Application of the princples of Diffraction

# Determination of the track spacing on optical disks by usage as reflection gratings.

*Author:*
Cori Dion Haws (27570274)

School of Physics and Astronomy
University of Southampton

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**Abstract**

The track spacing, also known as track pitch, of several different types of optical storage media has been determined using lasers of differing wavelengths by exploiting the physical structure of the discs, and the fact that their data layers are similar to that of standard diffraction gratings. The resulting interference pattern has been used to calculate the track spacing when coherent light of a known wavelength is used.

The track spacing of a CD (Compact Disc) was found to be $1.6\mu m$, a DVD (Digital Versatile Disc) was $0.74\mu m$, and for a BD (Blu-ray Disc) was $0.31\mu m$.

# Contents

# 1 Introduction

It has been noted by many that upon looking at CD in white light that at certain angles the reflected light is split up into its component colours and a rainbow is visible. This is an example of the phenomena of diffraction. The rainbow pattern is caused by the fact that light is "bent" by varying amounts depending on its wavelength. This diffraction pattern is somewhat complicated and would seem apparently useless and have little significance. This is very much the case when a non-directed white light source is used, however, this diffraction can be in fact very useful when a slit of directed light is used. Even more so when this light is monochromatic and coherent.

Diffraction of non-directed white light incident on a CD

This report highlights how the principles of diffraction and the grating equation can be applied to determine properties of highly regular systems such as those in optical storage media, and how it can be used to measure the spacing of data tracks.

## 1.1 Introduction to Optical Discs

Optical storage media such as the CD, DVD and BD are several of the many ways of storing binary data. Data is read off of the disc by use of lasers of wavelengths which vary depending on the disc type.

They are primarily made of several layers of material; a thin layer of aluminium, or silver oxide, to which data is stored; and a pair of polycarbonate disks that are 12cm in diameter which acts as the backbone and as protection to the data-layer(s) which is sandwiched in-between. There may well also be additional layers such a sticker for labelling purposes. For the case of dual layer discs, there will be an additional data layer which is partially reflective placed in-front, on the side which is closest to the reading laser, of the fully reflective data layer. These would be held together with an adhesive [Byers, 2003].

Ridges are physically stamped using a pressing machine (dual layer) or burned/etched by the use of a high power laser, onto the data-layer (single layer) [Bennett, 2003] and [Bennett, 2004].

These ridges form part of a continuous track which spirals from centre to the outside (this allows for discs to be smaller than 12cm, at the cost of storage capacity).

Due to the spiralling track, ridges are positioned adjacent to each other with equal spacing and so when light is shone onto the surface of a disk, the reflected light exhibits properties similar to that of light directed through a diffraction grating, namely interference.

Making use of the known properties of standard diffraction gratings, it is possible to determine some properties of the disk such as the track spacing, that is the spacing between adjacent ridges.

# 2 Principles and Theory

Diffraction is a phenomenon which is observed when waves interact with obstacles, and it is the apparent spreading out of a wavefront caused by interference according to the Huygens-Fresnel principle. The obstacle(s) and the properties of the wave itself ultimately characterise the diffraction observed with maximum diffraction occurring when obstacles are separated by a distance equivalent to the wavelength.

In the case of light and of many obstacles, such as the ridges in a diffraction grating, there are many points of diffraction, which results in the superposition of many wavefronts. This superposition results in constructive and destructive interference, and thus there are periodic regions or "fringes" of high intensity (maxima) and low intensity (minima) light which are observed.

The position of these fringes are characterised by the grating equation

$$d(sin(\theta_r) - sin(\theta_i)) = m\lambda \quad m = 0, 1, 2, 3 \tag{1}$$

where $d$ is the distance between adjacent ridges, $\theta_r$ and $\theta_i$ are the angles of reflection and incidence respectively from the normal of the grating, $\lambda$ is the wavelength, and $m$ is a integer number corresponding to the order of the fringe in question, with $m = 0$ the central fringe or the expected specular reflection from the plane of the grating. [Hecht, 1987]

This is derived by the fact that for there to be a maximum the superposing waves must be in-phase, and so the path difference of light incident on two adjacent ridges of the grating must be equal to an integer number of wavelengths. A full derivation can be found in Appendix A.

As the tracks on optical discs' data-layers form the ridges of a simple diffraction grating, the same principles can be applied to find the track spacing, $d$ in the grating equation.

# 3 Experimental Set-up and Methods

## 3.1 Wavelength of Lasers

As per Equation. 1 it is important to know the wavelength of light which is incident on the disc. In order to calculate this, we can use Equation. 1 with a grating of known $d$. We will use LP vinyl to do this.

Due to the way music is encoded onto LPs, a section of the music of low amplitude will result in tracks with the smallest separation and with approximately equal spacing. To aid in this a Mozart symphony was chosen. Once a section of uniform spacing is identified by eye, a travelling microscope with a vernier scale is used to measure 40 adjacent tracks. The mean track spacing is then calculated and is used for the $d$.

A manufactured diffraction grating would provide more accurate results due to being more uniform than an LP and higher resolution(more maxima observable due to reduced diffraction angles) as there are significantly more ridges per unit length.

The vinyl is then positioned at the midpoint of the laser which the wavelength is to be determined and a screen which the diffraction pattern will be observed and the positions maxima will be measured.

The laser light is directed onto the vinyl section and is reflected onto the screen like shown in Fig. 1. The $sin(\theta_i)$ and $sin(\theta_r)$ are calculated using trigonometry by first finding $tan(\theta_i)$ and $tan(\theta_r)$, by either measuring the distance of the laser from the disc and the height of the laser for $tan(\theta_i)$, or by measuring the distance of the disc from the screen and the height of the maximum on the forward screen for $tan(\theta_r)$. In some cases, the light will be reflected at an angle such that the maximum is on the top or rear screens which will require a revised method.

Any difficulty in calculating these values can be overcome by setting up a coordinate system and taking measurements in a reference to those coordinates. Measurement of these coordinates is the primary source of error in this method, however, it should be possible to measure these distances to $\pm 1mm$, so this error will not be significant when propagated. As the fringes produced are not always well defined there will also be some uncertainty due to this.

Using the following rearrangement of Equation. 1

$$sin(\theta_r) = \lambda\left(\frac{m}{d}\right) + sin(\theta_i) \tag{2}$$

the wavelength of the laser can be determined as the gradient of the fitted solution of the plot of $sin(\theta_r)$ against $\frac{n}{d}$. There are other rearrangements of Equation. 1, however Equation. 2 does not require explicit measurement of $sin(\theta_i)$ as it can be determined from a fitted solution to the data. Though, $sin(\theta_i)$ can be easily measured, again with trigonometry, and using this rearrangement allows for additional error analysis.

### 3.2 Track Spacing of Optical Discs

The track spacing of the discs is determined using the same method and setup that is shown in Fig. 1 however a different rearrangement of Equation. 1 is subsequently used. As the wavelength of the laser is now known, we are able to use:

$$sin(\theta_r) = \left(\frac{1}{d}\right) m\lambda + sin(\theta_i) \tag{3}$$

The track spacing is determined by the reciprocal of the gradient of the fitted solution to the plot of $sin(\theta_r)$ against $m\lambda$.

It is to be expected that as the track spacing on the discs decreases that it will be increasingly more difficult to take large datasets for high angles of the diffracted light, as these beams will be of extremely low intensity and so are not well define or not visible.

In these cases, it will be important to ensure that multiple smaller datasets are taken so that statistical analysis can be carried out to reduce uncertainties in the measurement of the track spacing.

### 3.3 Diagrams

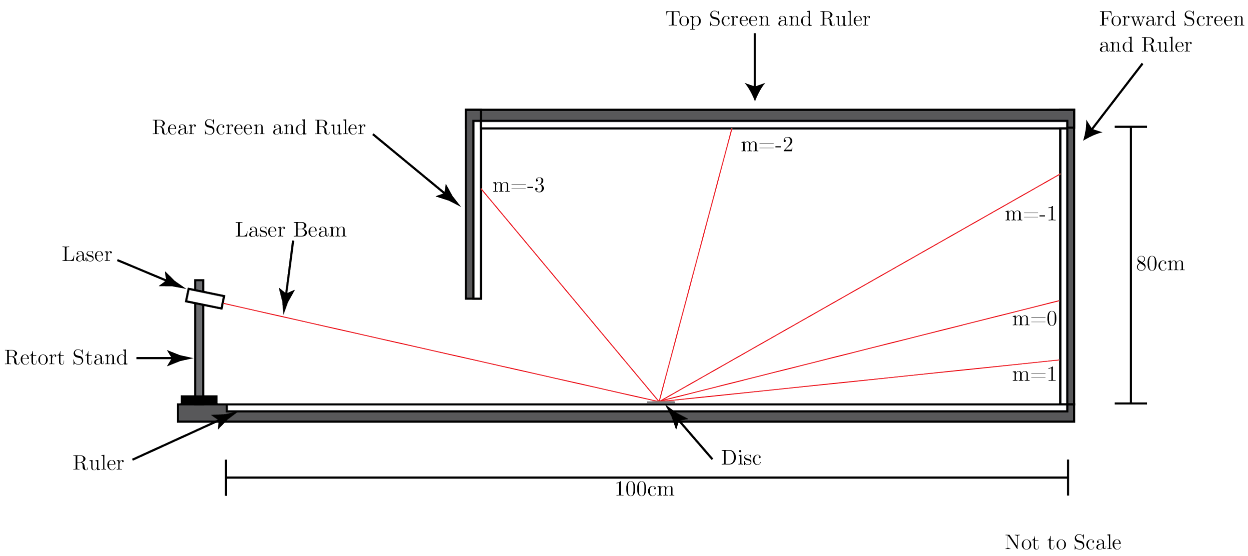



Figure 1: Diagram of experimental set-up with approximate dimensions and examples of positions of several orders of diffraction fringes. The fringes are ordered sequentially and such that for when $sin(\theta_r) < sin(\theta_i)$ the orders are negative.

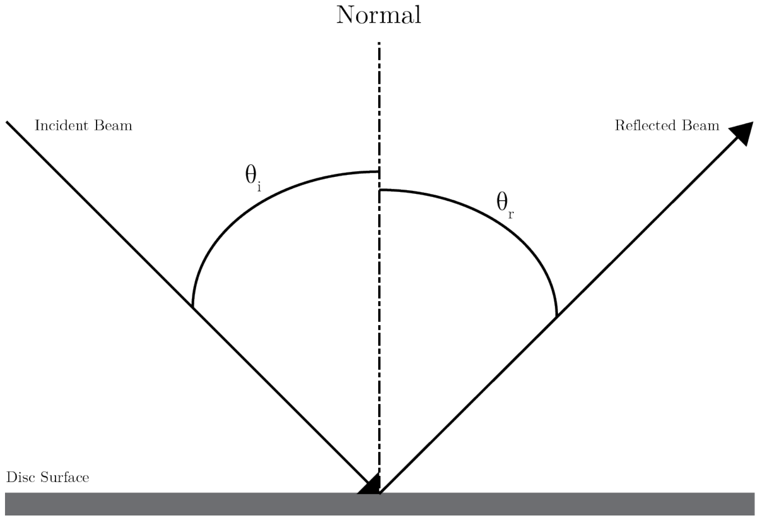



Figure 2: The angles required are those that are measured from the normal to the surface of the diffraction grating. I.e the surface of the disc.

# 4 Results and Discussion

## 4.1 Wavelength of Lasers

In this experiment Thorlabs manufactured Semiconductor Diode lasers that emit coherent red and green light were used. In the case of the red laser, the fitted solution shown in Fig. 3 gives a value of $645nm \pm 3nm$. The Adj. R-Squared value indicates that the data fits the solution well. The intercept of the solution is also within the uncertainty calculated for $sin(\theta_i)$.

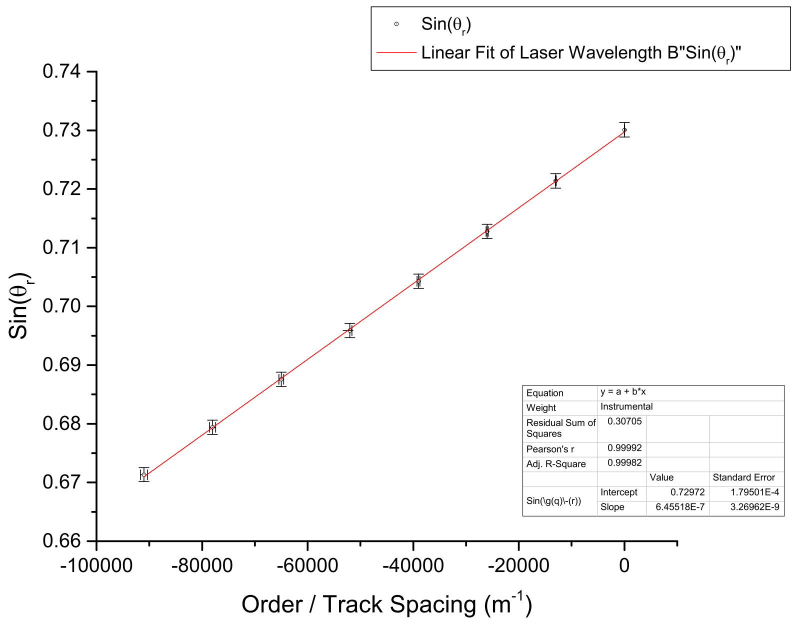



Figure 3: Linear fit of Equation. 2 that allows the wavelength of the red laser to be determined to be $645nm$

For the green laser, the fitted solution shown in Fig. 4 gives a value of $536nm \pm 3nm$. As with the Red laser the Adj. R-Squared value indicates a strong fit and the intercept is within the uncertainty of $sin(\theta_i)$.

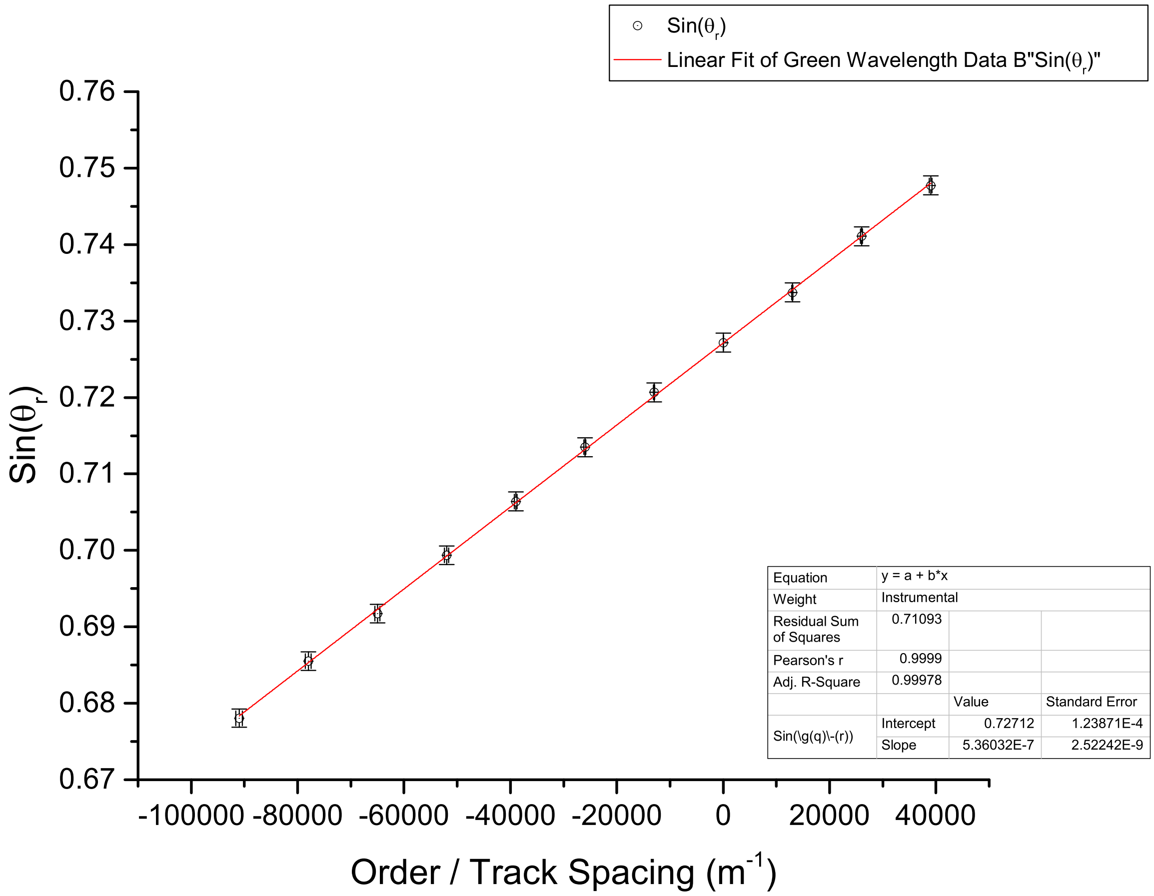



Figure 4: Linear fit of Equation. 2 that allows the wavelength of the green laser to be determined to be $536nm$

The wavelengths calculated for both are typical of lasers of these colours.

## 4.2 CD Track Spacing

With the wavelengths of the lasers now known we can determine the track spacing.

Using the red laser the track spacing of the CD is found in Fig. 5 to be $1.560\mu m \pm 3nm$. The intercepts are within the calculated uncertainties for $sin(\theta_i)$.

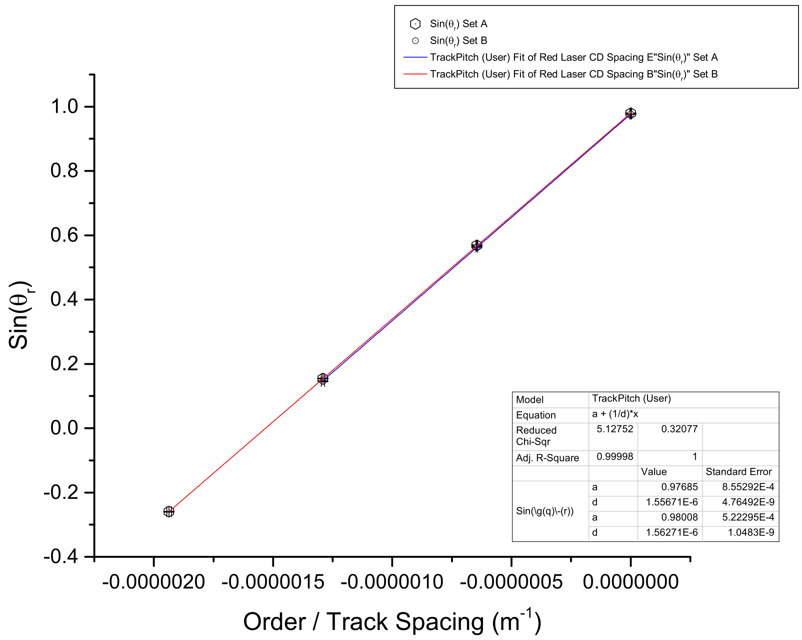



Figure 5: Linear fit of Equation. 3 that allows the track spacing of the CD by use of the red laser to be determined to be $1.560\mu m$

Using the green laser the track spacing of the CD is found in Fig. 6 to be $1.572\mu m \pm 8nm$. Out of the two data sets, both give similar values for the track separation, however dataset A has an intercept which is outside of the uncertainties calculated for $sin(\theta_i)$. This is likely to be due to human error in measuring the distance of the laser or the height of the laser, and the data represents the actual value of $sin(\theta_i)$.

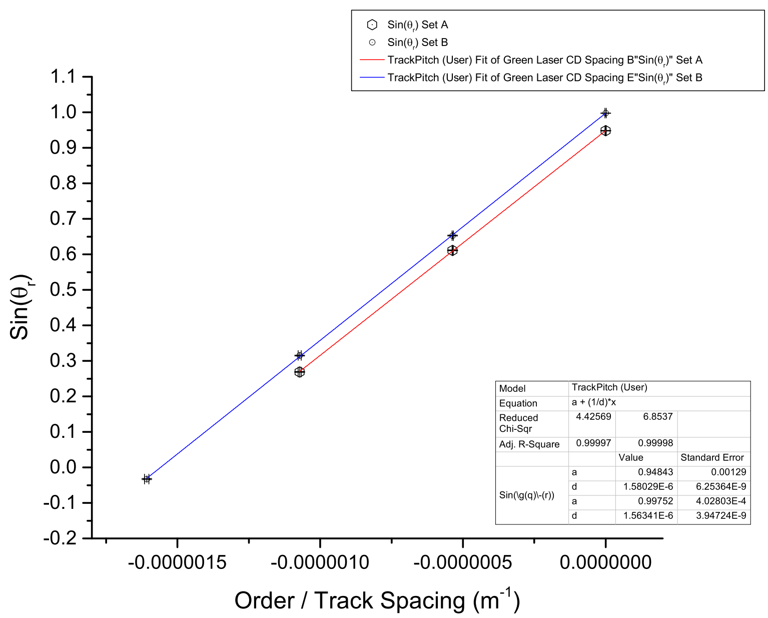



Figure 6: Linear fit of Equation. 3 that allows the track spacing of the CD by use of the green laser to be determined to be $1.572\mu m$

For both lasers, the fitted solutions have a good Adj. R-Squared value so the solutions are representative of the data.

The track spacing of the CD is so found to be $1.566\mu m \pm 5nm$. The mean average of all the data sets and the standard error of this.

## 4.3 DVD Track Spacing

Using the red laser the track spacing of the DVD is found in Fig. 7 to be $0.76\mu m$. However, due to the wavelength of the red laser, it was only possible to see two of the refracted orders which reduces any fitting on a graph to be the joining of the two data points.

It is not possible to derive any meaningful uncertainty from this and this makes the Adj. R-Squared value irrelevant. Ideally, multiple datasets should have been taken, so statistical analysis could have been carried out.

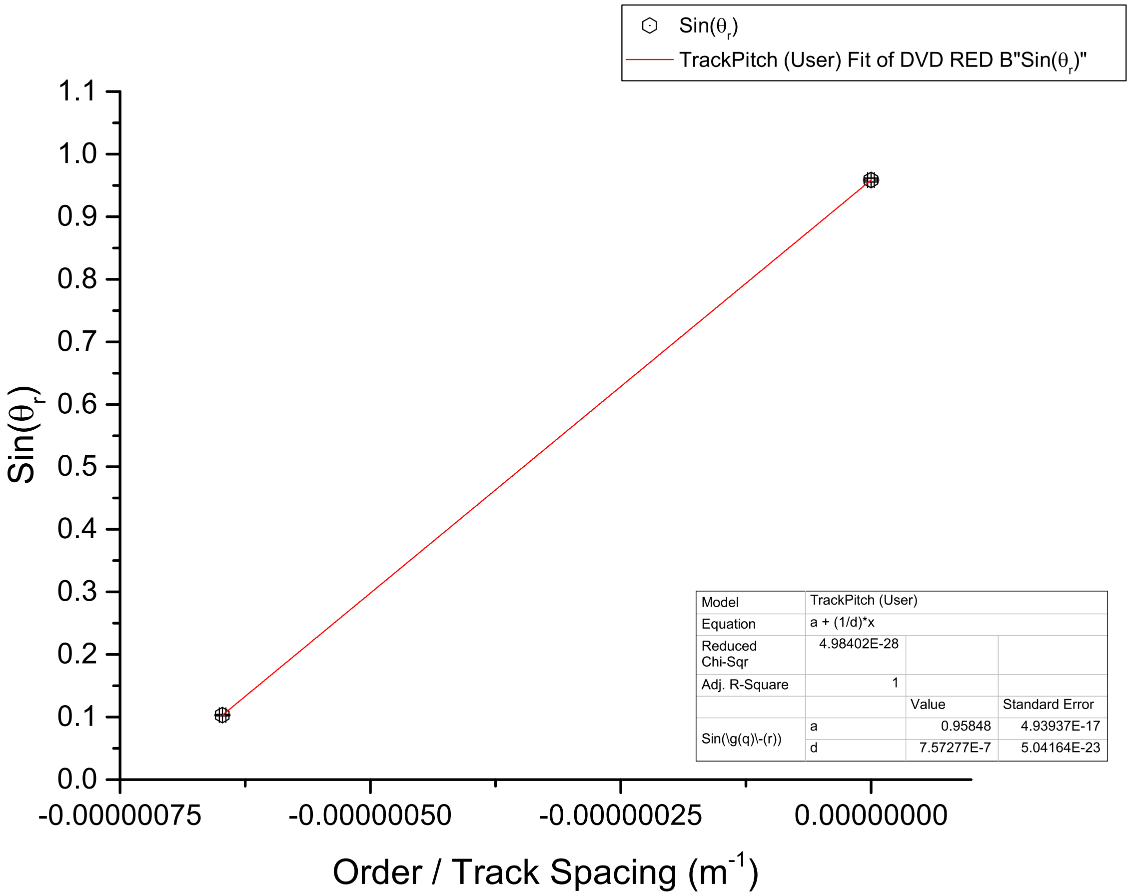
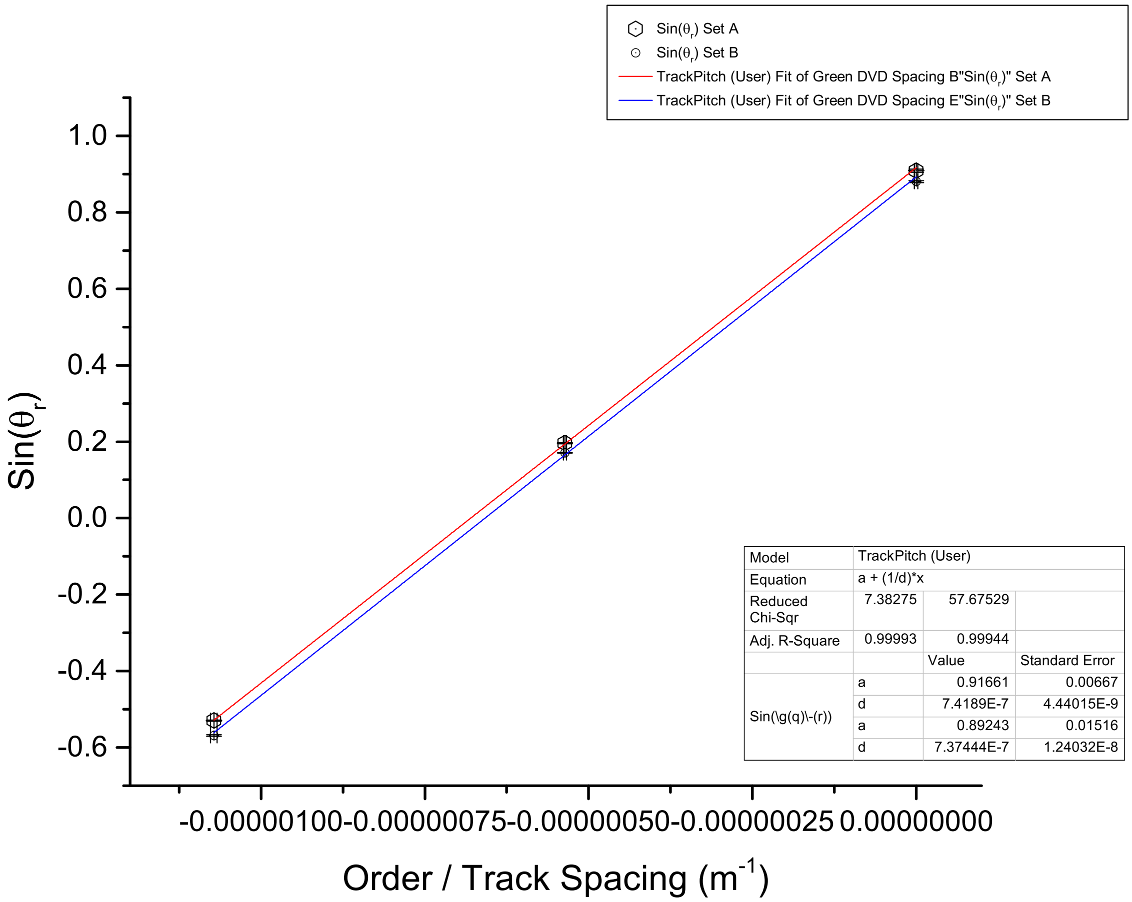



Figure 7: Linear fit of Equation. 3 that allows the track spacing of the DVD by use of the red laser to be determined to be $0.76\mu m$

Using the green laser the track spacing of the DVD is found in Fig . 8 to be $0.740\mu m \pm 2nm$. This is the mean average and standard error of the two datasets. The Adj. R-Square values of the datasets are good and the intercepts fall within the uncertainties of the calculated $sin(\theta_i)$.




| Model | TrackPitch (User) | | |
|---|---|---|---|
| Equation | a + (1/d)*x | | |
| Reduced Chi-Sqr | 7.38275 | 57.67529 | |
| Adj. R-Square | 0.99993 | 0.99944 | |
| | | Value | Standard Error |
| Sin(\g(q)\-(r)) | a | 0.91661 | 0.00667 |
| | d | 7.4189E-7 | 4.44015E-9 |
| | a | 0.89243 | 0.01516 |
| | d | 7.37444E-7 | 1.24032E-8 |

Figure 8: Linear fit of Equation. 3 that allows the track spacing of the DVD by use of the green laser to be determined to be $0.740\mu m$

Moving on to the Blu-ray disc, only the green laser was used as like before, with the red laser and the DVD, the angles of diffraction were significant enough that only the expected reflection, $m = 0$, was observable.

### 4.4 Blu-ray Disc Track Spacing

Even the green laser was experiencing high diffraction angles and only two data points were obtainable. To improve the reliability of the calculated spacing like before, three data sets were collected and the mean average and standard errors were used.

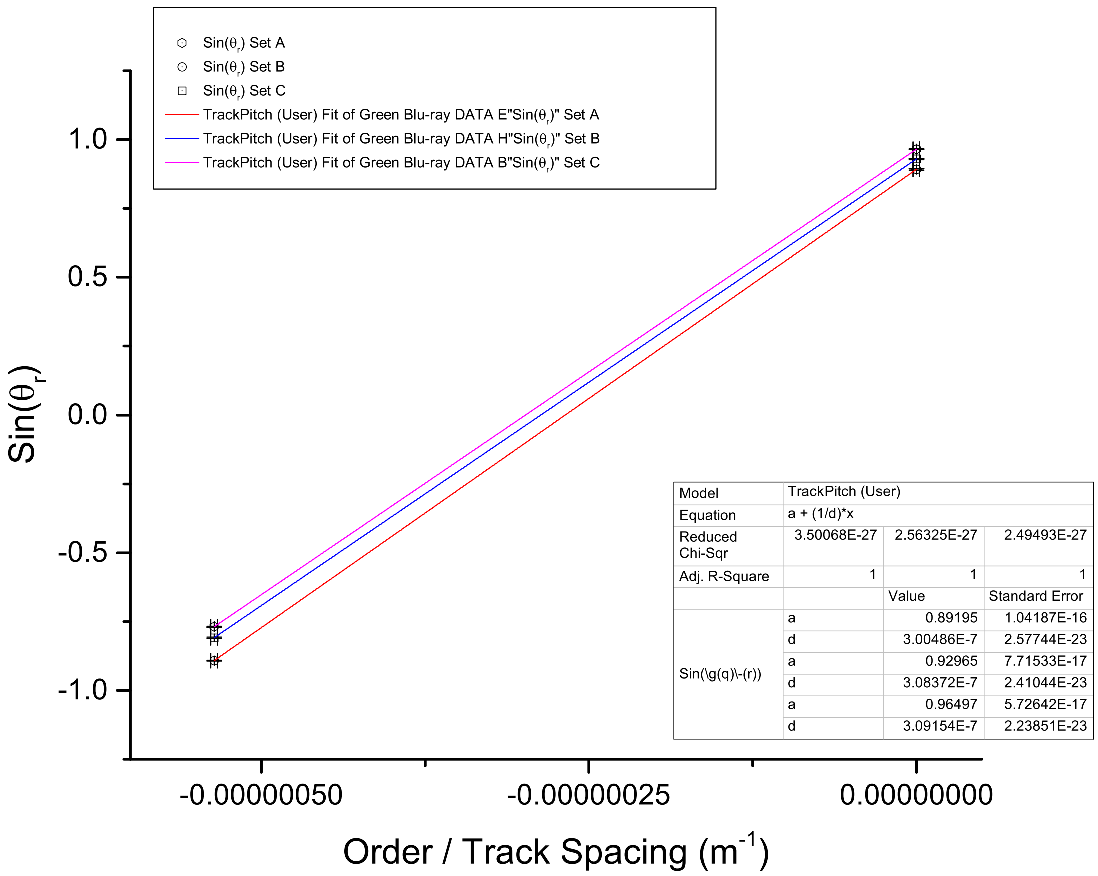



Figure 9: Linear fit of Equation. 3 that allows the track spacing of the BD by use of the green laser to be determined to be $0.306\mu m$

It is found in Fig. 9 that the track spacing of the Blu-ray disc is $0.306\mu m \pm 3nm$

## 5 Conclusion

The track spacings of CDs, DVDs, and BDs have been determined to be $1.566\mu m \pm 5nm$, $0.740\mu m \pm 2nm$, and $0.306\mu m \pm 3nm$ respectively as measured by use of the diffraction of light incident on the discs' surface. This method has been calculated to have give uncertainties less than $\pm 10nm$.

Comparison of the calculated values of the track spacing in this experiment to that of the expected values, $1.6\mu m$, $0.74\mu m$, and $0.32\mu m$ [Waser, 2012], indicate that the method undertaken in this report yielded results which are within 2.5%, for the CD, and within 5%, for the BD, of the expected values.

These uncertainties could be reduced practically by using lasers of smaller wavelength, for example, a violet laser with a wavelength of $405nm$. With this, the reflected angles of diffracted light would be reduced allowing for more readings to be taken.

A separate and unrelated method to measuring the track spacing would be the use of Scanning Electron Microscopy(SEM), which would yield results with uncertainties negligible which are due to fundamental limits such as those defined by the uncertainty principle.

Usage of the data presented in this report has potential application in calculating other properties of optical discs such as capacity and data density.

## References

[Bennett, 2003] Bennett, H. (2003). Disc construction and manufacturing. In *Understanding CD-R & CD-RW*, pages 36–38. Optical Storage Technology Association, 1st edition.

[Bennett, 2004] Bennett, H. (2004). Disc construction and manufacturing. In *Understanding Recordable & Rewritable DVD*, pages 32–34. Optical Storage Technology Association, 1st edition.

[Byers, 2003] Byers, F. R. (2003). Disc structure. In *Care and Handling of CDs and DVDs*, chapter 3, pages 5–12. Council on Library and Information Resources.

[Hecht, 1987] Hecht, E. (1987). The diffraction grating. In *Optics*, chapter 10.2.7. Addison-Wesley, 2nd edition.

[Waser, 2012] Waser, R. (2012). *Nanoelectronics and Information Technology*, page 617. Wiley-VCH, 3rd edition.

# A Derivation of the Grating Equation

Take a diffraction grating which comprises two ridges like in Fig.10. If two parallel and in phase light waves are incident on the grating $d$ apart. The path difference of the waves is the difference of the distance wave 2 travels after wave 1 is reflected before being reflected itself and the distance wave 1 travels after being reflected before wave 2 is reflected. Simply put, $AC - BD$, which by simple trigonometry is equal to $d(sin(\theta_r) - sin(\theta_i))$.

The principle of superposition and constructive interference implies that the reflected waves must be in phase where a maximum is observed. For the waves to be in phase the path difference of the two light waves must be equal to an integer number of wavelengths.

These relationships are expressed in the grating equation, Equation. 1.

As it is largely uncommon to have only two waves of light incident on a diffraction grating at one time, the collective interference of many waves of light results in the diffraction pattern observed.

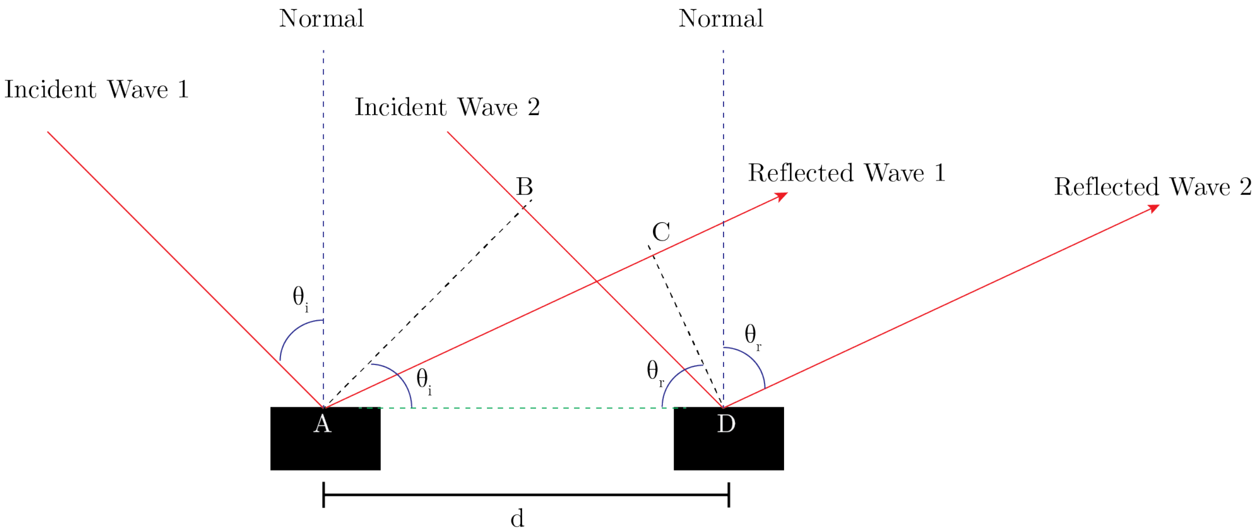



Figure 10: Diagram of the paths of two parallel and in-phase waves of light incident on simple diffraction grating.