Optical system for multilayer disk storage using a confocal pinhole

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1 Introduction

Optical data storage technology has been widely used in our daily life since early last decade. CDs and DVDs are among the most popular medium for carrying music and movies. In this project, I am trying to design a multilayer DVD-ROM which is able to read out 20-layer DVD disk which has a capacity of 94 GB. This system features a confocal pinhole detection system which can reduce the crosstalk from other layers than the desired one.

2 System illustration

![Fig. 1. A multilayer optical readout system.](image)

The pinhole in the detection system is used to filter the data of other layers than our desired one, which could reduce the crosstalk between different layers. So the goal of this design project is to maximize the reflection from the desired layer and minimize the reflection from the other layers. We want use as many layers as possible to increase the capacity of this optical storage device, but the number of the layers is limited by the allowable separation between adjacent layers. We
could use high NA lens to reduce the allowable separation, but it will introduce bigger spherical aberration. We would try to optimize the objective lens to make the spherical aberration smaller and independent of the distance between the lens and the desired layer.

3 System Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity:</td>
<td>94 GB</td>
<td>4.7GB × 20</td>
</tr>
<tr>
<td>Access time:</td>
<td>200 ms</td>
<td>seek+settling+latency</td>
</tr>
<tr>
<td>Data rate:</td>
<td>22 Mbit/s</td>
<td></td>
</tr>
<tr>
<td>Diameter:</td>
<td>12.0 cm</td>
<td>Same size as standard CD and DVD disk</td>
</tr>
<tr>
<td>Thickness:</td>
<td>1 mm</td>
<td>Protection layer and 20 data layers</td>
</tr>
<tr>
<td>Separation:</td>
<td>20.0 um</td>
<td>Distance between adjacent layers</td>
</tr>
<tr>
<td>Wavelength:</td>
<td>633 nm</td>
<td>Red laser diode</td>
</tr>
<tr>
<td>NA:</td>
<td>0.53</td>
<td>Objective lens</td>
</tr>
</tbody>
</table>

The specifications in this table is the goal of my design project. I will focus more on the optical part of the system especially on the objective lens and the confocal pinhole detection system.

4 System designs: step by step

This part of the report will be divided by several sub-sections which correspond to different optical components in the optical drive. Each sub-section will generally have two steps. First step is the thin lens and Gaussian beam calculation and the second step is the design in Zemax. The order of the sub-sections is: Optical source, Feedback reducing, Objective lens, Confocal pinhole, System considerations.

4.1 Optical source and beam collimation

In this optical drive, we use a 633 nm red laser diode (LD) as the optical source. These LDs are cheap nowadays. They only cost a few dollars or less. They can be operated at low voltage and has an output of about 3mw-20mw. But these LDs have a very small emitting surface about a few microns, so they diffract very quickly. Even worse the output beams are elliptical [Fig.2].

![Divergent laser beam](Fig. 2. Laser diode and elliptical output beam)
The elliptical laser beam is unsatisfactory so an additional prism pair is used to circularize the beam [Fig. 3.].

![Diagram of laser beam circularizing using prisms](image)

Fig. 3. Elliptical beam circularizing using prisms

Assume the optical beam from the laser diode has a y/x ratio of 3:1. One prism can expand the laser beam by a factor of 1.5 [Fig. 4.], which is the index of refraction of the prism.

![Diagram of circularizing factor by single prism](image)

Fig. 4. Circularizing factor by single prism

If we combine a two prism together, each of them will contribute a factor of 1.5, thus we can exactly eliminate the ellipticity. So now we have successfully collect and collimate the light from the laser diode. The laser beam after collimation has a radius of 2.5mm. The collection lens we use has a NA=0.25 assuming the laser beam has a divergent angle of 30 degrees. The focal length of this lens should be 10mm.
4.2 Reducing optical feedback

Laser feedback is a serious problem for optical drives, because the reflected beam from the recording medium will be go exactly the same route back to the laser diode. In this section, we are trying to reduce the feedback from the recording medium. We are going to use a polarizing beam-splitter and a quarter-wave plate combination to fulfill this task [Fig. 5.].

![Fig. 5. Reducing optical feedback](image)

Laser beam from the laser diode is P-polarized and can pass through the polarizing beam-splitter (PBS) without any loss. It then reflects at the turning prism due to total internal reflection and passes through the quarter-wave plate (QWP) changing its polarization to right-hand circular polarization. In this design, QWP is put after the turning prism, so the Guoy phase shift will not affect the polarization of the laser beam. After being reflected from the medium, the beam’s polarization becomes left-hand circular. Then the beam passes through the QWP again changing its polarization to S-polarized. So the reflected beam will not pass through the PBS, instead it reflects to the detector.
4.3 Objective lens design

The challenge for design of the objective lens for this multilayer optical storage drive [Fig. 6.] lies on the different amount of spherical aberrations (SA) for each individual layer. The design purpose is to try to reduce the average SA for the total of twenty layers. So for each individual layer, the capacity will not be degraded by SA.

![Objective lens diagram](image)

**Fig. 6.** Objective lens for multilayer optical storage. $d_1$ and $d_2$ are working distance between last surface of the lens and protection layer respectively. $t_1$ and $t_2$ are the distances from the last surface of the protection layer to the desired storage layer respectively.

It is shown in Fig. 6. that the working distance $d$ will change for focusing on different storage layers. For each layer, the SA is different. So the design goal is to optimize the lens to make the SA within certain accepted range at all of the storage layers.

The start point for this design is to use an objective lens whose SA is optimized at a single layer. Then optimize it in Zemax to make it work at different locations inside the storage medium. But it turns out that using a single lens cannot compensate SA for all layers. The detailed results from Zemax are shown for the following pages. So we have to use lens combination to increase the freedoms in order to compensate SA for all layers.
A Galilean telescope with aspheric elements is used for compensating SA for different layers [Fig. 7.]

![Diagram](image_url)

Fig. 7. In the dashed square is the Galilean telescope. The zoom length T can be changed to optimize the focusing size of the beam in the recording material.

Fig. 7 shows the combination of a Burch-type objective lens and a Galilean telescope for multi-layer data storage. We can control the working distance d and the zoom length T to optimize the SA inside the recording material for different layers. The physics behind this system is that the zoom length T can introduce necessary defocus to compensate for spherical aberration.

This system can be used for layer thickness from 0.4 mm to 1.2 mm. In this project, in order to store data in 20 different layers, we will set the first layer at 0.6 mm, which is the typical DVD layer thickness. The layer separation between adjacent layers will be 20 um. So this gives the variation of the thickness from 0.6 mm to 0.98 mm.

Now I introduce this system into Zemax and optimize the working distance d and zoom length T to try to get diffraction limited spot in the recording material at different layers. Detailed results from Zemax are shown in the following pages which include the parameters of the working distance and zoom length.

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4.4 Confocal lens design

This multilayer optical data storage system features a confocal reflection detection, which means before the detector we are going to use a confocal pinhole to block the noise from other layers than the desired one [Fig. 8].

![Confocal Lens Diagram](image)

Fig. 8. Confocal pinhole is used before detector.

We would like to have a large pinhole for easy alignment. So we need to use a confocal lens to magnify the focal spot in the recording material. This confocal lens is chosen to give a transverse magnification of 11.5 which corresponds to an image of 15 μm in diameter. This system also gives a longitudinal magnification of 133, which means that for adjacent layer detection the pinhole needs to move 1.78 mm. In the following pages, transmission versus the z axis movement are plotted for particular pinhole size. SNR were defined as the ratio of transmission for the desired layer to the transmission of the adjacent layer. We can see as we decrease the size of the pinhole SNR increases at first but eventually it will be limited by the signal power passing through it. We could get as large as 13 dB when we step down the pinhole to 15 mm in diameter.
4.5 System considerations

In this section, we will briefly discuss the system considerations such as, tolerance, power budget etc.

The red laser diode in this system has an maximum output power of 5 mW and its noise is less than -134 dB/Hz. And the power supply for this diode can be about 2 V, which means that it does not require a special power supply. But laser diode is very delicate device and is very fragile. Under nominal operation, the average lifetime is about 10000 hours.

The disc tilt limit for each layer is about 0.8 degrees in the radial direction and 0.3 degrees in the tangential direction. So basically this tolerance is not difficult to achieve.

In order to satisfy the power budget, we have to consider the reflection of this multilayer medium. Each layer must be partially transparent so that the laser beam can penetrate all the layers. Each surface, however, must also be reflective enough so that the data can be read. On average the reflection from each layer is about 5%. So the last layer will reflect about 1.7% of the total power. When the 1.7% reflected beam pass all the layers the output from the medium is only about 0.06%. So this is really a big problem when we add more and more layers in the material. The SNR as well as BER will just degrade a lot when using more layers.

Because of the extremely small track pitch (0.6um), the tracking tolerance for optical recording systems is much smaller (0.1um). So additional servo-systems composed of optical position sensors with complex feedback circuits has to be used. The detection system itself can be a very interested project and it is beyond the scope of this project.

In order to calculate the SNR of the system, the detection system has to be specified. Generally for a CD system, SNR is about 90 dB. But the for this multilayer drive, the SNR will degrade due to the reflection from all the layers.

5 Summary

A multi-layer optical storage system is successfully designed in this project. It has 20 storage layers and has a capacity up to 94 GB. This system features a confocal pinhole system in order to reduce the crosstalk between the adjacent layers. A Galilean telescope is used to compensate the spherical aberration at different layers by adjusting the zoom length of the telescope thus changing defocus of the system. It successfully compensates the SA from 0.6 mm to 1 mm, which is the designed range of this multi-layer storage disk.