Numerical simulation of a plasmonic lens for laser light focusing

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Abstract. In this paper, the design of a plasmonic lens in gold and silver thin films for focusing the light with radial polarization is presented. Using the finite difference time domain method the optimal parameters of the plasmonic lens design are found. It was shown that the silver plasmonic lens produces a tight focal spot with a full width at half maximum of 0.38 of the incident light wavelength.

1. Introduction

At present, a large number of studies are devoted to the focusing of electromagnetic radiation by plasmonic lenses, which make it possible to excite and focus surface plasmon polaritons. The surface plasmon-polariton is a highly localized surface wave of the optical range propagating along the interface between two media, whose real parts of the permittivity have different signs [1,2]. Due to their special properties, plasmons have a large number of applications in science: physics, biology, chemistry and etc. [3-5]. Optical components based on plasmon effects are considered as an ideal choice for the fabrication of nano-integrated optical circuits [6]. Optical sensors based on plasmonic effects are widely used in biomedical, chemical, and food industries [7,8]. Surface plasmon polaritons are used for subwavelength optics in microscopy and lithography beyond the diffraction limit [9,10].

Plasmonic lenses focusing damped waves near their surface often have a fairly simple structure as a set of concentric rings and/or grooves [11-14]. For example, in [11], a plasmonic lens with a set of concentric nano-slots in the inner part of an element and nano-grooves on the outer radii etched in a thin metal film deposited on a substrate was experimentally investigated. The lens sharply focuses light with wavelengths of 650 nm and 750 nm. In both cases, it allows reaching a depth of the focus (DOF) of 400 nm. At the same time, the narrowest spot (the full width at half maximum (FWHM) is 0.32 of the wavelength) was obtained for the beam with a wavelength of 650 nm. In [13], an immersion lens design is considered. It consists of arrays of holes in a gold film deposited on a silica substrate. The numerical simulation predicts the presence of a sub-wavelength focal spot with FWHM = 0.22 of the wavelength when focusing in oil. The focal length is about 300 nm. It should be noticed that in the air this lens focuses into a spot with FWHM = 0.38 of the wavelength. In [14], three types of plasmonic lenses based on sets of concentric rings in the central part of the lens and an array of nanoholes around a larger radius circle were proposed. It is shown that the shape of nanoholes strongly influences the diffraction properties of the lens. The narrowest focus (0.14 of the wavelength for modeling and 0.2 of the
wavelength for the experiment) gives the design of a plasmonic lens with T-shaped holes. In [15] a plasmonic lens based on a zone plate with a gold relief on silica glass was numerically investigated. It was shown that for the linear polarized Gaussian beam plasmonic lens gave a tight focal spot with the FWHM of \(0.38\lambda (\lambda = 532 \text{ nm})\). A plasmonic lens with a variable relief depth fabricated in the aluminum film on a glass substrate was considered in [16]. The lens which focuses in a point was examined numerically, and its planar analog was manufactured and examined by scanning near-field optical microscopy. While focusing in a point the spot width was FWHM = 0.9\(\lambda\).

In this paper, a plasmonic lens in a thin metal film of gold or silver is numerically investigated by frequency depended finite difference time domain ((FD)\(^2\)TD) method which is implemented in the FullWAVE software package. The influence of metal film thickness on focusing properties was evaluated. The optimal parameters of plasmonic lens design were obtained by comparative simulation of the focusing process. The first part of the paper describing the lens structure, launch field, and simulation parameters. Next, the study of film thickness influence is presented. The last part shows results of comparative modeling for different parameters of the lens design.

2. Design and simulation parameters

In this study, we propose a plasmonic lens which relief is made in thin metal film deposed on silica glass. Silver and gold were considered as materials of the thin film. The lens was a circular diaphragm with a diameter of \(D_2 = 5 \mu\text{m}\) and a thickness \(h_2 = 350 \text{ nm}\) and a disc-shaped depression in the center with a diameter \(D_1\) and a depth \(h_1 = 80 \text{ nm}\). The lens was illuminated by a radially polarized Gaussian beam. The optical scheme is presented in Fig. 1.

![Figure 1](image.png)

**Figure 1.** The numerical simulation scheme: the plasmonic lens template and the incident light beam.

The simulation was conducted by using (FD)\(^2\)TD-method implemented in the FullWAVE package. The next parameters were used: spatial grid size is 10 nm, pseudo time step (\(\tau = ct, c\) is the speed of light, \(t\) is time) is 5 nm. Materials permittivities were described by the Sellmeyer’s model [17] and the Drude-Lorentz’s model [18] and presented in Fig. 2.

It can be seen from Fig. 2 that the bigger the wavelength, the greater the difference in the values of the imaginary part of the dielectric permittivity of metals and the real part of quartz glass (or air) permittivity. This difference directly affects the strength of the plasmonic effects. In this regard, we chose a wavelength of incident light equal to 633 nm. The averaging of the calculated fields for 5 periods was carried out while analysis of simulation results.
The dependence of permittivity for silica glass (a), silver (b), and gold (c) on the wavelength of the incident light.

The incident field was calculated in MATLAB and was set from the file into FullWAVE to produce radial polarization. The calculation was carried out by using the next equations for each component of the field:

\[
\begin{align*}
E_x &= \frac{2\sqrt{2}}{\delta} x e^{-\frac{x^2 + y^2}{\delta^2}} \\
E_y &= \frac{2\sqrt{2}}{\delta} y e^{-\frac{x^2 + y^2}{\delta^2}}
\end{align*}
\]  

(1)

where \( E_x \) and \( E_y \) are the components of an electric field, \( \delta \) is the waist of the Gaussian beam.

The radius of the waist of both Gaussian beams (for \( E_x \) and \( E_y \) components) was chosen equal to 2.5 \( \mu \)m and maximum intensity was normed to 1 a.u. Fig. 3 shows the incident light for the simulation.

It can be seen from Fig. 3 that the maximum input intensity is at the radius of 2.5 \( \mu \)m, so the maximum intensity of the radiation fell on the diaphragm of the plasmonic lens.

3. Influence of metal film thickness

Firstly, we estimated the influence of the metal film thickness on the process of the plasmonic radiation focusing. We considered films with a thickness of \( h = 100 \) nm and \( h = 200 \) nm. The diameter of a disc-shaped depression in the center was fixed at \( D_1 = 1 \) \( \mu \)m. The simulation results are shown in Fig. 4.
Figure 4. The intensity distribution along the optical axis for the plasmonic lens in silver film (a) and in gold film (b) with relief height $h$.

It can be seen from Fig. 4 that for both metals a thick film gives a higher intensity near the element. However, this field is rather difficult to use for practical application. In this regard, design optimization was carried out to obtain maximum intensity at a certain distance from the plasmonic lens. Therefore, the most acceptable was the film thickness of 100 nm.

4. Optimization of plasmonic lens design
Next, we fixed the film thickness at 100 nm and tried to optimize the plasmonic lens design by varying the diameter of the inner recess. The diameter $D_1$ was varied from 1 μm to 2 μm with a step of 100 nm. The simulation results are shown in Fig. 5.

Figure 5. The intensity distribution along the optical axis for the plasmonic lens in silver film (a) and in gold film (b) with different diameter of the inner recess $D_1$.

It can be seen from Fig. 5 that the $D_1 = 1.5$ μm is optimal for the silver plasmonic lens, and $D_1 = 1.9$ μm is optimal for the gold plasmonic lens. The full width of the focal spot at the half maximum of the intensity for silver was FWHM = 0.38λ and for gold was FWHM = 0.40λ. The intensity at the focus of both lenses was approximately the same and amounted to 3 a.u. Fig. 6 shows the distribution at the focus ($f = 580$ nm) of a silver plasmonic lens.
Figure 6. Focusing by a plasmonic lens: the two-dimensional distribution at y = 0 (a) and at the focus (b); the intensity cross-section along the X-axis in focus at a distance of 580 nm.

5. Conclusion
In this paper, a plasmonic lens with a continuous relief in thin films (200 and 100 nm in height) of gold and silver was investigated using the numerical simulation by the frequency depended FDTD method. The lens was a circular diaphragm with a diameter of 5 μm and a thickness of 350 nm and a disc-shaped depression in the center with a depth of 80 nm. A radially polarized Gaussian beam with a wavelength $\lambda = 633$ nm was used as the launch field. The dependence of the focal spot characteristics on the height and material of the relief, as well as on the diameter of the central depression was studied. It is shown that the design of the lens significantly depended on the material of the relief, so parameters of the plasmonic lens should be recalculated for each metal film.

It is shown that a plasmonic lens made in a silver film of 100 nm thick with a central depression of 1.5 μm in diameter allows focusing radiation at a distance of 580 nm into a spot with FWHM = 0.38 $\lambda$.

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References
[1] Barnes W L, Dereux A, and Ebbesen T W 2003 Nature 424 824
[2] Dyshlyuk A V, Bogdanov A A, Vitrik O B 2020 Computer Optics 44 893
[3] Fafin A, Camellio S, Pailloux F, Babonneau D 2019 J. Phys. Chem. C 123 13908
[4] Uenoa K, Yang J, Suna Q, Aoyoa D, Yua H, Oshirikia T, Kuboc A, Matsuoa Ya, Gongb Q, Misawa H 2019 Applied Materials Today 14 159
[5] Nesterenko D V, Pavelkin R A, Hayashi S 2019 Computer Optics 43 596
[6] Sistani M, Bartmann M G, Güsken N A, Oulton R F, Keshmiri H, Seifner M S, Barth S, Fukata N, Luong M A, den Hertog M I, Lugstein A 2019 Appl. Phys. Lett. 115,161107
[7] Kazanskiy N L, Butt M A, Degtyarev S A, Khonina S N 2020 Computer Optics 44 295
[8] Nesterenko D V 2020 Computer Optics 44 219
[9] Minn K, Lee H W H, and Zhang Zh 2019 Opt. Express 27 38098
[10] Kim E S, Kim Y M, Choi K C 2016 Plasmonics 11 1
[11] Chang K-H, Chen Y-C, Chang W-H, Lee P-T 2018 ACS Photonics 5 834
[12] Kozlova E S, Kotlyar V V 2016 Computer Optics 40 629
[13] Zhu Y, Yuan W, Yu Y, Wang P 2016 Plasmonics 11 1543
[14] Chang K-H, Chen Y-C, Chang W-H, and Lee P-T 2018 Sci. Rep. 8 13648
[15] Kozlova E S, Kotlyar V V 2018 20th International Conference on Transparent Optical Networks
(ICTON), Bucharest, 2018, 1
[16] Wang H, Deng Y, He J, Gao P, Yao N, Wang C, Luo X 2014 *Journal of Nanophotonics* 8 083079
[17] Couairon A, Sudrie L, Franco M, Prade B, Mysyrowicz A 2005 *Phys. Rev. B: Cond. Mat.* 71 125435
[18] Rakic A D, Djurisic A B, Elazar J M, Majewski M L 1998 *Appl. Opt.* 37 5271