Objective Lens System for Variable Thickness of Disk Base

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As the thickness of a disk base is varied, the variation of spherical aberration becomes remarkable. An objective lens system with compensating lenses on the light source side is designed. By moving the compensating lenses along the optical axis backward or forward, the spherical aberration caused by the variation in thickness of the disk base is corrected.

Key words: objective lens, variable thickness, disk, base, compact disk, digital video disk

1. Introduction

A high density and large capacity optical disk is used in a digital video disk (DVD). Because the value of the numerical aperture (NA) of an objective lens is as large as 0.6, axis tilt sharply decreases the image quality. To lessen the influence of axis tilt, a thin disk base is widely adopted. In DVD, the thickness of this base is 0.6 mm, while it is 1.2 mm in compact disk (CD). However, because spherical aberration is sensitive to the thickness of the disk base, it is difficult to correct the aberrations of the objective lens used with different disk bases. Several methods have been reported to solve this problem. The first is setting an aspherical compensating element before the objective lens. The compensating element is not usually used with a DVD with disk thickness $t=0.6$ mm, but to CD with disk thickness $t=1.2$ mm. For a DVD with a disk thickness other than 1.2 mm, different compensating elements are needed. The second method is setting a holographic lens before the objective lens. No device for replacing the compensating element is needed, but corresponding to DVD and CD respectively, different zones on the holographic lens are used and a whole band of ray can not pass through the objective lens even under maximum NA, let alone the decrement in luminous flux caused by diffraction. For a disk base of a different thickness, different holographic lenses are needed. The third method is one matching the thickness of the disk base with an objective lens. Although good image quality can be obtained with this technique, the number of objective lenses has to be increased as the number of disk base thickness is increased.

In this paper, a geometrical optics based method is proposed. An objective lens system which can be used in both DVD and CD was designed, and the spherical aberration was corrected even though the thickness of disk base was continually varied.

2. Analysis of Spherical Aberration

The spherical aberration of a positive objective lens is sensitive to the thickness of the disk base. Increasing the thickness results in an over-correction of spherical aberration, and decreasing the thickness results in an under-correction. The spherical aberration of a positive objective lens also varies with the object distance $L_M$ (see Fig. 1). When the incident light beam is changed from parallel to divergent, there is an under-correction of spherical aberration, while when it is changed from parallel to convergent, an over-correction of the aberration is observed. Determination of an optimal object distance will allow the spherical aberrations associated with different disk bases of varying thickness to be corrected.

For example, the spherical aberration of one objective lens system, where the focal length of the lens $f_0$ is 4.5 mm, designated disk thickness $t_0$ is 0.6 mm, and designated object distance $L_{opt}$ is infinite, is well corrected (Fig. 2). When this lens system is used with the same object distance and with a disk other than 0.6 mm thick, spherical aberration increases (Fig. 3). In this situation, spherical aberration can still be corrected by selecting a suitable object distance. Corresponding object distances are found to the disk thicknesses in Fig. 3, and spherical aberrations are corrected (see Fig. 4).

3. Design Method and Example

Following are two design methods we have adopted.

Case 1. Object distance is finite

The configuration of the optical system is shown in Fig. 5. From left to right are object point, compensating lens, objective lens and disk base. If the compensating lens is moved, the object distance relative to the objective lens changes. The following ideas were employed in this technique.

(1) When disk base thickness is the designated value, set the object point close to the front focus so that the light beam emerging from the compensating lens is collimated.

(2) When the disk base is thinner than the designated value, there is an under-correction of the spherical aberration. By moving the compensating lens backwards, as shown in Fig. 5(a), a convergent light beam out from the compensating lens is obtained and thus the spherical aberration is corrected. This corresponds to the situation of DVD and NA being 0.6.

(3) When the disk base is thicker than the designated value, there is an over-correction of spherical aberration. By moving the compensating lens towards the object point, as shown in Fig. 5(b), a divergent light beam from the compensating lens is obtained and
Fig. 1. Illustration of object distance. $L_u$ is the distance from the 1st surface of objective lens to light source (on the optical axis).

$$\begin{align*}
L_{DM} = \infty & \quad L_M = \infty \\
t=0.5 & \quad NA=0.6
\end{align*}$$

Fig. 2. Spherical aberration of objective lens: $f=4.5\text{ mm}$, $t=0.6\text{ mm}$ and $L_u=\infty$.

thus the spherical aberration is corrected. This is the case for CD and NA being 0.375.

Even when the incident NA is large, good image quality is obtained by compensating lenses consisting of two elements. This configuration is shown in Fig. 6.

Case 2. Object distance is infinite.

The 1st configuration of the optical system is shown in Fig. 7. This is a beam-expanding optical system in which the light beam from the collimator is expanded by compensating elements before it enters the objective lens. From left to right are the compensating lens system consisting of the 1st negative lens and the 2nd positive lens, objective lens and disk base. Varying the distance between the 1st negative lens and the 2nd positive lens, the composed focal length, and consequently the image position, are altered. The distance between the two compensating elements is used to compensate the different spherical aberrations corresponding to different disk bases. The following are the basic ideas involved in the new method.

1. When disk base thickness is fixed, set the distance between two compensating elements so that the rear focus of the 1st negative lens and the front focus of the 2nd positive lens are overlapped.

2. When disk base is thinner than the fixed value, under-correction of spherical aberration exists. As shown in Fig. 7(a), by increasing the distance between the two compensating elements, a convergent light beam out from the compensating elements is obtained.

3. When disk base is thicker than the fixed value, there is an over-correction of spherical aberration. As shown in Fig. 7(b), by decreasing the distance between the two compensating elements, a divergent light beam out from the compensating elements is obtained.

4. In the above, relationship $0 < -f_1 < f_2$ must be satisfied to maintain the distance between the 1st negative lens and the 2nd positive lens a positive value when $t$ is varied from 0.6 mm to 1.2 mm. Here $f_1$ is the focal length of the 1st negative lens and $f_2$ is the focal length of the 2nd.

It is also possible to configure the compensating lens system with the lens elements inversely set. This compensating lens system is shown in Fig. 8. This is a beam-reducing optical system in which the light beam from the collimator is reduced by compensating elements before it enters the objective lens. The distance between the two compensating elements is adjusted for different disk bases. Relationship $0 < -f_2 < f_1$ between the focal length of the 1st lens, $f_1$, and that of the 2nd lens, $f_2$, is required to keep the distance between the 1st positive lens and the 2nd negative lens a positive value when $t$ is varied from 0.6 mm to 1.2 mm. The compensating method is the same as described above.

4. Design Result and Discussion

A lens data example of the design result is listed in Table 1 for the optical system shown in Fig. 7. The symbols used in the table stand for the following:
Fig. 3. Dependence of spherical aberration on disk thickness. Objective lens: $f=4.5\,\text{mm}$, $t$ is variable and $L_M=\infty$ ($t_0=0.6\,\text{mm}$, $L_{\text{air}}=\infty$).

Fig. 4. Connected spherical aberrations depending on object distance and disk thickness. Objective lens: $f=4.5\,\text{mm}$, $t$ is variable and $L_M$ is variable ($t_0=0.6\,\text{mm}$, $L_{\text{air}}=\infty$).
Fig. 5. Configuration of objective lens with one element compensating lens. \( L_a \) is finite, (a): \( t=0.6 \text{ mm}, \text{NA}=0.6 \), (b): \( t=1.2 \text{ mm}, \text{NA}=0.375 \).

Fig. 6. Configuration of objective lens with a two positive element compensating lens. \( L_a \) is finite, (a): \( t=0.6 \text{ mm}, \text{NA}=0.6 \), (b): \( t=1.2 \text{ mm}, \text{NA}=0.375 \).

Fig. 7. Configuration of objective lens with a two element (negative and positive) compensating lens. \( L_a \) is finite, (a): \( t=0.6 \text{ mm}, \text{NA}=0.6 \), (b): \( t=1.2 \text{ mm}, \text{NA}=0.375 \).

Fig. 8. Configuration of objective lens with a two element (positive and negative) compensating lens. \( L_a \) is infinite, (a): \( t=0.6 \text{ mm}, \text{NA}=0.6 \), (b): \( t=1.2 \text{ mm}, \text{NA}=0.375 \).

\[ ri \quad \text{Radii of curvature of spherical surfaces or vertex radii of curvature of aspherical surfaces} \]

\[ di \quad \text{The thickness of lenses or air gaps} \]

\[ ni \quad \text{Refractive index of lens or disk base materials at a wavelength of 650 mm} \]

\[ WD \quad \text{Working distance between objective lens and disk base (mm)} \]

\[ f \quad \text{Focal length of the entire system (mm)} \]

\[ f_a \quad \text{Focal length of the objective lens (mm)} \]

\[ f_{c_1} \quad \text{Focal length of the first negative lens element (mm)} \]

\[ f_{c_2} \quad \text{Focal length of the second positive lens element (mm)} \]

\[ \text{NA} \quad \text{NA of the entire system} \]

\[ \text{NA}_a \quad \text{NA of the objective lens} \]

\[ \text{\( L_{\text{obj}} \)} \quad \text{Object distance used in the design of the objective lens} \]

The configuration of the aspherical surface is expressed as follows:

\[ x = \frac{ch^2}{1+\sqrt{1-(1+K)c^2h^2} + \sum A_{2n}h^{2n}} \]

where

\[ X \quad \text{Distance of one point on the aspherical surface to} \]
Table 1. Example of lens design data.

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<th>SN.</th>
<th>ri</th>
<th>dl</th>
<th>ni</th>
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<td>8</td>
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<th>f</th>
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<td>2.712</td>
<td>0.605**</td>
<td>2.272</td>
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<tr>
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<td>0.375</td>
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Aspherical Surface Coefficient

\[ r_1 = -7.59018E-01, r_6 = -2.90545E+01 \]

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<th>A6</th>
<th>A8</th>
<th>A10</th>
<th>A12</th>
<th>A14</th>
<th>A16</th>
<th>A18</th>
</tr>
</thead>
</table>

\[ f_5 = -16.810, f_6 = 25.942, f_7 = 4.5 \]

\[ NA_0 = 0.6, L_{ap} = \infty \]

*1: Entrance light beam of r5 is converge
*2: Entrance light beam of r5 is diverge

Fig. 10. Aberrations of compensating lens plus objective lens, \( t = 0.6 \) mm and \( t = 1.2 \) mm.

Fig. 9. Aberrations of objective lens \( t = 0.6 \) mm.

Based on the diaphragm.

The aberration curves are shown in Figs. 9, 10 and 11. Figure 9 gives the aberration curves of the objective lens \((t = 0.6 \text{ mm}, t_0 = 0.6 \text{ mm})\), Fig. 10 shows the curves of the compensating lens plus the objective lens \((t = 0.6 \text{ mm}, t = 1.2 \text{ mm}, t_0 = 0.6 \text{ mm})\), and Fig. 11 those for the compensating lens plus the objective lens \((t = 0.5 \text{ mm}, t = 0.7 \text{ mm}, t_0 = 0.6 \text{ mm})\). The change of working distance, \( \Delta WD \), is not a serious problem because for \( t = 0.6 - 1.2 \text{ mm}, \Delta WD = 0.1 - 0.18 \text{ mm} \).

Whether the object distance is finite (as shown in Fig. 5 and Fig. 6) or infinite (as shown in Fig. 7 and Fig. 8), spherical aberration can be corrected very well by these two methods. The coma is increased slightly and deviation caused by the shift in translation during tracking must be taken into consideration, however. Therefore the variation in the disk base thickness of DVD with large NA should preferably be kept within 20% of a designated value. The wavelength currently used in CD is 780 nm and NA = 0.45. In DVD, wavelengths used are 650 nm, 635 nm etc. If wavelength 650 nm or 635 nm is used in CD, then the equivalent NA will be:

\[ \text{For } 650 \text{ nm; } NA(t) = 0.45 \times (650/780) = 0.375 \]
\[ \text{For } 635 \text{ nm; } NA(t) = 0.45 \times (635/780) = 0.366 \]

Even in such cases, satisfactory results can be gained in a situation where the thickness of disk base varies over a
large range as from 0.6 mm to 1.2 mm.

No matter what the designated object distance is \( L_{0m} < 0 \), \( L_{0m} = \infty \), or \( L_{0m} > 0 \), good results are obtained. Details of the compensating properties of the two methods are:

When the object distance is finite: (a) with one compensating element and incident NA<0.09, a satisfactory result is obtained; (b) with two compensating elements and incident NA<0.12, the result is satisfactory; and (c) the decrement in image quality caused by the shift of objective lens is small.

When object distance is infinite, the incident NA is determined by the NA of the collimator.

5. Conclusions

A new method to correct the aberrations caused by the variation of disk base thickness between two values of DVD and CD is proposed.

The merits of the method are:
1. There is no decrement in luminous flux caused by diffraction.
2. The method is employable for different disk base thicknesses, such as \( r = 0.5, 0.55, 0.6, 0.65, 0.7, 1.2 \) mm, etc.
3. The variation of working distance (\( \Delta WD \)) is small.
   For \( r = 0.6-1.2 \) mm, \( \Delta WD = 0.1-0.18 \) mm.

The defects of the method are:
1. Compensating lens is not fixed and movable.
2. Stop is necessary when used in CD, although the center of stop to match optical axis is not rigorously required.

One objective system designed with this method will be put into production very soon. It is expected that this technique can also find use in optical systems in which the variation of disk base thickness is more than two values, i.e., the thickness can vary continually, as the focal length can continually vary in the zoom system.

References