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Abstract. The formation of a narrow nanojet by polyester microcylinder with metall shell was presented by using the finite element method implemented in COMSOL Myltiphysics. Linear polarized light at a wavelength of 532 nm was used as incident light. The presence of a metal layer allows to increase the focal depth.

1. Introduction

The resolution of optical devices is restricted by diffraction limit. A lot of papers are devoted to the diffraction limit overcoming[1-5]. Tight focusing is used in such a field as optical memory systems [6,7], Raman spectroscopy [8], nano-structuring [9], optical manipulation [10-11], and nanolithography [12].

Subwavelength focal spots created by microoptical elements are called photonic nanojets[13-15]. Dielectric cylinders are widely used for producing nanojets. In [16,17] the method was shown which allows to achieve focusing of TE-polarized radiation in a region that is more than two times smaller than the diffraction limit in the two-dimensional case (the focus full width at the half maximum of the intensity was FWHM = 0.44λ). In [18] author has simulated using high-resolution finite-difference time-domain (FDTD) numerical modeling localized nanoscale photonic jets with waists 160-230 nm generated at the shadow-side surfaces of micron-scale, circular dielectric cylinders illuminated by a plane wave. The detailed analysis of localized photonic nanojets generated at the shadow side surfaces of dielectric (n=1.5) elliptical microcylinder illuminated by a plane wave a wavelength of 500 nm is reported [19]. The focusing of light at by the cylinder with the major axis of 2.5 μm and a minor axis of 1.25 μm is simulated by using FDTD method. The photonic nanojet has smallest FWHM (230 nm) for the rotation angle equal to 0°. Special attention is paid to multilayer cylinders and microspheres [20-22]. In some works, only dielectrics are used as the material of devices [20,21], while in others works metal parts are additionally considered [22]. In [20], using the exact Mie theory, it is shown that ultralong nanojets can be generated using a glass-based two-layer (BaF and LaSF) microsphere with total radius of 5λ. Propagation of laser light at a wavelength of 632.8 nm through this microsphere results in the formation of ultra-long nanojet with FWHM=0.89λ (563 nm) and the length equal to 0.22λ. The whispering gallery modes and their influence on the subwavelength light focusing was investigated in [21] by using the existing analytical solution of the diffraction problem on
a cylinder. The FWHM of focal spot is equal to \((0.155 \pm 0.001)\lambda\). Simulations based on FDTD method shows the presence of a nanojet while propogation of laser light with a wavelength of 532 nm through the dielectric microcylinder \((n=1.5)\) with a 10 nm gold shell [22]. The focal spot is formed at a distance equal to the wavelength and has FWHM=250 nm.

In this paper we also consider the focusing of laser light by dielectric cylinders with a metal shell. All simulation are carried out by finite difference method (FEM) implemented in COMSOL Multiphysics software package. The wavelength of the radiation is 532 nm. As materials of the shell, silver and gold were considered. In this paper, the dependence of the focal spot characteristics, such as the maximum intensity and FWHM, on the thickness of the metal layers is investigated.

2. Simulation of light focusing by microcylinder with one metal shell
In the early works we considered the resonant focusing of radiation by a polyester [23]. In this study resonant cylinder radii equal to \(r_p=2.1749\lambda\). However, this peak is formed near of the cylinder. Thin metal films can increase the length of the focus, forming the so-called nanojet [22].

We consider a dielectric cylinder from polyester with a radius \(r_p=2.1749\lambda\), covered by a thin metal film with the width of \(\Delta r\). Figure 1 shows the optical scheme. Silver and gold were chosen as materials of the film.

![Figure 1. Simulation scheme for one shell.](image)

Gold and silver which dielectric permittivity is described by the Drude-Lorentz model [24] were used as materials of shell. For the considered wavelength, we obtain the following values of the permittivity (refractive index) for silver and gold, respectively: \(\epsilon_{Ag}=-9,1375+0,8025i\) \((n_{Ag}=0,1326+3,0257i)\) and \(\epsilon_{Au}=-4,4602+2,5355i\) \((n_{Au}=0,5789+2,1815i)\).

We simulate the propagation of TM-polarized light with a wavelength of 532 nm through the microcylinders by using the COMSOL Multiphysics package. We vary the thickness of the metal layer from 10 nm to 30 nm in steps of 1 nm while simulations. Figure 2 shows the dependence of the maximum intensity \(I_{max}\) and the full width at half maximum of intensity (FWHM) \(d_{FWHM}\) of the focal spot on the thickness of the metal layer. It should be noticed that focal spot near the surface of the cylinder has two peaks located close to each other. As a consequence, the maximum intensity was measured at a distance of 150 nm from the cylinder.

After that, we simulate focusing of TE-polarized light by the proposed cylinders and do the similar investigation of the dependence of the maximum intensity and FWHM of the focal spot on the thickness of the metal layer. It should be noticed that in this case the measurement was done near the cylinder surface since in the case of using TE-polarization the focus has one peak.
Figure 2. Dependence of the maximal intensity (a) and the FWHM (b) of the focal spot on the thickness of the metal layer for TE polarization and TM polarization.

It can be seen from Figure 2 that the maximum intensity is obtained in focal spots formed by a multilayer cylinder with a gold shell. It is because gold has a lower absorption coefficient than silver at this wavelength. However, the focal spot with minimal FWHM is formed by the cylinder with a silver shell. In both cases, increasing of the metal layer thickness leads to a decreasing of the maximum intensity and increasing of the FWHM. The optimal thickness of the metal shell was 10 nm in both cases. Figure 2 also shows that focal spots formed by a multilayered cylinder with a gold shell has the maximal intensity. However, unlike the previous case, the focal spot with the minimal FWHM is also formed by the cylinder with a gold shell. In both cases, increasing of the metal layer thickness leads to a decreasing of the maximum intensity and increasing of the FWHM. The optimal thickness of the metal shell was 10 nm in both cases.

Figure 3 presents the simulation results for a multilayer cylinder with a gold shell which thickness is 10 nm.

Figure 3. The intensity distribution i along the X axis immediately behind the cylinder (a) and along the Z axis at x = 0 (b) after the TE-polarized beam propagating through a dielectric cylinder with a 10-nm gold metal shell.

Figure 4 shows that focus overcomes the diffraction limit. The nanojet length at the half maximum of intensity is 0.72λ.
Figure 4. The intensity distribution in the XZ-plane after the TE-polarized beam propagating through a dielectric cylinder with a 10-nm gold metal shell.

3. Conclusion

In this paper, we consider the focusing of laser light by polyester cylinder with a silver and gold shell. All simulation are carried out by using COMSOL Multiphysics software package. The radius of the cores was equal to \( r_p = 2.1749 \lambda \). The wavelength of the incident light was 532 nm. The analysis of shell thickness influence on the light focusing shows that the design with the thinner metal shell is optimal. Comparative analysis also showed that the gold shell provides less absorption of light and the greater intensity in the focus. Moreover, a narrower focus can be achieved while propagating of TE-polarized light. As a result, a microcylinder with a gold shell of 10 nm was chosen. The simulation shows the presence of the nanojet with FWHM=0.39\( \lambda \) (207 nm). The presence of a metal layer allows to increase the focal depth till 0.72\( \lambda \) (383 nm). The obtained results can find their application in the systems of processing and storage of information, spectroscopy, and nanolithography.

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