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Exploiting meniscus lenses for surface plasmons focusing

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Abstract

Here, we present the design and study of an ultra-compact plasmonic meniscus lens for surface plasmon focusing. Our approach is based on using the lens maker equation allowing us to design a positive meniscus lens. The proposed plasmonic device is then implemented by shaping a block of Si_3N_4 placed on a semi-infinite metal, gold, slab. We evaluate the performance of the designed lens showing an improvement when compared to similar sized plasmonic lenses in terms of spatial resolution and power enhancement at the focus.

1 Introduction

The area of research of plasmonics has expanded rapidly in recent decades. The devices made using these theories have shown their ability to be highly efficient, while remaining compact, in a wide range of applications such as focusing [1–2], sensing [3], nanoantennas [4–5] and plasmonic circuits [6], among others. Devices with the ability to produce the focusing of surface plasmons polaritons (SPPs) into a focal spot have also been benefited from the research in plasmonics. In this context, different focusing structures have been proposed by borrowing concepts found in classical optics such as Fresnel [7], Luneburg and Eaton lenses [8] as well as lenses designed using the lens maker equation [9], such as plano-convex/concave, bi-convex. However, to date there has been no analysis conducted around plasmonic meniscus lenses, despite the fact that they may have the ability produce smaller focal spots [10].

Meniscus lenses consist of a combination of convex and concave elements. In terms of enhancement and resolution, they have demonstrated the capability to exceed the performance of similarly sized focusing elements. This is due to the curvature of both faces being able to focus a greater amount of incident angles into the focal point, resulting in reduced spherical aberrations [11]. Hence, such lenses can produce a much tighter focus with greater power enhancement, a higher resolution when compared to plano-convex lens of similar dimensions.

2 Design & methods

The meniscus lenses studied here are designed using the lens maker equation by taking into account parameters such as radii of curvature, effective refractive indices of the regions and the thickness of the lens [9] :

$$\frac{1}{EFL} = \left(\frac{n_{SP,r2}}{n_{SP,r1}} - 1\right)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{\left(\frac{n_{SP,r2}}{n_{SP,r1}} - 1\right)t}{n_{SP,R_2}R_1R_2}\right] \quad (1)$$

where *EFL* is the effective focal length $n = n_{SP,r2}/ n_{SP,r1}$ is the ratio between the effective refractive index of the different regions where the SPPs travel: region 1, composed of insulator-metal and region 2 which corresponds to the insulator-insulator-metal, R_1 and R_2 are the radii of curvature of the input and output surface of lens (right and left faces of the lens in Fig. 1, respectively) and t is the thickness of the lens along the z-direction at $x = y = 0$. A schematic representation of the lens maker equation can be seen in Fig 1.

A common technique for the design of plasmonic lenses is by placing dielectrics on top of semi-infinite dispersive metals. By immersing the whole structure in air, we can determine the effective refractive index of each of the two regions described above by exploiting the concept of effective media. In region 1 one can use the well-known equation for the dispersion relation of surface plasmons [2], $n_{SP,r1} = [(n_{air}^2 n_m^2)/(n_{air}^2+n_m^2)]^{1/2}$ while in region 2, the effective refractive index can be tailored by varying the height of the dielectric [12].

Following this approach, in this communication, we designed the plasmonic lens to operate at the telecommunications wavelength of $\lambda_0 = 633$nm. Silicon nitride (Si_3N_4) was used for the dielectric and gold (Au)

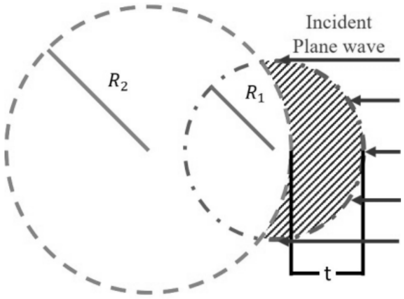

Figure 1. A schematic representation of the lens maker equation used to design lenses. Presented here is a positive meniscus lens where R_1 and $R_2 > 0$, illuminated by surface plasmon polaritons from the right.

was implemented for the semi-infinite metallic slab. At the back of the lens, SPPs are excited using narrow slits carved in the Au medium [13–14]. The SPPs propagate in the positive *z*-direction at the Au-air interface with the electric field having *y*- and *z*- components and a magnetic field parallel to the *x*-axis (i.e., a TM wave).

The plasmonic lens was designed with an EFL of $2\lambda_0$. To reduce shadowing effects[15–16], R_1 was designed to be equal to the EFL. The height of the block was then chosen to provide a large enough $n_{SP,r2}$ as to enable $R_1 \approx R_2$ and therefore a sufficiently curved face. The thickness was chosen to be 500nm in order to manipulate the SPPs while keeping the compactness of the lens. The plasmonic lens was simulated using the commercial software COMSOL Multiphysics®.

3 Results

The numerical results of the power enhancement (defined as the ratio between the power distribution with and without the lens measured on the focal plane) along the *z*-axis calculated on the surface of the metal ($y = 0$) at $x = 0$ (centre of the lens) are shown in Fig 2. As observed, a clear focus is obtained appearing at z = 1500nm (~$2.37\lambda_0$), in agreement with the design value.

The power enhancement along the transversal *x* direction at the focal length is also presented in Fig 3. 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 = 333nm = $0.53\lambda_0$.

The configuration presented in the results here can offer a wide range of applications such as optical tweezers and plasmonic sensors. Our efforts to develop plasmonic meniscus lenses will be presented in more detail during the conference [10].

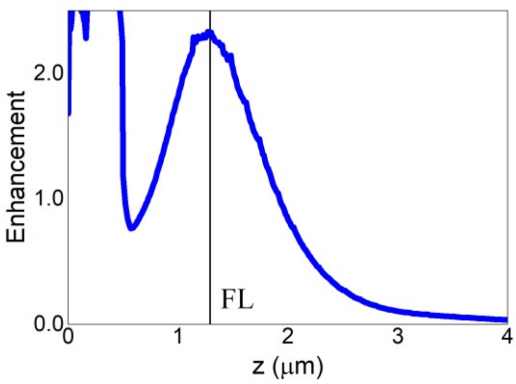

Figure 2. Numerical results showing the power enhancement along the z-direction on the surface of the metal ($y = 0$) at the centre of the lens ($x = 0$).

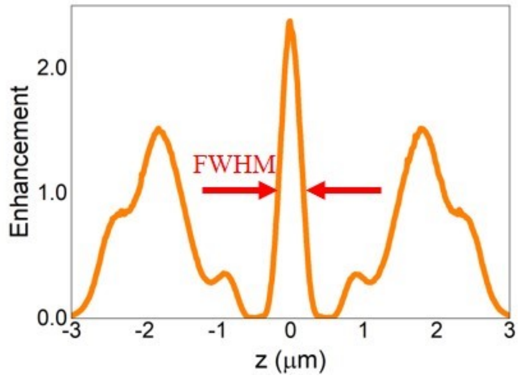

Figure 3. Numerical results showing the power enhancement along the transversal x-direction on the surface of the metal ($y = 0$) at the focus (z = 1500nm).

4 Conclusions

In conclusion, we have shown a method of developing plasmonic meniscus lenses. The design of the lens was done using the lens maker equation and exploiting the effective medium concept of SPPs. The lens were demonstrated showing their ability to generate a clear focus close to the design value of $2\lambda_0$.The proposed approach offers an ultra-compact method of producing a focus which has opportunities in a number of avenues such as in optical tweezing and sensing.

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