Diffraction by electronic components of everyday use

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We demonstrate the use of CCD image sensors and LCD screens from discarded electronic devices as elements for performing simple optical diffraction experiments. The experiments can determine the spatial structure of these components by analyzing diffraction patterns generated by their interaction with monochromatic light. This article presents the design and results of such experiments.
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I. INTRODUCTION

Most basic physics courses for science and engineering students include the study of interference and diffraction as a fundamental property of wave phenomena.[1,2] As we know, diffraction is a wave phenomena observed when light interacts with an obstacle or aperture with a size comparable to its wavelength. It plays an important role in the formation of images in real optical systems, since the small size of lenses and mirrors forming the image constrict the light rays available to the imaging system. This constriction makes the image of a point object become a diffraction spot, the dimensions of which limit the resolution of the imaging system.

Despite diffraction effects in real systems the study of diffraction is usually perceived by students as something of purely academic interest, requiring complicated mathematical treatment and topic-specific scientific components for observation. These include monochromatic light sources, apertures, slits of very small size, and diffraction gratings. We have found that nothing is further from reality, either in terms of interest or in the difficulty to create and perform experiments that illustrate diffraction.

To this end, a great variety of creative works have been published concerning the wave phenomenon of light[3–7] and, more specifically, concerning diffraction. For example, diffraction experiments have been performed using slits made with graphic arts films.[8] Similarly, diffraction-ready slits have been produced by a low-cost photolithographic process.[9] Another example is the use of compact discs (CDs) as an example of an everyday object that can be used for diffraction,[10–13] with the tracks of the CD acting as a one-dimensional diffraction grating. The diffraction patterns of gratings generated by the Cantor set and the Fibonacci sequence have even been studied.[14,15] In many of these experiments, a CCD (charged-coupled device) image sensor is used for the digital registration of the diffraction patterns,[16] although the cost of "scientific grade" CCD camera can be prohibitive.

As with many phenomena in physics, simulations of diffraction phenomena are a valuable alternative. Appealing educational software has been developed to study Young's double slit experiment and the diffraction grating,[17] and while simulations are a good alternative to costly equipment, we believe real laboratory experiences are always more desirable.

In this work, laboratory experiments related to diffraction are illustrated using electronic components such as CCD image sensors[18] or LCD (liquid crystal display) screens[19,20] as the diffracting elements. These components are extracted from discarded mobile phones and digital cameras. A monochromatic laser pointer is used as the light source. The analysis of the obtained diffraction patterns is then used to determine the characteristics of the pixel structure of these components and their spatial resolution.

The outline of this paper is as follows. In Sec. II, we review an important result of Fraunhofer diffraction. In Sec. III, the experimental set up is described, followed by the results of four diffracting objects in Sec. IV. Lastly, Sec. V closes with some conclusions.

II. FRAUNHOFER DIFFRACTION: A NEEDED RESULT

In this work, the distance between the diffracting element and the imaging screen is kept large, casting this work into the realm of Fraunhofer diffraction. This theory is well discussed in a variety of places and will not be repeated.[1,2] Here, we remind the reader of one important result.

For a given diffraction pattern, the distance p between the consecutive maxima depends on the distance d between the slits of the grating according to

$$p = \frac{\lambda D}{d}, \tag{1}$$

where λ is the wavelength of the light and D is the diffraction element to screen distance. Strictly speaking, this equation is valid when $d<<D$. The overall premise of this work is that if

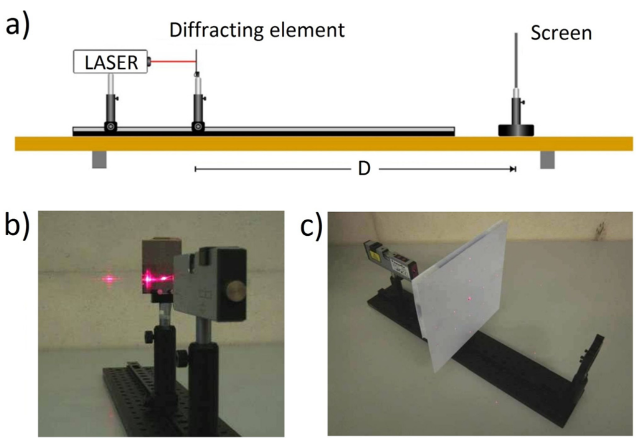

Fig. 1. (a) Schematic representation of the experimental set up, (b) device used to obtain the transmission diffraction pattern, and (c) device used to obtain the reflection diffraction patterns.

p can be measured, then d can be found, thus revealing the characteristic spatial dimension of the diffracting element.

In the more general case of a two-dimensional diffraction grating, the result is a two-dimensional diffraction pattern. For each direction (x or y), the distance between the diffraction maxima depends on the period of the grating in the corresponding directions (d_x and d_y), which need not be the same. Thus, we have

$$p_x = \frac{\lambda D}{d_x} \tag{2}$$

and

$$p_y = \frac{\lambda D}{d_y}. \tag{3}$$

Again, since p_x and p_y can be measured from a diffraction pattern of a (2D) periodic object, solving for d_x and d_y can reveal the spatial structure of the diffracting element (in this case CCD image sensors and LCD screens). As we will show, both such electronic components behave as 2D diffraction gratings because their pixel structure is formed by a large number of identical pixels (elemental apertures of a given form and size) that are replicated in two directions with a given period.

Table I. Experimental values of the distance between the maxima in the diffraction pattern for the CCD image sensor of the Nokia 6102 phone.

Direction	x	y
p_{exp} (mm)	13.41 ± 0.01	13.31 ± 0.01
	13.46 ± 0.01	13.50 ± 0.01
	13.36 ± 0.01	13.41 ± 0.01
p_{ave} (mm)	13.41 ± 0.04	13.40 ± 0.08
d_{DP} (μm)	10.49 ± 0.11	10.49 ± 0.14
d_M (μm)	10.44 ± 0.01	10.44 ± 0.01
Disc (%)	0.12	0.12

III. EXPERIMENTAL SET UP

The experimental set up used to obtain the diffraction patterns is straightforward (Fig. 1). A monochromatic laser diode (Powerfix KH 4179) is used as the light source. The wavelength ($\lambda = 650$ nm) provided by the manufacturer is verified using an Ocean Optics HR4000 spectrometer as $\lambda = 654 \pm 2$ nm. The setup also includes a mount for the object to be studied and a diffusing screen for viewing the diffraction pattern.

One type of diffracting element to be used in our experiments is an LCD screen, a device whose functioning is based on the light-modulating properties of liquid crystals.[18] LCDs are present in many everyday devices including computer monitors, video game consoles, clocks, watches, and calculators. The diffraction pattern from an LCD screen is obtained by transmission and is observed on a diffusing screen located a few meters away. Note that for a typical LCD whose distance between pixels is on the order of 200 μm, a laser with a spot-size diameter of $\sim$2 mm will cover $\sim$10 periods of the diffracting structure.

The other type of diffracting device used in our experiments is a CCD image sensor. These are used for light detection in digital devices when high-quality images are required, such as in digital cameras.[19] In a CCD image sensor, pixels are formed by p-doped MOSFET capacitors.[20] Unlike LCDs, the diffraction pattern of CCD sensors is produced by reflection instead of transmission. The distance between pixels in a CCD is much smaller than for the LCD, typically on the order of 10 μm (or smaller), offering an entirely different length scale for the experiments. The same laser spot will now cover $\sim$200 periods of the diffracting structure in both directions.

The LCD and CCD are obtained from discarded digital cameras and mobile phones. The extraction of these electronic components is relatively simple, although in the case of the LCD there is a risk of breaking the screen. The results discussed here were obtained from devices in which the components were extracted by students prior to performing the experiments.

A Vernier caliper is used to determine the distance between the consecutive diffraction maxima (p_x and p_y). The

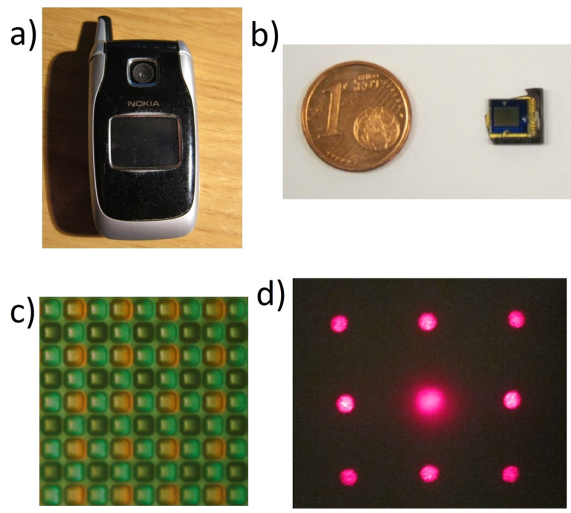

Fig. 2. (a) General view of the Nokia 6102 mobile phone, (b) photograph of the CCD sensor in comparison to a one (euro) cent coin, (c) the microscope image of the sensor, and (d) the central area of the reflection diffraction pattern.

Table II. Experimental values of the distance between the maxima in the diffraction pattern for the CCD image sensor from a Canon Ixus 80 IS digital camera.

Direction	x	y
p_{exp} (mm)	42.67 ± 0.01	42.61 ± 0.01
	42.60 ± 0.01	42.55 ± 0.01
	42.61 ± 0.01	42.61 ± 0.01
p_{ave} (mm)	42.63 ± 0.03	42.59 ± 0.03
d_{DP} (μm)	3.30 ± 0.03	3.30 ± 0.03
d_M (μm)	3.33 ± 0.01	3.33 ± 0.01
Disc (%)	0.23	0.23

Table IV. Experimental values of the distance between the maxima in the diffraction pattern for the LCD screen of a Sony DSC P73 digital camera.

p_{exp} (mm)	12.19 ± 0.01
	12.15 ± 0.01
	12.18 ± 0.01
p_{ave} (mm)	12.17 ± 0.02
d_{DP} (μm)	186.2 ± 0.9
d_M (μm)	183.94 ± 0.01
Disc (%)	0.31

distance D between the diffracting element and the observation screen is determined with a measuring tape. Substituting these values into Eqs. (2) and (3), the period of the grating in each direction (d_x and d_y) can be determined. In order to verify the reliability of the results, the values of d_x and d_y derived from the diffraction pattern are compared with those measured directly using a calibrated microscope (TE-2000).

IV. RESULTS

Four examples of the results obtained with the aforementioned devices are now presented, two for the CCD image sensors (subsections A and B) and two for the LCD screens (subsections C and D).

A. CCD image sensor of the Nokia 6102 mobile phone

In Table I, the measurements of the distance between the consecutive diffraction maxima on the x and y axes of the diffraction pattern produced by the CCD sensor of the Nokia 6102 mobile phone (Fig. 2) are presented. The distance to the observation screen is $D = (21.5 \pm 0.1)$ cm. The size of the pixel was calculated by taking the average values of the positions on the x and y axes. Comparative results between the measurements of the diffraction pattern and those obtained using a microscope with a 10$\times$ objective lens are also shown. In Table I, p_{exp} represents the experimental values (with p_{ave} its average), d_{DP} is the pixel size calculated from the diffraction pattern using Eqs. (2) and (3), and d_M is the pixel size obtained using the microscope. The error indicated for p_{exp} in the table is the caliper precision, 0.01 mm. The error for the average of the measurements (p_{ave}) is the maximum value of either the precision of the caliper or the

Table III. Experimental values of the distance between the maxima in the diffraction pattern when the LCD screen from a HTC Smartphone is used.

Direction	x	y
p_{exp} (mm)	12.55 ± 0.01	12.62 ± 0.01
	12.59 ± 0.01	12.56 ± 0.01
	12.67 ± 0.01	12.56 ± 0.01
p_{ave} (mm)	12.6 ± 0.05	12.58 ± 0.03
d_{DP} (μm)	174.9 ± 1.3	175.2 ± 1.0
d_M (μm)	175.23 ± 0.01	175.23 ± 0.01
Disc (%)	0.05	0.004

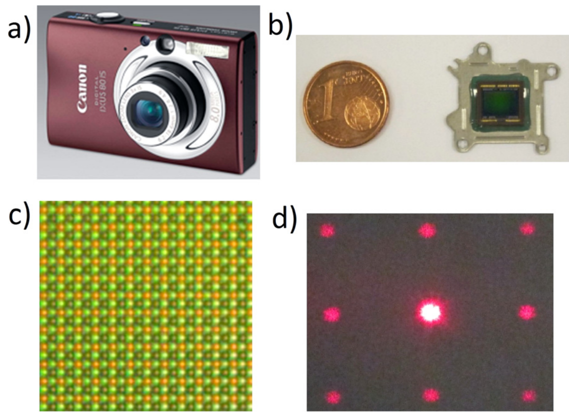

Fig. 3. (a) General view of the digital camera Canon Ixus 80 IS, (b) photograph of the CCD sensor in comparison to a one (euro) cent coin, (c) the microscope image of the sensor, and (d) the central area of the reflection diffraction pattern.

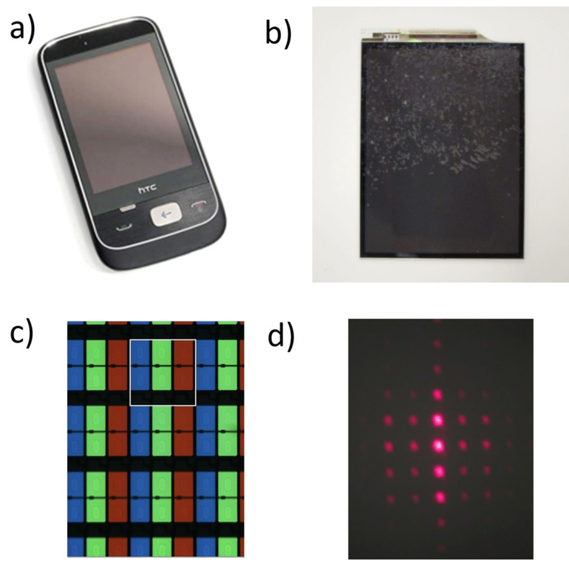

Fig. 4. (a) General view of the LCD screen of the HTC smartphone, (b) photograph of the screen panel, (c) its microscope image, and (d) the central area of the transmission diffraction pattern.

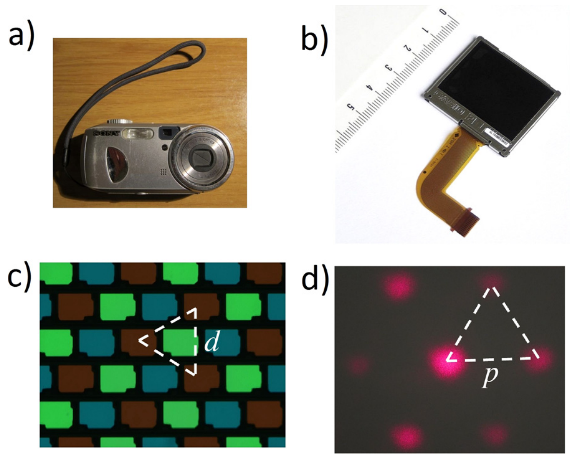

Fig. 5. (a) General view of the Sony DSC P73 digital camera, (b) photograph of the LCD screen, (c) its microscope image, and (d) the central area of the transmission diffraction pattern.

standard deviation of the measurements. In Tables I to IV, the latter is larger than the precision due to the difficulty in localizing the maxima on the observation screen. In order to determine the error associated with the indirect measurement of d_{DP}, a standard propagation of errors procedure is used. Finally, the discrepancy (Disc, as a percent) between the pattern and microscope pixel sizes is shown in the last row of the tables.

B. CCD image sensor of the digital camera Canon Ixus 80 IS

The experimental measurements for the diffraction pattern produced by the CCD sensor of the Canon Ixus 80 IS digital camera (Fig. 3) are presented in Table II. As in the previous experiment the distance to the observation screen is $D = (21.5 \pm 0.1)$ cm. Note that the pixels are smaller than in the previous example due to the higher resolution of this camera. The image shown in Fig. 3(c) was captured using a 40× microscope objective.

C. LCD screen of HTC Smartphone

The experimental measurements for the diffraction pattern produced by the LCD screen of the HTC Smartphone (Fig. 4), are shown in Table III. The distance to the observation screen is $D = (337.0 \pm 0.1)$ cm. The image shown in Fig. 4(c) was captured using the 10× microscope objective.

D. LCD screen of a Sony DSC P73 digital camera

The experimental measurements for the diffraction pattern produced by the LCD screen of a Sony DSC P73 digital camera (Fig. 5) are shown in Table IV. The distance to the observation screen is $D = (300.0 \pm 0.1)$ cm. This experiment is different from the previous experiments because pixels are arranged in a hexagonal lattice. Taking into account, the elementary reciprocal lattice vectors,[19] Eqs. (2) and (3) can be generalized for this situation as

$$p = \frac{\lambda D}{d \sin \alpha}, \tag{4}$$

where $\alpha = 60^\circ$ is the interior angle of a triangle defined by three equivalent pixels, d is the distance between equivalent pixels [see Fig. 5(c)], and p is the distance between nearest-neighbor diffraction orders [see Fig. 5(d)]. For the experimental values shown in Table IV, the size of the pixel d_{DP} is calculated using Eq. (4).

V. CONCLUSIONS

CCD image sensors and LCD displays from discarded mobile phones and digital cameras are used as diffracting apertures, and the results of experiments are used to determine the pixel size of these electronic components. The experiments are simple and inexpensive and can be performed with a laser pointer and a Vernier caliper. Furthermore, the use of electronic components from discarded mobile phones and cameras directly contributes to the repurposing of these materials. Results obtained from the diffraction patterns are compared with those obtained using an optical microscope, yielding very good agreement (discrepancies lower than 0.5%).

When microscopes are unavailable, a comparison can still be performed when using camera CCDs. The size of the pixels can be determined from the area of the screen divided by the number of pixels reported by the manufacturer, usually expressed in megapixels. For example, in the case of the CCD with the highest resolution [Fig. 3(b)], the value provided by the manufacturer is 8 Megapixels (Mp), and the area of the CCD is 6.4×4.7 mm^2. Dividing the area by the distance between two equivalent pixels (3.3 μm, see Table II), the number of pixels of the same type is found to be $1940 \times 1424 = 2{,}762{,}560$ pixels $= 2.76$ Mp. This is consistent with the fact that there are three types of pixels (red, green, and blue), and the resolution of the CCD is stated to be 8.3 Mp (i.e., 3×2.76 Mp ≈ 8.3 Mp).

The proposed experiments are useful as culminating activities when studying interference and diffraction of light and can be undertaken either qualitatively or quantitatively.

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Simple Dynamo Electric Machine

This is a Miller-Cowan-type demonstration dynamo, developed sometime before 1920 by two physics teachers in the Boston school system. The magnetic field is provided by a couple of dry cells connected in series to the field coil at the bottom. Depending on which set of brushes and slip rings are used, the machine will produce either direct or alternating current. In the 1929 Chicago Apparatus Company, this piece of Milvay Apparatus is listed at $19.50. It is on long-term loan to the Greenslade Collection from the Appalachian State University Physics Department. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)