Surface Plasmon Polaritons and Its Applications

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(Invited Paper)

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Abstract: Surface plasmon polaritons (SPPs) have become one of the most rapidly expanding fields in photonics today. Exciting advances were made in research on SPPs in 2011. This review summarizes the significant progress and major achievements of super-resolution imaging, SPP lithography, SPP-assisted absorption, SPP-based antennas, light manipulation, and the current state-of-the-art in loss-compensation and process. The potential applications, future challenges, and opportunities are also discussed.

Index Terms: Nanostructures, nanophotonics, surface plamsmon polariton.

The unique properties of surface plasmon polaritons (SPPs) provide pathways to harnessing light in ways not possible with conventional optics. Many SPP-based achievements have been continuously emerging through deep research in 2011.

The first breakthrough is SPPs super-resolution imaging. The spatial resolution of conventional imaging systems is inherently restricted by diffraction limit. A hyperlens lens, following Pendry's perfectlens or superlens [1], was the first step toward magnifying subdiffraction-scale objects to the far-field with subdiffraction resolution imaging. Based on alternating stacks of metallic and dielectric films with nanoscale thickness, semispherical and cylindrical hyperlens designs were proposed to magnify nano-objects [2], [3]. Rahman *et al.* realized subwavelength optical imaging with an array of silver nanorods [4], while Robillard report on the subwavelength imaging capabilities of a photonic crystal (PC) flat lens consisting of triangular array of steel cylinders in methanol, all surrounded by water [5].

Despite many years of investigation into alternative lithographic techniques, no obvious replacements for optical approaches have been developed. With the help of SPPs, this trend will keep on going. The pioneering efforts for nanolithography with SPPs [6], [7] indicated that SPPs might provide one promising alternative to optical lithography and imaging with resolution far smaller than the wavelength without the need for complicated optics and expensive light sources. The most important challenge has been to achieve sufficient demagnification using SPPs lithography. Luo *et al.* proposed to apply a phase-shifting mask (PSM) that comprises chromium slits alternatively filled by Ag and PMMA to achieve $\sim\lambda/10$ ($\sim$35 nm) resolution ($\sim\lambda/6$ without the PSM) [8]. In fact, an entirely new SPPs lithographic scheme to realize lithographic imaging with a

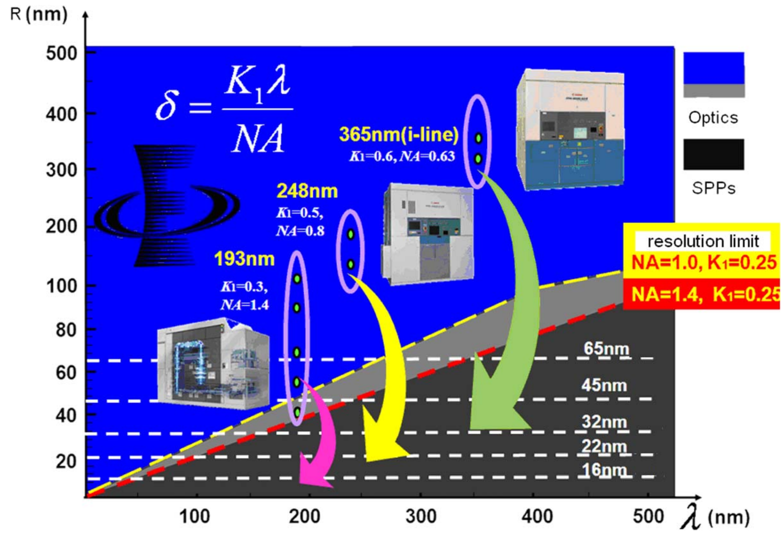

Fig. 1. Roads for SPPs nanolithography using UV light.

reduction-ratio beyond the diffraction limit has been demonstrated [9]. (Fig. 1 indicates the roadmap of SPPs nanolithography using UV light with increased resolution.) The latest experiment of SPPs lithography demonstrated printing of about 32 nm lines by demagnifying a mask pattern. Theoretical calculations predict SPPs lithography to achieve a spatial resolution beyond the 22-nm node [9]. Of course a number of engineering challenges will need to be addressed before this approach can be introduced into real world nanomanufacturing applications.

Another fascinating advance is the demonstration of the nearly complete light absorption in plasmonic structures [10]. This conversion can be realized utilizing specific micro-nano metallic structures to create desired surface impedance, resulting in complete coupling of the incident light into regions with large losses. Microcavity structures are introduced at the entrance and exit sides of a slit to realize the resonant field enhancement to enhance the optical absorption in subwavelength slits [11]. Truncated spherical voids nanostructured tungsten films are shown to have nearly perfect absorption with characteristics of broadband, polarization-independent and wide-incidence angle [12]. For tolerance to fabrication errors, quite recently, a broadband light harvesting nanostructures robust to edge bluntness is proposed and investigated [13]. Coherent perfect absorption of light is proposed and demonstrated in a planar intrinsic silicon slab when illuminated on both sides by two beams with equal intensities and correct relative phase [14]. Such a device is termed a coherent perfect absorber (CPA) and a "time-reversed laser." The coherent absorption enhancement can also be extended to strong scattering media [15]. Compared with the perfect absorbers (PAs) based on metamaterials or plasmonic structures [16], CPA provides additional tunability of absorption through the interplay of absorption and interference. The coherent control of absorption is potentially useful in transducers, modulators, or optical switches. Recently, Luo *et al.* proposed a ultrathin broadband nearly PA with symmetrical coherent illuminations to avoid the intrinsic narrow band problem of the CPA [17].

Optical antennas are an enabling technology for manipulating and controlling optical radiation at subwavelength or nanometer scales [18], [19], while also providing optimal control of transduction in the far-field. A detailed formalism allowing analytical calculations of the radiation properties for nanoantennas design (Yagi–Uda configurations) is given in [20]. In addition and more promising, optical antennas have also been explored to enhance the efficiency of photovoltaic devices, particularly for solar energy harvesting. Fan *et al.* identified the number of optical states as the major factor for light absorption, as well as the presence of the high-index material near the interface effectively raised the refractive index of the low-index material [21]. Most recently, Atwater's team generalized this idea by showing that cramming in more optical states can make thin-film absorbers take up more light than usual, also providing a comprehensive study of various designs that potentially go beyond the ray-optic limit [22]. Enhanced radiation is the opposite side of light absorption, which is of great importance for light sources, such as light-emitting diodes (LEDs). Several notable demonstrations have been done to improve the efficiency of LEDs (or OLEDs) aided by the plasmonic structures [23]–[25].

Another application of optical antennas is biosensing [26]. Bartoli *et al.* experimentally demonstrated a plasmonic Mach–Zehnder interferometer (MZI, formed by patterning two parallel nanoslits in a thin metal film) integrated with a microfluidic chip for ultrasensitive biosensing [27], yielding enhanced refractive index sensitivities greater than 3500 nm/RIU and record high sensing figures of merit exceeding 200 in the visible region. Dregely *et al.* reported a palladium-based plasmonic PA at visible wavelengths and its application to hydrogen sensing [28]. Their design exhibits a reflectance $< 0.5\%$ and zero transmittance at 650 nm, and thus, the exposure to hydrogen gas causes a rapid and reversible increase in reflectance on a time scale of seconds.

Beam manipulation is another example taking advantage of the strong coupling of metallic structures with electromagnetic wave [29]. Since the pioneering work made by Ebbesen *et al.* [30], SPPs have been demonstrated to provide the opportunity to confine light into very small dimensions by means of surface corrugation, opening new opportunities for subwavelength optical devices [29]–[32]. Luo *et al.* present a design for a subwavelength hole array decorated with an electric resonance ring to realize angle-insensitive extraordinary optical transmission in the far-infrared regime [29]. Levy *et al.* propose and experimentally demonstrate the nanoscale focusing of surface plasmons by constructing an integrated plasmonic/photonic on chip nanofocusing device in silicon platform [33]. Palacios *et al.* analyzed both experimentally and theoretically the physical mechanisms that determine the optical transmission through deep subwavelength bull's eye structures [34]. In addition, various schemes of "lens" or beam focusing have been proposed [35]–[37].

In reality, the existence of SPPs not only depends on the strong dispersion of the metal, but also the specific pattern design on the metal surface [38]. In the Terahertz region, the spoof SPP's structure is designed to collimate light beams [39], which is composed of a 1-D array of L-shaped metallic elements horizontally attached to a metal surface. In the microwave region, another new radiation mode, surface polaritons radiation mode, was proposed to design a corrugated antenna, achieving higher aperture efficiency and stronger directivity with elements' space beyond a wavelength [40].

The intrinsic loss in metals is a fundamental challenge, which would dramatically limit the performance of plasmonic devices. Searching for materials with low loss has become one necessary step to realize optimal plasmonic properties for specific frequencies and applications [41]. Gain medium, amplifiers, and lasers based on SPPs have been studied for decades [42]. Various metallic structures such as planes, films, stripes, wires and particles, have been integrated with gain materials. In particular, Zayats *et al.* experimentally demonstrated suppressed absorptions and stimulated emission of SPP with more than 10 times efficiency compared with out-of-plane pumping [43]. Such approach may open up a possibility for active nanophotonic integration. Gather *et al.* demonstrated amplified spontaneous emission of long-range SPPs in planar metallic waveguides embedded in a fluorescent polymer with a net gain coefficient of 8 ± 2/cm for propagation up to 2 mm [44]. Plasmon laser [45] and loss compensated active metamaterials [46] are also proposed as alternatives.

No progress in SPPs research will be possible without further developments in fabrication. Surface roughness and other inhomogeneities have so far limited SPPs propagation in real plasmonic devices. Last year, Shalaev's group at Purdue University obtained a significant result showing how to create ultrathin, ultrasmooth and low-loss Ag films and silver–silica lamellar composite films [47]. They further developed a fabrication method for creating semicontinuous metal films with arbitrary thickness and a modeling technique for such films using realistic geometries [48].

Ultrasmooth patterned metals for SPPs have been realized by combined template stripping with precise patterned silicon substrates [49]. These achievements may remarkably improve the performance of superlens and hyperlens structures for high-resolution and subwavelength imaging. The properties of SPPs at the plasmon resonance frequency can also help develop various passive or active (dynamic) nano-optic devices. Devices that have potential applications in telecommunications including optical interconnect or photonic integrated circuits are of great interests [50]–[53]. Recently Février demonstrated a total energy transfer from a TE mode to a transverse plasmon mode of a coupled metal nanoparticle chain at 1550 nm [54]. So-called "Giant coupling" effects happened from record coupling lengths as short as ~560 nm. Such a design opens the way for localized plasmon-based devices into photonic integrated circuits. Gjonaj *et al.* achieved active control (both the amplitude and phase) of the coherent properties of SPPs excited on a nanohole array [55]. Their observations revealed SPPs dressed with the Bloch modes of the periodic nanostructure (dressed plasmons DP). Actively controlling DP waves via programmable phase patterns offers the potential for high field confinement applicable in lithography, surface-enhanced Raman scattering, and plasmonic structured illumination microscopy. In addition, as evidenced by the nonlinear tunneling conduction between gold electrodes separated by a subnanometer gap under illumination, Ward *et al.* further proved that a strong confinement of the field with an enhancement factor exceeding 10^3 for interelectrode distances on the order of a few Angstroms does exist [56].

Within only one year, we have witnessed many remarkable breakthroughs. Without any doubt, SPPs have become an extremely exciting research area. The unique electromagnetic properties provided by SPPs have attracted considerable attention from researchers in multiple disciplines. In turn, the merging of knowledge and expertise across different areas will further drive the astounding advances of SPPs research. The advances in the field are so extensive and it is inevitably difficult to include all in this brief review. Important future practical applications of SPPs are strongly dependent on further theoretical and technological advanced in this area.

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