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Enhancement of Localized Plasmonic Fields in the Ultraviolet Region of Two-Dimensional Silver Nanotips

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Abstract

The concentration of optical energy at a specific point has gained significant importance and wide applicability in nanoimaging and nanosensing technologies. This is particularly notable in the ultraviolet wavelength region (300–400 nm), which offers high spatial resolution, stronger interaction with matter, enhanced sensor sensitivity, and high-density optical data storage. Despite the substantial potential of this spectral range, several limitations still exist. In this article, a trapezoidal plasmonic silver nanotip is investigated for the concentration of the electric field within the 300–400 nm wavelength range. Silver is selected due to its favorable balance between the interband transition threshold and intrinsic losses. To optimize the geometrical dimensions, a multiparametric sweep over the nanotip dimensions (small base and large base) is performed, and the optimal configuration is subsequently identified.

Keywords: Plasmonics, Ultraviolet Nanophotonics, Silver Nanotips, Geometrical Optimization, Finite-Difference Time-Domain (FDTD)

Introduction

Silver, due to its favorable dielectric function and relatively low intrinsic losses, is one of the most effective plasmonic materials for enhancing electromagnetic fields at the nanoscale. It has been widely employed in applications such as optical sensors, surface‑enhanced Raman spectroscopy (SERS), optical imaging, and the enhancement of solar cell efficiency [1]. However, most of these applications have so far focused on the visible to near‑infrared spectral regions. Extending the plasmonic response into the ultraviolet (UV) range can open new opportunities in photochemistry and photolithography, UV sensing, and high‑resolution imaging [2].

The plasmonic response of silver nanostructures is strongly dependent on their geometry. Parameters such as shape, aspect ratio, tip radius, gap size, and the surrounding dielectric environment play a decisive role. This strong geometrical dependence is well demonstrated by the wide variety of reported nanostructures, including nanowires, nanocubes, nanodisks, and nanopyramids [2,3]. Nevertheless, the systematic geometric optimization of two‑dimensional silver nanotips to achieve maximum field enhancement in the ultraviolet region has received comparatively little attention.

Plasmonic nanotips are widely used in techniques such as tip‑enhanced Raman spectroscopy (TERS) and SERS to confine electromagnetic fields to dimensions well below the diffraction limit and to generate intense localized “hot spots.” Previous studies have shown that modifying the geometry of metallic tips, such as conical gold or silver nanotips, can increase the field enhancement factor by several hundred times. Consequently, in nanoscale optical imaging, metallic nanotips capable of guiding propagating surface plasmon polariton (SPP) modes along the tip and concentrating them at the apex are of particular importance [4].

By controlling parameters such as the width of the small base, the tip angle and length, as well as the thickness of the structure, it is possible to tune the resonance between quasi‑localized plasmonic modes at the apex and guided SPP modes propagating along the tip. The realization of such nanotips can enable important applications in refractive‑index sensing, nanophotolithography, and nanoscale photochemical excitation in the near‑ultraviolet region with spatial resolutions on the order of a few nanometers.

In many sharp‑tip structures, SPPs propagate along the surface of the tip and are converted into localized surface plasmon resonances (LSPRs) at the apex. In this study, the primary objective is to guide optical energy from the base toward the apex and concentrate it there. Therefore, SPP modes must be efficiently excited on the surface of the tip and guided toward the apex, where, if possible, the field is further localized in the form of an LSPR. Accordingly, the nanotip design must ensure the condition for SPP propagation along the entire length of the tip [5,6].

Numerous studies have investigated SPP modes in silver‑based structures; however, the main focus has generally been on the visible and near‑infrared spectral regions. For example, silver thin films with thicknesses of 40–60 nm have been reported to support SPP resonances in the 736–762 nm range (red to green spectral region) [7]. In another study, it was shown that SPP modes can propagate toward a tip apex with a radius of approximately 20 nm without significant interruption, leading to substantial field enhancement, although the resonance wavelengths of such tips were primarily reported in the visible range [4].

More detailed analyses indicate that scattering effects and interband transitions in silver also influence SPP properties in the near‑ultraviolet region. Nevertheless, this spectral range has been less explored experimentally, particularly in the context of designing plasmonic nanotips specifically optimized for UV operation [5]. Overall, silver plasmonic nanotips operating predominantly in the SPP regime for the ultraviolet spectrum have been investigated far less extensively, with most studies focusing on LSPR resonances or hybrid LSPR–SPP modes. Limitations such as increased losses due to interband transitions in the UV and fabrication challenges associated with precise geometries required for SPP guiding at these wavelengths are among the main reasons for this gap [4,5]. Therefore, the design and optimization of silver plasmonic nanotips supporting guided SPP modes specifically tailored for the ultraviolet region remain a relatively open and active research area, with significant potential applications in UV sensing, photochemistry, and high‑resolution imaging.

In this article, a two‑dimensional silver nanotip with a trapezoidal cross‑section is designed and geometrically optimized for plasmonic field enhancement in the ultraviolet region. The primary objective is to investigate the influence of geometrical parameters on the field enhancement factor and its spatial distribution at two representative wavelengths of 300 and 342 nm. The results of this study can serve as a guideline for the design of advanced plasmonic probes for ultraviolet nanophotonic applications.

Simulation and Methodology

In this study, three key factors are considered for optimizing and concentrating the electric field: the use of silver as the plasmonic material, the excitation and guidance of propagating plasmon modes, and operation in the ultraviolet spectral region. To support guided surface plasmon polariton (SPP) modes, the nanotip surface must be sufficiently smooth or appropriately graded to allow plasmonic waves to propagate from the base toward the apex with minimal scattering losses. In addition, by selecting an appropriate sidewall angle and a suitable small‑base radius, the plasmonic field is effectively concentrated from the edges of the tip toward its center, facilitating the conversion of the guided SPP mode into a localized surface plasmon resonance (LSPR) at the apex.

The resonance wavelength of the SPP mode supported by the nanotip can be tuned by adjusting parameters such as the metal thickness, the sidewall inclination angle, and the surrounding dielectric environment. Achieving resonance in the ultraviolet region therefore requires a careful and precise selection of these geometrical and material parameters.

In this work, a three-dimensional silver nanotip with a trapezoidal cross-section and a thickness of less than 50 nm is designed and investigated. The trapezoidal geometry is chosen due to its advantages in efficient field concentration and its flexibility in enabling precise control over the geometrical parameters. The simulations are performed in the xy plane using the Lumerical software package, as illustrated in Figure 1. The amplitude of the incident electric field is set to 1 V/m, and the system is analyzed at two representative wavelengths of 300 nm and 342 nm. The influence of these wavelengths on the field enhancement and spatial field distribution is clearly demonstrated in the corresponding simulation results.

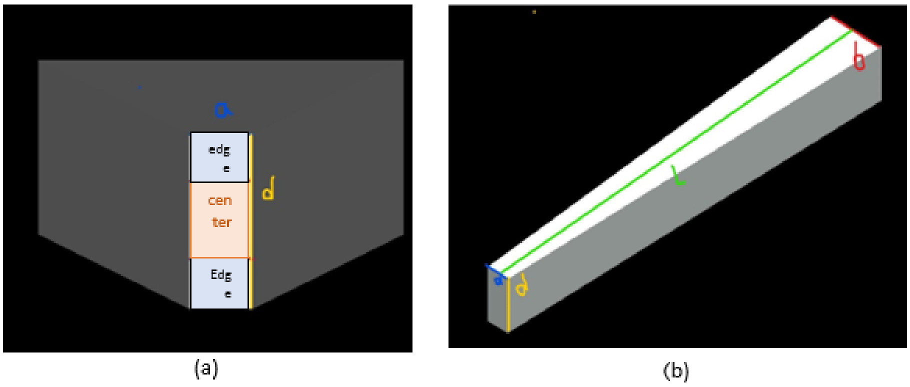

Figure 1. *Schematic illustration of the plasmonic nanotip:* (a) the overall geometry of the nanotip with labeled geometrical parameters; (b) front view of the lateral surface at the small base.

The variable geometrical parameters of the structure include the small base and the large base, whose dimensions are varied according to Table 1. Simultaneously with the variation of these dimensions, not only the magnitude of the electric field changes, but also the spatial location of field concentration is altered. Depending on the intended application, it must therefore be determined whether field confinement at the center of the structure or along its edges is preferred. Accordingly, in this work, the geometry of a plasmonic nanotip with a trapezoidal surface is optimized with the objective of achieving a dominant propagating surface plasmon polariton (SPP) mode. The primary design criterion is the maximization of the electric field intensity at the center of the nanotip while suppressing the dominance of edge-localized field concentrations.

Table 1. Geometrical parameters used in the optimization of the plasmonic nanotip.

Parameter	Minimum (nm)	Optimal (nm)	Maximum (nm)
B (Large base width)	75	80	85
A (Small base width)	8	14	16

Increasing the small base width to 14 nm leads to a reduction in edge-localized field concentrations and a simultaneous enhancement of the electric field in the central region of the nanotip. In this analysis, the parameters b and d are kept constant at 80 nm, while the total tip length is fixed at L = 650 nm (Fig. 2).

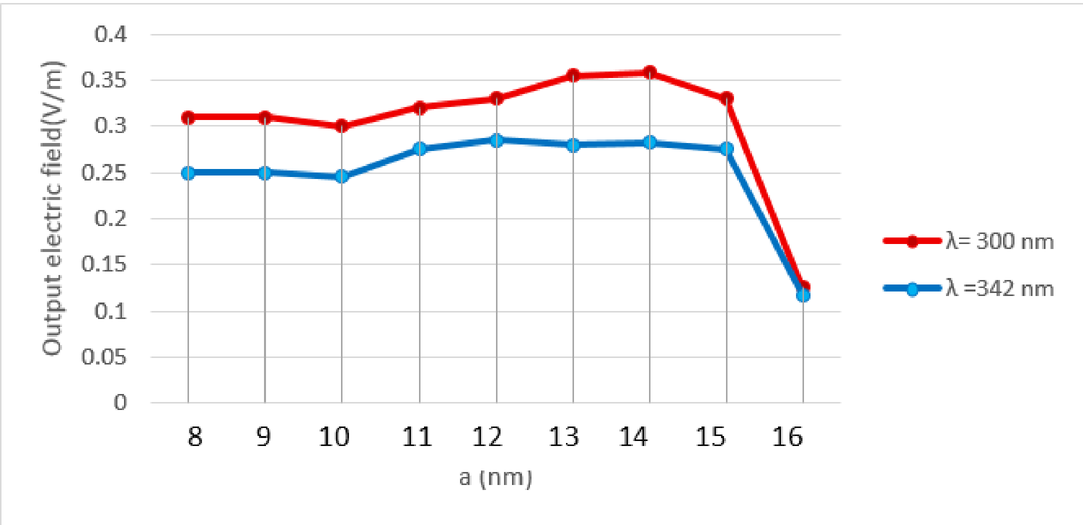

Figure 2. Effect of the small base width of the nanotip on the output electric field intensity.

The results indicate that increasing the large base width (B) leads to a smoother electric field response and an improved field distribution within the central region of the nanotip. Selecting a large base width of B = 80 nm provides a balanced ratio between the electric field intensities at the center and the edges, indicating the formation of a stable surface plasmon polariton (SPP) mode. In this stage of the analysis, the priority is not solely the maximization of the field intensity, but also the spatial location of field confinement. It is observed that for B ≥ 79 nm, the electric field concentration predominantly occurs in the central region of the nanotip. In contrast, for large base widths smaller than 79 nm, the electric field becomes localized at the edges rather than at the center; therefore, these configurations are excluded from consideration. Throughout this analysis, the parameters L = 650 nm, A = 14 nm, and d = 80 nm are kept constant (Fig. 3).

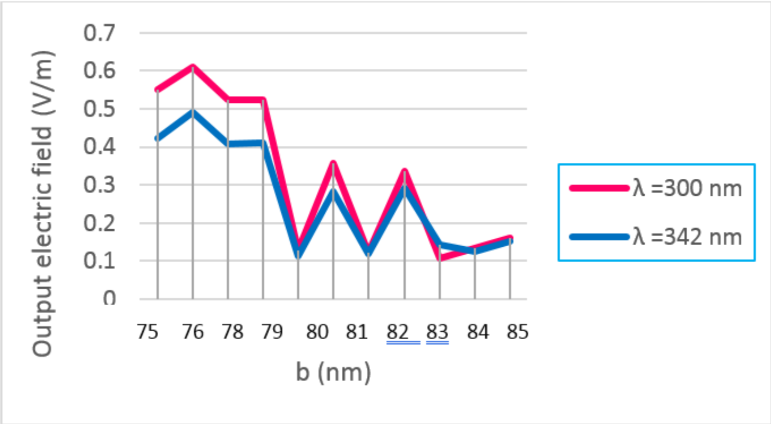

Figure 3. Effect of the Large base width of the nanotip on the output electric field intensity.

Figure 4 illustrates the spatial distribution of the electric field at the apex of the plasmonic nanotips.

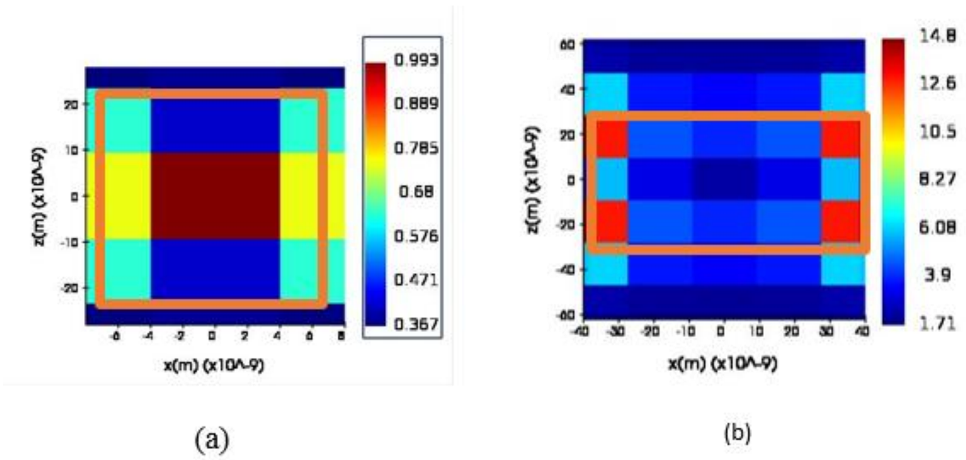

Figure 4. Electric field distribution along the plasmonic nanotip at a wavelength of **300 nm**. The orange rectangle outlines the nanotip boundaries, overlaid with the electric field intensity map. Panel **(a)** indicates the location where the electric field exits from the **small base**, while panel **(b)** denotes the region where the field is launched from the **large base**.

The optimal values for the nanotip thickness and length were determined through systematic optimization. Ultimately, the optimized geometry—comprising a large base width of 80 nm, a small base width of 14 nm, a thickness of approximately 50 nm, and a total length of about 550 nm—is identified as a structure exhibiting a dominant surface plasmon polariton (SPP) behavior with maximum electric field confinement in the central region of the tip. Following the selection of the optimal geometrical parameters, the performance of the optimized nanotip was further investigated on different surrounding substrates, including air, silicon, glass, and water. The results indicate that the most favorable field enhancement and confinement are achieved when the nanotip operates in air. Consequently, micromachining-based fabrication techniques are proposed as suitable approaches for the realization of the optimized plasmonic nanotip structure.

Conclusion

In this paper, the geometrical optimization of two-dimensional silver plasmonic nanotips for electric field confinement in the ultraviolet region was systematically investigated. The results demonstrate that a design with a length of approximately 560 nm, a small base width of 14 nm, a large base width of 80 nm, and a thickness of about 46 nm is capable of concentrating the electric field at the nanotip apex. Consequently, the optimized tip exhibits predominantly localized behavior, with the response mainly governed by localized surface plasmons (LSPs).

These findings provide clear design guidelines for ultraviolet two-dimensional plasmonic devices that are compatible with planar nanofabrication technologies. However, despite the formation of surface plasmon modes, no significant electric field enhancement is observed in the investigated structure. This limitation arises from the intrinsically high losses of metals in the ultraviolet spectral region. In this wavelength range, interband transitions substantially increase the imaginary part of the metal's dielectric function, leading to a pronounced degradation of the plasmonic resonance quality factor. As a result, although the SPP mode is formed and propagates along the surface, its energy is dissipated before strong field confinement can occur, and the structural response manifests as a distributed field without pronounced enhancement.

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