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Focusing of laser light by circular microcylinders with a metal shell

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Abstract

Propagation of the TE-polarized light at a wavelength of λ=532 nm through a circular microcylinder from a polyester with a gold shell was simulated by using the finite difference method implemented in COMSOL Myltiphysics. The microcylinder radius was 2.1749λ and thickness of gold shell was 100 nm. The simulation showed the presence of a narrow nanojet with the maximum intensity in 6 times higher than the intensity of the incident light. The full width and depth of the nanojet at half maximum of intensity were 0.39λ (207 nm) and 0.72λ (383 nm), respectively. It was shown that using of thin metal shell can increase the nanojet length.

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Keywords: amplitude zone plate; surface plasmon polariton; frequency dispersion; sharp focus; FDTD method; SNOM

1. Introduction

The diffraction limit in optics restricts the resolution of optical devices, so a large number of works are devoted to overcoming of the diffraction limit [1-5]. Using of narrow focal spots is critical in such a field as optical memory systems [6,7]. Subwavelength focal spots created by microoptical elements (photonic nanojets[8-10]) are applicable in Raman spectroscopy [11], nano-structuring [12], optical manipulation [13-14], and nanolithography [15].

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Dielectric cylinders are widely used for sharp focusing. In [16] author has reported about localized nanoscale photonic jets generated at the shadow-side surfaces of micron-scale, circular dielectric cylinders illuminated by a plane wave. Using high-resolution finite-difference time-domain (FDTD) numerical modeling that these photonic nanojets have waists smaller than the diffraction limit (160-230 nm) and propagate over several optical wavelengths without significant diffraction [16]. 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 is reported [17]. The focusing of light at a wavelength of 500 nm 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. Authors have further analyzed the effect of the rotation angle of elliptical microcylinder upon the focal length and width of photonic nanojets. The photonic nanojet has smallest FWHM (230 nm) when the rotation angle is 0°. Special attention is paid to multilayer cylinders and microspheres [18-19]. In some works, only dielectrics are used as the material of devices [18], while in others works metal parts are additionally considered [19]. In [18], using the exact Mie theory, it is shown that ultralong nanojets can be generated using a glass-based two-layer microsphere. The inner part of two- layer microsphere was made from BaF (n=1.6028) with radii of 2.5λ while the shell was made from LaSF (n=1.8445). The total radius of two-layer microsphere was 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 super-enhancement of photonic nanojets generated at the shadow side surfaces of core-shell microcylinders illuminated by a plane wave is reported in [19]. 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 [19]. 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 layer is investigated. The simulation showed the presence of a narrow nanojet with the maximum intensity in 6 times higher than the intensity of the incident light for case of microcylinder which radius was 2.1749λ and thickness of gold shell was 10 nm. The full width and depth of the nanojet at half maximum of intensity were 0.39λ (207 nm) and 0.72λ (383 nm), respectively. It was shown that using of thin metal shell can increase the nanojet length.

2. Modeling of plasmons on the surface of metal cylinder with circular cross section

A metal cylinder located in the air is considered. To calculate the resonant radius, we should calculate the length of the circle, which can fit the integer number of the surface plasmon-polariton (SPP) wavelengths. The TM-polarized laser beam with a wavelength λ=532 nm is taken as the input radiation. Gold and silver which dielectric permittivity is described by the Drude-Lorentz model [20] were used as materials of cylinders:

$$\varepsilon_m(\omega) = \varepsilon_\infty(z) + \frac{\omega_p^2}{-2i\omega\nu - \omega^2} + \sum_m \frac{A_m\omega_m^2}{-\omega^2 - 2i\omega\delta_m + \omega_m^2} \quad (1)$$

where ω is a frequency; ω_p is the plasma frequency; ν is the collision frequency; A_m is the resonance strength; δ_m is the damping factor; ω_m is the resonant frequency. Tables 1 and 2 show parameters for the Drude-Lorentz's permittivity model of silver and gold, respectively.

For the considered wavelength, we obtain the following values of the permittivity (refractive index) for silver and gold, respectively: ε_{Ag}=-9,1375+0,8025i (n_{Ag}=0,1326+3,0257i) and ε_{Au}=-4,4602+2,5355i (n_{Au}=0,5789+2,1815i).

We calculate the wavelength of the surface plasmon-polariton by the formula [21]:

$$\lambda_{SPP} = \sqrt{\frac{\mathrm{Re}(\varepsilon_m) + \varepsilon_d}{\mathrm{Re}(\varepsilon_m)\varepsilon_d}}\lambda \quad (2)$$