Simulation of light focusing by a dielectric microcylinder with a metal film and gap on shadow side

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Abstract. In this work, using the FullWAVE software package, numerical simulation of focusing of TM-wave with a wavelength of 633 nm was performed. It is shown that a dielectric microcylinder made of polyester with a radius of 2.1749 of wavelength, coated on the shadow side with a silver film of 90 nm with a 100 nm hole, allows to get a focus with a maximum intensity of 1.37 times more (10.61 a. u), than a conventional dielectric cylinder (7.73 a. u).

1. Introduction

The phenomenon of tight focusing of light is actively studied in modern nanophotonics [1-7]. In [1] authors presented a hybrid metalens design enables microwave focusing with large efficiency (η = 0.479) and near-unity numerical aperture ( NA = 0.98 ), yielding a sharp focal point at the diffraction limit in the far field (FWHM = 0.332 λ ). The formation of subwavelength photonic nanojet in specular-reflection mode (s-PNJ) is theoretically considered in [3]. In [4] authors simulated focusing of short pulses by an aplanatic lens for different polarization states and vortex singularity orders in the Debye approximation. It was shown that the polarization state and the presence of vortex phase singularity essentially affect the distribution in the focal area for a subcycle Poisson pulse. The tight focusing of a second-order cylindrical vector beam by a hyperbolic secant gradient index lens with a thickness of 10 μm, a radius of 9.43 μm, and a refractive index on the axis of 3.47 (silicon) is investigated in [5]. Sharp focusing of a light field with polarization and phase singularities of an arbitrary order is theoretically investigated by using the Richards-Wolf formalism in [6]. In [7,8] a method for calculating a “spectral” diffractive lens that forms a given set of fixed-position foci or ensures the preservation of the focal position at multiple operating wavelengths.

As it can be seen from previous review different techniques are used for light focusing. The formation of nanojets is also one of the ways to obtain tight focal spot. The nanojet is an ultra-narrow light spot that propagates over several wavelengths [11-13]. Micro cylinders [14,15], microspheres [16,17], microdiscs [18] and other nano elements [19] can be used as a focusing element. In [14], using the finite element method (FEM) implemented in COMSOL Myltiphysics, the focusing of TE-wave with a wavelength of λ = 532 nm on a round cylinder made of polyester with a radius of 2.1749λ, and with a gold shell of 10 nm was studied. The presence of a narrow nanojet with a maximum intensity of 6 times the intensity of the incident light was demonstrated. The full width at half maximum (FWHM) and the full depth at half maximum (DOF) were 0.39λ and 0.72λ, respectively. It
is concluded that the metal shell increases the length of the nanojet. The results of numerical simulation of focusing of plane-wave with a wavelength of \( \lambda = 600 \) nm by microspheres made of silica glass are described in [16]. It is shown that using the hole on the shadow side of the microsphere allows to reduce the geometric dimensions of the focal spot and increase its maximum intensity. It is possible to obtain a focal spot with FWHM and DOF of 0.2\( \lambda \) and 0.14\( \lambda \) and a maximum intensity of 112 a. u. as a result of focusing by a microsphere with a radius of 3.5\( \lambda \) and a hole with a diameter of \( \lambda/15 \). Note that a similar microsphere without a hole gives a spot with FWHM and DOF of 0.35\( \lambda \) and 0.74\( \lambda \) and a maximum intensity of 61.1 a. u. In [18], the focusing of laser light by microdisks made of silica glass and silicon nitride was studied theoretically and experimentally. The experimental data are consistent with the results of modeling by the finite difference time domain method (FDTD method).

It should be noticed that the ultra-small focal spots have a wide range of applications in various fields, including ultra-high resolution microscopy [20,21], nanolithography [22], and optical sensors [23].

In this paper, using numerical simulation we study the focusing of light by polyester cylinders with metal shells on their shadow part. A hole is provided in the metal film on the optical axis to allow light transmission. The thickness of the metal shell was varied to obtain maximum intensity in the focus. A TM-wave with a wavelength of 633 nm is considered as incident light. Numerical simulations were conducted in the FullWAVE software package that implements the FDTD-method. In work a comparative analysis of the results was carried out and the optimal thickness of the metal film was revealed.

2. Simulation results
We consider the process of focusing of TM-polarized light with a wavelength of 633 nm, which falls on a round dielectric cylinder with a metal shell on the shadow side. Polyester with a refractive index of \( n_d = 1.59 \) was used as the material for the cylinder. The refractive index of the metal shell is equal to \( n_m = 0.14368 + 3.8065j \). There is a hole on the optical axis in the shell. The numerical experiment scheme and the design of the cylinder is shown in Fig. 1.

![Figure 1. The scheme of numerical simulation.](image)

The FullWAVE software package was used for numerical modeling. This package is based on the FDTD method. In this work we use the following modeling parameters: space discretization steps are 5 nm, time discretization step is 0.3 nm (pseudo-time \( ct \) is used, where \( c \) is the light speed in a vacuum, \( t \) is time). During the calculations, the diameter of the dielectric cylinder was 2.1749\( \lambda \) (\( \lambda = 633 \) nm) and the width of the hole in the shell on the shadow surface was 100 nm. The thickness of the metal shell was varied from 10 to 120 nm in increments of 10 nm. Silver and gold were used as the
material for the film. During the analysis of the simulation results we measured the maximum intensity $I_{\text{max}}$ of the formed field. The simulation results are presented in Tables 1 and 2.

**Table 1.** The dependence of the focal spot parameters on the thickness of gold film

| $D_m$, nm | 120 | 110 | 100 | 90  | 80  | 70  | 60  | 50  | 40  | 30  | 20  | 10  |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $I_{\text{max}}$, a. u. | 6.02 | 6.64 | 7.04 | 7.20 | 7.14 | 6.75 | 6.09 | 5.12 | 4.41 | 3.54 | 3.58 | 5.96 |

**Table 2.** The dependence of the focal spot parameters on the thickness of silver film

| $D_m$, nm | 120 | 110 | 100 | 90  | 80  | 70  | 60  | 50  | 40  | 30  | 20  | 10  |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $I_{\text{max}}$, a. u. | 6.61 | 7.22 | 9.73 | 10.61 | 9.88 | 9.09 | 8.17 | 7.38 | 6.32 | 5.30 | 3.90 | 4.87 |

The tables show that the best result gives a nanocylinder with a silver shell on the shadow surface with a thickness of 90 nm. It produces the nanojet with maximum intensity of 10.61 a.u. As for the cylinder with a gold shell, the optimal film thickness was also found for it, which is 90 nm as for silver. However, the maximum intensity of the resulting nanojet is only 7.2 a.u., which is 1.47 times less than the maximum intensity obtained by a cylinder with a silver film of a similar thickness.

For comparison, a simple micro cylinder without silver shell was simulated. The maximum intensity of focal sport is 7.73 a. u. The simulation results of both cylinders are presented in Fig. 2-3.

![Figure 2](image)

**Figure 2.** Intensity distribution for a) a simple dielectric cylinder made of polyester and b) a cylinder made of polyester with a silver film on the shadow side with thickness of 90 nm and a hole with a diameter of 100 nm.

![Figure 3](image)

**Figure 3.** Simulation results for a simple dielectric cylinder (red line) and a cylinder with silver shell on the shadow side with thickness of 90 nm and a hole with a diameter of 100 nm (blue line).

Based on these results, we can note, that a cylinder with a metal shell on the shadow side and a hole with a diameter of 100 nm forms a field with a maximum intensity of 1.37 times more than a simple dielectric cylinder made of polyester.
3. Conclusion
In this paper we studied focusing of TM-wave with wavelength of $\lambda = 633$ nm on polyester cylinders with metal shell and a hole on the shadow side with a diameter of 100 nm. The simulation was performed in FullWAVE software package, that implements the FDTD-method.

It is shown that a dielectric cylinder made of polyester with a radius of $R = 2.1749\lambda$ and with a silver film of 90 nm on the shadow side and a hole in the film with a diameter of 100 nm makes it possible to obtain a field with a maximum intensity of 10.61 a.u. It should be mentioned that the dielectric cylinder made of polyester allows to get a focal spot with a maximum intensity of 7.73 a.u. In the future, it is planned to continue research in this area using various metals and cylinder designs.

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