Extended Abstract of Diffraction on Optical Disks

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Incident light on an optical disk produces a distinct bright line on its surface, with the line's characteristics influenced by the relative orientations of the light source, the optical disk, and the observer. While this phenomenon is commonly observed and discussed, prior research presents incorrect underlying principles. This study employs the Fraunhofer diffraction framework to investigate the underlying physics of the observed single line and to precisely quantify its position, color, and geometry. The developed theoretical model demonstrates excellent agreement with experimental data from both spectrometry and color comparisons between digitally reproduced simulations and directly observed colors.

I. INTRODUCTION

Due to the micro-scale data track lining the surface of optical disks (CD with the pitch $1.6\mu m$ and DVD with $0.74nm$), any incident light rays undergo diffraction. This is the reason why the bottom sides of the disks always illuminate with rainbow-like colors. Moreover, when the light source reduces to a point (i.e. a filament lamp), the line magically reduces into a single colorful line.

FIG. 1. Clear lines are visible when the line from a filament lamp is incident on the surface of optical disks. On the left is the phenomenon observed on a CD, and on the right is a DVD.

Despite the ubiquity, however, a common misconception is held about the position of the line. The paper published by De Luca et al.[1] argues that the line forms at the angle bisector between the light source and the observer due to a reflection that occurs in the direction parallel to the alignment of the grating. However, this argument is invalid since simple diffraction does not occur in the specified direction. Due to the dispersion relation, the diffracted light takes a more complicated geometry, which depends on the order of diffraction of the ray in question. The result is that the line takes the shape of a curve, whose geometry and position depend on many parameters.

In this light, the main aim of this research is (1) to provide a theoretical framework that accurately predicts the geometry, position, and, additionally, the color of the observed line; and (2) to validate the physical principles that lead to the creation of a peculiarly single line.

II. THEORETICAL ANALYSIS

For all practical purposes, the pitch between two adjacent data tracks is negligible compared to the distance to the light source. Therefore, the linear model of Fraunhofer diffraction had been employed. The system was characterized by a spherical coordinate system, as shown in fig 2.

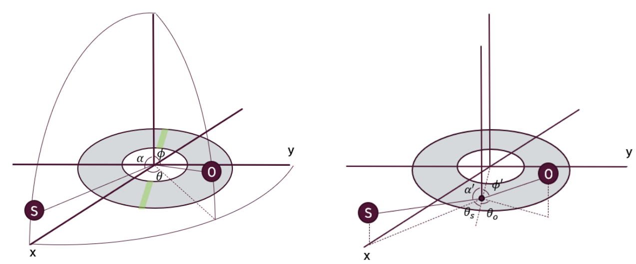

FIG. 2. Coordinate System. O represents the observer, and S represents the light source.

The complex amplitude of light arriving at the observer consists of two contributions: one from the data tracks, and another from the lands (pits between consecutive data tracks).

$$U = U_o \iint_{\text{track}} e^{-i\left(\widetilde{k_x}x+\widetilde{k_y}y\right)}dxdy + U_o e^{in_{pc}k\Delta OPL} \iint_{\text{land}} e^{-i\left(\widetilde{k_x}x+\widetilde{k_y}y\right)}dxdy \tag{1}$$

$\widetilde{k_x}$ and $\widetilde{k_y}$represent the difference in the wave vector component between the reflected and incident rays along x and y axes, respectively. Since the track and land are necessarily square waves, evaluating the Fourier integral results in diffraction.

$$I = I_o \frac{\sin^2\left(\frac{N}{2}\widetilde{k_x}\Lambda\right)}{\sin^2\left(\frac{1}{2}\widetilde{k_x}\Lambda\right)} D(\alpha', \phi', \theta_o, \theta_s)\delta(\widetilde{k_y}) \tag{2}$$

where I_0 stands for the initial spectral power distribution of the filament lamp, and $\frac{\sin^2\left(\frac{N}{2}\widetilde{k_x}\Lambda\right)}{\sin^2\left(\frac{1}{2}\widetilde{k_x}\Lambda\right)}$ accounts for the discrete diffraction orders. $\delta(\widetilde{k_y})$ is responsible for the formation of a singular line, and $D(\alpha', \phi', \theta_o, \theta_s)$ is the diffraction envelope, given as follows:

$$D(\alpha', \phi', \theta_o, \theta_s) = w^2 \mathrm{sinc}^2\left(\frac{\widetilde{k_x}}{2} w\right) + (\Lambda - w)^2\, \mathrm{sinc}^2\left(\frac{\widetilde{k_x}}{2}(\Lambda - w)\right)$$
$$+2w\,(\Lambda - w)\, \mathrm{sinc}^2\left(\frac{\widetilde{k_x}}{2} w\right) \mathrm{sinc}^2\left(\frac{\widetilde{k_x}}{2}(\Lambda - w)\right) \cos\left(\frac{\widetilde{k_x}}{2}\Lambda - n_{pc} k \Delta OPL\right). \tag{3}$$

III. EXPERIMENTS AND RESULTS

A. Position of the Line

First, the predicted position of the line $\left(\delta(\widetilde{k_y}) = 0\right)$ had been premarked on the disk, and directly compared with the observed position.

FIG. 3. Photographs obtained by varying θ between 45° (left) and 135° (right). The premarked position of the line was highlighted with a red line for visibility. $r_s = 70cm$, $\alpha = 83.5°$, $r_o = 23cm$, and $\phi = 38°$.

All of the observed lines virtually coincided with the theoretically predicted position. It could be concluded that the above theoretical model is valid for predicting the position of the line.

B. Spectrometry of the Light

Second, using a spectrometer, the predicted peak wavelengths were compared with the theoretically predicted peaks.

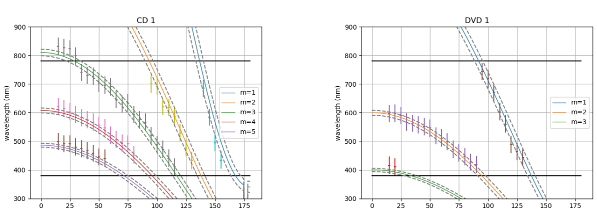

FIG. 4. Spectrometry of the CD and the DVD. $r_s = 70cm$, $\alpha = 83.5°$, $r_o = 23cm$, $\phi = 38°$, and θ was varied from 15° and 180° with 5° intervals.

Each colored line on the graph denotes the predicted peak wavelength per θ, and the grey lines that surround each colored line represent the minimum and maximum wavelengths, allowing error bounds.

The y-axis error bar on the data points reflects the error rate in wavelength measurement reported by the spectrometer manufacturer, and the x-axis error bar the uncertainty in the angle measurement of θ (1°). As the graphs show, the predicted peaks were well within the error bound.

C. Visual Comparison of the Color

Last, the color predicted by formula 2 was digitally converted to the sRGB colorspace, and was visually compared to the actually observed color.

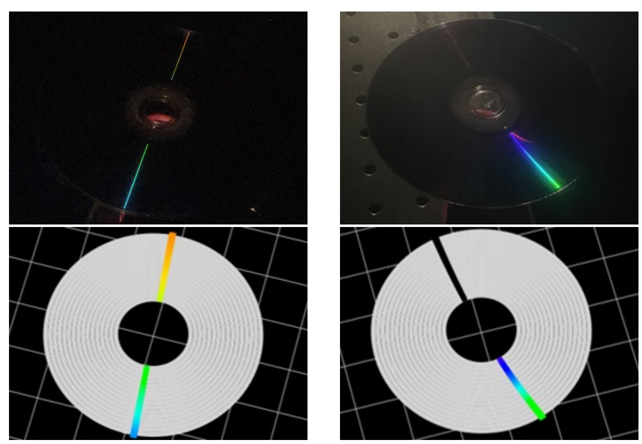

FIG. 5. Comparison between the colors on real DVD-R (top) and simulated (bottom). $r_s = 70cm$, $\alpha = 83.5°$, $r_o = 30cm$, $\phi = 29°$, and θ was varied between 15° (left) and 165° (right).

Considering the sensitivity of the peak wavelength with respect to slight variations in the position of the camera, some minor errors are present. Plus, because the RGB value of each pixel had been independently normalized to the range $[0, 1]$, the simulation fails to reflect the relative intensities between different sections of the line. Nevertheless, the simulated color shows great agreement with what was observed.

IV. CONCLUSION

This paper (1) proposed a new theoretical model based on Fraunhofer diffraction that accurately (as experimentally verified) predicts the geometry, position, and color of the line. This paper also (2) elucidated the physical causes that create a single colored line on the surface of an optical disk when light is incident. It occurs due to the $\delta(\widetilde{k_y})$ term that appears upon computing the Fraunhofer diffraction formula, which makes the observed intensity vanish everywhere except where $\widetilde{k_y} = 0$, or $\sin(\alpha')\sin(\theta_s) = \sin(\phi')\sin(\theta_o)$.

Due to the limited space, only a select few example data had been presented in this synopsis. The full paper and supplementary materials, especially video-based color simulations and comparisons, may be found on my personal `GitHub` repository [2].

[1] R. De Luca, M. Di Mauro, O. Fiore, and A. Naddeo, A compact disc under skimming light rays, American Journal of Physics **86**, 169 (2018).

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