Spot size and depth of focus in optical data storage system

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Abstract. Different definitions of spot size and depth of focus in optical data storage systems are analyzed and compared numerically. It appears that the differences between the definitions become more significant as the numerical aperture of the optical system increases. The relationship between spherical aberration and axial intensity is studied, and a general definition of the depth of focus based on this analysis is proposed.
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1 Introduction

In a high-density optical data storage system, the widely accepted definition of the spot size of the focusing lens is given by $\lambda/(2\,\mathrm{NA})$, where λ is the wavelength and NA is the numerical aperture of the optical system. Another definition uses the full width at half maximum (FWHM) of the intensity spot on the focal plane of an optical system. We have found that the two definitions agree well for low-numerical-aperture lenses if the system is illuminated with uniformly distributed light on the pupil; for high numerical aperture the difference becomes significant.

The depth of focus (DOF) of a microscope system has been defined by a number of authors,[1–4] and these definitions do not agree with each other. For optical data storage systems, people use the distance between the focal point and the point where the intensity decreases to 90% as the DOF, while in applications like imaging systems, people use 50%.[1] In 1993, I.T. Young used the Rayleigh limit to characterize the distortion due to defocusing, and gave a corresponding DOF definition.[2] Different definitions of DOF give very different results, which can be misleading. In this paper, we analyze the focused-spot size at different NAs numerically, based on vector diffraction theory, and compare the results with the spot size defined by $\lambda/(2\,\mathrm{NA})$. We propose a general definition of DOF based on the analysis of the relationship between the defocus spherical aberration and the axial intensity, taking both into account.

2 Analysis

2.1 *Spot Size*

The focused spot size is usually defined as $\lambda/(2\,\mathrm{NA})$, where λ is the incident wavelength, and NA is the numerical aperture of the focusing lens. To evaluate the accuracy of this definition, we modeled the focusing of different NA lenses with vector diffraction theory.[5–8] Suppose the field on the aperture of the focusing lens is circularly polarized. Then the field in the focal region is given as

$$E_x = -iA[I_0 + I_2(\cos 2\varphi + i \sin 2\varphi)], \tag{1}$$

$$E_y = -iA[iI_0 - iI_2(\cos 2\varphi + i \sin 2\varphi)], \tag{2}$$

$$E_z = -2AI_1(\cos\varphi + i \sin\varphi), \tag{3}$$

where

$$I_0 = \int_0^\alpha (\cos\theta)^{1/2} \sin\theta\,(1 + \cos\theta) J_0(k_0 r \sin\theta) \exp(ik_0 z \cos\theta)\, \mathrm{d}\theta, \tag{4}$$

$$I_1 = \int_0^\alpha (\cos\theta)^{1/2} \sin^2\theta\, J_1(k_0 r \sin\theta) \exp(ik_0 z \cos\theta)\, \mathrm{d}\theta, \tag{5}$$

$$I_2 = \int_0^\alpha (\cos\theta)^{1/2} \sin\theta\,(1 - \cos\theta) J_2(k_0 r \sin\theta) \exp(ik_0 z \cos\theta)\, \mathrm{d}\theta. \tag{6}$$

Here $\alpha = \arcsin(\mathrm{NA}/n)$ is the largest focusing angle; n is the refractive index of the material in the focal region; φ is the azimuthal angle; $k_0 = 2\pi/\lambda$; J_0, J_1, and J_2 are the zero-order, first-order, and second-order Bessel functions, of the first kind; and the constant $A = \pi l_0 f/\lambda$, where $l_0 = 1$ for unit illumination and f is the focal length.

The FWHM of the intensity $(E_x^2 + E_y^2 + E_z^2)$ profile in the focal plane for lenses of different numerical aperture was calculated using Eqs. (1) to (6) with $z = 0$. Because we are mainly concerned about the effect of focusing angle on focused spot size, the refractive index of the material in the focal region is taken to be 1.0. Figure 1 shows that the FWHM decreases with increase of the NA of a lens, the spot size obtained with the vector diffraction integration method is always a little larger than that defined by $\lambda/(2\,\mathrm{NA})$, and this difference increases with the increase of NA. If we take the result obtained with vector diffraction

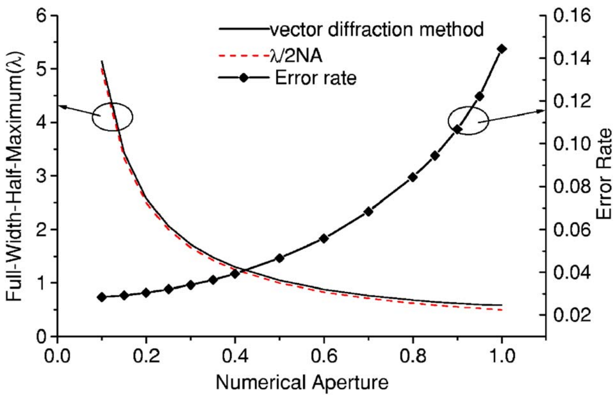

Fig. 1 Comparison of spot size calculated with different methods.

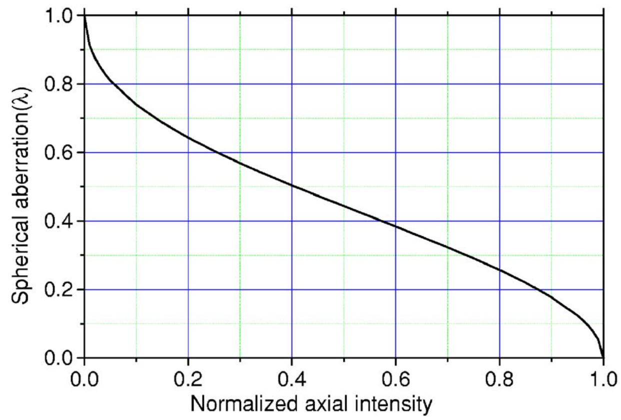

Fig. 2 Relationship between axial intensity and spherical aberration.

method as the true spot size and denote it by SC, and denote the result obtained with $\lambda/(2\,\mathrm{NA})$ by SR, the error rate can be calculated as $(\mathrm{SC}-\mathrm{SR})/\mathrm{SC}$. It can be seen in Fig. 1 that the error rate increases with NA.

2.2 *Depth of Focus*

For a specific focusing lens, different defocus distances correspond to different axial intensities and spherical aberrations. However, we found that, for an ideal focusing lens, the defocusing spherical aberration is directly related to the on-axis intensity, and this relationship does not depend on the numerical aperture. The relationship between spherical aberration and the on-axis intensity is shown in Table 1 and Fig. 2; the on-axis intensity varies from the first minimum to the maximum on the focal point. One can see in Fig. 2 that the maximum spherical aberration is 1 wavelength when the intensity decreases to its first minimum, and zero when the intensity is maximum (1.0).

Based on the analysis of intensity and spherical aberration, we propose a general definition of DOF,

$$\mathrm{DOF} = \frac{A}{n\{1-[1-(\mathrm{NA}/n)^2]^{1/2}\}}, \tag{7}$$

where $\mathrm{NA}=n \sin \alpha$ is the numerical aperture of the focusing lens, n is the refractive index of the material (supposed isotropic) in the focal region, α is the largest focusing angle within the material, and A represents the spherical aberration that the application is able to tolerate ($A \leq \lambda$); $A=\lambda/4$ corresponds to the DOF defined by I. T. Young. Thus, for a certain focusing lens, the DOF can also be calculated from the on-axis intensity using the relationship between the spherical aberration and the axial intensity. Table 2 shows the DOF in the optical disk, calculated according to Eq. (7) and Table 1; we take the distance between the focal point and the position where the intensity decreases to 0.9 as the DOF. The calculation here is based on the fact that objective lenses for the optical disk are specially designed, so that the aberration caused by the interface[9–11] and the substrate thickness[12,13] are eliminated.

Table 1 Relationship between axial intensity and the spherical aberration.

Intensity	Aberration (wavelengths)	Intensity	Aberration (wavelengths)	Intensity	Aberration (wavelengths)
0	1	0.3	0.56876	0.8	0.25776
0.01	0.91404	0.35	0.53556	0.85	0.22064
0.02	0.87744	0.4	0.50396	0.9	0.17816
0.03	0.85078	0.45	0.47334	0.95	0.12456
0.04	0.82912	0.5	0.44346	0.96	0.11122
0.05	0.81048	0.55	0.4139	0.97	0.09602
0.1	0.7397	0.6	0.38432	0.98	0.07822
0.15	0.68716	0.65	0.35438	0.99	0.05508
0.2	0.6432	0.7	0.32366	1	0
0.25	0.60432	0.75	0.29172		

Table 2 DOF calculation for different NA and n.

λ (μm)	n	NA	α (deg)	DOF (μm)
0.65	1.58	0.6	22.32	0.9784
0.405	1.62	0.85	31.65	0.2995
0.405	1.62	0.65	23.66	0.5300
0.405	1.62	0.9	33.75	0.2643
0.405	1.62	0.95	35.90	0.2344
0.405	1.62	1.0	38.12	0.2088
0.405	1.62	1.45	63.52	0.0803

3 Conclusion

In conclusion, we have analyzed the spot size and the depth of focus of optical data storage systems numerically, and compared the spot size obtained with two different methods. We have proposed a general definition of the depth of focus, where both the spherical aberration and the axial intensity are taken into account. The results obtained in this paper are also applicable to general imaging systems, such as microscopes.

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