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Perspective

Optics and photonics at nanoscale: Principles and perspectives

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Abstract – Nanophotonics is a multidisciplinary frontier of science that merges nanoscience and nanotechnology with conventional optics and photonics. We focus on two principal issues of nanophotonics: manipulation of optical field and light-matter interaction via various optical nanostructures. These two issues are behind all the efforts to explore, design, and build nanophotonic devices to accomplish the fundamental cause of large-scale optical integration for information processing, interconnection, and computing. We discuss various mechanisms of light-matter interaction enhancement to realize bright fluorescence, Raman, and nonlinear optical radiation, and explore methodologies and various devices for highly sensitive optical sensing and detecting, ultrahigh spatial resolution imaging, and high-efficiency energy conversion between light and electricity, heat, and other forms. All these concepts, insights, methodologies, and technologies in nanophotonics will set a solid platform to explore and achieve better future information and energy technologies that use light as powerful information and energy carriers and as prominent media to probe and manipulate the intrinsic properties of matters via light-matter interaction.

Introduction. – Optics has a very long history as human beings live in the environment of sunlight [1–3]. From the era of Newton to Einstein, the pursuit of the nature of light has become a great force to push forward physics and science. Since the 1960s, the invention of lasers, optical fibers, and semiconductor optoelectronics has significantly changed and shaped the way human beings live and work, and brought humans beings into the era of information technology. Besides, new optical materials such as high-efficiency light-emitting diodes (LEDs) have fundamentally changed the way in which human beings use energy in everyday life and industries. Due to the important role and fundamental impact of light in our societies, the United Nations have set 2015 as the International Year of Light. This is good news for optics and photonics, the science and technology of light. People would naturally wish that optics and photonics continue to play an increasingly important role in the information and energy technologies and industries of our future society.

On the eve of the 21st century, the rapid growth of nanoscience and nanotechnology and their merging with optics and photonics have led to the emergence and maturity of nanophotonics, which is a brand new big regime and frontier to understand, manipulate, and make use of light at nanoscale [4,5]. The idea of nanophotonics can be most conveniently understood by referring to the traditional optics and photonics. But nanophotonics has many new features that go beyond the conventional optics and photonics and only manifest significantly at subwavelength nanoscale. To fully explore and utilize various intrinsic properties of light and photons as information and energy carriers and as media to probe and manipulate the intrinsic properties of matters via light-matter interaction at nanoscale, one must address the following two key issues: the manipulation of optical field and light-matter interaction at nanoscale. In this perspective I will address these two issues by briefly summarizing the current state-of-the-art of nanophotonics and suggesting its future prospect. In the past three decades, a series of science topics connected with nanophotonics have emerged, such as photonic crystals (PCs) [6], plasmonics [7], metamaterials [8], optical nanocavities [9], optomechanics [10], metasurfaces [11], semiconductor quantum dots [12], metal nanoparticles [13], and many others, and
each has quickly expanded into a big frontier of science research. It is far beyond the scope of this perspective to have a comprehensive review upon all these topics and areas. Instead, I will rather prefer to discuss the most common aspects in all these fields of nanophotonics.

**General aspects.** To fully explore the great powers of managing, manipulating and making use of light at nanoscale, it is necessary to understand the basic physics underlying different processes involved in information processing and energy exchange of light. These should include a series of important topics.

The first issue is the **generation of light.** One of the fundamental roles of nanophotonics is to increase the efficiency of transformation of energy from other forms to that of light and increase the efficiency of radiation of light from the sources. A classic example is laser, which has the brilliant power to transform energy from very cheap electricity or incoherent white light into highly bright coherent light. Other examples are LEDs operating in visible spectra. They have extremely high energy conversion efficiency from electricity to light. Their great success has been recognized with the 2014 Nobel Prize in physics. Nanophotonics can offer solutions to build ultracompact laser and LED sources at the wavelength and subwavelength scales, which have been long desired for the use as an indispensable and key building block in an optical integrated chip [7].

The second issue is the **modulation of light.** Light can serve as a good information carrier only when it is in the controllable form of various modulations to its internal freedoms such as amplitude, wavelength, polarization, and modal profile. The fundamental goal here is to realize high speed, dense bit rate, broad bandwidth, and high fidelity of information modulation, which usually requires controllable interaction of light with matters and materials. Nanophotonics can offer a useful solution to generate information carriers via various schemes as amplitude, wavelength, and polarization with the ultracompact device size comparable with the wavelength of light. This seemingly simple functionality would actually lead to a tremendous difficulty and a challenge to our wisdom because a sufficiently strong and fully controllable light-matter interaction must be supported at these small size scales.

The third issue is the **transport of light.** The fundamental goal is to ensure low loss, broad bandwidth, high efficiency, and high fidelity of light signals when transporting information and energy from one to another position of the system. The silica optic fiber is a brilliant success in long-distance optical information transport, and little space is left for further promoting the performance and capability of optical-fiber communication. In this circumstance, the emphasis of research has been shifted to another equally important issue, namely, how to enable an efficient information transport in ultracompact integrated optical chips, which should involve many functionalities such as information transport, modulation, exchange, processing, computing, and detection. Whereas optical-fiber communication represents one end of the whole chain of the information communication, an optical integrated chip stands at the other end of the chain. Together they allow optical information to be generated at one entrance position by a machine, delivered into optical fiber networks, transported along the long-distance optical fiber to another position, and finally detected and sensed by another machine at the exit position in the form of information.

The fourth issue is the **detection of light.** As has been mentioned, light as an information carrier has several significant advantages against electronics. Detection of light information serves as an indispensable node in the whole chain of information technology and industry. Generally speaking, light as information carrier can be understood at two different levels. The low level concerns the most general use of light as information carrier, which means using light to detect and sense macroscopic and microscopic objects. This level involves a very broad range of categories in optics and photonics. Use is made of Hubble space telescope to observe, image, and analyze distant galaxies, stars, and planets; of man-made satellites to remotely sense and govern the local and global environment and weather of our planet; of optical microscopes to observe and image the shape and motion of plant and animal cells; of fiber sensors for remote detection and management of dangerous or poisonous areas and environments and safeguard from fire or gas explosion disasters; and of fluorescence and Raman spectroscopy to detect and identify microscopic objects as atoms, molecules, and others, and observe their motions and changes.

The high level concerns a narrower range of applications of light as information carrier, namely optical information in modulated digital form to represent more abstract meanings, such as languages, pictures, or motions. These applications comprise the most basic functionalities of standard optics communication technologies and industries and they appear in both the long-distance global fiber optical networks and ultracompact optical integrated chips for signal processing, communication, and computing. The key issue here is the construction of high-efficiency optoelectronic detectors and high-sensitivity optical detectors. Nanophotonics can help to offer a wide variety of solutions to enhance the sensitivity, bandwidth, and speed of these detectors and sensors.

The last issue is the **transformation of light.** This issue is most closely correlated with light as energy carrier. The long history of science tells us that light can be exchanged with and transformed into many other forms of energy, either macroscopic in the form of heat, sound, electricity, mechanical motion, etc., or microscopic in the form of electronic levels, chemical bonds, lattice vibrations in solids, molecular vibrations and rotations, plasma motions, etc. Photosynthesis in green plants is a brilliant example in nature where the energy of sunlight is transformed into the energy of chemical bonds, and it is the most important
energy source of our planet. Solar cells and photovoltaics are now the most charming man-made machines to transform sunlight energy into electricity. Another equally important issue is to transform light of one wavelength into light of other wavelengths. Fluorescence, Raman scattering, photoluminescence, and various nonlinear optical processes are prominent examples. The central issue in these applications is the high efficiency of energy transformation and light-matter interaction engineering holds the key towards this aim. Nanophotonics can offer very useful solutions to these problems because light-matter interaction naturally takes place at subwavelength size scales and can be greatly enhanced by many nanophotonic structures and devices, such as surfaces, interfaces, and resonant cavities.

It can be said that the above five fundamental issues cover all the important problems involved with the intrinsic properties of light as information and energy carriers. They also encompass all the important problems that deal with the extrinsic properties of light when they participate in light-matter interaction of probing and manipulating the intrinsic properties of matters, such as atoms, molecules, condensed matters, and biological objects. Nanophotonics can manage to offer many useful concepts, approaches, and technologies to promote the functionalities and performances of devices related to each of these five fundamental processes. In the following we illustrate some examples to discuss how to handle these issues.

**Optical integration.** – It has been since the 1980s a long-pursued dream to bring together optical components and devices implementing any of the above five processes into a single photonic integrated chip (PIC) [14,15]. Simply speaking, this means a large-scale optical or optoelectronic integration, in the same way as microelectronics integrated circuits that have set the cornerstone of current information technology. Large-scale optical integration requests miniaturization of optical components and devices, and their compact connections, dense packages, and cooperative actions on a monolithic chip. Nanophotonics is naturally expected as a reasonable solution to address these requests, as it can offer a promising technological roadmap towards smaller, faster, and greener optical devices for information and energy technology.

A PIC will resolve the bottleneck encountered in current microelectronics industries, which arises as soon as miniaturization of integrated semiconductor transistors reaches the size limits imposed by physical laws such as the emergence of quantum size effects and difficult heat dissipation. A PIC can help to connect different microelectronic chips by first transforming the input electronic signal from one microelectronic chip into optical signals. The optical signals then feed into and transport within an intermediate nanophotonic chip, and finally connect to another microelectronic chip which transforms the optical signals back to electronic signals. In these optical interconnection applications, the keys issues are high-speed and dense-rate-bit optoelectronic modulation, broad-band, high-speed and low-loss transport of optical signals, high-efficiency channel-drop filters for dense wave division multiplexer/demultiplexer, and high-efficiency and high-sensitivity optoelectronic-conversion detector [16–22]. Such high-performance nanophotonic chips would bridge the two cornerstones of modern information technology, the microelectronics chips, which are local information processing units, and optical-fiber communication systems, which are long-distance information transport units.

Great efforts have been paid to push forward the construction of a PIC. However, a true large-scale PIC is still at a premature stage. There are several unsolved major issues. First, the overall architecture for a large-scale PIC is not clear so far. Can a PIC directly copy the architecture for a well-established large-scale microelectronic IC? Currently, many optical components that are necessary building blocks of a PIC have been extensively investigated and successfully made in the material platform of silicon. The operation principle of these devices can either be photonic band gaps and defects (point defects for cavities and line defects for waveguides) in a silicon PC [23,24], or total internal reflection in a silicon nanowire (both waveguides and ring resonators) [25]. Extremely low-loss waveguide on the order of dB/mm has made success, and cavities with a quality factor (Q-factor) on the order of 1000–10000 that are compatible for building channel-drop filters, a basic information processing block, are easily made [26]. High-Q cavities with a Q-factor up to 107 can also be made [27]. Many other functional devices such as splitter [23], filter [23], buffers [25,27,28], memories [29,30], and switches [31,32] have been explored. Despite these progresses, little is done to bring these devices into a small-scale PIC, not to mention a large-scale PIC. Second, several key devices that are indispensable for an information processing and computing PIC are still lacking and the routes to build them are not clear. These include optical diodes [33], isolators [34], logic gates [35,36], and transistors [37]. Without these key devices, a general PIC with functionalities comparable to the central-processing unit (CPU) in current electronic computers would not be possible. Schemes based on linear transport effects, nonlinear optical effects, electro-optic or magneto-optic effects, and active-passive combination effects have been investigated [31–37]. However, real breakthroughs are still lacking and highly desirable. The major challenge is that current materials for PICs, such as silicon and other semiconductors, are far from being satisfactory for building devices with small footprint (∼µm), fast response speed (<ps), low consumption power, and high signal contrast. Therefore, the advent of these devices and thus of an optical CPU strictly depends on finding better materials, brighter physical mechanisms, and suitable architectures.

Third, a large-scale PIC might need bringing together passive devices (information transport, memory, buffer, routing devices, etc.) and active devices (light source,
modulator, detector, switches, transistors, etc.). However, the technologies for this kind of hybrid integration are still not mature. Finally, there is a question as to whether optical transistors should play a central role in an optical CPU or PIC much as a conventional transistor does in current microelectronic ICs, and if yes, as to how to construct an optical transistor [37]. Currently there is no clue as to how to make a high-performance optical transistor with small footprint, fast response speed, low energy consumption, and large bandwidth. Perhaps active materials with nonlinear electro-optic light amplification might be a promising solution towards this big challenge in PICs.

Although it might be a long way to go for accomplishing a general optical CPU that is necessary for building an optical computer, special PICs that are designed to only implement one or several functions are immediately ready for practical use and are still in rapid process of promotion. A prominent example is the optical interconnection PIC [16,17], which only involves input/output waveguide channels, modulators, and detectors. However, it has been very useful to enhance the performance of many technologies such as high-speed fiber-to-the-home communication, mass data exchange, and supercomputers. Another good example consists in various kinds of lab-on-a-chip that can be very useful in biochemistry analysis, drug design, medical diagnosis and disease therapy [38,39].

Light-matter interaction enhancement. – Light-matter interaction is a central issue in many nanophotonic devices and integrated circuits. In these systems, the interaction length between light and matter (atoms, molecules, semiconductor quantum dots and wells, nonlinear crystals, etc.) is smaller than the wavelength of light, greatly limiting the overall interaction strength. As a result, many important phenomena, such as fluorescence, Raman scattering, electro-optic (EO) and magneto-optic (MO) activities, nonlinear optical effects, optical modulation, optical sensing, and light amplification, which are of premier importance in optics and photonics, is not efficient and strong enough in most nanophotonic devices. This fundamental weakness brings a great obstacle for miniaturization of these devices and the consequent optical integration. A prominent example is the Mach-Zehnder interferometer, which can serve as optical modulator, switch and logic gate based on the well-established EO effect of silicon or LiNbO3. However, the EO effect of these materials is so small that the device size must reach a threshold on the order of a millimeter. To reduce the size to around a micrometer, the EO interaction strength need be enhanced by 2 orders of magnitude. This simple example is already clear enough to show the grand challenge before large-scale optical integration.

The strategy to overcome this difficulty is twofold. The first one is to find new materials with better optical properties. The history has shown that this strategy in itself may be a grand challenge, too. Nowadays, people working in material science and technology have not been successful in finding good routes to building light and laser sources in silicon, despite struggling efforts for decades. The second one is to find various light-matter enhancement approaches and mechanisms. This physical strategy has been explored extensively in past decades and fruitful results have been obtained. Simply speaking, many of these methods are trying to increase the light-matter interaction time duration in a limited size and volume, and serve as an alternative to increasing the interaction path via increasing the size of devices. In effect, both methods efficiently increase the overall light-matter interaction strength.

An obvious approach to increase the interaction time is to slow down the speed of light, and this is the essential secret of many slow-light devices. For instance, a photonic slow-light waveguide can reduce the light speed by two orders of magnitude [24], and this can significantly enhance the EO effect and the nonlinear optical effect by many orders of magnitude [40]. A more popular route is to make use of strong optical resonances. A prominent example is a PC high-Q nanocavity [27], which can trap and confine light into a tiny volume by a time duration equal to millions, or even billions of light oscillation periods. This creates a very efficient way to accumulate and store the energy of light input from external channels. The consequent high-energy density allows a significant enhancement of EO and nonlinear optical effect [32,35], and also enables strong coupling of light with quantum objects such as quantum dots [9,41], which is very useful for quantum state manipulation, quantum information processing and computing.

An equally popular, while simpler, way to create a strong optical resonance is to incorporate the unique and intrinsic dielectric response properties of some special materials. Plasmonic metal nanostructures are such prominent examples, which can support many kinds of optical resonance modes. A noble metal (e.g. Ag or Au) nanoparticle in a fairly simple geometric configuration already supports fruitful local surface plasmon resonance (LSPR) modes [42,43]. When a SPR occurs, the incident light is strongly coupled with the oscillation of free-electron clouds around the metal nanoparticles and the energy of light is stored at the surface plasmon polariton (SPP). Because of the oscillating charge nature of SPP, the enhancement factor of the local electric field can reach a very high value, in particular in the “hot spot” [44–46]. Compared with high-Q dielectric resonators, for instance, PC nanocavities, the optical resonance in LSPR has a relatively small quality factor, which means short accumulation time duration. However, owing to the charge nature and far smaller modal volume of the “hot spot”, the energy density of light in a LSPR is comparable with or even larger than that in high-Q dielectric nanocavities. These advantages, together with the relative ease to prepare metal nanoparticles in copious amount by
using inexpensive chemical synthesis approaches, make these plasmonic nano-systems very attractive as agents to enhance light-matter interaction in optical sensing and detection.

Optical resonances can be explored to enhance light-matter interaction in various phenomena, such as fluorescence, Raman scattering, photoluminescence, nonlinear optics, photocatalysis, and photoelectric activity. In many situations, the enhancement can happen in several folds. In the case of fluorescence and Raman scattering, a plasmonic nanoparticle can serve as an optical nano-antenna to collect efficiently the incident pump light, focus them on a tiny “hot spot” and interact with molecules with a greatly increased efficiency, and finally help the fluorescence or the Raman signal to radiate away from the nano-antenna to the detector in the far field region with similar enhanced efficiency. In these physical phenomena the plasmonic resonance contributes twofold to light-matter interaction, in the excitation and the radiation process. With this insight it would then be natural to design a nanophotonic structure that can provide two optical resonances matching both with the excitation wavelength and the radiation wavelength of the fluorescence and Raman scattering. This double-resonance mechanism indeed has led to significantly enhanced fluorescence of a molecule from gold nanorods [47], a successful high-intensity low-threshold Raman laser from silicon materials by using a dual-mode high-Q PC nanocavity [48], and enhanced second-harmonic generation from Ag-LiNbO3 core-shell hybrid nonlinear nanoparticles [49].

Light-matter interaction enhancement can be further engineered by improving the figure of merit for optical resonance. In plasmonic nanocavities this can be assisted via introducing gain media to compensate for the metal absorption dissipation that has proved to be the dominant factor limiting the growth of the Q-factor and thus the local field enhancement factor [50,51]. The mechanism proves to be invaluable for enhancing the Raman scattering intensity to the single-molecule detection level [50,51]. Alternatively, the light-matter interaction strength can be promoted by increasing the coupling efficiency of pump light into an optical nanostructure. A good example is an adiabatic tapering waveguide [23]. As the total energy power is comparable with the incident pump light and it passes through a far smaller cross-section, the energy density can reach a very high value in these nanoscale waveguides. Another good example is a plasmonic funnel nano-antenna [52], which supports both the global and local focusing effect. The global antenna effects help to collect a wide-area incident light energy into the tiny apex of the funnel structure, while the local plasmon resonance effect helps to further focus the energy into the even tinier gap in the apex. This twofold focusing effect can enhance the local field intensity by several orders of magnitude in the ultra-violet regime [52].

To further increase the light-matter interaction, material properties are the remaining item for the choice in addition to the above structural configuration design and optimization. The reason is simple: whereas the structural configuration addresses the interaction from the side of light via slow light and optical resonance effects to prominently enhance the intensity of light, the material issue considers the interaction from the side of matter. The material issue must go to the microscopic level of the light-matter interaction in order to gain better insights and routes, and focus on the quantum nature of electrons in atoms, molecules, quantum dots, and so on. It is easy to understand that molecules with larger fluorescence and Raman scattering cross-section naturally have brighter fluorescence and Raman emission. A promising way is to use resonant transitions between atomic or molecular electronic levels to achieve the so-called chemical resonance enhancement in Raman scattering [53]. The same rule applies to nonlinear optical interaction. Recently it has been shown that polystyrene, an organic polymer material that has a very large Kerr nonlinearity (coefficient \(\sim 100 \text{ times larger than silicon}\)) and extremely fast nonlinear optical response (down to several femtoseconds, compared with nanosecond for silicon), can efficiently improve the optical switching and logic functionalities of nonlinear PCs [54].

The above analysis naturally brings one to an important conclusion: The best route to enhance a specific light-matter interaction should incorporate both the intrinsic material properties that support microscopic enhancement of concerned physical process, e.g., via material design and atomic or chemical resonant transition, and appropriate structural configurations that support the macroscopic enhancement of the physical process, e.g., via slow light or optical resonance. The analyses also clearly indicate that the light-matter interaction enhancement should be placed in the center stage for those nanophotonic devices that directly aim at applications as high-sensitivity optical sensing and detecting and high-efficiency energy conversion and consumption.

**Optical sensing, detecting, and imaging.** – Whereas large-scale optical integration is a fundamental dream of nanophotonics that still needs hard work from many disciplinary areas for many years to come, nanophotonics has found immediate applications in other equally important fundamental fields as optical sensing, detecting, imaging, and energy conversion. An optical sensor used to probe a particular object basically relies on light interaction with that object and the detection of changes in some of its fingerprint internal states, via technologies such as fluorescence and Raman spectroscopy, light absorption and transmission spectroscopy, SPR spectroscopy, optical cavity resonance spectroscopy, and so on. Many schemes discussed in the last section can be used to improve the performance of these sensors and detectors.

A standard optical sensor is composed of a key infrastructure: a substrate that supports light-matter interaction for light signal with objects under probe. The objects are deposited onto the substrate, interact with the
probe light, and cause the change in light intensity, phase, polarization, or spectrum. By analyzing and calibrating these changes, the objects are identified and the functionality of optical sensing is fulfilled. A good example to implement optical sensing is a standard SPR device, which relies on the change in the excitation wavelength or angle of SPP at the interface between a homogeneous gold thin film and the objects (macromolecules, bacteria, virus, etc.) under probe and detection [7]. Whereas the SPR device only depends on the refractive index change sensed by the SPP and does not support chemical composite identification of the probed objects, the technology of surface-enhanced Raman spectroscopy (SERS) can do this [50,51,53], because each kind of material has a unique fingerprint Raman spectrum. However, the usual Raman scattering cross-section of molecules is very tiny, and giant enhancement of this scattering must be supported, either via optical resonance or via chemical resonance, for obtaining a sufficiently strong Raman signal to identify the composite of the probed objects down to the single-molecule detection limit.

In many situations, one is interested not only in finding a microscopic object, e.g., a molecule, within the field of view of an optical microscope, but also in identifying its exact position. The latter operation is optical imaging and mapping, a never-ending dream of science. While conventional optical microscopy is hampered by the Rayleigh resolution limit [1], great efforts have been made to overcome this limitation. One major category toward such super-resolved optical imaging is to explore innovative ways in the framework of far-field microscopy. A possible way would be to construct superlenses based on negative-refraction metamaterials [55–57], yet, the resolution has not yet improved much over the Rayleigh limit due to some imperfect physical and material problems. An alternative way is fluorescence microscopy, which combines far-field optical microscopy and fluorescence marking, emission, and data processing technologies. It has proved to be very powerful for biological and chemical studies as it has propelled the resolution of optical imaging to a tiny value of 10–20 nm, thus paving the way to nanoscopy. This historical revolution in optical imaging has been awarded the 2014 Nobel Prize in Chemistry. However, it remains a big question whether a purely physical approach is possible that does not depend on fluorescence marking, which is more or less a chemical approach. Perhaps another great innovation in the framework of nanophotonics is required to address this grand challenge.

Another major category toward super-resolved optical imaging and mapping is to use scanning near-field optical microscopy (SNOM) working in various operation schemes [58,59]. However, these near-field imaging technologies have encountered severe limitations in many aspects, including imaging resolution and speed, and weakness in signal excitation and collection efficiency. The key to resolve these difficulties is to develop a more efficient SNOM tip that has a smaller aperture size, thus better spatial resolution, while at the same time maintains a sufficiently large throughput of the light signal through the aperture. In an alternative frontier of optical imaging, the high spatial resolution offered by various scanning probe microscopy, including scanning tunneling microscopy, atomic force microscopy, and SNOM, can be incorporated with ultrahigh signal sensitivity offered by various plasmon-enhanced optical spectroscopy technologies, leading to both ultrahigh spatial imaging and ultra-sensitive optical sensing. A recent work has shown that tip-enhanced Raman spectroscopy can allow for probe and identification via Raman signal of the chemical structure within an organic molecule at a sub-nanometer spatial resolution [60]. This is a good example of how nanophotonics can help to revolutionize the conventional optical imaging and spectroscopy technologies.

**Energy conversion enhancement.** – With respect to energy applications, nanophotonics can provide brand new insights and solutions to address several strategic problems concerning conversion of light energy into other forms of energy such as electricity in solar cells and conversion of electricity into light in LEDs [61–63]. The most important issue in this regard is the efficiency of energy conversion. By tailoring the interaction of light with nanostructured active semiconductor materials, which would include a number of optical processes including focusing, refraction, absorption, scattering, radiation, and collimation of light, especially resonant enhancement of light-matter interaction, one can drastically enhance the efficiency of light absorption by different kinds of solar-cell material for the generation of electron-hole pairs. Together with wise management upon the flow and collection of optoelectronic currents, the overall efficiency of electricity power generation can be greatly improved.

Whereas the high-efficiency conversion between the energy of light and electricity plays a pivotal role in enhancing the performance of optoelectronic devices as solar cells and LEDs, conversion of the energy of light with other forms of energy, such as chemical energy and thermal energy, can also be engineered. For example, SPR in metal nanoparticles called gold nanocages can greatly enhance the absorption cross-section of near-infrared light and enable efficient conversion of light energy into thermal energy. This unique property, in turn, can improve the efficiency of optical coherence tomography, photo-acoustic tomography, and photo-thermal destruction of cancer, which can find many potential biomedical applications as early detection and therapy of cancer and other diseases [64–66]. Nanophotonics has also made an increasingly important contribution to another large class of energy conversion processes, the conversion of light of one wavelength into light of another wavelength via nonlinear optical technologies. Nonlinear PCs with various types of modulation on the second-order nonlinear susceptibility enable very flexible schemes of quasi-phase matching and ensure high efficiency of energy conversion
in second-harmonic generation and many other nonlinear optical processes [67,68]. PC fiber can accumulate very strong nonlinear interaction strength via both a long interaction path and enhanced nonlinear optical interaction between confined modes with porous nonlinear materials, and has made great success in creating supercontinuum light sources [69]. The SPR effect in various engineered metal nanostructures offers another very promising means to enhance various nonlinear optical processes [49,70].

Conclusions and perspectives. — In summary, we have briefly introduced nanophotonics and discussed its two intrinsic principal issues: manipulation of optical field and light-matter interaction via various optical nanostructures. These two issues are behind all the efforts to explore, design, and build nanophotonic devices to accomplish the fundamental cause of human being to construct large-scale optical integrated chips that enable information processing, interconnection, and computing at smaller size, faster speed, larger bandwidth, and fewer energy. Various mechanisms of light-matter interaction enhancement, such as slow light and optical resonances, can be used to realize bright fluorescence, Raman, and nonlinear optical radiation. These mechanisms can help to explore methodologies and devices toward highly sensitive optical sensing and detecting, ultrahigh spatial resolution imaging, and high-efficiency energy conversion between light and electricity, heat, sound, and other forms.

All the concepts, insights, methods, and technologies that have been developed in nanophotonics in the past decades will set a solid platform to explore and achieve better future information and energy technologies that use light as the prominent information and energy carriers and as media to probe and manipulate the intrinsic properties of matters via light-matter interaction. In addition, the innovative concept and methodology developed in nanophotonic sciences and technologies can promote other disciplines of sciences and technologies, including those in acoustic systems and electronic systems [71].

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