Structured plasmonic beam: in-plane manipulation of light at the nanoscale

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Abstract. The brief review on recent approaches on the formation of a new class of subwavelength scale localized structured surface plasmon polaritons (SPP) beams is discussed. For the Janus-like particle (including the geometrically symmetric particles with different dielectrics) the morphology of the field localization area and its properties depends on the particle shape and material. Plasmonic hook (PH) beam does not propagate along straight line but instead follow curved self-bending trajectory. Wavefront analysis behind of such symmetric and asymmetric mesoscale rectangle structure reveals that the unequal phase of the transmitted plane wave results in the irregularly concave deformation of the wavefront inside the dielectric which later leads to creation of the PH. Such dielectric structures placed on metal film enable the realization of new ultracompact wavelength-selective and wavelength-scaled in-plane nanophotonic components. SPP have potential to overcome the constrains on the speed of modern digital integrated devices limitation due to the metallic interconnects and increase the operating speed of future digital circuits.

1. Introduction
A number of works have been devoted to the various physical principles and possibilities of manipulating biological samples, materials, etc. using light [1-7] since the discovery of optical traps. Both continuous (including resonant) and pulsed light illumination have played an important role in the development of this research [1, 6-11]. Note that the effects of pulsed illumination are quite complex and can significantly change the optical force. For example, heating effects can change the dielectric constant of a particle, which can significantly increase the optical power [12].

However, it is quite difficult to capture and trap Rayleigh particles well below the diffraction limit directly using conventional optical tweezers - since the nanoparticles dimensions are much smaller than a focused beam spot, and the nanoparticle volume limits the amount of light that can be used for trapping [13]. Among others tweezers, plasmonic tweezers are based on a surface plasmon (SP) wave refer to charge density oscillations and generated at the interface between a dielectric structure and a conductive film. The nanoscale confinement of SPs excited by laser light can give rise to many scientific and practical applications. SP waves are two-dimensional in nature. However, with the transition from three-dimensional to two-dimensional space, the quantum nature of matter begins to manifest itself - new opportunities are created to control the interaction between structures and light. Among the different ways of SPs manipulation, the great interest is directed at the implementation of the simple, low cost and compact method for subwavelength localization and curving the trajectory of SP wave at the nanoscale. One of the potential applications of curved surface plasmonic beams is in the fields of surface trapping of nano-objects. The optical power generated by surface plasmon in resonant mode has been proposed and investigated since 2001 [14-20]. Plasmonic tweezers were
rapidly developed in the last 10 years, resulting in improved trapping parameters and their use in different area including biological. In addition, the SP waves provide further spatial resolution towards the nanoscale [21,22] and opens new horizons in the realization of optically driven on-a-chip devices.

In this regard, a promising direction is the development of simple and effective methods for localizing SPs in the sub-diffraction volume and even below the diffraction limit. Also among the important domains in plasmonics is the study of the transport of SPs and the development of physical methods for manipulating them at the nanoscale.

2. Wavelength-selective mesoscale dielectric structures

The in-plane Fresnel zone plate to focus the SPP waves was studied in [23] and 15 times the field intensity enhancement at the focal length of 60 nm was obtained. Later, a conical in-plane nanoslit-based Fresnel zone plate was proposed to realize focusing below the diffraction limit by exciting SPPs and enabling them to couple with radiating propagation modes [6, 24]. The focal spot size was as small as 0.31 times the illumination wavelength at the focal distance of 8 wavelength. The depth of focus was 0.6 of illumination wavelength. The theoretical possibilities of plasmonic photonic jet formation for flat dielectric disc [25] and square [26] single particles were also considered, demonstrating the capability to control the subwavelength focusing properties of a plasmonic particle-lens by profiling the height of the dielectric structure at the operation wavelength in order to obtain the required effective refractive index contrast. The resolution of plasmonic jet produced by single Si$_3$N$_4$ cube was 0,40 $\lambda$ at 1300 nm wavelength with field intensity enhancement of 9 dB [26]. The array of flat dielectric Si$_3$N$_4$ cuboids [27], in despite of the dissipation of SP energy while propagation is caused due to Ohmic absorption in metals, allow to increase the propagation length of SPs. Later, the effect of the plasmonic nanojet formation was experimentally verified for the first time in [28]. The experimental value of the propagation length of plasmonic nanojet of 3.53 $\lambda$ at telecom wavelength of 1530 nm (Fig.1). It can be seen that the best (minimum) resolution is observed at a small negative detuning of the wavelength of the irradiating radiation.

![Figure 1](image1.png)

Figure 1. Dependences of the half-width of the field intensity distribution across (FWHM – full width at half maximum) and along the plasmonic jet (FLHM – full length at half maximum) vs illuminating wavelength (left) and the focal length, the length of the plasmon jet vs height of the dielectric structure (right).

For moving nanoparticles around obstacles the concept of so-called photonic hook [29] (PH) was investigated theoretically [30] and experimentally [31,32,33] in free space. At the same time, based on the discoveries in free space [29] the concept of in-plane plasmonic hook was theoretically predicted in [34] and experimentally verified for the first time in [35]. It has been shown that SP hook bend angle occurs within the excitation the telecom wavelength and propagates along a wavelength-scaled curved trajectory in contrast to that for the other today known self-bending Airy-family plasmonic beams usually having a parabolic beam trajectory. The PH angle of curvature, defined as an angle of beam bending, in the smaller dimensions structure is higher and increase with increasing of excitation wavelength than that for the more bigger structure, in which the speed of change of the curvature little
with the change vs wavelength. Thus, PH could be used to focus and deflect SPs through a Janus dielectric particle [35]. Moreover, it has been shown both for electromagnetic 3D case, acoustics and in-plane SP that in the photonic hook family beams there is an inflection where the curved beam changes its propagating direction (Fig.2). This property is not possessed by the Airy-family beam and demonstrates one of the fundamental differences between subwavelength curvature photonic hook and classical Airy-like beams [6,29,31-35].

Figure 2. Bending angle (left) and propagation length and FWHM of the SPP hook (right) vs illuminating wavelength. The bending angles (left) are shown for different dimensions of dielectric Janus particle (small – red and big - black).

Our analysis for different wavelengths has shown that the situation is quite complicated. Although for a sufficiently large Janus particle size, the change in the bending angle versus frequency is not large, nevertheless, a "quasi-resonance" behavior of the considered dependence is observed. For a smaller particle, the bending is slightly larger, and the resonance structure is not visible. It is interesting to note that regardless of the size of the Janus microparticle, the range of the bending angle is the same.

3. Discussions
In summary, it was confirmed, realized and demonstrated high performance of SPP-based wavelength selective nanophotonic mesoscale elements operating at telecom wavelengths: dielectric flat cuboid plasmonic lens and plasmonic hook generator, thereby enabling the realization of ultracompact wavelength-scaled plasmonic components. Wavelength-scaled dielectric cubic-based particle is a simple planar structure overcoming the block of limited functionality and difficulty of integration. Credibly, it will play an important role in the development of the research of future miniature and high-precision equipment. The authors applied their experience in this field to solving modern SPP photonics problems. It has been shown that auxiliary dielectric structures both symmetrical and with broken symmetry can be used to modify properties of SPP manipulation in-plane, assist configuring SPP optical forces and obtain extraordinary parameters of light-matter interaction. It could be noted that in order to obtain a curved SPP flux the geometrically symmetric cubic particles, but with a specially imposed asymmetry of the refractive index (two different dielectrics) may be used. The optical manipulation of micro- and nano-objects with structured near-field SPP beams and the problem of sharp sub-wavelength structured SPP beams formation by mesoscale dielectric particles is also solved. The experiments showed that the SPPs hook propagate over 5 of wavelength at telecom wavelengths along propagation directions in gold film and exhibit strong subwavelength confinement with low bend losses [35]. Due to its flexibility, ease of fabrication and good reproducibility, the proposed platform can be adapted to accommodate future applications ranging from nanoscale light control to photonic devices on a chip. SP fields can be shaped, localized (focused) and guided by simple dielectric mesoscale structures.
4. Conclusions
The effects of localized structured field in the form of the plasmonic jet and the plasmonic hook can be used both to increase the limitation of photocarriers in terahertz photoconductive devices (PD) [36,37] by introducing single or multiple Janus dielectric particles into the PD’s gap [38] and to create, for example, curvilinear waveguide structures similar to [27]. To tune the focal length and the localized structured field of surface plasmonic modes a dielectric structure based on optofluidics may be used [39,40]. Experimental results show that these in-plane refraction-diffraction methods has a general sense with which the realized plasmonic functions are expected to find promising and wide applications for future plasmonic beam technology and integrated optical circuits [19, 41-43].

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