Simulation of laser light focusing by a dielectric nanocylinder with gold core

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Abstract. Using the finite difference time domain method it was shown that a nanocylinder from silica glass with a diameter of 360 nm and a gold core of 40 nm focuses TM-polarized laser light into a nanojet with a full width at half maximum of 298 nm. Maximum intensity in focal spot is about 4 times higher than intensity of incident Gaussian beam.

1. Introduction
Optical devices for light focusing are widely used in modern technics. Tightly focused light has a wide range of applications in different areas: image quality improvement [1], storage on optical disks [2], nanolithography [3], optical manipulation [4], etc. Therefore, a large number of scientific works are devoted to the issues of light focusing and also formation of nanojets [5-8].

The nanojet is an ultra-narrow light spot. Transparent spheres, cylinders, disks, and prisms are widely used to produce nanojets [9-11]. In [10] the resonant excitation of modes shown while monochromatic light focusing by a cylinder with square cross section. The paper [12] discusses the method for obtaining of nanojets by spheres with different diameters. The authors use two types of spheres: ordinary dielectric sphere and sphere with a metal core. The best result was achieved using a two-layered sphere.

In addition, the widespread use of such an optical phenomenon as a surface plasmon polariton (SPP) is discussed at the present time. These waves arise as a result of the light interaction with a metal. They propagate along the medium between a dielectric and a metal [13]. SPPs can be a powerful tool for enhancing the light focusing. Due to resonant effects, it is possible to focus such light near the element. The authors in [14] revealed the presence of a central SPP while light passes through silver nano-elements on a silica glass substrate. In [15] in order to reduce the focal spot size a metal nanoantenna was placed in the focus area formed by the amplitude Fresnel zone plate.

In this paper, we consider the method for obtaining an ultra-small focal spot, based on the formation of photonic nanojets. Dielectric nanocylinder from silica glass with a metal core is proposed to focus TM-polarized light at a wavelength of 633 nm in nanojet. Investigation of light focusing is made by using the frequency depended finite difference time domain method ((FD)\(^2\)TD-method) implemented in the FullWAVE package.
2. Numerical simulation scheme

In this paper we consider process of focusing of TM-polarized light with a wavelength of 633 nm by a circular dielectric cylinder with a metal core. Air is considered as a medium in which nanocylinder is placed ($n_1 = 1$). The total diameter of the $D_d$ nanocylinder and the diameter of the metal core $D_m$ are indicated in Fig. 1 which shows the numerical simulation scheme. Silica glass is considered as a material for the dielectric shell.

![Figure 1. Optical experiment diagram for a core cylinder.](image)

The permittivity of silica glass is described by the Sellmeier formula:

$$
\varepsilon_2(\lambda) = \varepsilon_\infty + \sum_m \frac{\Delta \varepsilon_m \lambda^2}{\lambda^2 - \lambda_m^2 + i\lambda \eta_m}
$$

(1)

where $\lambda$ is wavelength, $\varepsilon_\infty(x,z)$ is dielectric constant at high frequencies, $\Delta \varepsilon_m(x,z)$ is resonance value, $\lambda_m(x,z)$ is resonant wavelength, $\eta_m(x,z)$ is damping factor. The parameters of the Sellmeier model for silica glass can be found in Table 1[15].

| $m$ | $\Delta \varepsilon_m(x,z)$ | $\lambda_m(x,z)$ | $\eta_m(x,z)$ |
|-----|----------------------------|-----------------|---------------|
| 1   | 0.69616630                 | 0.068404300     | 0             |
| 2   | 0.40794260                 | 0.11624140      | 0             |
| 3   | 0.89747940                 | 9.8961610       | 0             |

| $\varepsilon_\infty = 1$ |

Gold is considered as the core metal, the dielectric constant of which is described by the Drude-Lorentz model [16]:

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

(2)

where $\omega$ is frequency, $\omega_p$ is plasma frequency, $\nu$ is collision frequency, $A_m$ is resonance strength, $\delta_m$ is damping factor, $\omega_m$ is resonance frequency. The parameters of the Drude-Lorenz model for gold are presented in Table 2[16].

3. Simulation results

Using the FullWAVE package which implements the $(\text{FD})^2$TD method we simulate the light focusing by the two-layered nanocylinder with design shown in Fig. 1. Hereinafter, the following simulation...
parameters were used: space discretization steps are 5 nm, time discretization step is 0.35 nm (pseudo-time \( ct \) is used, where \( c \) is the light speed in a vacuum, \( t \) is time). We fix the cylinder size at 360 nm for all calculations while the gold diameter core was varied. During the analysis of the simulation results we measured such focal spot parameters as the focal length \( f \), the maximum intensity \( I_{\text{max}} \), the full width at half maximum (FWHM) and the depth of field (DOF). The simulation results are presented in Table 3.

Table 2. Parameters for the Drude-Lorentz's permittivity model of gold.

| \( m \) | \( A_m \) | \( \delta_m \) | \( \omega_m \) |
|---|---|---|---|
| 1 | 11.36293 | 0.610274 | 2.101774 |
| 2 | 1.183639 | 0.873629 | 4.203549 |
| 3 | 0.65677 | 2.203065 | 15.03655 |
| 4 | 2.645486 | 6.315 | 21.79768 |
| 5 | 2.014826 | 5.60642 | 67.45936 |

\( \varepsilon_\infty = 1 \)
\( \omega_p = 39.86873 \)
\( \nu = 0.13421 \)

The table shows that the best result gives a nanocylinder with a core diameter of 40 nm. The simulation results for it are presented in Fig. 2-3.

Table 3. Dependence of the focal spot parameters on the gold core diameter.

| \( D_m, \) nm | \( I_{\text{max}} \), a.u. | \( \text{FWHM}_x, \) nm | \( \text{FWHM}_x, \lambda \) | \( f, \) nm | \( \text{DOF}, \) nm | \( \text{DOF}, \lambda \) |
|---|---|---|---|---|---|---|
| 220 | 0.824 | 418 | 0.66\( \lambda \) | 371.5 | 2216 | 3.50\( \lambda \) |
| 120 | 1.086 | 424 | 0.67\( \lambda \) | 211.5 | 1709 | 2.70\( \lambda \) |
| 100 | 1.269 | 417 | 0.66\( \lambda \) | 166.5 | 1899 | 3.00\( \lambda \) |
| 80 | 1.415 | 424 | 0.67\( \lambda \) | 146.5 | 1836 | 2.90\( \lambda \) |
| 60 | 1.535 | 424 | 0.67\( \lambda \) | 156.5 | 1899 | 3.00\( \lambda \) |
| 40 | 3.755 | 298 | 0.47\( \lambda \) | 65.0 | 1646 | 2.60\( \lambda \) |

Figure 2. Intensity distribution along the longitudinal (a) and the transverse coordinates (b).

For comparison, we model the process of light focusing by a conventional dielectric nanocylinder from silica glass. The simulation results show that the dielectric cylinder gives a focal spot at a distance of 191.5 nm. The maximum intensity of focal spot equals to 1.586 a. u. and the FWHM and DOF are 449 nm (0.7\( \lambda \)) and 1988 (3.14\( \lambda \)) nm, respectively. From obtained results it could be seen, that using of metal core helps to increase the maximum intensity of the focal spot in 2.5 time and decrease the FWHM in 1.5 times.
4. Conclusion

In this paper, using the (FD)2TD method implemented in the FullWAVE package, the focusing of TM polarized light at 633 nm wavelength by a two-layered nanocylinder made of silica glass with a gold core is investigated. During the simulation the total diameter of the cylinder was fixed while the diameter of the metal core was varied to obtain a narrower spot. The best results were shown by the nanocylinder with gold core diameter of 40 nm. It produces the focal spot with maximum intensity of 3.755 a.u., FWHM= 298 nm (0.47λ) and DOF= 1646 nm (2.6λ), respectively. It should be noticed that the nanojet formed by a two-layer cylinder has a maximum intensity of almost 2.5 times more than a simple dielectric nanocylinder from silica glass. Moreover, its FWHM was 1.5 times narrower and its DOF turned out to be 1.2 times shorter.

5. References

[1] Chitnis A, Nogare D D 2018 Methods 150 32-41
[2] Kallelpalli D L N, Alshehri A M, Marquez D T, Andrzejewski L, Scaiano J C and Bhardwaj R 2016 Scientific Reports 6 26163
[3] Li Y, Yan W, Hu S, Feng J and Wang J 2016 IEEE Photonics Journal 8(1)
[4] Singh B K, Nagar H, Roichman Y and Arie A 2017 Light: Science & Applications 6 17050
[5] Zuo R, Liu W, Cheng H, Chen S and Tian J 2018 Advanced Optical Materials 6(21) 1800795
[6] Degtyarev S A 2016 3D simulation of focusing a laser beam by a dielectric conical microaxicon Computer Optics 40(4) 588-593 DOI: 10.18287/2412-6179-2016-40-4-588-593
[7] Wu M, Chen R, Ling J, Chen Z, Chen X, Ji R and Hong M 2017 Optics Letters 42 1444-1447
[8] Kozlova E S, Kotlyar V V and Degtyarev S A 2015 Journal of the Optical Society of America B 32(11) 2352-2357
[9] Geints Yu E and Zemlyanov A A 2016 Journal of Applied Physics 119(15) 153101
[10] Kozlov D A, Kozlova E S and Kotlyar V V 2016 Sharp resonant focusing of light by a dielectric cylinder with square cross-section and cube Computer Optics 40(4) 431-438 DOI: 10.18287/2412-6179-2016-40-4-431-438
[11] Abolmaali F, Brettin A, Green A, Limberopoulos N I, Urbas A M and Astratov V N Optics Express 25 31174-31185
[12] Grojo D, Grojo D D, Sandeau N, Boarino L, Constantinescu C, Leo N D, Laus M and Sparnacci K 2014 Optics Letters 39(13) 3989-3992
[13] Barnes W L, Dereux A and Ebbesen T W 2003 Nature 424 824-830
[14] Kozlova E S and Kotlyar V V 2016 Tight focusing of laser light using a surface plasmon polariton in a silver nano-strip and nano-ring on silica glass Computer Optics 40(5) 629-634 DOI: 10.18287/2412-6179-2016-40-5-629-634
[15] Couairon A, Sudrie L, Franco M, Prade B and Mysyrowicz A 2005 Physical Review B: Condensed Matter 71(12) 125435-125441
[16] Rakic A D, Djurisic A B, Elazar J M and Majewski M L 1998 Applied Optics 37(22) 5271-5783
Acknowledgments
This work was partly funded by the RF Ministry of Science and Higher Education within the state project of the FSRC “Crystallography and Photonics” RAS under agreement 007-Г3/Ч3363/26 (Simulation of ordinary nanocylinder) and the Russian Foundation for Basic Research under project ## 18-07-01380 (Symulation of two-layered nanocylinder).