A simple experiment to distinguish between replicated and duplicated compact discs using Fraunhofer diffraction

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Compact discs are a useful tool for studying interference and diffraction. We propose an easy and inexpensive experiment to distinguish between replicated and duplicated compact discs based on Fraunhofer diffraction. The nonvisible differences of the surface of compact discs depend on the way that they have been manufactured and can be seen by using a laser beam in a simple diffraction experiment. The method has been tested on many different brands of CDs and is reliable.

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I. INTRODUCTION

Compact discs (CDs) are a common medium for storing and distributing digital data.[1–3] There are essentially two types of CDs. Replicated CDs are mass-produced using a hydraulic press, and duplicated CDs (CD-Rs) are more typically used for shorter runs and are "burned" using a laser.

We describe here a simple diffraction method to distinguish between the two types of CDs, a distinction that is not visible to the eye. The success of this method is based on the different ways in which data are pressed onto the replicated CDs and burnt onto their duplicated counterparts. We have tested more than 100 CDs of different makes with different types of audio and video data and have found that the method is completely reliable. The experiment represents an example of the connection between the theory of diffraction (which students often find difficult to grasp) and the characteristics of everyday objects such as CDs.

II. DIFFRACTION EXPERIMENT

We start by asking students to perform a simple experiment at home: Illuminate the surface of different types of CDs with a laser pointer (borrowed from the teacher) and observe and analyze the reflected diffracted light that can be seen against a white screen or a wall. The only instructions given to them are to turn off the ambient light, vary the distance between the laser and the CD and between the CD and the screen, take digital photographs of the diffracted pattern, and try to relate the pattern to the type of CD (students usually have different types of CDs at home).

The diffraction experiment can also be performed in the laboratory or classroom by directing a laser beam (in our case a He–Ne beam with a wavelength peak at 632.8 nm) on any part of the surface of a CD except the center or edge, where no information is stored. The CD should be placed about 1 m from the laser and oriented more or less perpendicular to it. The light is diffracted after being reflected from the microstructures of the surface[4–8] which contain the information. The diffraction pattern is then projected onto a screen which is ≈ 1 m away from the CD (see Figs. 1 and 2). Without a lens the beam on the CD surface has a cross section of several square millimeters, so that the laser sees a surface grating with hundred of lines per millimeter. The resulting diffraction pattern corresponds to Fraunhofer diffraction.[9,10] This simple experiment is similar to published experiments[4–8] in which students estimate the track spacing on a CD by shining a laser at a CD and measuring the positions of the different diffraction orders. In our experiment we need the room to be very dark to relate the diffraction pattern to the type of CD and a distance of ≈ 1 m between the CD and the screen to clearly observe the difference of the zero-order diffraction patterns.

From both their home and lab experiments the students will recognize that the diffraction patterns of replicated CDs and of CD-Rs are distinct. The diffraction pattern for a CD-R (blank or burned and any age or make) has two parallel lines on the screen that pass through the diffraction pattern at equal distances from the center as shown in Fig. 3(a). (These lines are oriented perpendicularly to the tracks illuminated by the laser beam.) The separation between the two lines is $\approx 1.4°$ or 25 mm when using the distances shown in Fig. 1. In contrast, pressed CDs do not have these two parallel lines as shown in Fig. 3(b). We will explain these differences in the following.

III. SOME BASICS ABOUT CDS

The digital information on a replicated CD is stored in the form of pits and "lands" (not pits) which follow a spiral track. The zeros and ones of the binary data are represented by an encoding[3] in which the change from pit to land or land to pit indicates a one, and no change indicates a zero. CDs also use an encoding scheme that avoids really short pits or pits too close together by ensuring that there are always at least two 0 bits between any 1 bit and avoiding tracking problems by ensuring that there are no more than ten consecutive 0 bits.

The pits and lands lie along concentric circular grooves separated by 1.6 μm in the plastic substrate, which are coated with an aluminum film to make them reflective.[1,2] (There are about 625 tracks per millimeter, which is similar to ordinary laboratory diffraction gratings.) A protective coating is applied to the top, and the laser system reads the data from below. A 12 cm diameter CD can store more than 6 billion bits of binary data or 782 megabytes. The laser beam tracks the concentric circular lines of pits, which are each 0.8–3 μm long. The rotation speed must be adjusted as the tracking system moves outward. A constant linear speed of 1.25 m/s is maintained by increasing the rotation speed from 3.5 to 8 revolutions per second as the beam tracks toward the center of the disc.[1,2] The reading laser usually has

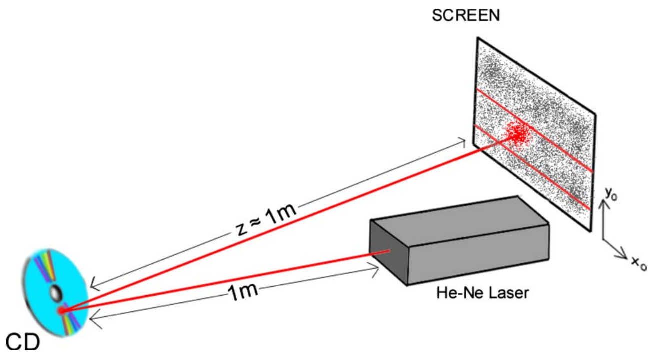

Fig. 1. The Fraunhofer diffraction experiment used to distinguish between replicated and duplicated compact discs. Although it is not shown clearly in the diagram, the angle of incidence is roughly normal and the screen is parallel to the surface of the disc. In this arrangement only the zero-order diffracted image is visible in the photographs (see Fig. 3). If the screen were moved closer to the CD, higher orders would become visible.

a wavelength of 780 nm in air, just beyond the limit of detection of the human eye. Once the laser beam enters the polycarbonate, the wavelength decreases by a factor of 1.55, the index of refraction of the polycarbonate.[8]

The pit depth is designed to equal one quarter of the wavelength λ of the light so that light reflected from the pit will be 180° out of phase with light reflected from a land. Destructive interference occurs for a narrow beam of light incident at the edges of the pits. The resulting reduction of light intensity is recorded as a 1.[8] The spacing between pits is also carefully set because the image of a beam passing through a round aperture will form a characteristic pattern called an Airy disk.[8] The full width at half maximum center of the Airy disk pattern is a spot about 1.7 μm wide and falls neatly on top of the pit track. The nulls in the Airy pattern are carefully situated to fall on the neighboring pit tracks, therefore minimizing crosstalk from neighboring pits.

IV. MANUFACTURING PROCESSES

Replication or pressing is the standard method used for manufacturing many CDs. A glass master with information encoded as pits and lands is made. The master is used to produce "stampers" which are used for injection molding the information onto a CD. The information is then protected by layers of polycarbonate plastic, lacquered, usually screened, and then packaged. This process becomes cost effective for orders greater than thousands of CDs.

Duplication or burning is the standard method for manufacturing smaller quantities. A blank CD-R has a different

Fig. 2. Photograph of a CD used in the experiment. The missing segment was used in the scanning electron microscope study.

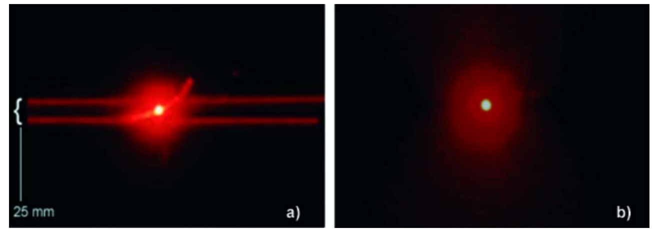

Fig. 3. Diffracted laser light patterns for (a) a burned CD and (b) a pressed CD. The diffraction patterns were photographed by a digital camera. In both cases the tracks are vertical and only the zero-order diffracted image is visible in the photograph.

structure than a replicated CD. A CD-R usually contains five layers of different materials, each with a different purpose. At the base is a polycarbonate plastic substrate containing a shallow spiral groove or pregroove extending from the inner to the outer diameter of the disc; the groove is used for timing and tracking. On top of the polycarbonate substrate is an organic dye recording layer (cyanine, phthalocyanine, or azo) followed by a thin metal reflective layer (gold, silver alloy, or silver) (Fig. 4). Finally, there is an outer protective lacquer coating. Some discs have additional layers which improve scratch resistance, increase handling durability, or provide a surface suitable for labeling.[1,2]

Data are written on the spiral track from the center of the disc outward using the writing laser to burn marks into the organic dye. The organic dye is marked (burned) by a high-powered laser (ten times as powerful as the reading laser). This writing laser can heat and melt the recording layer of organic dye on the polycarbonate substrate, thereby changing its reflectivity. As a result the dye layer can either absorb or reflect the beam of light emitted by the reading laser (the information is not stored as pits but as colored marks).

V. MICROSCOPIC SURFACE DIFFERENCES

We used a SEM to visualize the different microscopic structures of pressed CDs, blank CD-Rs, and burned CD-Rs (see Fig. 5). An area of 1 cm^2 (see Fig. 2) was cut from each of the three types of CD. The SEM image of the pressed CD [see Fig. 5(a)] shows the pits and lands (well defined contours) etched on the plastic substrate. The small scratches in the image are due to cutting the sample for observation by the SEM. The image of a blank CD-R [see Fig. 5(b)] contains parallel grooves that are part of a spiral track which is much larger than the image.

The SEM image of a burned CD [see Fig. 5(c)] appears to be almost identical to that of a blank CD because the pits, which were produced by the melting of the organic dye on the polycarbonate substrate, are only slightly above the pregroove. This important difference (the existence of a pregroove) between the structures of replicated and duplicated CDs cannot be seen with the naked eye because it is only a few μm. The light diffracted by the structure of the CD renders this difference easy to detect.

VI. DIFFRACTION SIMULATIONS

Students who are familiar with Fourier optics and have some experience with image processing software can better understand how the surface properties of CDs are converted into the diffraction pattern observed in the experiment.

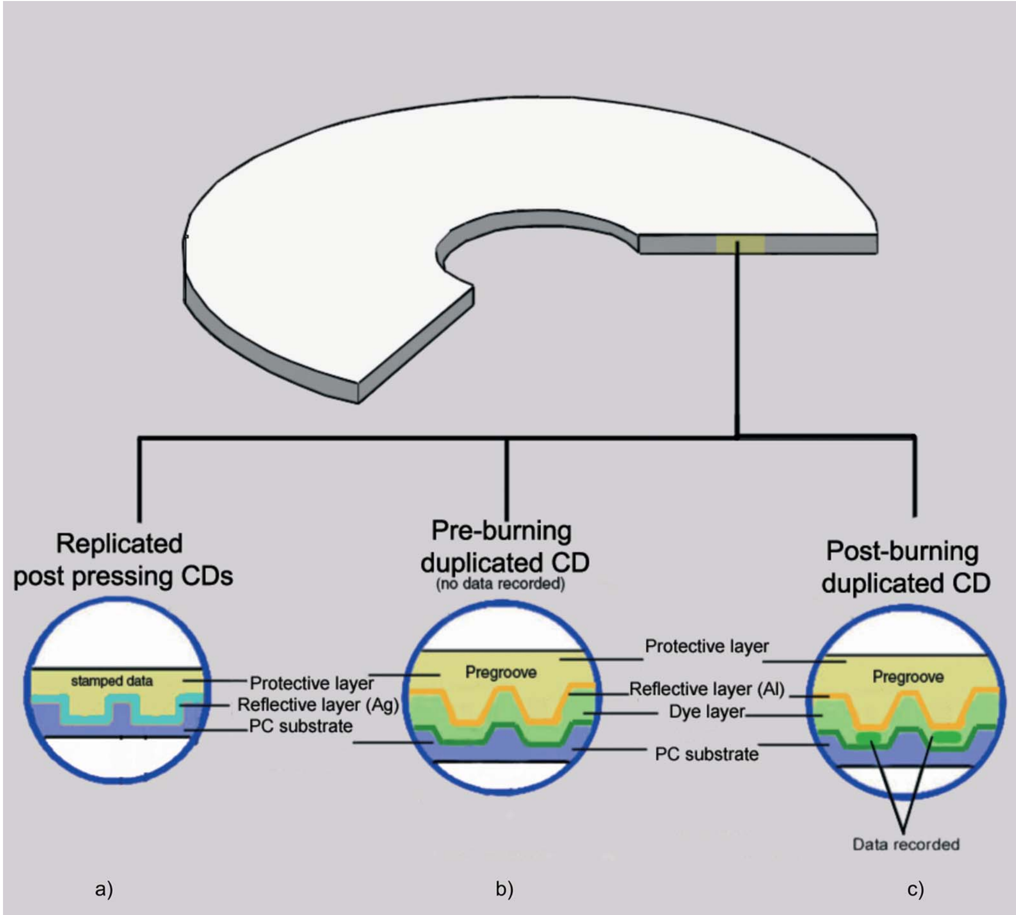

Fig. 4. A schematic cross section of (a) a replicated CD, (b) blank recordable CD-R, and (c) a burned CD-R.

The distances in the diffraction experiment satisfy the criteria for Fraunhofer diffraction. In this far-field limit the diffracted beam reflected from the CD surface and seen on the screen can be described using Fourier analysis.[12] Thus, the intensity of the reflected diffraction pattern is proportional to the squared Fourier transform of the field just after it has been reflected from the CD surface.[8] This bidimensional Fourier transform can be implemented, for example, by the Image Processing Toolbox of MATLAB,[11] so that students with a basic knowledge of optics and Fourier optics can perform the simulations. In the simulations the SEM images (see Fig. 5) provide realistic spatial distributions of the pregroove, pits and lands on the different types of CDs.

How do we model the amplitude of the field of light just after it has been reflected from the CD surface? Students can be presented with different approaches of varying degrees of difficulty. If we assume normal incidence by a unit amplitude monochromatic plane wave and far-field diffraction conditions (Fraunhofer diffraction), the light field at the screen is given by[8]

$$U(x_0,y_0) \propto F\{r(x_1,y_1)\}_{f_x,f_y} = F\{r(x_1,y_1)\}_{x_0/\lambda z, y_0/\lambda z}, \qquad (1)$$

where F denotes the bidimensional Fourier transform, z is the distance between the CD and the screen, (x_1,y_1) and (x_0,y_0) are the spatial coordinates on the diffraction object and on the screen, respectively, $r(x_1,y_1)$ is the reflectance of the diffraction object, and f_x and f_y are the spatial frequencies at the screen (corresponding to $x_0/\lambda z$ and $y_0/\lambda z$, respectively).

The simplest is to assume that the CD is flat (has no depth) and that the field reflected from its surface is the incidence field multiplied by the bidimensional reflectance that characterizes the surface of the disc. This reflectance can be modeled by a binary function, assuming binary phase modulations for the perfect case (π rad for a pit and 0 rad for a land)

$$r(x_1,y_1) = \begin{cases} 0 & \text{for a pit} \\ 1 & \text{outside a pit.} \end{cases} \qquad (2)$$

A more accurate simulation is to include the impact of the finite depth d of the pits in the CD. In this case we can model the reflectance of the CD surface as a phase function

$$r(x_1,y_1) = \begin{cases} e^{i(2\pi/\lambda)2d} & \text{for a pit} \\ 1 & \text{outside a pit.} \end{cases} \qquad (3)$$

The experiment works even though the wavelength of the laser used in the laboratory (632.8 nm) does not produce efficient destructive interference of the light reflected from pits and lands, but rather causes a phase difference of 225° because the depth of the pits is designed for light with a wavelength of 790 nm. Nevertheless, the simulations yield results similar to those seen in the laboratory, as seen for

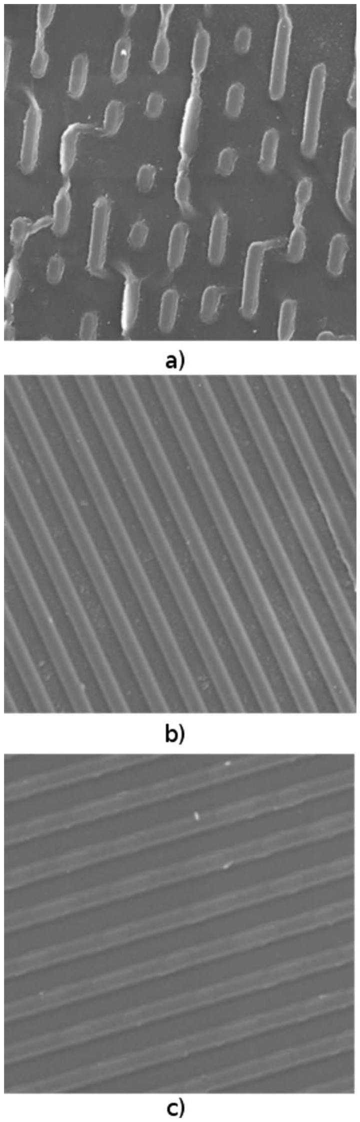

Fig. 5. Scanning electron microscope images of the surfaces of (a) a pressed CD, (b) a blank CD-R, and (c) a burned CD-R. The bar in the bottom left-hand corner of each image corresponds to 1 μm in the CD's surface.

example in Fig. 6, where the two lines obtained in the simulation using Eq. (3) are close to the ones photographed in the lab as seen in Fig. 3(a).

Different degrees of approximation can be made when considering the spatial power distribution of the laser beam. Students can consider it to have a circular cross section or, more realistically, to be a near-Gaussian beam.

The two parallel lines that appear on the diffraction experiment on CD-Rs are due to the pregroove. Because the pregroove is only slightly modified by the burning and melting process on duplicated CDs, which act only on the surface of the pigment layer, the two lines are not affected by the burning process. In contrast, pressed CDs are fabricated without a pregroove and consequently the two lines are not present in its diffraction pattern.

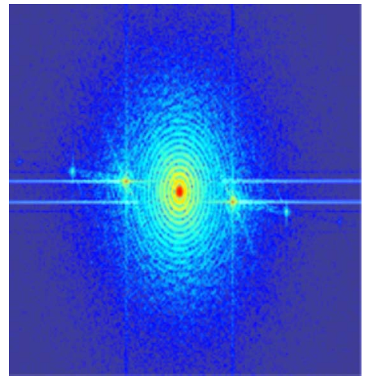

Fig. 6. Simulation of Fraunhofer diffraction using the reflectance of a burned CD-R surface and Eq. (3). In this simulation we assumed the use of a 633 nm He–Ne laser.

VII. SUMMARY

We have used diffraction of laser light to distinguish between replicated and duplicated CDs. The different fabrication process and the microstructures of the two types of CDs are too small to be seen by the naked eye, but produce distinct diffraction patterns of laser beams that strike the surface of CDs at almost normal incidence and are reflected onto a screen. We have recently submitted a patent application[13] for the method and associated apparatus.

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