Conference Paper

Phase Filters for 3D Localization of Point Light Sources

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Abstract

The work relates to the engineering and research of phase filters for three-dimensional localization of point light emitters. These phase filters form a light field having two clearly visible maxima in their intensity distribution (i.e. two-lobe fields). By means of numerical simulation, the influence of the amplitude and phase distortions of the wave front of the illuminating beam on the two-lobe field formation has been studied in the work.

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Keywords: spiral light beams, amplitude distortions, phase distortions, three-dimensional localization, two-lobe field.

Received: 28 January 2018
Accepted: 15 March 2018
Published: 25 April 2018

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Selection and Peer-review under the responsibility of the PhIO Conference Committee.

1. Introduction

The light fields with the intensity distribution rotating in the propagation can be applied in manipulation with micro-objects [1-3] and for the problem of increasing a longitudinal resolution of fluorescent optical microscopes [4, 5]. The latter is achieved by adding of the phase filter into the microscope optical system which changes the optical transfer function of the microscope. One of the most promising scenario for modification consists in obtaining of the point spread function (PSF), in the form of two maxima of intensity. And the angular orientation of the axis passing through the intensity maxima in the image plane depends on the longitudinal coordinate of the emitter. The computer processing of the obtained images allowed to achieve a longitudinal resolution of 5 nm [6]. Basing on the optics of spiral beams of light, being structurally stable during propagation, while changing in scale and turning, it's quite achievable to develop such phase filters [7-9]. For the first time it was proposed in paper [10] to create a phase filter facilitating the formation of the two-lobe PSF, on the base of the Laguerre-Gauss modes superposition. Note that the used superposition is a spiral beam. However, the researchers faced with the problem of a low diffraction efficiency of this phase mask. By applying the iterative procedure of the phase filter calculation, S.R.P. Pavani and R. Piestun in [11] managed to increase the diffraction efficiency of the field formation up to 56%. Later on this was followed by a whole number of works confirming the successful use of their calculated phase filter for localization of nanoscale objects [4, 5, 12, 13]. Some alternative methods for realization of the phase filter that generates a field rotating during propagation were also explored [14, 15]. In works [16-19], based on the theory of spiral beams of light, phase masks were offered, allowing to generate two-lobe light fields with different rotation speed.

In the present work the influence of the amplitude and phase distortions of the wave front on the quality of two-lobe fields formation is investigated through the example of the filter proposed in [16]. The choice of the filter is caused by a rather high estimated value of the diffraction efficiency 66%, obtainable with this filter. The phase filter under consideration is intended for the illuminating beam with a homogeneous intensity distribution and flat wavefront (Fig. 1). In the real microscope optical system, the radiation falling on the phase filter may have inhomogeneity and distortions in the intensity and phase distribution. Various types of amplitude and phase distortions that may occur in real devices have been considered in the paper. The conclusions were made about the permissible deviations of the intensity and phase distribution of the illuminating beam, which still allow the two-lobe field to be steadily formed with the help of the proposed phase mask.

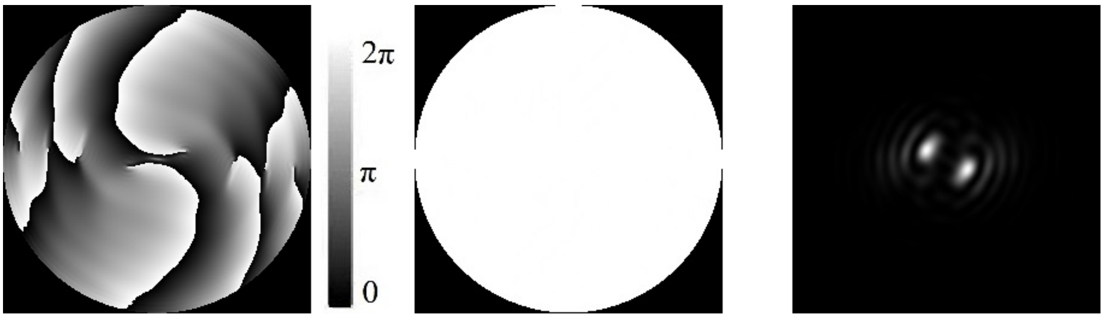

Figure 1: (left to right) Phase filter profile in grayscale, the intensity distribution in the phase filter plane, intensity distribution of the field being generated.

2. Modeling of amplitude distortions

In the course of the phase filters development aimed to form two-lobe light fields, it was found that during the field formation it was of great importance to match the size of the illuminating beam to the size of the phase mask. When the width of the illuminating beam is reduced, the two separate peaks of the intensity distribution of

DOI 10.18502/ken.v3i3.2061

the generated field tends to merge and become a ”dumbbell”, still further decrease of the aperture of the illuminating beam results in its turning into a line segment, and if we persistently continue to decrease it, the intensity will be a single central maximum. In the reverse situation, i.e. with the increase of the illuminating beam aperture, the portion of energy consumed for the field formation will be redistributed from the main peaks (maxima) into the ring embracing them [17]. During the calculation of the phase mask, the optimal ratio of the phase mask aperture and the width of the illuminating beam was selected, providing the formation of two separate maxima without an additional ring around them. Consider the case when a two-lobe field is formed under illumination of the phase mask by the beam with a planar wave front, and the intensity distribution not homogeneous at all. A very likely is the situation when the phase mask is lightened with a beam with Gaussian intensity distribution. Denote a half-width of the Gaussian beam by ($\frac{I_{\max}}{e^2}$) level with symbol w and then look how the field being generated changes with the width change. $I_{\max}$ is the highest value of the intensity distribution. Fig.2 presents the results of modeling. It is seen that two clear peaks (maxima) of the intensity distribution of the field being generated can be distinguished for the radius of the illuminating beam w equal or more than 0.8 radius of the phase mask.

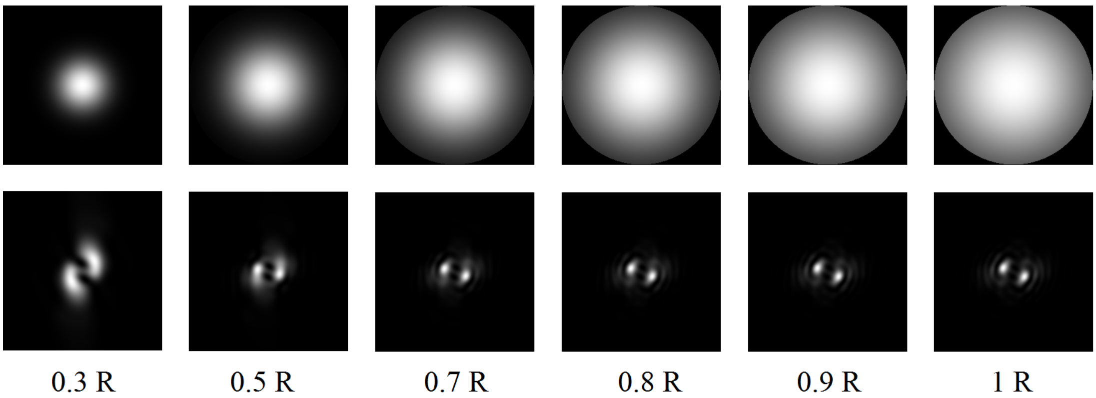

Figure 2: The result of modeling of the illumination of the phase mask by the Gaussian beam of various width. The upper row shows the intensity distribution of the incident beam. The bottom row shows the field formed in the plane of the beam waist. R is radius of the phase mask.

And now estimate the efficiency of formation of the two-lobe field during the phase mask illumination with the Gaussian beam of different width. The ratio η of the light power per two lobes, P_{tl}, by the level exceeding 0.4 I_{max}, to the total power, P_t, within the registration plane is meant by the word “efficiency”. The graph of intensity versus the beam width is shown in Fig.3. For the beam width of ≥0.7 R, the efficiency reaches the stationary value of 33.3% that is equal to the value of efficiency in case of the phase mask illumination by the beam with a homogeneous intensity distribution.

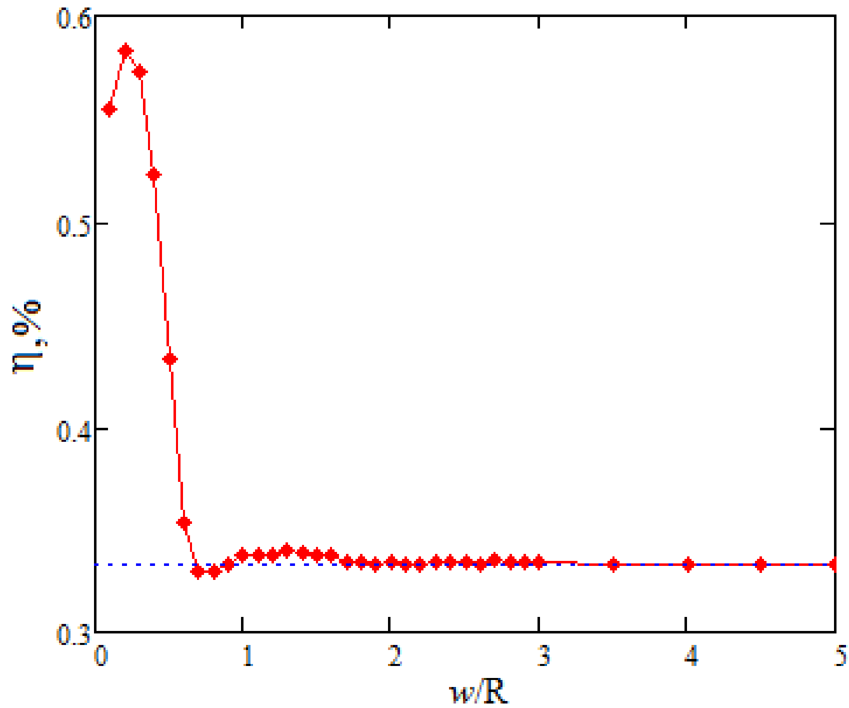

Figure 3: Efficiency of the two-lobe field formation versus the width of the illuminating beam. R is radius of the phase mask.

Let us also evaluate the deviation of the intensity distribution obtained in case of the phase mask illumination by a Gaussian beam of different width, from that obtained in case of the phase mask illumination by a beam with a homogeneous intensity distribution. Let's define the value of the mean square deviation of one image from another by formula (1):

$$\delta I = \sqrt{\frac{\sum_{i=0}^{N}\sum_{j=0}^{N}(Ig_{i,j} - Ih_{i,j})^2}{N^2}} \cdot \frac{100\%}{\sum_{i=0}^{N}\sum_{j=0}^{N} Ih_{i,j}}, \quad (1)$$

where $Ig_{i,j}$ is the intensity value in point (i,j) of the intensity distribution obtained for the case of the phase mask illumination by the Gaussian beam, $Ih_{i,j}$ - is the intensity value in point (i,j) of the intensity distribution obtained for the case of the phase mask illumination by the beam with a homogeneous intensity distribution. The obtained dependence of δI on the width of the illuminating Gaussian beam is shown in Fig. 4. It is seen from this graph that at the radius of the illuminating beam ≥0.8 R, no noticeable change occurs in δI, this value starts to asymptotically tend to zero. Thus it is possible to determine that under illumination of the phase filter by the beam having the Gaussian profile of intensity distribution, the radius of the beam must be ≥0.8 of the radius of the phase filter for a qualitative formation of the two-lobe field.

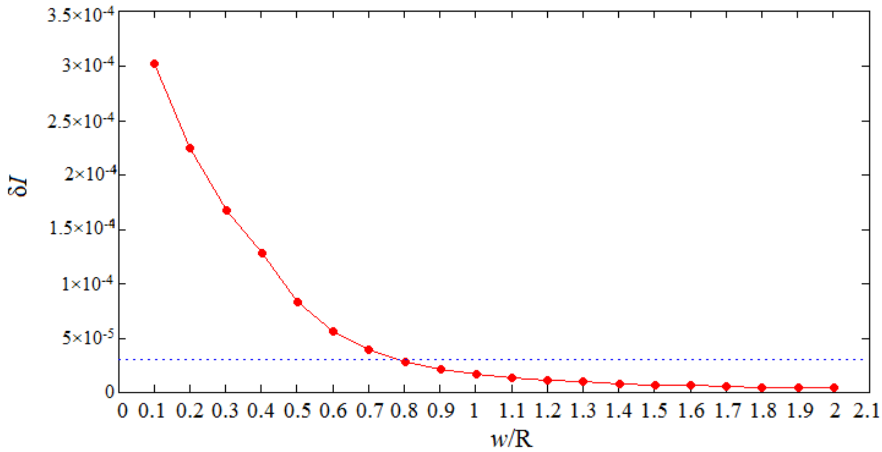

Figure 4: Graph of the δI dependence on the radius of the Gaussian beam illuminating the phase mask. R is the phase mask radius.

In case of an inaccurate adjustment of an optical scheme or when the irradiating object is located at the edge of the microobjective field of vision, it is quite probable that the illuminating beam will be displaced relative to the center of the phase mask. The modeling of the displacement of the illuminating Gaussian beam relative to the center of the phase mask for beams of different widths was fulfilled. Beams with the radius of 0.8 R, 1 R, 1.2 R, 1.5 R, 2 R were considered in our research. Figure 5 shows the results of modeling for the beam radius equal to the radius of the phase filter. This beam was chosen since its width satisfies the above determined requirement to the size of the illuminating beam (≥0.8 R).

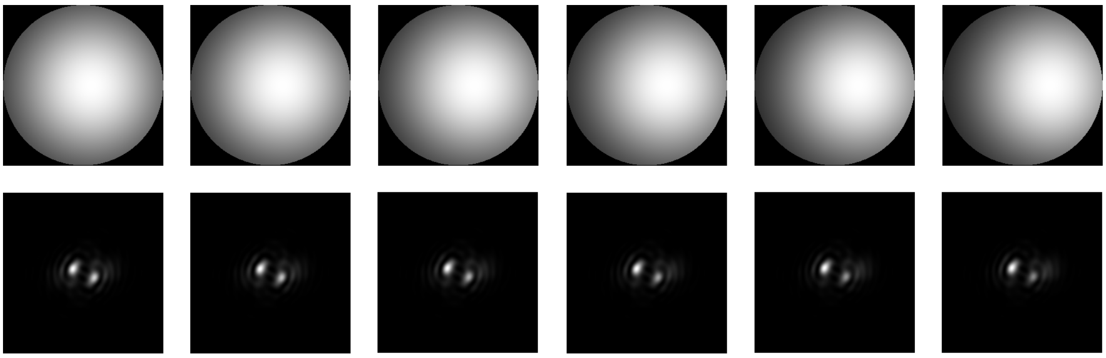

Figure 5: Result of modeling of the phase mask illumination by a Gaussian beam with a radius *w* equal to 1R. Upper row shows the intensity distribution of the incident beam. The bottom row shows the field formed in the plane of the beam waist under illumination of the phase filter by this beam. R is radius of the phase mask.

Next, we estimated the dependence of relationship of power in the left and right maximum of the intensity distribution of the generated field on the value of displacement Δ of the illuminating beam (Fig. 6). It was found that the allowable displacement of the illuminating beam relative to the center of the phase mask generating the field was 20% of the illuminating beam width. The permissible value of displacement was determined in accordance with the following criterion: the power in a weaker maximum should be at least half the power in the brighter maximum. This value is assessed basing on the assumption that the power in the main peaks (maxima) should not differ greatly. The power in the spots was estimated by the level $I > 0.3\, I_{max}$. If the brighter maximum is on the left (Fig. 5) and less bright one – on the right, this condition can be written as: $\frac{P_r}{P_l} \geq 0.5$ where P_l is the power the left peak, while P_r – in the right one.

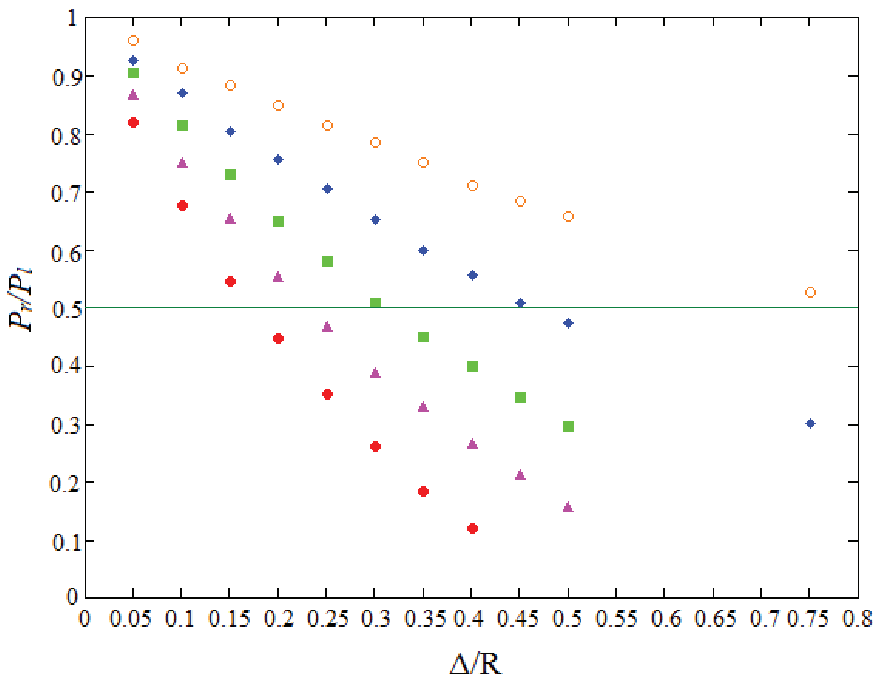

Figure 6: Graph of ratio of the power falling of the left and right maxima in the focusing plane when the phase filter is illuminated by the shifted Gaussian beam with a radius of 0.8 R (red circles), 1 R (purple triangles),1.2 R (green squares), 1.5 (blue rhombus), 2 R (orange circle circumference). R is radius of the phase mask.

The light falling on the phase mask may also have some intensity distribution not described by any law, and include heterogeneities of an irregular spontaneous nature. Modeling of the field formation under illumination of the phase mask by the intensity distribution, having a chaotic arrangement of light and dark spots was performed. These spots were of various sizes relative to the phase mask diameter of and amounted 0,1%, 0,2%, 0,4%, 0,8%, 1,6%, 3,2%, 6,4%, 12,8%, 25,6%. The two cases were considered: 1) when the intensity values of the spots were binary (Fig.7), and 2) when the intensity of the spot may have any intermediate value between the minimum (i.e. zero) to maximum.

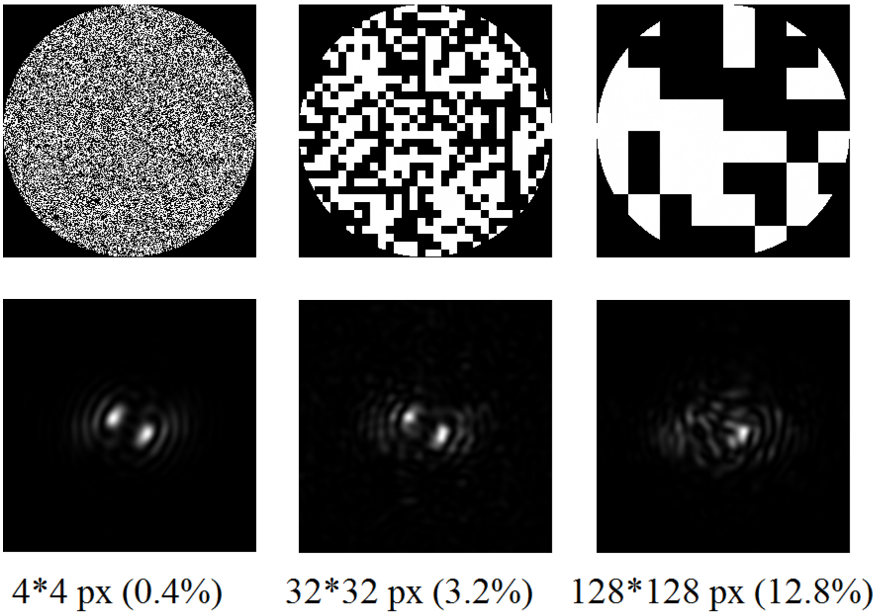

Figure 7: Modeling of impact on the field formation of chaotic binary heterogeneities of different sizes (0.4%, 3.2% and 12.8% of the phase mask radius) within the intensity distribution of the illuminating beam.

The results of modeling showed that such heterogeneities in the illuminating beam do not lead to any significant problems during the field formation as long as the spatial frequencies of the distortions become comparable with the spatial frequencies of the phase mask (Fig. 8).

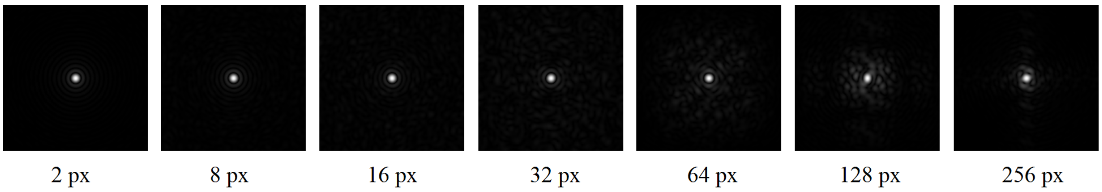

Figure 8: Spatial spectra of random amplitude distortions existing in the intensity distribution of the illuminating beam.

Regular amplitude distortions were studied as well. The phase mask was illuminated by the field having in its intensity distribution a system of concentric dark and light rings of equal thickness (Fig. 9). Noticeable changes in the picture being generated appear upon reaching of the period of rings equal to or exceeding 3.2% of the phase mask diameter. This can be explained by overlapping of spatial frequencies of distortions and spatial frequencies of the generated field.

From the above results it follows that for the two-lobe field formation it is necessary to maintain the ratio between the illuminating Gaussian beam width and the aperture of the phase mask, i.e. the illuminating beam radius should be ≥0.8 of the phase mask radius; to prevent a strong shift of the illuminating beam relative to the center of the

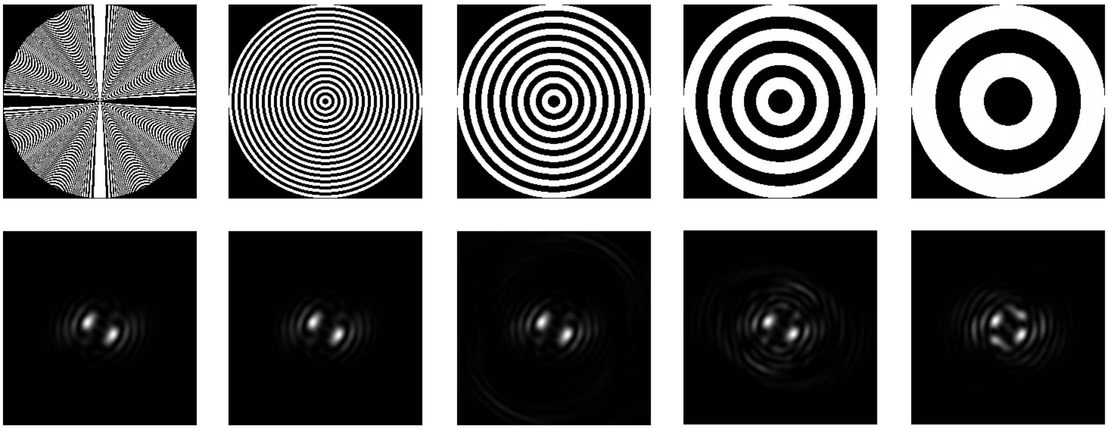

Figure 9: Modeling result on the two-lobe field formation under the illumination of the phase mask with the system of rings.

phase filter, the permissible displacement of the beam center is 20% of the illuminating beam width; and to ensure that there were no overlapping of the spatial spectrum of noise in the intensity distribution of the beam incident on the phase filter, and spatial spectrum of the field being generated.

3. Modeling of phase distortions

The modeling of the effect of phase distortions on the two-lobe field formation was also carried out. The phase distortions of the light field illuminating the phase mask may be caused by optical masks included in the optical system, or by inaccurate adjustment of the scheme (i.e. by offset and slope of the masks of the scheme). Besides, the phase distortions in the beam can be also caused by a transparent sample, where the nanoscale light emitters under study are placed.

It is known that the phase distortions are making big changes in the formation of light fields. Previously we considered the effect of the phase distortion in the form of aberrations, represented as Zernike polynomials [17]. It is discovered that for low values of the aberration amplitudes in the OSA standard, the picture formed with the aid of the phase mask becomes greatly distorted.

We also fulfilled modeling of the influence of chaotic phase distortions (Fig. 10) on the two-lobe field formation by analogy with the amplitude distortions (Fig. 7). This case can describe the situation when a multi-pixel spatial light modulator (SLM) is used for the field formation, and a part of its pixels is not working (i.e. phase delay on them is zero). In our modeling different degree of the SLM degradation was examined, and percentage of inoperative pixels was gradually increased. It is seen that such distortions existing in the phase leads to the destruction of the picture generated by the phase mask. When the number of inoperative (defective) pixels is small, <10%, then the field being generated is practically indistinguishable from the field obtained by the operable or properly functioning phase mask. On increasing the number of inoperative pixels up to 15%, the third peak emerges in the center of the generated pattern, which is getting brighter with the increase of the amount of inoperative pixels. At 35%, the power of all three peaks becomes approximately the same, and with the further increase of the amount of defective pixels only one central maximum is left.

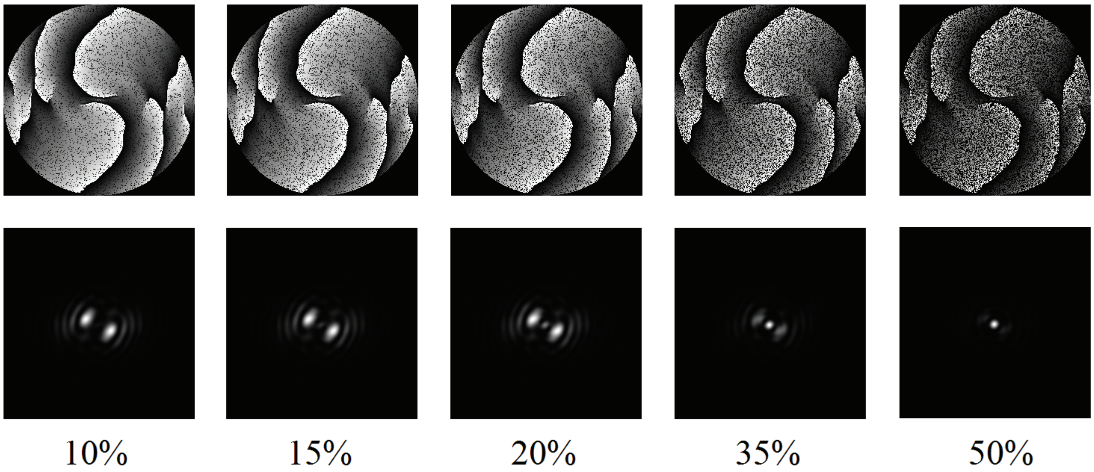

Figure 10: The evolution of the pattern generated in the focal plane with the growing degradation of the SLM that forms the phase profile.

The modeling of the inaccurate set of the phase for the phase mask that generates the field was also carried out. The amount of the phase modulation may change, provided that the mask is designed for one wavelength but is illuminated by radiation at a different wavelength. A similar situation is also probable in case when the phase mask formation is fulfilled with the SLM and a wrong calibration of this device. The calibration curve was assumed to be linear during the modeling, but the range of the phase change is not equal to 2π. Deviations from the required range are given in percents, showing the deficient or excessive amount relative to the initial phase at each point (Fig. 11). At the range of the phase modulation less than 2π, the principal maxima of the intensity distribution tend to merge in the area close to the focal plane (f 0,99 – 1,01 f). In the focusing plane a central major maximum emerges, which is more intense than the major maxima observed at the value deviation of -25%.

This central maximum decreases at the deviation of the phase modulation of -10%, and almost completely fades at -5%. With the raise of the phase modulation range the effect of a "twofold" image is observed that is particularly clear at the deviation values exceeding +35%. This effect results in the blurry image at the edges of the phase modulation range both in front of the focusing plane and behind it. And again, as in the previous case the third maximum appears in the focusing plane, though it is substantially weaker than two major peaks and originates in the intensity distribution only under significant deviations of the phase normalization (+25% and more). Maxima in the areas close to the focal plane are also clearly visible.

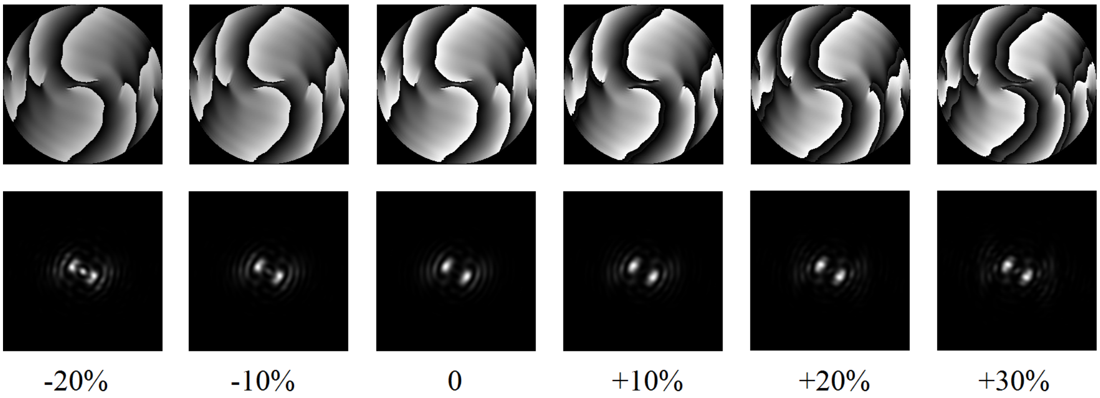

Figure 11: Intensity distribution in focal plane for the case of inaccurate posing of phase. Phase deviation is given in percent.

Thus, the acceptable deviations for calibration are: less than 10% reducing of the phase modulation depth, and less than 20% exceeding the depth of the phase modulation.

4. Discussion of the results

All stated above testifies in favor of the fact that the generated field is more sensitive to the changes in the structure of the phase component, than to the changes in the amplitude component structure. Let's make a specific comparison. As mentioned, in the researches described in [17] a study of the influence of aberrations on the formation of the fields was conducted. The aberrations were represented by Zernike polynomials in the OSA standards. Similar to the phase distribution, we can specify the amplitude distribution in the form of Zernike polynomials and compare the result of the influence of distortions that are identical both in amplitude and phase, on the field formation. Fig. 12 shows the results for the coma in the distribution of amplitude and phase.

It follows from Fig. 12 that the changes in the amplitude and phase distributions described by the same mathematical formula leads to different results. The change in phase distributions results in a cardinal destruction of the pattern, while change in amplitude distributions leads to no noticeable changes in the pattern. This confirms the decisive role of the phase distribution in the light field formation.

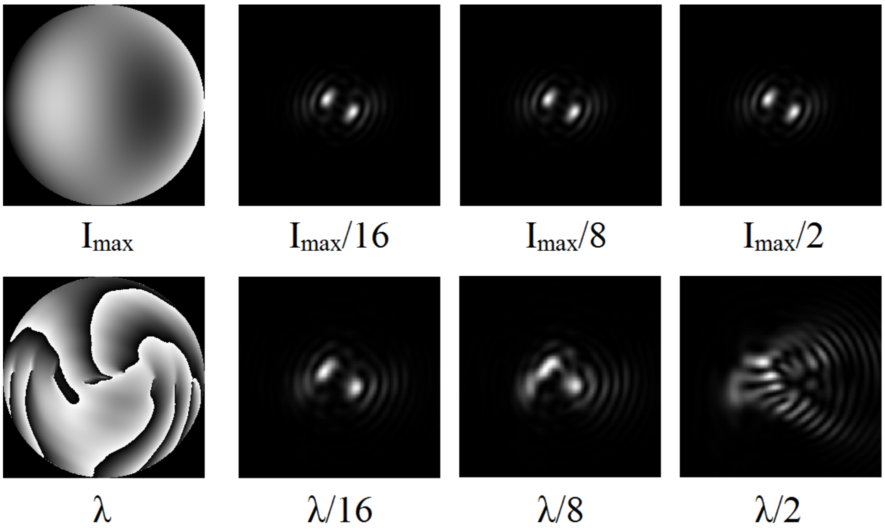

Figure 12: Influence of the coma aberration of various sizes on the distribution of amplitude (upper row) and phase (lower number) of the two-lobe light field. The two leftmost pictures correspond to the depth of modulation of amplitude 1 and to the phase filter with the overlaid coma of the amplitude value λ.

5. Conclusion

The work presents the results of modeling of the influence of the spatial structure of the illuminating beam on the formation of a two-lobe field by means of the developed phase mask for 3D localization of point light emitters. Different intensity distributions of the illuminating beam having the Gaussian profile, irregular and regular distortions, are considered. The results obtained by the modeling, allow us to define the specified below requirements to the intensity of the beam illuminating the phase filter.

It is necessary to maintain the ratio between the width of the illuminating Gaussian beam and the aperture of the phase mask. The illuminating beam radius should be 0.8 of the radius of the phase mask. The allowable displacement of the center of the illuminating Gaussian beam relative to the phase filter center should not exceed 20% of the width of the illuminating beam.

The formation of the two-lobe field of satisfactory quality is quite possible when there exist regular and chaotic heterogeneities (noise) in the intensity distribution of the illuminating beam with a planar wave front, provided that the amplitudes of the noise spectrum are small with regard to the base frequencies of the spatial spectrum of the generated field.

Possible distortions in the phase distribution of the illuminating beam are examined. The permissible value of degradation for the phase mask is <10% of the phase mask area. If this condition is satisfied, the generated field is practically indistinguishable from that generated by a properly operating phase mask. The permissible deviation of the phase modulation depth from 2π lies within the range from -10% to +20%**.**

Acknowledgement

The researches under this work are carried out with the financial support of RFBR (projects No.16-29-11809 and No.16-42-630773 p_a)

References

[1] Grier D.G. A Revolution in Optical Manipulation. Nature, 2003, 424. 810-16.

[2] V G Volostnikov, S P Kotova, N N Losevsky, M A Rakhmatulin, Microobject manipulation by laser beams with a nonzero orbital momentum, QUANTUM ELECTRON, 2002, 32. 565–66. DOI: 10.1070/QE2002v032n07ABEH002248

[3] Abramochkin E.G., Kotova S.P., Korobtsov A.V., Losevsky N.N., Mayorova A.M., Rakhmatulin M.A., Volostnikov V.G. Microobject Manipulation Using Laser Beams with Nonzero Orbital Angular Momentum. Laser Physics, 2006, 16. 1-7. DOI: 10.1134/S1054660X06050161

[4] Lew M.D., Thompson M.A., Badieirostami M., Moerner W.E. In vivo Three-Dimensional Superresolution Fluorescence Tracking using a Double-Helix Point Spread Function. Proceeding of SPIE, 2010, 7571: 75710Z. DOI: 10.1117/12.842608.

[5] A.V. Naumov, I.Y. Eremchev, A.A. Gorshelev// European Physical Journal D.2014. Vol. 68. № 11. p. 348

[6] Fernández-Suárez M., Ting A.Y. (2008). Fluorescent probes for super-resolution imaging in living cells. Nat. Rev. Mol. Cell. Biol. 9, 929–943

[7] Abramochkin, E., Volostnikov, V. Spiral-type beams, Optics Communications, Year: 1993 Volume: 102, Issue: 3-4, Pages: 336-350. DOI: 10.1016/0030-4018(93)90406-U

[18] Abramochkin E G, Volostnikov V G "Spiral light beams" Phys. Usp. 47 1177–1203 (2004); DOI: 10.1070/PU2004v047n12ABEH001802

[9] Abramochkin EG, Volostnikov VG. Modern Optics of Gaussian beams. Moscow: "Fizmatlit"; 2010.

[10] A. Greengard, Y. Schechner, R. Piestun //Optics letters. 2006. V. 31 (2). P. 181-183.

[11] S.R.P. Pavani, R. Piestun //Optics express. 2008. V. 16 (5). P. 3484-3489.

[12] Pavani S.R.P., Thompson M.A., et. al. // PNAS. 2009. V.106 (9). P. 2995-2999.

[13] Ghosh S., Preza Chr. // Journal of Biomedical Optics. 2013. V.18 (3). P. 036010.

[14] Baránek, M. Rotating vortex imaging implemented by a quantized spiral phase modulation / M. Baranek, Z. Bouchal //Journal of the European Optical Society-Rapid publications. 2013. – Vol. 8

[15] Grover, G. New approach to double-helix point spread function design for 3D super-resolution microscopy / G. Grover, R. Piestun //SPIE BiOS. – International Society for Optics and Photonics, 2013. – P. 85900M-85900M-6.

[16] Volostnikov V.G., Vorontsov E.N., et al. // Bulletin of the RAS: Physics. 2016. V.80 (7). P. 766-769.

[17] Vorontsov EN, Losevsky NN, Prokopova DV, Razueva EV, Samagin SA. Study on generating light fields with the intensity patterns characterized by different rotational rates. Computer Optics 2016; 40(2): 158-63. DOI: 10.18287/2412-6179-2016-40-2-158-163.

[18] Razueva, E.V. Fast rotating spiral light beams / Razueva E.V., Abramochkin E.G. // Proc. XII Int. Workshop on Quantum Optics (IWQO-2015) (eds. V.V. Samartsev, E.A. Vinogradov, A.V. Naumov and K.R. Karimullin), Troitsk, 4-16 August 2015.

[19] Razueva, E.V. Parametric families of paraxial light fields thesis PhD. Year: 2015