Towards structured SPP manipulation of light at the nanoscale

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Abstract. Surface plasmon photonics is a rapidly developing area of physics, optics, and nanotechnology. The unique ability of meso- and nano-structures to manipulate light in the subwavelength range down to nanoscale volumes stimulated their use in a vast research endeavours. The investigations are driven by interests in both fundamental and practical applications aspects where plasmonic light concentrators elegantly interface mesoscale dielectric structure with thin metal films. The effects of a photonic nanojet and a photonic hook, discovered by Minins, have been studied in sufficient detail in the literature, but only recently have they been able to be confirmed experimentally for low-dimensional systems – in-plane surface plasmon waves. The nature of these phenomena lies in the dispersion of the phase velocity of waves inside the dielectric structure, which leads to constructive interference of the transmitted, diffracted, and near-field waves. Our results set the grounds for in-plane plasmonic wavelength scaled optics with unprecedented control of the energy flow at the nanoscale, and shown a way toward realizing the densely packed optical elements needed for future plasmonic and optical devices.

1. Introduction
The manipulation of subwavelength-scaled optical fields is attracting great interest owing to the key potential applications, including ultrafast communication, integrated plasmonic circuits, biophotonics, molecule diagnostics and quantum optics on a chip [1-5]. To this end the surface plasmon polaritons (SPPs) are perspective candidates for studying different optical phenomena and manipulate light at the nanoscale because SPPs are highly localized at metal–dielectric interface decaying exponentially away from it and thus have a shorter wavelength than the excitation radiation [6]. Such a planar system with a subwavelength confinement is attractive for “flatland” optics and photonics [7]. Different structures based on curved slits, circular and rectangle holes, dielectric structures, parabolic mirrors and dielectric metasurfaces have been proposed to realize subwavelength focusing [8-16] as the localization and propagation properties of SPPs are dictated by the surface morphology of the interface between the dielectric and metal film.

2. Plasmonic nanojet
The theoretical possibility of SPP nanojet (SPPJ) formation based on simulations was considered in [17-20] for dielectric structures of different shape. It has been shown that the effective refractive index contrast lies between 1.3 and 1.75. It was also demonstrated by the simulations that it is possible to produce SPPJs using dielectric mesoscale particles with a subwavelength focal spot and detect subwavelength metal particles [18]. The experimental observation of SPPJ propagation for the SPP
waves under the optical excitation of telecom $\lambda_0 = 1530$ nm are shown in Figure 1 [21]. Structures were manufacturing at Technical University of Denmark. The experimental value of FWHM (Full Width at Half Maximum) was equal to 0.68 $\lambda_0$ and the SPPJ propagation length of 3.53 $\lambda_0$.

![Figure 1](image_url). Plasmonic nanojet propagation for the SPP waves. The optical excitation of telecom wavelength $\lambda_0 = 1530$ nm is incident on the backside of the diffraction grating resulting in the excitation of SPP waves. Adapted from [22].

3. Plasmonic hook

Modern in-plane optical applications require so-called structured beam, tailored in shape (trajectory), amplitude and phase. It is well known how to spatially structure light [23], first demonstrated by Young in fringes about 200 years ago and more recently for SPP, in so-called structured beam [24-26]. SPP Airy beams, as example of structured beams, have been suggested theoretically [27] and confirmed experimentally [28,29] in plasmonics. Until recently, in low-dimensional systems SPP waves propagating along the curved trajectory were only SPP Airy-family beams.

A new class of curved localized surface plasmon wave, called the SPP hook (SPPH), was theoretically introduced in [30] and was suggested on the basis of in-plane manipulating SPPs as classical light in 3D free space, discovered in [31] and investigated in [32-39]. When we shift from 3D free space into two dimensions (in-plane), the quantum nature of matter manifests itself, creating new options for manipulation of light at nanoscale and controlling the interaction between matter and light [40]. For SPP waves we use of dielectric thin-film structures of controlled geometric shapes with broken symmetry on top of a metal (Gold) film surface [41]. To obtain the intensity distribution of the SPP wave field near the dielectric structure, the method of scanning near-field optical microscopy was used [42,43].

The SPPH is created using the in-plane focusing of the SPP wave through a dielectric Janus particle (broken symmetry of the shape). Mesoscale dielectric particle is a simple planar structure overcoming several of limited functionality and difficulty of integration. The word "particle" in this content means a mesoscale dielectric particle, i.e. the size of which is larger and comparable to the radiation wavelength, when strong coupling of scattered and evanescent waves in the near-field region is important [31]. Evidently, it will play a key role in the development of the future research of miniature and high-precision equipment. The SPPH propagates along wavelength scaled curved trajectory with radius less than the SPP wavelength, which represents the smallest curvature of the beam ever recorded for the SPP, and can exist despite the strong energy dissipation at gold film surface. While being by nature non-paraxial beams, SPPH demonstrates a number of remarkable properties similar to their three-dimensional analogue in free space. In addition, SPPH tightly confines optical energy near the metal-air interface and demonstrates significant beam bending over their propagation.

Recently, we have reported on the first experimental observation of a SPP hook, which is an in-plane localized SPP beam self-bending at the sub-wavelength scale [44,45] (see Figure 2). We use a
dielectric AR-P 6200 resist [45] that was placed on a 100 nm thick Au film. The dielectric Janus particle has widths of cuboid rib of about from 4000 to 5100 nm, with thickness from 220 to 280 nm and the angle of the prism is equal to 27°. The samples were prepared in Department of Photonics Engineering, Technical University of Denmark. It is obvious from the Figure 2 that there is an inflection point in the SPPH, where the SPP beam changes the direction of propagation [31, 44] at a distance from the rear surface about the SPP wavelength. This property shows one of the key differences between well-known SPP Airy-like beams and SPPH [46].

Figure 2. Experimental images of the SPPH. The diffraction grating is used for launching the SPP wave [47]. The SPP wave with a wave vector \( k_{\text{spp}} \) is excited at the telecom wavelength of \( \lambda_0 = 1530 \text{ nm} \) and is incident on the SPPH from left to right. The FWHM and propagation length are 1180 nm and 7660 nm, respectively. The beam-bending angle was equal to 15 degree for structure with width of 5 nm. Adapted from [44].

The reason for the appearance of the bent form of the localized SPP beam is constructive interference between the incident, diffracted, and scattered fields near the shadow surface of the dielectric structure due to interactions in the near field. The bending effect of the SPP beam (curvature) at a fixed shape of the dielectric structure depends on its size. A decrease in size leads to a decrease in the effective length of the SPP hook and full propagation lengths, but a slight increase in its curvature (and the SPPH deflection angle) due to the stronger manifestation of diffraction effects on the edges of the structure. So, for the structure shown in Figure 2, the change in the bending angle is in the range from 3 to 16 degrees with a change in wavelength by ±2% with a maximum corresponding to zero detuning. At the same time, with a decrease in the size of the structure, the change in the bending angle is from 6 to 18 degrees with a maximum corresponding to a change in the wavelength by +2%, i.e. moves to the right. This is an additional degree of freedom that can be used to control light to a nanoscale level and dynamical manipulation of SPP waves including switching. The optically controlled electronic circuitry for energy-efficient and faster switching with photonic functionality is an appealing notion.

4. Discussions
Well-known idiom since ancient times is “Seeing is believing”. The concepts of photonic nanojet and hook now has gone beyond classical optics and penetrated such fields, as THz, acoustic [48-50] and now low dimension system - surface plasmons. Highly confined structured low-dimension electromagnetic fields play a significant role in SPPs because of their outstanding subwavelength nature [51, 52]. The plasmonic jet and hook represents an exciting new field for the application of surface-plasmon waves in which SPP based concepts merge the fields of electronics and photonics at the nanoscale [3, 53]. We succeed in developing the first in-plane plasmonic wavelength-scaled refractive-diffractive lens. The results described above open the exciting possibility of a readily available structured SPP beam toolkit that can both create and deliver exotic states of beam at nanoscale. It is remarkable that this possibilities is achieved with inexpensive and a simple unusual optical element.
It is interesting to note that recently local excitation of plasmonic PMMA waveguides by hole was considered in [54]. The results are shown in Figure 3. The structure consists of a circular hole with 800 nm diameter milled in 200 nm thick gold film. The hole is adjacent to a 5 μm long and 300 nm thick PMMA line. The field confinement 0.5 μm after the end of the dielectric rectangle similar to SPP nanojet. However, the characteristics of the localization region of the SPP in the shadow part of the dielectric particle are not given.

![Figure 3](image-url)

**Figure 3.** (a) Proposed in [54] structure. (b) Fabricated sample. (c) NSOM measurement results. Adapted from [54] under a Creative Commons Attribution 4.0 International License.

From a future applications possibilities, photonic and plasmonic hooks are important because the Airy-family beams now are not the only self-bending beams. Importantly, these effects prove that the concept of wave acceleration can be observed in non-paraxial approximation in the near-field due to constructive interference of refracted and diffracted waves. And investigations shown that photonic and plasmonic nanojet and hook are exceptionally easy to manipulate in unusual ways and realize. The effects of the SPP nanojet and hook could open new horizons for manipulating the interaction between matter and light at the nanoscale. One may highlight several key potential applications of mentioned above effects: plasmonic trapping and tweezers [55,56], plasmonic and nanoscale biosensing sensors and nature [57-60]. These effects also could be potentially used to increase photocarrier confinement in THz receivers, emitters and antennas [61-66].

5. Conclusions

Full two-dimensional in-plane control of structured light through the use of near-field effects and non-paraxial approaches based on common dielectric materials may open a new possibilities for control of localized beam parameters beyond the diffraction limit in printed photonic-driven devices. For example, we believe that the curved trajectory of the photonic hook structured beam can break the limitations of classical condition of line-of-sight in in-plane photonic interconnection [67,68] and switching on-a-chip. These exciting perspectives are surely worthy of further deep attention from the optical community. It is our great hope that this work should attract the attention of scientists to get engaged with plasmonic investigations and its potential applications, including on-chip virus detection [69-72] and provides new ideas for the development of new in-plane devices [73,74].

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