The Theoretical consideration of the readout system for the photochromic optical disk

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ABSTRACT

The data are stored in the alternative pits and lands for present optical disk, which is similar to the grating. Accordingly, the grating theory becomes the basis theory for the optical disk. The work presented in this paper focused on several aspects of the following: outlining the optical disk models adopted by the theories in print, analyzing the foundation basis of the models, and bringing forward a model which can be used for the new-fashioned optical storage, multi-wavelength photochromic optical storage. The classical scalar diffraction theory supposed that the effects of the optical disk on the incident beam were introducing the local phase delay that could be described by the optical path difference \( \Delta s \), and the energy of the incident beam would not be absorbed. The two equations could respectively express the difference of the optical path: (1) \( \Delta s = n^* \Delta h \) and (2) \( \Delta s = n^* \Delta h \). As the result of the analysis, we concluded that the tradition optical disk model fit for pit-land recording format and the cavity or bubble recording format. For the photochromic optical disk, the recording material, which absorbed the energy of the incident beam, was similar to the amplitude grating. The diffraction theory of this system was presented, and the equations for the readout signal were educed.

Keywords: optical disk model, scalar diffraction theory, refractive index, photochromic, optical storage, grating, multi-wavelength, transmittance coefficient

1 INTRODUCTION

The optical disk has become the mainstream of the digital storage field with its advantages, such as high density, low cost, long life, easy carry etc. during the recent three decades. And the optical storage technology has made great progress as the explosive growing of the information amount. There are two evolutive directions to increase the storage density, one is to increase the areal density, including the adoptions of the shorter wavelength (for the digital video disk (DVD), \( \lambda = 635\text{nm} \); for green laser optical disk, \( \lambda = 500\text{nm} \); and for blue-violet optical disk, \( \lambda = 405\text{nm} \)) and the larger numerical aperture (NA), especially near-field optics and solid immersion lens (SIL) etc. which break through the limitation of the optical resolution. The other is to increase the volume density, for example, the holographic data storage, two photon absorption, optical spectral hole burning and photochromic multi-wavelength etc.. These new technologies urgently require the proper theory support to accelerate the industrialization.

During the early development of the optical disk, the dimension of the information mark is large enough to satisfy the scalar diffraction theory. For the read-only optical disk, such as compact disk (CD) and so on, the digital information is stored in the alternative pit and land. And the diffraction is the main optical phenomenon when the incident beam wave and the information mark interact. Generally, the grating is adopted as the optical disk model. The models of the information mark include the one-dimensional groove, square pit, and rectangular pit and so on. But the permittivity and the thickness of the metallic film cannot be considered with the scalar diffraction theory. As the decreasing of the information mark dimension, for DVD and higher density optical disk, the interaction between the information mark and the incident light wave must be described by the electromagnetic boundary conditions, which is called the vector diffraction theory. For the limitation of the computer performance and the complexity of the vector diffraction theory, the optical disk information mark is usually simplified as the one-dimensional rectangular groove. In recent years, the great progress in the vector diffraction theory for grating establishes the foundation of the rigorous vector theory for the optical disk. Two-dimensional rectangular pit even the pit with a half circle on either side is adopted as the model of the information mark.

While these models above-mentioned are only fit for the tradition optical disk adopting the pit-land as the recording format, the new optical disk model must be considered as for other optical storage technology, such as the holographic storage and the photochromic multi-wavelength etc.. Photochromic means that the color of some inorganic
compounds or organic compounds changes under the shining of some light with special wavelength, which can be described by,

\[
\begin{align*}
A & \xrightarrow{h\nu_1} B \\
& \xleftarrow{h\nu_2}
\end{align*}
\]

\( h \) is the Planck Constant, \( \nu_1 \) and \( \nu_2 \) are the light frequency. \( A \) and \( B \) have the different absorption spectrum. So testing the changes of the transmission index can get the readout signal. In addition, the information can also be read out by detecting the changes of the refractive index. Either of these two methods will need to absorb the energy. In this paper, we aim at founding the diffraction theory and the model of this storage method.

This paper was divided into Five major sections as follows: Section two introduced the models of the traditional optical disk used by the scalar and vector diffraction theory; Section three analyzed the foundation gist of the optical disk model; the model and the diffraction theory of the photochromic storage was presented in Section Four; and in the last section, we provided the conclusions.

2 THE MODELS FOR THE TRADITIONAL OPTICAL DISK

2.1 The models adopted by the scalar diffraction theory

The scalar diffraction theory has the advantage of brief calculation, institutional physical explanation etc., which make it the basis theory for the diffraction analysis in the early days of the optical disk. The polarization of the incident wave is ignored, and the effect of the information mark is supposed to introduce local phase delay. In addition, the refractive index of the aluminum (Al) is considered as constant, and generally equals to 1. As a result, the scalar diffraction theory can only apply to the optical disk whose information mark dimension is larger than the incident light wavelength and NA is not higher than 0.5. Usually, the grating is adopted as the optical disk model by most scalar diffraction theory, while the models of the information mark differ from the theories.

In 1978, A. Korpel \[6\] presented a half-qualitative diffraction theory for the read-out system of the visual disk. The thin grating was regarded as the optical disk model and information mark model was rectangular, shown in Figure 1. The fill factor was 1:1 between the pit and the land. It is tellable that the incident beam was also assumed as the square beam, which made the qualitative analysis very easy.

In the same year, C. H. F. Velzel \[7\] applied the image theory in partially coherent light to the readout of the phase objects. He also introduced the periodic thin phase grating, and the information marks were arrayed along the straight parallel lines with an even spacing. The rectangular with two half circles on both sides acted as the model of the

![Figure 1](image1.png)  The square pit model of the information mark

![Figure 2](image2.png)  The transformation of the square beam

![Figure 3](image3.png)  The optical disk model adopted by C.H.F.Velzel
information mark.

H. H. Hopkins \cite{Hopkins} founded the classical integrated scalar diffraction theory for the readout system of the optical disk referring to the diffraction theory of the optical scanning microscope in 1979. The optical disk was predigested as the two-dimensional grating. And the model of the information mark was similar to C. H. F. Velzel’s. The incident focusing beam had the Gauss distribution and the function of the objective lens was carrying through Fourier transformation. In addition, the slope of the pit wall was also considered by this theory.

![](image1.png)

Figure 4 The models of the optical disk and the information mark adopted by Hopkins

2.2 The models adopted by the vector diffraction theory

As the decreasing of the information mark, the errors turns bigger and bigger for the scalar diffraction theory applied to the quantitative calculation. And the polarization of the incidence beam etc. should be considered in the analysis, which demand the vector diffraction theory. The geometrical models of the optical disk adopted by the vector diffraction theory are resemblant to those of the scalar diffraction theory. Due to the complexity of the vector calculation, most theories used the simpler configuration of the information mark. And the models of the incident beam adopted by these theories include the taper focusing beam, the plane wave and the pyramid-focusing beam. In addition, to predigest the boundary condition of the electromagnetic field, the metallic reflective film is often regarded as the ideal conductor.

In 1978, Ping Sheng \cite{Sheng} brought forward the vector diffraction theory fit for the study on the readout signal of the RCA visual disk. Limit to the performance of the computer of that time, one-dimensional grating and the pyramid-focusing beam were hired to save the calculation time. Accordingly, one-dimensional rectangular groove was the model of the information mark. Besides, the slope of the groove wall and the practical permittivity were not taken into account.

![](image2.png)

Figure 5 One-dimensional rectangular groove adopted by Peng

As the developing of the calculated method for the electromagnetic, the vector diffraction theory made great progress. Lapchuk A. S. \cite{Lapchuk} computed the Fourier transformation of Gauss beam with Tailor series. And he adopted two-dimensional grating with rectangular pit as the optical disk model. But the metallic reflective films on the surface of the pit and pit wall were still considered as the perfect conductor.

In 1993, Kiyoshi Kobayashi \cite{Kobayashi} put forward a more rigorous vector diffraction theory. Although the incident beam and the reflective film were still made some predigestions, the model of the optical disk became more complicated. He
took the rectangular pit as the model of the information mark and one-dimensional rectangular grooves were arranged every other pit. Accordingly, this theory could be applied to analyze the servo and readout signal of double period configuration and the effects of this geometrical structure on the readout signal.

The optical disk models before mentioned are all periodic, while the incident beam may fall on the single or the aperiodic structure for the practical optical storage. In 1997, D. S. Marx [12] applied the integral method to the analysis of the far field diffraction from a simple information mark. The geometrical configuration of the information mark is one-dimensional groove with sinusoidal section. In virtue of this theory, the diffraction of the DVD could be studied. But the models of the incident beam and the reflective film made the same treatment as those up-mentioned.

Cheng Xianfu [13-14] established the rigorous vector diffraction theory for high-density optical disk with coupled wave theory and the curvilinear coordination method. For the first theory, the three-dimensional periodic grating was adopted as the optical disk model, and the model for the information mark was the rectangular pit with two half circles on either side. According to the characters of the coupled wave theory, the slope of the pit wall and the thickness of the aluminous reflective film were not considered. Shown in Figure 10, the two parameters could be discussed with the curvilinear coordination method.

Figure 6  The models of the incident beam and the optical disk adopted by Lapchuk
Figure 7  the optical disk used by Kiyoshi Kobayashi
Figure 8  The single structure model of the information mark
The models of the optical disk introduced by the scalar and vector theories all are the pit or the groove structure, which are fit for the conventional optical disk with concavo-convex pit-land structure. Especially for the scalar diffraction theory, the grating is regarded as the pure phase grating. However, for the photochromic optical storage, the recording layer will absorb the energy of the readout beam and the recording format is not the alternative pit and land but the changes of the refractivity or the transmission index of the recording material. So the new optical disk model need be founded.

3 ANALYSIS OF THE OPTICAL DISK MODEL FOUNDATION

According to the scalar diffraction theory, the effect of the information mark on the incident beam is bringing the local phase delay. And the phase change could be expressed by the optical path difference $\Delta s$. For the recording format of the alternative pit and land, $\Delta s$ could be given by

$$\Delta s = n^* \Delta h$$

(1)

$n$ was the refractive index of the substrate, $h$ was the depth of the information pit, and $\Delta h$ was the changes of the pit depth. Namely, by the changes of the pit depth, we could get the different optical path difference and the phase changes; consequently the digital information was recorded.

If we remained the pit depth $h$ constant and let the refractive index changing, for example, the Write Once Read Many (WORM) disk, which stores the information with the cavity or the air bubble produced by the recording layer absorbing the laser energy, the optical path difference of the incidence beam still occured,

$$\Delta s = n^* h$$

(2)

**Figure 9** The model adopted by the coupled wave theory

**Figure 10** The model used by the curvilinear coordination method

**Figure 11** The optical path difference induced by pit depth $h$

**Figure 12** The optical path difference induced by refractive $n$
So the grating model could apply to either the pit-recording format or the cavity-recording format.

### 4 THE MODEL OF THE PHOTOCHROMIC OPTICAL DISK

The photochromic optical storage utilizes the inter-conversion of the different structure of photochromic material molecule with different absorption spectrum, and the inter-conversion is induced by the light irradiation or the photons at least in one direction. Namely, the polymer or the compound A can turn into B that has the different configuration from A under the irradiation of the light with a certain wavelength. And A can involute if the laser with the other wavelength shines on it or it is heated. The stored information can be read out by testing the changes of the transmittance or refractivity. When the readout beam $\lambda_2$ falls on the coding “0” (state B), the transmittance is very small because state B will absorb the incident energy. And for the coding “1” (state A), the incident energy will mostly be transmitted for the absorption of state A for beam $\lambda_2$ is very little. Detecting the transmittance, the readout signal can be obtained. In addition, with the analysis and the experiment, we can know the transmittance of one coding is not uniform because the writing beam has the Gauss distribution.

According to the characteristics of the photochromic optical storage, we found our model based on the sine amplitude grating. And the complex transmission coefficient of the optical disk was denoted by $T(u,v)$

$$T(u,v) = \frac{1}{2} + \frac{m}{2} \sin[2\pi(u/p + v/q)]$$

(3)

$m$ was the modulation of the amplitude transmittance function, which was concerned with the concentration of the photochromic material, $p$ was the tangential period, and $q$ was the radial period. Supposed $m$ equaled 0.6 and $p$ was 1.6 $\mu$m, the transmission coefficient on the center vertical section ($v$ equals to zero) of the information pit calculated was shown in Figure 14. Adopted the Gauss incident beam, the distribution of complex amplitude on the exit pupil sphere was $f(x,y)$, which was given by
\[ f(x, y) = \begin{cases} A(x, y) \exp[i2\pi O(x, y)] & (x^2 + y^2) \leq 1 \\ 0 & (x^2 + y^2) > 1 \end{cases} \tag{4} \]

\( A(x, y) \) described the real amplitude over the exit pupil sphere and \( O(x, y) \) denoted the wavefront aberration of the objective lens. Assumed the exit pupil is infinite, the complex amplitude distribution falling on the surface of the optical disk was expressed as

\[ F(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \exp[-i2\pi(ux + vy)] dx dy \tag{5} \]

the Fourier transform of \( f(x, y) \). So the complex amplitude diffracted by the optical disk could be obtained by

\[ a(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(u, v) T(u, v) \exp[i2\pi(ux + vy)] dudv \tag{6} \]

\( t(x, y) \) was the inverse Fourier transform of the \( T(u,v) \). Thereunder, we could get the readout light intensity on the surface of the entrance pupil

\[ I = \int_{x^2 + y^2 \leq 1} a(x, y) \cdot a^*(x, y) dx dy \tag{7} \]

**CONCLUSION**

In this paper, we firstly summarized the models of the optical disk and its information mark adopted by the scalar and the vector diffraction theories. And then the foundation of the optical disk model was revealed. Finally, we found the diffraction theory of the readout system for the photochromic optical disk. On the basis of our theoretical analyses, the following conclusion could be made: the periodic phase grating could be applied for both the pit or groove recording format and the cavity or bubble recording format, because the changes of the pit or groove depth and the refractive index could both induce the phase change of the incident beam; the amplitude grating fit for the photochromic optical storage which absorbs the incident beam energy.

**ACKNOWLEDGEMENT**

We highly acknowledge the financial support from the ‘Specialized Research Fund for the Doctoral Program of Higher Education’ and ‘National physical science fund (60207001)’.

**REFERENCE**

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