Optimization of information pit shape and read-out system in read-only and write-once optical storage systems

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The 3-D diffraction behavior of an optical recording is investigated using the rigorous mode approach. Relationships between desirable pit shapes, write-in conditions, and read-out characteristics are discussed.

I. Introduction

Whether or not the pregroove exists, information pits in read-only and write-once optical information storage systems will change the distribution of the output optical field by the diffraction effect. On the other hand, objective lenses with different numerical apertures and incident beams with different wavelengths also will change the read-out characteristic. Thus an optical disk system and its diffraction characteristics must be carefully analyzed to get good write-in and read-out characteristics and reproduce exactly the information recorded on the optical disk.

II. Theory

Information storage and read-out on an optical disk by optical methods is becoming an active area of study around the world. The principle of optical disk storage is to project a modulated diffraction-limited light spot onto a rotating disk, which has been coated with the recording medium. Then a series of information pits is formed spirally or concentrically on the disk. Thus the information is recorded. During read-out, the recorded time-dependent information is reconstructed by the position of pit centers and their geometric shapes. The sizes of the convergent spot and information pits are usually not much larger than the laser wavelength. Therefore, diffraction effects must be considered in read-out. Some diffraction models have been established in recent years. The purpose of this paper is to set up a rigorous 3-D math model of the optical disk diffraction process by means of electrodynamics, Fourier transform, and mode coupling theory and to give some useful numerical results.

The 3-D read-out geometric model is shown in Fig. 1. According to this, the whole space distribution of the optical field can be divided into three parts: the incident and diffracted fields outside the pit, \( E_i \) and \( E_d \), and the optical field inside the pit, \( E_p \). Using Maxwell's continuity condition, we get the following equation:

\[
E_i + E_d = E_p. \tag{1}
\]

In a practical system, convergent light transmitted from a lens is perfectly circularly polarized, and light diffracted back to the lens from the disk surface is also circularly polarized, if the effect of the information pits on the polarization is neglected. According to the characteristics of polarized light, circularly polarized light can be decomposed into two perpendicular linearly polarized components along the X and Z axes. We treat the components separately. Following is the mathematical derivation of the linearly polarized components along the Z axis \( E_z \). The treatment of \( E_x \) is analogous to that of \( E_z \).

First, by the use of Fourier analysis, the expression of the resultant field in \( Y \geq 0 \) space is derived:

\[
E_z^2 = \frac{1}{\lambda^3} \left[ \int_0^{+\infty} \int_{-\infty}^{+\infty} G(\alpha, \beta, x', z') \exp[ik(\alpha x + \beta z - \sqrt{1 - \alpha^2 - \beta^2} y)] d\alpha d\beta \right] + \\
\int_{-\infty}^{+\infty} D(\mu, \nu, x', z') \exp[ik(\mu x + \nu z + \sqrt{1 - \mu^2 - \nu^2} y)] d\mu d\nu, \tag{2}
\]

where

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\[
G(\alpha\beta,x',z') = \begin{cases} 
\exp[-ik(\alpha x' + \beta z')], & |\alpha| \leq a, |\beta| \leq \eta \\
0, & \text{other} 
\end{cases}
\]

is the incident Fourier complex amplitude assumed according to the characteristics of the incident light at \(O'(x',z')\). Here \(D(\mu,\nu,x',z')\) is the complex amplitude of the unknown diffraction field, and \(\alpha, \beta, \mu, \nu\) are all direction cosines. It is clear from Eq. (2) that \(E^*_m\) is a function of five variables \(x, y, z, x', z'\). The distribution of the field \(E^*_m\) in the whole space of \(xyz\) changes for different values of \(x'\) and \(z'\).

On the other hand, in the space of \(y \leq 0\),

\[
E^*_m = \sum_{m=1}^{\infty} \sum_{n=0}^{\infty} C_{mn}^* g_{mn} 
\]

where

\[
g_{mn} = \sin \frac{\pi x}{a} \cos \frac{\pi y}{b} \sin[k \sqrt{1 - \frac{(m \pi)^2}{a^2} - \frac{(n \pi)^2}{b^2}} (y + h)]
\]

is the solution component along the \(Z\) axis of the Helmholtz equation under boundary conditions which suit our model. For convenience of deduction, we define

\[
S_m(x,a) = \sin \frac{\pi x}{a} \left( x + \frac{a}{2} \right),
\]

\[
C_n(z,b) = \cos \frac{\pi z}{b} \left( z + \frac{b}{2} \right),
\]

\[
Q(m,n) = \sqrt{1 - \frac{(m \pi)^2}{a^2} - \frac{(n \pi)^2}{b^2}},
\]

so that

\[
g_{mn} = S_m(x,a) C_n(z,b) \times \sin[k \cdot Q(m,n) \cdot (y + h)].
\]

Here \(g_{mn}\) is called the \(mn\)th pit mode in the information pits, and \(C_{mn}\) is the weighting factor in the linear superposition.

Finally, at \(y = 0\), the continuity conditions are applied to \(E_z\) and \(\partial E_z/\partial y\):

\[
E^*_z(2y=0) = E^*_z(2y=0),
\]

\[
\partial E^*_z/\partial y|_{y=0} = \partial E^*_z/\partial y|_{y=0},
\]

to obtain

\[
\sum_{m=1}^{\infty} \sum_{n=0}^{\infty} C_{mn}^* S_m(x,a) C_n(z,b) \times \sin[k \cdot \sqrt{Q(m,n)} \cdot (y + h)]
\]

Substituting Eq. (8) into Eq. (9) results in linear equations of the \(mn\)th order:

\[
\begin{cases}
\sum_{m=1}^{\infty} \sum_{n=0}^{\infty} C_{mn}^* S_m(x,a) C_n(z,b) \times \sin[k \cdot \sqrt{Q(m,n)}] \\
0
\end{cases}
\]

\[
\times \cos[k \cdot \sqrt{Q(m,n)}] \cdot Q(m,n),
\]

where \(C_{mn} = \lambda^2 C_{mn}\). Multiplying Eq. (6) with \(\exp[-ik(\mu x + \nu z)]\) and integrating it for \(x, z\) from \(-\infty\) to \(+\infty\) results in
\[
\sum_{m,n} (\Psi_{nmnm'} + \delta_{mnmn'}T_{mn'})C_{mn} = \Phi_{nm}(x',z'),
\]

where

\[
\Psi_{nmnm'} = \sin [kHQ(m,n)]
\]

\[
\times \int_0^\infty \left[ 1 - \alpha^2 - \beta^2 R_m(a)R_n(b)R_{mn}(a)R_{mn}(b) \right] d\alpha d\beta
\]

represents the interaction of the \( m \)th, \( n \)th, \( m' \)th, and \( n' \)th modes:

\[
\Phi_{mnm'n'} = 2 \int_0^\infty G(\alpha,\beta,x,z) \left[ 1 - \alpha^2 - \beta^2 R_m(a)R_n(b) \right] d\alpha d\beta
\]

is the stimulating term of the \( m'n' \)th pit mode, and

\[
T_{mn'} = i \frac{ab}{4\lambda^4} Q(m,n') \cos[kHQ(m',n')]
\]

\[
\delta_{mnmn'} = \begin{cases} 1 & m = m' n = n' \\ 0 & \text{other.} \end{cases}
\]

It is clear that the distribution of the Fourier complex amplitude \( D(\mu,\nu,x',z') \) in the diffraction field is uniquely determined by Eqs. (8) and (10).

Dividing the diffracted light intensity received by the detector,

\[
I_D = \iint |D(\mu,\nu,x',z')|^2 d\mu d\nu
\]

by the incident light intensity

\[
I_I = \iint |G(\alpha,\beta,x',z')|^2 d\alpha d\beta,
\]

produces the normalized response of the detector \( I = I_D/I_I \), which represents the quantitative relationship between the optical disk diffraction output and pit sizes, the numerical aperture of the lens, and the working wavelength. Through the analysis of this relation, we can obtain a criterion for choosing parameters for optimal output format, coding method, and tracking errors tolerances.

III. Numerical Experiment

Figure 2 is the block diagram of the computer program where

\[
I_{nmnm'} = \iint \left[ 1 - \alpha^2 - \beta^2 R_m(a)R_n(b)R_{mn}(a)R_{mn}(b) \right] d\alpha d\beta,
\]

\[
I_{nmnm'}' = \iint R_m(a)R_n(b)R_{mn}(a)R_{mn}(b) d\alpha d\beta.
\]

First, the Fourier integral is reasonably simplified by use of the symmetry, the oddness, and orthogonality of the integrals. Next, while a certain precision requirement is met, the linear equations of indefinite order are cut off appropriately. Finally, using a suitable numerical calculation method and a few tricks helps to simplify the problem and speed the calculation.

Numerous results of computer simulation have shown that output intensity \( I \) and the SNR are strongly dependent on the above parameters. Figure 3 shows the curve of output intensity vs numerical aperture. Note that the normalized output intensity \( I \) is rather large when the numerical aperture is too small or too large and that the curve has an optimal point. For the conditions given in the figure, \( I \) reaches a minimum when the numerical aperture is nearly 0.4.

It should be noted that this curve consists of values, each of which is the minimum value in the diffraction field of a given pit. These values are smaller than those from the center of the given pit when the diffraction of the pit edge cannot be neglected. For convenience, we draw the curves by choosing the values in the center of the given pit.
Figure 4 shows the relationship between wavelength and output intensity. For an optical disk structure in which pit depth is equal to a quarter-wavelength, two facts appear: (1) the output intensity has a maximum for shorter wavelengths, and (2) for longer wavelengths, the longer the read-out wavelength, the less diffracted light is collected by the objective lens.

Figure 5 shows the relationships between the pit width $a$, length $b$, depth $h$, and output intensity $I$. For a given pit width $a$, independent of $b$, each curve of $I$ vs $h$ has a minimum at the same value of $h$, but the value of the minimum is different due to the different values of $b$. While $a$ decreases, the depth $h$ corresponding to the minimum of $I$ increases.

IV. Conclusions

The diffraction output of optical disks depends on the pit structure $a$, $b$, and $h$. Small $a$ and large $h$ help to increase the storage density and improve the detection.

The pit depth for a minimum value of $I$ changes with the pit width rather than staying constant at a certain value (e.g., $\lambda/4$ or $\lambda/8$).

Increasing the numerical aperture will somewhat increase information storage density, but the numerical aperture cannot be too large without making $I$ decrease and the information unresolvable.

A shorter wavelength and an appropriate pit structure will be helpful in increasing the storage density and lowering the crosstalk between the tracks.

References

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