A simple experimental setup for investigating light diffraction with a thin copper wire and a LED

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Abstract

A simple experimental setup for quantitatively investigating single-slit diffraction is described, which uses only inexpensive materials and can be reproduced at home, making it suitable for distance learning. The theoretical basis exploits Babinet's principle, according to which a thin wire – much easier to obtain than a slit – produces, with a very good approximation, a diffraction pattern which is the same as that produced by the slit. A copper wire is placed directly on the camera of a smartphone, and the resulting photos are quantitatively analyzed with Tracker. As light sources, LEDs of different colors are used.

Keywords: wave optics, low-cost experiments, distance learning

1.Introduction

Single slit diffraction is a significant topic in physics curricula, both at the high school and the undergraduate level [1,2]. Indeed, many research papers in Physics Education, also in recent years, addressed this topic from the theoretical [3], experimental [4,5] or educational [6-10] point of view. However, experimental realizations in didactic laboratories are often hindered by the fact that this experiment usually requires expensive calibrated slits, and hazardous laser sources. In this paper, we propose an alternative approach based on Fraunhofer diffraction by thin copper wires, exploiting Babinet's principle, employing commercial Light Emitting Diodes (LEDs) as light sources, and a smartphone to acquire pictures of the resulting diffraction patterns. The photos are then analyzed using the Open Source app Tracker [11], which allows to obtain quantitative results. The experiments we propose can easily be performed at home, hence they are suitable for distance learning.

2. Theory

In recent years, several papers investigated how well single-slit diffraction approximates diffraction around a thin wire. According to Ref. [12], this approximation will produce an error smaller than 5% for wires of diameter greater than $6\ \mu m$ when red light is used, while Ref. [13] discusses how the application of Babinet's principle leads to erroneous results when Fraunhofer diffraction of a Gaussian wave field on a thin wire is considered instead of a plane wave. In Ref. [14], the diffraction pattern of waves scattered by a thin wire was evaluated by means of the Rayleigh-Sommerfeld integral in the Fraunhofer approximation: comparing the results of Babinet's principle with the direct evaluation of the scattering integrals showed that the principle holds excellently for this problem. In light of this, we will employ Babinet's principle. We recall that according to this principle, stated in 1837 by Jacques Babinet [15], the sum of the fields scattered by an obstacle, and by the complementary aperture, is equal to the unobstructed incident wave [16].

In the following, we refer to the usual textbook expression for the intensity $I(\theta)$ of the Fraunhofer diffraction pattern by a single slit of width a, given by [16]:

$$I(\theta) = I_m \left(\frac{\sin\alpha}{\alpha}\right)^2 \tag{1}$$

where

$$\alpha = \frac{\pi a}{\lambda} \sin\theta \tag{2}$$

and I_m is the greatest value of the intensities in the pattern, which occurs at the central maximum (where $\theta = 0$). Intensity minima occur when

$$m\pi = \frac{\pi a}{\lambda} \sin\theta, \ \ for \ \ m = 1,2,3,\ldots \tag{3}$$

where in our case we can approximate $\sin\theta \approx \theta$, since we shall only conseder cases in which the angles are very small. From Eq. (3) we see that the distance between the minima is proportional to the wavelength and inversely proportional to the width of the slit. According to Babinet's principle, in the case of a wire of the same width of the slit, the diffraction pattern is the same, apart from the central maximum, and in particular we expect the same dependence of the distance between these minima on the wavelength and on the width of the wire.

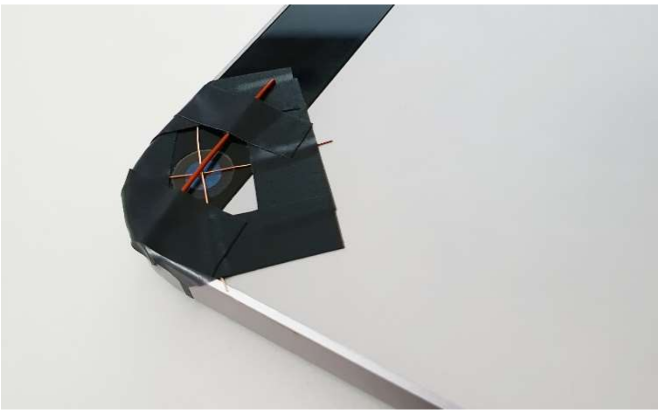

Figure 1. Positioning of three wires of different widths on the camera.

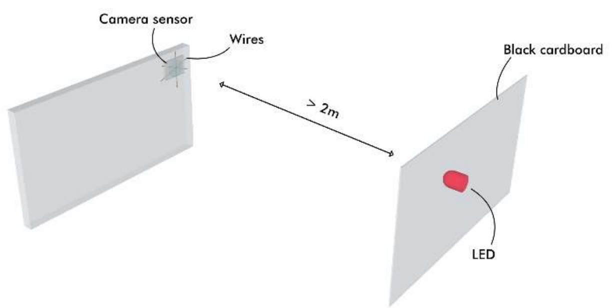

Figure 2. Drawing (not to scale) of the experimental setup.

2. Experiment

The experimental setup consists in placing copper wires of known width directly on the smartphone camera, as shown in Fig.1. This is the most practical way to put the diffracting wires in front of the camera, and moreover the camera lens ensures the validity of the Fraunhofer approximation. In order to compare the diffraction patterns obtained with wires of different widths, we can employ a reference wire, which must be always present. Then, the LEDs are framed from a distance of 3 meters. All measurements are best performed with the room lights off, but we observed that good results are possible even if the lights are on, provided a black cardboard sheet is put behind the LED to enhance contrast. The setup of the experiment, including the cardboard, is depicted in Fig. 2. Let us now describe two different experiments which can be conducted with this setup, allowing to probe the two dependences of the distance between minima.

2.1 Experiment 1: Diffraction patterns of a monochromatic source

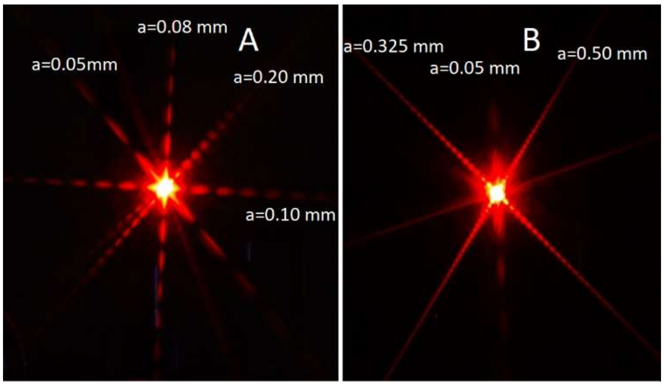

Figure 3. Diffraction patterns obtained with a red LED and using wires of width: (A) 0.05, 0.08, 0.1, 0.2 mm and (B) 0.05, 0.325, 0.5 mm.

In the first experiment, we frame a red LED and photograph the diffraction patterns thus obtained, as shown in Fig. 3. The results of the measurements, obtained by analyzing the photos with Tracker by using standard routines, are reported in Table 1 and depicted in Figs. 4 and 5. They are in good agreement with the expected dependence of the distance between minima on the inverse of the width.

Thickness (mm)	Distance between dark fringes (pixels)
0.05	82 ± 4
0.08	41 ± 4
0.1	35 ± 2
0.2	14 ± 2
0.325	13 ± 2
0.5	9 ± 2

Table 1. Data acquired from Fig. 2 with Tracker. The widths are the nominal ones, provided by the manufacturer. The widths are the nominal ones, provided by the manufactures. We verified them with a digital calibre with a 0.01 mm accuracy.

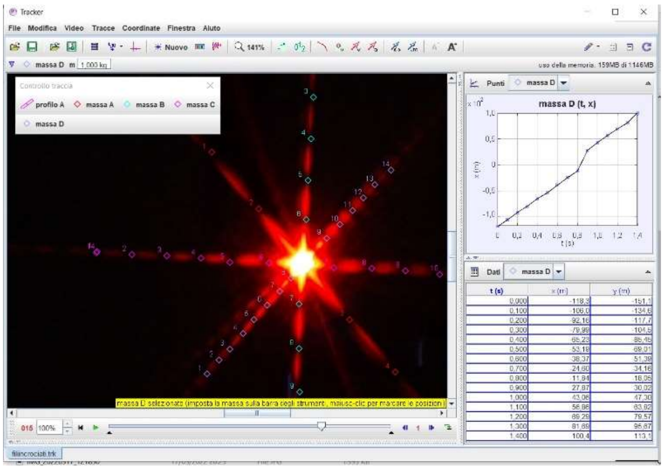

Figure 4. Example of the Tracker analysis of the diffraction patterns also shown in Fig. 3.

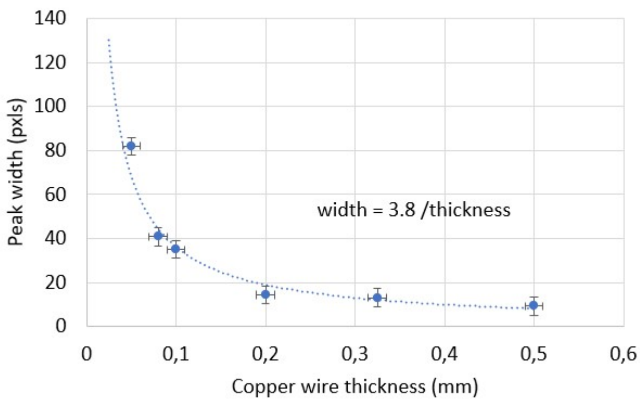

Figure 5. Distance among the minima as a function of the width of the wire.

2.1 Experiment 2: Diffraction patterns of several coloured sources

In the second experiment we investigate the dependence of the distance between minima on the wavelength of the light. For this purpose, we use a single wire with a thickness of 0.08 *mm* and six LEDs of different colors, placed along a horizontal rod, as shown in Fig. 6, where the photo of the diffraction patterns is shown as well. Fig. 7 shows the Tracker analysis. In Fig. 8 we plot the resulting luminance, computed according to Ref. [17], for the yellow LED.

We then measured the distances between minima for the different LEDs, which are reported in Table 2 and plotted in Fig. 9. The proportionality between the distances between minima and the wavelength is evident.

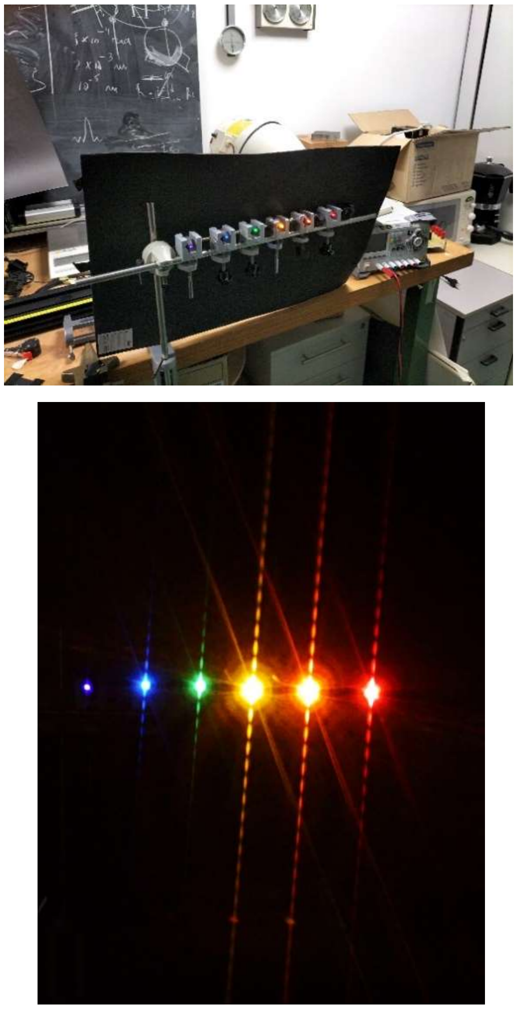

Figure 6: The six different LEDs placed on a horizontal rod, and the diffraction patterns (the violet one is too weak to be seen).

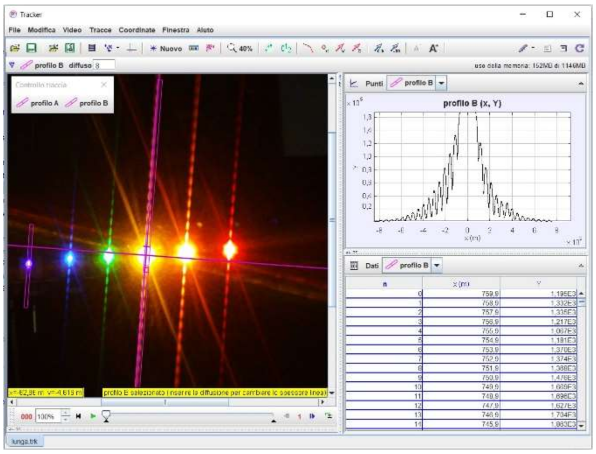

Figure 7: Example of the Tracker analysis of the diffraction patterns also depicted in Fig. 6.

LED color	Wavelength (nm)	Peak width (Pixels)
Red	630	50 ± 4
Orange	605	49 ± 2
Yellow	592	47 ± 2
Green	525	43 ± 4
Blue	470	37 ± 4
Violet	405	32 ± 4

Table 2. Width of the peaks and nominal wavelength of the LEDs as provided by the manufacturer. Additional information is available on the website [18]. We also verified them by using a home-made spectrometer as described in Ref. [19].

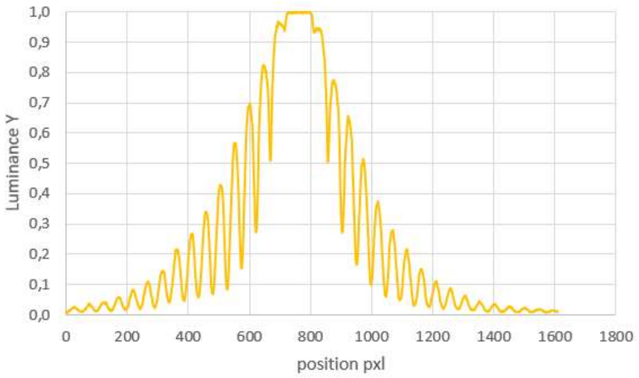

Figure 8. The Measured Luminance for the Yellow LED.

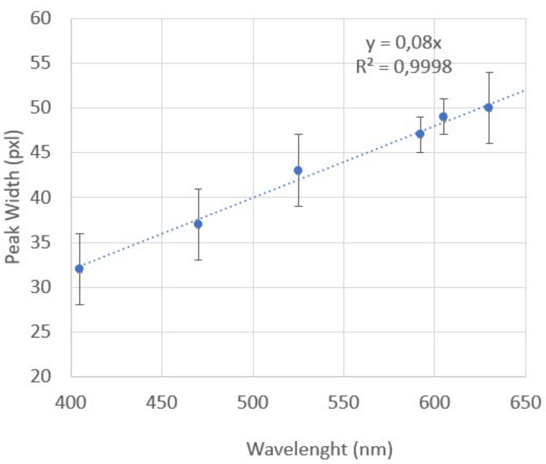

Figure 9. Width of the peaks as a function of the wavelength.

3. Conclusions

We have demonstrated how the laws of diffraction can be quantitatively investigated without using lasers and expensive materials, but only copper wires, a common smartphone camera and the free Tracker software. Such a setup is especially suitable for distance learning. It can also be important in view of more advanced uses, such as a low-cost spectrometer [20].

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