Diffractive super-resolution elements applied to near-field optical data storage with solid immersion lens

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\textit{New Journal of Physics} 6 (2004) 75
Received 28 August 2003
Published 6 July 2004
Online at \url{http://www.njp.org/}
doi:10.1088/1367-2630/6/1/075

\textbf{Abstract.} The intensity distribution in near-field optical data storage with a solid immersion lens (SIL) and a binary phase-only diffractive super-resolution element (DSE) is expressed in a single definite integral by using angular spectrum theory. The super-resolution of binary two-zone phase DSEs for SIL systems is numerically studied for low and high numerical aperture (NA) systems. The results for the low-NA systems show that optimizing the zone boundary and phase of binary two-zone phase DSEs can decrease the spot size. The Strehl ratio, sidelobe intensity and axial characteristic length are also discussed. In addition, a binary two-zone phase filter can change the position of focus that shifts from the SIL–air interface to air, but the spot size increases. For the high-NA systems, the $y$- and $z$-polarized components of the transmitted field increase as the boundary and depth of phase of the DSE increase. When the phase boundary is smaller and the depth of phase depth is close to $\pi$, super-resolving effect of DSE is more obvious but the intensity of sidelobes is larger for the high-NA system. In this way, it may be possible to improve both the resolution and focal depth of the SIL with high-NA systems.
1. Introduction

Solid immersion lens (SIL) technology is one of the most promising new optical methods for achieving higher data densities in optical storage [1]. The difference between SIL technology and conventional far-field optics is that an additional lens element is placed in proximity to the recording layers. To achieve high enough lateral resolution, many studies have concentrated on the designs of SIL, such as hemisphere [2], aplanatic hyper hemisphere [3] or other structures [4]. Focusing through an SIL–air interface introduces aberrations that are relevant to the design of SIL. Also, the cost of fabricating the SIL with complex structure is larger. Another approach to improve the resolution of an SIL system is to obtain higher refractive index materials that are transparent in visible light, such as GaP ($n = 3.3$) [5]. But an SIL with high refractive index decreases not only the optical spot size, but also the effective focal depth of SIL system greatly, which means that SIL must be put in close vicinity to the sample, generally several to tens of nanometres. Such nanoscale working distance is a severe barrier for the design of optical storage head with SIL.

Diffractive super-resolution elements offer an alternative means of increasing the areal density of recording and/or readout by modification of the phase information at the exit pupil of the optical head to produce a super-resolved stylus. This method has been widely used for far-field optical data storage [6] and general confocal imaging [7, 8]. Recently, Lu et al [9] optimized the optical field of SIL by using a special two-zone $\pi/2$-phase filter where the $y$- and $z$-polarized components were neglected. In this paper, we introduce a class of rotationally symmetric phase-only diffractive super-resolution elements (DSEs) to SIL imaging systems. The phase of each zone of DSEs can generally assume an arbitrary value. Super-resolution properties and optimization of these elements are investigated as a function of the available degree of freedom, i.e. the zone-boundary positions and the phase transmittance. In addition, the shift of focus is also discussed. In section 2, we present a description of the scalar diffraction for lens. The vector method is given in section 3. The conclusions are presented in section 4.

2. Scalar method

Figure 1(a) shows the geometry of a hemispherical SIL system. SIL is placed behind a converging lens with the focus on the plane facet of SIL. Here, it is a little different from the general SIL system because a binary DSE (see figure 1(b)) is closely placed in front of the converging lens. The $z = 0$ plane is set at the interface between the SIL and air. A unit-amplitude, normally incident, monochromatic plane wave with a azimuthally polarized polarization illuminates a DSE situated immediately in front of a low numerical-aperture (NA) lens of local length $f$. In
Figure 1. The scheme of DSE: (a) the SIL system includes the DSE used in this paper; (b) phase function $\Phi$ of a binary DSE with maximum phase transmission $\phi_0$ and unit amplitude transmission. The aperture coordinate is normalized to 1.

In the paraxial approximation, the scalar focal field of the lens can be evaluated by applying the Fresnal diffraction formula [6]

$$u_{in}(r) = \sum_{j=1}^{N} \exp(i\phi_j) \left[ \frac{\varepsilon_j^2 J_1(\varepsilon_j k_1 r NA)}{\varepsilon_j k_1 r NA} - \frac{2 J_1(\varepsilon_j k_1 r NA)}{\varepsilon_j k_1 r NA} \right],$$  \hspace{1cm} (1)

where NA is the numerical aperture of the lens and $\{\phi\} = \phi_j, j = 1, \ldots, N$, defines the phase of zone $j$. The radial position of each zone is given by $R_j = \varepsilon_j R$ ($R$ is radius of the exit pupil), $j = 1, \ldots, N$, where the set $\{\varepsilon\}$ defines normalized boundary coordinates with $\varepsilon_0 = 0$ and $\varepsilon_N = 1$, by definition (see figure 1(b)).

In the binary case, each element of $\{\phi\}$ can assume only two possible values. Consequently, the field can be written in the more convenient form

$$u_{in}(r) = \frac{2 J_1(k_1 r NA)}{k_1 r NA} \left[ 1 - \exp(i\phi_0)(-1)^{N+1} \sum_{j=1}^{N-1} (-1)^j \frac{2 J_1(\varepsilon_j k_1 r NA)}{\varepsilon_j k_1 r NA} \right].$$ \hspace{1cm} (2)

where $\phi_0$ is the maximum value of phase transmission (the minimum is set to zero) and $J_n$ is the Bessel function of the first kind of order $n$. The angular spectra $A_{in}(k_r)$ of the incident field in the vicinity of the interface can then be obtained from (2) (or (1)) through the Bessel–Fourier transformation

$$A_{in}(k_r) = \int_{0}^{\infty} u_{in}(r) J_0(k_r r) r \, dr$$

$$= \frac{4\pi}{(k_1 NA)^2} \left[ \text{circ} \left( \frac{k_r}{k_1 NA} \right) - [1 - \exp(i\phi_0)](-1)^{N+1} \sum_{j=1}^{N-1} (-1)^j \text{circ} \left( \frac{k_r}{\varepsilon_j k_1 NA} \right) \right].$$ \hspace{1cm} (3)

The angular spectra $A_{tr}(k_r)$ of the transmitted fields in the vicinity of the interface can be obtained according to Fresnel formulae:

$$A_{tr}(k_r) = \frac{2}{1 + k_{z2}/k_{z1}} A_{in}(k_r),$$ \hspace{1cm} (4)
where \( k_{z1} = \sqrt{k_1^2 - k_2^2} \), \( k_{z2} = \sqrt{k_2^2 - k_r^2} \) and \( k_1 (=nk) \) and \( k \) are the wave numbers in the SIL with the refractive index of \( n \) and in vacuum respectively. The transmitted field therefore has the form

\[
u(r, z) = \int_0^\infty \frac{2}{1 + k_{z2}/k_{z1}} A_i(k_r) J_0(k_r r) \exp(i k_{z2} z) \, dk_r.
\] (5)

Inserting (3) into (5) can give the diffracted pattern of the binary-DSE-SIL system in the closed-form expression and leads to

\[
I(r, z) = |\nu(r, z)|^2.
\] (6)

Equations (5) and (6) can be used to compute the optical field anywhere on the right-hand side of the SIL. Considering the definition of circle function, in practical computation, the infinite integral in (5) can be transformed into a definite integral in the interval \([0, k_1 NA]\).

To characterize a super-resolved pattern we use four quantities. The normalized spot size \( G \) gives a measure of the resolution and is defined as the full-width at half-maximum of the focal spot divided by the corresponding value without DSEs. Super-resolution is generally accompanied by an increase in the intensity \( M \) of the sidelobes or the diffraction rings. We define \( M \) as the maximum sidelobe intensity relative to the central core. Another important parameter is the Strehl ratio \( S \), defined as the ratio of the intensity of the super-resolved pattern and the intensity without DSEs, both calculated at the origin. \( S \) gives a measure of the image brightness. The final quantity is the characteristic length \( L \) and is defined as the distance between the interface and the axial position where the intensity values are equal to \((1/e)I(0)\) divided by the corresponding value without DSEs. The characteristic length represents the change in the depth of focus and a greater \( L \) benefits the design of an optical storage header.

A certain value of Strehl ratio is required for proper recording of an optical head. Additional power can be used to increase the energy density of the optical stylus and thus compensate for the low level of Strehl ratio. But then laser noise and the spurious modes become a problem, which require a more complex optical design for proper correction. Special attention must be paid to the sidelobes to prevent unwanted pits from being recorded. An acceptable level of sidelobe intensity depends on the recording medium, but in general it is preferable to keep it as low as possible. In readout, a certain reduction in Strehl ratio is acceptable, but sidelobes must also be kept at lower levels. We assume that, for optical storage applications, the minimum acceptable value of Strehl ratio is in the 0.4–0.5 range and typically assume that the maximum acceptable sidelobe intensity is between 0.2 and 0.3 and that the minimum acceptable characteristic length is 0.5.

Consider a binary DSE with two zones phase-shifted by \( \phi_0 \). The zone boundary is defined by the normalized pupil position \( \epsilon \). The refractive index of SIL is taken as 2 and the numerical aperture of the convergent lens is 0.866 in vacuum. Figure 2 shows the spot size \( G \) and figure 3 shows the Strehl ratio \( S \). In figure 4 the sidelobe intensity ratio \( M \) is presented, whereas figure 5 shows the characteristic length \( L \). Only the region useful for super-resolution is shown. From these figures, we can see that \( G \) and \( L \) seem to take the minimum values, \( S \) decreases rapidly and \( M \) increases rapidly, as \( \epsilon \) increases. In general, any attempt to super-resolve an object will lead to a loss of the image brightness. The price paid by a super-resolved spot is often reflected in increased sidelobe intensity, sometimes by several orders of magnitude with respect to the central core. As a result, the usable field of view can be dramatically reduced. Depending on the values of \( \epsilon \) and \( \phi_0 \), lateral super-resolution can be observed.

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As $\phi_0 \to 0.9\pi$, the spot size tends to assume its smallest values followed by a decrease in Strehl ratio and a rapid increase of sidelobe intensity (see also figure 6). However, the characteristic length when $\phi_0 = 0.9\pi$ is greater than those for $\phi_0 = 0.5\pi$ and $0.7\pi$. The characteristic length when $\phi_0 = 0.7\pi$ is smallest. The specification of some design solution will depend on the criteria adopted for what are acceptable regarding $G$, $S$, $M$ and $L$. For example, if we impose $M \leq 0.2$, the two-zone filter presents a usable field only in the interval $\varepsilon \in [0, 0.41]$ when $\phi_0 = 0.9\pi$. In this region, the minimum spot size is 0.85 with a Strehl ratio of 0.52 and a characteristic length of 0.79. When the maximum phase transmitted by the filter $\phi_0 \neq 0.9\pi$, the diffraction pattern tends to exhibit an increase in the range of solutions with a large field of view.
combined with a higher Strehl ratio, whereas the characteristic length is reduced. Synchronously, the spot size \( G \) tends to increase and the sidelobe intensity decreases. The numerical results show that for the binary two-zone phase DSE–SIL systems the minimum spot size does not correspond to \( \phi_0 = \pi \) but to \( \phi_0 = 0.9\pi \) (see figure 6), which is not the same as that of far-field DSE–lens system where the minimum spot size corresponds to \( \phi_0 = \pi \) [6]. Although \( \phi_0 = 0.9\pi \) results in a smaller spot size, the sidelobe effects are always stronger and are combined with low levels of Strehl ratio, for a given design. The parameter \( \phi_0 \) provides an additional degree of freedom to help control these unwanted effects.
Figure 6. Imaging properties of a two-zone element with $\varepsilon = 0.5$.

Figure 7. Axial intensity distribution as a function of $\varepsilon$ for $\phi_0 = 0.9\pi$.

We also notice that the binary two-zone DSEs are not able to arbitrarily reduce the spot size of a near-field SIL system and the minimum $G$ value is 0.6 (in this circumstance sidelobe intensity is 2, Strehl ratio 0.1 and characteristic length 0.6), which is different from its application in far field where the spot size can tend to zero if $S$ and $M$ are not considered [7].

Another interesting case is that binary two-zone phase filters can change the position of focus. It is known that the focus of an SIL system is at the position of the SIL–air interface. By choosing larger $\varepsilon$, the focus can be shifted from the interface to air, as shown in figure 7. Consequently, the characteristic length increases greatly, which benefits the design of an optical storage header. However, it is seen that the intensity distribution in air is not much sharper than what would be produced without binary filters for direct focusing in the interface (see figure 8). Thus the super-resolving effect is not significant. Our explanation of this is as follows. In the SIL, a focused spot is produced which is smaller than what can be produced in air. The
Fresnel effects on transmission through the interface result in a phase change of the evanescent components, which is equivalent to an aberration. Thus the focused spot in air is increased in size.

3. Vector method

Scalar theory is critical when working with very high-NA systems that are essential in SIL. In this section we will analyse the transmitted vector field of the high-NA SIL systems with a phase DSE. Assume that linearly $x$-polarized monochromatic light is incident on a lens with a DSE. According to Richards and Wolf’s vector refractive angular theory [10], the transmitted field for the high-NA SIL system can be obtained as

$$E_x(r, \beta, z) = -i[I_0(r, z) + I_2(r, z) \cos 2\beta],$$  

$$E_y(r, \beta, z) = -iI_2(r, z) \sin 2\beta,$$  

$$E_z(r, \beta, z) = 2I_1(r, z) \cos \beta,$$  

where

$$I_0(r, z) = \sum_{j=1}^{N} (T_j - T_{j+1}) \int_{0}^{\alpha_j} A_{0x}(\theta)J_0(k_0nr \sin \theta) \exp(ik_0z \cos \theta) \text{d}\theta,$$  

$$I_1(r, z) = \sum_{j=1}^{N} (T_j - T_{j+1}) \int_{0}^{\alpha_j} A_{1x}(\theta)J_1(k_0nr \sin \theta) \exp(ik_0z \cos \theta) \text{d}\theta,$$
\[ I_2(r, z) = \sum_{j=1}^{N} (T_j - T_{j+1}) \int_0^{\alpha_j} A^{2\alpha}(\theta) J_2(k_0 \rho \sin \theta \cos \theta) \exp(ik_0 z \cos \theta) \, d\theta, \quad (12) \]

\[ A^{0\alpha} = B(\theta)(t_s + t_p \sqrt{1 - (n \sin \theta)^2}) \sin \theta, \quad (13) \]

\[ A^{1\alpha} = B(\theta)t_p n^2 \sin^2 \theta, \quad (14) \]

\[ A^{2\alpha} = B(\theta)(t_s - t_p \sqrt{1 - (n \sin \theta)^2}) \sin \theta, \quad (15) \]

with \( \alpha_j = \epsilon_j \alpha_N, \epsilon_j \) being the parameter of the phase-zone boundary and \( \alpha_N \) the convergence angle of the lens. \( B(\theta) = \sqrt{\cos \theta} \) is a sine apodization function. \( t_s \) and \( t_p \) represent, respectively, the transmission (Fresnel coefficients) of the s- and p-polarized light through the SIL–air interface. \( T_j \) is the transmittance through an annular phase-only DSE, which can be expressed as

\[ T_j(\theta) = \exp(i\phi_j), \quad \alpha_j \leq \theta < \alpha_j, \quad j = 1, 2, \ldots, N, \quad \text{where} \quad \alpha_0 = 0, T_{N+1} = 0. \quad (16) \]

The intensity of the transmitted light is the modulus square of the electric field, which can be written as

\[ I(r, \theta, z) = I_x(r, \theta, z) + I_y(r, \theta, z) + I_z(r, \theta, z), \quad (17) \]

\[ I_{x,y,z} = |E_{x,y,z}|^2, \quad (18) \]

where \( I_{x,y,z} \) are the intensities of the \((x, y, z)\) components of the electric field respectively.

To compare with the situations occurring in a high-NA SIL system, we compute the intensity distribution of the systems only with a two-zone phase DSE, which does not represent a generality loss of the equations given in this paper. The condition \( n = 2 \) and \( \alpha_2 = 60^\circ \), i.e. NA = 0.866, is applied in all the following calculations. Figures 9 and 10 show, respectively, the intensity of the field components and the total intensity behind the bottom surface of the SIL without and with a binary DSE of \( \phi_0 = \pi \) and \( \epsilon = 0.5 \). We can see that the resolution due to the two-zone phase DSE is improved when compared with no DSEs, but the peak sidelobe intensity is increased. Moreover, the \( y \)- and \( z \)-components are also increased greatly, \( I_x : I_y : I_z \) increasing from 1 : 0.09 : 1.08 to 1 : 0.35 : 2.67, and the effect of the \( x \)- and \( z \)-components, especially the \( z \)-component, cannot be ignored because the intensity of the \( z \)-component is larger than that of the \( x \)-component. The \( z \)-component has been observed to affect the exposure of photoresist and may play a role in themomagnetic writing [11]. The \( z \)-component is completely independent of the azimuthal angle and its importance increases with increasing NA.

Figures 11 and 12 show the transverse profiles of the intensity as a function of the phase-zone boundary \( \epsilon \) behind the bottom surface of the SIL when \( \beta = 0^\circ \) and 90°, respectively. For comparison, the profiles for the SIL with no DSE are also shown (the solid lines in figures 11 and 12). It is seen from figures 11 and 12 that the resolution and the sibelobe intensity are increased as \( \epsilon \) increases, which is the same as that of the scalar theory in section 2. When \( \epsilon \) is larger, the resolution is lowered but not increased due to the existence of the stronger \( x \)- and
Figure 9. Intensity of (a) the x component of the polarized light, (b) the y component, (c) the z component and (d) the total light in the $z = 0$ plane of an SIL system without DESs.

Figure 10. Intensity of (a) the x component of the polarized light, (b) the y component, (c) the z component and (d) the total light in the $z = 0$ plane of an SIL system with a two-zone phase DSE of $\phi_0 = \pi$ and $\varepsilon = 0.5$.

$z$-components, which is different from the result of the scalar theory. Note that the increase in resolution is more pronounced when $\beta = 90^\circ$ than for $\beta = 0^\circ$, since the $z$-component of the electric field depends on $\cos \beta$ (which is zero when $\beta = 90^\circ$, see (9)). This result is different from that in [9] in which the authors found that the decrease of the spot size along the $x$-axis is larger than along the $y$-axis because the $z$-component is neglected. Figures 13 and 14 show the
Figure 11. The intensity in the $x$-axis: (a) no phase DSE, (b) two-zone phase DSE with $\varepsilon = 0.5$ and $\phi_0 = \pi$, (c) two-zone phase DSE with $\varepsilon = 0.3$ and $\phi_0 = \pi$, (d) two-zone phase DSE with $\varepsilon = 0.8$ and $\phi_0 = \pi$.

Figure 12. The intensity along the $y$-axis: (a) no phase DSE, (b) two-zone phase DSE with $\varepsilon = 0.5$ and $\phi_0 = \pi$, (c) two-zone phase DSE with $\varepsilon = 0.3$ and $\phi_0 = \pi$, (d) two-zone phase DSE with $\varepsilon = 0.8$ and $\phi_0 = \pi$.

Transverse profiles of the intensity as a function of the phase depth behind the bottom surface of the SIL when $\beta = 0^\circ$ and $90^\circ$, respectively. From figures 13 and 14 it is seen that the resolution is the highest when $\phi_0 = \pi$, which is similar to that of the scalar theory [12]. Figure 15 shows the axial distribution as a function of phase depth behind the SIL. Note that the focal depth becomes smaller compared with the absence of DSE. For the given boundary of $\varepsilon = 0.5$, the larger the phase depth $\phi_0$, the shorter the focal depth. Figure 16 shows the axial distribution as a function of the phase boundary $\varepsilon$. For the given phase depth of $\phi_0 = \pi/2$, when $\varepsilon$ is smaller the focal depth becomes shorter, whereas when $\varepsilon$ is larger it became longer compared with that without
Figure 13. The intensity along the x-axis: (a) no phase DSE, (b) two-zone phase DSE with $\varepsilon = 0.5$ and $\phi_0 = \pi$, (c) two-zone phase DSE with $\varepsilon = 0.5$ and $\phi_0 = \pi/3$.

Figure 14. The intensity along the y-axis: (a) no phase DSE, (b) two-zone phase DSE with $\varepsilon = 0.5$ and $\phi_0 = \pi$, (c) two-zone phase DSE with $\varepsilon = 0.5$ and $\phi_0 = 2\pi/3$.

DSE. It is of interest to note that the focal depth became shorter under the critical angle (the boundary parameter of $\varepsilon = 0.5$) of the SIL but did not become longer as those in section 2 or in [9]. This result gives us a revelation that the rigorous analysis of the focal field for high-NA lens should be described by using vector theory but not scalar theory. In addition, the shift of focus in section 2 can also be produced by using the vector method, e.g. the focus moves from $z = 0$ to $0.16\lambda$ when the two-zone phase DSE of $\varepsilon = 0.7$ and $\phi_0 = \pi$ is placed at the exit pupil of the lens.
Figure 15. Axial intensity as a function of phase depth $\phi_0$ when $\epsilon = 0.5$.

Figure 16. Axial intensity as a function of phase-zone boundary $\epsilon$ when $\phi_0 = \pi/2$.

4. Conclusions

In summary, a simple single definite integral for computing the field distribution of the SIL system with a DSE was first derived by using scalar angular spectrum theory. With regard to the binary two-zone phase DSE, we presented design solutions for application in near-field optical data storage with a solid immersion lens. The decrease of spot size is only within a certain range by using a two-zone phase filter. For optical data storage, if we impose the minimum of sidelobe intensity as 0.2, the minimum spot size of 0.85 can be obtained accompanied by a Strehl ratio of 0.52 and a characteristic length of 0.79 for a filter of $\epsilon = 0.41$ and $\phi_0 = 0.9\pi$. When $\epsilon$ is larger, the binary two-zone filter can change the position of focus, e.g. the focus shifts from the interface to $0.225\lambda$ for $\epsilon = 0.7$ and $\phi_0 = 0.9\pi$. Although in this circumstance the characteristic length is greatly increased, the resolution of SIL system is markedly decreased. Moreover, with
a two-zone phase design, there is no way to decrease sidelobe intensity and at the same time reduce the spot size even further. This question may probably be overcome by using mutiphase and multiboundary DSE, which will be studied in the future.

Secondly, we analysed the light field distribution behind a high-NA SIL system with the binary phase DSE using the vector theory. The phase DSE increases the $y$- and $z$-components of the transmitted field and may change the resolution and the focal depth. Future investigations may be directed towards the use of more than two-zone phases to improve the resolution and focal depth as well as to decrease the intensity of sidelobes. We would like to point out that only a few special cases with high-NA systems were discussed in this paper and our examples were not optimized for any particular applications. The numerical computations in this paper are simplified by the use of two-zone phase DSE.

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