Beyond maxima and minima: A hands-on approach for undergraduate teaching of diffraction

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ABSTRACT

Since the discovery of the wave behavior of light, diffraction has been a cornerstone in optics. The teaching of the diffraction theory has been usually done theoretically based on a mathematical approach that could hinder the understanding of the physical phenomena. In this work, the simplicity in the architecture of an accessible, cost-effective, and 3D-printed digital lensless holographic microscope is used as an educational tool to study the diffraction theory by providing experimental validations of the phenomena for undergraduate students. The recording and reconstruction steps of the lensless holographic technique take the students to the bidirectionally of the diffraction phenomena in a completely hands-on approach. The integration of the theory with an accessible experimental setup generates an innovative way of teaching the diffraction phenomena in a classroom.

Keywords: Diffraction, single-slit, microscopy.

INTRODUCTION

In 2017, UNESCO recognized light-related technologies as a key factor for human development, as they provide answers to the needs of humanity by enabling access to information, promoting sustainable development, and improving well-being and living standards [1]. The study of light has led to promising life-saving medical advances in diagnosis and treatment [2–4], support electromagnetic communications at different levels, developed advanced manufacturing, and many other technologies that have revolutionized our understanding of the universe and opened new scientific frontiers[5]. As common factor to these applications, the understanding of diffraction has been a mainstay, with diffraction-related developments that span fields such as fiber optics implemented in structural health monitoring in civil and aerospace engineering [6], spectroscopic techniques in the analysis and measurement of various substances [7], diffractive optics [8,9], holographic microscopy [10], and advanced applications in quantum computing [11].

Despite the importance and all the diverse applications of diffraction, the initial approximation that students usually have with its study is through defining diffraction as “the numerous spatial radiation propagation effects that cannot be explained by geometrical optics or light interference” [12]. Along these lines, the wave properties of light are often taught so that students are conducted to solve complicated math problems [13], and when it comes to actually observing the phenomenon, the first readily-available experimental setup to demonstrate diffraction is the single-slit experiment [14,15]. This is usually done with a monochromatic light source, a laser diode in most cases, a slide with a narrow opening, and a projection screen to visualize the diffraction pattern. In this way, students can validate the wave nature of light and make on-screen measurements to determine the wavelength of the light source used and/or the size of the aperture.

Regardless of the importance of conducting the single-slit experiment in understanding diffraction, students are limited to making measurements on a screen placed some meters away from the slit, often leaving the comprehension of the phenomenon behind and failing to observe important features of particular diffraction patterns and identify the differences between them [16]. Moreover, the paradigm jump from geometrical optics to wave optics is not easily grasped; since these demonstrations use a geometric approach to obtain the measurements and wavelengths, the concept that diffraction is a direct consequence of the wave nature of light is not fully understood [17,18]. Additionally, by performing the said measurements in a 1D projection, the 2D structure of diffraction is left behind.

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Diverse technologies and new educational tools are being implemented to improve the quality of teaching and learning processes [19]. In this sense, laboratory experiments require hands-on, accessible, and cost-effective tools and equipment [20–22]. This work presents the use of a digital lensless holographic microscope (DLHM) to teach and analyze the diffraction phenomenon beyond the typical measurements of the distance between high-intensity peaks in 1D diffraction patterns. Using the DLHM and an image processing plugin, diffraction can be taught as the enabling physical phenomenon to produce images of micro-sized objects.

CLASSICAL TEACHING APPROACHES TO DIFFRACTION

For undergraduate students, the first approach to the wave nature of light is through phenomena such as interference and diffraction[14]. Initially, interference is presented as the superposition of light waves of the same wavelength in a given region or point in space. The phenomenon is demonstrated by showing how two waves interact to produce a periodic interference pattern. This allows students to relate this observation to common phenomena, such as thin films of oil and soap bubbles that create a rainbow interference pattern and are easy to teach and understand[14]. Diffraction is commonly presented to students, in a first approximation, as the special propagation effect that cannot be explained by refraction or interference [12]. In this way, students usually do not get much further than the validation of the classical phenomena by a theoretical analysis, or, in the most fortunate case, the experimental observation of this phenomenon using a monochromatic collimated light source and an aperture or obstacle. Figure 1.(a) illustrates the schematic of the diffraction through a single slit, and the experimental diffraction pattern using a 30 μm narrow aperture is shown in Figure 1.(b).

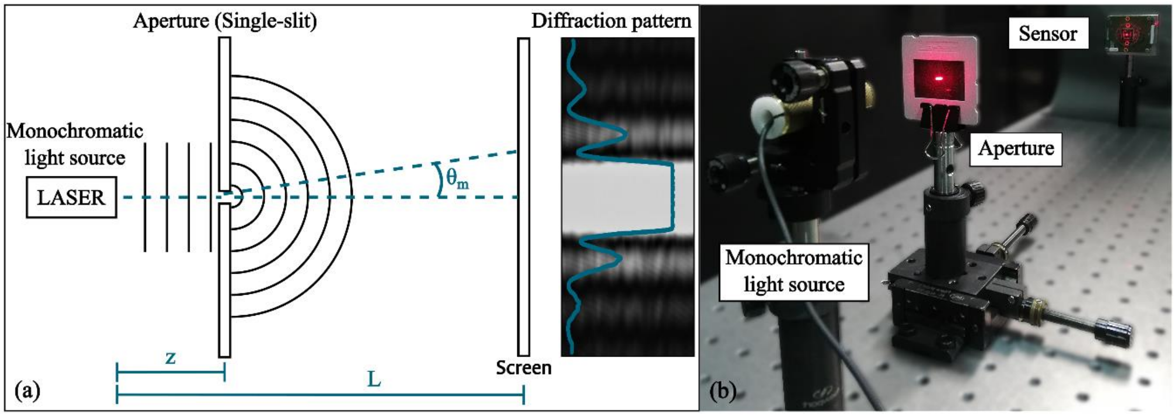


Figure 1. Diffraction through a single-slit aperture (a) schematic with experimental diffraction pattern and (b) teaching laboratory setup.

The common teaching approach to diffraction is to present the 1D intensity profile in Figure 1.(a) as the diffraction pattern given by[14]

$$I(\theta) = I_0 \left[\frac{\sin\left(\frac{\pi\, b \sin\theta_m}{\lambda}\right)}{\frac{\pi\, b \sin\theta}{\lambda}} \right]^2 , \tag{1}$$

where b is the size of the slit, θ is the angle subtended between the optical axis and the m-th minima to be measured, as shown in Figure 1.(a), λ is the illumination wavelength, and I_0 is the intensity of the pattern when $\theta = 0$. The position of the diffraction minima is determined by solving Eq (1) for $I(\theta) = 0$ where the term $\sin\theta_m$ is replaced by a geometrical expression in terms of the distance z, measured from the slit to the screen, and the distance y_m, measured from the optical axis to the m-th minima. This condition can be written as:

$$b \frac{y_m}{\sqrt{y_m^2 + z^2}} = m\lambda. \tag{2}$$

From Eq. (2), the 1D diffraction pattern can be characterized using only the geometric variables of the system. In a common approach to this experiment, the optical setup is used to measure the slit width. This experiment is usually conducted in the framework of the Fraunhofer diffraction regime[23], where the projection screen is placed at a long distance from the object plane that contains the aperture or obstacle. This long distance is necessary to ensure that the diffraction pattern magnifies until it becomes visible to the naked eye and the measurements can be made with a regular ruler without any digital recording system support.

In more advanced approaches, diffraction theory can be extended to students as a phenomenon that occurs beyond the simple 1D apertures such as the single-slit. In a practical approach, the diffraction patterns produced by 2D apertures and stops are studied[23]. Nevertheless, this analysis is usually limited to theory due to the limitations in laboratory supplies and equipment. A common case of these studies is the circular aperture, where students are taught that, under the same illumination and distance conditions of the previous analysis, its corresponding diffraction pattern is a bright central region with a series of concentric disks, called the Airy disk pattern[23], with the 2D intensity distribution [24]

$$I(x,y) = I_0 \left[\frac{J_1\left(\frac{\pi\, d\, \sqrt{x^2+y^2}}{\lambda\, z} \right)}{\frac{\pi\, d\, \sqrt{x^2+y^2}}{\lambda\, z}} \right]^2 , \tag{3}$$

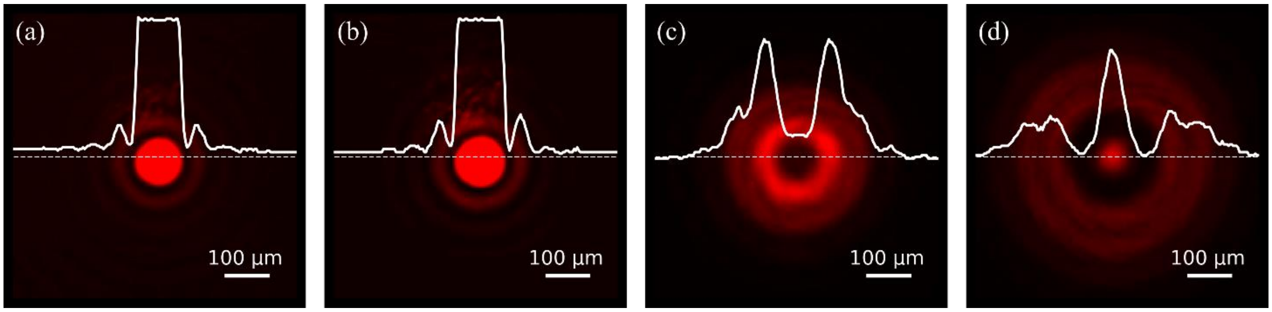
where (x,y) are the coordinates at the observation plane place a distance z from the aperture, d is the diameter of the circular aperture, and $J_1(\vec{r})$ is a first-order Bessel function of the first kind [23,24]. From this expression, it is again possible to determine the minima position by solving Eq. (3) for $I(\vec{r}) = 0$. A common expression for the first minima of the circular aperture pattern is[23]

$$\sin\theta = \frac{y_m}{\sqrt{y_m^2 + z^2}} = 1.22\frac{\lambda}{d}. \tag{4}$$

Students can be further encouraged to ask themselves what happens when the illumination characteristics are changed. For example, using the circular aperture in the same laboratory setup with a divergent illumination. When a divergent light source is used as the illumination, the produced diffraction pattern changes with the propagation distance; as the distance increases, the pattern becomes increasingly magnified and differences in the shape of the pattern are observed.

As shown in panels (a) and (b) of Video 1, this new implementation displays the typical Airy pattern when the distance of the screen from the aperture is large; as the aperture gets closer to the illumination source, new diffraction patterns, unlikely to be observed under a plane wave approximation are produced, as shown in panels (c) and (d) of the same figure. These new patterns are characterized by a highly structured shape that is unexplainable by the Airy disk description in Eq. (3) that students are accustomed to, this new kind of information corresponds to the Fresnel[23] diffraction pattern of the circular aperture, which demands, under a plane wave approximation to be capable of recording the produced diffraction pattern at a distance around 0.1 mm away from the circular aperture; that is a highly demanding task even with top level equipment and skills. Even though this is a really interesting phenomenon to be observed, it can be seen from the intensity profiles plotted in Video 1, that recovering the aperture information from these patterns demands an analysis that goes beyond measuring the distances between maxima and minima.

A clear advantage of the implementation described above is that a more compact and flexible system can be used to observe diffraction patterns that are experimentally demanding. Moreover, the generation of diffraction patterns with changing shapes and morphologies allows an improved comprehension of diffraction that enables the understanding of patterns far side of the Fraunhofer regime as it is usually studied, where students can go beyond an operational and repetitive approach of measuring distances between high-intensity peaks. Instead, this physical phenomenon can be shown to be the key feature that enables high-performance microscopy when the sample under analysis is not constrained to a well-defined stop or aperture.



Video 1. Frames of the video of diffraction through a circular aperture using a divergent illumination source as the distance *z* changes. Panels (a), (b), (c), and (d) show the diffraction pattern registered at the screen with the circular aperture placed at 1.0 mm, 0.5mm, 0.12 mm and 0.07 mm from the point source. http://dx.doi.org/**10.1117/12.2662594.1**

BEYOND ONE DIMENSION, THE STUDY OF 2D DIFFRACTION PATTERNS

The implementation to generate the patterns shown in Video 1 can be accomplished with an accessible, cost-effective, and 3D-printed digital lensless holographic microscope (DLHM)[25], presented in Figure 2 (a). This microscope is based on a monochromatic point source of spherical waves that illuminates a sample located at a distance *z* from the said source. The diffraction pattern of this sample is recorded on a CMOS sensor located at a distance *L* from the said source, as shown in Figure 2 (b). In this configuration, the sample plane is analogous to the aperture plane of the previous cases, and the sensor corresponds to the screen shown in Figure 1.

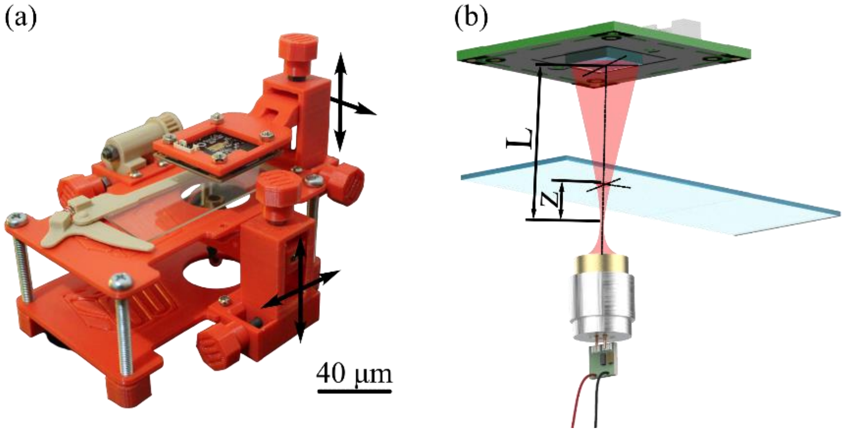


Figure 2. (a) DLHM prototype (b) Components of the prototype

The divergent illumination of the DLHM allows the magnification of the diffraction pattern to be varied by changing the position of the illumination source. This mechanism, linked to a 3D-printed XY stage (Figure 2.(a)), empowers the students to reproduce a variety of diffraction patterns with different magnifications and to observe changes in morphology, such as the ones illustrated in Video 1. Being an open-source and cost-effective implementation, the fabrication of the device costs only about 55$ USD, and all of its documentation can be found on its GitHub page [26].

As mentioned previously, not all the diffraction patterns allow the analysis of the maxima and minima to obtain information about the diffracted object. However, for educational purposes, the DLHM can provide this information. Since holography is a two-stage imaging method, the bidirectional nature of the diffraction phenomena can be presented to students. In the first stage, a micrometer-sized object, as shown in Figure 3(a), is illuminated using the DLHM (Figure 3(b)) to generate its corresponding diffraction pattern, which is recorded in the digital sensor. These patterns, called holograms in this technique, are shown in Figure 3(c).

The second stage is the recovery of the sample information. As mentioned before, a setup like the DLHM produces diffraction patterns with different morphologies than those produced in a typical teaching laboratory. The patterns are digitally recorded without knowing their analytical expressions, unlike those for the single-slit or circular aperture. Thus, recovering the information of the object used to obtain the diffraction pattern, requires going beyond maximum and minimum measurements and understanding the structure of the diffraction pattern as that which conveys the information of the sample that produced it. For this stage, a user-friendly ImageJ plugin[27] is used (Figure 3 (d)). This plugin can computationally emulate the diffraction phenomenon, just like the DLHM physically allows it. Consequently, the information of the object that produced the diffraction pattern can be recovered by reversing the diffraction phenomenon; that is, by digitally recreating the propagation that the light underwent in the microscope, but in the opposite direction. Like the single-slit or circular aperture calculations, the plugin receives as input the diffraction pattern (hologram), the geometric parameters of the setup, and the wavelength of the light source. And, just as the analytical expressions allow the determination of the slit or aperture sizes, the propagated diffraction pattern recovers the information of the diffracted objects that generated it, as shown in Figure 3(e). Detailed information on how to download, install, and use the DLHM plugin is available online [27,28].

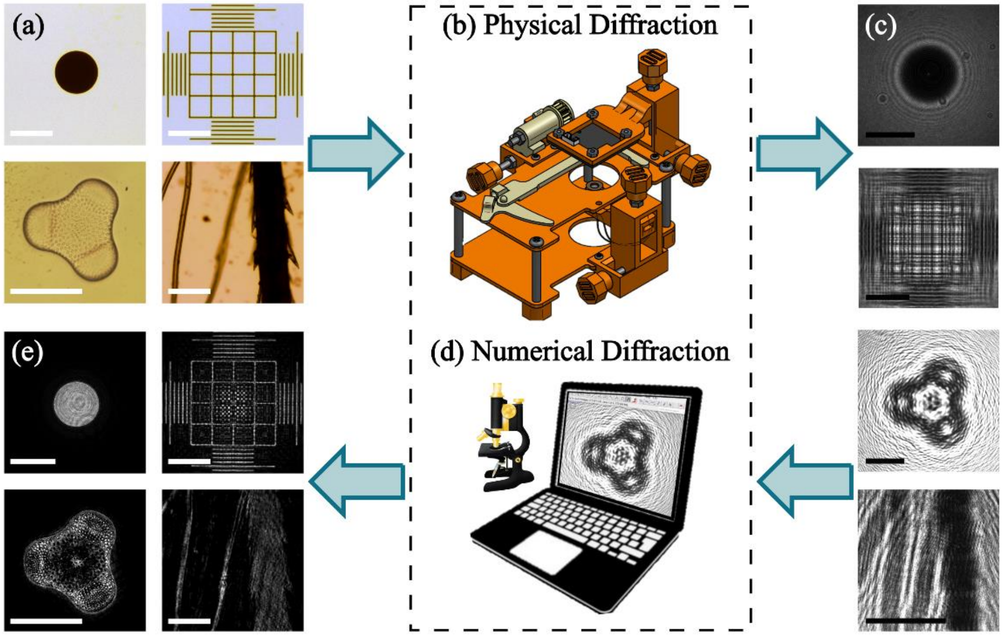


Figure 3. Bidirectionally of the diffraction phenomena using four different objects; (a) 0,1 mm diameter circle, reticle, *Diatom algae,* and *Poaceae* flower spike (b) Diffraction with the Micro-DLHM (c) Diffraction patterns (holograms) of the four objects registered in the Micro-DLHM camera (d) Diffraction of the holograms with the ImageJ plugin (e) Recovered objects. White scale bars correspond to 100 µm and black scale bars correspond to 1mm.

Once the information of the diffracted object is recovered, it is possible to perform measurements of the lateral dimensions of the features of the object. This allows additionally to the visualization, accurate measurements of the object properties. A simple DLHM setup and reconstruction process permits the retrieval of the information from micrometer-sized objects, emphasizing the utility of the diffraction phenomenon. Therefore, students can directly interact with the DLHM and the ImageJ plugin to obtain images of microscopic objects, understanding diffraction as the key factor that enables this process.

This way of understanding and learning diffraction allows thinking far beyond simply measuring the position of maxima and minima on a screen, and to understand diffraction as a consequence of the wave nature of light. The DLHM provides a hands-on experience where the students obtain a variety of non-traditional diffraction patterns without the need for expensive or complex laboratory setups, while promoting a “learning by doing” approach. With the reconstruction stage, students can understand the relevance of diffraction in today’s technology, where it is not just a theoretical phenomenon, but a behavior of light that enables endless applications in science, such as microscopy.

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