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The tight focusing of ultrashort pulse with dielectric cylinder

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Abstract. The tight focusing of light is observed during the propagation of a femtosecond laser pulses duration of 17 fs and 8 fs trough the dielectric cylinder with a refractive index n=1.59 and the radius R = 0.7152λ_0. It allows to reach the focal spot width at half intensity equal 0.235 λ_0.

1. Introduction

Recently, much attention is paid to the study of subwavelength focusing laser light on microparticles, including microspheres and microcylinders radii comparable with the wavelength of light [1]. The focusштп by elliptical [1] and multiple [2] microcylinders is discussed. The minimum size of the focus at full width at half maximum (FWHM) equal 0.46 λ_0 has been obtained [2]. Resonance focusing of TE-polarized laser light by polyester microcylinder (refractive index n=1.59) is analytically considered in [3]. The series of Bessel functions is used for this. The formation of resonant mode (whispering gallery mode) is considered in [4]. The focus for the 18th mode (whispering gallery mode) FWHM=0.22λ_0 outside of microcylinder is received by analytical method [3] and finite difference time domain (FDTD) method [4].

2. Simulation

We simulate the resonance focusing of the femtosecond pulses durations of t_s 17.08 fs and 8.54 fs by dielectric microcylinders. It is possible to calculate the resonance radius of the cylinders (Table 1) using the methods in [5].

Table 1. Radius of the cylinder.

Type of material	Polyester, *(n=1.59)*	Silica glass, *(n=1.46)*	Silica glass, *(n(ω))*
R, λ_0	0.7152	0.7588	0.7588
R, μm	0.3802	0.4037	0.4037

The materials such as polyester and silica glass are considered in this paper. The refractive index are equal 1.59 and 1.46, respectively. The simulation are performed in the package FullWAVE. The approximation steps for the spatial variables are 0.002 μm. The approximation step for the time variable is 0.0001 μm. The simulation results are shown in Figure 1-2. Tables 2-3 show the parameters of the focal spot in the considered cases.

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Table 2. The parameters of the focal spot in the case for the cylinder from polyester (n=1.59).

t_s, fs	$FWHM_x$, λ_0	DOF_z, λ_0	I_{max}, a.u.
17.08	0.235	0.271	9.447
8.54	0.243	0.271	8.091

Table 3. The parameters of the focal spot in the case for the cylinder from silica glass (n=1.46).

t_s, fs	$FWHM_x$, λ_0	DOF_z, λ_0	I_{max}, a.u.
17.08	0.255	0.316	8.204
8.54	0.262	0.320	7.634

It is shown in [6] that in case of simulation of femtosecond pulses it is necessary to consider the frequency dependence of the permittivity. We make a simulation using frequency depended FDTD ($(FD)^2TD$) method implemented in the package FullWAVE. To take into account a frequency dependence of the permittivity we use the Sellmeyer 's model of silica glass [7]. Simulation parameters is the same as before. The simulation results are shown in Figure 1. Tables 4 shows the parameters of the focal spot in the considered cases.

Table 4. The parameters of the focal spot in the case for the cylinder from silica glass (n(ω)).

t_s, fs	$FWHM_x$, λ_0	DOF_z, λ_0	I_{max}, a.u.
17.08	0.255	0.316	8.241
8.54	0.262	0.316	7.605

The comparison of Table 3 and Table 4 shows that in this case, the frequency dispersion of the medium can be neglected. The deviation of the results is less than 2%.

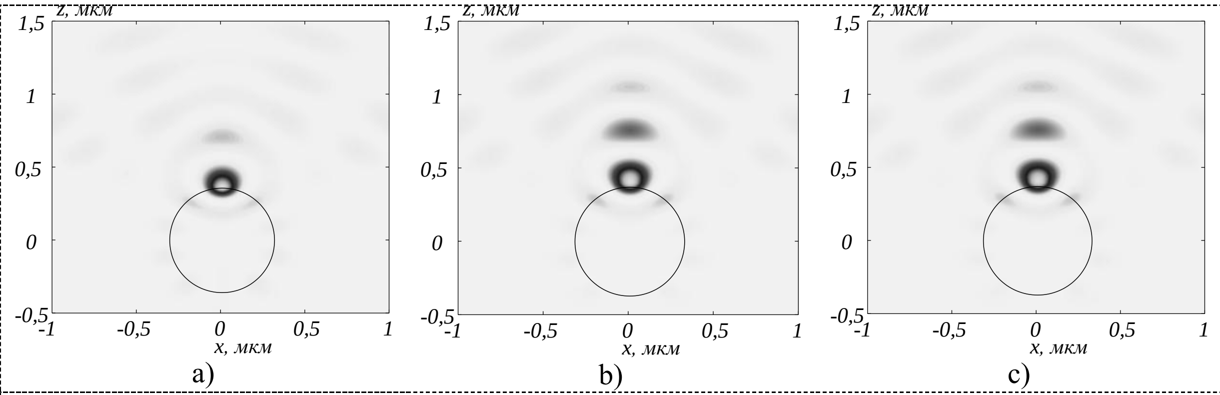

Figure 1. The diffraction pattern of the resonance focusing by the cylinder with (a) n=1.59, (b) n(ω); and (c) n=1.46 for the pulse duration of 17.08 fs

Figure 1 shows that the whispering gallery mode is formed in the waveguide. Unfortunately it quickly leaves the waveguide because of the short duration of the pulse. Tables 2-4 and Figure 2 show that during the resonance focusing of femtosecond pulse it is possible to beat the diffraction limit. The diffraction limit is equal $0.44\lambda_0/n = 0.28\lambda_0$ and is equal $0.44\lambda_0/n=0.30\lambda_0$ for polyester and silica glass, respectively.

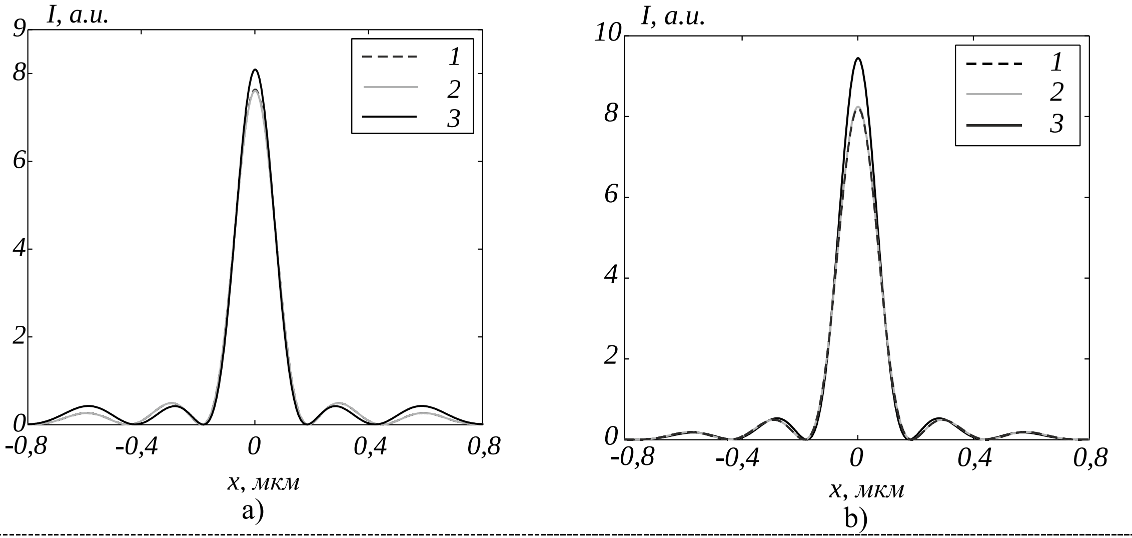

Figure 2. The intensity distribution in the focus for the different cases of cylinder medium n(ω) - line 1; n=1.46 - line 2; n=1.59 - line 3 and pulses durations of (a) 8.54 fs and (b) 17.08 fs.

For comparison, we simulate the propagation of the femtosecond pulse durations of 17.08 fs through a cylinder from the silica glass (n = 1.46) with the radius $R=0.8\lambda_0$ different from the resonance radius. The width of the focal spot at half intensity was $FWHM=0.269\lambda_0$. Thus the change in the radius of the cylinder 5% entail changing the width of the focal spot at 5%. It demonstrates that the short duration of the pulse does not give the resonance effects. Figure 3 shows the dynamics of the intensity in the focus.

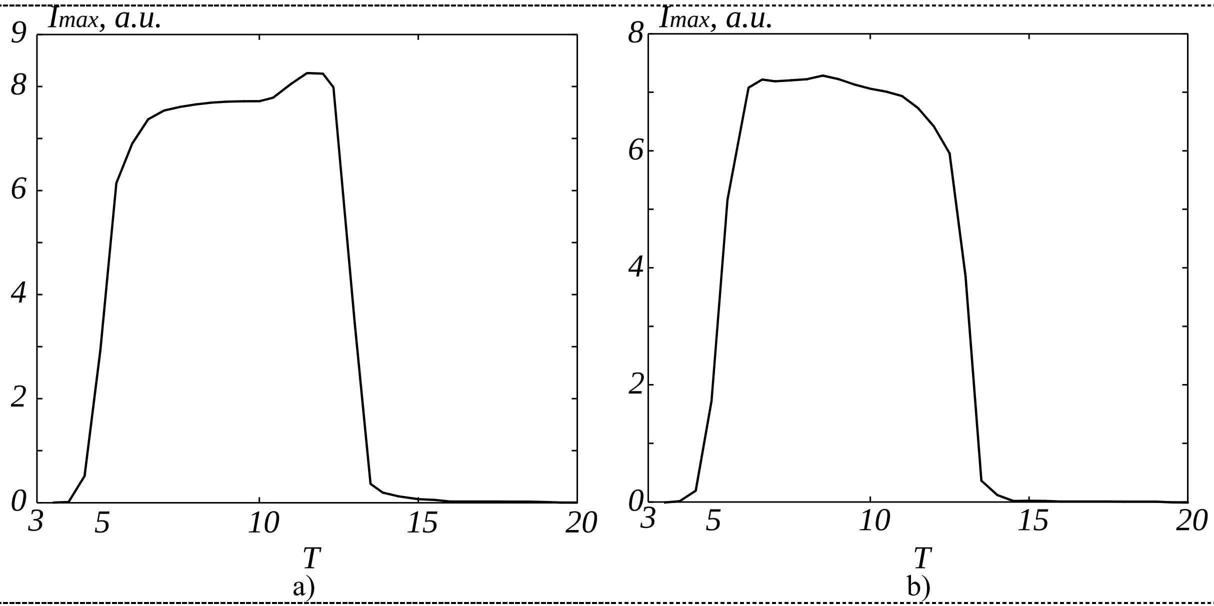

Figure 3. Dynamics of the intensity in the focus during the propagation of pulse durations of 17.08 fs through the cylinder from the silica glass with the radius (a) $R = 0.8\lambda_0$ and (b) $R = 0.7588\lambda_0$

Figure 3a shows that the intensity of focus increases when the pulse pass through the cylinder with resonance radius. The intensity reaches 8.204 a.u. during the time at which the pulse is passing. Figure

3b shows that the intensity of focus decreases when the pulse pass through the cylinder with nonresonance radius. The intensity reaches 7.3 a.u. during the time at which the pulse is passing.

3. Conclusion

In this work e shows tightly focusing of femtosecond pulse using FDTD method. We show that during the resonance focusing of femtosecond pulse it is possible to beat the diffraction limit (Table 2-4). The narrowest radius of the spot (FWHM=0.235λ_0) is obtained for the pulse duration of 17.08 fs which propagates through the cylinder from polyester (n=1.59) with resonant radius R=0.7152λ_0. Also we demonstrate that the short duration of the pulse does not give the resonance effects. But the intensity of focus increases when the pulse pass through the cylinder with resonance radius and the intensity of focus decreases when the pulse pass through the cylinder with nonresonance radius. This fact suggests that it is possible to choose the pulse width at which it will be possible all resonance effects.

Acknowledgements

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