CHAPTER 9

APPLICATIONS: NANOPHOTONICS AND PLASMONICS

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9.1 VISION FOR THE NEXT DECADE

Both nanophotonics and plasmonics concern investigations into building, manipulating, and characterizing optically active nanostructures with a view to creating new capabilities in instrumentation for the nanoscale, chemical and biomedical sensing, information and communications technologies, enhanced solar cells and lighting, disease treatment, environmental remediation, and many other applications. Photonics and plasmonics share the characteristic that at least some of their basic concepts have been known for 40–50 years, but they have come into their own only in the last ten years, based on recent discoveries in nanoscience. Photonic materials and devices have played a pervasive role in communications, energy conversion, and sensing since the 1960s and 1970s. Photonics at the nanoscale, or nanophotonics, might be defined as “the science and engineering of light-matter interactions that take place on wavelength and subwavelength scales where the physical, chemical, or structural nature of natural or artificial nanostructure matter controls the interactions” (NRC 2008). Broadly speaking, over the next ten years nanophotonic structures and devices promise dramatic reductions in energies of device operation, densely integrated information systems with lower power dissipation, enhanced spatial resolution for imaging and patterning, and new sensors of increased sensitivity and specificity.

Plasmonics aims to exploit the unique optical properties of metallic nanostructures to enable routing and active manipulation of light at the nanoscale (Barnes et al. 2003; Schuller et al. 2010; Brongersma and Shalaev 2010). It has only been in the past 10 years that the young field of plasmonics has rapidly gained momentum, enabling exciting new fundamental science as well as groundbreaking real-life applications in the coming 10 years in terms of targeted medical therapy, ultrahigh-resolution imaging and patterning, and control of optical processes with extraordinary spatial and frequency precision. In addition, because plasmonics offers a natural integration compatibility with electronics and the speed of photonics, circuits and systems formed of plasmonic and electronic devices hold promise for next-generation systems that will incorporate the best qualities of both photonics and electronics for computation and communication at high speed, broad bandwidth, and low power dissipation.

Changes in the Vision over the Last Ten Years

Despite their relevance to many key technologies going forward, neither nanophotonic nor plasmonics devices were explicitly considered in the 1999 report Nanotechnology research.

For the institutional affiliations of authors, please see Appendix B, List of Participants and Contributors.
directions: Vision for nanotechnology R&D in the next decade (Roco, Williams, and Alivisatos 1999). In part, this may have resulted from the fact that one-dimensional nanoscale structures, such as antireflection coatings and distributed Bragg mirrors, have long been a part of optical design and engineering. The first quantum well laser, operating at room temperature with an active layer 20 nm thick, was reported in 1978 (Dupuis et al. 1978); today quantum well lasers are the standard for room-temperature solid-state semiconductor devices; they have high efficiency and can be manufactured at relatively low cost.

Many of the critical concepts for today’s rapidly growing and diverse field of nanophotonics were established in past decades, but recent progress in the ability to control materials at the nanoscale in multiple dimensions has allowed the validation of those concepts and the anticipation of yet more intriguing and powerful photonic behaviors. For example, an early paper by Yablonovitch (1987) discussed dielectric materials with spatial variations in index of refraction on the order of a wavelength of light. He anticipated that these photonic crystals would have a dramatic effect on the spontaneous emission of light within these structures. Negative index materials, a component of a class of metamaterials, were anticipated as early as the 1960s by Veselago (1968). Surface plasmons have played an important role in surface-enhanced Raman spectroscopy (SERS), an active area of research since the late 1970s (Jeanmaire and Van Duyne 1977; Albrecht and Creighton 1977). Today’s research in plasmonics encompasses an even broader range of structures and applications (Brongersma 1999), as is the case for nanophotonics.

**Vision for the Next Ten Years**

Advances in the fabrication of optical structures at the nanoscale and improved control of materials properties have allowed researchers to demonstrate and realize the potential of nanophotonics and plasmonics, and they provide strong impetus for further investments in these fields. In the next ten years, we envision that nanophotonics and plasmonics will have dramatic enabling capabilities for new medical therapies; low-power, high-bandwidth, and high-density computation and communications; high-spatial-resolution imaging and sensing with high spectral and spatial precision; efficient optical sources and detectors; and a host of profound scientific discoveries about the nature of light–matter interactions.

### 9.2 ADVANCES IN THE LAST 10 YEARS AND CURRENT STATUS

**Nanophotonics**

Over the last 5–10 years we have witnessed an enormous increase in the number and diversity of photonics applications. This has resulted from the significant advances in computational design tools and their accessibility, the emergence of new nanofabrication techniques, and the realization of new optical and structural characterization methods. At the forefront of these advances are the developments in the area of micro- and nano-photonic devices that have dimensions on the order of or below the wavelength of light.

Advances in electromagnetic and electronic device simulation tools have been tremendous over the last decade. Good commercial and freeware codes (e.g., finite difference time domain (FDTD), discrete dipole approximation (DDA), boundary element methods (BEM), or finite-difference frequency domain (FDFD)) codes are inexpensive and available to virtually everyone. Improvements in nanofabrication techniques, greater accessibility of high-resolution patterning (e.g., electron beam lithography), and pattern transfer processes (e.g., low-damage ion-assisted etching) have produced photonic crystal, microdisk, and ring resonator devices with exceptional performance.
Discovery in nanophotonics has been enabled by the accessibility of optical nanoscale characterization tools such as scanning near-field optical microscopy (SNOM). Accessibility results from the increasing number of commercial companies that sell such equipment and because the tools have become substantially more user-friendly.

Similarly, progress in nanophotonics has benefited from advances in structural characterization tools such as atomic force microscopy (AFM), nano-Auger, nano-secondary ion mass spectrometry (nano-SIMS), scanning electron microscopes (SEMs), and transmission electron microscopes (TEM). These instruments have had a major impact on the ability to correlate the size, atomic structure, and spatial arrangements of nanostructure to the observed optical properties.

The progress in both simulation and fabrication of nanophotonic structures has resulted in the formation of ultrahigh-quality (Q, meaning low-optical-loss) optical structures (Song et al. 2005; Figure 9.1). These structures, in turn, have allowed researchers to engineer distinctive optical states, localize and slow the velocity of light, and create efficient light-emitting sources and strongly coupled light–matter interactions, resulting in new quantum mechanical states.

![Figure 9.1. (a) SEM of fabricated photonic crystal structure. (b) spectrum of the cavity, showing Q = 600,000 (Song et al. 2005)](image)

In particular, for dielectric materials:

- **Slowing of light** has been observed in photonic crystal waveguides (Notomi et al. 2001; Gersen et al. 2005) and in coupled ring resonators (Vlasov et al. 2005). This is an achievement not only scientifically, but also for the implication in controlled delay and storage of light in compact, on-chip information processing (Figure 9.2).

- **Strong coupling between dielectric nanocavities and quantum dots** has by now been observed by a number of research groups (Yoshie et al. 2004; Reithmaier 2004; Hennessy et al. 2007). The exciton-photon (polariton) states that result can form the basis of quantum information schemes, or produce ultra-low threshold lasers.
Plasmonics

Although surface-enhanced Raman spectroscopy (SERS), one of the first “killer applications” of metallic nanostructures, was discovered in the 1970s (Fleischmann et al. 1974; Jeanmaire and Van Duyne 1977; Moskovits 1978), the young field of plasmonics only started to rapidly spread into new directions in the late 1990s and early 2000s. At that time it was demonstrated in rapid succession that metallic nanowires can guide light well below the seemingly unsurpassable diffraction limit (Takahara et al. 1997), that metal films with nanoscale holes show extraordinarily high optical transmission (Ebbesen 1998; Figure 9.3), and that a simple thin film of metal can serve as an optical lens (Pendry 2000). Plasmonic elements further gained importance as popular components of metamaterials, i.e., artificial optical materials with rationally designed geometries and arrangements of nanoscale building blocks. The burgeoning field of transformation optics elegantly demonstrates how such materials can facilitate unprecedented control over light (Shalaev 2008).
losses when they interact with light. For this reason, it will be valuable to explore ways to get around that issue. In some cases, local heat generation may be used to advantage, and in some cases heating losses can be neglected. In the coming decade, it will be worth exploring the use of new materials such as transparent conductive oxides and to engineer the band structure of metals (West et al. 2010).

A very diverse set of plasmonics applications has emerged in the last ten years. Early applications included the development of high-performance near-field optical microscopy (NSOM) and biosensing methods. More recently, many new technologies have emerged in which the use of plasmonics seems promising, including thermally assisted magnetic recording (Challener et al. 2009), thermal cancer treatment (Hirsch et al. 2003), catalysis and nanostructure growth (Cao, Barsic, and Guichard 2007), solar cells (Pala et al. 2009; Atwater and Polman 2009), and computer chips (Cai et al. 2009; Tang et al. 2008). High-dielectric-constant materials also can effectively be used as antennas, waveguides, and resonators, and their use deserves further exploration (Cao et al. 2009; Schuller et al. 2009). Materials that exhibit strong optical resonances are particularly interesting, because they can exhibit high positive, negative, and near-zero magnitudes of the dielectric constant and/or permeability.

Several of the applications noted above capitalize on light-induced heating, which was originally considered a weakness of plasmonics. After researchers realized that long-distance information transport on chips with plasmonic waveguides would suffer too strongly from heating effects (Zia et al. 2006), it now has been established that modulators and detectors can be achieved that meet the stringent power, speed, and materials requirements necessary to incorporate plasmonics with CMOS technology. Plasmonic sources capable of efficiently coupling quantum emitters to a single, well-defined optical mode may first find applications in the field of quantum plasmonics and later in power-efficient chip-scale optical sources (Akimov et al. 2007; Hryciw et al. 2010). In this respect, the recent prediction (Bergman and Stockman 2003) and realization (Hill et al. 2007; Noginov et al. 2009; Oulton et al. 2009) of coherent nanometallic light sources constitutes an extremely important development (see Figure 9.4).

In terms of advances in theory and simulation related to plasmonics, photonics, and electronics, Nader Engheta (2007) recently developed an elegant theoretical framework that treats nanostructured optical or “metactronic” circuits much akin to conventional electronic circuitry. In this framework, insulators are modeled as capacitors, metals as inductors, and energy dissipation (heating) can be accounted for by introducing resistors. The desired response of an optical circuit can now be realized simply through the optimization of an electronic circuit.
9.3 GOALS, BARRIERS, AND SOLUTIONS FOR THE NEXT 5-10 YEARS

Nanophotonics

Achieve Integration with Electronic Circuits for Ultrasmall, Ultrahigh-speed Information Communications Applications

Advances in nanophotonic device structures have proceeded rapidly in the past 10 years. Using these miniscule optical components, one could envision creating photonic circuits with scales of integration rivaling today’s electronic integrated circuits. However, we have by no means fully capitalized on the enormous information capacity and high speed of photons that could enable novel optical information processing capabilities of almost unthinkable speed. Whereas optical fibers are already the preferred information link for long distance, it is now becoming eminently clear that photons are also going to play a number of important roles in future computers. Although on-chip and chip-to-chip optical interconnects have been explored for some time, the accelerated growth in microprocessor performance and the recent emergence of chip multiprocessors (CMP) have dramatically increased the need for the kind of communications infrastructure that nanophotonics can address. With the rapid advances in CMOS and CMOS-compatible processing techniques, it comes as no surprise that Si-based devices, such as the coupled resonator-waveguide shown in Figure 9.5 have started to gain popularity, despite the indirect gap nature of Si (Hogan 2010 and Kia et al. 2007). In addition, ultrasmall-dimensioned lasers utilizing semiconductor or metal materials can provide highly efficient optical sources that can be readily integrated on-chip (Service 2010).

Figure 9.5. SEM image of a Si-based ring resonator coupled to a waveguide. Inset shows the entire ring structure (Alameda 2004).

Control Light Trapping and Device Integration for Applications in the Living World

Besides its increased importance for information technology, the photon is an essential source of energy for the living world and is finding use in a larger number of applications in chemistry, biology, and medicine. New light trapping technologies for solar cells, photocatalysis for clean fuel generation, thermal/heat management, and other “green” photonics technologies are expected to gain tremendous momentum in the coming decade. Miniature integrated optoelectronic sensor platforms that are coupled to information networks may well revolutionize biology and healthcare. Because electronics and photonics can be integrated effectively on a common platform, a myriad of new, inexpensive applications can be realized that will benefit from the same economy of scales as Si-based electronics is capitalizing on.
Next to the visible and near-IR range, the mid-IR and THz frequency regimes will gain importance as more inexpensive, user-friendly infrastructure (i.e., sources, switches, detectors) becomes available and the number of applications in biology, homeland security, and defense grows. As photonic devices keep on shrinking to the nanoscale, new physics also emerges that could enable new ways to route and actively manipulate photons.

**Use Light to Control Thermal and Mechanical Performance of Materials.**

There has been much recent excitement at the coupling of optical modes with mechanical modes: phenomena that occur at the right match of the mechanical and optical energies that apply to nanostructures (Figure 9.6). This promises much scientific richness in the interplay of temperature, mechanical modes, and optics, and also promises new device applications.

**Plasmonics**

*Achieve Control over the Flow of Light*

Ultrasmall plasmonic or high index semiconductor cavities and waveguides (Figure 9.6) are currently giving rise to new, unexpected opportunities. Plasmonic structures and metamaterials consisting of deep-subwavelength building blocks enable light to be concentrated and actively manipulated in new ways. Along with new mathematical frameworks, such as transformation optics and newly emerging simulation tools, recent advances in the laboratory are describing how we may attain ultimate control over the flow of light.

![Figure 9.6. Light can induce vibrations in a micron-size optical resonator by exerting pressure (bottom), creating pushes or pulls (top left), or causing the material to constrict (top right) (Cho 2010).](image)

The most important advances in plasmonics seem to rely heavily on one key property of engineered metallic structures: they exhibit an unparalleled ability to concentrate light. Even a simple spherical metallic nanoparticle can serve as a tiny antenna capable of capturing and concentrating light waves, and its basic operation is quite similar to the ubiquitous radio frequency (RF) antennas at work in cell phones or radios. By squeezing light into nanoscale volumes, plasmonic elements also allow for fundamental studies on light–matter interactions at length scales that have been inaccessible in even the most advanced dielectric components such as photonic crystals. The relevance of confining light is most easily explained by considering a resonator or cavity with a (mode) volume $V_M$. Many physical processes are
dramatically enhanced when light is forced to interact with materials confined to ultrasmall volumes. Of course, the strength of the interaction in plasmonic resonators is diminished by optical losses that can shorten the lifetime of a photon in such a cavity; this lifetime is often quantified by the optical quality factor, or Q, and the effectiveness of many optical processes tends to scale with the ratio of $Q/V_m$ to some power. Despite the modest values of $Q$ in nanoscale metallic cavities (typically between 10 and 1,000), metallic cavities can have such small $V_m$ values that often they are capable of outperforming dielectric cavities with Qs that are orders of magnitude higher. The small size and low Q values of plasmonic structures come with the added benefit of an ultrahigh speed (<100 femtosecond (fs)\textsuperscript{33}, Stockman 2010) and broadband optical response.

**Exploit Synergies between Plasmonics, Photonics, and Electronics**

Over the last decade, it has gradually become clear what role plasmonics can play in future device technologies and how it can complement electronics and conventional photonics. Each of these device technologies can perform unique functions that play to the strength of the key materials. The electrical properties of semiconductors enable the realization of truly nanoscale elements for computation and information storage; the high transparency of dielectrics (e.g., glass) facilitates information transport over long distances and at very high data rates. Unfortunately, semiconductor electronics is limited in speed by interconnect (RC) delay-time issues, and photonics is limited in size by the fundamental laws of diffraction. Plasmonics offers precisely what electronics and photonics do not have: the size of electronics and the speed of photonics (Figure 9.7). Plasmonic devices might therefore naturally interface with similar-speed photonic devices and with similar-size electronic components, increasing the synergy between these technologies.

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\textsuperscript{33} \text{10}^{-15} \text{ of a second}
The semiconductor and photonics industries have continued to rapidly develop, and it will be exciting to see what the next decade will bring for plasmonics in these industries. In order to continue and even accelerate the advances in nanophotonics and plasmonics, a number of barriers will have to be overcome. The barriers relate to the enabling resources in the scientific and technological infrastructure, and thus they will be described in the next section.

9.4 SCIENTIFIC AND TECHNOLOGICAL INFRASTRUCTURE NEEDS

Develop Simple Design Rules and Coupled Optical Simulations for Nanophotonics and Nanoplasmonics

Although advances in electromagnetic and electronic device simulation tools have been considerable, new challenges have also emerged. As the complexity of integrated photonic systems increases, the development of simple design rules for nanophotonics and plasmonics components is absolutely essential. The power of good design rules lies in their ability to hide much of the complexity within an individual device; the aim is to capture the essence of the device function and focus on its interactions with other devices. Such simplifications then enable the construction of system-level theories and simulators that can predict the behavior of larger circuits. Theoretical frameworks should continue to be developed to address functions of nanostructured optical, or metactronic, circuits.

To properly predict the behavior of optoelectronic circuits, simulation tools are required that can simultaneously capture the flow of electrons and photons and their impact on each other. Currently, these types of simulations tend to be performed separately for the electrons and photons and then combined in an *ad hoc* fashion. The coupling to other degrees of freedom (including mechanical, thermal, magnetic, biological) will become important as well. Coupling of optical simulations to quantum mechanical simulation tools is also needed for an increasing number of applications. In many optical simulation tools, the materials properties are taken into account by utilizing macroscopic properties, such as the real and imaginary part of the dielectric constant. This is inadequate for many nanostructured active and passive systems, and we will need to return to more basic theories.

Support New and Expanded Fabrication Tools and Facilities for Nanophotonic and Plasmonic Devices and Circuits

Over the last decade, the field of nanotechnology has provided a wide range of new nanofabrication and synthesis techniques. With the rapid advances in CMOS and CMOS-compatible processing techniques, it comes as no surprise that silicon-based devices have started to gain popularity (despite the indirect gap nature of Si). This trend is further augmented by the fact that more materials are becoming allowed in Si fabs, and new techniques such as wafer bonding enable convenient ways to add materials with more desirable optical properties for active devices (e.g., III-Vs). It will be of value to educate and train the next generation of optical engineers to take advantage of Si fabs and provide easy access to such facilities. It also will be important to build new infrastructure to facilitate the anticipated increase in demand.

Other important fabrication or prototyping techniques for nanophotonics/nanoplasmonic circuits and devices are state-of-the-art electron beam lithography and focused ion beam milling tools. These tools are extremely powerful and enable the realization of feature sizes below the 10 nm length scale. The cost of such tools will need to come down in order to provide access to an increasing number of users. The increasing divergence between capital equipment costs and equipments grants in the United States is making it harder and harder to provide critical infrastructure to research groups in academia, and industry is facing...
similar challenges. For this reason, it is also of the utmost importance to further develop less expensive printing technologies (e.g., nanoimprint lithography), patterning techniques (i.e., nanosphere lithography), and materials chemistry approaches (e.g., directed self-assembly, nanoparticles and nanowire growth, and catalysis). Many of these provide access to similar (10 nm) length-scales, although cleanliness, reproducibility, and versatility need to be further improved.

All nanophotonics fabrication technologies will require (1) higher precision tools to control structure size, shape and placement, (2) larger reproducibility, (3) improved control over the material’s purity, and (4) new ways to integrate and interface with electronics and conventional optics. Chip-scale devices face additional challenges in terms of cleanliness requirements and materials compatibilities. We must also give thought to newly emerging health and safety issues associated with the use of photonic and plasmonic (and all) nanostructures.

**Expand Optical and Structural Characterization Capabilities for Nanophotonic and Plasmonic Materials and Devices**

While the research community has benefited greatly from access to optical nanocharacterization tools, quantitative interpretation of SNOM images is still a challenge and requires significant expertise, the development of better SNOM tips, and better software. There is an increasing need for characterization tools that can correlate the structural and materials properties at the atomic-scale to the optical properties of nanophotonic devices and nanostructured materials. Emerging optical characterization tools in the fields of nanophotonics and plasmonics include cathodoluminescence, optical scanning tunneling microscopy, and electron energy loss spectroscopy (EELS) in a transmission electron microscope; these techniques have already enabled studies of plasmonic modes with nanometer resolution (1-2 orders of magnitude better than SNOM). Equipment like this will help realize simulation tools that properly take into account the optical, electronic, and quantum mechanical effects that will play an increasingly important role in nanophotonic and nanoplasmonic devices.

Researchers will also continue to rely on the availability of and access to state-of-the-art structural characterization tools, as their performance parameters keep on improving every year.

**Build New Educational Systems that Promote Diversity, Interdisciplinarity, and Collaboration**

As the fields of nanophotonics and plasmonics expand rapidly into many applications, ranging from information transport to biology, it will also be important to restructure and further develop our education system in the right way. The interdisciplinary nature of these fields requires the development of a common language and new educational methods and tools. In such a rapidly-developing field that has widespread applications, the background training of participants in the field will rapidly diversify. For example, just 10 years ago a symposium on plasmonics was rare, and the audience would primarily consist of hardcore theoreticians and a few scattered experimentalists. Currently, there are well over 20 plasmonics symposia/conferences around the globe annually, filled with people from academia and industry with backgrounds in physics, chemistry, materials science, electrical engineering, biology, chemistry, and medicine. In order to take advantage of the many views and uses of optics, a diverse educational program should be constructed to reduce misunderstandings due to the differences in vocabulary used to identify common concepts and enhance new and valuable collaborations.
9.5 R&D INVESTMENT AND IMPLEMENTATION STRATEGIES

Over the past decade, there has been significant maturation of the nanotechnology facilities network supported by the Federal Government that is focused on fundamental understanding of nanotechnology. The National Nanotechnology Initiative has provided a framework for the development of numerous centers supported by both Federal and state agencies. Many of these centers have been developed as complementary centers involving coordinated Federal, university, and industry funding sources. Major investments have been made by the Department of Defense, Department of Energy, National Institutes of Health, and National Science Foundation, among other Federal agencies.

The center focus is important in bringing together the numerous critical building blocks and kinds of expertise that comprise research in nanophotonics, linking complex simulations, materials synthesis, state-of-the-art fabrication, and characterization. The breadth and diversity of these centers also helps to link scientific innovation with applications.

In order for nanophotonics to have the greatest possible opportunity for impact, innovative means should be sought for coordinating these research facilities and capabilities with industry:

- Decisionmakers at academic institutions should be educated about and sensitized to needs-driven research that is critical to industry.
- Means should be explored for expediting technology transfer from the laboratory to processing facilities and accelerating scale-up and manufacture of innovations in nanophotonics.

9.6 CONCLUSIONS AND PRIORITIES

The field of nanophotonics has advanced enormously in the past 10 years, but we have by no means fully capitalized on the potential of these technologies for high-speed information transmission, energy capture and storage, and sensing. Integrated advances in materials synthesis, high-resolution fabrication, computation and modeling of optical behavior, and nanoscale optical and structural characterization have given rise to exceptional demonstrations of photonic coherence, localization, and switching in compact structures with dimensions that are at or below the wavelength of light. Nanophotonic components appear to be making progress in true integration into mainstream electronic technologies.

Research priorities should involve bringing some of the substantial recent advances in this area to the next level of development in ways that may change the paradigm of imaging and information processing using photons. These areas include:

- The design and fabrication of optical cavities that truly allow full control of the lifetimes and interaction of photons. Among the many impacts that such cavities have had and could have in the future:
  - Recent achievements of ultralow-threshold lasers with 10s of nanoWatts thresholds. We look in the future towards “threshold-less” lasers, where the efficiency of energy transfer between cavity and gain medium is so great that lasing can be initiated with miniscule power input to achieve exceptionally high power gains.
  - Recent achievement of “slowed light” in solid-state optical cavities. This presents the possibility, for the first time, of scalable, on-chip delay and storage of photons for photonic information processing, and provides a key enabler for all-optical processing with tremendous advantages in bandwidth and high-speed at greatly reduced power dissipation. We look in the future towards light slowed to the point
where lossless storage of light can be achieved with storage times of milliseconds or longer.

- The rapid advances in the field of plasmonics, opening up tremendous new possibilities for the application of photonics in broad areas of application. Some of the many impacts that could be realized in this area include:
  - Recent advances in single-molecule imaging enabled by local-excitation and enhanced signal emission could ultimately result in the controlled and specific absorption and emission of light from single molecules.
  - Plasmonic structures have been used for the initial demonstrations of metamaterials at visible and near-infrared wavelengths. These are materials with negative index of refraction. Although there have been some initial demonstrations of enhanced imaging using these structures, we look ahead to the realization of true ‘superlenses’ with spatial resolution substantially below the wavelength of light used.
  - There have been demonstrations of discrete plasmonic devices such as antennas and waveguides. The size scale and performance of these metallic components makes them ideally suited to be integrated within complex electronic circuits, leading to electro-optic circuits with increased bandwidth, with operation at higher frequency and lower dissipation.

The community of researchers that is key to capitalizing on the broad potentials of nanophotonics depends on advances in and accessibility of state-of-the art:

- Computational tools that can span different length scales, coupling optical simulations to quantum mechanical simulations and coupling optical modes with thermal, mechanical, magnetic, and electrical energy states.
- Optical and structural characterization tools that could help to correlate the structural properties of materials with their photonic performances.
- Nanofabrication techniques that allow high local precision (~1nm), relative ease of use, and compatibility with different materials and technologies (e.g., electronics).

Continued investment in consortia and centers of excellence is also encouraged for this rapidly developing and multidisciplinary area, with a focus on new educational approaches and the ability to link fundamental science to the demonstration of compelling new applications.

9.7 BROADER IMPLICATIONS FOR SOCIETY

As indicated earlier in this chapter, the applications of nanophotonics to societal benefit are profound and pervasive. Nanophotonic elements are already being integrated into the dominant silicon electronic platform to provide high-bandwidth, low-latency information transfer that challenges the scalability of future computing systems. Nanophotonics has an important role to play in more efficient energy-harvesting; in high-sensitivity, integrable sensing in biological, security, and other platforms; and in curing disease (e.g., see Figure 9.8) and remediating environmental degradation. In looking at the broad range of possible applications for nanophotonics, it is not simply the size of the components or systems that provides benefit, it is also the new physical mechanisms at play. The small (and ever smaller) size of nanophotonic device elements provides benefits for their integration and incorporation into heterogeneous material systems and into a variety of different technological platforms. The reduction in size of the nanophotonic components also gives rise to new physical behaviors, for example, control over optical states and frequencies, and the ability to localize light at sub-wavelength scales. As we gain further understanding and
mastery of nanophotonic elements and systems, the benefits to society should increase considerably.

![Image 1](image1.png)

Figure 9.8. Use of Au-coated plasmonic elements (nanoshells) for cancer treatment. (1) Each nanoshell is about 10,000 times smaller than a white blood cell. (2) Via antibodies that functionalize them, about 20 nanoshells cover a tumor cell. (3) Plasmonic responses concentrate externally delivered infrared radiation, selectively directed to and destroying the tumor cells (Kelleher 2003).

9.8 EXAMPLES OF ACHIEVEMENTS AND PARADIGM SHIFTS

9.8.1 Nanophotonics on a Chip

**Contact person: Michal Lipson, Cornell University**

Future electronics will rely on nanophotonics for transmitting information across the chip. This will enable the electronics industry to continue scaling in size and bandwidth without the existing limitations in power. In order to realize this vision, the optical elements are required to be compatible with silicon, the material of choice for electronics, or in other words, one requires *silicon nanophotonics* (Figure 9.9). Devices that enabled this technology were proposed in 2004.

![Image 2](image2.png)

Figure 9.9. IBM vision of silicon photonics for optical interconnects in future electronics.

Until recently, silicon nanophotonics was viewed as highly limited due to the inability to amplify light and emit light efficiently in silicon. However, recent work by Cornell University researchers and others has shown that light amplification and emission can be achieved by using silicon as a nonlinear optical material. One of the primary reasons for this is that the refractive index for silicon is very high, and thus extremely compact waveguides can be created that confine light very tightly (Figure 9.10). This results in the ability of the devices to operate at very low power levels. While this is certainly an important property, these tightly
confining waveguides offer the ability to use the waveguide dispersion to conserve momentum (i.e., phase match) of nonlinear processes, which greatly improves the efficiency.

This dispersion control has been applied to achieve amplification over extremely large bandwidths (Foster et al. 2008). One could then envision using a single micron-size device for amplifying the entire telecommunications bandwidth. Based on such a device, researchers have also demonstrated an ultrasmall device that can emit light over very broad range of frequencies. The light emitted is laser-like and can be used as a source for lighting up silicon chips (Levy et al. 2009; Figure 9.11).

Silicon nanophotonics applications range from future computing to communication. Today, largely due to the advances described above, startups are already commercializing this technology. In addition, the computing industry (e.g., Intel, IBM, has significant efforts in silicon nanophotonics development that aim to embed this technology in future computing systems.
9.9 INTERNATIONAL PERSPECTIVES FROM SITE VISITS ABROAD

9.9.1 U.S.–European Union Workshop (Hamburg, Germany)

Panel members/discussants

Fernando Briones Fernandez-Pola (co-chair), Spanish National Research Council (CSIC), Spain
Evelyn Hu (co-chair), Harvard University, Cambridge, Massachusetts, United States
M. Alterelli, European X-ray Free-Electron Laser (XFEL), Germany
Y. Bruynserade, Catholic University of Leuven, Belgium
J. C. Goldschmidt, Fraunhofer Institute for Solar Energy Systems (ISE), Germany
M. Kirm, Institute of Physics of the University of Tartu, Estonia

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Distinguishing discussions in this workshop focused on the utilization and leveraging of innovation in photonics and plasmonics for the advancement of research in fields such as photovoltaic research, efficient catalytic processes, and improved medical imaging. As in many of the other workshops, substantial progress and promise was found in the rapidly growing area of plasmonics, but additional opportunities included:

- Rapid, reliable single-photon sources for quantum communications and computing
- Development of new, higher-spatial-resolution imaging and characterization tools, extending the characterization frequencies into the infrared and THz regimes
- Optical control of spin-based phenomena with higher spatial and time resolution

In addition, participants in this session saw the potential for better integration of nanophotonic and plasmonic components into existing nanoelectronic platforms.

Discussion also centered on the need for better utilization of new larger-scale facilities such as synchrotron radiation sources and free electron lasers, both for the characterization of nanoscale components that comprise the photonic elements and for potential roles in the fabrication of nanophotonic devices. Such high-power light sources have the capability to carry out 3D imaging of nanoscale structures with sub-picosecond time resolution.

In realizing the full benefits of innovation in photonics and plasmonics to the breadth of potential fields related to energy-efficient devices (e.g., photovoltaics) and biomedical research (e.g., imaging), participants pointed out the necessity of making broadly available a common infrastructure platform for materials synthesis, nanoscale fabrication, and characterization.

Discussions on R&D strategies that would promote rapid advances in this field brought forth ideas of collaborative research environments that in one sense was a common theme among all workshops in this area but also may have addressed issues unique to European research. These recommendations include:

- Promoting interaction between engineering and science by creating collaborative, critical-size R&D environments (cluster competencies) at the precompetitive research level
- Improving collaboration between universities and large research facilities
- Funding brilliant young researchers at substantial levels, modeled on existing European Research Council funding programs (http://erc.europa.eu)
Finally, although there was no specific discussion at the workshop, it should be noted that the European community has been active in developing strategic roadmaps in photonics and nanotechnology. The MONA (Merging Optics and Nanotechnologies) consortium, launched in June 2005, developed a roadmap for photonics and nanotechnologies in Europe by involving several hundred researchers in industry and academia, who participated in a series of workshops, symposia, and expert interviews over a period of two years (MONA 2008; Figure 9.12). This roadmap was updated in January 2010 by the Second Strategic Research Agenda in Photonics (Nanophotonics Europe Organization 2010; Figure 9.13).

Figure 9.12. Cover of roadmap report of Merging Optics and Nanotechnologies (see MONA 2008).

Figure 9.13. Cover of Second Strategic Research Agenda in Photonics (see Nanophotonics Europe Organization 2010).
As stated by Martin Goetzeler, CEO of OSRAM, in the foreword to that report,

> When the first agenda was published in 2006, photonics in Europe looked very different. Photonics21 had only just begun its task of building a community...Today more than 5,000 companies, most of them small and medium-size enterprises, manufacture photonics products in Europe. The sector employs almost 300,000 people directly and many more work for its suppliers. No fewer than 40,000 jobs have been created here in Europe within the last four years. Photonics innovations are key drivers for profitable growth. The world market for photonics products reached €270 billion in 2008, of which €55 billion was produced in Europe—a growth of nearly 30% since 2005. We are particularly strong in lighting, manufacturing technology, medical technology, defence [sic] photonics and optical components and systems.

In September 2009 the European Commission designated photonics as one of five key enabling technologies for our future prosperity. This signifies not only the economic importance of photonics, but its potential to address what have been called the 'grand challenges' of our time.

In addition, an "Emerging Nanophotonics Roadmap" (Figure 9.14) has been formulated by the members of the EU Network of Excellence in NanoPhotonics to Realize Molecular Scale Technologies (PhoReMoST). Further information can be found by accessing the website of the Nanophotonics Europe Association (http://www.nanophotonicseurope.org/).

![Figure 9.14. Part of nanophotonics roadmap in the PhoReMoST document (2008).](image)

### 9.9.2 U.S.–Japan–Korea–Taiwan Workshop (Tokyo/Tsukuba, Japan)

**Panel members/discussants**

- Satashi Kawata (co-chair), Osaka University, Japan
- Evelyn Hu (co-chair), Harvard University, Cambridge, Massachusetts, United States
- Yasuhiro Arakawa, University of Tokyo, Japan
- Susumu Noda, Kyoto University, Japan
Professor Kawata began this session by a discussion of the long-term investments into photonics by Japan, Korea, and Taiwan. For example, as early as 1981, the Japanese government founded the Optoelectronics Joint Research Laboratory (OJL) to conduct basic research to enable fabrication of optoelectronic integrated circuits and transfer of the technology to its nine member companies at the end of the project.

Several topics were given more in-depth discussion at this workshop, representing the expertise and the sustained contributions made by the various workshop participants. Professor Kawata discussed the use of two-photon reduction to form 3-dimensional metallic nanostructures, of great potential interest for plasmonic applications. He also discussed “tip-enhanced” Raman spectroscopy, innovative instrumentation for imaging with super-resolution. Professor Arakawa, one of the leaders in the science and technology of semiconductor quantum dot photonic devices, discussed the advantages in speed and high-temperature stability offered by quantum dot lasers. His vision of the benefits to be gained from these nanostructured photonic devices can be represented by Figure 9.15.

Professor Noda, internationally recognized for his contributions to the science and applications of photonic crystal cavities, discussed the progress and vision in the “ultimate control of photons” for energy-efficient sensors, optical sources, and next-generation information processing. His vision can be represented by Figure 9.16.
There was a greater in-depth discussion of the applications of photonics and plasmonics to biomedicine, given by Professor Sun. His discussion ranged broadly and included the use of plasmonic structures and colloidal quantum dots as imaging agents for biomedical applications, as well as microbial diagnostics using novel photonics platforms. His vision for biomedical applications and platforms for nanophotonics is represented in Figure 9.17.

Professor Lee discussed the importance of nanophotonics and plasmonics to information processing, providing on-chip integrated photonic sources, detectors, waveguides, and interconnects. His vision is represented in Figure 9.18.
The workshop participants also discussed the need for long-term investment in people and ideas, working in collaborative environments, and providing new education/research centers that will allow exploration of new nanophotonic concepts that go beyond the purview of older, more conventional disciplines.

9.9.3 U.S.–Australia–China–India–Saudi Arabia–Singapore Workshop (Singapore)

Panel members/discussants

Paul Mulvaney (co-chair), University of Melbourne, Australia
Mark Lundstrom (co-chair), Purdue University, West Lafayette, Indiana, United States
Chennupati Jagadish, Australian National University, Australia
Chen Wang, National Center for Nanoscience and Technology, Beijing, China

The breakout session had input from Australian and Chinese participants, in addition to the U.S. moderators. Some differences in emphasis were apparent from these discussions.

Australia places a strong emphasis on environmental science at present. Nanophotonics is seen as an important platform for economical environmental sensors. There is a tremendous interest generally in “sensing the small.”

Biosensors, bioassays, and other applications in the biological and medical fields are also seen as important drivers for nanophotonics. The highest-profile activities in this field are two consortia working towards the development of the bionic eye. The bionic ear was pioneered in Australia, and this technology for interfacing electronics to neural structures is seen as an important platform that makes the bionic eye look feasible.

Australia is ideally placed to exploit solar energy, given its high solar insolation, large area (about 85% of the area of the U.S. mainland), and low population density (national population is comparable to that of the State of California). Consequently, the potential of nanophotonics to provide solutions in photovoltaics and smart windows for efficient energy use are high-profile activities.
Less strong in Australia compared to the United States are the fields of interfacing to defense applications and using nanophotonics to provide advances in electronics industries. However, it is also apparent that Australian researchers see the integration of optical structures with conventional electronics as a very desirable long-term goal.

This breakout session identified important applications and goals for nanophotonics in the next ten years:

- The all-optical chip
- Metamaterials operating at visible wavelengths
- Single-(bio)molecule detection
- Artificial photosynthetic systems for energy applications

Workshop participants in this session similarly discussed infrastructure needs:

- Collaboration (sharing of information, construction of joint databases)
- Networked fabrication, metrology, and characterization resources.
- Wider availability of open-source, multiscale computational tools (especially for designing nanophotonic circuits)

Here too, participants stressed the need for strategic, longer-term, perhaps “center-level” funding; precompetitive collaborations between universities and industry, and better training of a nanotechnologist generation. They also called for a “Nanophotonics Roadmap” (note the activities on “roadmapping” as carried out by the European Community, Section 9.9.2).

9.10 REFERENCES


