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Investigating diffraction phenomena with low-cost material and augmented reality

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So far, there have only been a few articles in this column that discussed diffraction¹ or augmented reality (AR) enhancements.^{2,3} In this article, we want to bring both aspects together and describe an experiment that can be used to investigate diffraction phenomena with low-cost materials and augmented reality in the classroom. Diffraction experiments in schools often have (at least) two difficulties:

- A real-time measurement and visualization of the intensity distribution is not available.
- The positions of minima on a screen are often not precisely determinable. However, this would be crucial for diffraction experiments, especially with a single slit.

The experiment presented here addresses these difficulties and allows the measurement and visualization of the intensity distribution of diffraction phenomena in real time using low-cost means.

Theory

In the following, it is assumed that the incoming laser beam is at the normal incidence to the grating and that the Fraunhofer condition $s^2/(D\lambda) \ll 1$ (where λ is the wavelength of the laser used, s is the size of the largest diffracting structure, and D is the distance between the diffraction object and the plane of observation) is satisfied.

Therefore, for diffraction gratings, the following well-known intensity distribution results⁴:

$$I(\alpha) = I_0 \left[\frac{\sin\left(\frac{\pi \cdot w \cdot \sin(\alpha)}{\lambda}\right)}{\frac{\pi \cdot w \cdot \sin(\alpha)}{\lambda}} \right]^2 \cdot \left[\frac{\sin\left(\frac{p \cdot \pi \cdot g \cdot \sin(\alpha)}{\lambda}\right)}{\sin\left(\frac{\pi \cdot g \cdot \sin(\alpha)}{\lambda}\right)} \right]^2.$$

Here, I_0 denotes the intensity at the diffraction angle zero, λ the wavelength of the light used, α the angle at which the respective intensity can be observed, g the distance between two adjacent slits, p the number of slits contributing to the diffraction phenomenon, and w the width of the slits. The fraction on the right is important if the diffraction object consists of

multiple slits. When studying diffraction at a single slit ($p = 1$), as described below, this fraction goes to 1.

For the fraction on the left side, the zeros of the intensity distribution resulting from the diffraction at the individual single slits can be calculated to be

$$\sin \alpha_{\min} = \pm \frac{\lambda}{w}, \pm \frac{2\lambda}{w}, \dots, \pm \frac{n\lambda}{w} \text{ for } n = 1, 2, \dots \quad (1)$$

(where n is the diffraction order).

The maxima of the left fraction, on the other hand, cannot be determined directly from the given formula, but only graphically or numerically.

Using the small-angle approximation $\alpha \approx \sin \alpha \approx \tan \alpha = x/l$ (where l is the distance between the diffraction object and the viewing plane and x is the distance between a point of the interference pattern and the central maximum), the constant a for the background intensity, the transformation $x \rightarrow x - d$ (where d is the distance between the central maximum and the origin of the coordinate system), and the substitutions $c = w/(\lambda l)$, $e = g/(\lambda l)$, and $b = I_0 p^2$, one can deduce the following alternative representation of the relationship, which is easier to fit to the measured intensity distribution:

$$I(x) = a + b \cdot \frac{\sin^2[\pi \cdot c \cdot (x - d)]}{[\pi \cdot c \cdot (x - d)]^2} \cdot \frac{\sin^2[\pi \cdot p \cdot e \cdot (x - d)]}{p^2 \cdot \sin^2[\pi \cdot e \cdot (x - d)]}. \quad (2)$$

By substituting $b = I_0 p^2$, the right fraction can be limited to values between 0 and 1. The maximum of $I(x)$ is therefore always $a + b$.

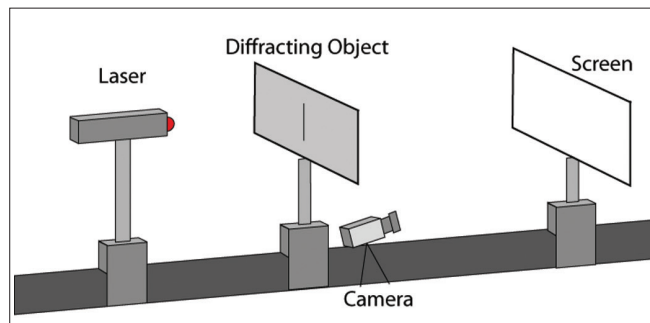


Fig. 1. Illustration of the experimental components.

Experimental setup

The setup of the experiment is depicted in Fig. 1. A commercially available laser, such as those offered by manufacturers of teaching aids, is directed at a diffraction object. Behind the diffraction object, there is a white screen on which the diffraction image is visible. Furthermore, a low-cost webcam is necessary for the setup. The webcam points in the direction of the screen and records the diffraction pattern. Cameras that allow manual adjustment of focus, zoom, and aperture are best suited for this purpose. The camera used in the experiment described here has a maximum resolution of 3264×2448 pixels.

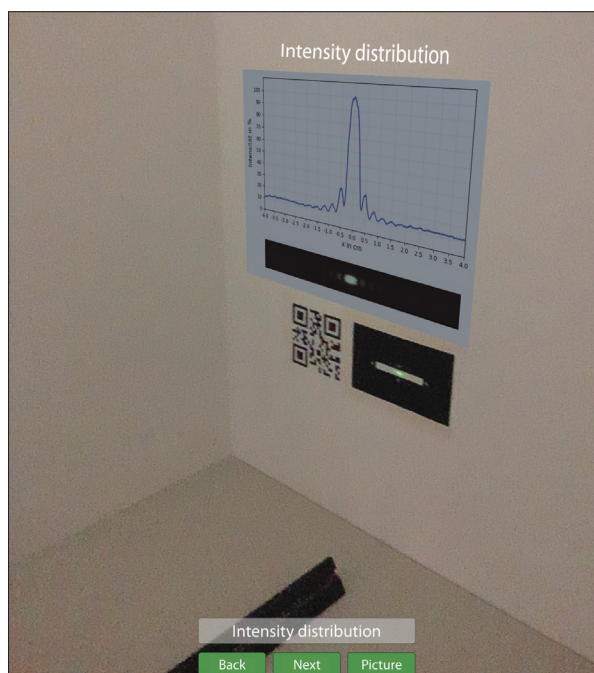


Fig. 2. Diffraction pattern and intensity distribution of a single slit. Screenshot of the augmented reality iOS application.

Investigating the dimensions of a single slit

To investigate diffraction phenomena on a Windows computer, the webcam must be connected to the computer via USB. The .exe file of the Windows application and a manual for the software can be downloaded from the following link: <https://www.didaktik.physik.uni-muenchen.de/sims/resources/diffraction/DiffractionApp.zip>.

To perform the AR version of the experiment with iOS devices or the HoloLens 2, beside the adapted software for these end devices, a Raspberry Pi is required for data processing and provision.

The intensity distribution is measured and displayed in real time and makes it possible that changes at the diffraction object (e.g., if the width of a single slit is changed) are instantly observable not only in the interference pattern but also in the intensity distribution. Thereby, the AR application allows the measured intensity distribution to be displayed next to the observed diffraction pattern (Fig. 2).

To investigate diffraction, the application supports the following two approaches:

- First, measuring the positions of minima and maxima of the intensity distribution and using the formula for the theoretically expected positions [e.g., Eq. (1) for the single slit].
- Second, fitting Eq. (2) to the measured intensity distribution. Figure 3 shows the corresponding user interface of the Windows application and a possible fit. From the fit parameter $c = 2.96 \text{ cm}^{-1}$, the wavelength of the laser ($\lambda = 532 \text{ nm}$), and the distance between the diffraction object and the viewing plane ($l = 110 \text{ cm}$), a slit width of 0.173 mm results for the examined single slit. The uncertainty in adjusting c with the slider can be estimated to a max-

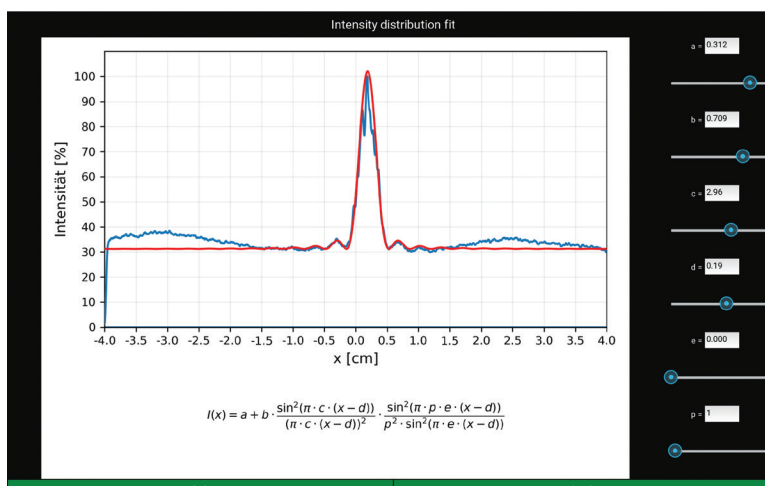


Fig. 3. Screenshot of the Windows application for fitting the intensity distribution of a single slit.

imum of 0.1 cm^{-1} . The uncertainty of the wavelength is 1 nm (manufacturer specification) and of the distance between the screen and the laser 1 mm. Overall, the uncertainty for the width in the worst case is $6.3 \mu\text{m}$, which corresponds to a deviation of 3.7%.

Conclusion

The experiment presented here allows the measurement and visualization of the intensity distribution of diffraction phenomena in real time using low-cost means. In addition, possibilities are given to precisely determine the positions of the minima and maxima on the screen. Handling in the beam path is not necessary, which means that the experiment can also be carried out independently by the learners. As a next step, we will use process data⁵ to investigate whether the AR or desktop application is best suited to foster students' learning.

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iPhysicsLabs are short articles featuring uses of smartphone technology in physics teaching. To submit, please email Jochen Kuhn (jochen.kuhn@lmu.de) and Patrik Vogt (Patrik.Vogt@pl.rlp.de).