Innovations in Optics and Photonics: Enabling Technology for Our Future

A Summary of Optics and Photonics: Essential Technologies for Our Nation, a Report by the National Research Council of the U.S. National Academy of Sciences

OSA
The Optical Society
About the Optical Society

Uniting more than 180,000 professionals from 134 countries, the Optical Society (OSA) brings together the global optics community through its programs and initiatives. Since 1916 OSA has worked to advance the common interests of the field, providing educational resources to the scientists, engineers, and business leaders who work in the field by promoting the science of light and the advanced technologies made possible by optics and photonics. OSA publications, events, technical groups and programs foster optics knowledge and scientific collaboration among all those with an interest in optics and photonics. For more information, visit www.osa.org.
Introduction

Optics and photonics technologies are ubiquitous in our daily lives—from laser surgery to high-speed Internet via fiber optics to precision manufacturing of computer chips—and have the potential to enable entirely new innovations that would boost energy independence, improve communications, and save lives, all while creating jobs, growing the economy, and reducing healthcare costs. The promise of optics and photonics can be realized if the United States acts now to cultivate this versatile scientific field through collaborative research and development activities, along with coordinated support from the public, academic, and private sectors working together. That is the conclusion of Optics and Photonics: Essential Technologies for Our Nation, a report written by the National Research Council of the United States National Academy of Sciences taskforce of distinguished business people, researchers, academics, and government officials.

Such a concerted effort and focus, the taskforce concludes, is vital to ensuring that U.S. companies participating in key industries enabled by optics and photonics—communications, energy, biomedicine, and manufacturing, among many others—each satisfy critical market demands thus ensuring the continued growth of the U.S. economy. In communications, it is the challenge of expanding Internet speed and capacity by 100 times within 10 years. In energy, it is the need to rapidly bring solar power costs to parity with that provided by fossil fuels and thus shrink both U.S. dependence on foreign energy sources and climate-changing carbon emissions. In medicine, it is the need to provide personalized medicine, e.g. drug therapy tailored to each individual, by making individual genome sequencing easily affordable, along with understanding and controlling
the response of an individual’s immune system. These advances will lead to more rapid, individualized patient diagnosis—a potential revolution in modern healthcare that could dramatically reduce healthcare costs and prevent unnecessary procedures. In manufacturing, it is the growing demand for customized, quick-turnaround, advanced manufacturing design processes.

Standing alone, each separate need requires significant investment in time and money. Taken together, they represent a national challenge. If successfully met, the result would be economic growth, good paying jobs, and sustained technological U.S. competitiveness—and a significant return on investment that will benefit future generations.

The report emphasized several factors that underscore the promise of such an effort.

- Optics and photonics have an enormous impact on the industries they benefit. When lasers were invented more than 50 years ago, it was unknown where the technology would prove useful. Today, diode and fiber lasers essentially allow the modern telecommunications system to function—the linchpin of a $4 trillion industry in the U.S. One single cell phone photo transmission across the continent, for example, can be routed through multiple data centers, each containing as many as one million lasers.

- The well-being of the U.S. economy and the quality of life for its citizens has a lot to gain from advances in optics and photonics, not only as a scientific discipline but also from its remarkable influence as an enabling technology across a broad swath of industries. This powerful integration of photonics in the marketplace, as evidenced by the growth of the electronics, precision manufacturing, and telecom industries in the 20th century, will continue into the 21st. Despite its ubiquity as a significant driver to myriad enterprises, raising awareness of the critical importance of optics and photonics among the public and funding agencies is difficult because the field is not generally recognized as such a critical contributor to so many separate industries.

Although many people could readily name an electronics company or a computer company, few could cite a photonics company even though many well-known companies such as Intel, Apple, and Google are rapidly incorporating more and more

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What are Optics & Photonics?

From fiber optics and telecommunications to medical imaging and cancer research, optics and photonics are advancing today’s essential technologies. Based on the science of light, optics and photonics are specialized fields of physics and engineering. These technologies are prevalent in almost every aspect of day-to-day life. From your iPad screen to the inner workings of your mobile phone and high-speed Internet connection, optics and photonics are critical technologies that will continue to grow and enhance people’s lives.
photonics into their products. Similarly, optics and photonics do not easily fit into standard industry classification schemes that track revenue, employment, industrial research and development, educational curricula, or other key indicators. Accordingly, cultivation and investment in photonics as its own “domain” would provide the visibility and recognition it deserves, while developing a strong infrastructure that is vital to job creation, economic growth, and innovation in the U.S.

As the report says: “The absence of such information reduces the visibility of photonics within the industrial community....” This lack of visibility has implications up and down the industry food chain. To cite just one example, U.S. community college training of highly-skilled shop floor technicians who could support manufacturers using optical and photonic technologies is virtually non-existent. By contrast, such training is readily available in Germany.

Progress in optical technologies offers tremendous benefits across numerous specialty areas. For instance, photonics R&D in engineering could lead to significant enhancements in sensitivity and precision for biomedical instrumentation. Without centralized support and coordination for photonics, researchers continue to work in isolation, creating barriers to collaborative scientific advances. These silos are often mirrored within the same institutions. With a few exceptions (e.g. University of Washington) biomedical academic researchers and clinicians enjoy only limited contact, let alone dynamic opportunities for collaborative discovery, with photonics researchers and engineers.

The monumental advances made possible through the synergies of photonics with entire industries—from computing and optical networking to laser medicine and robotics—are well documented. For future breakthroughs in communications, biomedicine, manufacturing, defense, and security to be achieved, the report suggests that the U.S. can support growth in optics and photonics through research investment and coordinated progress monitoring, which could encourage increased venture capital investment.

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— National Academy of Sciences Report Optics & Photonics: Essential Technologies for Our Nation

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Projected improvements in certain key technologies offer enormous potential to cut through the various sub-disciplines and bring new efficiencies to all. Development of a readily manufacturable photonics integrated circuit (PIC), to cite one major example, would virtually eliminate billions of high-power-loss electronic interconnects in data centers and save hundreds of millions of dollars per year in wasted energy. A workable PIC would have equally dramatic effects across biomedical instrumentation, defense, manufacturing, and energy. Other emerging optical technologies such as extreme ultraviolet lithography (EUV) and soft x-rays would utilize these largely unexploited short wavelengths to further reduce transistor size. These technologies would not only extend semiconductor manufacturing down the Moore’s Law cost curve (the underlying driver for ever smaller, more powerful, and cost-effective computers), they would make possible high-precision 3-D printing, the emerging discipline of “additive manufacturing,” a technique that, rather than removing material to create a basic commodity, builds products one microscopic layer at a time.

Indeed, the report authors’ overall appraisal of the state of photonics is that “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.”

**A National Photonics Initiative**

How to harness that growth for the benefit of the U.S. economy? The authors call for new approaches to partnerships between government, academia, and industry, one version of which might be a National Photonics Initiative (NPI). The partnership would be based on earlier successful collaborations such as the U.S.’s Semiconductor Research Council or Germany’s Fraunhofer Institutes.

An NPI—or similar public/private/academic partnerships—would focus attention and funding on photonics research and development. It would work with government institutions like the U.S. Bureau of Labor Statistics to clarify the outlines of distinct photonics economic activity. It would identify key technologies with cross-disciplinary potential and support pre-competitive research. And it would not only fund research into such technologies, but actively support collaboration between sub-disciplines.

As the report states: “In the absence of some coordinating initiative, it will prove difficult to develop an effective strategy for public and private R&D investment that seeks to support longer-term R&D and to translate innovation into economic opportunities for U.S. firms and employees across the diversity of emerging photonics applications. Accordingly, the committee’s judgment is that the time is overdue for a federal initiative in photonics that seeks to engage industry, academic, and government researchers and policy makers in the design and oversight of R&D and related programs that include federal as well as industry funding.”
Specific Challenges by Industry

The report addressed photonics challenges in seven distinct technical disciplines (communications, information processing, and data storage; energy; health and medicine; advanced manufacturing; defense and national security; advanced photonic measurements; and strategic materials). This Executive Summary will discuss the first four, as areas with the broadest potential impact on employment and economic growth.

Communications, Information Processing, and Data Storage

The report notes that the world has experienced a factor-of-100 Internet capacity increase every decade since the 1970s with no likelihood of slowing. In contrast to the period before the last expansion in the early 2000s, however, when Wave Division Multiplexing technology (a way to combine multiple lasers on a single fiber optic cable to transmit many signals simultaneously) was deployed, the authors see no similar technology solutions existing today that will provide the next 100-fold increase in capacity. The choice, they say, is either stagnation in communications capability or significant investment in photonics innovation and the invention of new technologies.
Thus the report’s first Grand Challenge: **How can the U.S. optics and photonics community invent technologies for the next factor-of-100, cost-effective capacity increases in optical networks?**

Specifically, the report emphasized the need for more efficient short-range optical communications hardware with applications ranging from fiber-to-the-home to major data centers. Such hardware would not only increase system capacity, it would reduce energy loss by eliminating inefficient electronic interconnects that must currently be used to transfer signals between individual optical components.

The report’s second Grand Challenge addresses this point: **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?**

The report urged the U.S. Department of Defense to take the lead in promoting such technologies, not only because of proven past success of such leadership, but also, the authors say, because maintaining economically healthy data centers in the U.S. represents a vital national security interest. Most of the world’s centers, maintained by such companies as Google, Apple, and Yahoo, have been sited within U.S. borders, in part because of the country’s top-quality long-haul telecommunications capability. Any loss of U.S. technological leadership might, the report contends, encourage outmigration of data centers, diminish employment, and increase vulnerability to national data disruption.

In addition, successful solutions to the challenges of next generation communications and information processing would have a major ripple effect across medicine and health, advanced manufacturing, and energy production, and our dependence on communications to function as a society in the 21st century, among others.

### Medicine and Health

The report notes considerable ongoing progress in biomedical optics, but singles out two areas for special research and development recommendations:

- **Immune system diagnostics.** According to the report: “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.”

  The report notes that the latest generation of flow cytometry instruments, which combine optical detection with mass spectrometry, represents a major step toward such improved immune system understanding. The ultimate goal of these and subsequent generations of optical instruments will be to identify immune cell types along with their associated functions in affected tissues—arthritic joints, inflammatory tissues, pancreatic islets, etc. That capability, in turn, will allow a more complete understand-
ing of the local and systemic processes that underlie such degenerative diseases as rheumatoid arthritis, diabetes, Alzheimer’s disease, and heart disease.

Streamlined drug development. The report envisions “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.” Such efforts are necessary, the report says, to significantly improve specificity of treatment tailored to an individual’s unique genetic makeup and to reduce exorbitant drug development costs.

Finally, of note, the report looks to improved optical instrumentation to bring the cost of individual genome sequencing from many tens of thousands of dollars that it costs today to $1,000 per individual, making such testing widely accessible and ushering in a new era of personalized medicine. And the report strongly advocates setting two high priorities for institutional partnerships: (i) government incentives for collaboration between medical and engineering departments at universities and (ii) government and medical society collaboration to create an information technology infrastructure for transfer of large amounts of clinical data for research use.

Energy

The challenge of renewable energy generation earned the topic a Grand Challenge question: 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 urgency expressed reflects not just economic necessity, but geopolitical and climate-related imperatives.

The report’s authors see parity as attainable, but a goal that would require a
major effort to achieve. That effort would include greater focus on concentrated solar power (CSP) technologies that would augment thermal power generation with electrical power generation. It would also include more active planning by government land use policy makers for industrial-scale solar power generation. Finally, the report urged the Department of Energy to aid the acceleration of Light Emitting Diode (LED) development, which the authors see on the verge of product maturity in the home and commercial lighting sectors. More LED use would reduce demand for electric power and reduce pressure for system growth.

Advanced Manufacturing

This topic draws a Grand Challenge, as well: 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? The challenge addresses two separate, but complementary developments.

- The first is the continued effort to sustain the Moore’s Law cost and transistor size curves that have applied during the entire computer revolution. Semiconductor circuitry design has already penetrated deep into the nanoscale and faces clear limits. As defined earlier, EUV wavelength lithography offers a potential next generation solution, followed by another generation based on soft x-rays. The former is already in the industrial development pipeline. But the latter, the report says, offers an important opportunity for federally funded, precompetitive research to “capture intellectual property” and maintain a leadership role for U.S. industry.

- The second development is the emergence of additive manufacturing, which promises a new era of customized, fast-turn manufacturing design, ideal for a sophisticated, nationally-based workforce. Such technology—also called 3-D printing—would potentially allow machines to make customized products, from bioengineered human tissue to military spare parts directly from electronically-transmitted designs.

Both processes—deep nanoscale lithography and additive manufacturing—require a level of precision available only with the development of new light-sensitive materials and new laser sources, including short wavelength deep UV and soft x-ray lasers.

Finally, the manufacturing section emphasizes the importance of training directed
specifically at the optics and photonics industry. The opportunities for specialized train-
ing for technicians in precision manufacturing using optics and photonics are extensive.
Moreover, photonics companies themselves could do more to attract and reward holders
of advanced degrees, focusing their efforts on the fundamental science and engineering
underlying high-volume and low-cost optical manufacturing methods. Photonics not only
offers great economic potential, it offers multiple career opportunities to graduates of
community colleges and to holders of advanced degrees.

Conclusion

The report concluded its overview of the global impact of optics and photonics with a
vibrant vision of the future that a concerted effort among government, industry, and
academic stakeholders might bring:

- Electronic imaging devices implantable in the eye that can restore
  sight to the blind

- Genome sequencing for every baby upon birth

- Cost-effective, laser-based, 3-D desktop printing of many different
  types of goods

- The generation, detection, and manipulation 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 development of a flexible display on a Smartphone

- The availability of holographic images at home

- The ability of mobile lasers to neutralize threats from afar with high
  accuracy and speed

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