A compact disc under skimming light rays

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A compact disc under skimming light rays

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The optical properties of a compact disc (CD) under "skimming" light rays have been analyzed. We have noticed that a clear green line can be detected when the disc is irradiated with light rays coming from a lamp in such a way that only those skimming the CD, held horizontally, are selected. We provide a physical interpretation of this phenomenon on the basis of elementary optics concepts. Extension of these concepts to digital versatile discs (DVDs) is given.

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I. INTRODUCTION

It is well known that compact discs (CDs), having a distance (called pitch) between adjacent tracks of the order of one micrometer,[1] could be used as diffraction gratings in laboratories where diffraction gratings are not otherwise available.[2–6] In one of these applications,[2–4] for example, by using a monochromatic light source (a laser pointer, for instance), one can obtain a sharp diffraction pattern on a distant screen, placed at a distance from a small piece of CD, with clearly visible maxima. Such experiments, using common material, can be also performed in a classroom, after having explained to students the risks involved in using a laser pointer. However, the present paper refers, instead, to one possible non-destructive use of CDs: the observation of the colored line under the skimming light of a table lamp, as illustrated in Fig. 1.

A compact disc (CD) has a standard diameter of 12.0 cm. The pitch is $a \approx 1.6\,\mu$m. Within the tracks of a recorded CD, pits and lands are present. In an empty recordable CD, on the other hand, there are no pits and all tracks are even. Besides the known phenomenon of iridescence in a CD, due to diffraction, we have noticed a different reproducible phenomenon: When the CD is illuminated with light coming from a desk lamp, as shown in Fig. 1, in such a way that only "skimming" light rays are incident on it, when keeping the CD horizontal to the furthest distance possible with our arm, a clear green line is visible across the CD, and this line changes its color for different inclinations. In the present work, we give a simple experimental recipe for observing colored lines of different and predictable colors on the back of a horizontally held or inclined CD. Moreover, we also present a plausible explanation for this particular phenomenon. A further extension to the case of horizontally held DVDs is also given.

II. WHY DO WE SEE A SINGLE LINE ON THE CD UNDER SKIMMING LIGHT?

In order to give a plausible explanation for the phenomenon of the green line, we might first argue that only one line of reflected light should be visible. Let us then consider an observer in O and a light source in S. Both O and S are placed on the same horizontal plane. The light source sends light rays to the CD at any frequency $\nu = c/\lambda$ in the visible spectrum, where c is the speed of light and λ is the wavelength of the radiation. These light rays are incident on each track and are reflected back as shown in Fig. 2. When these light rays are incident on the line bisecting OS shown in Fig. 2, at points P and P', for example, the observer is able to see the reflected ray. In all other cases (see reflection of the light ray in P'' in Fig. 2, for instance) the same is not true; i.e., the light ray incident at points P'' not on the bisecting line passing through points P and P' is reflected in a direction away from the observer. Therefore, the observer should be able to see a colored line on the CD, which forms along a direction in between his position and the position of the lamp, as shown in Fig. 2.

III. WHY DO WE SEE A GREEN LINE?

In order to see why a green line, clearly seen in Fig. 3, should form, we might proceed as follows. Consider a generic point P on the colored upper segment lying along the bisecting line passing through HC, as seen in Sec. II and as shown in Fig. 4. By letting d represent the length of the segment HC and by taking the radius of the region of the CD not covered by tracks to be r_0, we have that the length of the path followed by the light ray from P to O is

$$r = \frac{(d + r_0 + ma)}{\cos\alpha}, \tag{1}$$

where m is an integer defining the number of tracks lying above the region not covered by tracks. Therefore, in the approximation of scalar diffraction theory,[7] the observer at O will see reflected rays at a frequency $\nu = c/\lambda = ck/2\pi$ from each track characterized by the following expression of the electric field:

$$\begin{aligned}\vec{E}_m &= \vec{E}_0 e^{i[(k(d+r_0+ma))/(\cos\alpha)]}\\ &= \vec{E}_0 e^{i[k(d+r_0)/\cos\alpha]}\left(e^{i[ka/(\cos\alpha)]}\right)^m,\end{aligned} \tag{2}$$

where, as usual, only the real part of $\vec{E}_m$ is considered. By summing from $m = 0$ to N, where N is the total number of tracks, we may write the total electric field at any frequency delivered from P to O as follows:

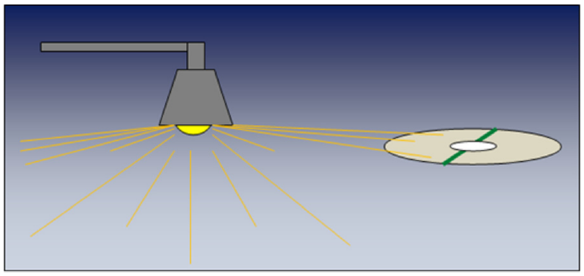


Fig. 1. A desk lamp (on the left) emitting light rays in all directions below the plane containing its rim.

$$\vec{E} = \sum_{m=0}^{N} \vec{E}_m = \vec{E}_0 e^{i[(k(d+r_0))/\cos\alpha]} \sum_{m=0}^{N} \left(e^{i[ka/\cos\alpha]}\right)^m. \tag{3}$$

We notice that the partial sum

$$S_N = \sum_{m=0}^{N} s^m = 1 + s + s^2 + \cdots + s^N \tag{4}$$

is equal[8] to $S_N = (s^{N+1} - 1)/(s - 1)$. Therefore, by setting $s = e^{i\tilde{k}a}$, where $\tilde{k} = k/\cos\alpha$, we have

$$\vec{E} = \sum_{m=0}^{N} \vec{E}_m = \vec{E}_0 e^{i\tilde{k}(d+r_0)} \frac{\left(e^{i\tilde{k}a}\right)^{N+1} - 1}{\left(e^{i\tilde{k}a}\right) - 1}. \tag{5}$$

Let us now write Eq. (5) in a slightly different way. In fact, by simple algebraic manipulations we may set

$$\vec{E} = \vec{E}_0 e^{i\tilde{k}(d+r_0)} e^{\left(i(N/2)\tilde{k}a\right)} \frac{\sin\left[\frac{(N+1)}{2}\tilde{k}a\right]}{\sin\left(\frac{\tilde{k}a}{2}\right)}. \tag{6}$$

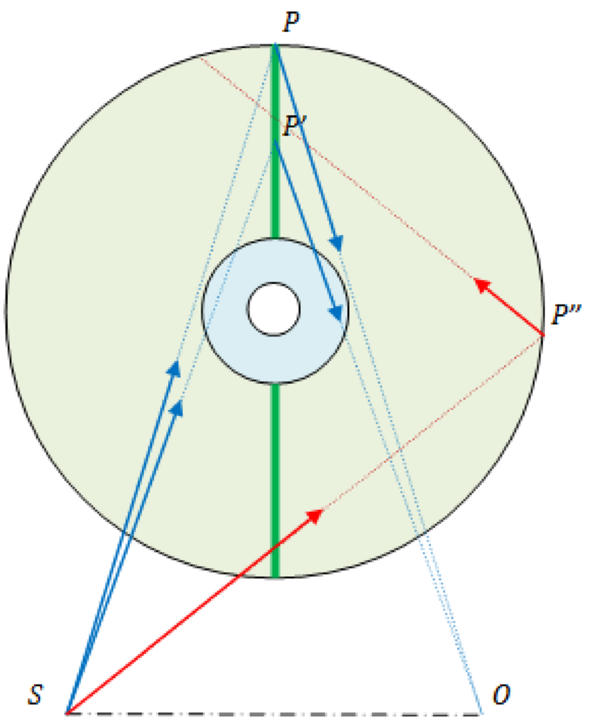


Fig. 2. The green line visible on a CD under skimming light. An observer is at O and a light source is at S.

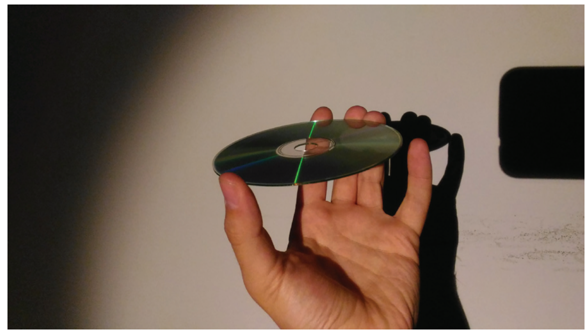


Fig. 3. A photograph of the visible green line on a horizontally held CD under skimming light.

Since the light intensity I at O is proportional[9] to $|\vec{E}|^2$, we have

$$I = I_0 \frac{\sin^2\left[\frac{(N+1)}{2}\tilde{k}a\right]}{\sin^2\left(\frac{\tilde{k}a}{2}\right)}. \tag{7}$$

By now recalling that $\tilde{k} = k/\cos\alpha = 2\pi/\lambda\cos\alpha$, where λ is the wavelength of the radiation coming from the tracks, we may write Eq. (7) as follows:

$$I = I_0 \frac{\sin^2\left[\frac{(N+1)\pi a}{\lambda\cos\alpha}\right]}{\sin^2\left(\frac{\pi a}{\lambda\cos\alpha}\right)}. \tag{8}$$

We have thus obtained a function which closely recalls the pattern of a diffraction grating.[9,10] The maxima of these curves are for values of the quantity $a/\lambda\cos\alpha$ equal to an integer M (see Fig. 5), so that

$$\lambda_M = \frac{a}{M\cos\alpha}. \tag{9}$$

For small values of the angle α (we hold the CD in our hand at the farthest allowable distance and place our eyes not too distant from the lamp), the ratio $a/\cos\alpha$ can still be

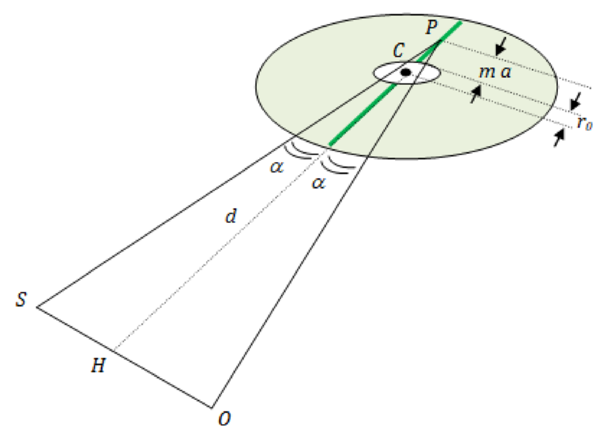


Fig. 4. The green line visible on a horizontal CD under skimming light. An observer is in O and a light source as in Fig. 1 is placed at S.

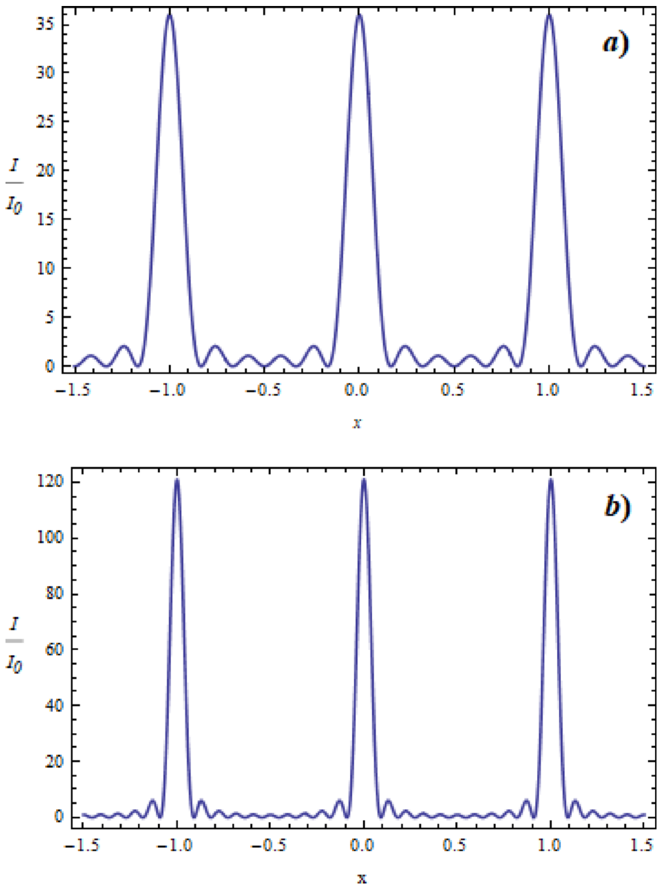


Fig. 5. Light intensity I as a function of $x = a/\lambda \cos\alpha$, detected by an observer at O for $N = 5$ (a) and $N = 10$ (b). As the number N increases, the curves become more and more peaked around integer values of x, attaining maximum values equal to $(N+1)^2$.

taken to be about $1.6\,\mu$m. In order to get visible light out of the pattern in Eq. (8), we need to set

$$400\,\text{nm} < \lambda_M < 700\,\text{nm}. \tag{10}$$

For $M = 1, 2, 3, 4$, we have

$$\lambda_1 \approx 1600\,\text{nm};\ \lambda_2 \approx 800\,\text{nm};\ \lambda_3 \approx 533\,\text{nm};\ \lambda_4 \approx 400\,\text{nm}, \tag{11}$$

so that the condition in Eq. (10) is strictly fulfilled only by $\lambda_3 \approx 533\,$nm, which corresponds to the green portion of the visible light spectrum, roughly comprised within the interval 495–570 nm. The same analysis can be carried out for the lower portion of the "green" line lying in the region not covered by tracks. In this respect, a word of caution is in order. If the CD is not held at the farthest possible distance from the light source, the approximation $a/\cos\alpha \approx a$ cannot be used. As a consequence, the upper and lower portion of the CD cannot be treated on the same footing, so that different colors could be observed on each portion. In fact, by considering finite values of the angle α with a given average angular difference between the upper and lower portion, we notice that the sequence in Eq. (11) tends to present larger wavelengths, in such a way that a violet color due to the term λ_4 could also be detected.

IV. INCLINING THE CD

Let us now consider a CD inclined with respect to the horizontal plane by a small angle β as shown in Fig. 6, where we take the points C, S, H, and O to be fixed. The former generic point P on the CD is now rotated to the point P', as shown in Fig. 7, because the segment CP of length $r_0 + ma$ is rotated by angle β as shown. Therefore, in order to calculate the electric field $\vec{E}'_m$ for this new configuration, as done in Eq. (2), we need to evaluate the distance $r' = OP'$. Considering the geometry of the problem, schematically shown in Fig. 7, we have

$$r' = \frac{HP'}{\cos\alpha} = \frac{\sqrt{d^2 + (r_0+ma)^2 + 2d(r_0+ma)\cos\beta}}{\cos\alpha}. \tag{12}$$

By then noticing that $(r_0 + ma)/d \ll 1$, we may write Eq. (12) as

$$\begin{aligned} r' &\approx \frac{d}{\cos\alpha}\sqrt{1 + 2\frac{(r_0+ma)}{d}\cos\beta} \\ &\approx \frac{1}{\cos\alpha}[d + (r_0+ma)\cos\beta] \end{aligned} \tag{13}$$

from which we have

$$\begin{aligned} \vec{E}'_m &= \vec{E}'_0 e^{ikr'} \\ &= \vec{E}'_0 e^{i[(k(d+r_0\cos\beta))]/(\cos\alpha)} \left(e^{i[(ka\cos\beta)/(\cos\alpha)]}\right)^m. \end{aligned} \tag{14}$$

By repeating the same analysis done for $\beta = 0$, we obtain the following light intensity pattern:

$$I' = I'_0 \frac{\sin^2\left[\dfrac{(N+1)\pi a\cos\beta}{\lambda\cos\alpha}\right]}{\sin^2\left(\dfrac{\pi a\cos\beta}{\lambda\cos\alpha}\right)}. \tag{15}$$

Once again, the maxima of these curves are obtained for values of $\pi a\cos\beta/\lambda\cos\alpha$ equal to an integer M, so that

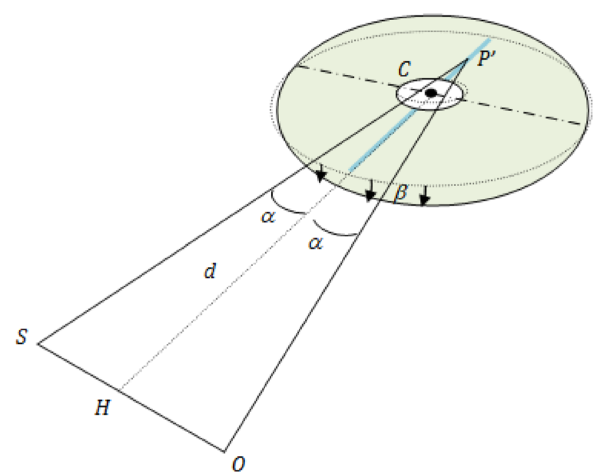


Fig. 6. The line visible on an inclined CD under skimming light (coming from S) as seen by an observer at O goes from green to higher frequency colors when the inclination angle grows.

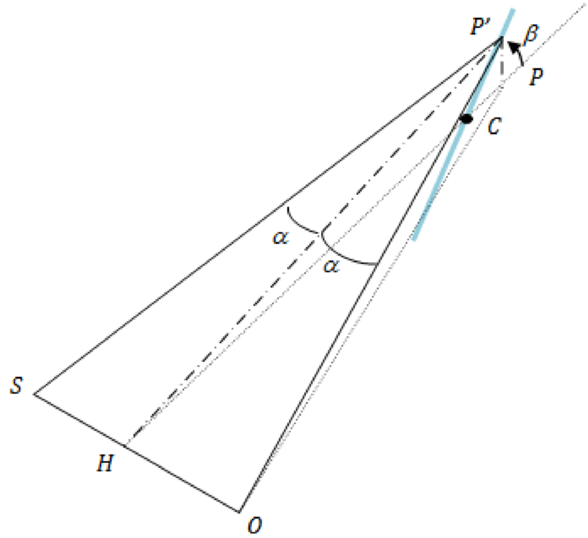


Fig. 7. The distance OP' can be calculated by considering the geometry of the figure. The CD is inclined by an angle β with respect to the horizontal plane and the point P is now P'. By considering the triangle $HP'O$, the distance HP' can be found so that, by knowing the angle α, $OP' = HP' \cos\alpha$.

$$\lambda'_M = \frac{a\cos\beta}{M\cos\alpha}. \tag{16}$$

For small enough values of the angle α we may approximate

$$\lambda'_M \approx \frac{a\cos\beta}{M}. \tag{17}$$

For rather small values of β ($\cos\beta \approx 1$) we still observe a greenish line crossing the CD. However, for larger values of β, say $\beta = 25^\circ$, we write: $\lambda'_M = 1545/M$ nm. Therefore, for the first four values in M, we have: $\lambda'_1 = 1450$ nm; $\lambda'_2 = 725$ nm; $\lambda'_3 = 483$ nm; $\lambda'_4 = 362$ nm. Once again the only contribution is now given by a single line, in this case a blue (483 nm) line. If we now increase the inclination angle to $\beta = 35^\circ$, we have: $\lambda'_M = 1311/M$ nm. We therefore get the following first four values in M: $\lambda'_1 = 1311$ nm; $\lambda'_2 = 655$ nm; $\lambda'_3 = 437$ nm; $\lambda'_4 = 328$ nm. This time we have two contributions: $\lambda'_2 = 655$ nm (red) and $\lambda'_3 = 437$ nm (blue). The composition of these two colors (see, for example, Ref. 10 for additive synthesis of colors) gives the magenta color, which is clearly visible on the CD under skimming light conditions for $\beta \approx 30^\circ$.

V. DVDs

The analysis developed in Sec. III will now be applied to Digital Versatile Discs (DVDs). By applying Eq. (9) under the small-α hypothesis, and using the distance between two adjacent layers (pitch) as $a \approx 0.74\,\mu$m, for $M = 1, 2, 3$, we have

$$\lambda_1 \approx 740\,\text{nm};\ \lambda_2 \approx 370\,\text{nm};\ \lambda_3 \approx 247\,\text{nm}. \tag{18}$$

We thus get two contributions from the extreme portions of the visible spectrum, giving rise to the colored line shown in Fig. 8 (left). In Fig. 8 we show, for comparison, the colored lines forming on a DVD (on the left) and on a CD (on the right) under skimming light. With this rather simple experimental observation we are able to distinguish a CD from a DVD.

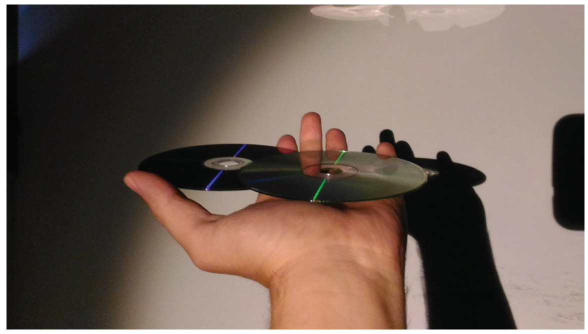


Fig. 8. Colored lines visible on a horizontally held DVD (on the left) and a CD (on the right) under skimming light.

VI. CONCLUSIONS

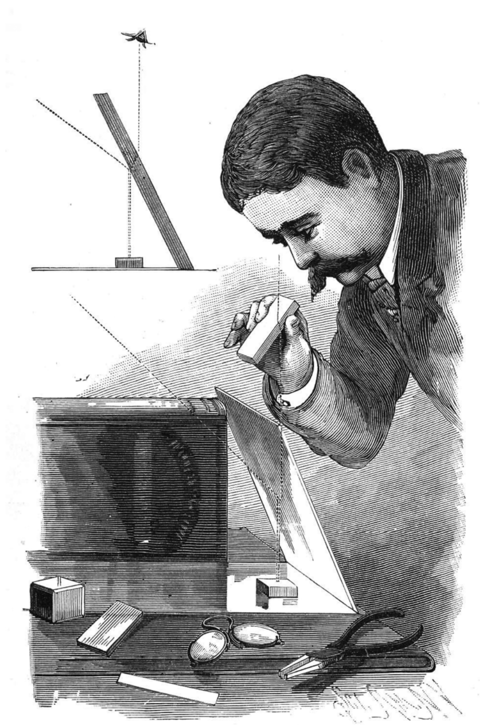
When a CD is illuminated by skimming light rays coming from a table lamp, a reproducible phenomenon can be observed: for a CD held horizontally, a green line forms in a direction between the direction to the lamp and that to the observer. If the CD is inclined by an angle β with respect to the horizontal plane, the color of the line goes first bluish and then turns magenta. An analogous colored line is also visible on a horizontally held DVD.

We have investigated this phenomenon, giving a plausible explanation based on the principles of elementary optics. The reason we are able to observe a green line on the horizontal CD, and then, upon gradually inclining the disc, a bluish one and finally a magenta line, is because the CD acts as a diffraction grating.[2–6] By considering the reflection pattern of light rays coming from the lamp in S, we first argue that only those rays following the path in between the observer and the source can reach the observer. By next considering all contributions from all tracks, we notice that the interference among all possible wavelengths selects, for the specific value of the CD pitch ($a \approx 1.6\,\mu$m), a green wavelength of about 533 nm if the CD is held horizontally. An extension of the analysis done for a CD lying horizontally, i.e., on the same plane as the source and the observer, is given by inclining the CD through a range of angles β. Under these tilting conditions, the diffraction pattern undergoes only minor changes, the pitch a being rescaled by the constant $\cos\beta$. In this way, the qualitative experimental observations can be reproduced by elementary optics principles. If we repeat the same simple experimental observation on horizontally held DVDs, we also observe a colored line. This feature can be explained by the same type of analysis carried out for a CD, with the only change being the replacement of the pitch (track separation) of the CD by that of the DVD.

A portion of the present work (a CD held horizontally) has been used in the Summer School of Physics at University of Salerno, in September 2015, dedicated to advanced high-school students. We believe that the present analysis provides quite a simple way of introducing to students the effects of interference and diffraction in optical systems.

[1]J. Cope, "The physics of the compact disc," Phys. Educ. **28**, 15–21 (1993).
[2]C. Nöldeke, "Compact disc diffraction," Phys. Teach. **28**, 484–485 (1990).

[3] J. E. Kettler, “The compact disk as a diffraction grating,” Am. J. Phys. **59**, 367–368 (1991).
[4] H. Kruglak, “The compact disc as a diffraction grating,” Phys. Educ. **26**, 255–256 (1991); , “Diffraction demonstration with a compact disc,” Phys. Teach. **31**, 104 (1993).
[5] J. Fernández-Dorado, J. Hernández-Andrés, E. M. Valero, J. L. Nieves, and J. Romero, “A simple experiment to distinguish between replicated and duplicated compact discs using Faunhofer diffraction,” Am. J. Phys. **76**, 1137–1140 (2008).
[6] R. Khare, “Use of a CD as a dispersive element in a tunable dye laser,” Am. J. Phys. **73**, 559–562 (2005).
[7] J. W. Goodman, *Introduction to Fourier Optics* (Roberts and Company Publishers, Greenwood Village, 2005).
[8] B. Kolman and A. Shapiro, *Precalculus, Functions & Graphs* (Academic Press, Orlando, 1984).
[9] D. Halliday, R. Resnick, and J. Walker, *Fundamentals of Physics*, 7th ed. (Wiley and Sons, New York, 2005).
[10] P. A. Tipler, *Physics* (Worth Publishers Inc., New York, 1980).



Nörrenberg Doubler

This illustration from George M. Hopkins, “Experimental Science” (Nunn & Co., New York 1893), pg 245, shows the basic physics behind the Nörrenberg doubler, a device for viewing birefringent materials between crossed polarizing filters. It was first described in 1858. The basic plan is shown at the top of the figure: a light beam from the second quadrant reflects at Brewster’s angle from the bottom of a stack of glass plates, is thus plane polarized, and passes through the object placed on the mirror at the bottom. It is then reflected back through the object (hence the word *doubler*) and passes through the stack of glass plates, becoming polarized in a perpendicular direction during the passage through the plates. To build your own version, see: Thomas B. Greenslade, Jr., “An Inexpensive Modern Nörrenberg Doubler”, *Phys. Teach.*, **19**, 626–627 (1981). (Picture and Notes by Thomas B. Greenslade, Jr., Kenyon College)