

# Harnessing Light

for America's Technological Future



The Global Impact of Optics and Photonics

NATIONAL RESEARCH COUNCIL  
OF THE NATIONAL ACADEMIES



## About the Report

The present booklet *Harnessing Light for America's Technological Future: The Global Impact of Optics and Photonics* is based on the full report *Optics and Photonics: Essential Technologies for our Nation* from the National Materials and Manufacturing Board (NMMB), a unit of the National Research Council of the National Academies. Details about obtaining copies of this booklet and the printed copies of the full report, as well information on the NMMB and the Division on Engineering and Physical Sciences, can be found online at <http://nationalacademies.org/deps>. A PDF of the full report is available for free at <http://www.nap.edu>.

*Optics and Photonics: Essential Technologies for our Nation* was authored by the Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research.

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DUNCAN T. MOORE, University of Rochester

DAVID C. MOWERY, University of California, Berkeley

N. DARIUS SANKEY, Zone Ventures

EDWARD WHITE, Edward White Consulting

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Main cover image by Erik Svedberg. Back cover image (laser beam slowing erbium atoms) by NIST. Heading fonts "Typo Latin Serif," "Geosans Light" and "Old Sans Black" by Manfred Klein.

## Harnessing Light for U.S. Economic Advancement

### The Economics of Photonics: A Case Study of Lasers

Microwave research from the 1950s was partially responsible for one of the nation's most prominent technological contributions of the last century: the laser. The laser has shaped the direction of several large sectors, including transportation, defense, and information technology. Since 1960, when it was demonstrated by Theodore Maiman of Hughes Aircraft, the laser has been used in applications including communications, welding, and surgery. The technology itself has been transformed by a series of important innovations, and its range of applications has broadened dramatically. The results have produced significant improvements in the performance of existing technologies, opened up completely new areas of R&D, and enabled important development in some of the nation's leading industries.

### What would have happened in the absence of the laser?

According to Baer and Schlachter's 2010 study for the White House Office of Science and Technology Policy (OSTP), lasers had a notable impact on three economic sectors: transportation (total market estimated at \$1 trillion in output during 2009-2010), the biomedical sector (\$2.5 trillion) and telecom, e-commerce and IT (\$4 trillion). To assess the economic impact of the laser, it is important to distinguish between the ways in which it has enabled growth and its role as an indispensable facet of these three sectors.

The value of lasers by itself deployed in each of these three sectors was respectively estimated at \$1.3B, \$400M and \$3.2B, with a total approximate value of nearly \$5B, as compared to the economic impact on markets valued at \$7.5 trillion.

Optics and photonics technologies are ubiquitously used to make and inspect the integrated circuits in nearly every electronic device we use. Moreover, optics and photonics technologies are responsible for the displays on smart phones and computing devices, optical fiber that carries the information in the Internet, advanced precision manufacturing, enhanced defense capabilities, and a plethora of medical diagnostics tools. The opportunities arising from optics and photonics offer the potential for even greater societal impact in the next few decades, including solar power generation and new efficient lighting that could transform the nation's energy landscape and new optical capabilities that will be essential for supporting the continued exponential growth of the Internet.



As described in the National Research Council report *Optics and Photonics: Essential Technologies for our Nation*, it is critical for the United States to take advantage of these emerging optical technologies for creating new industries and generating job growth.

## Ensuring U.S. Leadership in an International Field

Optics and photonics provide critical enabling technologies across the U.S. and world economies, and the development and applications have substantially increased around the world since 1998. This is an encouraging trend for the world economy and its people, while providing a challenge to U.S. leadership in these areas.

Although researchers have achieved some dramatic feats, much is unknown when pursuing basic optical science and its transition to engineering and ultimately to products. For example, optics and photonics now provide clocks that are so stable they will slip less than one second in more than 100 million years; while much-more-primitive clocks have enabled our incredibly useful global positioning system (GPS), it remains unclear how to fully harness these new clock advances for the benefit of society. In many ways, this might be analogous to the dawn of the laser in 1960, when many of the transforming applications of that fantastic invention were not yet contemplated. But this is only one example of a technological innovation in optics and photonics that can have major impacts in the future.

Within optics and photonics, there are a number of areas with the distinct potential for contributing to innovations that, like the laser in the 1960s, could create new sectors that guide both the direction of technology on a global scale and set the U.S. apart as a leader in these technologies.

Growth in these industries—Communication, Defense, Energy, Health, Manufacturing, Detection, Materials, and Displays—will enable a new wave of secondary markets with the potential to provide a significant impact on the U.S. economy and job pool. This makes the next decade potentially a very exciting time for optics and photonics, with significant opportunities for U.S. leadership in these areas.

## The State of Economic and Technological Progress in Global Industries

Key developments in materials for optics and photonics include the emergence of meta materials and the realization of how vulnerable we are to the need for certain critical materials.

The major current display industry is primarily based on technologies mostly invented in the U.S. but with manufacturing operations located overseas. While labor costs were a factor, other factors such as availability of capital were significant in creating this situation. However, the U.S. is still dominant in many of the newer display technologies and still has an opportunity to maintain a leading presence in those newer markets as they develop.

Whereas the U.S. was for decades the leader in telecommunications equipment, China went from having no company in the top 10 largest telecommunications companies in the world in 1998 to having 3 such companies in 2011. A similar scenario of the emergence of Chinese companies exists for companies that specifically specialize in selling optical components and subsystems. In contrast to these trends in the production of optical equipment, however, data centers—which rely on optical technologies for high-bandwidth server connections and may contain as many as one million lasers—remain overwhelmingly located in the U.S.

As outlined in the following pages, the 2012 NRC report *Optics and Photonics: Essential Technologies for our Nation* recommends actions for the maintenance and acceleration of U.S. leadership in the global photonics-driven industry.

The report assesses the current state of optical science and engineering in the U.S. and abroad—including market trends, workforce needs, and the impact of photonics on the national economy—and identifies the technological opportunities that have arisen from recent advances in, and applications of, optical science and engineering. The report also calls for improved management of U.S. public and private R&D resources, emphasizing the need for public policy that encourages adoption of a portfolio approach to investing in the wide and diverse opportunities now available within photonics.



# Communications, Information Processing, & Data Storage

Optics has become the way we send most information over non-trivial distances; it is the primary method of long-haul, terrestrial transmissions. The remarkable growth of networks and the Internet over the past decade has been enabled by previous generations of optical technology. Optics is, furthermore, the only technology with the physical headroom to keep up with this exponentially growing demand for communicating information. The exceptionally high carrier frequency and low-loss optical fiber allow transmission of high bandwidths. Satisfying that future demand will, however, require the continued research and development of new technologies for optics and continued innovation in its interface with electronics.

The use of optics will not be restricted to the traditional market of long distance telecommunication. Increasingly, optics will be used for ever-shorter distances, possibly providing high-bandwidth links between the silicon chips themselves. One key driver for such shorter distances will be to attain sufficient density of communications. A second key driver will be to control the growing power dissipation due to electrical switching/transmission elements and the environmental impact of information processing.

## Communication Devices

*Goal:* Strive towards harmonizing optics with silicon-based electronics to provide a new, readily accessible and usable, integrated electronics and optics platform.

*Likely Participants:* U.S. government

*Recommendations:* The size and number of data centers in the U.S. and globally is expected to grow dramatically over the next decade to address the needs of a global digital society, especially if cloud services become more pervasive. These data centers will be the focal point for the development and deployment of new optics and photonics communications technologies.



The Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance Systems Integration Laboratory (CSIL) of the U.S. Army is the site for all lab-based risk reduction for systems prior to Network Integration Evaluations. Credit: Conrad Johnson/U.S. Army Research, Development and Engineering Command

A number of solutions in communications, information processing, biomedical, sensing, defense, and security applications would only be possible with national R&D support in low-cost, high-volume circuits and systems that utilize the best of optics and electronics to enable seamlessly-integrated systems.

## Network Capacity

*Goal:* Invent technologies for the next factor of 100 cost-effective capacity increase in Long Haul, Metro, and Local Area Optical Networks.

*Likely Participants:* U.S. government and private industry in combination with academia

*Recommendations:* The Internet's growth has fundamentally changed how business is completed, and how people interact. Photonics has been a key enabler of this communication revolution, which is expected to 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 every decade; however, a technology wall is currently inhibiting achievement of the next factor of 100 growth. There is a need to champion collaborative efforts, including consortia of companies, to find new technologies—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.

*Goal:* Position the United States as a leader in the optical technology for the global data center business

*Likely Participants:* U.S. government and private industry. Strong partnering between users, content providers, and network providers—as well as between businesses, government, and university researchers—is needed for ensuring continued U.S. leadership in the data center business, and thus in the optics and photonics business.

*Recommendations:* Just as capacity demand has required the advantages of optics to be pushed further to the edges of the network, data centers will increasingly depend upon optics for interconnection and eventually for reconfigurability and switching. A future of cloud services, in which most if not all digital services are performed by shared resources in the network, is looking increasingly attractive. This new paradigm, which would depend upon ubiquitous, instant, and highly reliable access to the network could place demands on the network, equivalent to the transition from voice to data in the late 1990s.



## Advanced Manufacturing & Precise Detection

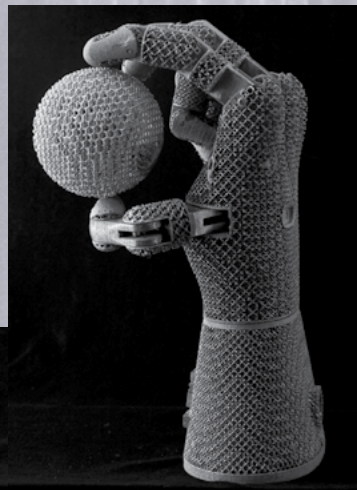
As of 2009, the U.S. accounted for 21% of global manufacturing value added, measured at 2009 purchasing-power exchange rates. The U.S. share has declined since at least 1990 and the share of producers—including U.S.-owned production facilities—in the industrializing economies located in Southeast Asia and elsewhere has grown. Nevertheless, a great deal of cutting-edge innovation, as well as a modest amount of manufacturing activity to support such innovation, has remained in the U.S. This generalization applies to photonics as well as other high-technology industries.

In displays and optoelectronic components, the vast majority of manufacturing has moved to developing countries where labor and engineering are cheaper. In solar, however, the leading producer, Germany, is a developed country with direct-line and engineering wages are as high, or higher, than in the U.S. The close tie between R&D and manufacturing also results in different consequences across the three cases. In the case of displays, this close tie led U.S. firms to collaborate with foreign manufacturers in order to remain at the cutting edge of innovation. In the case of solar, the close tie between R&D and manufacturing means that R&D largely occurs in the same country as manufacturing. This aspect has enabled U.S.-based R&D and manufacturing of thin film technologies to remain dominant. Finally, in the case of optoelectronic components for communication systems, the close tie between R&D and manufacturing-led firms that moved manufacturing overseas to abandon monolithically integrated technologies. As a result, these technologies continue to be dominated by private firms that remain in the U.S.

### Additive Manufacturing

Additive manufacturing, also called 3D printing, describes a group of technologies that are used to manufacture—or, in effect, “grow”—parts by building them layer-by-layer. Additive processes are fundamentally different from traditional subtractive processes where material is removed from a block to create a part; one advantage is that the amount of waste material is greatly minimized.

Electron-beam additive manufacturing produced this fully functional lightweight robotic hand holding a complex impeller, both made from titanium powder. Credit: Oak Ridge National Laboratory.



*Goal:* Develop additive manufacturing technology and implementation, including soft x-ray lasers and imaging for lithography and 3D manufacturing.

*Likely Participants:* U.S. government and industry

*Recommendations:* Advanced manufacturing is critical for the economic well-being of the U.S. While there are issues concerning the ability of the U.S. to compete successfully in high-volume, low-cost manufacturing, it is likely that the U.S. can continue to be a strong competitor in lower-volume, high-cost manufacturing. Current developments in the area of high-end, low-volume manufacturing include, for example, additive manufacturing, which has the potential to allow for the production of parts near the end user no matter where the design is started. Thus, if the end user is in the U.S., that would be where the printing and, therefore, manufacturing occurs. Optical approaches, such as laser sintering, are very important approaches to 3D printing. Advances in table-top sources for soft x-rays will have a profound impact on lithography and optically based manufacturing. Therefore, investments in these areas would be critical for the U.S. to capture the intellectual property and maintain leadership in the manufacturing of these applications.

### Single-Photon Detection

The fundamental quantum nature of light is such that our ability to produce light beams with pre-arranged photonic structure is intimately tied to our ability to measure the arrangement of photons in a light beam. Although tremendous progress has been made in the last couple of decades in “seeing” photons, it remains a technical challenge to detect light at the single-photon resolution with a high degree of confidence and precision, and certainly in a cost-effective manner. Nonetheless, progress is being made; devices and instruments with arrays of single-photon detectors for imaging applications are beginning to appear on the market, and technologies based on superconducting devices have been demonstrated in research labs.

*Goal:* Advance the technology for generating light beams with pre-arranged photonic structure.

*Likely Participants:* U.S. funding agencies with universities and national labs

*Recommendations:* U.S. funding agencies should make it a priority to fund the R&D—at universities and in national labs where such research is carried out—in this highly fundamental area in order 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 area, if successfully developed, can transfer significant technology to products for decades to come.



# National Security & Healthcare

Because optics and photonics is playing an increasingly important role in national defense, the United States is at a critical juncture in maintaining technological superiority. The gap between sophisticated and less sophisticated adversaries is not as large as it once was, with little or no advantage in several key technical areas, such as conventional night vision equipment. Sensor systems are becoming more prominent; in addition, laser weapons are poised to cause a revolution in military affairs, and integrated opto-electronics is on the verge of replacing many traditional integrated circuit functions.

This workforce relies on advanced training in technical areas with a basis in science, technology, engineering, and math (STEM), which are precisely the areas becoming more limited within the United States. The ability of U.S. defense forces to leverage technology for dominance while using a small military fighting force is also threatened by an ongoing migration of optics and photonics capabilities to offshore manufacturing sites. This means the United States may lose both first access and assured access to new optics and photonics defense capabilities.

## Defense and National Security

*Goal:* 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, and speed of light laser strike and defense against both missile seekers and ballistic missiles.

*Likely Participants:* U.S. defense and intelligence agencies

*Recommendations:* It is becoming increasingly clear that sensor systems are becoming the next “battleground” for dominance in intelligence, surveillance, and reconnaissance (ISR), with optics-based sensors representing a significant fraction of ISR systems. Ubiquitous knowledge across an area will be a huge defensive advantage, along with the ability to communicate information at high bandwidths and from mobile platforms. Speed of light attack can provide a significant advantage to U.S. forces. Defense against missile attacks, especially ballistic missiles, is another significant security need. These areas have been pursued primarily as separate technical fields, but it is recommended that they be pursued together to gain synergy.



The XM157 Class IV Unmanned Aerial Vehicle (left) has a range and endurance appropriate for supporting the Brigade Combat Team Commander with communications relay, long endurance persistent stare, and wide area surveillance. Credit: U.S. Army.

## National Healthcare

The U.S. healthcare industry, representing approximately \$3 trillion of annual expenditures and employing roughly 15 million people, comprises one of the largest sectors of the national economy. Our nation boasts the most technologically advanced, and the most costly, healthcare system in the world, with almost 20 cents of every dollar spent on healthcare. To remain the world leader in developing innovative medical instrumentation while bringing down the cost of health care will require continued investment in R&D. Photonics technologies play a key role in providing the most effective, lowest cost approaches for diagnosing, treating and preventing disease and maintaining a healthy U.S. citizenry.

*Goal:* 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.

*Likely Participants:* U.S. optics and photonics community working with medical practitioners and industry

*Recommendations:* Many health issues could be addressed by an improved knowledge of the immune system which represents one of the major areas requiring better understanding. Provide new approaches, or dramatic improvements in existing methods and instruments for detecting antibodies, enzymes and important cell phenotypes.

Present day technology, driven by advances in laser sources, nanophotonics, and detectors, generate enough data in one hour to fill the contents of ten, 24-volume encyclopedias. Continuing advances in several critical areas of technology have dramatically increased the capabilities and heralded a new era of innovation in biomedical optics, leading to improvements in treating many types of diseases. New optical sources and materials, imaging devices, microfluidic technologies, and detection methods, will provide remarkable increases in speed, sensitivity, and precision for biomedical optical instrumentation.

*Goal:* 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.

*Likely Participants:* 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.

*Recommendations:* Improved medical instrumentation will save lives, and provide additional business opportunities for U.S. companies.



# Energy Production & Efficient Technologies

## Energy Production

Photonics can provide renewable solar energy, while solid state lighting can help reduce the overall need for energy used for lighting. For an electric utility, sunlight can be concentrated to generate solar power in a potentially more cost-effective manner, depending on the cost of the concentrating technology. For example, Concentrated Solar Power (CSP) uses a heated liquid and a turbine. The heated liquid stores energy until it is converted to electricity.

This is advantageous since one of the issues with solar energy generation is storage of energy for when the sun is not available, such as during night and overcast situations. Concentrated Photovoltaic power generation (CPV) involves the use of solar cells after the incoming light is concentrated. For CPV the price of the actual solar cell is not as critical since the area covered by solar cells can be reduced up to 2000 times. With CPV higher cost, and more efficient, solar cells can be used.

*Goal:* Plan for grid parity across the U.S. by 2020

*Likely Participants:* U.S. Department of Energy

*Recommendations:* Not only is there a need for affordable renewable energy, but there is also a need for creating jobs in the U.S. It is understood that cheap solar power electric plants will be more difficult in New England than in the southwest of the U.S., but 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 subsidies, and to maintain a significant role for the U.S. in developing and manufacturing these solar energy alternatives.

## Oil and Gas Production

Optical systems are increasingly being used by the oil and gas industry as a means for monitoring wells, allowing increased production and mitigating risks. Industry adoption of optics has been relatively recent, as the high pressure and temperature conditions in a well reduce the life time of conventional fiber optics to be substantially shorter than the 20 years over which most wells are expected to produce. Since 2000, fiber-based Distributed Temperature Sensors (DTS) have become common tools for monitoring the performance of wells and have proven to be a robust source of information about the well performance.

These systems rely on the process of fluids in the well bore affecting the local temperature of the fiber and the scattering of light back up the fiber. Thus when combined with a pulsed laser source, the back-scattered light allows a temperature profile of the well to be determined. This information is combined with geothermal models to accurately locate and quantify fluid flows in the well. More recently, fiber systems have been deployed for distributed acoustic sensing (DAS) to monitor well activity during several phases of well completion.

## Efficient Technologies

Solid State (SS) lighting is clearly the next step in lighting. It has already become entrenched in many niche applications and is moving quickly toward adoption as the new standard for general lighting. The record efficiency for SS light today is 231 lumens per watt, compared to 4-15 lumens per watt for a conventional incandescent bulb and about 55 lumens per watt for a compact fluorescent bulb. The main issue with SS lighting preventing widespread adoptions is cost, but substantial progress is being made in lowering the cost of LEDs.

LEDs for lighting purposes are becoming more feasible. Wal-Mart recently replaced the overhead lighting in many of its stores with LEDs. A number of cities have replaced the street lighting with LEDs. When the cost of labor to replace bulbs is taken into account, this can be economically reasonable even now. As the prices come down and efficiency increases, LEDs are likely to comprise a larger portion of lighting in the United States.

*Goal:* Encourage development of highly efficient LEDs for general purpose lighting and other applications.

*Likely Participants:* U.S. Department of Energy

*Recommendations:* Solid state lighting can also contribute to energy security in the U.S. For example, the DOE could move aggressively toward their 21st century light bulb. Since one major company has already published results meeting the technical requirements for the 21st century light bulb, DOE should consider releasing this competition this year. Major progress is being made in SS lighting, which has such advantages over current lighting alternatives as less wasted heat generation and fast “on”-time. The U.S. needs to exploit the current expertise in SS lighting to bring this technology to maturity and to market.



# Filling Economic & Technological Gaps

## Development and Maintenance of Global Leadership in the Photonics-Driven Industry

The structure of the U.S. R&D system has changed since 1980. As the share of federal R&D funding has declined, the role of large-firm R&D laboratories has decreased in significance, the influence of defense-related procurement within maturing high-technology sectors such as lasers (and, the committee believes, other photonics technologies) has declined, and offshore R&D has grown in importance.

What do these trends imply for the structure of federal R&D in photonics and the ability of such R&D investments to produce significant economic payoffs for U.S. taxpayers? In other high-technology sectors, ranging from nanotechnology to semiconductors, there is one policy that has proven useful: public-private collaboration in R&D.

*Goal:* Develop an integrated initiative in photonics that seeks to bring together academic, industrial, and government researchers, managers, and policymakers to develop a more integrated approach to managing industrial and government photonics R&D spending and related investments.

*Likely Participants:* Organized by the federal government as a collaboration among experts from academia, industry and government.

*Recommendations:* 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 field as a whole is likely to experience a period of growth in opportunities and applications that more nearly resemble 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.

The “National Photonics Initiative” could 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. It is essential that an initiative such as the “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.

## How can the U.S. optics and photonics community develop...

...innovative technologies for cost-effective capacity increases in our optical communications networks?

The world has experienced a factor of 100 cost-effective capacity increase in communications every decade thus far, and user demand is expected to grow continuously. The mechanisms that have enabled the previous gains cannot sustain further increases at that high rate, so the world will either see a stagnation in capability increase or will have to invent new technologies.

...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?

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 and thus open up a large set of future possibilities.

## How can the United States achieve...

...cost parity across the country’s electrical grid for solar power versus new fossil fuel powered electric plants by the year 2020?

The impact of achieving this goal on the U.S. and world economies would be substantial. Imagine what could be done with a renewable energy source, with minimum environmental impact, that is more cost effective than non-renewable alternatives.

...progress in the optical technologies required to support advanced defense and national security initiatives?

These include platforms capable of wide area surveillance, exquisite object identification, high-bandwidth free-space communication, laser strike and defense against missiles. Providing these optics and photonics technologies in a synergistic way for a laser strike fighter or a high altitude platform can provide ubiquitous 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.



# What are Optics and Photonics?

The phrase “optics and photonics” describes the dual, powerful nature of light. Specifically, light can be viewed in one of two ways: as a propagating wave, like a radio wave, and as a collection of traveling particles called photons. Recent advances in photonics allows precision manipulation and detection of the properties of light, resulting in dramatic improvements in the performance of existing technologies—such as remote sensing, medical diagnostics and communications—opened up completely new areas of R&D, and enabled important developments in some of the nation’s leading industries. Also in harnessing light, high amounts of energy can be precisely directed with low energy loss. The laser provides a source of light that can be coherent, meaning that a group of photons can act as a single unit, and monochromatic, referencing the ability of photons to have a well-defined single color.

## About the Report

Previously, the National Research Council (NRC) undertook the writing of an optics and photonics study in 1988, *Photonics: Maintaining Competitiveness*, and then again in 1998 with *Harnessing Light: Optical Science and Engineering for the 21st Century*. After 14 years of dramatic technical advances and economic impact, there was a need for another study that would help guide the nation’s strategic thinking in this area. Many other countries have developed their own strategic documents and organizations in the area of optics and photonics since 1998, and many have cited the U.S.’s *Harnessing Light* study as instrumental in influencing their thinking.

The most recent NRC report *Optics and Photonics: Essential Technologies for our Nation* found that optics and photonics provide critical enabling technologies across the U.S. and world economies. It addresses the updates that have taken place since *Harnessing Light* was published in 1998, as well as technological opportunities that have arisen since then, the state of the art in the U.S. and abroad, and recommendations for maintenance of U.S. global leadership. *Optics and Photonics* illustrates an encouraging trend for the world economy and its people, while providing a challenge to U.S. leadership in these areas.

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