High focal depth with a pure-phase apodizer

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High-density optical data storage requires high-numerical-aperture (NA) lenses and short wavelengths. But, with increasing NA and decreasing wavelength, the depth of focus (DOF) decreases rapidly. We propose to use pure-phase superresolution apodizers to optimize the axial intensity distribution and extend the DOF of an optical pickup. With this kind of apodizer, the expected DOF can be 2–4.88 times greater than that of the original system, and the spot size will be smaller than that of the original system.

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1. Introduction

In high-density optical data storage, the small diameter of a converged laser beam is used to increase the capacity of a disk. The diameter of a converged laser beam at the beam waist is \( D = 0.5\lambda/\text{NA} \), where \( \lambda \) is the wavelength, NA is the numerical aperture of the objective lens, \( D \) is the full width at half-maximum of the intensity profile. NA is defined as \( \text{NA} = r_0/f_0 \), where \( r_0 \) is the radius of the objective aperture of the system and \( f_0 \) is the focal length of the optical system. Thus we can decrease the diameter by reducing the wavelength of the laser or increasing the NA of the lens. The shortest wavelength and the largest NA used in high-density optical storage are 0.266 \( \mu \text{m} \) and 0.9, respectively\(^1 \) (a solid immersion lens and an oil immersion lens are not considered here). Accordingly, the diameter of the converged laser beam at the beam waist is 0.148 \( \mu \text{m} \), but, with decreasing wavelength and increasing NA, the depth of focus the (DOF) decreases rapidly, because the DOF can be denoted \( \text{DOF} = \lambda/\text{NA}^2 \). For a pickup with the wavelength and the objective mentioned above, the DOF is 0.328 \( \mu \text{m} \), a value that makes tracking by the track servo system difficult. Several techniques for achieving a large DOF of an optical imaging system, which include use of some specially designed apodizers,\(^2–7 \) image processing methods,\(^8–10 \) and quasi-bifocus birefringent lens methods,\(^11,12 \) were reported recently. Those specially designed apodizers are quite complex in phase and amplitude transmittance, so fabricating them is difficult and their efficiency is low. In this paper we propose using a pure-phase three-portion phase-shifting superresolution apodizer to optimize the axial intensity distribution and extend the DOF. We assume that the acceptable intensity variation near the focus along the axis is 10%. With the proposed apodizer, the longest attainable DOF is 4.88-fold that of the original pickup, the axial intensity distribution is ideal, the half-width ratio (HWR) of the converged beam in the beam-waist plane is \( \text{HWR} = 0.787 \), the relative side-lobe peak intensity (ratio of sidelobe peak intensity to main lobe peak intensity) is 12%, and the Strehl ratio is 0.213. The relation among inner radius, Strehl ratio, HWR, and relative sidelobe intensity (RSI) is also studied through simulation under the condition that the axial intensity is optimized. This kind of apodizer is easy to produce and duplicate for mass production.

2. Operating Principle of the System

Figure 1 shows that the collimated light passes through a phase-shifting apodizer and then converges through an objective lens onto an optical disk. For an \( N \)-portion annular phase-shifting apodizer, the normalized amplitude distribution in the image side can be defined as \(^{13–16} \)

\[
G(r, u) = 2 \sum_{j=1}^{N} \exp(i\phi_j) \int_{r_{j-1}}^{r_j} r g(r) J_0(pr) \times \exp[-(1/2)iur^2]dr,
\]

(1)

where \( r \) is the radial coordinate of the objective lens's pupil plane and \( g(r) \) is the amplitude distribution in
the radial direction of the lens’s pupil plane. \{\phi_j = \phi_j, j = 1, \ldots, N\} defines the phase of zone \(j\) on the pupil plane. The radial position of each zone is given by \(r = r_j, j = 0, \ldots, N\), where \(r_0 = 0\). \(\rho\) and \(u\) are the simplified radial and axial coordinates, respectively, on the image side:

\[
\rho = (2\pi/\lambda)(NA)R, \\
u = (2\pi/\lambda)(NA)^2Z,
\]

where \(R\) and \(Z\) are the genuine radial and axial coordinates on the image side. \(NA\) is the numerical aperture of the objective lens.

For a uniform-intensity-distribution light source, the function \(g(r) = 1\). So the normalized amplitude distribution on the image side can be simplified as

\[
G(\rho, u) = 2 \sum_{j=1}^{N} \exp(i\phi_j) \int_{r_{j-1}}^{r_j} rJ_0(\rho r) \\
\times \exp[(-1/2)iur^2]dr,
\]

in the beam-waist plane where \(Z = 0\), i.e., \(u = 0\). Thus the amplitude distribution on the image side can be written as

\[
G(\rho, 0) = 2 \sum_{j=1}^{N} \exp(i\phi_j) \int_{r_{j-1}}^{r_j} rJ_0(\rho r)dr \\
= 2 \frac{1}{\rho} \sum_{j=1}^{N} \exp(i\phi_j)[r_jJ_0(\rho r_j) - r_{j-1}J_1(\rho r_{j-1})].
\]

For a three-port \(\pi\) phase-shifting apodizer (Fig. 2) the phases of the three portions are 0, \(\pi\), and 0, \(0, \pi, 1\). Thus we get the radial amplitude distribution in the beam-waist plane:

\[
G(\rho, 0) = \frac{2}{\rho} \{J_1(\rho) - 2[\alpha J_1(\alpha \rho) - \beta J_1(\beta \rho)]\}.
\]

(6)

The Strehl ratio is

\[
S = [G_{a \neq b}(0, 0)/G_{a=b=0}(0, 0)]^2 = [1 - 2(a^2 - b^2)]^2.
\]

(7)

For small values of \(\rho\), we use Eq. (A1) (see Appendix A) to generate an approximate formulation of the third-order term. Then we get

\[
G(\rho, 0) = 1 - 2(a^2 - b^2) + \rho^2 \left(\frac{a^4 - b^4}{4} - \frac{1}{8}\right),
\]

(8)

\[
HWR = \frac{1 - 2(a^2 - b^2)}{1 - 2(a^4 - b^4)}^{1/2}.
\]

(9)

The amplitude along the axis is

\[
G(0, u) = 2 \sum_{j=1}^{N} \exp(i\phi_j) \int_{r_{j-1}}^{r_j} r \exp[(-1/2)iur^2]dr \\
= \frac{2}{iu} \left(\exp[(-1/2)iur] - 1 \right) \\
- 2[\exp[(-1/2)iua^2] - \exp[(-1/2)iub^2]]).
\]

(10)

Thus the intensity along the axis is

\[
I(u) = |G(0, u)|^2 = \left\{10 + 16 \sin \left[\frac{u}{4} \left(a^2 - b^2\right)\right] \right. \\
\times \sin \frac{u}{4} \cos \left[\frac{u}{4} \left(1 - a^2 - b^2\right)\right] \\
- 8 \cos \left[\frac{u}{2} \left(a^2 - b^2\right)\right] - 2 \cos \frac{u}{2} \frac{4}{u^2} \left[\left(a^2 - b^2\right)\right].
\]

(11)

According to Eqs. (7) and (11),

\[
I(u) = \left\{10 + 16 \sin \left[\frac{u}{4} \left(1 - S^{1/2}\right)\right] \right. \\
\times \sin \frac{u}{4} \cos \left[\frac{u}{4} \left(1 - 2b^2 - 1 - S^{1/2}\right)\right] \\
- 8 \cos \left[\frac{u}{2} \left(1 - S^{1/2}\right)\right] - 2 \cos \frac{u}{2} \frac{4}{u^2} \left[\left(1 - S^{1/2}\right)\right].
\]

(12)

Equation (12) indicates that the axial intensity distribution is affected by two factors. One is the Strehl ratio. The other is the inner radius of the three-port apodizer. For a Strehl ratio \(S\), the axial intensity distribution changes with the inner radius \(b\).
3. Numerical Results

We use scalar diffraction theory to calculate the intensity distribution of light that converges in the proposed system. For different values of the inner radius, the axial intensity distribution is optimized, and then the Strehl ratio, the DOF, the HWR, and the RSI are calculated. The defocus effect is also studied.

Figure 3 shows the axial intensity distribution of the optimized and the original systems. The solid curve corresponds to the original system; it is easy to see that the intensity decreases rapidly when it is defocused. For the optimized system, if inner radius \( b \) is smaller than 0.3, the axial intensity remains almost unchanged for a wide range and then decreases. For a certain value of inner radius \( b \), the axial intensity distribution is optimized by suitable selection of outer radius \( a \). All the curves have been normalized for comparison.

Figure 4 shows the relation among inner radius \( b \), outer radius \( a \), the HWR, the Strehl ratio, and the RSI of the optimized system. It can be seen that, with increasing inner radius \( b \), the outer radius increases almost linearly. The HWR, the Strehl ratio, and the RSI decrease with increasing inner radius. In Fig. 5 the relation between the depth of focus and the inner radius is shown. Comparing Figs. 4 and 5, we can see that a longer depth of focus corresponds to a lower RSI and a smaller HWR. This result is quite satisfying.

Figure 6 shows the defocusing effect of the optimized system. The three curves correspond to the three optimized curves in Fig. 3. The HWR represents the spot size. As is shown, the spot size increases with increasing defocusing distance, and all the spot sizes within the depth of focus are smaller than those of the original system.

Figure 7 is the three-dimensional intensity distribution of the original system. Figures 8–10 are the three-dimensional intensity distributions of the optimized system with different inner radii. It can be seen that increasing inner radius \( b \) extends the depth of focus. When inner radius \( b \) is less 0.3, the intensities near the focal plane are almost equal. But, when inner radius \( b \) is bigger than 0.3, the intensity variation near the focal plane tends to increase, as can be seen from Fig. 10. Accordingly, a further attempt to gain a wide-range equal intensity distribution in the axial direction would be fruitless.

Fig. 3. Axial intensity distribution of the optimized and the original systems.

Fig. 4. Relation among the inner radius, the outer radius, the HWR, the Strehl ratio, and the RSI.

Fig. 5. DOF versus inner radius \( b \) for the optimized systems.

Fig. 6. Defocusing characteristics of the optimized systems.
4. Conclusion

In summary, we have proposed to use three-portion phase-shifting apodizers to extend the DOF of an optical pickup and at the same time minimize the spot size. The intensities near the focal plane are almost equal in a wide range when inner radius $b$ is less than 0.3. Suppose that a 10% variation of the intensity along the axis is allowed; the maximum attainable DOF will be 4.88-fold that of the original pickup. If a wavelength of 0.266 $\mu$m and a NA of 0.9 are chosen, the longest attainable DOF is 1.62 $\mu$m. Therefore it is possible to record with ultraviolet light whose DOF is sufficient for a track servo system.

Fig. 8. Three-dimensional intensity distribution of the optimized system with an inner radius $b = 0$.

Fig. 9. Three-dimensional intensity of the optimized system with an inner radius $b = 0.3$.

Fig. 10. Three-dimensional intensity distribution of the optimized system with an inner radius $b = 0.35$.

Appendix A

The following is the approximate formula for a Bessel function of the first order:

$$J_1(z) = \left(\frac{z}{2}\right) \sum_{n=0}^{\infty} \frac{(-1)^n(z/2)^{2n}}{n!(n+1)!}$$

$$= 2.0 \left(\frac{z}{4}\right)^2 - 4 \left(\frac{z}{4}\right)^3 + 2.7 \left(\frac{z}{4}\right)^5 - 0.89 \left(\frac{z}{4}\right)^7$$

$$+ 0.18 \left(\frac{z}{4}\right)^9 - \ldots \ldots \quad (A1)$$

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References


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