

A study on reducing of the focal spot size using spatial filtering and phase apodization

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Abstract. The resizing of focal spot using an annular diaphragm with phase jump in the scalar paraxial case was investigated numerically. Due to the apodization optical system, we succeeded in reducing the size of the focal spot in 2.3 times.

1. Introduction

One of the drawbacks of the conventional light microscope - beams out of focus, which reduce image contrast. If in the scheme of optical microscope to introduce a special aperture located in the intermediate image plane, it will miss the only light rays that come from a very small area of the object. Aperture will act as a spatial filter. The smaller the diameter of the aperture then is the smaller the area.

It is well known that one way the formation of narrow beams of extended focal plane is to use a narrow annular aperture blocking radiation in the central portion of the lens [1]. Modifications of this method in the full-aperture pupil apodization function using amplitude-phase and pure phase distributions are considered in [2-4]. Reducing the size of the focal spot, usually accompanied by a redistribution of power from the central portion to the side lobes, which is consistent with the theory Toraldo di France [5]. In [6,7] numerically investigated reducing the size of the focal spot in the radial polarization using binary annular element. It was shown that due to making the phase jump and simultaneously broadening the annular aperture can form a focal spot and size of this spot does not exceed the limit corresponding to a narrow annular aperture, and the intensity is increased by almost 6 times.

In this paper numerically investigate the influence of the size of the size of annular aperture with a radial phase jump to the formed the focal spot in the scalar paraxial case. The scalar case corresponds to uniform polarization and focusing with a small numerical aperture will not lead to strengthening of the longitudinal component of the electric field which broadens in this case, the focal spot [8,9].



2. Spatial filtering and phase apodization

In this paper, to focus limited plane wave (wavelength $\lambda = 0.633$ micrometres) with a lens radius R and the focal length f (numerical aperture $NA \approx f/R$) used transformation of Fourier-Bessel. The intensity in the focal plane in this case is:

$$I(\rho) = \left| \frac{2\pi}{\lambda f} \int_0^R J_0 \left(\frac{2\pi \rho r}{\lambda f} \right) r dr \right|^2 = \left| \frac{R}{\rho} J_1 \left(\frac{2\pi \rho R}{\lambda f} \right) \right|^2. \quad (1)$$

The radius of the central spot in the focusing (1) without apodization is determined by the first zero of the Bessel function of the first order ($J_1(\gamma_{11}) = 0$, $\gamma_{11} = 3.83$):

$$\rho_{lens} = \frac{3.83\lambda f}{2\pi R} = \frac{0.61\lambda f}{R} \approx 0.61\lambda/NA. \quad (2)$$

If limited the exit pupil to the narrow annular aperture with a relative width Δ , we obtain [6]:

$$I_{\Delta}(\rho) = \left| \frac{2\pi}{\lambda f} \int_{R(1-\Delta)}^R J_0 \left(\frac{k\rho r}{f} \right) r dr \right|^2 \approx \left| \frac{2\pi R^2 \Delta}{\lambda f} J_0 \left(\frac{k\rho R}{f} \right) \right|^2. \quad (3)$$

Then the radius of the focal spot is determined by the first zero of the Bessel function of zero order ($J_0(\gamma_{01}) = 0$, $\gamma_{01} = 2.405$):

$$\rho_{ring} = \frac{2.4\lambda f}{2\pi R} = \frac{0.38\lambda f}{R} \approx 0.38\lambda/NA, \quad (4)$$

that is, 1.6 times less than without apodization.

The additional introduction of a radial phase jump can further reduce the size of focal spot [6]:

$$\rho_{min}^{jump} = \frac{0.22\lambda f}{R} \approx 0.22\lambda/NA, \quad (5)$$

Thus, theoretically, the amplitude-phase apodization reduces the size of the focal spot of 2.77 times, but this comes at the expense of a significant loss of energy. To estimate the losses, perform the numerical simulation.

The calculation parameters: the radius of the lens is 1 mm (equal to the outer radius of the diaphragm), the focus is 100 mm ($NA = 0.01$), r_1 - the inner radius of the diaphragm, r_2 - the radius of the phase jump on π radians. Figure 1 shows the schema of using installation.

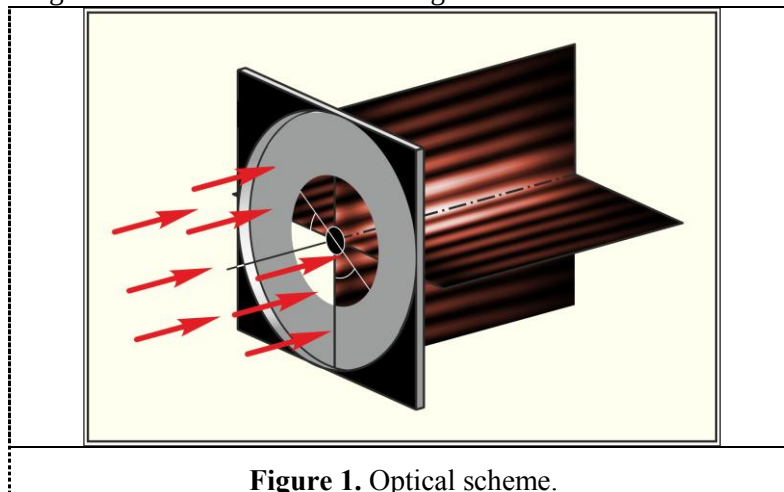


Figure 1. Optical scheme.

To evaluate the effectiveness type the following expression:

$$\varepsilon = \frac{I}{I_0}, \quad (5)$$

I - a value of intensity at the focus using the spatial filtering and phase apodization, I_0 - maximum value of the focus (without apodization).

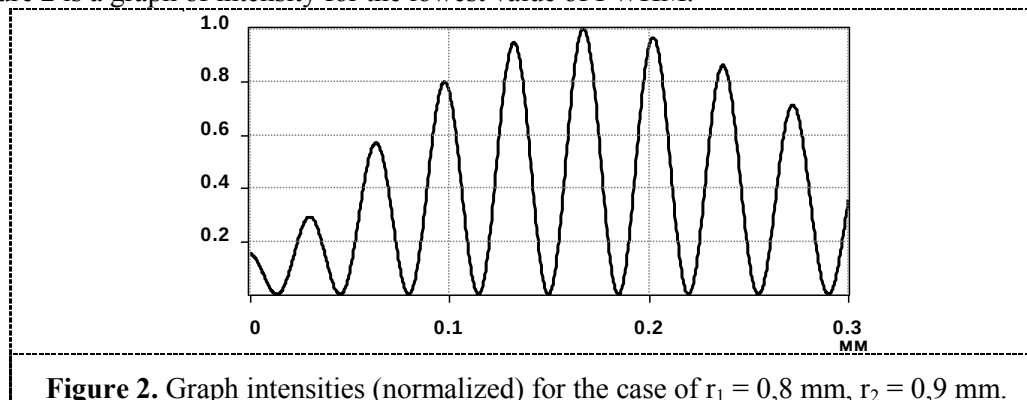
Table 1 shows the cross-section intensity pattern obtained in the focal region, and input values of the phase and amplitude of the diaphragm (the dotted line in the pictures shows the amplitude size of the inner radius of the aperture).

Table 1. Change the radius of the diaphragm and the phase jump (picture 2 mm×2mm).

The radius of the aperture, $r_1 \setminus r_2$, mm	without apodization	0,2 \ 0,6	0,4 \ 0,7	0,6 \ 0,8	0,7 \ 0,85	0,76 \ 0,88	0,8 \ 0,9
Input, amplitude							
Input, phase							
The focus, intensity							
FWHM, mm	0,0326	0,0208	0,0192	0,0159	0,015	0,0144	0,014
ε	1	0,102	$3,2 \cdot 10^{-2}$	$6,1 \cdot 10^{-3}$	$1,9 \cdot 10^{-3}$	$7,8 \cdot 10^{-4}$	$3,6 \cdot 10^{-4}$

As seen from table 1, the decrease in the radius of the phase ring and amplitude ring reduces the size of the focal spot, which is accompanied by the growth of side lobes. The lowest value was obtained when $r_1 = 0.8$ mm, $r_2 = 0.9$ mm and made FWHM = 0.014 mm, it is better theoretical value 2.3 times. However, in this case, the intensity value is 0.036% of the peak without using a aperture. It looks acceptable result for $r_1 = 0.6$ mm, $r_2 = 0.8$ mm. Then, the intensity value is about 0.6% of the maximum value when the size of focal spot of 0.0159 mm.

On figure 2 is a graph of intensity for the lowest value of FWHM.



As seen from the graph, the total intensity of the picture there are significant side lobes, yet they are commensurate with the height of the central peak, in contrast to super-oscillating functions [10].

3. Conclusion

Thus, it is numerically shown that the focus is uniformly polarized plane wave at a low numerical aperture lens can be used the annular diaphragm with the phase jump. Thus it was possible to achieve reduction of the size of the focal spot is 2.3 times as compared with the theoretical value (the minimum value of FWHM = 0,014 mm) but in this case an increase in the intensity of the side lobe in a significant drop in intensity at the focus.

Acknowledgments

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4. References

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