishing the first key recommendation of this chapter concerning the factor-of-100 increase in Internet capability.

Key Recommendation: The U.S. government and private industry should position the United States as a leader in the optical technology for the global data center business.

Optical connections within and between data centers will be increasingly important in allowing data centers to scale in capacity. The committee believes that strong partnering between users, content providers, and network providers, as well as between businesses, government, and university researchers, is needed for ensuring that the necessary optical technology is generated, which will support continued U.S. leadership in the data center business.

Chapter 4: Defense and National Security

In Chapter 4, the committee discusses the area of defense and national security. It is becoming increasingly clear that sensor systems are the next “battleground” for dominance in intelligence, surveillance, and reconnaissance. Comprehensive knowledge across an area will be a great defense advantage, along with the ability to communicate information at high bandwidths and from mobile platforms. Laser weapon attack can provide a significant advantage to U.S. forces. Defense against missile attacks, especially ballistic missiles, is another significant security need. Optical systems can provide synergistic capability in all these areas.

Key Recommendation: The U.S. defense and intelligence agencies should fund the development of optical technologies to support future optical systems capable of wide-area surveillance, exquisite long-range object identification, high-bandwidth free-space laser communication, “speed of light” laser strike, and defense against both missile seekers and ballistic missiles. Practical application for these purposes would require the deployment of low-cost platforms supporting long dwell times.

These combined functions will leverage the advances that have been made in high-powered lasers, multi-function sensors, optical aperture scaling, and algorithms that exploit new sensor capabilities, by bringing the developments together synergistically. These areas have been pursued primarily as separate technical fields, but it is recommended that they be pursued together to gain synergy. One method of maintaining this coordination could include reviewing the coordination efforts among agencies on a regular basis.

Chapter 5: Energy

Chapter 5 deals with optics and photonics in the energy area. Both the generation of energy and the efficient use of energy are discussed in terms of critical national needs. Photonics can provide renewable solar energy, while solid state lighting can help reduce the overall need for energy used for lighting.

Key Recommendation: The Department of Energy (DOE) should develop a plan for grid parity across the United States by 2020.

Grid parity is defined here as the situation in which any power source is no more expensive to use than power from the electric grid. Solar power electric plants should be as cheap, without subsidies, as alternatives. It is understood that this will be more difficult in New England than in the southwestern United States but the DOE should strive for grid parity in both locations.

Even though significant progress is being made to bring down the cost of solar energy, it is important to the United States to bring the cost of solar energy down to the price of other current alternatives without subsidy and to maintain a significant role for the United States in developing and manufacturing these solar energy alternatives. Not only is there a need for affordable renewable energy, but there is also a need for creating jobs in the United States. A focus in this area can contribute to both. Lowering the cost of solar cell technology will involve both technology and manufacturing advances.

Solid state lighting can also contribute to energy security in the United States.

Key Recommendation: The DOE should strongly encourage the development of highly efficient light-emitting diodes (LEDs) for general purpose lighting and other applications.

For example the DOE could move aggressively toward its 21st-century lightbulb, with greater than 150 lm/W, a Color Rendering Index greater than 90, and a color temperature approximately 2800 K. Since one major company has already published results meeting the technical requirements for the 21st century lightbulb, the DOE should consider releasing this competition in 2012. Major progress is being made in solid state lighting, which has such advantages over current lighting alternatives as less wasted heat generation and fast turn-on time. The United States needs to exploit the current expertise in solid state lighting to bring this technology to maturity and to market.

Chapter 6: Health and Medicine

Chapter 6 discusses the application of optics and photonics to health and medicine. Photonics plays a major role in many health-related areas. Medical imaging, which is widely used and is still a rapidly developing area, is key to many health-related needs, both for gaining understanding of the status of a patient and for guiding and implementing corrective procedures. Lasers are used in various corrective procedures in addition to those for the eye. There is still great potential for further application of optics and photonics in medicine.

Key Recommendation: The U.S. optics and photonics community should develop new instrumentation to allow simultaneous measurement of all immune-system cell types in a blood sample. Many health issues could be addressed by an improved knowledge of the immune system, which represents one of the major areas requiring better understanding.

Key Recommendation: New approaches, or dramatic improvements in existing methods and instruments, should be developed by industry and academia to increase the rate at which new pharmaceuticals can be safely developed and proved effective. Developing these approaches will require investment by the government and the private sector in optical methods integrated with high-speed sample-handling robotics, methods for evaluating the molecular makeup of microscopic samples, and increased sensitivity and specificity for detecting antibodies, enzymes, and important cell phenotypes.

Chapter 7: Advanced Manufacturing

Chapter 7 addresses the field of advanced manufacturing and the way in which it relates to optics and photonics. Advanced manufacturing is critical for the economic well being of the United States. While there are issues concerning the ability of the United States to compete successfully in high- volume, low-cost manufacturing, it is likely that the United States can continue to be a strong competitor in lower-volume, high-end manufacturing. Current developments in the area of lower volume, high-end manufacturing include, for example, three-dimensional printing, also called additive manufacturing. This technology has the potential to allow the production of parts near the end user no matter where the design is done. Thus, if the end user is in the United States, it is there that the printing or manufacturing would occur. Optical approaches, such as laser sintering, are very important approaches to three-dimensional printing.

Key Recommendation: The United States should aggressively develop additive manufacturing technology and implementation.

Current developments in high-end, low-volume manufacturing are—for example, in three-dimensional printing—also called additive manufacturing. With continued improvements in the tolerance and surface finish, additive manufacturing has the potential for substantial growth. The technology also has the potential to allow the three-dimensional printing near the end user no matter where the design is done.

Key Recommendation: The U.S. government, in concert with industry and academia, should develop soft x-ray light sources and imaging for lithography and three-dimensional manufacturing.

Advances in table-top sources for soft x rays will have a profound impact on lithography and optically based manufacturing. Therefore, investment in these fields should increase to capture the intellectual property and maintain a leadership role for these applications.

Chapter 8: Advanced Photonic Measurements and Applications

Chapter 8 discusses sensing, imaging, and metrology in relation to optics and photonics. Sensing, imaging, and metrology have made significant progress since the publication of the NRC's Harnessing *Light* in 1998.[11] Notable developments having resulted in at least one Nobel Prize awarded for developing dramatic increases in the precision of time measurement.[12] Single-photon detectors have been developed, but at

[11] National Research Council (NRC). 1998. *Harnessing Light: Optical Science and Engineering for the 21st Century*. Washington, DC: The National Academies Press.
[12] For example, the 2005 Nobel prize in physics. More information can be found at http://www.nobelprize.org/nobel_prizes/physics/laureates/2005/. Accessed on August 2, 2012.

this time they are only available with a dead time after detection, not allowing single-photon sensitivity for detecting all incoming photons. Extreme nonlinear optics has made significant progress, providing the potential for soft x-ray sources and imaging. Entangled photons and squeezed states are new areas for R&D in the optics and photonics field, allowing sensing options never previously considered.

Key Recommendation: The United States should develop the technology for generating light beams whose photonic structure has been prearranged to yield better performance in applications than is possible with ordinary laser light.

Prearranged photonic structures in this context include generation of light with specified quantum states in a given spatiotemporal region, such as squeezed states with of over 20-dB measured squeezing in one field quadrature, Fock states of over 10 photons, states of one and only one photon or two and only two entangled photons with over 99 percent probability. These capabilities should be developed with the capacity to detect light with over 99 percent efficiency and with photon-number resolution in various bands of the optical spectrum. The developed devices should operate at room temperature and be compatible with speeds prevalent in state-of-the-art sensing, imaging, and metrology systems. U.S. funding agencies should give high priority to funding research and development—at universities and in national laboratories where such research is carried out— in this fundamental field to position the U.S. science and technology base at the forefront of applications development in sensing, imaging, and metrology. It is believed that this field, if successfully developed, can transfer significant technology to products for decades to come.

Key Recommendation: Small U.S. companies should be encouraged and supported by the government to address market opportunities for applying research advances to niche markets while exploiting high-volume consumer components. These markets can lead to significant expansion of U.S.-based jobs while capitalizing on U.S.-based research.

Chapters 9 and 10: Strategic Materials for Optics and Displays

Chapter 9 deals with strategic materials for optics. The main developments in materials for optics and photonics are the emergence of metamaterials and the realization of how vulnerable the United States is to the need for certain critical materials. At this time, some of those materials are only available from China.

Chapter 10 addresses display technology. The major current display industry is based on technologies primarily invented in the United States, but this industry's manufacturing operations are mostly, located overseas. Labor costs were a consideration but, other factors such as the availability of capital were significant in creating this situation. However, the United States is still dominant in many of the newer display technologies, and it still has an opportunity to maintain a presence in those newer markets as they develop.

CONCLUDING COMMENTS

In reviewing the technologies considered here a number of potential future opportunities have come up that allow one to imagine changes to daily life. Some examples found in the chapters are these: optics helping to diagnose many possible health parameters by simply "scanning" one's finger; cost-effective, laser-based, three-dimensional desktop printing of many different types of objects; the generating, detecting, and manipulations of single photons in the same way as is done with single electrons, and doing it all on a photonic integrated circuit; the use of optics as interconnects between integrated circuit chips, with dramatic increases in power efficiency and speed; the unfurling of a flexible display on a smartphone or the watching of holographic images at home; and the ability of mobile lasers to neutralize threats from afar with high accuracy and speed. These are just a few interesting examples of potential changes that can occur as a result of the enabling technologies considered in this study.