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Low-cost measurements of the 'resonant' wavelengths reflected by a compact disc under skimming light rays

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Abstract

We demonstrate the construction and utilization of an affordable apparatus using readily available materials to accurately measure in a quantitative manner the wavelengths reflected by a compact disc (CD) under skimming light rays. In fact, only a limited number of wavelengths can be revealed when light rays from a white lamp are directed at a CD (or a DVD) in a manner that specifically selects the rays that graze the surface of the horizontally held disc. We compare the results with the ones obtained with a commercial spectrometer, finding that they are in good agreement among them and with the theoretical predictions.

Keywords: wave optics, low-cost experiments, spectroscopy

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1. Introduction

Optical spectroscopy is a fundamental technique in physics that allows us to study the interaction of light with matter and which, in the last years, started to play a central role also in physics education research (PER) [1]. Indeed, measurements of optical spectra are particularly engaging for undergraduate students and prospective physics teachers, for example allowing insight into stellar structure and evolution [2]. Traditionally, spectroscopy setups can be expensive and complex, making them less accessible for educational purposes. However, in recent years several inexpensive educational setups were proposed for spectral measurements [3–8]. In these setups, a diffraction transmission grating, which can be obtained inexpensively, is employed to disperse the light into its constituent wavelengths. A simple smartphone camera can then effectively serve as the detection system, capturing the dispersed light and allowing for further processing, based on image analysis [9, 10].

The aim of this work is to report on some quantitative experiments that have been performed to measure the wavelengths reflected by a compact disc (CD) under skimming light rays [11]. In fact, when the CD is exposed to light emitted by a desk lamp, as depicted in figure 1 (left), in a manner where only grazing light rays interact with it, and the CD is held horizontally, a distinct green line becomes visible spanning the surface of the CD. Consequently, the observer should perceive a colored line on the CD, positioned along a direction intermediate to their own location and that of the lamp, as illustrated in figure 1 (right). This line's color alters when the CD is tilted at varying angles. Similarly, a bluish line can be observed if a DVD is used instead. As explained below, these lines result from the fact that light waves reflected from all the different tracks on the disc interfere, and only light with certain resonant wavelengths, which correspond to constructive interference peaks (computed in [11]), reaches the eye after the reflection.

The experiments, which employ a low-cost apparatus, can be carried out in any school or college laboratory, and the resulting data can be easily analyzed. Analogous measurements were performed by using a commercial compact spectrometer AvaSpec-2048$^{\text{TM}}$ [12], confirming and extending the results obtained with the cheaper apparatus. The measured wavelengths were also compared with the ones predicted by theory [11].

2. Theoretical background

As mentioned, the observed effect is due to the interference of the light waves reflected by the different tracks of a CD or a DVD. Constructive interference of the reflected wavelets produces sharp peaks, which can be detected as spectral lines in a spectrometer. Some of these spectral lines correspond to wavelengths falling within the visible spectrum. The information gathered from experimental results and knowledge of the physiology of the human eye can thus allow a correct interpretation of the observed phenomena.

We recall that CDs and DVDs are composed of tracks with a width denoted as a: for a standard CD $a_{\mathrm{CD}} = 1600$ nm, while for a standard DVD $a_{\mathrm{DVD}} = 740$ nm. These widths can also be determined from the experimental data presented in this paper. In [11] (to which we refer for the complete theoretical analysis) it has been shown that when light from a source, emitting over all wavelengths in a spectrum that includes visible light, grazes the surface of the disc (see figure 2), the wavelengths corresponding to the peaks are obtained by the formula:

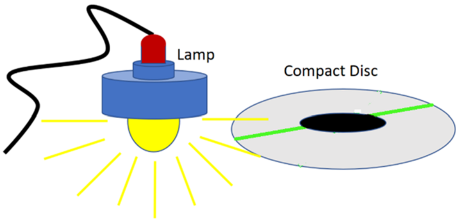

Figure 1. Left: Schematic drawing of the desk lamp emitting light in all directions below its rim. Right: Colored lines visible under skimming light under horizontally held discs: a CD (left) and a DVD (right).

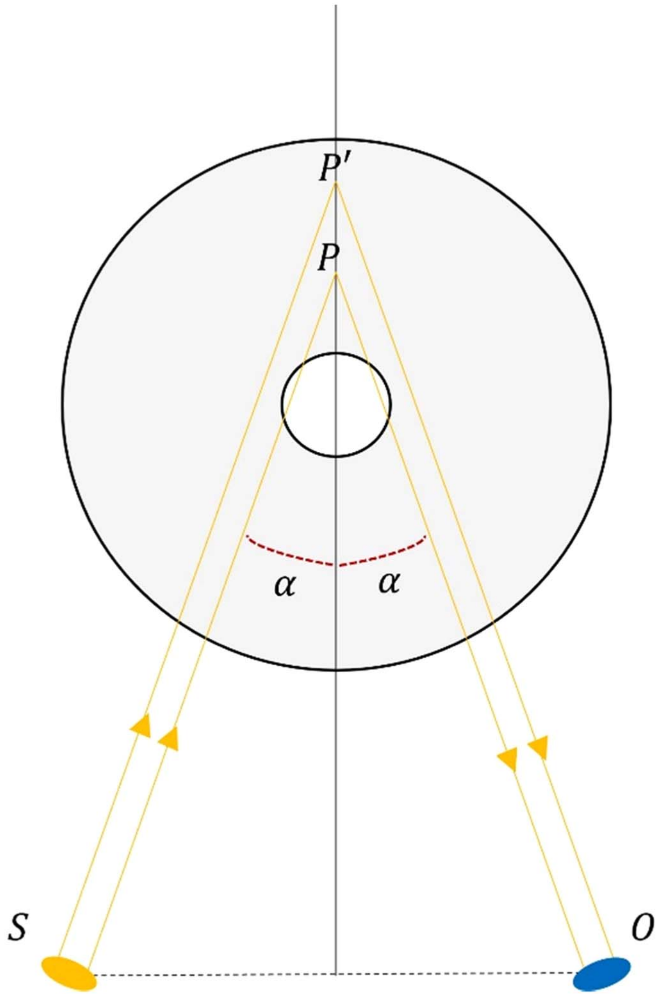

Figure 2. Scheme of the experiment: two parallel light rays coming from the source S are reflected by the CD in two different tracks, passing through the points P and P′, respectively, at an angle α. The reflected rays reach an observer O.

$$\lambda_M = \frac{2a}{M}\cos\alpha, \tag{1}$$

where M is the order of the maximum, and α is half the angle between the lines connecting the light source and the observer with the point where light is reflected. Since this angle is typically very small, its cosine can be approximated to 1. Additionally, as noted in [11], tilting the CD/DVD at an angle β relative to the horizontal plane about an axis which is orthogonal to the line connecting the observer and the CD, the above equation is modified as follows:

$$\lambda'_M = \frac{2a}{M}\cos\alpha\cos\beta. \tag{2}$$

We now compare the experimental results obtained with the above formulas. For a CD, setting $a = a_{\text{CD}} = 1600$ nm and taking $\alpha \approx 0$ in equation (1) we obtain, by direct computation, the following three wavelengths in the visible spectrum (which, we recall, is comprised between 380 and 740 nm):

$$\lambda_5 = \frac{2}{5}a = 640 \text{ nm, (red)} \tag{3a}$$

$$\lambda_6 = \frac{1}{3}a = 533 \text{ nm, (green)} \tag{3b}$$

$$\lambda_7 = \frac{2}{7}a = 457 \text{ nm.(blue)} \tag{3c}$$

By multiplying these values by $\cos\beta$, we can observe how the wavelengths of the peaks decrease as β increases, i.e. when the disc is progressively tilted. This means that it is possible for maxima that were originally in the infrared (IR) range to become visible while maxima that were originally visible may shift to the ultraviolet (UV) range and become invisible.

On the other hand, for a DVD, setting $a = a_{\text{DVD}} = 740$ nm and considering again $\alpha \approx 0$, equation (4) gives the following visible frequencies:

$$\lambda_2 = a_{DVD} = 740 \text{ nm, (red)} \tag{4a}$$

$$\lambda_3 = \frac{2}{3}a_{DVD} = 493 \text{ nm.(blue)} \tag{4b}$$

3. The experimental setup

The experimental setup is shown in figure 3. To ensure a light source with a reasonably uniform spectrum across all visible wavelengths and a reasonably collimated beam, we employed an old slide projector instead of a table lamp. The latter feature is particularly important to avoid interference from reflected light. If the experiment is solely qualitative, beam collimation may not be as critical.

To perform the measurements, a CD/DVD was placed on a wooden plate whose inclination could be adjusted. To prevent spurious spectra from light reflection, small pieces of black scotch tape were placed on the edges of the disc. Note that this precaution is not necessary for qualitative experiments. The distances were such that the angle α could be considered as very small in all situations.

As mentioned in the Introduction, two measurement methods were employed. The first involved taking pictures of the CD with a smartphone camera, using a 100 lines/mm

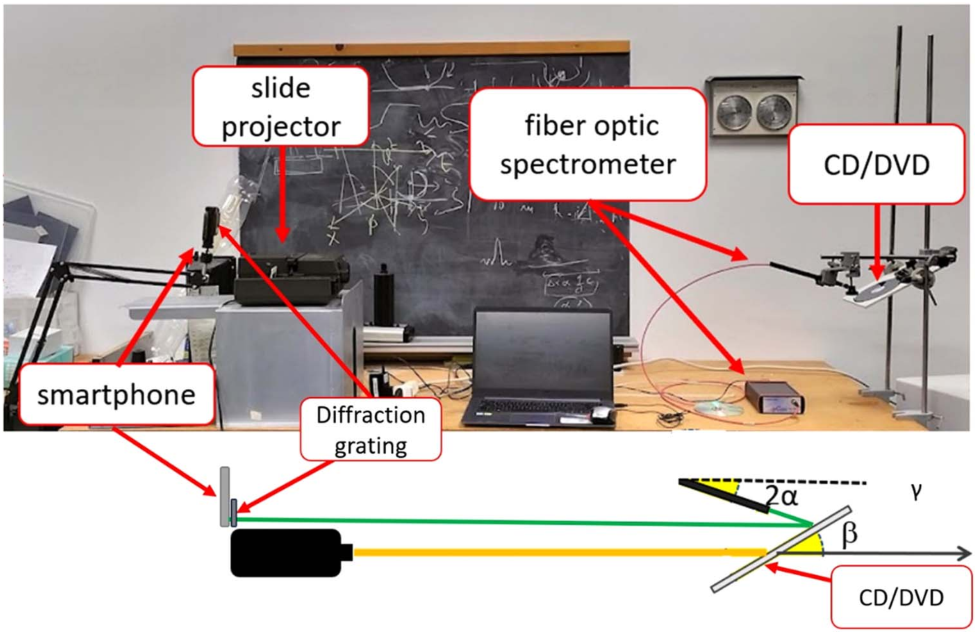

Figure 3. Upper panel: a photo of the experimental setup with both the smartphone and the AVANTES spectrometer used to perform the measurements. Lower panel: a schema of the setup.

diffraction grating put in front of the lens, placed as close as possible to the projector. This allowed for direct images of the spectral lines, which were then analyzed using the free app Tracker [10, 13] according to a procedure described in [14]. To calibrate the measurements, three different LEDs of known peak wavelength were placed behind the CD/DVD, so that their spectra were included in the photos. This experimental method is visually very appealing, since one can get nice pictures of the CD with the spectral lines clearly visible, as shown in figure 4.

The second method required more sophisticated instrumentation and involved directly measuring the spectrum of the line with a commercial AVANTES spectrometer [12]. This method may be less suitable for schools or not well-equipped laboratories, but it allows for a greater range of wavelengths to be analyzed, including infrared light. It is also quicker, as it does not require calibration LEDs or photo analysis and provides data at more angles in a reasonable time. We used the second method for both the CD and DVD, while the first method was applied only to the CD because, when a DVD was used, the spectral lines were not clearly visible.

4. Experimental procedure and results

In the first round, we collected data from the pictures with Tracker, according to the first experimental method described in the previous section. A picture of the CD for each angle β was taken and the wavelengths of the resulting lines were acquired with Tracker. Some of these pictures are shown in figure 4. The angle β was measured by means of a second smartphone, using the inclination tool of the Phyphox free app [15]. The reference LEDs used

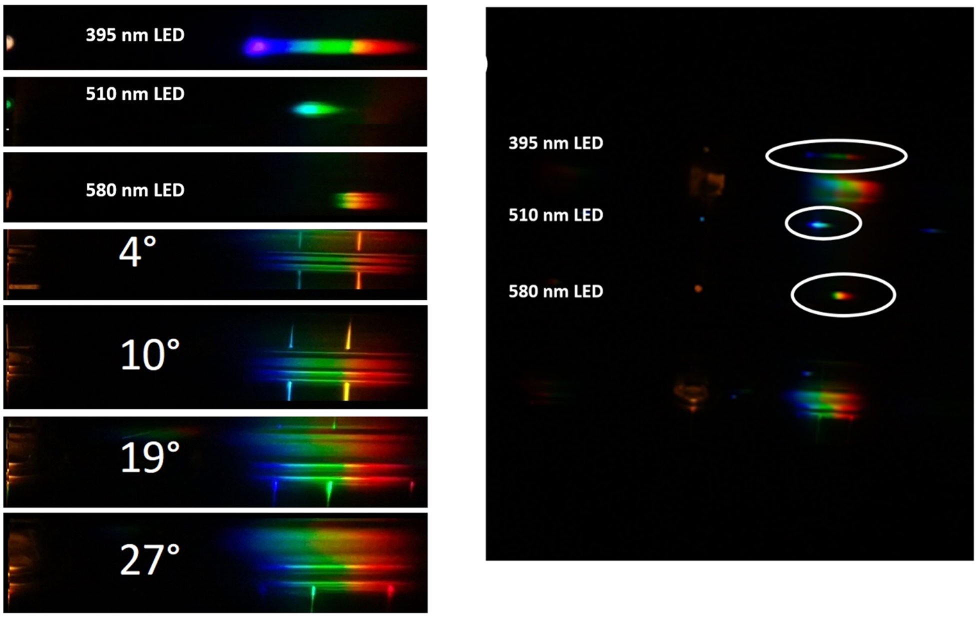

Figure 4. (Left). The spectral lines visible with a 100 lines/mm diffraction grating in front of the lens, for the CD titled by various angles, together with the spectra of the calibration LEDs. The calibration is performed by using the two-point calibration in Tracker on the 395 nm and on the 510 nm LED to set the scale (the calibration is performed taking as reference the peak of the emission, with uncertainty given by the full width at half maximum), then checking that this scale agrees with the third LED (which it does within 5 nm), and finally performing the measurement on the lines. Details on this procedure can be found in [14]. (Right). An example of a full picture of the CD and the calibration LEDs, for the 19° case. The full rainbows which are visible both on the left and on the right, close to the spectral lines, are spurious effects due to light reflected from the edge of the CD, which could not be completely shielded. Of course, this reflected light does not undergo interference like the light reflected from the tracks of the disc. These rainbows are completely irrelevant to the measurements.

in this first experimental method had peak wavelengths at 580, 510 and 395 nm, respectively. The data for the CD are reported in figure 5 and fitted against equation (2) (with $\alpha = 0$) but allowing for an offset angle β_0 (i.e. the fitting function was taken to be of the form $\lambda(\beta) = \lambda_{M,0}\cos(\beta + \beta_0)$).

In this expression, the parameter $\lambda_{M,0}$ corresponds to $2a/M$, where M is the order of the maximum, and it can be compared directly with the theoretical results for $\beta = 0$, i.e. equations (3a)–(3c), where the three wavelengths falling within the visible spectrum are seen to correspond to the $M = 4$, 5, 6 maxima. The three experimental values found for $\lambda_{M,0}$ are reported in figure 5 and fall within 10% of the predicted values. This small discrepancy is likely due to the setup, which can only approximately reproduce the ideal conditions assumed in the calculation. The linear fit $\lambda_{M,0} = K/M$ (figure 5, right) gives $K = (3.2 \pm 0.2) \times 10^3$ nm, hence $a = (1.6 \pm 0.2) \times 10^3$ nm, in agreement with the nominal value a_{CD}.

In the second round of measurements, we collected data using a commercial spectrometer, which allowed us to observe peaks with widths smaller than one nanometer and extend our measurements to the near IR up to 900 nm. As shown in figure 3 (lower panel), the probe was

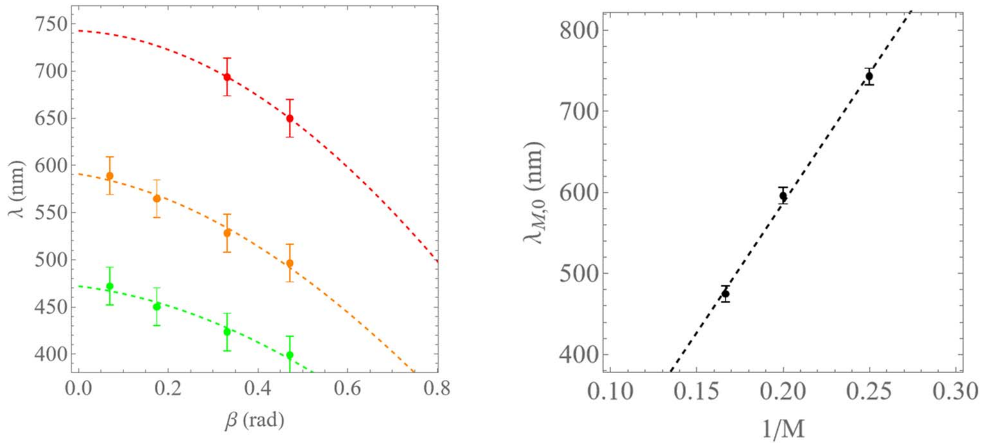

Figure 5. (Left). The experimental data acquired with the smartphone and Tracker for the case of the CD, and the fitting curves (dashed lines), corresponding to the lines $M = 4, 5, 6$ (red, orange and green line, respectively). For the angles, we assume an uncertainty of 0.01 rad (i.e. 0.5°), while for each measurement we have an uncertainty of ± 20 nm, obtained taking the full width at half maximum. All fits give $\beta_0 \approx 2°$. The wavelengths of the maxima for zero angle are: (745 $\pm$10) nm, (596 $\pm$10) nm, (475 $\pm$10) nm, respectively; these were obtained by fitting three series of data. (Right). The linear fit $\lambda_{M,0}$ versus $\frac{1}{M}$. The slope of the dashed curve is $K = (3.2 \pm 0.2) \times 10^3$ nm.

tilted by an angle γ with respect to the horizontal, so that the angle to be considered in equation (2) is actually $\beta + \gamma$. We measured this angle by taking photos of the plate and probe and using Tracker.

The data analyzed in this second round are based on the measurable spectral lines, which are now 5 (as shown in the left panel of figure 6) and correspond to the maxima labeled by $M = 3, 4, 5, 6, 7$. As before, these results are within 10% of the observed data. The discrepancies may be explained in the same way as done for first-round data, and the differences with respect to the previous setup depend on the slightly different conditions in which the measurements were performed. The linear fit, shown in the right panel of figure 6, now gives $K = (3.16 \pm 0.12) \times 10^3$ nm, hence $a = (1.58 \pm 0.06) \times 10^3$ nm.

When the CD is substituted with the DVD, even using the commercial spectrometer, only the $M = 2, 3$ lines are observed. From these lines, following the same procedure adopted for the CD, we could extrapolate the results: $\lambda_{2,0} = (736 \pm 4)$nm, and $\lambda_{3,0} = (488 \pm 2)$nm, which are in very good agreement with the theoretical values reported in equations (4a) and (4b), and from which an estimate of the pitch of the DVD could be extrapolated, giving $a_{\mathrm{DVD}} = (735 \pm 05)$nm, again in agreement with the nominal one.

Although we did not consider such a situation, we remark that cases where the angle α cannot be considered small can also be analyzed with the same procedure described above. In fact, in equation (2) we can parametrize the product $\cos\alpha \cos\beta$, which is a number comprised between 0 and 1, by $\cos\delta$, where δ is some angle, and fit the expression $\lambda(\delta) = \lambda_{M,0} \cos(\delta + \delta_0)$.

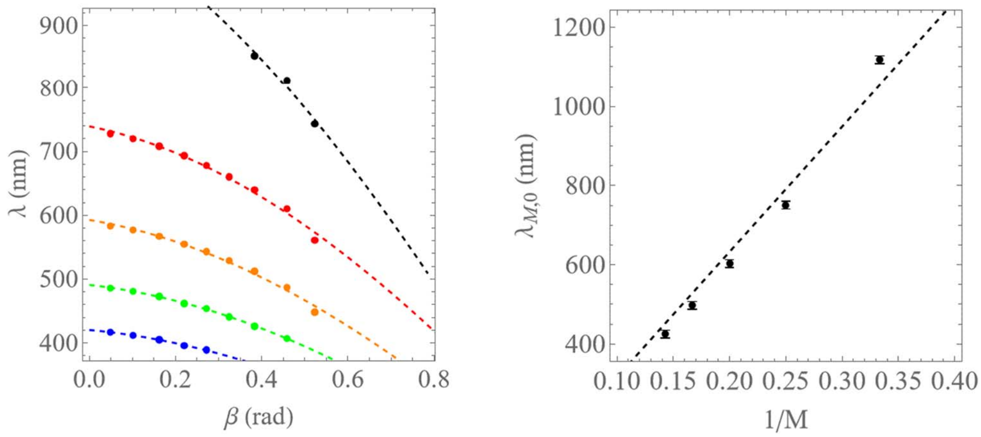

Figure 6. (Left). The experimental data acquired with the commercial spectrometer for the case of the CD, and the fitting curve, corresponding to the lines $M = 3, 4, 5, 6, 7$ (black, red, orange, green and blue line, respectively). For the angles, we assume an uncertainty of 0.01 rad (i.e. 0.5°). All fits give $\beta_0 \approx 3°$. The wavelengths of the maxima for zero angle are (omitting the IR points which were too few): (751 ± 10) nm, (603 ± 10) nm, (497 ± 10) nm, (425 ± 10)(Right). The linear fit $\lambda_{M,0}$ versus $\frac{1}{M}$. The slope of the dashed curve is $K = (3.16 \pm 0.12) \times 10^3$ nm.

5. Conclusions

We have investigated a phenomenon that occurs when a CD is illuminated by skimming light rays from a table lamp. When the CD is held horizontally, a green line emerges in a direction that lies between the lamp and the observer. If the CD is inclined at an angle β with respect to the horizontal plane, the color of the line transitions from green to blue and eventually becomes magenta. A similar colored line can also be observed on a horizontally held DVD. We measured the resonant wavelengths using both a low-cost apparatus and a commercial spectrometer, the results are in good agreement among them and with the theoretical predictions. Indeed, between experimentally measured and theoretically calculated values, the discrepancy is always less than 2%.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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