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On the performance of plasmonic meniscus lenses for surface plasmon focusing

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Abstract

In this work, we present the design process and response of an ultra-compact plasmonic meniscus lens for Surface Plasmon Polariton (SPP) focusing. To design the lens, we adapted the lens maker equation (a classical optics technique) by introducing the concept of effective media for SPPs traveling within different multilayered media. This adapted equation was then exploited to design a convex-concave lens, also known as a positive meniscus lens, for use in plasmonics. The lens was designed by placing a meniscus-shaped block of silicon nitride (Si_3N_4) on top of a semi-infinite slab of gold (Au). The performance of the lens is evaluated in detail in terms of the power enhancement, depth of focus, and spatial resolution of the focus. Moreover, the lens robustness is studied using off-axis illumination along with its spectral response, demonstrating how the adapted lens maker equation can be used in the design of such plasmonic meniscus devices.

1. Introduction

Plasmonics research has become an area of great interest in recent decades allowing the manipulation and control of Surface Plasmon Polaritons (SPPs) [1,2]. SPPs have shown potential to be used in a wide range of devices and applications such as focusing [3], including nanojets [4], nanoantennas [5,6], and plasmonic circuits [7], among others. In the field of lensing, several different structures have been proposed for SPP focusing utilizing concepts that have been first developed in classical optics such as Luneburg and Eaton lenses [8], Fresnel designs [9], as well as shaped lenses such as plano-convex/concave and bi-convex [10,11], among others. However, there has been no work conducted around plasmonic lenses shaped as a meniscus, despite the evidence that when used in a classical optics setting (considering ideal dielectric lenses immersed in free space and illuminated with a planewave) they offer improvements to the spatial resolution of the generated focal spots [12,13].

A positive meniscus lens consists of a convex input face and a concave output face. In classical optics, when compared to similarly-sized focusing devices, they have demonstrated the ability to exceed the focusing performance in terms of power enhancement and spatial resolution at the position of the focus [14]. This can be attributed to both faces being curved and therefore can focus a broader range of incident illumination angles into a single focal point, resulting in a reduction of spherical aberrations [15]. Hence, meniscus lenses offer the potential to produce a focus that has both a greater power enhancement at the focus while also having a higher spatial resolution compared to plano-convex lenses of similar dimensions [14].

Inspired by the potential improvements meniscus lenses offer, in this communication, we will present how an adapted version of the lens maker equation can be used in plasmonics to design a plasmonic meniscus lens. We will discuss how this classical method can work in plasmonic structures with the generated focus of the designed meniscus lens in agreement with the designed position. A full study of the focusing characteristics of the lens is presented in terms of the power enhancement and spatial resolution of the focus. We also present a test of the robustness of this design method by studying the focusing performance when considering off-axis illumination, demonstrating how the plasmonic meniscus lenses still work as expected for incident angles of up to 15°. During the conference, we will further explore the performance of the lens with regards to the power enhancement, depth of focus, and transversal resolution as well as exploring its spectral response. These results demonstrate how meniscus lenses can be implemented in plasmonics enabling their potential use in applications such as plasmonic sensing and optical tweezing.

2. Design & methods

Plasmonic lenses for SPP focusing can be designed by exploiting effective medium concepts of SPPs traveling in multilayered media. This can be done by placing shaped dielectrics on top of semi-infinite metals (such as, in our case, silicon nitride (Si_3N_4) on top of semi-infinite gold (Au)) with the whole structure immersed in air [16]. This results in two regions, region 1 (r_I) being insulator-metal (air-Au in our case) and region 2 (r_{II}) being insulator-insulator metal (we use air-Si_3N_4-Au), each with an effective refractive index described using two separate equations. For r_I (insulator-metal) one can use the well-known equation for the dispersion relation of surface plasmons [16], $n_{SPP,r_I} = (n_{air}^2 n_{Au}^2)/(n_{air}^2+n_{Au}^2)^{1/2}$ while in

r_{II} (insulator-insulator-metal) one follows the method described in ref [17], where variations to the height of the dielectric allow the effective refractive index to be tailored as required.

We designed the shape of the lens by using an adapted version of the lens maker equation, shown as Eq. 1 [12]. To do this we must take into account several parameters including the radii of curvature of each face, effective refractive indices of the lens and surrounding region (II and I, respectively), and the thickness of the lens [12,18]:

$$\frac{1}{EFL} = \left(\frac{n_{SPP,r_{II}}}{n_{SPP,r_I}} - 1\right)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{\left(\frac{n_{SPP,r_{II}}}{n_{SPP,r_I}} - 1\right)t}{n_{SPP,r_{II}}R_1R_2}\right] \quad (1)$$

where EFL is the effective focal length, $n_{SPP,r_{I,II}}$ are the effective refractive indices in each different region where the SPPs travel: r_I, which is air-Au and r_{II} corresponds to air-Si_3N_4-Au, R_1 and R_2 are the radii of curvature of the input and output faces of the lens (right and left faces of the lens in Figure 1, respectively) and t is the thickness of the lens in the direction of propagation at $x = y = 0$. A schematic representation of the lens maker equation can be seen in Figure 1.

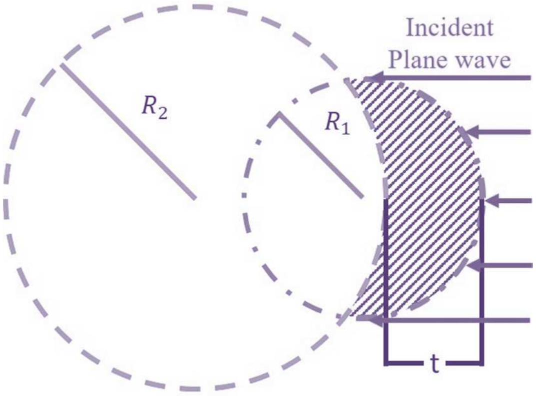

Figure 1. A schematic representation of the lens maker equation used to design lenses. Here it is shown a positive meniscus lens where R_1 and $R_2 > 0$, illuminated by SPPs from the right.

In this communication, we follow the approach stated above to design the plasmonic lens working at the telecommunications wavelength of $\lambda_0 = 633$nm. For the dielectric, we used Si_3N_4 while for the semi-infinite metallic slab Au was implemented. SPPs are excited using narrow slits carved in the Au slab [19,20]. The SPPs propagate along the positive x-direction at the Au-air interface with the electric field having y- and x-components and a magnetic field parallel to the z-axis (i.e. a TM wave) [21].

The plasmonic lens was designed with an EFL of $2\lambda_0$ and R_1 was designed to be equal to the EFL. A height was then chosen for the dielectric block so r_{II} had a large enough $n_{SPP,r_{II}}$ so when Eq. 1 was used we produce a curved output face ($R_1 \approx R_2$). The plasmonic lens was simulated using the commercial software COMSOL Multiphysics®. Full details about the device design will be presented at the conference [12].

3. Results

First, the power enhancement (defined as the ratio between the power distribution with and without the lens measured on the focal plane) along the x-axis calculated on the surface of the metal ($y = 0$) at $z = 0$ (centre of the lens) is shown in Figure 2a. As observed, a clear focus is obtained at $x = 1470$nm ($\sim 2.32\lambda_0$), in agreement with the design value.

The power enhancement along the transversal z-direction at the position of the focus is presented in Figure 2b. From these results, the Full-Width at Half Maximum (defined as the distance at which the power enhancement at the focal length has decayed to half its maximum along the transversal x-direction) is FWHM = 353nm = $0.56\lambda_0$.

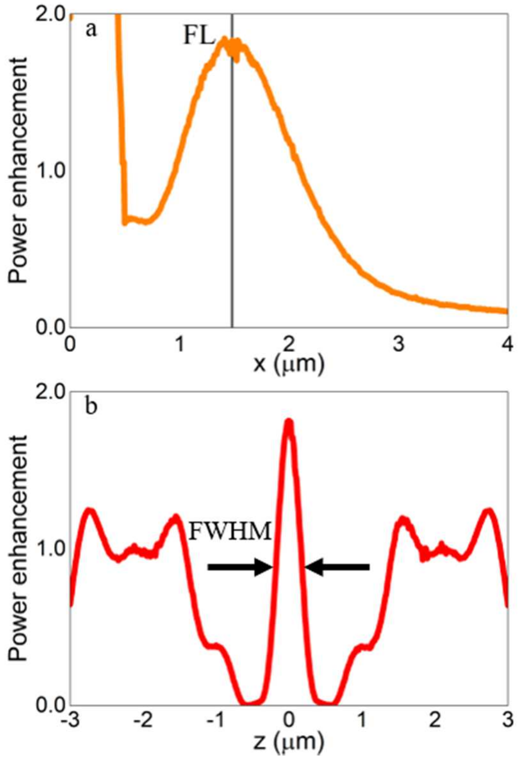

Figure 2. Numerical results showing the power enhancement (a) along the propagation x-direction on the surface of the metal ($y = 0$) at the centre of the lens ($z = 0$) and (b) along the transversal z-direction at the surface of the metal ($y = 0$) at the position of the focus ($x = 1470$nm).

We then tested the robustness of the lens by illuminating the lens as it is rotated about the output surface of the lens at the centre ($z = 0$). The effect of doing this is presented in Figure 3. As it is shown, the position of the focus shifts as the angle increases from 0° to 15° to 30° in Figure 3a,b,c respectively. We can also observe the impact that changing the rotation angle of the lens has on the power enhancement of the focus. From these results, when the rotation angle is below 15° there is a small change of the power enhancement before a significant decrease for angles larger than 15°. This shows that the lens is robust, still functioning well even when under less than perfect illuminating conditions.

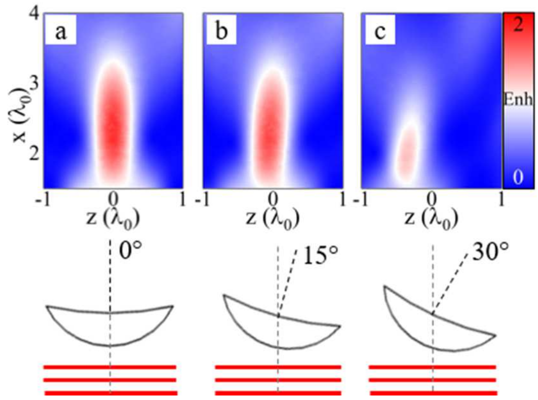

Figure 3. Numerical results showing the power enhancement at the surface of the metal ($y = 0$) for different angles of (a) 0° (b) 15° and (c) 30° with a schematic representation shown underneath.

The configuration presented in the results here can offer a wide range of potential applications such as optical tweezers and plasmonic sensors. Our efforts to develop plasmonic meniscus lenses will be shown in detail during the conference, with a detailed comparison to an ideal case (two-dimensional lenses illuminated by plane waves) discussing the similarities and differences of the power enhancement, depth of focus and transversal resolution in these different cases [12].

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