Experimental Determination of the Storage Capacity of a CD*

Zander Mausolff

Physics and Astronomy Department, University of San Francisco

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Abstract

The examination of an off the shelf compact disk (CD) illustrates many concepts in optical physics. The storage capacity of a compact disk was determined by directing light from a HeNe laser onto a CD and viewing the resulting diffraction pattern. The distance between CD tracks (track length) was determined to be $1.56\mu m \pm 0.032\mu m$. With simple assumptions about the track length and pit-bit correspondence resulted in a measured storage capacity of $475MB$, differing 32% from the known value of $700MB$. Realizing the pit size distribution and the method in which CDs are encoded a new model was employed. Using the new model of a CD the storage capacity was calculated to be $713MB$ and differs by 1.8% from the known value.

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I. INTRODUCTION

The development of the compact disk involved a combination of laser physics, optics, and computer science. To highlight these topics we will provide background on the CD and undergo an experiment to determine the storage capacity of an off the shelf CD. We begin by describing the strucuture of a CD. Second, we will discuss the experiment and the results obtained with a simple data storage model. Third, we will look at how information is encoded and read, in order to develop an accurate CD storage model. Finally an improved CD model is put forth and is used to determine the data capacity of a CD.

A CD is produced so that it has contains series of alternating pits and lands that spiral around the CD. When laser light is incident on a CD the tracks of pits and lands cause the CD to behave as a diffraction grating. The pattern produced by the diffration like behavior and the spacing of these pits and lands determines the amount of data on a CD. Thus an important factor is the distance between adjacent tracks, commonly referred to as the track pitch. By guiding the laser onto the CD and examining the diffraction pattern via evaluation of the grating equation at normal incidence we determined the track pitch to be $1.56m \pm 0.031m$. Our experimental value agrees with the known value of $1.60\mu m$.

To determine the storage capacity of a CD from the track pitch two assumptions were made. The first is that the CD contains alternating square pits with a height and width equal to one-half of the track pitch. The second is that every pit on the CD stores one bit of information. Using these assumptions the capacity was calculated to be $475MB \pm 11MB$, which differs from the known value of $700MB$ by 32%. It appears these assumptions were flawed as the initial measurement of the track pitch was determined accurately.

To understand why the assumptions used were too simple we will look at how information is encoded on a CD. Information is encoded on a CD using a method called 8-14 modulation, which takes 8 bits from a computer and maps them to a corresponding 14 bit representation. These 14 bit characters are imprinted onto the CD. This encoding method ensures a distribution of pit sizes on the CD. Additionally, a method called non-return-to-zero-inverted is employed by the CD reader and returns a bit value of 1 at the edge of a pit and reads a 0 otherwise.

Taking into account the method in which CDs are encoded and read, the storage capacity of a CD was accurately determined. We will discuss the calculations and assumptions used to determine the storage capacity last. Using these calculations the data storage was calculated to be $711MB$ and only differs from the known value by 1.5%.

II. CD STRUCTURE

The construction of a CD involves layering multiple materials on top of one other, most of which protect the data storing layer.

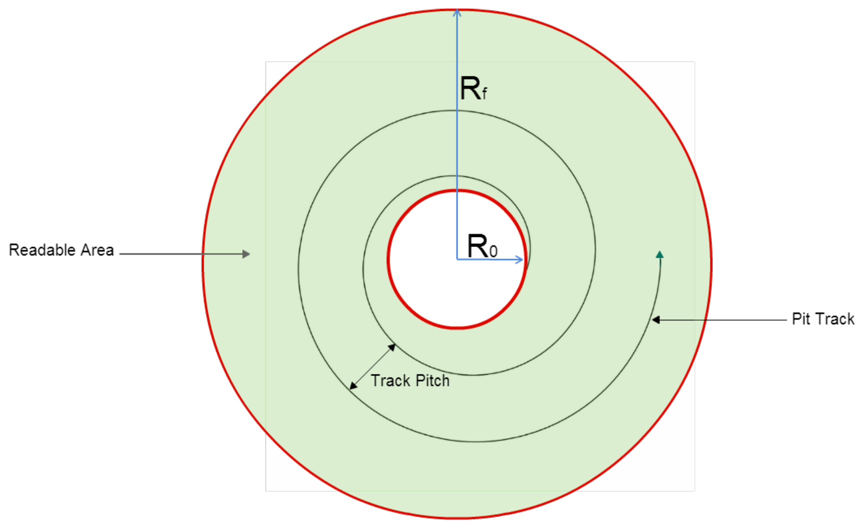

FIG. 1. A CD contains a spiral track of pits that form nearly concentric circles. Adjacent tracks are seperated by a distance known as the track pitch. The readable area of the CD is highlighted in green.

The data storing layer has a spiral track of pits, which stores information. The distance between tracks, exaggerated in Fig. 1. is referred to as the track pitch, and is what will be experimentally determined. Information on the CD is read by scanning a laser precisely over the pits. We will discuss in detail how the data is read in a subsequent section.

The pits, magnified in Fig. 2. are made such that they are $^1/_4$ the size of the incoming wavelength in depth. This ensures the light incident on a pit travels $^1/_2$ of a wavelength more than those on a land [1]. The light reflecting off of the pit results in a definite phase relationship with the light reflecting off of the land and an interference pattern emerges. The protective layer just before the pit has an index of refraction of 1.55 and effectively changes the wavelength of light propagating through it. Besides protection, the smaller wavelength of light allows smaller pits and thus more on the CD.

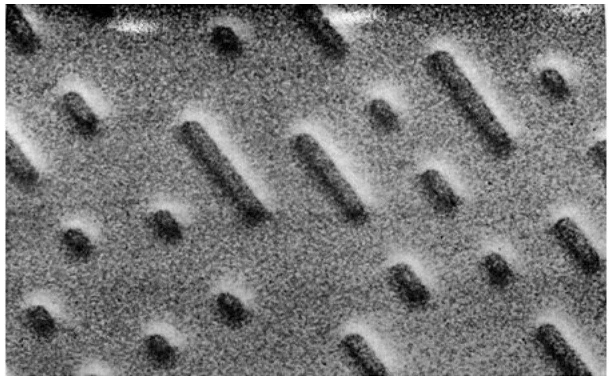

FIG. 2. The readable area of a CD is magnified in order to see the pit and land sizing. The length scale of these pits are on the order of micrometers and can only be imaged by an electron microscope.

III. EXPERIMENTAL SET UP

A block diagram of the experiment is provided in Fig. 3. There are two parts to the experiment, the first was to measure the track pitch and the second was to determine the readable area of the CD.

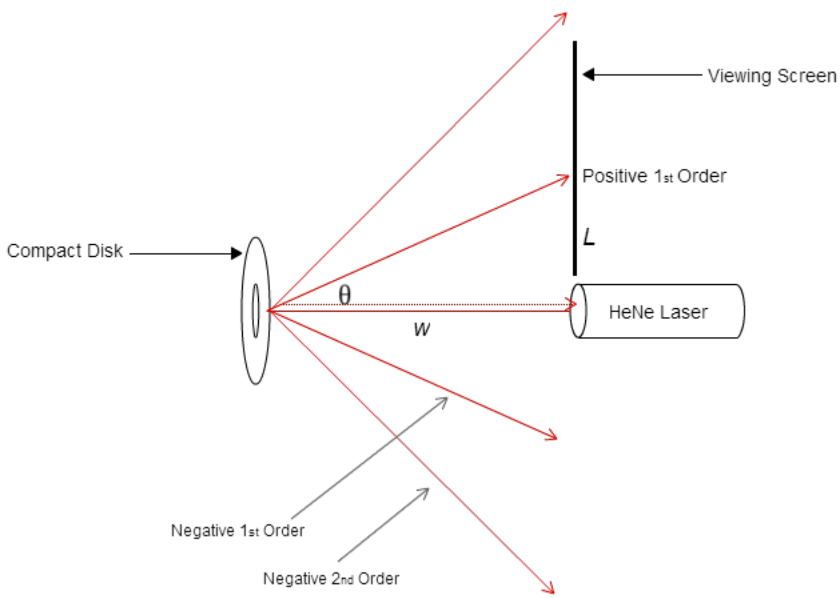

FIG. 3. Light from a HeNe laser reflects off of the CD and creates a diffraction pattern on the viewing screen. By measuring w and L it is possible to determine θ.

The track pitch was determined by guiding laser light from a HeNe laser onto the readable area of a CD at normal incidence to the CD. The 0^{th} order fringe is observed at the aperture of the laser and the positive 1^{st} order fringe is observed on a screen next to the laser. The distance between the laser and the CD, w, is measured and the distance between the 0^{th} and 1^{st} order, L is measured as well. The angle, θ is determined using the following equation

$$\theta = \arctan \frac{L}{w} \tag{1}$$

With the wavelength of the laser and the angle between the 0^{th} and 1^{st} order Eq. 2 can be used to determine the track pitch, d.

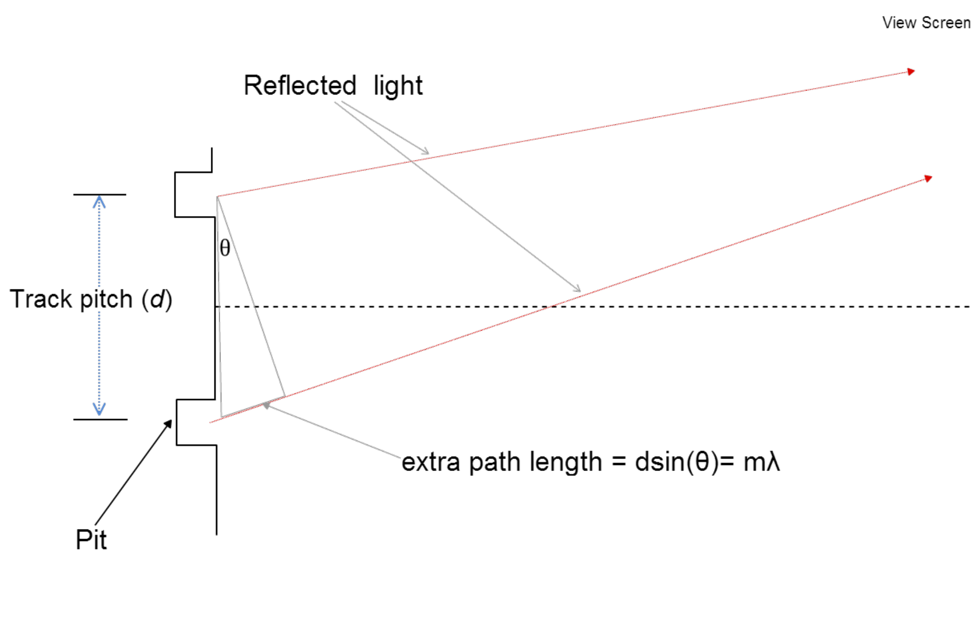

FIG. 4. Shown here is the interaction of incoming light with just two tracks. The extra path length traveled by the reflected light gives rise to a diffraction pattern. In the experiment the laser light interacted with many of these tracks to produce the diffraction pattern.

To obtain the track pitch of the CD the grating equation at normal incidence can be used and was derived by examining the geometry of Fig. 4 [2].

For the first diffraction order at normal incidence the grating equation can be written as

$$dsin(\theta) = \lambda \tag{2}$$

Where d corresponds to the track pitch, θ the angle between the 0^{th} and 1^{st} order, and λ the incoming wavelength of light. The determination of d allows for a simple model of the pit geometry and pit-bit relation to be utilized for determining the storage capacity. It was assumed that each pit is a square with sides equal $^1/_2$ of the track pitch, as seen in Fig. 5 . Additionally it was assumed that one pit stores one bit of information. Obtaining the number of pits contained in the readable area allowed the number of bits to be calculated simultaneously.

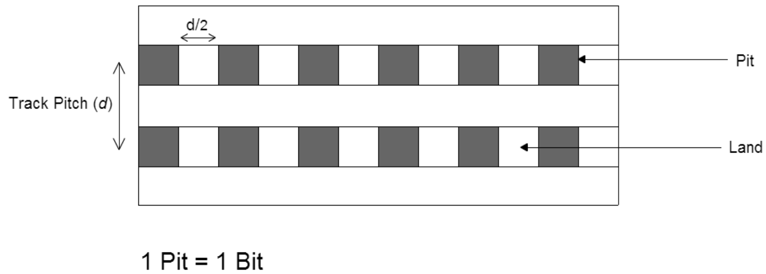

FIG. 5. Assumed mode of the pit size, and pit-bit relation.

The readable area was determined by finding the arc length of a circular spiral with steps equivalent to the track pitch (denoted as d). The number of circles, n, to integrate around is determined by taking the the difference in R_f and R_0 and dividing by the track pitch, d. The arc length was then calculated using

$$Length = \int_0^F \sqrt{(R_0 + q\theta)^2 + (q)^2}\,\mathrm{d}\theta. \tag{3}$$

where $F = 2\pi n$, and $q = \frac{d}{2\pi}$. To determine the amount of pits stored on the CD, we take the Readable length and divide it by the area of one pit. However, as we are only concerned with the number of pits we divide the track length by two. This is done because the assumed model in Fig. 5. shows that pits only occupy half of the readable length.

$$bits = \frac{L_r}{L_p} = \frac{(Length)}{(\frac{d}{2})} * \frac{1}{2} \tag{4}$$

IV. EXPERIMENTAL RESULTS

The distance between the laser and the CD and the distance between the 0^{th} and 1^{st} order fringes were measured to determine the track pitch. The track pitch of the CD was caclulated to be $1.56\mu m \pm 0.032\mu m$, which differs from the manufacturers value of $1.6\mu m$ by 2.5%. The error is 1.25 times bigger than the standard deviation and be considered to be one of the times the measured value is more than one standard deviation away. The small relative error indicated that the CD can be modeled as a diffraction grating. Using the experimental value for the track pitch the data storage capcity was calculated.

A calculated storage capacity of $475MB \pm 11MB$ was calculated using Eq. 4. The storage capacity differed from the known value by 32%. It appeared that the problem stemmed not from the readable length but from the model used for the pit size and correspondence of pit to bit amount. Modeling the pits as simply alternating from pit to land and having sides equal to half of the track pitch appeared to be invalid.

V. CD ENCODING AND READING

The results of the experiment yielded an accurate value of the track pitch but found the storage capacity to be innacurate. To understand why the model is incorrect and to provide an improved model we will look at how a CD is encoded and read.

A CD is encoded by a method called 8-14 modulation (EFM). EFM was developed to mitigate payback errors due to damage and small production defects on the CD. 8-bit information is mapped to 14 bit sequences, which are written on the CD (commonly referred to as channel bits) [3]. EFM rules only allow sequences of $0's$ and $1's$ with a minimum of two $0's$ and maximum of ten $0's$ between $1's$ [5].

Instead of pits having the same area, they have characteristic distribution to satisy the EFM conditions, shown in Fig. 7.

Additionally to ensure the EFM rules are maintained 3 merging bits are placed inbetween every group of channel bits. So in order to store 8 bits of information from a computer it requires 17 channel bits (14 bits for $8-14$ conversion plus 3 merging bits).

Now that we understand how CDs are encoded we will look briefly at how CDs are read. Laser light goes through a diffraction grating and collimating lens to produce three parallel light rays, which are focused onto the CD as shown in Fig. 8. When these three rays encounter a pit, the center ray traverses $\frac{1}{2}\lambda$ more than the other rays and destructively interferes with the adjacent rays. If these three rays do not encounter a pit they are reflected and captured by a photodiode [5].

Using a method called NRZI (nonreturn-to-zero-inverted) a 1 is only read at the transition of a pit and 0 everywhere else. This implies that both pits and raised areas (commonly called

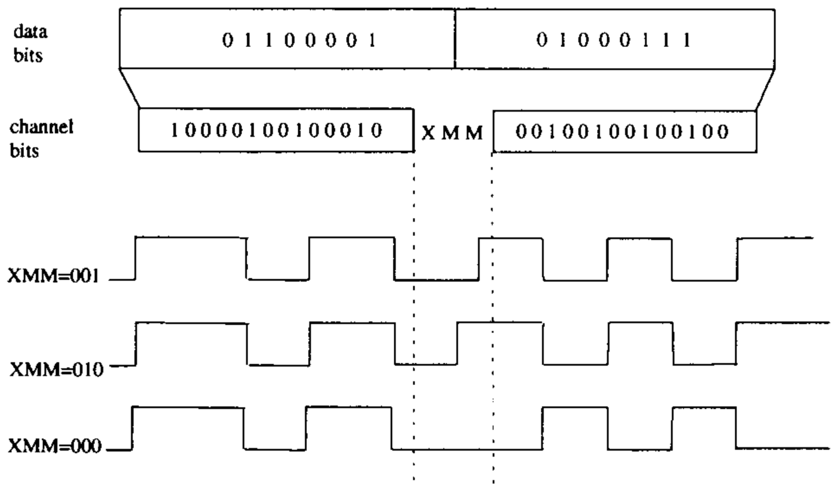

FIG. 6. 8 data bits from a computer are mapped to their 14 bit equivalent. These 14 bit representations are encoded onto the CD with 3 merging bits inbetween them. Three merging bit sequences are given here, and are used to ensure the EFM rules are maintained.

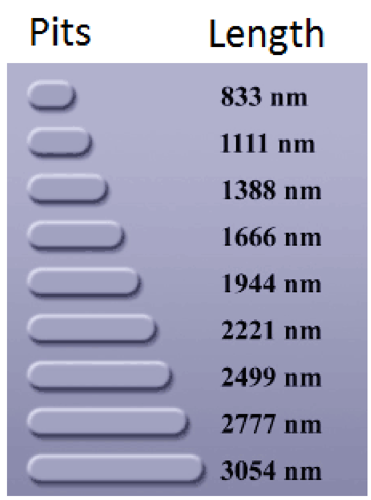

FIG. 7. There are nine possible pit sizes in the distribution. This distribution of sizes comes from the EFM rules enforces on the channel bits.

lands) contain channel bits.

VI. ACCURATE DETERMINATION OF CD DATA

Understanding how data is encoded and read on a CD allowed us to correlate the number of channel bits to the pit/land size. The average pit size was found using Fig. 7 and found

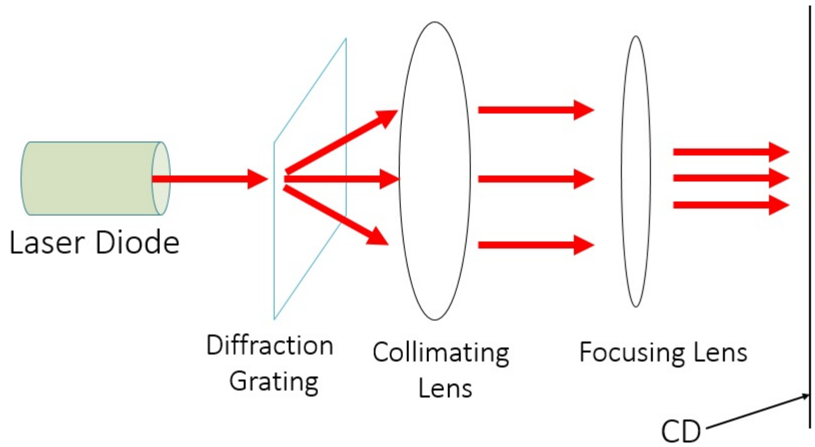

FIG. 8. Laser light is emitted and passed through a diffraction grating creating 0^{th} and 1^{st} diffraction orders. The diffracted light is guided throuhgh a collimating lens and then focused onto the CD. Some optics that guide the reflected light have been omitted in this diagram.

to be $1944nm$. By considering the EFM rules the average number of channel bits was found. These rules ensure a minimum of two $0's$ so adding the $1's$ on each end the minimum amount of channel bits per pit/land is 4. Similarly the maximum amount of $0'$s in a row is 10 so the maximum amount of channel bits per pit/land is 12. The average of the maximum and min is 8. This implies that each pit/land contains 8 channel bits, or 1 byte. Finding the number of pit/lands on a CD provides the number of channel bytes stored on the CD.

The number of pits/lands on the CD was calculated this time using the average pit/land length of $1944nm$. Taking the spiral arc length to be $6004m$, we can simpy divide the arc length by the average pit/land length to obtain the number of features on a CD. Since each feature is equivalent to 1 byte, the number of features is equal to the number of bytes. Taking into account the EFM conversion we multiply the number of features by $^8/_17$ in order to convert from channel bits to computer bits. Preliminary calculations gave a storage of $713MB$. This value differs from the known by only 1.8%! However, going through the calculation again there was a factor of two that could be unaccounted for. Without this factor of two the storage capacity differs from known by 50%. It seems unlikely that this factor of two is unphysical, unfortunately at this time we cannot provide a reason for why this factor should be included.

VII. CONCLUSION

The storage capacity of a CD was determined by observing the diffraction pattern resulting from laser light interacting with the groves of the CD. The storage capcity of a CD was determined first by a model that proved too by too simplistic and only gave a rough estimate of the storage capacity. Looking at the EFM storage method and NRTI reading scheme a more accurate model was used. Though there appears to be an unaccounted for factor of 2, using an improved CD model yielded a storage capacity that differs from known by 1.8%.

A. References

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