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REVIEW ARTICLE

Nanophotonics in China: Overviews and highlights

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The major purpose of this paper is to present a brief overview of the history and the current status of nanophotonics research in China, and to highlight some research results in the past years made by the Chinese nanophotonics communities. I will first briefly introduce the principles of nanophotonics and several of its major disciplines including photonic crystals, plasmonics and metamaterials, and related artificial acoustic structures. Then I will highlight some major progresses made by Chinese research groups in these areas with the selection made merely based on my personal taste. The aim is to let these results better known and appreciated by researchers in the Chinese communities of nanophotonics and related areas, and provide better opportunities of researchers in different areas to have more communications. I also hope that this brief introduction will help to make a better bridge to connect Chinese nanophotonics communities with the broader communities in the world.

Keywords nanophotonics, photonic crystals, plasmonics, metamaterials, phononic crystals

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Contents

1 Principles of nanophotonics

Optics has a very long history as human beings live in the environment of light. In the era of modern sciences ranging from the Newton's era to Einstein's era, the pursuit of the nature of light has become a great force to push forward physics and natural sciences. From 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. In the eve of 21st century, the rapid growth of nano-science and nano-technology has offered another big opportunity for optics. The merge of these interdisciplinary areas has led to the emergence and maturity of nanophotonics, which is a brand new big regime and frontier for human beings to understand, manipulate, and make use of light at the micrometer and nanometer subwavelength scales.

Nanophotonics is a multidisciplinary science, whose success fundamentally relies on cooperation of optics, photonics, physics, chemistry, materials sciences, and nanosciences and technologies. Simply speaking, the fundamental purpose of nanophotonics is to explore and use various intrinsic principles and advantages of light and photons as information and energy carries and as media to probe and manipulate the intrinsic properties of matters via light-matter interaction. 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. i) Generation of light. One of the fundamental goals of nanophotonics is to increase the efficiency of transformation of energy from other means to that of light and increase the efficiency of radiation of light from the sources. ii) Modulation of light. Light can serve as good information carrier only when it is in the controllable form of various modulations to its internal freedoms such as amplitude, wavelength, and polarizations. The key issues are high speed, large bit rate, broad bandwidth, and high fidelity of information modulation. iii) Transport of light. The fundamental goal in this regard is to ensure low-loss, broad-bandwidth, high-efficiency of light signal as the information carrier and energy carrier transporting from one position to another position as designated. iv) Detection of light. Information in the form of light signals can be perceived only when they are probed, detected, and recorded in the other forms of information carrier that our current industries are familiar with, such as electronics. One key issue is the construction of high-efficiency optoelectronic detectors and high-sensitivity optical detector. v) Transform of light. Light as energy carrier can be exchanged with and transformed into other forms of energy carrier such as heat, sound, electronics, mechanics, and so on, or into light of other wavelengths, e.g., in nonlinear optical processes. The key issue here is the high efficiency.

All the above five processes cover all the important issues involved with the intrinsic properties of light as information and energy carriers. They also encompass the important issues 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 biologic objects.

It has been a long-pursued dream of human beings since 1980s to bring together optical components and devices implementing all these five processes into a single chip. Simply put, 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 that involves a large number of individual cells. Nanophotonics is naturally expected as a reasonable solution to address these requests, as it can offer a promising technological roadmap toward smaller, faster, and greener optical devices for information and energy technology.

An optical integrated chip will revolutionize the state-of-the-art information technology, as it is expected to resolve the bottleneck encountered in current microelectronics integrated circuit industries, which arises because miniaturization of integrated semiconductor transistors will soon reach their limitation of size set by the physical laws including quantum size effects and difficult heat dissipations. There is a demanding request for solution of these difficulties, which will allow the information technology to go forward continually with faster processing speeds, larger information capacities, and smaller energy consumptions. Nanophotonic chips 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 output and connect with another microelectronic chip via again transforming the optical signals into electronic signals. In these optical interconnection applications, the key 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. Such high-performance nanophotonic chips would be able to set up a broad way bridge connecting the two cornerstone 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. From the long-term point of view, nanophotonic chips would be able to perform local information processing and computing in a way very similar to current microelectronic chips, but with faster speed, larger capacity, and lower energy consumption. They also allow direct and easy connection with optical fiber communication systems.

In the aspect of 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, for which solar cells are a prominent example, and conversion of electricity into light, for which light emitting diodes (LEDs) are a prominent example. The most important issue in this regard would be the efficiency of energy conversion. By tailoring the interaction of light with microstructured/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 generation of electron-hole pairs. Together with genuine management upon the flow and collection of optoelectronic currents, the overall efficiency of electricity power generation can be greatly improved. Similarly, optical microstructures/nanostructures brought into semiconductor light emitting diodes can selectively enhance light radiation along certain desired directions, for instance the vertical direction of planar LEDs, while simultaneously inhibit radiation into other unwanted directions, usually the lateral direction. A genuine example is LEDs enhanced by surface scattering grating or photonic crystal structure.

Nanophotonics can bring great advantages when high-sensitivity monitor, sensor, and detector for environment and biomedicine applications are concerned. An optical sensor or detector used to probe a particular object basically relies on light interaction with the matter of that object and sees the change of some fingerprint internal states or freedoms of that object. A wide variety of nanophotonic technologies can be adopted for this purpose, such as fluorescence and Raman spectroscopy, light absorption and transmission spectroscopy, surface plasmon resonance spectroscopy, optical cavity resonance spectroscopy, and so on. Many of these technologies rely on enhancing light interaction with the fingerprint states of monitored objects when they are incorporated into nanophotonic structures as a substrate. In many situations, violent optical resonance related to a special geometric and dielectric response properties of designed nanophotonic structure have to be implemented to enhance by orders of magnitude the interaction strength of the incident light with the fingerprint states and freedoms of monitored objects. The situation is quite common in the technology called surface enhanced Raman spectroscopy.

In addition to applications in information technology, energy technology, and environment monitoring technology, and biomedicine technology, nanophotonics can also find promising perspectives in many other areas. To accomplish these applications, nanophotonics needs to address several key issues of manipulating the intrinsic properties of light and photon and controlling the interaction characteristics of light with matters. During the past two decades, significant progresses have been made continually in the nanophotonics community to resolve these key issues. Different ways have been developed to manipulate light and photons at micrometer and nanometer size scales, among which photonic crystals, plasmonics, and metamaterials have attracted intense interests and attentions. Each of these three research fields has now evolved into a wide-area platform for studies by a large numbers of researchers and a large number of publications have been seen every year. Despite the difference in these three branches of nanophotonics, the fundamental purpose of them is the same: Developing smaller, faster, and creating more efficient optical, photonic, and optoelectronic integrated devices and circuits for the purpose of advancing our information, energy, environment and biomedicine technologies. In addition, the innovative concept and methodology developed in optical sciences have also been directly extended to other disciplines of sciences and technologies, including acoustic systems and electronic systems.

Although the cornerstones of the above key disciplines of nanophotonics were not founded by scientists from China, the Chinese nanophotonics community has caught up quickly with the worldwide fashion in many major research fields of nanophotonics [1]. Some results are of innovative significance in either fundamental sciences or technological disciplines, and have drawn intensive attention in the world nanophotonics community. In the following I will present an overview of the history of these nanophotonic fields in China and highlight some major progresses made by the Chinese nanophotonics community. Before going into the details, I would like to emphasize that these selections are made merely based on my personal taste, and they are never meant to exhaust all the excellent research results by our colleagues. In addition, I will only focus my introduction on those research results made by our Chinese colleagues and within China. In addition, I will confine my introduction only to literal discussions. I will not present any pictures, figures, and photos to illustrate my ideas since this paper is not meant to be a full review of the research fields. I strongly suggest interested readers directly refer to the concerned literatures for more detailed information about the works. On the other hand, I will not try to make comprehensive introductions to the research highlights made in the broader world communities, which seems to me an impossible task to accomplish. Therefore, I will only cite a few references, namely, those pioneering literatures in nanophotonics, that are very much relevant to my introduction as a basic context of knowledge.

2 Photonic crystals

Photonic crystals are a class of inhomogeneous optical structures with periodic modulation of refractive index or dielectric constant, which are usually made from two different kinds of materials. The concept of photonic crystal was first proposed in 1987 by Yablonovitch [2] and John [3] independently. Photonic crystals, known as "semiconductor for photons," have very unique optical properties. The Bragg scattering of light by the periodic array of unit cells will lead to creation of photonic bands and bandgaps, in much the same way as electrons do in semiconductor materials. Defect states can be created within the bandgap, which offers a powerful means to confine light and photons in any subwavelength region as desired [4]. This power has made it possible to build ultrasmall optical devices, such as waveguides, cavities, filters, and to integrate them into a monolithic platform of photonic crystal with the ultimate dream of constructing large-scale integrated optical chips, much the same as the current powerful microelectronic ultra-large-scale integrated circuits. The capability to manipulate photonic bands also offers a powerful means to realize a wide variety of dispersion control for light, such as the effects of negative refraction, superprism, self-collimation, and so on. The formation of photonic bands and bandgaps also means that the photon density of states (DOS) and local density of states (LDOS) are very much different from those in vacuum or other homogeneous media, and this has raised a profound power to influence the light-matter interaction. For instance, the spontaneous emission of atoms can be completely inhibited when they are placed within a photonic crystal with a three-dimensional (3D) complete bandgap covering the radiation frequency of the atoms.

2.1 Research activities in early days

On the early days of photonic crystal research, which is around 1990s, only a few groups in the world were involved in advancing the field. In 1994 a research group led by Dao-Zhong Zhang in Laboratory of Optical Physics, Institute of Physics (IoP), Chinese Academy of Sciences (CAS) reported the experimental effort to make a periodic array of dielectric spherical particles by means of laser standing wave field [5]. The work was the first publication in the field of photonic crystal in mainland China. In 1998 Zhi-Yuan Li from IoP, CAS found that photonic bandgaps in 3D and 2D photonic crystals could be improved by adopting anisotropic dielectric materials [6, 7]. In 2000 he set up a rigorous method to understand spontaneous emission and other quantum optical processes of atoms in photonic crystals by considering the vector field nature and inhomogeneous spatial distribution of Bloch mode photons [8–10]. The theory shows that the LDOD rather than the DOS of photons is the physical quantity that determines the light-atom quantum interaction, and this contrasts with the conventional wisdom that had been widely visualized in the community.

Another theoretical work from Zhi-Yuan Li is the discovery of highly fragile nature of photonic bandgap in inverse-opal 3D photonic crystals [11, 12]. It is well known that the 3D photonic crystal made from high refractive index materials such as Si, Ge, and TiO_2 have a complete bandgap between 8 and 9 bands, and self-assembly is a promising route to build these structures, thus, the approach has attracted notices of many prominent international groups, with many results published in Nature, Science, and other prominent journals. However, the numerical results made by Zhi-Yuan Li show that the complete bandgap is highly fragile to geometric disorders (fluctuation and randomness in lattice site and sphere radius), and will be easily closed even when the disorder strength is smaller than a small value as 2% of the lattice constant. The reason is that the bandgap is located at higher photonic bands and thus is highly sensitive to geometric disorders compared with usual low bandgaps. As this work clearly reminds people to impose strict control over the crystalline quality of inverse opal photonic crystal in order to have a sizeable bandgap, it has attracted broad attention in the chemical self-assembly research community.

Experimental studies continued in the Dao-Zhong Zhang's photonic crystal group. In the early days many experiments were performed in the microwave regime because it was easy to make periodic and quasiperiodic photonic crystal samples with the lattice constant on the order of centimeter. In 1999, the group presented the world first experimental demonstration of 2D quasiperiodic photonic crystal (QPC) [13–15]. The microwave 2D QPC are made from alumina cylinders, and the transmission spectra shows that the QPC has a complete band for S-wave (with the electric field parallel to the axis of cylinders). More importantly, when the microwave is incident from different directions, the position and width of the bandgap do not change at all. This is the first experimental observation of isotropic photonic bandgap in QPC. In 2005, the team designed and constructed a 2D photonic quasicrystal that exhibits negative refraction and superlensing properties [16]. This is the first demonstration of anomalous light wave propagation in a system other than periodic photonic crystals.

2.2 New physics exploitation

Besides the IoP photonic crystal group, more and more researchers at other institutions have been involved in photonic crystal studies and made extensive contributions in regard to the unique fundamental properties and their applications. A research group led by Prof. Jian Zi from Fudan University has made an outstanding contribution to better understanding the origin of color in some ordinary natural species of life system. In 2003 they reported their discovery of the mechanism of color production in peacock feathers [17]. They found that the cortex in differently colored barbules, which contains a 2D photonic-crystal structure, is responsible for coloration. Simulations revealed that the photonic-crystal structure possesses a partial photonic bandgap along the direction normal to the cortex surface, for frequencies within which light is strongly reflected. Coloration strategies in peacock feathers are very ingenious and simple: controlling the lattice constant and the number of periods in the photonic-crystal structure. Varying the lattice constant produces diversified colors. The reduction of the number of periods brings additional colors, causing mixed coloration. This study had opened up a new insightful aspect to look into the secret of nature in regard to some very usual phenomena, such as color in animals. In

2012, this group further found that amorphous diamond-structured photonic crystal exists in the feather barbs of the scarlet macaw and plays a key role in the color [18]. Before this work, noniridescent coloration by the spongy keratin in parrot feather barbs had fascinated scientists. Nonetheless, its ultimate origin remained as yet unanswered, and a quantitative structural and optical description was still lacking. The group made structural and optical characterizations and numerical simulations of the blue feather barbs of the scarlet macaw. They found that the sponge in the feather barbs is an amorphous diamond-structured photonic crystal with only short-range order. It possesses an isotropic photonic pseudogap that is ultimately responsible for the brilliant noniridescent coloration. They further unraveled an ingenious structural optimization for attaining maximum coloration apparently resulting from natural evolution. The results showed that upon increasing the material refractive index above the level provided by Nature, there is an interesting transition from a photonic pseudogap to a complete bandgap.

Recently, the group has developed an experimental technique that allows for direct observation of iso-frequency contour of surface modes in defective photonic crystals in real space [19]. This method is based on combination of coherent scattering of light by the periodic lattice of the structure and noncoherent scattering of light by the randomly dispersed defects. The band-structures can also be obtained from the observed iso-frequency contours. The obtained band structure is in overall agreement with the simulation results. This method provides an easy approach to observe and investigate the iso-frequency contour in real space. It enables us a fresh point of view to characterize the photonic structures and obtain their dispersion relationships. The group has extended the concept of photonic crystal to other wave phenomena. In 2004 they presented experimental observations and numerical simulations of superlensing effect in liquid surface waves [20]. Rigid cylinders were used to create a 2D periodic lattice, in which liquid surface waves propagate. Through the observation of a superlensing effect, the existence of negative refraction as well as complete bandgaps in surface waves was found.

A research group led by Prof. Xiang-Dong Zhang from Beijing Normal University has made extensive studies on the anomalous physical properties of light transport in photonic crystals [21]. In 2001, they showed that the 12-fold triangle-square tiling is very good for the realization of photonic gaps and found absolute gaps in systems with air holes in dielectric, dielectric cylinders in air, and metal cylinders in air. However, for the case of air-holes in a dielectric background, absolute gaps appear only when the dielectric contrast is sufficiently high, and both silicon nitride and glass have refractive indices below the threshold. This study is helpful for designing bandgaps in photonic quasicrystals [22]. In 2004 they presented design of 2D photonic crystals that exhibit all-angle absolute negative refraction for both polarizations of electromagnetic wave [23]. In addition, the focusing and image of unpolarized light can be realized by a microsuperlens consisting of the designed photonic crystals. Recently the group has used photonic crystals to model some important electronic systems to offer insightful studies on their unique physical properties. In 2008 they showed for the first time that the *Zitterbewegung* of photons, a strange quantum physical phenomenon that had been predicted since the early days of quantum mechanics, can appear near the Dirac point in a 2D photonic crystal. Compared with usual quantum particles like electrons, such a phenomenon for photons can be found in different scaling structures with wide frequency regions, which can be observed by measuring the time dependence of the transmission coefficient through photonic crystal slabs [24]. This theoretical prediction was soon confirmed experimentally in phononic crystals by their collaboration work with the group led by Zheng-You Liu from Wuhan University [25]. The group also studied Dirac-cone photonic surface states in 3D photonic crystal slab [26] and energy spectra for a photonic analog of multilayer grapheme made from metallic beads [27]. All these studies have borrowed fascinating concepts of quantum physics for electronic systems and extended them into photonic crystals. Therefore, they have broadened the aspects of photonic crystals.

The dispersion of light transport in photonic crystals can exhibit many anomalous properties. A group led by Prof. Songlin Zhuang from University of Shanghai for Science and Technology has recently reported observation of the inverse Doppler effect in negative-index materials at optical frequencies [28]. The Doppler effect is a fundamental frequency shift phenomenon that occurs whenever a wave source and an observer are moving with respect to one another. The counterintuitive inverse Doppler effect was theoretically predicted in 1968 by Veselago in negative-index materials. The group has built a photonic-crystal prism that has the properties of a negative index material and made the experimental observation of the inverse Doppler shift at an optical frequency (10.6 μm) by refracting a laser beam in the prism. Before this work, most investigations of the inverse Doppler effect had been limited to theoretical predictions and numerical simulations because of the tremendous challenges of frequency shift measurements inside such materials.

Recently, Prof. Xue-Hua Wang from Sun Yat-Sen University has presented an overview on their extensive theoretical study on the manipulation of spontaneous emission by photonic crystal or metallic micro-/nanostructures [29], and Prof. Min Qiu from Zhejiang University has presented an overview on their recent research on surface mode optical microcavities in photonic crystals [30].

2.3 Progress on fabrication technologies

After 25 years of extensive studies and hard working all around the world, a wide variety of unique and fascinating properties have been uncovered in photonic crystals. However, these properties are useful for practical applications only if the corresponding photonic crystals can be realized experimentally with high precision, low expense, and large areas or volumes. So far many experimental techniques have been explored and implemented in various research groups in China.

After the IoP, CAS Microfabrication Laboratory was launched and several nanofabrication facilities were set up in 2005, the IoP photonic crystal group led by Prof. Dao-Zhong Zhang began to fabricate silicon photonic crystals in the near infrared wavelengths that have technological relevance. Silicon has a large refraction index and low loss in infrared wavelengths, which makes it an important optical material that has been widely used for integrated photonics applications in the near infrared telecommunication regime around 1550 nm. The air-bridged 2D photonic crystal slab structures, which confine light by complete bandgaps within the slab and by total internal reflection off the slab, could be readily realized on silicon-on-insulator wafers by means of electron-beam lithography (EBL) and focused ion-beam (FIB) lithography together with wet and dry etching procedures. The nanofabrication accuracy of silicon photonic crystals is on the order of 10 nm [31]. The group realized the first infrared silicon photonic crystal samples in mainland China and the transmission spectrum measurement results showed that these samples have good bandgap properties [32]. The group, later on led by Prof. Zhi-Yuan Li, worked further to build various integrated optical elements on this excellent silicon photonic crystal slab platform [33, 34]. Heavy efforts of theoretical simulations and designs were made to closely collaborate with experimental studies within the same group. In 2008 the group designed and realized a novel type of waveguide in the triangular-lattice silicon photonic crystal and a corresponding 4-channel integrated optical filter [35, 36]. Later on, several anomalous transport properties of infrared light including negative refraction and self-collimation were experimentally demonstrated in silicon photonic crystals [37, 38].

Recently, the group further successfully realized high-Q photonic crystal cavities in silicon slab [39] by means of state-of-the-art nanofabrication techniques combining EBL and inductively coupled plasma (ICP) etching. Although Japanese groups have been pioneering and kept the world record in making highest-Q photonic crystal, the technique is still challenging for Chinese researchers. The value of Q-factor that is measured in experiment for the fabricated cavity is about 71 000, which is comparable to the theoretical value of 120 000 for an ideal cavity. The success is attributed to both hardware (reliable machines) and software (skillful man powers and technicians) of nanofabrication technologies. Another progress made in the group is the design and fabrication of a novel type of cavity, which is called cavity without confinement barriers, by combining two incommensurate photonic crystal superlattice waveguides in 2D photonic crystal slab [40]. A resonant mode with a high quality factor shows up in the pass band of waveguides. It has nearly no influence on the propagation of waveguide mode and can be directly coupled with the waveguide mode. The experimental measurement confirms the theoretical prediction of extraordinary coexistence of localized cavity mode and continuous waveguide mode with high coupling efficiency in the same frequency and space regime. Due to the extraordinary co-existence of localized cavity mode and continuous waveguide mode in both spatial and spectrum regions, the barrier-less cavity opens up a new avenue of cavity design and may find application in integrated optical devices for information processing and solid state lasers.

In addition to the nanofabrication facility platform that was first initiated in IoP, CAS, more and more similar facilities have been set up in other institutions. This allows many other research groups to build 2D infrared photonic crystal structures in seminconductor materials, including silicon and III-V semiconductors, and to explore potential applications in photonic integration and optoelectronic devices. In 2009, a research group led by Prof. Yi-Dong Huang from Tsinghua University fabricated a double-slots photonic crystal waveguides (PPCWGs) structure formed by introducing two slots into PCWGs with air-bridge structure on silicon-on-insulator substrate. Based on the theoretical and experimental mode characteristics of double-slots PCWGs, they found the existence of ministop band and then measured its temperature dependence. The device has potential application as temperature sensors [41]. In the same year, the group proposed a novel scheme, namely, coupling between even- and odd-like modes in a single asymmetric photonic crystal waveguide, to broaden the control of light in photonic crystal [42]. In 2012 the group further studied optical switch based on an ultra-compact double-slot photonic crystal waveguide with a titanium/aluminum microheater based on shifting a transmission-dip caused by the defect mode coupling in photonic bandgap. Based on the unique mode coupling in photonic bandgap, low switching power of 9.2 mW and high extinction ratio of 17 dB were achieved experimentally while the length of waveguide is only 16 μm [43].

A research group led by Prof. Xingsheng Xu from Institute of Semiconductor, CAS studied two-photon excited fluorescence from CdSe quantum dots located on the surface of fabricated 2D SiN photonic crystal and found a 90-fold enhancement in the two-photon excited fluorescence in the vertical direction [44]. In a later work, they further showed that the spectrum of two-photon excited fluorescence from CdSe quantum dots on SiN photonic crystal blue shifts compared to that from quantum dots on SiN without photonic crystals [45]. Another group coming from the same institute and led by Prof. Wan-Hua Zheng has made extensive efforts in making active photonic crystal optoelectronic devices in III-V semiconductor materials. In 2008 they demonstrated butt joint line-defect-waveguide microlasers on photonic crystal slabs, which were built on metal-organic chemical vapor deposition-grown InGaAsP/InP wafer including seven 9 nm thick quantum wells via electron-beam lithography [46]. It was found that the output power from the waveguide edge was remarkably enhanced to 214 times higher by introducing chirped structure in the output waveguide. The lasing mode operated in the linear dispersion region of the output waveguide so that the absorption loss due to the band-edge effect was reduced. A practical high power efficiency of 20% was obtained in this microlaser. In a later work [47], they demonstrated reduced divergence angle of the photonic crystal vertical-cavity surface-emitting laser. The measured divergence angles of the fabricated microlaser were between a very small value of 5.1° and 5.5° over the entire drive current range, consistent with the numerical results. All these works showed the potential power of photonic crystals in enhancing the performance of traditional optoelectronic devices.

Although the usual nanofabrication technologies including EBL and FIB have very high precision in fabrication of semiconductor photonic crystals, they have disadvantages of relatively high expense, slow fabrication speed, and small fabrication area. Several other optical approaches have been adopted as supplemental solution schemes to fabricating photonic crystals in the infrared and visible bands. One of such methods is the so-called holographic lithography [48], which basically works on the well-established multiple optical beam interference technique. Xia Wang, now a professor at Qingdao University of Science and Technology, together with her collaborators in Hong Kong University of Science & Technology, has made an extensive contribution in implementing and advancing this technology. Usually four beams can be combined to generate arbitrary 2D and 3D periodic photonic crystals. In 2003 the team presented fabrication of 3D photonic crystals by a four-beam holographic lithography method using visible photoinduced polymerization. High-quality face-centered-cubic (fcc) single crystals with a large range of polymeric matrix volume fraction were fabricated using optimal conditions that were obtained from computer simulations [49].

In 2004 the team demonstrated fabrication of large-area polymer mesoscale 2D Penrose quasi-crystals by using five-beam interference [50]. The method has a great unique advantage of versatility. By changing the number of optical beams, other rotational symmetries and 3D structures other than 2D pentagonal Penrose symmetry can be obtained. Furthermore, by varying beams intensities and polarizations a variety of structures with continuously varying volume ratios and shapes can be fabricated. Later on the team made continuous progress in advancing this technique to fabricate more complicated photonic structures. In 2006 they fabricated 3D *periodic* quasicrystals exhibiting quasiperiodicity of the Penrose structure in the x-y plane and periodic along the z axis using ten-beam visible light holographic lithography [51]. The quasicrystals show photonic bandgaps in the visible range. In 2007 they reported the fabrication and optical characterization of icosahedral quasicrystals in the visible range. The icosahedral pattern was generated using a novel 7-beam optical interference holography and recorded on photoresists and holographic plates [52].

Another method is the so-called two-photon polymerization technique [53]. It relies on the focused laser spot (with sufficiently high energy power) interacting with polymer materials (such as resins) with a large two-photon absorption and polymerization cross section. As only the focus spot can react with the polymer, the fabrication precision is half of the Rayleigh diffraction limit of the focusing microscopic objective, which can be below 100 nm for ultraviolet beam illumination. A research group led by Prof. Xuan-Ming Duan from the Technical Institute of Physics and Chemistry, CAS has made great efforts in applying and advancing this technique. The method is a direct-writing approach with a nature of serial processing, and thus is subject to a shortcoming of slow fabrication speed. In 2007, the group proposed a customizable multiple beam multiphoton polymerization micronanofabrication method for parallel processing of assembled structures [54]. The configuration and geometry of multiple beams were designed by changing the parameters of lenses set as well as aperture masks. Various assembled 2D and 3D microstructures including microgears and photonic crystals were demonstrated under nanometer scale resolution and high fabrication efficiency. The micronanofabrication method is a combination of serial direct-writing processing by single focusing beam and parallel processing by multiple focusing beams, and can be expected to play an important role in the fabrication of micromachines and microdevices. Later on, the group employed the technique to fabricate a 3D photonic crystal structure consisting of gradient quasidiamond lattices [55]. The results indicate that a 3D photonic crystal with gradient lattices could effectively expand the width of the photonic bandgap and may be beneficial for developing complete-bandgap photonic crystals with low refractive index materials for applications in polymer based optoelectronic devices and integrated systems. Recently, the group led by Prof. Da-He Liu from Beijing Normal University has employed the holographic method to fabricate photonic crystals with low refractive index materials, which was applied to the design of microlasers [56].

2.4 Nonlinear photonic crystals

Besides silicon photonic crystals, the IoP photonic crystal group has made extensive efforts to explore new physics of light manipulation in other special photonic crystals. Nonlinear photonic crystals (NPCs) have periodic modulation on second-order nonlinear susceptibility, which can be realized by domain inversion in ferroelectric crystals such as $LiNbO_3$. NPCs can facilitate high-efficiency nonlinear optical effects, such as second-harmonic generation (SHG) through the mechanism of quasi-phase matching (QPM). In usual periodic NPC structure, the reciprocal lattice vectors are discrete to satisfy the QPM for a limited number of nonlinear optical processes. Zhang and coworkers proposed the usage of quasi-periodic or amorphous NPC structures to satisfy simultaneously tunable multiple-wavelength SHG as they can offer quasi-continuous reciprocal vectors [57–59]. In experiment the SHG spectrum from the NPC samples almost covers the whole visible band with quite high efficiency, which is insensitive to sample temperature and incident angle, as well as to the area fraction of the inverted domain. Later on the group showed theoretically that combination of ordinary photonic bandgap properties, such as the slow light effect and the defect state resonance effect, can greatly enhance the efficiency by several orders of magnitude [60–63]. More recently, a new mechanism called super-QPM in a super-lattice of nonlinear photonic crystals was proposed to enhance nonlinear frequency conversion efficiency, which was confirmed by experiments [64].

Nonlinear photonic crystals made from materials of high Kerr nonlinearity offer a promising way to build ultrafast and low-power optical switching devices. When photonic crystals are built from materials with Kerr effect, the bandgap or defect state frequency can be controlled effectively by external pump light, leading to optical switching effect [65–67]. When this pump light is high-intensity ultrafast laser pulse with a duration of several femtoseconds and the Kerr material has an ultrafast optical response time down to several femtoseconds, 10 fs ultrafast optical switching can be realized in these Kerr nonlinear photonic crystals, according to a recent experimental report made by the IoP photonic crystal group [68]. Recently the group presented a versatile technique based on nano-imprint lithography to fabricate high-quality silicon-polystyrene compound nonlinear photonic crystal slabs [69, 70]. The approach allows one to infiltrate uniformly polystyrene materials that possess large Kerr nonlinearity and ultrafast nonlinear response into the cylindrical air holes with diameter of hundred nanometers that are perforated in silicon membranes. It is expected that the hybrid photonic crystal structures can incorporate both advantages of ultrafast and low power nonlinear optical effects. The fabricated compound NPC samples have uniform and dense polymer infiltration and are of high quality in optical properties, including sharp transmission band edges and nondegraded high quality factor of microcavities compared with those in the bare silicon photonic crystal. The versatile method can be expanded to make general semiconductor-polymer hybrid optical nanostructures, and thus it may pave the way for reliable and efficient fabrication of ultrafast and ultralow power all-optical tunable integrated photonic devices and circuits.

In most nonlinear photonic crystal switching devices, a high pump intensity is usually required because the nonlinear optical coefficient of conventional materials is relatively small. To make these devices be of practical means, the pump power must be lowered down, while still keeping the ultrasmall size scale. A research group from Peking University led by Profs. Xiao-Yong Hu and Qi-Huang Gong has made outstanding contributions to this important while difficult problem. In 2008 they demonstrated picosecond and low-power all-optical switching based on an organic photonic bandgap microcavity [71]. The key is to implement strong optical nonlinearity enhancement due to excited-state inter-electron transfer. Compared with the case without nonlinearity enhancement, the switching operation power is reduced by four orders of magnitude while the ultrafast response time, of the order of a picosecond, is maintained. This provides a strategy for constructing photonic materials with large nonlinearity and studying ultrafast low-power integrated photonic devices.

Later on, the group reported a novel nanoscale integrated all-optical diode, which was realized by combining the strong plasmonic responses of gold nanoparticles with the all-optical tunable properties of polymeric photonic crystal microcavities. Non-reciprocal transmission properties were achieved based on the effect of surface-plasmon resonance enhancing the optical nonlinearity and dynamic coupling of asymmetrical microcavity modes. An ultralow-threshold photon intensity of 2.1 MW cm^{-2} and an ultrahigh transmission contrast over 10^4 were realized simultaneously. Compared with previously reported all-optical diodes, the operating power was reduced by five orders of magnitude, while the transmission contrast was enlarged by three orders of magnitude [72]. They further reported experimental realization of a novel all-optical tunable nanometer-scale photonic metamaterial made of gold and lithium niobate. A positive-to-negative switching of the effective dielectric constant was achieved under excitation of a weak pump laser of 9 MW·cm^{-2}. The ultrafast response time of 24.2 ps was achieved. An ultrafast and low-power all-optical switching with a high switching efficiency of 80% was also realized. This scheme may offer an approach for the study of ultrafast and low-power integrated photonic devices [73].

2.5 One-way transport of light

A research group led by Prof. Yan-Feng Chen from Nanjing University has made extensive efforts to explore unidirectional transport of light and electromagnetic waves in specially designed photonic crystals and related optical structures. They proposed a kind of electromagnetic diode based on a 2D nonreciprocal gyrotropic photonic crystal that has separately broken symmetries in both parity and time reversal but obeys parity-time symmetry. The diode could support bulk one-way propagating modes either for group velocity or phase velocity with various types of negative and positive refraction [74]. Optical communications and computing require on-chip nonreciprocal light propagation to isolate and stabilize different chip-scale optical components. To address this fundamental issue, they have made collaboration with researchers from Caltech and UC San Diego, and designed and fabricated a metallic-silicon waveguide system in which the optical potential is modulated along the length of the waveguide such that unidirectional light propagation is obtained on a silicon photonic chip, with an aim to address the above fundamental issue [75]. Unidirectional light transport and one-way photonic mode conversion were demonstrated at the wavelength of 1.55 μm in both simulations and experiments. Although the elegantly designed complicated system is compatible with conventional complementary metal-oxide-semiconductor (CMOS) processing, it was later on realized that this structure does not have truly nonreciprocal transport of light because of the linear, passive, and time-independent nature of the silicon-metal composite waveguide structure, and it could not provide an efficient way to chip-scale optical isolators for optical communications and computing [76, 77].

The Zhi-Yuan Li group has also made considerable efforts in exploring the unique properties of magneto-optical photonic crystal (MOPC) or gyromagnetic photonic crystal (GPC). The group has built specially designed NdFeB permanent magnets that allow for generation of a uniform dc magnetic field with a relative large area of 30 cm × 30 cm. In addition, by adjusting the distance between the two magnets, the magnitude of the magnetic field can be continually tuned from 1400 to 3300 Gauss [78]. With this setup, they were able to explore a wide variety of one-way transport properties of microwave in gyromagnetic photonic crystals. They built a 2D square-lattice gyromagnetic photonic crystal from MO material of yttrium-iron-garnet (YIG) and demonstrated its tunable electromagnetic properties [78]. They further experimentally studied robust one-way modes in gyromagnetic photonic crystal waveguides with different interfaces [79]. The microwave one-way waveguides were formed between a YIG gyromagnetic photonic crystal and a dielectric Al_2O_3 photonic crystal based on the nonreciprocal property of the gyromagnetic photonic crystal. It was found that when the waveguide width changes, the forward propagating waves display a relative small change because of the immunity of the edge modes to the external influence. However, the backward-propagating waves are very sensitive to the width of the waveguide. Furthermore, the forward modes are very robust against intrusion of a metal plate while the backward modes are strongly influenced and easily blocked by the intruded metal plate.

One-way edge states realized in MOPCs are generally believed to be robust to scattering from disorders and even strong perturbations. The Li group has experimentally and theoretically studied the influence of obstacles on the transport of forward and backward edge states in 2D MOPCs under a dc magnetic field. They have found that the passage of electromagnetic wave around the obstacles mainly takes advantage of the formation of new edge states at the new interfaces formed between the obstacle and bulk MOPC. The forward edge states can be blocked when the new edge state channel is cut off or the coupling with the original edge states to the new edge states is strongly reduced [80]. They have studied the side coupling between guided modes and cavity modes in a one-way waveguide that is composed of a regular photonic crystal and a gyromagnetic photonic crystal. At the cavity resonant wavelength, the backward mode can be completely blocked while the forward mode is only slightly influenced in the transmissivity for a specially designed waveguide. This unique light transport property can be exploited to construct a unidirectional band stop filter and a unidirectional channel-drop filter that can selectively process a light signal propagating only along a particular direction [81]. They have further studied the influence of the one-way transport properties against structural disorders in MOPC [82]. The results show that the one-way transport band is magnetically tunable and robust against back scattering induced by external disturbance. More importantly, the unidirectional transport in the one-way waveguide that works within the magnetic resonance-induced band gap is immune to lattice disorders by a much greater extent than the conventional one-way waveguide that works within the Bragg scattering–induced bandgap. The experimental observation has been confirmed by numerical simulations, which show that the robust one-way transport property originates from the localized magnetic surface plasmon resonance.

To facilitate practical applications of one-way devices, it is important to design and realize these devices in the platform of silicon photonics, which is compatible with the CMOS processing technologies in semiconductor industry. The Li group has made major progresses in this aspect by building all-linear and passive silicon optical diode and isolator [83, 84]. Optical isolation is a long pursued object with fundamental difficulty in integrated photonics. Although widely used in lasers and optical communications, such devices are still lacking in semiconductor integrated photonic systems because of challenges in both materials integration and device design. Conventionally, an efficient routine to create optical isolation is via time-reversal symmetry breaking. However, the traditional schemes in this category, including magneto-optical isolators, nonlinear optical structures, and time-dependent optical structures, have disadvantages such as large loss of isolation signal, a relatively large size, and slow response. In addition, these schemes are incompatible with conventional CMOS processing. The need to overcome these difficulties is becoming increasingly urgent with the emergence of silicon nanophotonics.

The Li group reported the first demonstration of on-chip linear and passive silicon optical diode and isolator [83, 84]. The diode is made from a photonic crystal heterojunction with directional bandgap mismatch and spatial inversion symmetry breaking. It has an ultrasmall size scale of only about 6 μm × 6 μm, which is the world-record smallest all-optical diode so far. The experimental transmission spectra show an average of 21.3% of the forward peak transmissivity and 0.885 of the signal contrast at 1550 nm, which has reached the level of conventional electronic diodes (interestingly, they are made from semiconductor pn junctions). The performance could be improved by high nanofabrication precision. Further experimental studies show that the silicon photonic crystal heterojunction diode also exhibits promising performance of optical isolation [84], with a round-trip transmissivity two orders of magnitude smaller than the forward transmissivity for in-plane infrared light across the structure. The scattering matrix analysis indicates that the unidirectional transport of in-plane signal light can be attributed to the information dissipation and selective modal conversion in the multiple-channel spatial-inversion symmetry breaking structure and has no conflict with the reciprocal principle for a time-reversal symmetric structure. The achievement of the linear, passive, and ultracompact on-chip silicon optical diode and isolator would open up a road toward photonic logics and optical computing in silicon integrated optical devices and circuits.

3 Plasmonics

Plasmonics, a very active interdisciplinary research area covering physics, chemistry, biologic and medical sciences, information and energy sciences, materials and nanotechnology, has attracted intensive and extensive interests since Ebbesen and coworkers found anomalous light transmission (EOT) through periodic array of air holes perforated in metal thin films [85, 86]. When light interacts with metal nanoparticles and nanostructures, it will excite periodic oscillations of free electron gas on their surface relative to the positive ion background, and the motion of electron gas is called surface plasmon polaritons (SPPs). SPPs have a wide variety of unique physical properties [87]. First, they are localized electromagnetic modes that allow for strong confinement of light energy within a space of size far below the Rayleigh diffraction limit. This makes it possible to build nanoscale optical integrated devices that might be further compatible and integrated with microelectronic devices. Second, the oscillation of electron gas within a tightly confined space of SPPs greatly enhances the intensity of local electromagnetic field since electric charges are an important origin of electromagnetic fields, and therefore also enhances the light-matter interaction within SPPs. This feature can find important application in high-sensitivity fluorescence and Raman spectroscopy [so-called surface enhanced Raman scattering (SERS)], nonlinear optical processes such as second-harmonic generation and high-order harmonic generation, optical catalysis, and solar cells. Third, the strong localization of light energy within a tiny space and strong light-matter interaction makes the feature of SPPs, such as their dispersion and spectrum, very sensitive to the physical and chemical properties of the environment of SPPs. This can find important applications in high-sensitivity biochemical sensors and surface-plasmon resonance (SPR) detectors, for potential use as biomedical diagnosis and therapy agents.

3.1 Plasmonic nanostructures in metal thin films

Plasmonic structures can either be nanostructures built on metallic thin films, for instance, air holes and slits, shallow grooves, or other more complicated geometric patterns, which can be conveniently prepared by nanofabrication techniques such as FIB, or be metal nanoparticles of different shapes, sizes, composites, or topologies, which are usually prepared by chemical reaction synthesis approach. The former can support extended wave transport of SPPs, while the latter can support localized surface plasmon modes that exhibit various SPR properties when light is incident.

Plasmonics in metal nanostructures has raised extensive and intensive interest in the past 15 years. Periodic arrays of air holes perforated in metal thin films can strongly modulate the transport and scattering of SPPs and lead to many unique properties such as EOT of light. The IoP Zhi-Yuan Li group extended the concept of quasiperiodic photonic crystal to plasmonics, and built a series of plasmonic samples made from periodic, quasiperiodic, and aperiodic arrays of subwavelength circular air holes perforated in gold thin films. By measuring and comparing the optical transmission spectra of these samples, they found that the long-range order and short-range order could act collectively to shape and modulate the excitation, transport, and scattering of surface plasmonic waves and influence their optical spectral properties [88–90]. These works had opened up a new frontier of plasmonics, and several international groups carried out similar studies, which further confirm the findings that the long-range order in plasmonic quaisperiodic structures could play an important role in EOT properties [91–94].

The group investigated the influence on the SPP properties from various geometric patterns of perforated nanostructrues, such as circular holes, rectangular holes, and trapezoidal holes, and comparison was made [95]. Light transmission through more complicated nanostructures such as H-shape fractal and cross-shape fractal patterns was explored, and a self-similarity feature in the transmission spectra was found [96, 97]. In collaboration with this group, the group led by Prof. Xiang-Gang Qiu from IoP, CAS built metal films grown on an Si wafer perforated with a periodic array of subwavelength holes and observed anomalous enhanced transmission in the midinfrared regime [98]. High order transmission peaks up to Si $(2, 2)$ were clearly revealed due to the large dielectric constant contrast of the dielectrics at the opposite interfaces. The Si $(1, 1)$ peak splits at oblique incidence both in TE and TM polarization, which confirms that anomalous enhanced transmission is an SPP assisted diffraction phenomenon. The theoretical transmission spectra agree excellently with the experimental results and confirm the role of SPP diffraction by the lattice. Later, the Zhi-Yuan Li group theoretically and experimentally investigated collimation of light passing through nanoslits with periodic grooves perforated in a gold film, and different situations of geometric parameters and incident light properties were considered [99, 100]. Recently, they have investigated light transport in metal slits filled with a 1D periodic stack of low- and high-index dielectric media [101]. An exact independent-mode model where each transverse eigenmode is subject to its own Bragg scattering and dispersion modulation has been derived to gain insight into the physical problems.

More recently, the group demonstrated experimentally wavefront shaping of infrared light through a subwavelength hole [102]. Light passing through a subwavelength hole in an opaque plate is a fundamental concern in both optical science and applications. Using both simulations and experiments, the group shows that, when a subwavelength hole in a silver thin film is surrounded by well-designed patterns of grooves, the wavefront of the infrared light through it can be shaped into a preset complicated pattern such as a Latin letter “L” or “O” at a given position instead of being diffracted in all directions. The design is created via the surface-wave-holography method, which allows direct determination of the surface plasmonic structure for a given wavefront-engineering functionality without the need to solve complex inverse problems [103]. The results will deepen the current understanding of this enduring issue and will find applications in many fields such as wave manipulation and sensing. The method has borrowed some concepts from conventional holography and incorporated them into plasmonics. However, the new methodology is very different in the center core in that the holographic pattern is determined by interference between extended object wave (the preset image such as the Latin letters) and localized reference surface plasmonic wave, while the conventional holographic pattern is determined by interference between extended object wave and extended reference wave.

A great obstacle for practical usage of plamonic devices lies in the big loss problem that is related with metal dissipation when plasmonic structures interact with light. As a result, SPPs will be rapidly attenuated when they transport in plasmonic nanostructures. An efficient way to overcome this difficulty and pertain the desirable functionality performance of plasmonic devices is to introduce gain media into the structures in a hope to compensate the loss by gain media. Recently, the Li group has made some progresses in this rapidly advancing area. They reported on direct observation of amplified spontaneous emission (ASE) of SPPs at the interface of a silver film and a gain medium [104]. Based on a typical Kretschmann configuration incorporated with Rhodamine 6G molecules, the growing ASE spectra of SPPs were clearly identified by carefully conducting a pump-dependent angle-resolved spectral measurement. Spectral narrowing effects induced by the SPP amplification were also demonstrated. Both the methods and results provide an important understanding in accurate description and efficient exploit of the interactions between metallic structures and gain media. Such knowledge is useful for studies on plasmonic structure designing, loss compensation, plasmonic sensing, and nanosource applications. In the consequent work [105], by further carrying out the measurements, they reported that with the increase of gain, the ASE of SPPs undergoes an unusual angular response, i.e., the amplified SPP is decoupled to emit in a broadened angular range with increased pump intensity. The theoretical studies have indicated that this unusual angular response can be attributed to the growing net gain in the structure when the pump intensity is increased. The observed phenomena and theoretical studies could be helpful in understanding the interaction between gain media and plasmonic systems, and thus could be useful for plasmonic device designing. For example, the sensitivity of SPR sensor on external perturbations is hindered by the full-width at half-maximum of the reflection dip. The studies can help to explore and design plasmonic systems for efficiently compressing the angular response of the plasmonic system in order to get the optimal performance.

In another work, the group studied the loss compensation and light amplification properties of metal-insulator-metal (MIM) waveguides that are doped with gain material in the dielectric core [106]. An analytical approach based on Maxwell's equations is developed to evaluate quantitatively the influence of the gain coefficient on the loss compensation and light amplification efficiencies of the waveguide under different values of the waveguide width and working wavelengths. The results show that the light amplification efficiency obeys a strict linear relationship with the gain coefficient, and MIM waveguides with narrower widths and under shorter wavelengths have better efficiency. In addition, the MIM waveguides have higher light amplification efficiency than usual dielectric waveguides, which suggests a very positive role of the plasmonic structure in enhancing the light amplification when gain is introduced. These loss and gain behaviors can be well explained by looking at the modal profile of each transport mode and the corresponding light energy confinement effect and slow light effect.

As plasmonic modes can offer a powerful way to confine light wave within a very tine size scale, they have been extensively explored to construct ultrasmall optical devices. The Yi-Dong Huang group from Tsinghua University has made an extensive study on application of long-range surface-plasmon-polariton (LRSPP) waveguide. In 2009 they showed that the coupling strength between the LRSPP mode and the dielectric-waveguide mode is rather sensitive to the refractive index of the detecting layer [107]. This is promising in realizing an integrated refractive index senor with high resolution or a modulator with rather low driving power and insert loss. In another work, they showed extremely high efficient coupling (99%) between LRSPP mode of Au waveguide and TM mode of SiN dielectric waveguide that comprises a hybrid coupler [108]. Based on this hybrid coupler, a polarization splitter with pure TM mode output from one arm and TE mode output from the other arm with high TE/TM extinction ratio can be realized. The group also explored the excitation of short range surface plasmon polariton (SRSPP) mode, which has an antisymmetric field profile on the two sides of a thin metal film [109], and employed the unique coupling properties of this plasmonic mode with a usual dielectric waveguide mode for application in refractive index sensor [110]. This sensor was found to have significantly high effective sensitivity for detecting a hundred-nanometer-thick layer owing to the highly bounded field of the SRSPP mode.

The transport of plasmonic wave can be modulated in a desirable way by a careful design of nanostructures perforated in metal films. Tao Li and his coworkers from Nanjing University recently demonstrated broad band (bandwidth ∼100 nm) focusing and demultiplexing (resolution ∼12 nm) of in-plane propagating surface plasmons [111] by means of a well-designed nanoarray on metal surface. This device was designed based on a novel phase modulation method for in-plane diffraction processes. Moreover, sublattice arrays were developed to achieve an improved demultiplexer and confocal SPP beams. In another work they reported an experimental realization of a plasmonic Airy beam generated thoroughly on a silver surface [112]. With a carefully designed nanoarray structure, such Airy beams come into being from an in-plane propagating SPP wave, exhibiting nonspreading, self-bending, and self-healing properties. Besides, a new phase-tuning method based on non-perfectly matched diffraction processes was proposed to generate and modulate the beam almost at will. This unique plasmonic Airy beam as well as the generation method would significantly promote the evolutions in in-plane SPP manipulations and indicate potential applications in laboratory-on-chip photonic integrations.

The group theoretically studied nonlinear interactions between the SPP mode and conventional waveguide mode in nonlinear hybrid waveguide and proposed a possible method to enhance SPP wave via optical parametric amplification (OPA) [113]. The phase matching condition of this OPA process is fulfilled by carefully tailoring the dispersions of SPP and guided mode. The influences of incident intensity and phase of guided wave on the OPA process were comprehensively analyzed. It was found that not only a strong enhancement of SPP but also modulations on this enhancement can be achieved. This result might find potential applications in nonlinear optical integration and modulations.

More recently, the group has made an effort to integrate plasmonic structures with optoelectronic devices. They experimentally demonstrated an electrically excited surface plasmon source, which was fulfilled in a silver coated light emitting diode (LED) with well designed gratings [114]. With a DC current supply, SPP waves were generated directly from the illuminations of the LED via the grating coupler. By adjusting the grating to a tilted one, a unidirectional SPP beam was successfully attained with a high extinction ratio and an improved launching efficiency. This electrically generated unidirectional SPP has a considerable long propagation distance (∼14 μm), allowing for further manipulations in plasmonic integrations and sensors.

A group led by Prof. Guo-Ping Wang from Wuhan University has made an extensive effort to design plasmonic nanostructures for integrated optical devices. In 2004 they explored the different propagation characteristics of SPPs excited on different metallic surfaces and the tendency of SPPs to the region in which SPPs possess lower phase velocity [115]. Based on these features they designed a kind of metal heterowaveguide for nanometric focusing of light. Finite-difference time-domain simulations demonstrate that, by converting light into SPPs, such heterowaveguides constructed with both Ag and Al can focus incident light into about a 20 nm × 30 nm domain with higher than 15% coupling efficiency for a light wavelength of about 540 nm. In 2005 they investigated metal heterostructures on flat metallic surfaces to realize SPP Bragg reflectors and nanocavities [116]. A metal heterowaveguide structured by alternately stacking two kinds of metal gap waveguides (MGWs) shows periodically effective refraction index modulation to SPPs and produces plasmonic bandgap, in which SPP propagation is forbidden. By changing the width of one MGW in the heterowaveguide, an SPP nanocavity with high quality factor can be created. In 2006 the group proposed a simple metal waveguide array for realizing all-angle wide frequency bandwidth negative refraction from the visible to infrared frequencies [117]. Theoretical analysis from the rigorous coupled-wave theory reveals that the negative coupling constant resulting from the anomalous coupling of guided SPP modes contributes to the negative refraction. The result provides an alternative way to construct robust all-angle negative refractive materials operating in a wide range of frequency from the near-infrared to the visible range.

The group also made an effort to explore new technologies to build metal nanostructures with low cost, wide area, and high speed. In 2006 they experimentally demonstrated a far-field holography for the realization of Ag nanoparticles-embedded periodic and quasiperiodic microstructures with feature sizes beyond the diffraction limit [118]. Periodic cylindrical nanoshell arrays with about 240 nm hole diameter and 12-fold symmetry quasiperiodic structures with 220 nm feature sizes were achieved, respectively, by using a 632.8 nm laser beam. The results imply that conventional far-field optical technology is capable of fabricating nanostructures in modern micromanufacture.

Metal nanostructures exhibit a wide variety of unique plasmonic properties, and can be explored for optical devices in many areas. A group led by Prof. Xin-Ping Zhang from Beijing University of Technology has made a considerable contribution in exploring novel technology in constructing plamsonic devices and investigating their optoelectronic properties. In 2008 they demonstrated tunable ultrafast optical switching via waveguided gold nanowires by investigating the transient optical response of waveguided gold nanowires using femtosecond pump-probe spectroscopy [119]. It was found that the transient absorption kinetics shows an optical-switching effect as fast as 200 fs in the coupled spectrum, based mainly on the broadening and red-shift of the resonance spectrum of the plasmon polaritons, induced by electron–electron scattering and due to the strong optical excitation. This effect is enhanced and spectrally narrowed through coupling with the narrowband waveguide mode. Angle-resolved tunability of the waveguide mode enables high flexibility for related applications in different spectral ranges. This work also revealed the high sensitivity of photonic device in response to slight disturbances of the particle plasmon resonance, which is a very important characteristic for potential applications in sensors.

In another work they demonstrated band-selective optical polarizer based on gold-nanowire plasmonic diffraction gratings [120]. The simple plasmonic diffraction grating device consists of periodically distributed gold nanowires on top of a transparent glass substrate and operates based on the strong polarization dependence of the particle plasmon resonance of the gold nanowires. A high-efficiency secondary diffraction in the same device enhances the polarization extinction ratio significantly. In experiment, linearly polarized spectrum in the red with a bandwidth of 53 nm is selectively picked up from the nonpolarized white light, where a polarization extinction ratio higher than 100 at about 650 nm has been achieved. The scheme of plasmonic diffraction grating can bring insightful idea for exploiting new detection and sensor techniques.

In 2011 the group realized random laser based on waveguided plasmonic gain channels [121]. In their experiment, a waveguide-plasmonic scheme was constructed by coating the matrix of randomly distributed gold nanoisland structures with a layer of dye-doped polymer, which provides strong feedback or gain channels for the emission from the dye molecules and enables successful running of a random laser. Excellent overlap of the plasmonic resonance of the gold nanoislands with the photoluminescence spectrum of the dye molecules and the strong confinement mechanism provided by the active waveguide layer are the essentials for the narrowband and low-threshold operation of this random laser. This kind of feedback configuration potentially enables directional output from such random lasers. The flexible solution-processable fabrication of the plasmonic gold nanostructures not only enables easy realization of such a random laser but also provides mechanisms for the tuning and multicolor operation of the laser emission.

The group further demonstrated a biosensor based on metallic photonic crystals for the detection of specific bioreactions [122]. The device is composed of a periodic array of metal nanoparticles sitting on the top of indium tin oxide (ITO) glass waveguide. The enhancement of the sensitivity or the amplification of the sensor signal by the coupling between the waveguide resonance mode and particle plasmon resonance breaks through the "bottle-neck" of the intrinsic response sensitivity defined by the spectral shift of the particle plasmon resonance. The optical sensor was used to sense the specific reaction between the HIV-1 capsid protein (p24) antigen and the monoclonal anti-p24 antibody, where the dynamics of the bioreactions could be recorded with a potentially high time resolution. This novel scheme of optical sensor has advantages of compact design, new physics, simple operation, simple fabrication, and low cost.

In 2011 the group demonstrated direct writing of distributed feedback (DFB) polymer lasers using an UV laser interference ablation technique [123]. The single-step technique, consisting of single-shot exposure of the polymer film to a single laser pulse, enables mass fabrication of 1D DFB gratings of polymer semiconductors for the realization of laser devices. Furthermore, through multiexposure processes, a variety of 2D photonic crystal patterns can be realized with high reproducibility. Thus, interference ablation introduces a low-cost, high-quality, and large-area fabrication technique for polymer lasers based on DFB mechanisms and for active photonic devices.

3.2 Surface plasmon resonance in metal nanoparticles

Metal nanoparticles have a deep-subwavelength size that is much smaller than the wavelength of incident light. They can support localized surface plasmon modes and will exhibit unique SPR properties when they interact with incident light or other external excitations such as fast electron beams. These localized plasmonic modes strongly depend on the size, shape, composite, topology of the particles as well as the physical and chemical properties of the environment where the particles are embedded. The SPR properties are also strongly dependent on the feature of the incident light, such as its polarization and propagation direction relative to the orientation of metal nanoparticles. When SPR occurs, the interaction of light with electron gas connected with plasmonic modes is significantly enhanced, leading to great enhancement of local electric field intensity and sensitivity of plasmonic mode response to environment.

The direct consequence of local field enhancement is that when molecules located on metal nanoparticles are excited by incident light, their fluorescence and Raman signals can be significantly enhanced, with a fundamental goal to achieve single-molecule detection via these finger-print signals. Yet, there are many other consequences that originate from enhanced local field intensity at SPR. For instance, the classical scattering and absorption of light by metal nanoparticles can be greatly enhanced, leading to very large scattering and absorption cross sections [124]. These classical properties can find potential applications in biomedical sciences. In this aspect, the Zhi-Yuan Li group in IoP, CAS has made an extensive collaboration with Prof. Younan Xia group in University of Washington, USA [125–127].

The collaboration group can synthesize gold nanocages of <40 nm in dimension using the galvanic replacement reaction between Ag nanocubes and $HAuCl_4$ in an aqueous solution. By controlling the molar ratio between Ag and $HAuCl_4$, the gold nanocages could be tuned to display SPR peaks around 800 nm, a wavelength commonly used in optical coherence tomography (OCT) imaging. OCT measurements on phantom samples indicate that these gold nanocages have a moderate scattering cross section but a very large absorption cross section, which is five orders of magnitude larger than the conventional dye Indocyanine Green (ICG) molecules. As a result of this important feature, the nanocage particles can find potential use as a new class of contrast agents for optical imaging. Besides, when bioconjugated with antibodies, the gold nanocages can be used for specific targeting of breast cancer cells. In 2007 the collaboration group further presented an experimental result of using immuno gold nanocages with tailored optical properties for targeted photothermal destruction of cancer cells [128]. By tuning the size of gold nanocages, the SPR properties can be tailored so that they can achieve strong absorption in the near-infrared (NIR) region, which is useful for photothermal cancer treatment. Numerical calculations show that the nanocage has a large absorption cross section, facilitating conversion of NIR irradiation into heat. In the experiment, the gold nanocages were conjugated with monoclonal antibodies (anti-HER2) to target epidermal growth factor receptors (EGFR) that are overexpressed on the surface of breast cancer cells (SK-BR-3). The preliminary photothermal results show that the nanocages strongly absorb light in the NIR region with an intensity threshold of 1.5 W/cm^2 to induce thermal destruction to the cancer cells. In the intensity range of 1.5–4.7 W/cm^2, the circular area of damaged cells increased linearly with the irradiation power density. These results suggest that this new class of bioconjugated gold nanostructures, immuno gold nanocages, can potentially serve as an effective photothermal therapeutic agent for cancer treatment.

In a related work, the collaboration group, together with the group led by Lihong Wang in Washington University in St. Louis, has extended the application of immuno gold nanocages in biomedical sciences and demonstrated photoacoustic tomography (PAT) of a rat cerebral cortex in vivo with Au nanocages as an optical contrast agent [129]. In this work, poly (ethylene glycol)-coated Au nanocages have been evaluated as a potential NIR contrast agent for PAT. Previously, Au nanoshells were found to be an effective NIR contrast agent for PAT; however, Au nanocages with their more compact sizes ($<$50 nm compared to $>$100 nm for Au nanoshells) and larger optical absorption cross sections should be better suited for in vivo applications. The group sequentially injected Au nanocages into the circulatory system of a rat in three administrations and in vivo PAT was conducted immediately prior to the first injection and continued until 5 h after the final injection. A gradual enhancement of the optical absorption in the cerebral cortex, by up to 81%, was observed over the course of the experiment. All these works have clearly shown the potential power of exploring the classical optical properties (scattering and absorption) of metal nanoparticles at SPR in application as biomedical diagnosis and therapy agents.

SERS has been an active topic in the past 40 years as the fundamental pursuit of single-molecule detection via Raman finger-print signals has never ended for human beings. Previously this problem was handled almost exclusively from the point of view of “hot spot” engineering via geometric design of metal nanoparticles. Various schemes have been extensively investigated, including colloidal aggregates [130, 131], particle-dimers with nanogap [132], particles with sharp corners such as nanocube [133] and nanobar [134], and mesoscopic particles with sharp tips [135]. However, it has been well established that there is a certain limitation to the enhancement factor of SERS that can be achieved purely based on local field enhancement of “hot spot.” This limitation, which is about 10^{12}, is several orders of magnitude lower than the value requested for single-molecule detection, which is about 10^{15}. Questions on why there is such a limit and whether there is a way to significantly lift this limit remains rarely answered. In 2010, Zhi-Yuan Li and Younan Xia studied this problem theoretically and proposed a novel scheme for SERS engineering [136]. They showed that metal nanoparticles with gain can be a promising way toward single-molecule detection by SERS.

A model composite particle was taken into account, which is a gold nanobox particle with a gain medium embedded within their core region. The calculation showed that the major obstacle toward increasing the local field intensity is because of the dissipation nature of metal when interacting with light. Light energy is dissipated to heat and the electric field cannot accumulate for a very long time, leading to limitation on the local field intensity. In comparison, the composite active nanoparticles can create an extremely high enhancement factor of local field intensity that exceeds 10^8 and an SERS enhancement factor on the order of 10^{16}–10^{17}, which is sufficient for single-molecule detection. The giant enhancement effect of SERS is attributed to the amplification of metal nanoparticle SPR by the gain medium under pumping of the incident light. The transfer of energy from the gain material will feed SPP mode, amplify its amplitude and energy, and attain lasing of plasmon at a critical point of gain coefficient. This in turn causes significant light scattering, absorption of light by the metal, and amplification of light by the gain material, all of which gigantically increase the local electromagnetic field intensity within and around the active nanosystem to a level far exceeding the single-molecule SERS detection limit. In the related work [137], the Li group showed that core-shell active gold nanorods coated with proper gain media have higher efficiency in surface plasmon amplification than the core-shell active gold nanosphere. This means that one can further explore appropriate geometries to facilitate enhancement of SERS via plasmon amplification.

The topic of SERS engineering by metal nanoparticles has raised extensive interest from a number of research groups in China. The group led by Prof. Hong-Xing Xu in IoP, CAS has made a significant contribution to advancing this field. In 2008 the group investigated polarization dependence of SERS in gold nanoparticle-nanowire composite systems [138]. They synthesized gold nanoparticles and gold nanowires and packed them together to form a coupled gold nanoparticle-nanowire system. The coupling between the continuous nanowire plasmons and the localized nanoparticle plasmons results in significant field enhancements and SERS enhancements comparable to those found in nanoparticle dimer junctions. The SERS intensity is maximal when the incident light is polarized across the particle and the wire, and the enhancement is remarkably insensitive to the detailed geometrical structures of the nanoparticles.

In 2009 they synthesized highly surface-roughened “flower-like” silver nanoparticles for applications as extremely sensitive SERS substrates [139]. The synthesis of monodispersed silver particles with a novel, highly roughened, “flower-like” morphology were made via reducing silver nitrate with ascorbic acid in aqueous solutions. The nanometer-scale surface roughness of the particles can provide several hot spots on a single particle, which significantly increases SERS enhancement. Although the different “hot spots” on a single particle can have a strong polarization dependency, the total Raman signals from an individual particle usually have no obvious polarization dependency. Moreover, these flower-like silver particles can be measured by SERS with high enhancement several times, which indicates the high stability of the hot spots. All these features indicate that the flower-like silver particles can serve as highly sensitive and reproducible SERS substrates. In 2009 the group developed an experimental technique that is based on remote-excitation SERS using propagating Ag nanowire plasmons to probe Raman signal of molecules located within the nanowire-nanoparticle gap [140]. In this technique, the incident laser spot illuminates one end of Ag nanowire, excites SPP, transports to the nanowire-nanoparticle junctions, illuminates molecules, which radiates Raman signals. The key is that the excitation and detection of Raman signal is now located at two laser spots with sufficiently large separation. Therefore, the detected Raman signal is well separated from the scattering light from the incident laser spot. As a result, the technique allows for detection of Raman signal with higher sensitivity and lower noise level compared with the conventional scheme of excitation and detection of Raman signal by a single laser spot.

The group has also made an extensive exploration on the plasmonic transport properties of silver nanowire and their applications. In 2010 they investigated branched silver nanowires as controllable plasmon routers [141]. By controlling the polarization of the incident laser light, the wire plasmons can be routed into different wire branches and result in light emission from the corresponding wire ends. This routing behavior is strongly dependent on the wavelength of light. Thus for certain incident polarizations, light of different wavelength will be routed into different branches. The branched nanowire can thus serve as a controllable router and multiplexer in integrated plasmonic circuits. In 2011 they employed this unique routing feature of plasmonic waves to construct cascaded logic gates in nanophotonic plasmon networks [142]. Optical computing has been pursued for decades as a potential strategy for advancing beyond the fundamental performance limitations of semiconductor-based electronic devices, but feasible on-chip integrated logic units and cascade devices have not been reported. The group demonstrated that a plasmonic binary NOR gate, a 'universal logic gate', can be realized through cascaded OR and NOT gates in four-terminal plasmonic nanowire networks. This finding provides a path for the development of novel nanophotonic on-chip processor architectures for future optical computing technologies. In another work, they generated chiral SPPs on metallic nanowires by adopting linearly polarized light incident at the end of a nanowire, exciting a coherent superposition of three specific nanowire waveguide modes [143]. Images of chiral SPPs on individual nanowires obtained from quantum dot fluorescence excited by the SPP evanescent field reveal the chirality predicted in the theoretical model. The handedness and spatial extent of the helical periods of the chiral SPPs depend on the input polarization angle and nanowire diameter as well as the dielectric environment. Chirality is preserved in the free-space output wave, making a metallic nanowire a broad bandwidth subwavelength source of circular polarized photons. All the work has greatly deepened the understanding and application of plasmonic wave transporting in high-quality silver nanowire.

To have a deep understanding on the transport properties of plasmonic waves in the silver nanowire from the experimental side, the group developed a novel technique that implements the interaction between propagating surface plasmons in silver nanowires and excitons generated in quantum dots [144]. Propagating surface plasmons can excite excitons and results in quantum dot emission. In this process, the energy is directly transferred from the propagating surface plasmons to the excitons without converting to photons. As a result, by observing the quantum dot emission pattern, one can indirectly monitor the field profile of surface plasmons propagating along Ag nanowire. In 2011 they adopted this quantum dot-based local field imaging technique to reveal plasmon-based interferometric logic in silver nanowire networks [145].

The group has also investigated other topics of plasmonics with nanoparticles. In 2008 the group proposed a novel way to manage light polarization via plasmon–molecule interactions within an asymmetric metal nanoparticle trimer [146]. They used single molecules to characterize the interaction of surface plasmons with light, and showed that such interaction can strongly modulate the polarization of the emitted light. They considered the simplest nanostructures that enable such polarization modulation, asymmetric silver nanocrystal trimers, where individual Raman scattering molecules are located in the gap between two of the nanoparticles. The third particle breaks the dipolar symmetry of the two-particle junction, generating a wavelength-dependent polarization pattern. The scattered light becomes elliptically polarized and its intensity pattern is rotated in the presence of the third particle. The group used a combination of spectroscopic observations on single molecules, scanning electron microscope imaging, and generalized Mie theory calculations to provide a full picture of the effect of particles on the polarization of the emitted light. Furthermore, the observed phenomenon is very sensitive to the size of the trimer particles and their relative position, and this suggests future means for precise control of light polarization on the nanoscale.

More recently, the group investigated in situ plasmon-driven chemical reactions by means of high vacuum tip-enhanced Raman spectroscopy [147]. With strong surface plasmons excited at the metallic tip, tip-enhanced Raman spectroscopy (TERS) has both high spectroscopic sensitivity and high spatial resolution, and is becoming an essential tool for chemical analysis. It is a great challenge to combine TERS with a high vacuum system due to the poor optical collection efficiency. The group used an innovatively designed home-built high vacuum TERS (HV-TERS) to investigate the plasmon-driven in situ chemical reaction of 4-nitrobenzenethiol dimerizing to dimercaptoazobenzene. The chemical reactions can be controlled by the plasmon intensity, which in turn can be controlled by the incident laser intensity, tunneling current and bias voltage. The temperature of such a chemical reaction can also be obtained by the clearly observed Stokes and Anti-Stokes HV-TERS peaks. The findings offer a new way to design a highly efficient HV-TERS system and its applications to chemical catalysis and synthesis of molecules, and significantly extend the studies of chemical reactions.

In a similar job, in 2010 Prof. Zhen-Chao Dong and coworkers from University of Science and Technology of China reported on generation of molecular hot electroluminescence by resonant nanocavity plasmons [148]. Control of the radiative properties of functional molecules near metals is a key issue in nano-optics, and is particularly important in the fields of energy transfer and light manipulation at the nanoscale and the development of plasmonic devices. The group showed resonant hot electroluminescence arising directly from higher vibronic levels of the singlet excited state for porphyrin molecules confined inside a nanocavity in a scanning tunneling microscope by spectrally tuning the frequency of plasmons. They also demonstrated the generation of unexpected upconversion electroluminescence. These observations suggest that the local nanocavity plasmons behave like a strong coherent optical source with tunable energy, and can be used to actively control the radiative channels of molecular emitters by means of intense resonance enhancement of both excitation and emission.

The group led by Prof. Zhen-Lin Wang from Nanjing University has explored novel technologies to synthesize colloidal ordered structures of metal nanoparticles and more complicated core-shell nanoparticles, and investigated their plasmonic properties. In 2004 the group demonstrated the fabrication of microstructured silver films that are composed of hexagonal close-packed hollow silver spheres [149]. By using confined polystyrene colloidal crystals as templates, they successfully applied the seeding/electroless deposition of silver nanoparticles on polystyrene colloidal particles and fabricated 2D and 3D ordered close-packed silver-coated composite particles. The supporting cores can be removed by etching, which results in arrays of hollow silver spheres. Since standard methods exist for the electroless plating of virtually any metal, the method can be applied to the synthesis of other metal shell particles that have an ordering either in two or three dimensions. The prepared samples may find potential applications as substrates for the enhancement of Raman scattering. In addition, as the thickness of the metal shell and the radius of the core are both tunable, the structure can lead to adjustable plasmon resonance.

In 2006 the group studied anomalous infrared transmission of gold films on 2D colloidal crystals [150]. They demonstrated a new avenue for tuning SPP properties by depositing metal films on a monolayer colloidal crystal substrate made from periodic array of silica beads. Extraordinary transmission resonances through the metal film were demonstrated with unique dispersion properties that depend on both s- and p-polarizations of the incident light. Furthermore, a clear transition from localized SPPs to extended SPPs was observed, which leads to a sudden attenuation of transmittance in the low-energy limit. These findings would stimulate further theoretical and experimental efforts in engineering the optical properties of these 2D ordered metallodielectric microstructures and exploit their potential applications in the near-infrared spectral region. The relative ease of growing high-quality colloidal crystals with a high ordering and large single domain, and the low cost of fabricating such plasmonic crystals with submicrometer periodicity would make the technology applicable in areas ranging from biotechnology to optoelectronics.

In 2007 the group reported shape-selective synthesis of gold nanoparticles with controlled sizes, shapes, and plasmon resonances [151]. In the approach, the attachment of water molecules to poly(vinylpyrrolidone) (PVP) is used in conjunction with the region-selective distribution of PVP and water in a water/PVP/*n*-pentanol system to confine reactions along the surface of PVP, thus achieving the highly shape-selective synthesis of anisotropic Au nanostructures with controlled sizes and remarkable shapes such as regular octahedrons, triangles, rods, dumbbells, belts, and hexagons. According to the IR absorption spectra of the Au nanoparticles, the nanoparticles are formed around PVP and corroborate the adsorption of PVP on Au. The size, shape, and plasmon resonance of the Au nanoparticles can be readily tuned by modifying the adsorption behavior and/or the reducing ability of PVP by adjusting the relative amounts of PVP and water, directly adding gold seeds, or changing the stirring conditions in the reaction mixture. The obtained highly pure anisotropic Au nanostructures and the synthesis method enable one to study distinct nanostructures to search for novel physicochemical properties and technological applications. This method can also be successfully extended to preparation of highly pure silica spheres, tubes, and needles with controlled aspect ratios.

The Zhi-Yuan Li group in IoP, CAS has also made progresses in developing technologies to synthesize and pattern metal nanoparticles. The group has grasped the conventional chemical method to synthesize gold nanorod (GNR) particles. Moreover, they have developed a simple technique to make good alignment of GNRs embedded in a poly-vinyl alcohol (PVA) film based on a direct and easy-to-do stretched-film method [152]. The film, which consists of millions of GNRs, exhibits the same anisotropic linear plasmonic properties (in the form of absorption spectrum) as a single GNR. A stretched GNRs/PVA film shows distinct colors when the incident light is polarized parallel with and perpendicular to the stretch direction, respectively, while the original film shows the same color in both polarization directions. These color displays are inherently associated with the corresponding absorption spectra. The original film shows two absorption peaks irrespective of the light polarization directions as all GNRs are randomly oriented. After the stretch, the film possesses only one absorption peak upon each polarized excitation, which corresponds to the longitudinal SPR (LSPR) and transverse SPR (TSPR), respectively. This splitting of the LSPR and TSPR in the macroscopic films could find useful applications in polarization-dependent color display devices. Moreover, anisotropic and enhanced nonlinear absorption were also observed from the film.

Recently, the group has developed a novel technology that uses optical tweezers (basically strongly focused Gaussian beams) to trap, manipulate, and pattern gold nanoparticles, including nanospheres and nanorods [153]. They have successfully demonstrated the trapping, transferring, positioning and patterning of gold nanorods with dual-optical tweezers. The convenient manipulations are achieved by taking advantage of the LSPR of gold nanorods and the anisotropic optical trapping forces formed by two linearly polarized Gaussian beams. The trapped gold nanoparticles are positioned extremely firmly and quickly on a substrate compared with randomly dispersed ones. It was observed that gold nanorods show advantages over gold nanospheres with regard to positioning speed and stability. More importantly, versatile plasmon coupling effects have been achieved in some patterned nanorods. Complex patterns based on two GNRs as building blocks have already brought about many new plasmonic features that a single GNR cannot generate. These features originate from the coupling and hybridization of the two longitudinal dipolar modes excited in the two GNRs. By controlling the relative polarization state of laser light in the dual-optical tweezers, more controllable ways to generate complex shapes with small distances can be made based on two GNRs. In addition, since each GNR can have different diameters and lengths, more freedom for the overall geometric morphology of the pattern can be readily achieved by just using current technique of dual-optical tweezers. As the plasmonic property of the pattern strongly depends on its geometric configuration, dual-optical tweezers are very promising for controlling the property of SPR by creating a wide variety of complicated patterns. The technique can be further harnessed to produce a desirable SPR that comes from computer design. In this regard, the dual-optical tweezers can become a versatile experimental “design” tool to create controllable patterns from two GNRs. In a related work, the group has experimentally demonstrated optical trapping of gold nanoparticles using radially and azimuthally polarized beams [154]. The transverse optical trapping stiffness of gold nanoparticles was measured. The radially polarized beam exhibits a higher trapping efficiency than the azimuthally polarized beam and the Gaussian beam. The success in optical trapping of gold nanoparticles by cylindrical vector beam has broadened the routines of manipulating gold nanoparticles for plasmonic applications.

The Zhi-Yuan Li group has also made theoretical studies on several important plasmonic issues related with metal nanoparticles. In 2008 they developed a novel approach that allows for quantitative analysis of dipole and quadrupole excitation in surface plasmon resonance of metal nanoparticles [155]. They considered the optical extinction spectra of silver nanocubes with the edge length ranging from 15 to 200 nm, and developed a method to quantitatively separate the contributions of the individual dipole component and quadrupole component of the optical extinction cross sections. This allows one to specify unambiguously the physical origin of each SPR peak in the spectra. They also analyzed the distribution patterns of electric fields and electric charges within and around the silver nanoparticle. These patterns clearly show the dipole and quadrupole excitation features at the SPR peaks. The near-field analyses are consistent with the far-field extinction spectra analyses. This suggests that the combination of far-field spectra and near-field pattern analysis can greatly help to uncover the intrinsic physics behind light’s interaction with metal nanoparticles and excitation dynamics of local surface plasmonic waves.

In another work, they have developed an analytical model to describe optical bistability in nonlinear metal nano-antennae involving Kerr materials [156]. Optical bistability at nanoscale is a promising way to realize optical switching, a key component of integrated nanophotonic devices. In this work they presented an analytical model for optical bistability in a metal nano-antenna involving Kerr nonlinear medium based on detailed analysis of the correlation between the incident and extinction light intensity under SPR. The model allows one to construct a clear picture on how the threshold, contrast, and other characteristics of optical bistability are influenced by the nonlinear coefficient, incident light intensity, local field enhancement factor, SPR peak width, and other physical parameters of the nano-antenna. It shows that the key toward low threshold power and high contrast optical bistability in the nanosystem is to reduce the SPR peak width. This can be achieved by reducing the absorption of metal materials or introducing gain media into nanosystems.

The enhanced interaction between light and plasmon can be reflected in many other interesting and useful aspects. In 2011 the group theoretically studied surface plasmon assisted dipole–dipole interaction near metal surface [157]. It was found that the radiation energy from a dipole can excite SPPs and transport to another dipole through the channel of the localized SPP modes. This energy transfer can be much more efficient than direct energy transfer via dipole–dipole radiation interaction in free space. A simple analytical model was proposed to describe the underlying physics behind the influence of SPP on the dipole–dipole interaction energy, and it predicts a wide variety of complicated interaction features that agree well with rigorous calculations.

The group also investigated enhanced light absorption of TiO_2 nanoparticles in the near-ultraviolet band by Au nanoparticles [158]. The near-UV band absorption cross section of a rutile TiO_2 nanoparticle could be significantly increased by placing Au nanoparticles in its neighborhood. The results indicate that pure rutile TiO_2 has its maximum absorption located in the deep-UV band. With the existence of Au nanoparticles, a significant light harvesting effect occurs, and this maximum shifts to the near-UV band, where usual excitation wavelength falls. Later, the group further proposed the giant enhancement of near-ultraviolet light absorption by TiO_2 nanoparticles via 3D aluminum funnel-antennas (FA) [159]. As aluminum has a higher palsmonic resonance frequency than Au and Ag, it is expected that it will have better palsmonic properties in the near-UV regimes. For this reason, they proposed a 3D aluminum FA to enhance near-UV band absorption of a rutile TiO_2 nanoparticle. The 3D finite-difference time-domain simulations show that rutile TiO_2 nanoparticle placed within the antenna can significantly red shift its maximum absorption to the near-UV band around the mercury lamp 365 nm line, with a giant absorption cross section enhancement factor of more than two orders of magnitude. The field analysis indicates a significant 3D light harvesting effect, where the incident light energy impinging upon the wide-area antenna is efficiently collected, flows into the embedded TiO_2 nanoparticle, and results in giant enhancement of local near-UV field intensity and effective absorption cross section. The design of the 3D aluminum FA opens up a promising way to boost the photocatalytic activity of TiO_2 by using mercury lamp light.

4 Metamaterials

Metamaterials are another active research field that has caught extensive interest in the world since several pioneering works have presented the concepts of negative refraction, superlens [160–164], and electromagnetic invisibility cloaking [165, 166]. These have become popular topics in the Chinese academic community. Metamaterials are essentially effective electromagnetic media whose permittivity and permeability are determined by electromagnetic response of local resonant states of light within the unit cell comprising the structure. Although the unit cell has a size much smaller than the wavelength of light, the electromagnetic response can be very complicated because usually the unit cell consists of metal nanostructures with complex plasmon resonance properties. The response can be dielectric, magnetic, or even chiral, depending on the specific infrastructures of the unit cell. On the other hand, as the size of unit cell for all metamaterials is still much larger than atomic size, so far no homogeneous metamaterials medium has been constructed. Contrarily, they are all inhomogeneous media. In this regard, metamaterials are drastically different from photonic crystals, which depend on Bragg scattering rather than local resonance to create bandgaps and anomalous dispersion of bands. On the other hand, metamaterials are more closely correlated with plasmonics, as the plasmon resonance of the unit cell is largely responsible for the overall electromagnetic properties of metamaterials.

4.1 New concepts exploration

When metamaterials took the bright spot all throughout the world, the research on photonic crystals has lasted quite some years in China. On the basis of the concepts, methods, and technologies, Chinese scholars quickly caught up with the world fashion of metamaterials, and have made significant contributions to advancing the field. Quite a few research groups have made their reputations through the insightful thinking and hard working.

The group led by Prof. Tie-Jun Cui from the Southeast University has made extensive and intensive efforts to explore new frontiers of metamaterials [167]. Several pronounced discoveries made in the past years have earned him great reputations. In 2010 the group designed and realized 3D broadband ground-plane cloak made of metamaterials [168]. Since invisibility cloaks were first suggested by transformation optics theory, there has been much work on the theoretical analysis and design of various types and a few experimental verifications at microwave and optical frequencies within 2D limits. In the work, the group made hard experimental and technical efforts and realized the first practical implementation of a fully 3D broadband and low-loss ground-plane cloak at microwave frequencies. The cloak, realized by drilling inhomogeneous holes in multilayered dielectric plates, can conceal a 3D object located under a curved conducting plane from all viewing angles by imitating the reflection of a flat conducting plane. They also designed and realized, using non-resonant metamaterials, a high-gain lens antenna that can produce narrow-beam plane waves in the near-field region in a broad frequency band. The antenna constitutes the transmitter of the measurement system and is essential for the measurement of cloaking behavior.

In another work, the group designed and realized a 3D broadband and broad-angle transformation-optics lens [169]. The metamaterials lenses are Luneburg lenses, which have superior performance compared with conventional lenses made of uniform materials with specially designed surfaces, but they are restricted by the difficulty of manufacturing the required gradient-index materials and their spherical focal surfaces. Before their work, a new 2D imaging lens was proposed and realized using transformation optics by other group. Such a 2D lens overcomes the aberration problem, has a flattened focal surface and is valid for extremely large viewing angles. In this work, the Cui group went one big step. They showed the design, realization and measurement of a 3D approximate transformation-optics lens in the microwave frequency band. The 3D lens is made of non-resonant metamaterials, which are fabricated with multilayered dielectric plates by drilling inhomogeneous holes. Simulation and experimental results demonstrated excellent performance of the 3D lens for different polarizations over a broad frequency band from 12.4 to 18 GHz. The lens can also be used as a high-gain antenna to radiate or receive narrow beams in large scanning angles.

The group adopted the concept of metamaterials and reported the first experimental demonstration of an omnidirectional electromagnetic absorber in the microwave frequency [170]. The proposed device is composed of non-resonant and resonant metamaterial structures, which can trap and absorb electromagnetic waves coming from all directions spirally inwards without any reflections due to the local control of electromagnetic fields. The absorption rate can reach 99 percent in the microwave frequency. The all-directional full absorption property makes the device behave like an "electromagnetic black body," and the wave trapping and absorbing properties simulate, to some extent, an "electromagnetic black hole." Such a device could be used as a thermal emitting source and to harvest electromagnetic waves.

More recently, the group has made great progresses in exploring novel concepts and new frontiers of metamaterials. They presented the first experimental demonstration of a dc electric cloak for steady current fields [171]. Using the analogy between electrically conducting materials and resistor networks, a dc invisibility cloak was designed, fabricated, and tested using the circuit theory. The results showed that the dc cloak can guide electric currents around the cloaked region smoothly and keep perturbations only inside the cloak. Outside the cloak, the current lines return to their original directions as if nothing happens. The measurement data agreed exceptionally well with the theoretical prediction and simulation result, with nearly perfect cloaking performance. The proposed method can be directly used to realize other dc electric devices with anisotropic conductivities designed by the transformation optics. Manipulation of steady currents with the control of anisotropic conductivities has a lot of potential applications, such as electric impedance tomography, graphene, natural resource exploration, and military camouflage. This study, without any doubt, is one big step to advancing the frontiers of invisibility cloaking from conventional electromagnetic waves to electrostatic field.

In another innovative work, the group presented an efficient approach to realize the spatial power combination for omnidirectional radiation via metamaterials in the 2D case [172]. The structure is a radially anisotropic zero-index metamaterial which can always produce ominidirectional radiation, independent of the number and position of the sources inside the metamaterial. When the radial component of the permeability tensor is approaching zero and the wave impedance is equal to that of free space, waves emitted from all sources inside the metamaterial are transformed into perfectly cylindrical waves without any reflection, and powers from different sources can be combined together to enhance the omnidirectional radiation. The group designed and fabricated such a radially anisotropic metamaterial, and both the numerical and experimental results demonstrated the spatial power combination with high efficiency. The proposed idea can be extended to the 3D case to generate perfectly coherent isotropic radiation in nature, which does not exist now. The work indicates that metamaterial is a unique approach to obtain such a high-efficiency spatial power combination for omnidirectional radiation and isotropic radiation.

The scope of metamaterials has continuously broadened with new concepts raised and investigated. Illusion optics is one pronounced example. The group led by Prof. Che-Ting Chan from Hong Kong University of Science & Technology, together with his collaborators, including Yun Lai, now a young professor in Soochow University, has made pronouncing contributions to set up this new concept and method of metamaterials [173]. The concept of illusion optics was first presented in 2009, by which the group made optical transformation of an object into another object [174]. They proposed to use transformation optics to generate a general illusion such that an arbitrary object appears to be like some other object of their choice. This is achieved by using a remote device that can transform the scattered light outside a virtual boundary into that of the object chosen for the illusion, irrespective of the profile and direction of the incident light. This type of illusion device also enables people to see through walls. The work extends the concept of cloaking as a special form of illusion to the wider realm of illusion optics. In another work, the group presented the concept of complementary media, and employed the concept to propose an invisibility cloak operating at a finite frequency that can cloak an object with a prespecified shape and size within a certain distance outside the shell [175]. The cloak is comprised of a dielectric core and an "antiobject" embedded inside a negative index shell. The cloaked object is not blinded by the cloaking shell since it lies outside the cloak. Full-wave simulations in two dimensions verified the cloaking effect.

Recently, the group studied anomalous light transport properties in photonic crystals. They found that Dirac cones induced by accidental degeneracy in photonic crystals can have connection with zero-refractive-index materials [176], an interesting concept first proposed by the group in 2003 [177]. A zero-refractive-index metamaterial is one in which waves do not experience any spatial phase change, and such a peculiar material has many interesting wave-manipulating properties. These materials can in principle be realized using man-made composites comprising metallic resonators or chiral inclusions, but metallic components have losses that compromise functionality at high frequencies. It would be highly desirable if one could achieve a zero refractive index using dielectrics alone. In the work, the group showed that by employing accidental degeneracy, dielectric photonic crystals can be designed and fabricated which exhibit Dirac cone dispersion at the center of the Brillouin zone at a finite frequency. In addition to many interesting properties intrinsic to a Dirac cone dispersion, they used effective medium theory to relate the photonic crystal to a material with effectively zero permittivity and permeability. Then they made numerical and experimental demonstration in the microwave regime that such dielectric photonic crystals with reasonable dielectric constants could manipulate waves as if they had near-zero refractive indices at and near the Dirac point frequency.

The concept of zero-refractive-index materials has also been widely explored by the group led by Prof. Hong Chen from Tongji University. In 2003 the group showed theoretically that a 1D photonic crystal containing a negative-index material has an omnidirectional gap, owing to the mechanism of zero (volume) averaged refractive index [178]. In contrast to the Bragg gap, the edge of such a zero-$\overline{n}$ gap is insensitive to incident angle and polarization. When an impurity is introduced, a defect mode appears inside the zero-$\overline{n}$ gap with a very weak dependence on incident angle and invariant with scaling.

Photonic crystals made from dielectric materials have many properties that are related with Bragg scattering. When metamaterials are brought into photonic crystals, new properties arise. In 2004 the Hong Chen group studied the unique properties of 1D photonic crystals containing single-negative materials [179]. They investigated the transmission properties of a 1D photonic crystal containing two kinds of single-negative (permittivity- or permeability-negative) media theoretically, and showed that this structure can possess a type of photonic gap with zero effective phase (ϕ_{eff}). The zero-ϕ_{eff} gap distinguishes itself from a Bragg gap in that it is invariant with a change of scale length and is insensitive to thickness fluctuation. In contrast to a photonic gap corresponding to zero averaged refractive index, the zero-ϕ_{eff} gap can be made very wide by varying the ratio of the thicknesses of two media. A photonic quantum-well structure based on zero-ϕ_{eff} gaps was further proposed as a multiple channeled filter that is compact and robust against disorder. In another work, the group found that a new type of omnidirectional gaps can appear in 1D photonic crystals composed of two kinds of single-negative (permittivity- or permeability-negative) materials [180]. In contrast to the Bragg gaps, the properties (e.g., the central frequency and width of the gap) of such omnidirectional gaps are insensitive to the incident angles and the light polarizations, and are invariant upon the change of scale length. Such omnidirectional gaps result from the interaction of evanescent waves. When a defect layer is introduced, a defect mode appears inside the omnidirectional gap, and the spectral position of the defect mode is almost independent of incident angles and nearly invariant with the scaling.

In 2006 the group studied tunneling modes of photonic heterostructures consisting of single-negative materials [181]. They showed theoretically that heterostructures consisting of single-negative materials can possess tunneling modes inside forbidden gaps, owing to the resonant coupling of the evanescent-wave-based interface modes. The tunneling modes appear when the heterostructure becomes nihility. They are independent of incident angles and polarizations and have zero phase delay, which can be utilized to design zero-phase-shift omnidirectional filters. In another work [182], the group went one step further and made an experimental study of photonic crystals consisting of ε-negative and μ-negative materials. The ε-negative (ENG) and μ-negative (MNG) materials were fabricated by using composite right/left-handed transmission line. The ENG and MNG materials are opaque in experiments, but the completely tunneling phenomenon occurs in the ENG-MNG pair, if the wave impedance and the effective phase shift of ENG and MNG materials are under the conditions of match, respectively. They experimentally confirmed that photonic crystals consisting of ENG and MNG materials can possess left-handed propagation modes and right-handed propagation modes within forbidden gaps. At the same time, they also observed the Bragg gaps for the bandgap indices $m = \pm 1$ and the zero effective phase (zero-ϕ_{eff}) gaps.

The group led by Prof. Lei Zhou from Fudan University also made significant contributions to the field of metamaterials [183]. They have made an extensive and insightful theoretical investigation on the unique properties of thin metal wires, based on which many interesting phenomena of metamaterials can be understood and adopted for applications [184, 185]. In 2005 the group investigated the unique properties of electromagnetic-wave tunneling through negative-permittivity media with high magnetic fields [186]. They demonstrated that electromagnetic waves can transmit with unit transmittance through a slab of negative-permittivity media sandwiched between two identical slabs with high permittivity, although each single slab is nearly opaque. This type of transparency is accompanied by high magnetic fields, and is robust against incidence angles. The idea was also confirmed by microwave experiments, which is in excellent agreement with the finite-difference time-domain simulations. In 2007 the group showed that the polarization states of electromagnetic waves can be manipulated through reflections by an anisotropic metamaterial plate, and all possible polarizations (circular, elliptic, and linear) are realizable via adjusting material parameters [187]. In particular, a linearly polarized light converts its polarization completely to the cross direction after reflection under certain conditions. Microwave experiments were performed to successfully realize these ideas and the results were in excellent agreement with numerical simulations. In 2011 the group designed an anisotropic ultrathin metamaterial to allow perfect transmissions of electromagnetic waves for two incident polarizations within a common frequency interval [188]. The transparencies are governed by different mechanisms, resulting in significant differences in transmission phase changes for two polarizations. The system can thus manipulate electromagnetic wave polarizations efficiently in transmission geometry, including polarization conversion and rotation. Microwave experiments performed on realistic samples agree well with numerical simulations.

More recently the group has made a breakthrough of advancing the concept of metamaterials. They presented a novel scheme to design gradient-index meta-surfaces as a bridge linking propagating waves and surface waves [189]. This is an old topic that has attracted numerous studies from optical communities. The arbitrary control of electromagnetic waves is a key aim of photonic research. Although, for example, the control of freely propagating waves and surface waves has separately become possible using transformation optics and metamaterials, a bridge linking both propagation types has not yet been found. Such a device has particular relevance given the many schemes of controlling electromagnetic waves at surfaces and interfaces, leading to trapped rainbows, lensing, beam bending, deflection, and even anomalous reflection/refraction. In their work, the group demonstrated theoretically and experimentally that a specific gradient-index meta-surface can convert a propagating wave to a surface wave with nearly 100% efficiency. Distinct from conventional devices such as prism or grating couplers, the momentum mismatch between propagating wave and surface wave is compensated by the reflection-phase gradient of the meta-surface, which can be realized by placing metamaterials of different geometric parameters at different spatial positions. In this way, a nearly perfect propagating wave-surface wave conversion can happen for any incidence angle larger than a critical value. Experiments in the microwave region, including both far-field and near-field characterizations, accord well with full-wave simulations. The findings may have paved the way for many applications, including high-efficiency surface plasmon couplers, anti-reflection surfaces, light absorbers, and so on. This beautiful job has indicated that there still exist plenty of unknown spaces of concepts and applications of metamaterials for people to explore.

Another group from Fudan University led by Prof. Jian Zi recently showed that an anomalous phenomena called all-angle zero reflection can occur at metamaterial surfaces [190]. They studied theoretically reflection on the surface of a metamaterial with a hyperbolic dispersion and found that reflection is strongly dependent on how the surface is terminated with respect to the asymptote of the hyperbolic dispersion. For a surface terminated normally to the asymptote, zero reflection occurs for all incident angles. The theoretical prediction was confirmed by numerical simulations made for a metamaterial made of a periodic metal-dielectric layered structure with its surface properly cut.

4.2 Metamaterials experiments at microwave and optical frequencies

In addition to the investigation and exploration of new metamaterials concepts and phenomena from the theoretical sides, there appear more and more research groups that set up experimental facilities in both microwave and optical frequencies. With these setups, they are able to check and confirm their findings and discoveries made via theoretical analyses and numerical simulations.

So far, most metamaterials experiments in China have been carried out in the microwave regime, as the fabrication of complicated metamaterial structures becomes relatively easy there. Yet, these studies prove valuable as they cannot only be used to dip deeply into the basic physics of metamaterials, but also can help to build some useful microwave devices such as antennae. As I have shown in the above discussions, the group led by Prof. Tie-Jun Cui has made great achievements in the experimental exploration of microwave matermaterials. Another group led by Prof. Hong-Qiang Li from Tongji University has also made major progresses in the past years.

In 2010 the group presented theory and experimental realization of negative refraction in a metallic helix array [191]. They first developed a theory to compute and interpret the photonic band structure of a periodic array of metallic helices. Interesting features of the band structure include longitudinal and circularly polarized eigenmodes and wide polarization gap. The helical symmetry also implies unusual features such as negative group velocity bands at both sides of the polarization gap and band crossings pinned at the zone boundary. The group also performed experiment by building the designed helix metamaterial samples and measuring the spatial beam shift through a slab of the 3D helices. The experimental results gave a direct proof of negative refraction via a chiral route for the first time. In a related work [192], the group demonstrated theoretically and experimentally that a metallic helix array can operate as a highly transparent broadband wave plate in propagation directions perpendicular to the axis of helices. The functionality arises from a special property of the helix array, namely, that two branches of elliptically right-handed and left-handed polarized states are nearly rigidly shifted in frequency and their dispersions are controlled by different mechanisms that can be independently tuned by structural parameters.

In another work [193], the group considered a thin metamaterial slab comprising a dielectric spacer sandwiched between a metallic grating and a ground plane. They found that the structure possesses spatially coherent surface resonance states that span a large frequency range and can be tuned by structural and material parameters. The structure can give rise to nearly perfect angle-selective absorption and can thus exhibit directional thermal emissivity. Direct numerical simulations showed that the metamaterial slab supports spatially coherent thermal emission in a wide frequency range that is robust against structural disorder.

More recently, the group proposed an ultrathin chiral metamaterial slab stacked with twisted complementary split-ring resonators (CSRRs) for highly efficient broadband polarization transformation [194]. The polarization of linearly polarized electromagnetic waves can be rotated in a specific direction by passing it through such a slab with a thickness of about one-tenth the operational wavelength. Microwave experiments verified the theoretically predicted conversion efficiency of up to 96% coverage of a bandwidth of 24% of the central wavelength. CSRRs with circular symmetry provide increased interlayer coupling strength, which produces a high-efficiency broadband response and strong isolation of the original polarization. They also proposed a scheme for subwavelength electromagnetic diode by employing cascading nonlinear meta-atoms [195]. One-way response was conceptually demonstrated on a microwave transmission line comprising three metallic ring resonators acting as meta-atoms and a varactor as the nonlinear medium inclusion. Experiments showed that the structure can operate simultaneously as forward diode and backward diode at different frequencies. A transmission contrast of up to 14.7 dB was achieved between forward and backward transmission. Subwavelength size of the diode should be useful for miniaturization of integrated optical nanocircuits.

Although microwave metamaterials have many interesting implications in fundamental sciences and practical applications, it is highly desirable to realize metamaterials in infrared and visible bands, where a vast variety of optoelectronic devices and applications can be expected. As nanofabrication technologies and facilities have been set up in more and more institutions, the possibilities to carry out experimental work on optical metamaterials gradually become a reality. In this aspect, several groups from Nanjing University have made remarkable contributions in experimental exploration of the unique properties of optical metamaterials. All these works cannot be possible without the setup of a good facility of FIB lithography and the training of the corresponding nanofabrication techniques in Nanjing University.

Tao Li and coworkers experimentally demonstrated a plasmonic assisted Fabry–Perot cavity in a metal/insulator/metal trilayer structure with L-shaped hole arrays inside, which significantly contribute to the mechanism to realize a nearly complete polarization conversion ($\sim$0.93) in optical transmissions at near-infrared wavelength [196]. This interesting property was found to arise from an overlap of the cavity and plasmonic modes in two orthogonal polarization states.

Hui Liu and coworkers have made extensive studies on the unique properties of magnetic responses of metamaterials [197, 198]. In 2006 they studied a 1D magnetic plasmon propagating in a linear chain of single split ring resonators [199]. The subwavelength size resonators interact mainly through exchange of conduction current, resulting in stronger coupling as compared to the corresponding magneto-inductive interaction. Finite-difference time-domain simulations in conjunction with a developed analytical theory showed that efficient energy transfer with signal attenuation of less than 0.57 dB/μm and group velocity higher than $1/4c$ can be achieved. Afterwards, they theoretically studied the excitation of optical magnetic plasmons in chiral metallic nanostructures based on a magnetic dimer [200]. Hybridization of the magnetic plasmon modes and a type of optical activity was demonstrated at near-infrared frequencies. A linearly polarized electromagnetic wave was shown to change its polarization after passing through an array of magnetic dimers. The polarization of the transmitted wave rotates counterclockwise at incident light frequencies corresponding to the low energy and clockwise at the high energy magnetic plasmon state.

In 2009 they collaborated with Prof. Harald Giessen from University of Stuttgart, Germany and proposed the concept of stereometamaterials [201]. The concept is borrowed from stereochemistry, which is the subdiscipline of chemistry that studies molecular structures in three dimensions. In analogy to stereoisomers in chemistry, stereometamaterials refer to metamaterials with the same constituents but different spatial arrangements. As a model system of stereometamaterials, they theoretically and experimentally studied meta-dimers, which consist of a stack of two identical split-ring resonators in each unit cell with various twist angles, and found that the interplay of electric and magnetic interactions plays a crucial role for the optical properties. Specifically, the influence of higher-order electric multipoles becomes clearly evident. The twisting of stereometamaterials offers a way to engineer complex plasmonic nanostructures with a tailored electromagnetic response.

Later, in collaboration with Prof. Che-Ting Chan, they found that very strong negative optical pressure can be induced in plasmonic cavities by LC resonance [202]. In particular, they designed a plasmonic cavity system comprising a patch and a slab and found that the kinetic energy of conduction electrons plays a key role in inducing a strong negative optical pressure. This interesting effect could be described qualitatively by a Lagrangian model which shows that the negative optical pressure is driven by the internal inductance and the kinetic energy of the conduction electrons. If the metal is replaced by perfect conductors, the optical pressure becomes much smaller and positive. The mechanism and theoretical model reported in this work could have potential applications in many other subwavelength optomechanical plasmonic structures.

In 2008 the group led by Prof. Ru-Wen Peng clarified the role of interference between localized and propagating surface waves on the EOT through a subwavelength-aperture array [203]. When radiation is incident on a metal surface perforated with an array of ring-shaped subwavelength apertures, the phase difference between the propagating surface Bloch wave and the localized surface wave can be tailored by the geometrical parameters of the array so as to affect the shape of the transmission spectrum. Above the resonant frequency of the aperture, interference between the two kinds of surface waves leads to a minimum in the transmission spectrum, whereas below it, the interference leads to a maximum. This work can help to bring an insightful clue to understanding the long-standing controversial problems of EOT through subwavelength air hole arrays. In a later work, the group presented an approach to make metals transparent for white light by spoof surface plasmons [204]. First-principles computations revealed that metallic gratings consisting of narrow slits may become transparent for extremely broad bandwidths under oblique incidence. This phenomenon can be explained by a concrete picture in which the incident wave drives free electrons on the conducting surfaces and part of the slit walls to form spoof surface plasmons (SSPs). The SSPs then propagate on the slit walls but are abruptly discontinued by the bottom edges to form oscillating charges that emit the transmitted wave. This picture explicitly demonstrates the conversion between light and SSPs and indicates clear guidelines for enhancing SSP excitation and propagation.

In 2012 the group experimentally constructed transparent metals for ultrabroadband electromagnetic waves at THz band [205]. They showed that metallic gratings with narrow slits can become highly transparent for extremely broad bandwidths with oblique incidence or with normal incidence for oblique gratings. The broadband optical transmission was verified for the structured metals with thickness within the range of half a wavelength, and the high transmission efficiency is insensitive to the metal thickness. In particular, thick metal gratings possess both advantages of extremely high-efficiency transmission and high-performance electrical properties. Although the experiments were carried out in THz band, it is believed that continuous and nearly unitary transmission can be achieved in the broadband frequency ranging from visible light to radio wave. The experimental results demonstrate a simple yet efficient way to make broadband transparent metals, based on which more complicated applications on antireflection solar cells and stealth technologies can be anticipated. The physics underlying the shown phenomena may also shed new light on widening the bandwidths and increasing the efficiency of more complicated structured materials, including sonic artificial materials.

In 2008 the group demonstrated switching the electric and magnetic responses in a metamaterial [206]. Numerical simulations showed that in an assembly of stacked metallic U-shaped resonators, pure magnetic and electric responses are, respectively, realized, and the magnetic and electric responses can be switched at the same frequency by changing the polarization of incident light for 90°. This unique feature originates from the topological symmetry of the structure. This property might open a gateway to constructing metamaterial with tunable permittivity and permeability. In another work, the group presented construction of a chiral metamaterial with a U-shaped resonator assembly [207]. In an assembly of double-layered metallic U-shaped resonators with two resonant frequencies ω_H and ω_L, the effective induced electric and magnetic dipoles, which originate from the specific distribution of induced surface electric current upon the illumination of incident light, are collinear at the same frequency. Consequently, for left circularly polarized incident light, negative refractive index occurs at ω_H, whereas for right circularly polarized incident light it occurs at ω_L. This design might provide a new example of applying chiral structures to tune the electromagnetic properties, and could be enlightening in exploring chiral metamaterials.

5 Artificial acoustic structures

The concepts of electromagnetic metamaterials, or in a broader perspective, photonic crystals, and other artificial optical microstructures and nanostructures, are not only applicable to optical systems, but also applicable to other classical wave systems, including acoustic systems. Although the number of research groups in acoustic artificial structures in China is much smaller than in optical artificial structures, they have made quite a few research results of high international reputations and influences.

In 2007 the Yan-Feng Chen group from Nanjing University experimentally demonstrated negative birefraction of acoustic waves in a sonic crystal [208]. Optical birefringence and dichroism are classical and important effects originating from two independent polarizations of optical waves in anisotropic crystals. Furthermore, the distinct dispersion relations of transverse electric and transverse magnetic polarized electromagnetic waves in photonic crystals can lead to birefringence more easily. However, it is impossible for acoustic waves in the fluid to show such a birefringence because only the longitudinal mode exists. The emergence of an artificial sonic crystal (SC) has significantly broadened the range of acoustic materials in nature that can give rise to acoustic bandgaps and be used to control the propagation of acoustic waves. Similar to left-handed materials and photonic crystals, negative refractions have also been found in SCs. The group reported, for the first time, the acoustic negative-birefraction phenomenon in a 2D SC, even with the same frequency and the same "polarization" state. The SC was composed of an array of steel cylinders embedded in air. The effect was revealed via a novel double focusing-imaging phenomenon. These two refractive waves are coherent, which might be used for division of a wavefront in acoustic holography and acoustic communication. The artificial ultrasonic periodic composite material gives a means to control the propagation of acoustic waves, which will open a new horizon in the design of new acoustic devices.

The group also extended the concept and problems of nonreciprocal wave propagation in optical structures to acoustical structures. In 2011 the group utilized a sonic-crystal-based acoustic diode that had broken spatial inversion symmetry and experimentally realized sound unidirectional transmission in this acoustic diode [209]. These novel phenomena are attributed to different mode transitions as well as their associated different energy conversion efficiencies among different diffraction orders at two sides of the diode. This nonreciprocal sound transmission could be systematically controlled by simply mechanically rotating the square rods of the sonic crystal. Different from nonreciprocity due to the nonlinear acoustic effect and broken time reversal symmetry, this new model leads to a one-way effect with higher efficiency, broader bandwidth, and much less power consumption, showing promising applications in various sound devices.

Another acoustic group from Nanjing University, which is led by Prof. Jian-Chun Cheng demonstrated an acoustic rectifier in 2010 [210]. The detection of acoustic signals is of relevance for a range of practical applications, for example in medical diagnostics. Although rectification of electric current and other energy forms such as thermal flux had been demonstrated, acoustic rectification had not yet been achieved. In this work, on the basis of the earlier theoretical proposal of an "acoustic diode," the group presented the first experimental demonstration of a rectified energy flux of acoustic waves. A 1D acoustic rectifier was fabricated by coupling a superlattice (1D sonic crystal) with a layer of ultrasound contrast agent microbubble suspension. A significant rectifying effect was observed within two frequency bands at locations that agree well with theoretical predictions. In principle, the acoustic device works on nonlinear sonic effect of superlattice, which is very similar to the optical diode realized by means of nonlinear superlattices. The sonic crystal serves as an effective acoustic filter to yield different transmission properties between the fundamental wave and the second harmonic wave (SHW). The nonlinear medium (NLM) is introduced to destroy the system symmetry and to break the restriction of the reciprocal theorem in linear acoustic systems. If the acoustic wave comes from the proximal side of the NLM, it will hit the nonlinear material first, creating a SHW that passes through the filter. However, any sound coming from the opposite direction at the fundamental-wave frequency is blocked before it reaches the NLM. Therefore, an asymmetric propagation of acoustic waves can be expected and reasonably referred to as acoustic rectification.

By further optimization of the concentration of the microbubble suspension, rectifying ratios could be as high as 10^4. This realization of an acoustic rectifier should have substantial practical significance, for example in the focusing of ultrasound in medical applications. The proposed acoustic diode device offers several advantages, for example, a simple fabrication procedure, low cost, high extensibility and compatibility with other instruments. Therefore, it is promising to fabricate effective acoustic diode devices that may be applied to various practical situations where the acoustic waves need to be specially controlled, for example, the significant medical application of ultrasound. In particular, the acoustic diode device is extremely robust against backtracking waves with quite large amplitudes. This is particularly meaningful for therapeutic applications of high-intensity focused ultrasound. However, as the acoustic diode works on nonlinear effect of sonic structures, it still requires sufficiently high energy power of sonic wave, which might limit its practical application.

The group led by Prof. Zheng-You Liu from Wuhan University has made an extensive effort to study sonic crystals, sonic metamaterials, and other acoustic artificial structures. In 2000, he and coworkers from Hong Kong University of Science & Technology presented a pioneering work of locally resonant sonic materials [211]. They fabricated sonic crystals, based on the idea of localized resonant structures that exhibit spectral gaps with a lattice constant two orders of magnitude smaller than the relevant wavelength. Disordered composites made from such localized resonant structures behave as a material with effective negative elastic constants and a total wave reflector within certain tunable sonic frequency ranges. A 2-cm slab of this composite material was shown to break the conventional mass-density law of sound transmission by one or more orders of magnitude at 400 Hz. The experimental results also indicated that resonance-induced negative elastic constants should be possible, although the static elastic constant must be positive for maintaining structural stability.

In 2005 the collaboration group presented an analytic model to understand phononic crystals with local resonances [212]. The simple analytic model could describe the low-frequency effective mass densities of three component phononic crystals with local resonances. They found that the effective mass densities can turn negative close to the local resonances. Expressions for the effective mass densities were derived for both 3D systems with coated spheres embedded in a host matrix, and 2D systems with coated cylinders embedded in a host matrix. The theory was very useful for understanding the basic properties of sonic crystals. In 2006 they further studied effective mass density of fluid-solid composites [213]. They showed through rigorous derivation and experimental support that the dynamic effective mass density of an inhomogeneous mixture, used in the prediction of wave velocities in the long wavelength limit, can differ from the static version–the volume average of the component mass densities. The dynamic mass density expression was shown to give a closer correspondence between the acoustic and electromagnetic metamaterials by allowing for negative mass densities at frequencies around resonances.

In 2007 the group presented design and realization of a metamaterial that simultaneously possesses a negative bulk modulus and mass density [214]. This metamaterial was a zinc blende structure consisting of one fcc array of bubble-contained-water spheres (BWSs) and another relatively shifted fcc array of rubber-coated-gold spheres (RGSs) in epoxy matrix. The negative bulk modulus and mass density were simultaneously derived from the coexistent monopolar resonances from the embedded BWSs and dipolar resonances from the embedded RGSs. The Poisson ratio of the sonic metamaterial also turns negative near the resonance frequency. In 2009 the group further presented experiment of parallel acoustic near-field microscope made from a steel slab with a periodic array of slits [215]. This flat acoustic lens is similar to the flat superlens made from optical negative refraction material. In the acoustic microscope, the near field is transported by the coupling of the incident evanescent waves and the acoustic guided modes supported by the structured slab. The group derived the transmission coefficients of the structured slab as a function of the transverse wave vector, and employed a theoretical model to study the imaging of the proposed device. Both results showed that subwavelength imaging with good quality can indeed be realized.

6 Summaries and perspectives

In summary, I have made a brief introduction to the principle of nanophotonics, and have particularly discussed several major disciplinary areas as photonic crystals, plasmonics, and metamaterials. In my opinion, all these research disciplines share many common things ranging from basic physics, theoretical approaches, and experimental tools. Needless to say, these artificial optical structures and materials will offer a wide variety of means and recipes to manipulate and manage the fundamental nature of light and light-matter interaction. When people are able to fully control the motion of light at microscales and nanoscales, they see the potential to construct ultrasmall photonic integrated devices and build large-scale circuits from these individual devices, following much the same way as microelectronics.

With these fundamental concepts briefly but well explained and understood, I go further and present overviews of the history and the state of the art of these research fields in China. These fields have seen their rapid growth in the past ten years. The reasons might be twofold. First, the Chinese government has invested a large amount of money to support research on both basic sciences and high technologies along with the quick growth of economy in the past ten years. Second, the early activities in artificial optical structures, mostly photonic crystals, in China have helped to train a team of young scientists and technicians in the field. These scholars have played an important role in bringing into reality recent quick progresses in various research areas of nanophotonics.

Because better equipments, facilities, and technologies have become increasingly available in many institutions and more researchers that have got good training both domestically and abroad have joined the communities, Chinese nanophotonics communities have been continuously expanded in scope. More importantly, many groups have now been able to make remarkable contributions to the field through hard working, insightful thinking, genuine ideas, and beautiful theories and experiments. These achievements have been well appreciated by their international colleagues and have earned Chinese scholars reputations around the world. A large fraction of these achievements have been selected and highlighted in this paper as I believe that they represent the best results that many research groups working on various disciplines of nanophotonics have achieved through their long years of hard thinking and working. However, these works by no means exhaust all the excellent research results that have been made throughout China's nanophotonic communities in the past years. The selections are more or less my personal taste, and also because of the limited space and scope of this paper. There must be many excellent results that are not introduced in this paper, but this does not mean my complete ignorance and neglect of the importance of these works.

Frankly speaking, despite all these excellent results and major progresses made in the past years, in my point of view, truly original and innovative thinkings, theories, and experiments that have generated world-level impacts are still very limited. The communities are working even harder and passionately looking forward to the emergence of pioneering research work from some brilliant people with great wisdoms. History has set up many good examples for us. The concepts of photonic crystals, photonic crystal fibers, plasmonics, negative refraction, metamaterials, invisibility cloaking, and transformation optics all opened a brand new and broad frontier in science and technology. These fields have set a high standard and platform for many of our Chinese colleagues to work and explore. It is time that we Chinese scholars work hard to set some unknown new standards and platforms for the world communities to work and explore. The positive answer to this question might rely on our young generations who think hard, work hard, and insist with confidence.

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