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Tight focusing of azimuthally polarized optical vortex produced by subwavelength grating

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Abstract

Focusing of an optical vortex with sectorial azimuthal polarization is numerically investigated. An effect of sector numbers on the results of focusing is estimated. It is shown that the focal spot produced by a beam with six sectors does not differ from the ideally azimuthally polarized optical vortex; a difference in the focal spot diameter does not exceed 0.001 of the wavelength. For a four-sectoral beam, the difference does not exceed 0.028 of the wavelength. We have investigated a four-Sector transmission Polarization Converter for a wavelength of 633 nm, that enables the conversion of a linearly polarized incident beam into a mixture of linearly and azimuthally polarized beams. It was experimentally shown that light propagated through the four-Sector transmission Polarization Converter and focused by Fresnel zone plate with a focal length of 532 nm produces focal spot with diameters 0.46 and 0.57 of wavelength.

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Keywords: tight focusing; optical vortex; azimuthally polarized light; Fresnel zone plate; subwavelength grating; polarization conversion

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1. Introduction

Cylindrical vector beams (beams with polarization with a radial direction of symmetry) are currently an active topic of research [1]. Recent years have also seen an increased interest in the study of azimuthally and radially polarized optical vortices [2,3]. There are several ways to obtain beams with sectoral azimuthal or radial polarization (or quasi-cylindrical vector beams), including the use of half-wave plates [4-7], nonlinear optical crystals [8], polarizing films [9] and subwavelength gratings [10-12].

The tight focusing of quasi-cylindrically polarized beams was previously investigated in detail in [13] using numerical analysis. It was shown that a deviation of an eight-sector beam does not exceed 5.3% from the ideal beam. However, azimuthally polarized optical vortices have not been previously investigated. In this paper, we numerically investigate the tight focusing of a quasi-azimuthally polarized optical vortex with a wavelength of λ = 532 nm using a Fresnel zone plate (ZP) with NA = 0.95 and experimentally investigate the focusing of laser light propagated through a four-Sector transmission Polarization Converter (4-SPC). It is numerically shown that the focal spot produced by a beam with six sectors does not differ from the ideally azimuthally polarized optical vortex; the difference in the focal spot diameter does not exceed 0.001λ. For a four-sectoral beam, the difference does not exceed 0.03λ. Experimentally it was shown that by illuminating the ZP with a laser beam transmitted through a 4-SPC it is possible to obtain the focal spot with diameters $FWHM_x = 0.46\lambda$ and $FWHM_y = 0.57\lambda$.

2. The influence of the number of sectors on the focal spot

Our numerical simulation was performed using the Richards-Wolf formula. In the simulation, we assume that a Fresnel zone plate with NA = 0.95 is illuminated using a plane wave that has a different polarization and phase in each sector. Fig. 1 shows a sketch of the simulation.

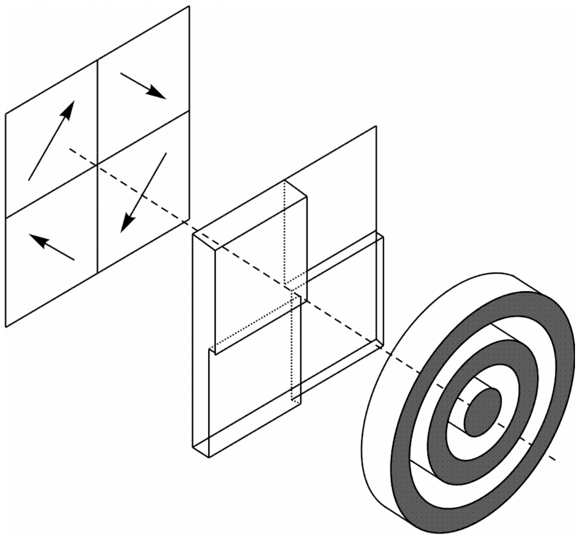

Fig. 1. Sketch of the simulation: the four-sector azimuthally polarized beam and four-sector spiral phase plate.

Figs. 2–4 show the simulation results. Fig. 2 shows a focal spot produced by the beam consisting of four sectors, and Fig. 3 shows the focal spot produced by the beam, consisting of six sectors. Fig. 4 shows the focus of the ideal azimuthally polarized optical vortex.

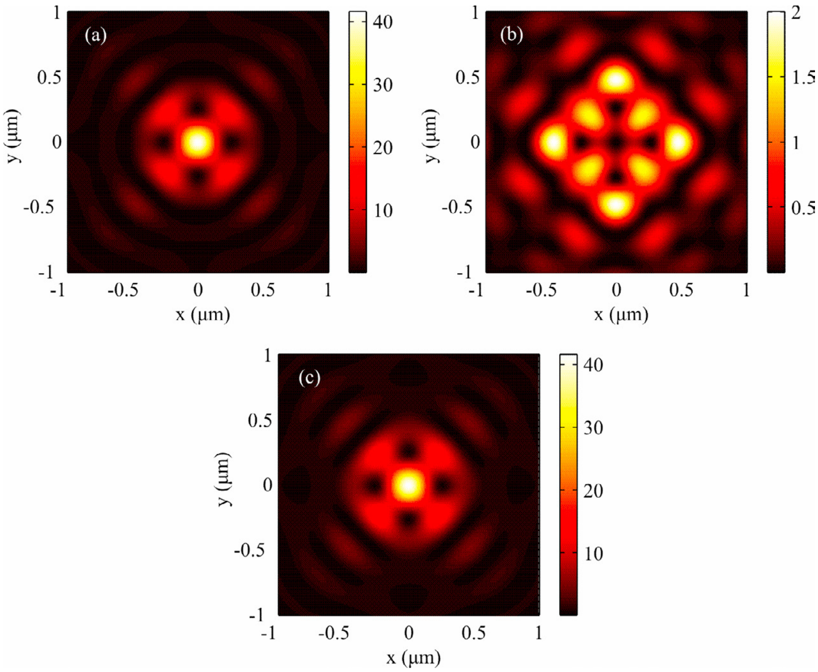

Fig. 2. Intensity in the focal plane for I_r (a), I_z (b), I (c). Focusing of a four-sector polarized beam transmitted through the four-sector SPP.

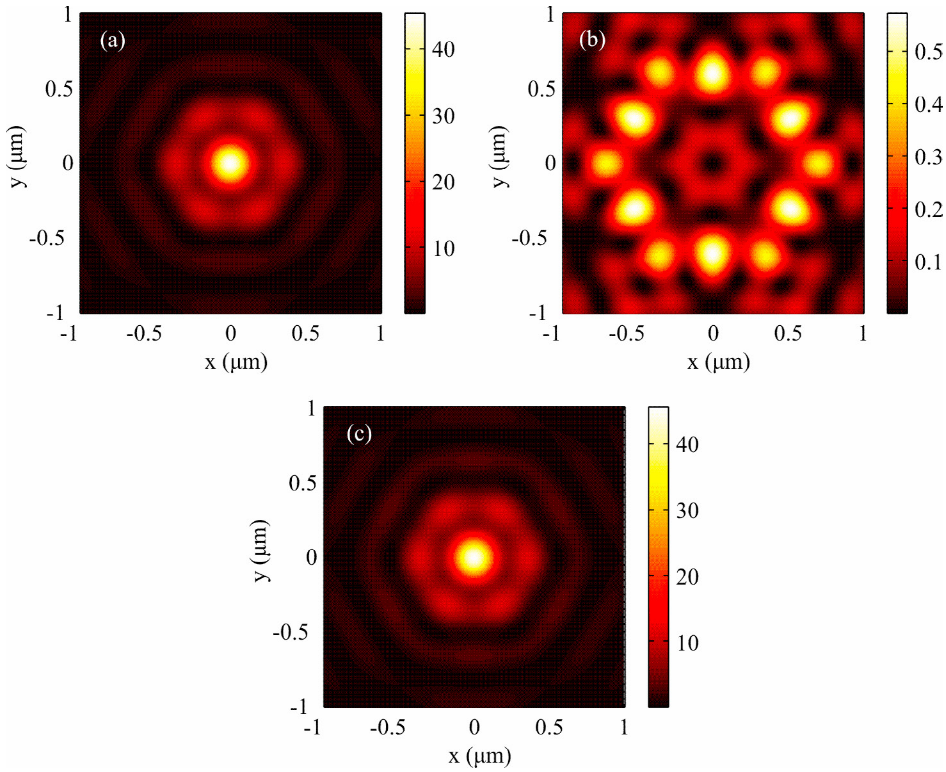

Fig. 3. Intensity in the focal plane for I_r (a), I_z (b), I (c). Focusing of a six-sector polarized beam transmitted through the six-sector SPP.

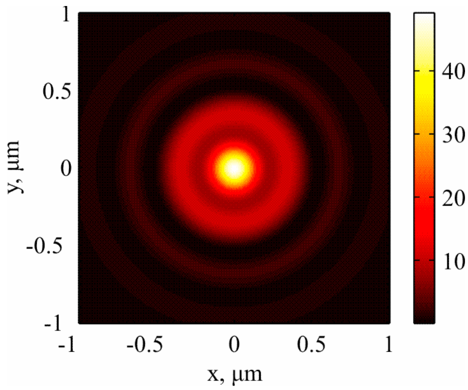

Fig. 4. Intensity in the focal plane. Focusing of ideally polarized optical vortex.

Figs. 2–4 show that the sector-polarized beams transmitted through the sectoral spiral phase plate (SPP) have a longitudinal component of the electric field, unlike the ideal azimuthally polarized optical vortex. Although its contribution to the formation of focus is small, the maximum transverse component of the four-sector beam is approximately 21 times the maximum longitudinal component, and that of the six-sector beam about 80 times. Fig. 5 shows the relative error in the intensity differences in the focus of an ideal beam (I_{ideal}) and a sectoral polarized beam (I_{quasi}), calculated as $|I_{ideal} - I_{quasi}|/\max(I_{ideal})$. The maximum relative error in Fig. 5(a) does not exceed 18%, and that in Fig. 5(b) does not exceed 9%. Table 1 shows the results of this simulation for comparison. Table 1 shows that the focal spot produced by a beam with six sectors does not differ from the ideally azimuthally polarized optical vortex; the difference in the focal spot diameter does not exceed 0.001λ. For a four-sectoral beam, the difference does not exceed 0.03λ.

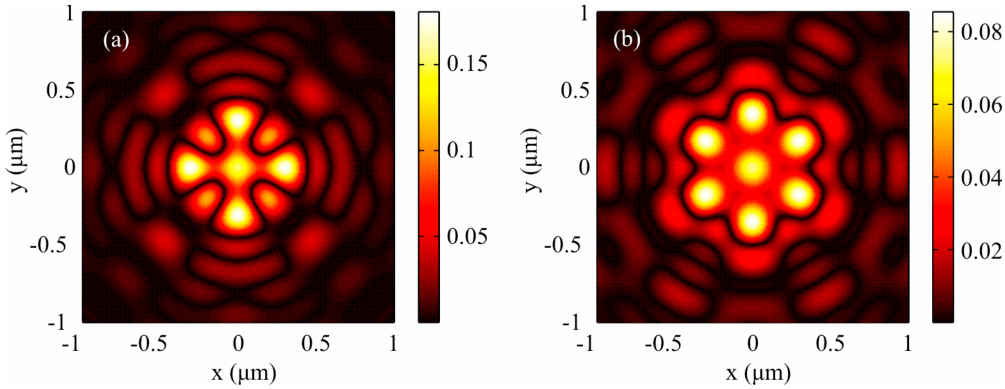

Fig. 5. Relative error in focus, calculated as |Iideal - Iquasi |/max(Iideal) for (a) a four-sector and (b) a six-sector azimuthally polarized beam.

Table 1. Focal spot diameters at half maximum.

Number of sectors	$FWHM_{min}$, λ	$FWHM_{max}$, λ
4 sectors	0.458	0.490
6 sectors	0.462	0.463
Ideal azimuthally polarized optical vortex	0.462	0.462

3. Four-Sector transmission Polarization Converter with a phase shift

3.1. Manufacturing of 4-SPC with a phase shift

The designed micropolarizer with half-wavelength shift for linear-to-azimuthal polarization conversion contains four sectors, with the subwavelength gratings grooves tilted by -60°, 60°, -60°, and 60° (Fig. 6). The gratings have a 230-nm period, a 138-nm step width, and a 92-nm grove width. The grating was fabricated in an amorphous silicon film. The microrelief height is 130 nm, the operating wavelength is 633 nm, and the complex refractive index of silicon is given by n = 3:87 - 0:016i. The fabricated micropolarizer measures 100×100 μm. The micropolarizer was fabricated by electron beam lithography. The surface of a 130-nm thick amorphous silicon (a-Si) found on a transparent pyrex 7740 substrate (refractive index is 1.47) was coated with a 320-nm thick PMMA resist, which was then baked at 180°C. To prevent charging the sample surface was coated with a 15-nm thick golden layer. The 4-sector grating-polarizer's pattern was created on the resist surface by a 30-kV electron beam. The sample was developed in a 3:7 water solution of isopropanol and the gold layer removed. The transfer of the gratingpolarizer's template from the resist to the aSi was carried out via reactive ion etching in the gas mixture of CHF_3 and SF_6. The resist thickness was chosen so as to enable the protection of pattern during the etching of the 130-nm aSi. The aspect ratio of etch rates of the material and the mask was found to be 1:2.5.

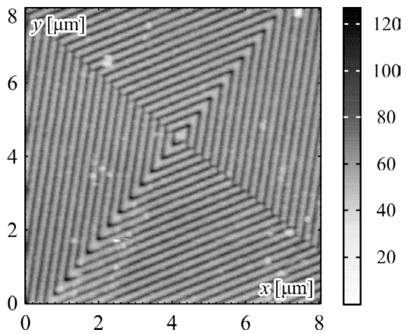

Fig. 6. An atomic-force-microscope image of the central part of the transmission 4-SPC.

3.2. Experiment

In the experiment, a laser beam of wavelength λ = 633 nm was focused with a ZP of focal length f = 532 nm after having passed through a 4-SPC. The optical arrangement for the experimental measurements is shown in Fig. 7.

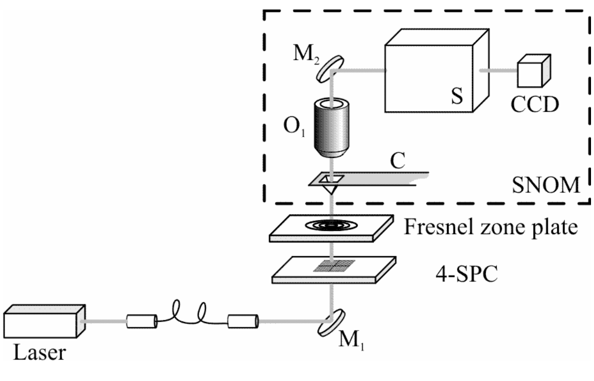

Fig. 7. Experimental optical arrangement: M_1, M_2 are mirrors, O_1 is a 100× objective, C is a probe, S is a spectrometer, and CCD is a video-camera.

Linearly polarized laser light from a 55 mW He-Ne laser of wavelength 633 nm was delivered via an optical fiber to a substrate containing a 4-SPC on its surface. The 4-SPC under study was rigidly attached to the other substrate (thickness is 0.5 mm) containing an array of ZPs. The location of the focal spot on the ZP and its size were controlled by shifting the mirror M1. After passing through the 4-SPC, the beam was focused with the ZP. The intensity distribution in the focal spot was measured at different distances from the ZP surface with a hollow metal pyramid taper C. There was a 100-nm pinhole in the taper tip. Having passed through the taper's pinhole, the light then traveled to a 100× objective O_1, before being transmitted through a spectrometer (Solar TII, Nanofinder 30) to filter off unwanted noise and registered by a CCD-camera (Andor, DV401-BV).

Measurements with a near-field scanning optical microscope have shown a focal spot to be formed at a distance of 250 nm from the ZP surface, with the spot size having FWHM = 0.46λ and FWHM = 0.57λ (Fig. 8). Numerically obtained values of diameters equal to FWHM = 0.42λ and FWHM = 0.59λ.

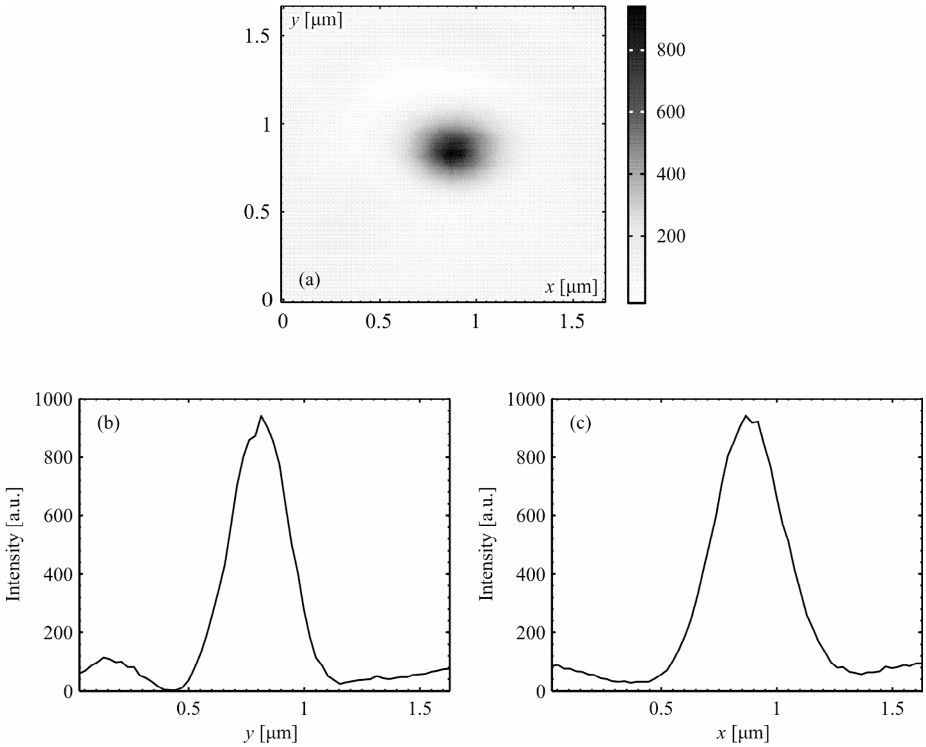

Fig. 8. Intensity profile of the focal spot measured using a NSOM Integra Spectra: 2D intensity distribution (a) and intensity profiles along the *y* (b) and *x*-axis (c).

4. Conclusions

In this paper, we numerically investigate the tight focusing of a quasi-azimuthally polarized optical vortex with a wavelength of λ = 532 nm using a Fresnel zone plate with NA = 0.95 and experimentally investigate the focusing of laser light propagated through a four-Sector transmission Polarization Converter. It is numerically shown that the focal spot produced by a beam with six sectors does not differ from the ideally azimuthally polarized optical vortex; the difference in the focal spot diameter does not exceed 0.001λ. For a four-sectoral beam, the difference does not exceed 0.03λ. Experimentally it was shown that by illuminating the ZP with a laser beam transmitted through a 4-SPC it is possible to obtain the focal spot with diameters $FWHM_x = 0.46\lambda$ and $FWHM_y = 0.57\lambda$.

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References

[1] Q. Zhan, Cylindrical vector beams: from mathematical concepts to applications, Adv. Opt. Photon. 1 (2009) 1–57.
[2] X. Hao, C. Kuang, T. Wang, X. Liu, Phase encoding for sharper focus of the azimuthally polarized beam, Opt. Lett. 35 (2010) 3928–3930.
[3] F. Qin, K. Huang, J.Wu, J. Jiao, X. Luo, C. Qiu, M. Hong, Shaping a subwavelength needle with ultra-long focal length by focusing azimuthally polarized light, Scientific Reports 5 (2015) 9977.
[4] R. Dorn, S. Quabis, G. Leuchs, Sharper focus for a radially polarized light beam, Physical Review Letters. 91 (2003) 233901.
[5] G. Machavariani, Y. Lumer, I. Moshe, A. Meir, S. Jackel, Efficient extracavity generation of radially and azimuthally polarized beams, Opt. Lett. 32 (2007) 1468–1470.
[6] G. Machavariani, Y. Lumer, I. Moshe, A. Meir, S. Jackel, Spatially-variable retardation plate for efficient generation of radially-and azimuthally-polarized beams, Optics Communications. 281 (2008) 732–738.
[7] S.V. Alferov, S.V. Karpeev, S.N. Khonina, O.Y. Moiseev, Experimental study of focusing of inhomogeneously polarized beams generated using sector polarizing plates, Computer Optics. 38 (2014) 57–64.
[8] R. Imai, N. Kanda, T. Higuchi, Z. Zheng, K. Konishi, M. Kuwata-Gonokami, Terahertz vector beam generation using segmented nonlinear optical crystals with threefold rotational symmetry, Optics Express. 20 (2012) 21896–21904.
[9] Z. Man, C. Min, Y. Zhang, Z. Shen, X.C. Yuan, Arbitrary vector beams with selective polarization states patterned by tailored polarizing films, Laser Physics. 23 (2013) 105001.
[10] A.G. Nalimov, L. O'Faolain, S.S. Stafeev, M.I. Shanina, V.V. Kotlyar, Reflected four-zones subwavelength microoptics element for polarization conversion from linear to radial, Computer Optics. 38 (2014) 229–236.
[11] S.S. Stafeev, A.G. Nalimov, M.V. Kotlyar, L. O'Faolain. A four-zone reflective azimuthal micropolarizer, Computer Optics. 39 (2015) 709–715.
[12] S.S. Stafeev, A.G. Nalimov, M.V. Kotlyar, L. O'Faolain, Subwavelength focusing of laser light of a mixture of linearly and azimuthally polarized beams, Computer Optics. 40 (2016) 458–466. DOI: 10.18287/2412-6179-2016-40-4-458-466.
[13] Z. Man, C. Min, S. Zhu, X.C. Yuan, Tight focusing of quasi-cylindrically polarized beams, J. Opt. Soc. Am. A. 31 (2014) 373–378.