Colored Line

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ABSTRACT

This problem states that when a compact disc or DVD is illuminated with light from a filament lamp in such a way that only rays with large angles of incidence are selected, a clear green line can be observed. The color of the line varies slightly when the angle of incidence is changed. The solution presented in this paper is based on analyzing the diffraction effects caused by the disc's structure and developing the geometrical characteristics of the colored line formed, as well as its dependencies on relevant parameters.

Keywords : : Colored line, Diffraction, filament lamp, Compact Disc

1. Introduction

1.1. Problem Statement

Based on the problem statement, it is evident that the lighting angle, the color of the line formed, and the disc inclination are crucial parameters. Additionally, the use of a filament lamp for illumination is recommended since the light spectrum it emits (Fig.1) covers the entire visible spectrum more uniformly than the spectrum produced by other light sources like LEDs.

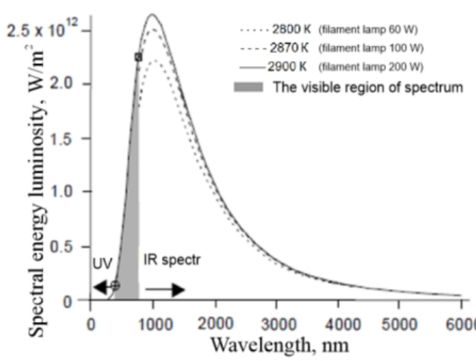

Fig. 1: Radiation spectrum of incandescent lamps with different power. Sidorenko, Alexey & Tupikina, Nadezhda & Sergey, Lisakov & Kin, Isa & Sypin, Eugene. (2019)

1.2. Disc Structure

The structure of optical media is based on storing binary information through pits carved in a radial track on one of the disc's layers (track layer). The size of the pits and the distance between the tracks of pits are from the order of one micrometer. A laser reads the alternation between the pits and the plain of the disc and returns binary values (Fig.2).

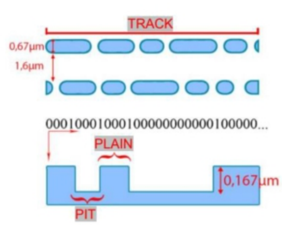

Fig. 2: Structure and reading of information stored on optical media (Author)

2. Theoretical Analysis

2.1. Light-Disc Interface

We can define a model for the interface between the incoming light rays hitting the disc as parallel wavefronts hitting an obstacle (Figs. 3 , 4).

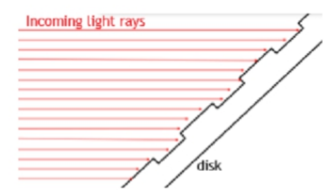

Fig.3: Incoming parallel light rays (Author)

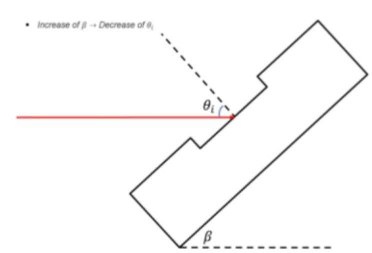

Fig.4: Behavior of angle of incidence with inclination of the disc (Author)

The length of the pits is of the same order of magnitude as the wavelength of light rays. This means that diffraction has a significant effect on the phenomenon of the colored line (Fig. 5).

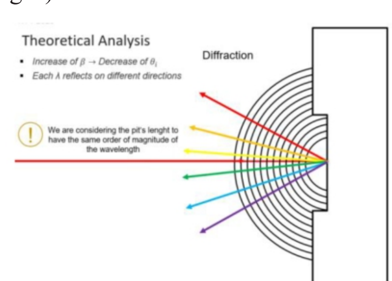

Fig.5: Diffraction effects caused by the pits (Author)

The organization of the pits in tracks leads to the creation of a line through constructive interference between diffracted and reflected light rays. Multiple angles, which are integer multiples of the angle between the light rays and the disc (θ), make different orders of magnitude for this constructive interference and result in the formation of the line (Figs. 6, 7).

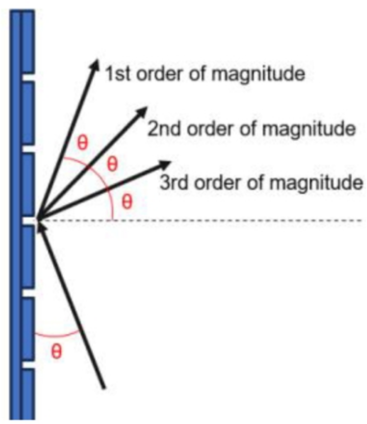

Fig. 6: Different orders of magnitude for an oncoming light ray being diffracted (author)

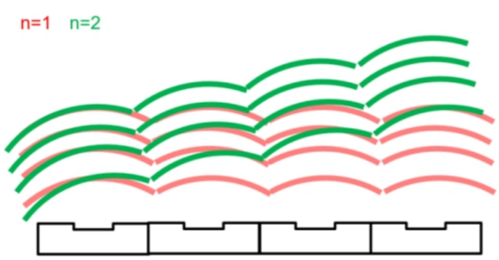

Fig. 7: Different colors (wavelengths) for each order of magnitude n (author)

Since for a single wavefront there may be many orders of magnitude that define constructive interference, for different angles of observation, the color of the colored line may change (Fig. 8).

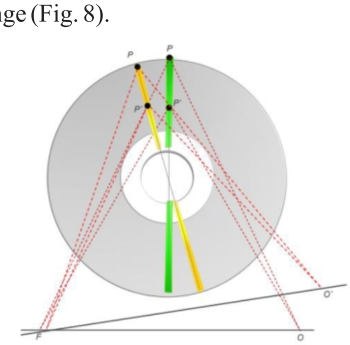

Fig. 8: Different observers obtain different colors for the colored line for the same wavefront (author)

2.2. Geometrical Description

We will initially define some essential characteristics of the discs in relation to the formation of the colored line, such as radius parameters and observational distances (Fig.9).

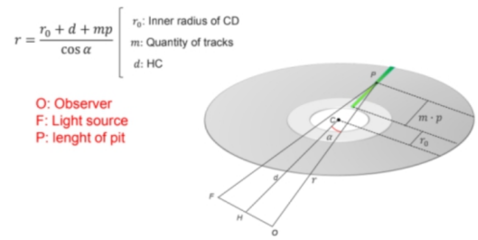

Fig.9: Radius parameters and observational distances (R. De Luca , M. Di Mauro , O. Fiore , and A. Naddeo , Am. J. Phys. 86(3), 169 (2018))

2.3. Physical Description

With the geometrical characteristics of the disc already defined, it is possible to calculate the interference between the electrical fields emitted to the disc and their points of maxima interference (where the colored line is formed) and solve the sets of equations using the vector of Poynting. Electrical fields on CD radius and sum of electrical fields are as written in Eqs. (1, 2).

$$\vec{E}_m = \vec{E}_m \exp(ikr) = \vec{E}_m \exp(ik\frac{r_0 + d + mp}{\cos\alpha}) \tag{1}$$

$$\vec{E} = \vec{E}_0 \exp\left(ik\left(\frac{r_0 + d}{\cos\alpha}\right)\right)\exp(\frac{iNkp}{2\cos\alpha})\frac{\text{sen}\left(\frac{(N+1)kp}{2\cos\alpha}\right)}{\text{sen}\left(\frac{kp}{2\cos\alpha}\right)} \tag{2}$$

The points of maxima interference (intensity of wavefronts) is calculated using the vector of Poynting (Eq. 3).

$$I = S_m = \frac{|E|^2}{\mu c}$$

$$I = \frac{1}{\mu c}|E_0|^2 = \frac{1}{\mu c}\exp\left(2ik\left(\frac{r_0 + d}{\cos\alpha}\right)\right)\exp(\frac{iNkp}{\cos\alpha})\boxed{\frac{\text{sen}^2\left(\frac{(N+1)kp}{2\cos\alpha}\right)}{\text{sen}^2\left(\frac{kp}{2\cos\alpha}\right)}} \tag{3}$$

← Maximize

Does not depend on r

The wavelength of the constructive interference observed at a certain angle will be given by the equation (4). Wavelength of observed colored line (λ) is in function to the number of tracks on the disc (P) and angle (α).

$$\frac{kp}{2\cos\alpha} = n\pi \Rightarrow \quad \lambda_n = \frac{p}{n\cos\alpha} \tag{4}$$

2.4. Geometrical Description – New Parameter

For the inclination of the disc a new parameter will be added (β) (Fig. 10).

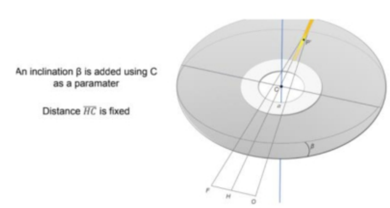

Fig. 10: New parameter added (angle of inclination of disc) (R. De Luca , M. Di Mauro , O. Fiore , and A. Naddeo , Am. J. Phys. 86(3), 169 (2018))

With this new parameter there must be a correction in our previous geometrical model as exemplified in Figure (11).

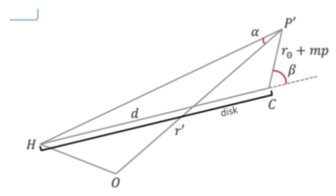

Fig. 11: Geometrical corrections (author)

With this new angle we can add to the (Eq. 4) the correction, where the colored line will suffer an interference in its wavelength according to the angle of inclination of the disc. Correction of wavelength of observed colored line at a certain angle of inclination will give (Eq. 5).

$$\lambda'_n = \frac{p\cos(\beta)}{n\cos(\alpha)} \quad (5)$$

3. Experimental Methodology

3.1. Verifying Assumptions

To verify the assumption that the discs behave as a diffraction grating we used a Scanning Electron Microscope in a collaboration with the Universidade Federal do Cariri laboratories of Materials Engineering (Fig. 12).

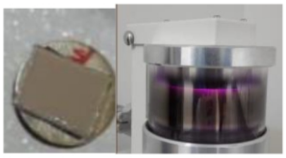

Fig. 12: Preparation of disc sample for analysis in SEM, the sample had to be covered in a thin gold layer using atom transference by plasma (author)

Fig. 13: Sample being inserted inside SEM (Author)

The images obtained show that the distance between the tracks of the disc is in fact from the same order of magnitude as observable light (Fig. 14).

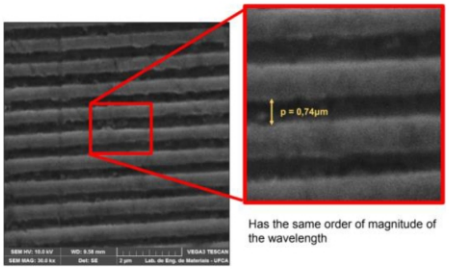

Fig. 14: Results from the SEM analysis (author)

3.2. Experimental Setup

To minimize human error and possible inaccuracies, stands and supports were utilized to provide accuracy in results. For the analysis of the images obtained, computer software Tracker was used (Fig. 15).

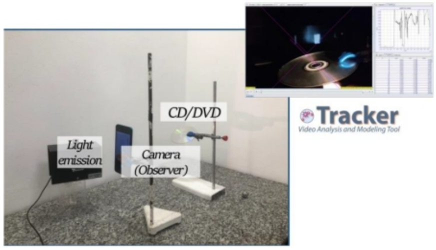

Fig. 15: Experimental setup and software tracker being used in the experimental methodology (author)

4. Experimental Results

4.1. Inaccurate and Unstable Results

Due systemic errors, the images we obtained were too noisy and the colors observed suffered many interference from other light sources (Fig. 16).

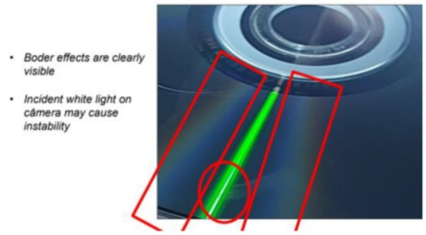

Fig.16: Border effects are seen as well as incident white light (author)

To reduce experimental flaws we isolated the light emitter and used a convex lens to make the incoming light rays parallel (Fig. 17).

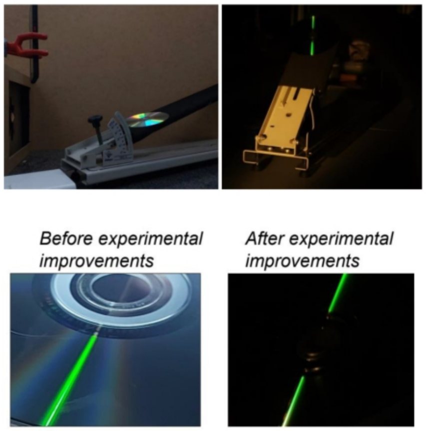

Fig. 17: Experimental setup with improvements (author)

4.2. Wavelength Measurement

The analysis of the wavelength of the colored line was made using a diffraction grating as a spectrometer. By positioning the grating in front of the camera, pointing to lasers with known wavelengths and measuring the distance in pixels of the next point of interference of the lasers we can draw a linear profile between the distance of the interference and the wavelength of the light observed by the camera (Fig. 18).

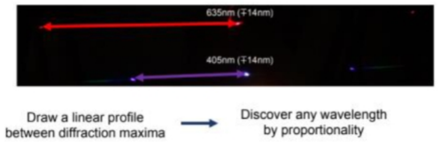

Fig.18: Experimental method for measuring wavelength of observed light (author)

4.3. Observed Results

By changing the angle of inclination of the disc we obtain different wavelengths for the colored line. In the same angle, the diffracted rays will compose a colored line at the points of maxima interference (n) (Fig. 19).

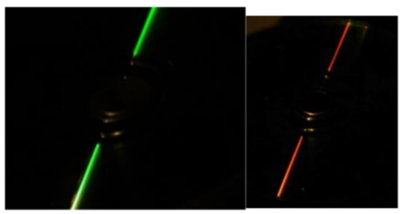

Fig. 19: Colored lines for different angles of inclination (author)

The relation between the wavelength of the colored line and the inclination of the disc fitted our theoretical explanation as shown in Figure (20).

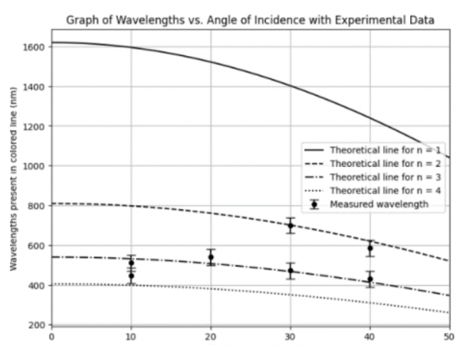

Fig. 20: Angle of inclination of the disc changing the wavelength observed (author) (CDs, p = 1600nm).

Since CDs and DVDs have different distance between tracks, the colored line will have differences in their wavelength at same angle of inclination (Fig. 21).

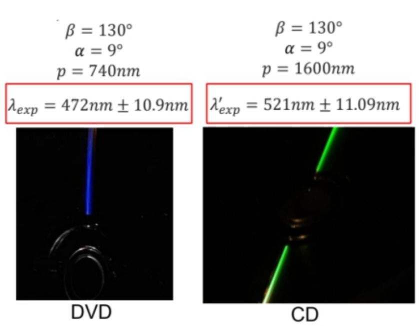

Fig. 21: Different wavelenghts in CD and DVD at same conditions of observation (author)

4.4. Observed Results

At certain angles of inclination, more than one order of magnitude may fit within the observable range. Forming an effect of "false colors". Using a diffraction grating we can separate the wavelengths and measure each one of them individually (Fig. 22).

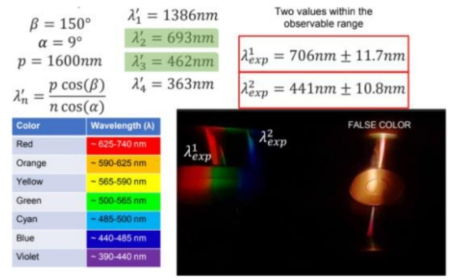

Fig.22: Observed false color of magenta decomposed using a diffraction grating. (author)

5. Conclusions

The problem statement proposes an analysis of the colored line formed on optical media discs and the changing of their colors as the angle of inclination is altered.

This paper proposed such analysis by using theoretical models to predict the behavior of the colored line and followed a rigorous experimental methodology to verify and test assumptions.

We initially assumed the disc to behave as a diffraction grating and later used a Scanning Electron Microscope to verify such an assumption. The white light emitted to the disc suffers diffraction and the diffracted light rays will interfere constructively to compose the colored line stated in the problem.

References

[1] Sidorenko, Alexey & Tupikina, Nadezhda & Sergey, Lisakov & Kin, Isa & Sypin, Eugene. (2019).

[2] R. De Luca , M. Di Mauro , O. Fiore , and A. Naddeo , Am. J. Phys. 86(3), 169 (2018))