DVD Optical System Design

Optical design will be designed to read DVD discs according to current DVD specifications.

Specifications

The optical system should be able to detect pits (or bumps from the optical system’s point of view) on a standard DVD disc.

Physical dimensions of the DVD tracks are as follows:

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Description</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit Width</td>
<td>Width of a single pit, representing a binary digit.</td>
<td>0.32 µm</td>
</tr>
<tr>
<td>Pit Height</td>
<td>Height of a pit.</td>
<td>0.12 µm</td>
</tr>
<tr>
<td>Track Pitch</td>
<td>Distance between two tracks of pits.</td>
<td>0.74 µm</td>
</tr>
<tr>
<td>Min Pit Length</td>
<td>Shortest length of a single pit.</td>
<td>0.40 µm (SL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.44 µm (DL)</td>
</tr>
<tr>
<td>Max Pit Length</td>
<td>Longest length of a single pit.</td>
<td>1.87 µm (SL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.13 µm (DL)</td>
</tr>
<tr>
<td>Protection Layer</td>
<td>Distance from the surface of the disc to the pit tracks</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Index</td>
<td>Refractive index inside the disc.</td>
<td>1.55</td>
</tr>
<tr>
<td>Thickness of spacing layer</td>
<td>Distance between layers in a dual layer (DL) disc</td>
<td>40 to 70 µm</td>
</tr>
</tbody>
</table>

For this particular project, this will be a proprietary disc reader needing no compliance to a specific standard. Thus, dimensions of the optical system itself will be left to my discretion. This will allow for more flexibility—and creativity—in the design.

Associated mechanics and electronics of the design (such as tracking, mounting, and processing) will be left out of this design.

Possible Approaches

Before outlining different approaches, let me first point out some considerations:

- Due to the fact that I will be dealing with conventional DVD discs, I will have to deal with pits that reflect, so if I choose a design that has a normal incidence beam onto the disc, I have to figure out a way to divert it so it doesn’t feedback into the laser.
- The design must include—or at least accommodate—a tracking system.
- Unlike smaller design problems, this project will take cost and availability of components into account (This, however, probably won’t be much of an issue until a general design is chosen and parts’ specifications become a large concern.)
Method 1: Angled Design

The first technique that I thought of would be a sort of angled design, inspired by oversimplified models of DVD optical systems that I encountered in various places while researching this topic (http://electronics.howstuffworks.com/dvd12.htm, for example).

This method would employ a laser light that would read the disc at an angle, reflecting off of the disc and onto a detector. Upon encountering a pit, the reflected beam would be displaced enough for detection. An example of such an oversimplified system is shown in Figure 1.

More realistically, we could take the concept and add lenses to compensate for the fact that the laser light is not an infinitely small beam, but a diverging light source (Fig. 2). The initial lens will focus the light on the DVD track surface, which then reflects back and focuses on the detector. The presence of a pit would displace the light enough to cause a noticeable effect on the input of the detector.

Tracking could be carried out in a similar manner, with two side peaks created by a diffraction grating before the initial lens, which follow a similar path.

At first glance, this looks like a pretty simple design. There is no optical feedback to worry about and only two lenses (at first glance) to deal with. After reviewing it further, however, there is plenty of worry about.

First of all, since we are coming in at an angle we need to worry about reflectivity issues for rays going into and out of the media. Examining this a little further, we can use the Fresnel formulae to plot the reflectivity from air into a medium with n=1.55. This plot is shown in Figure 3. The corresponding plot of ray reflectivity from the medium into air is plotted in Figure 4.
Looking at the two plots, it looks like the best bet would be to linearly polarize the input beam to parallel polarization set at around 30° to 35°. We need to realize that the angle of the optical axis of the lens to the DVD surface will be an even shallower angle: 30° to 35° should be the angle of the steepest rays coming out of the lens. All of this is assuming a perfect surface, which we couldn’t expect.

Another difficulty encountered when calculating the displacement we get when reflecting off of a pit 120nm high. Solving geometrically for a detector oriented at roughly the angle of the incident ray we get a displacement of

$$d = \frac{(120\text{nm}) \left( \frac{1}{1.55} \sin \Theta_i \right)}{\cos \Theta_i}$$

For a ray at the steepest angle, 35°—which would give us the most displacement—we would get just over 54nm. The optical invariant limits us at the lens that focuses onto the detector. We would need a huge amount of magnification at this lens (1000+, probably)—which would push the backfocal plane out probably much farther than any reasonable design should allow.

Method 2: “Shared” Lens Design

A second technique actually uses the DVD disc in a way it was designed for: it shines a beam at a nearly incident angle and uses the principle of positive and negative interference to determine where the pits are.

In this design, collimated light from the laser is displaced to one side of the principal focusing lens. The focal plane of this lens lies on the DVD track, which allows for the reflected beam to come back through the other side of the lens—thus the lens is shared between incident and reflected beams. With a return optical path separated from the
original one, we can now do whatever we want with it—like focus it back onto a detector. (See Figure 5.)

Tracking would be carried out through the existing setup, where three beams would be sent through the system—a center and two side peaks—to detectors (in a setup a bit more elaborate than shown here).

The practicality of such a system, however, is limited. Due to the high density of the tracks on the disc, a very small resolvable spot size is required. This means that we need as big of an NA as we can get. Limiting the beam to using only half of the lens limits the NA (making us think that we can do better…).

**Method 3: Optoisolator Design**

The third technique is one based on an optoisolator design—using polarization to separate the incident and reflected beams.

The incident beam is collimated and passed through a linear polarizer. The linear light is passed through the polarizing beam splitter cube and turned into circularly polarized light afterward by a quarter wave plate at $45^\circ$ orientation.

Once reflected, it remains circularly polarized, yet has the opposite polarization. Due to this switch, when the beam passes again through the quarter wave plate, it has linear polarity perpendicular to the initial linear polarization.

With this new polarization the beam is now reflected by the polarizing beam splitter cube into a lens that focuses it onto a detector.

This design is superior to the previous two in a number of ways. First of all, unlike
the first design, it is actually feasible to make. Secondly, unlike the second design, it allows use of the whole lens. This gives us a greater NA, which will be very important when trying to shrink down the spot size.

The optoisolator technique is the clear winner of the three different designs. That being said, let’s move on to paraxial design.

**Paraxial Design**

Taking the Optoisolator design and stretching it out, we can come up with an initial paraxial design that should give us a flavor of what we are dealing with. Instead of introducing it later, I think I’ll add in the diffraction grating now. Also, it turns out that the polarizing beam splitter cube does indeed polarize, so there will be no need for an initial linear polarizer. The resulting paraxial design is as follows:

(Because I will be dealing with components I know little about—the diode laser, diffraction grating, polarizing beam splitter, specifically—so I may have to make a few assumptions.)

There are a few more specifications that are necessary for this system to work. For example, the laser light needs to be around 650nm to get a ¼ wave reflection off of the pits, and, more importantly for proper light cancellation, the spot size (diameter to 1st null of the Airy disk) needs to be around 0.84 µm.

To calculate NA, we take the equation

\[ r_0 = 0.61 \frac{\lambda}{NA} \]

And rearrange it to get

\[ NA = 0.61 \frac{\lambda}{r_0} = 0.61 \frac{650/1.55}{840/2} = 0.6 \]

This gives us a PMR input angle of \( \alpha = 36.87^\circ \) (\( \alpha = 22.77^\circ \) for \( n=1.55 \)).
Backing up through 0.6mm of polycarbonate we have a cone with a diameter of 0.504mm.

If we read the disc at 1mm away from the surface we have a cone with diameter of:

\[ d = 2 \times \left( 1\text{mm} \times \tan(36.87) + \frac{0.504\text{mm}}{2} \right) = 2\text{mm} \]

With a well-collimated input gaussian beam with a very small divergence angle, the waist of the beam after the focusing lens occurs at the backfocal plane. Thus (assuming we can get a well-collimated input), we set the focal point of the lens at

\[ F = 1\text{mm} + 0.6\text{mm}/1.55 = 1.387\text{mm} \]

With the NA, distance to the DVD surface, and minimum lens diameter, and focal length, we have a starting place to build the rest of the system around.

One thing that we can do is to determine the parameters for the collimating lens.

Gaussian ray tracing techniques will be useful—I will use notation given by Mouroulis and Macdonald (Fig. 8).

Ideally, we want \( s' \) of the collimating beam at \( \infty \) and \( u' \). We can also note that

\[ s' = F - \frac{(s + F)F^2}{(s + F)^2 + z_0^2} \text{ where } z_0 = \frac{\lambda}{\pi \theta^2}. \]

Having looked at laser diodes, a typical value for parallel divergence, \( \theta \), is 28° (take Samsung SLD65018271L, for example). At 650nm this makes \( z_0 = 866\text{mm} \), a pretty negligible quantity when compared to the other terms—especially when squared. However, this does give us a fairly large NA, 0.46 to deal with.

For a negligibly small initial waist (not a bad assumption, I think, for a laser diode in this optical system), we calculate \( s = \frac{1\text{mm}}{\tan(28^\circ)} = 1.88\text{mm}. \)

If we set the focal point at 1.88\text{mm}, we can use the equation for \( s' \) above to find that placing the diode 1.89\text{mm} away from the lens gives us waist 353\text{mm} after the lens—essentially collimating the light like we wanted it to. Note that due to the small distance between the diode (through the grating) and the collimating lens the initial design will have to change: the polarizing beam splitter will need to come after the collimating lens. This also means that we will need to add a lens to focus the beam onto the detector. If anything, however, this probably improves the design since the beams will have normal incidence onto the beam splitter (less reflection, equal path length, etc).
Gaussian and Finite Design

Using Gullstrand’s equation, we can find the power and thickness of each lens. I’ll try to keep things simple by keeping the radius of curvature for each surface the same.

For an index of refraction of 1.5, the collimating lens came out to have a thickness of 1mm and a radius of curvature on each surface (both convex) of 5.1mm. The focusing lens will have a thickness of 1mm as well, and a radius of curvature of 3.6mm. Geometrically, this limits us to a maximum lens size of around 3.6mm, but we based the design on a 2mm lens, so we should be fine.

With these lenses, we find the principle planes by using the relations

\[ \delta' = \frac{h_t - h_k}{u'_k} \quad \text{and} \quad \delta = \frac{h_t - h_k}{u_t} \]

according to the notation in Mouroulis and Macdonald where each \( \delta \) is the distance from the surface of the lens to the respective principle plane. Subscripts 1 and k denote rays before and after the lens, respectively. Subtracting the length of \( \delta \) from the focal length, we can get the distances of the focal planes to the lens.

This gives us a distance of 1.51mm from the laser to the collimating lens, but only a mere 0.1mm distance from the focusing lens to its focal point (meaning even less distance from the lens to the surface of the disc).

If we put virtually no power on the back surface, this means the back principle plane will virtually be on it, and we will have more clearance of the lens; leaving the front surface to create most of the power of the lens. With a radius of curvature of only 2.1mm for the front surface, and 150mm for the back surface, we get the desired focal length, and the principle plane lies only 0.01mm inside the back surface. With a new thickness of 1.1mm, this gives us a lens diameter of 3mm.

For simplicity sake we can make the output lens onto the detector the same as the initial collimating lens. For a practical optical system, this is where we would insert the tracking optics (cylindrical lenses, detector arrays, etc). Though it wouldn’t take too much more to put it in, tracking will have to wait; I will not get into tracking due to time constraints.

We can use a quarter wave plate from Newport (05RP34): A plate 5.1mm in diameter and 3.3mm thick, and a 3mm polarizing beam splitter cube.
Here is a drawing of everything (distances, radii of curvature, diameters, etc.) to scale:

**Figure 9: Completed System**
The finite characteristics of the system are determined with the help of my Excel rays tracing program:

Because of its smaller diameter, the focusing lens is the aperture stop. The exit pupil is 1.81mm in front of the surface of the collimating lens with a radius of 0.6mm. Due to the symmetry of the system, the entrance pupil lies 1.81mm after the final lens to the detector with a radius of 0.6mm.

Now finding our chief ray and sending it through the center of the aperture stop, we find the field stop and exit window to be the final lens to the detector. Sending this ray back through the system, we find that the entrance window is 2.62mm before the collimating lens, with a radius of 2mm.

**Final Thoughts**

Though I was able to complete most of the fundamental parts of the system, there are a few parts that I would add or redesign (given the time of the desire…)

- The collimating lens is extremely touchy. A slight movement (on the order of 0.1mm) could have extreme effects. A larger lens with a longer focal length could fix this, but it would probably require at least one additional lens to focus the beam down or a change in its dimensions.
- Tacking was something I had studied and was set to do…but didn’t have the time to in the end. This design should accommodate a tracking system with little change. The primary difference would come after the beam splitter for the reflected beam. There would be a cylindrical lens and detector array for lateral tracking, and separate detectors for side beams for transverse tracking.
- Though I based the design off of some real components (laser, wave plate, etc.), I had difficulty finding good lenses for DVD lasers—therefore I made designed my own. In a practical design I would of course shop around a bit more for desirable lenses and build around those.
- The complete design would include tolerances, power/optical specifications, compensation for aberrations, etc. I thought I’d focus mainly on what we’ve learned in class for this design.

Overall, however, I feel that this is a pretty solid basic design—not too shabby for a first timer 😊.