

Simulation of an apodizer's effect for high-density optical storage

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The effect of an apodizer with two parallel taper refractive surfaces is theoretically investigated for high-density optical storage. The apodizer may modulate an incident Gaussian beam into an annular beam. Simulation shows that with the increasing inner radius of the modulated beam, the focal spot shrinks obviously. The depolarization effect gets strong simultaneously, which induces the circular symmetry loss of the focal spot. In this process, pattern density of the orthogonal and longitudinal diffractive fields increases remarkably.

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Super-high-density optical storage has become attractive because smaller size of recording marks on the optical disk is required. However, in optical storage system, the size of recording mark is restricted by diffractive limit^[1]. Aiming at breaking diffractive limit, many techniques have been proposed and implemented^[2-5], including phase-shifting apodizer^[6,7]. Recently, a new kind of apodizer was introduced to attain super-resolution^[8], though its subtle structure has not been given. The theoretical analyses of apodizers are usually based on scalar diffraction theory for relative ease. However, in focusing optical systems with polarized incident field or high numerical aperture (NA), the light intensity distribution in the focal region differs from the results of scalar theory, for example, a linearly polarized beam becomes depolarized in focal region due to high NA. In other words, the diffracted field in focal region includes not only a component with the same polarization as the incident beam, but also the orthogonal and longitudinal components^[9,10]. In this letter, a vector Gaussian beam is used as incident beam in optical storage system, and an apodizer with two parallel taper refractive surfaces is introduced to modulate the incident vector beam into an annular beam. Based on the vector diffraction theory, the effect of the apodizer is simulated, and the results show that the focal spot shrinks considerably with the increasing inner radius of the modulated beam.

The optical storage system is shown in Fig. 1. An incident Gaussian beam is shaped into an annular beam by an apodizer with two parallel taper refractive surfaces, then convergences through a lens. Assume that the incident polarization is in x -direction. According to the

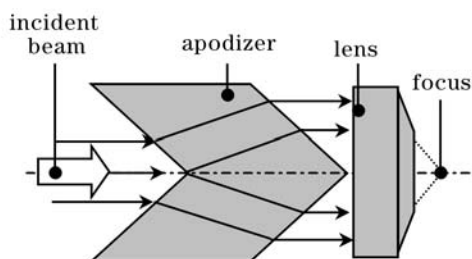


Fig. 1. Sketch of the system setup.

energy conversation theory and vector diffraction theory, the amplitude of electric field in the focal region can be written as^[10,11]

$$E(r, \phi, z) = \frac{\pi E_0 i}{\lambda} \{ [I_0 + \cos(2\phi) I_2] \mathbf{x} + \sin(2\phi) I_2 \mathbf{y} + 2i \cos \phi I_1 \mathbf{z} \}, \quad (1)$$

where \mathbf{x} , \mathbf{y} , and \mathbf{z} are the unit vectors in the x , y , and z directions, respectively. Constant E_0 is the amplitude of incident beam. It is clear that the incident beam is depolarized and has three components (E_i , E_j , and E_k) in x , y , and z directions, respectively. The variables r , ϕ , and z are the cylindrical coordinates of an observation point in focal region. I_0 , I_1 , and I_2 are defined as

$$I_0 = \int_{\beta}^{\alpha} \sqrt{\frac{(\sin \theta - d) \cos \theta}{\sin \theta}} \exp \left[- \left(\frac{\sin \theta - d}{w} \right)^2 \right] \sin \theta \times (1 + \cos \theta) J_0(kr \sin \theta) \exp(-ikz \cos \theta) d\theta, \quad (2)$$

$$I_1 = \int_{\beta}^{\alpha} \sqrt{\frac{(\sin \theta - d) \cos \theta}{\sin \theta}} \exp \left[- \left(\frac{\sin \theta - d}{w} \right)^2 \right] \sin^2 \theta \times J_1(kr \sin \theta) \exp(-ikz \cos \theta) d\theta, \quad (3)$$

$$I_2 = \int_{\beta}^{\alpha} \sqrt{\frac{(\sin \theta - d) \cos \theta}{\sin \theta}} \exp \left[- \left(\frac{\sin \theta - d}{w} \right)^2 \right] \sin \theta \times (1 - \cos \theta) J_2(kr \sin \theta) \exp(-ikz \cos \theta) d\theta, \quad (4)$$

where k is the wave number, $\beta = \arcsin(d)$ and $\alpha = \arcsin(d + w)$. $J_0(x)$, $J_1(x)$, and $J_2(x)$ are the zeroth-, first-, and second-order Bessel functions of the first kind, respectively. In this letter, d and w represent normalized inner radius and waist width, respectively, $d = d_0/f$ and $w = w_0/f$, d_0 is the inner radius of modulated beam, w_0 is the waist width of the incident Gaussian beam, f is the focal length. The light intensity in focal region is proportional to the modulus square of Eq. (1).

Without loss of validity and generality, it is assumed that $\pi E_0/\lambda = 1$. In order to understand the effect of apodizer more clearly, the intensity distribution in focal region of the original optical system, which does not contain apodizer, has been calculated. The result for $w = 0.1$ is illustrated in Fig. 2. It should be noted that the dimensionless coordinates $v_x = kx$ and $v_y = ky$, which satisfy the equation $v_x^2 + v_y^2 = v_r^2$, where $v_r = kr$. The intensity distributions of the total field and its three components ($|E_i|^2$, $|E_j|^2$ and $|E_k|^2$) in apodized system are simulated for $w = 0.1$, as shown in Fig. 3. It can be seen that when d is small, the orthogonal and longitudinal fields are much weaker than the diffractive field (that has the same polarization as the incident beam). So the diffractive field with the same polarization as the incident beam determines the light intensity distribution in focal region. The orthogonal and longitudinal fields have four and two light intensity peaks, respectively, as

shown in Figs. 3(c) and (d). With increasing d , the focal spot shrinks considerably, which increases the optical storage density. The patterns of all diffractive fields also get dense simultaneously. The intensity distributions of

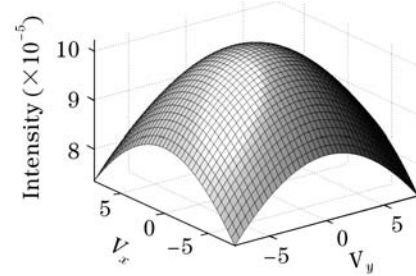


Fig. 2. Intensity distribution in focal region of optical system for $w = 0.1$.

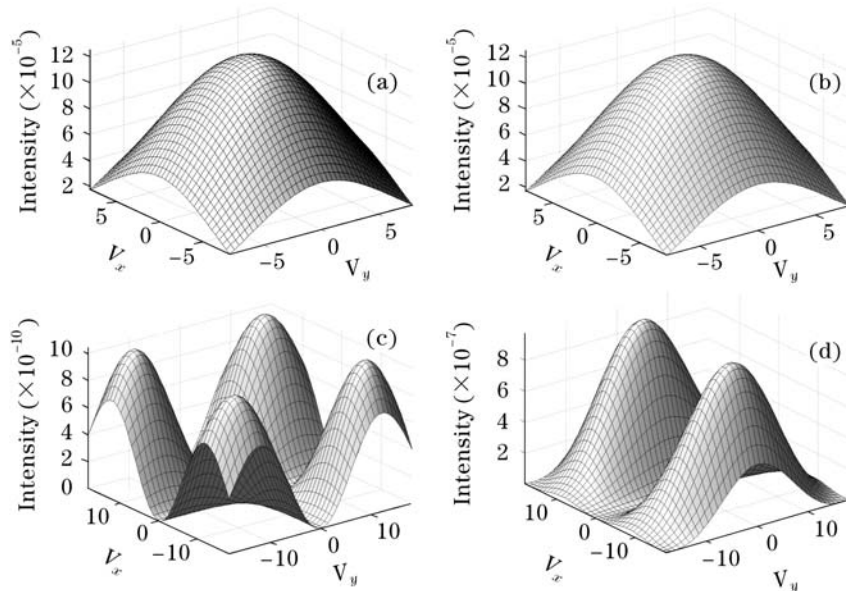


Fig. 3. Intensity distributions of (a) total field, (b) the diffractive field with the same polarization as the incident beam, (c) orthogonal field, and (d) longitudinal field for $w = 0.1$ and $d = 0.1$.

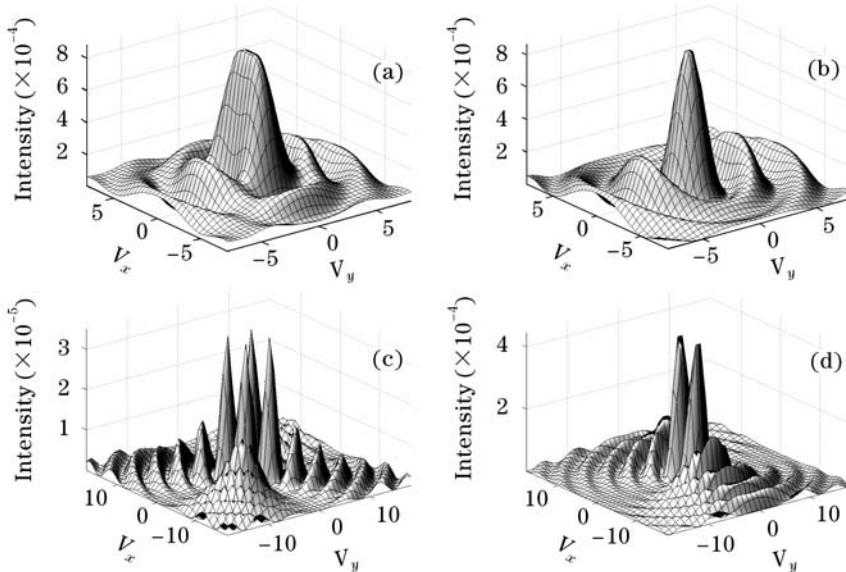


Fig. 4. Intensity distributions of (a) total field, (b) the diffractive field with the same polarization as the incident beam, (c) orthogonal field, and (d) longitudinal field for $w = 0.1$ and $d = 0.85$.

total field and its three components for $w = 0.1$ and $d = 0.85$ are also calculated, as illustrated in Figs. 4(a) — (d), which show that the focal spot loses the circular symmetry. The distribution of the diffractive field in x -direction is still circular symmetry, according with the result of scalar theory actually. So the reason that focal spot loses circular symmetry is depolarization effect. The light intensity of longitudinal diffractive field is stronger than that of the orthogonal diffractive field, and is comparable to that of the total field. The layout of the two peaks of longitudinal diffractive field also conforms to the asymmetry direction of focal spot. Therefore, it should be the longitudinal diffractive field that induces the asymmetry focal spot. Comparing Fig. 3(a) and Fig. 4(a) with Fig. 2, it can be seen that the introduced apodizer can induce the shrink of the focal spot, so the density of storage can be increased, but the depolarization effect is not negligible for large d .

In order to understand the depolarization effect further, the dependences of the peak ratios of $|E_i|^2/|E|^2$ and $|E_k|^2/|E|^2$ on d are illustrated in Fig. 5. It is shown that the effect of the diffractive field in x -direction on the total field weakens with the increasing normalized inner radius d . However, the peak ratio of $|E_k|^2/|E|^2$ increases with

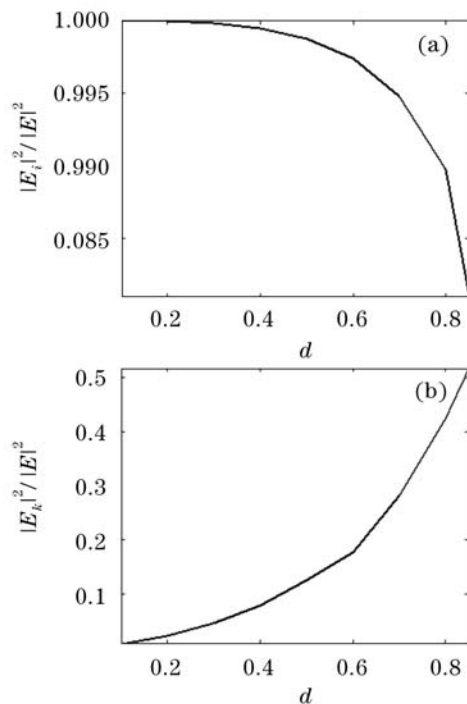


Fig. 5. The dependences of the peak ratios of (a) $|E_i|^2/|E|^2$ and (b) $|E_k|^2/|E|^2$ on d .

increasing d and reaches about 0.5 when $d = 0.8$, which indicates that the longitudinal diffractive field affects the total field remarkably for large d . This certifies that the longitudinal diffractive field induces the asymmetry of focal spot.

In conclusion, the effect of an apodizer with two parallel taper refractive surfaces is theoretically investigated for high-density optical storage. The apodizer may modulate the incident Gaussian beam into an annular beam. With the increasing inner radius of the modulated beam in the apodized optical system, the focal spot shrinks obviously. At the same time, the depolarization effect gets strong, which makes the focal spot lose circular symmetry. The density of the pattern of depolarized diffractive fields increases remarkably with increasing inner radius. The apodizer can increase the optical storage density considerably, however, the depolarization effect is not negligible for large inner radius of the modulated beam. In manufacturing process, the taper top of the proposed apodizer is not perfect, which may be spherical shape. Compared with taper surface, the top is very small, so its side effect is weak. And even the top is spherical, it may also alter incident beam to high frequency.

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