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A 3D-printed modular kit for low-cost wave optic experiments in education

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Abstract
In this paper, we present a low-cost, modular 3D-printed experimental system for teaching and learning wave optics and introductory quantum optics. The kit enables robust and reproducible setups for polarization and interference experiments, including Malus' law, Michelson and Mach-Zehnder interferometers, and a quantum eraser analogue. A brightness sensor, that can be read out with a mobile device, allows quantitative measurements. Designed for secondary education, the system supports hands-on experimentation and provides classical analogues for key quantum-optical concepts. Classroom tests demonstrate their suitability for guided student use at low cost.

Keywords: low-cost, wave optics, experiments, 3D-printing

INTRODUCTION

Quantum technologies are of great importance in research and industry. Their applications will have an increasing influence on our everyday lives. With this relevance, the importance of quantum optic experiments in secondary school curricula is also increasing word wide. However, the experiments themselves are often too expensive and complicated to be used by schools in the classroom. In fact, even setups for basic wave optics experiments such as interferometers usually exceed school budgets.

On the other hand, basic wave optics experiments are particularly exciting for school practice because they are simple enough to set up to allow pupils to experiment independently. In addition, the results can often be transferred to analogies in the case of individual photons, thus providing a basis for discussing quantum optics experiments.

Below, we present a system for low-cost experiments that can be used to conduct various experiments on interference and polarization. Because the experiments can all be produced using 3D printing, the cost factor is significantly lower than that of commercial educational equipment suppliers. At the same time, the setup is designed for use in educational contexts, so that the experiments can usually be carried out by secondary school students within a 90-minute lesson. This includes different scaffoldings for easier setup and the possibility to correct mistakes fast (Haverkamp et al., 2022).

Parts of an older version of this set have already been published in Haverkamp et al. (2022). The experiments presented here are based on an updated version of the components. In addition, the newly developed brightness sensor, which is presented in section 3.1, enables various quantitative measurements to be conducted.

ABOUT THE MODULAR SYSTEM

The experiments described here use a modular optical system that allows all components to be used flexibly for different experimental setups. The optical components are enclosed in cube-shaped, 3D-printed frames with an edge length of 50 mm (**Figure 1**). These frames ensure both high mechanical stability and the necessary protection for the optical components, which is important when working with schoolchildren.

The cubes are placed on a base plate with embedded magnets. These create a fixed grid with 6 × 4 locations

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Contribution to the literature

- We present a modular setup for 3D-printed wave optic experiments in educational settings.
- We show and describe exemplary results of these experiments.
- We suggest how these experiments can be used as a basis to talk about quantum optics.

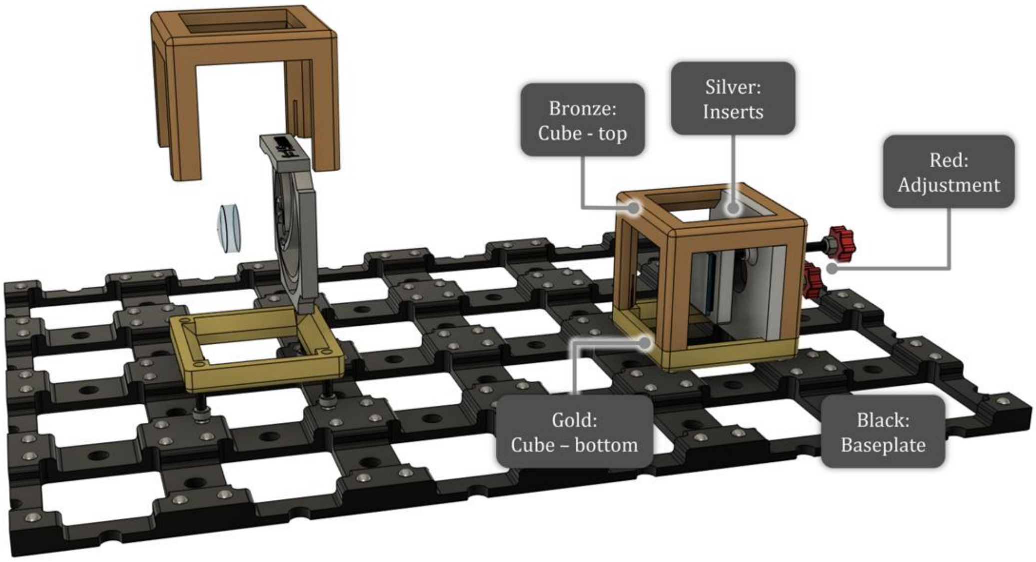

Figure 1. Overview of the modular system (on the left-hand side, an exploded view of a lens module can be seen & on the right-hand side, the color system is described on the example of an adjustable mirror) (the authors' own illustration)

where the modules can be easily positioned and securely fixed (**Figure 1**). Although the grid reduces flexibility, it makes it easier to overview and reproduce the positioning of the modules, thus helping to identify and prevent errors during assembly. Magnetic positioning enables quick assembly and easy modification of experimental setups. The system is based on and compatible with the open-source UC2 optics kit (Diederich et al., 2020).

The modular system is designed using a research-based design process (van den Akker & Nieveen, 2021) to make it as easy and intuitive to use as possible. For this purpose, a color system was used, as shown in **Figure 1**. It is worth highlighting that the underside of the otherwise very symmetrical cube has a different color to the top side, so that even in the low ambience light typical of optical experiments, it is clear which side of the cube belongs on the grid. In addition, the components that are adjusted or set during the experiment are marked in red.

During the design process, emphasis was also placed on ensuring that the set can be easily replicated by educators and learners. All components can be printed on an average FDM 3D printer without a support structure in around one day of printing time. The plant-based, recyclable and compostable standard material PLA is perfectly adequate for this purpose. All the other materials like optical components, screws and magnets are low-cost and commercially available and linked on the website.

POLARIZATION EXPERIMENTS

Polarization of light is an important aspect of wave optics that even has everyday relevance. It can be found, for example, in LCD displays, as filters for cameras, in 3D cinema glasses and in certain types of sunglasses. While these applications have been well known for a long time, experiments with individual photons have also been possible in recent decades. For example, photons can be entangled in their polarization state, the polarization state of photons can be used to exchange information, and polarization also plays a central role in quantum eraser experiments.

It is therefore also relevant to understand and describe the polarization properties of single photons. Typically, the description is then based not on intensities, but on probabilities.

Our low-cost experiments are not capable of simulating entanglement. However, they are well suited for investigating the fundamentals of polarization. Two example experiments are presented below. In addition, we present an analogy to the quantum eraser, which can help to understand delayed choice experiments.

Examining Malus Law

Malus' law describes how much polarized light is transmitted by a polarizing filter. The transmitted intensity is given by $I = I_0 \cos^2(\gamma)$, where I_0 is the incident intensity and γ the angle between the

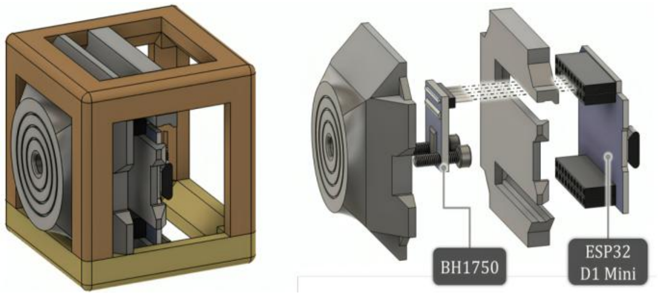

Figure 2. Brightness sensor (left: fully assembled brightness sensor; right: exploded view; & BH1750 is plugged directly into the ESP32) (the authors' own illustration)

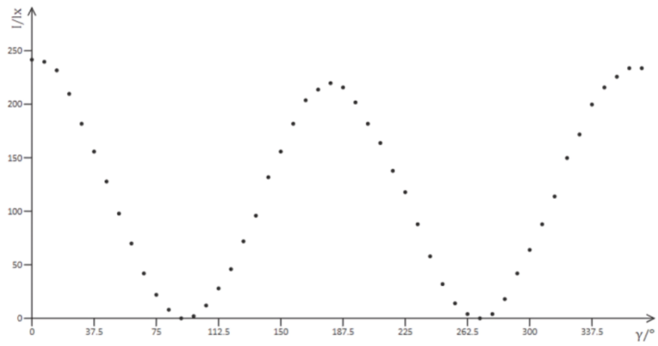

Figure 3. Sample measurements used to investigate Malus' law (screenshot of the brightness sensor interface; measurements were taken at intervals of 7.5°) (the authors' own illustration)

polarization direction of the incident light and the transmission axis of the polarizer.

This relationship can be quantitatively investigated using the experiment kit presented here. The brightness sensor module (**Figure 2**) is used for this purpose. It consists of a BH1750 brightness sensor connected to an ESP32 D1 Mini. As soon as the ESP32 is powered via USB, it hosts a local Wi-Fi network and provides a local website. Wi-Fi-enabled devices can access this website via their browser when they are connected to the Wi-Fi network of the ESP32, where they can control and read the sensor. Among other things, multiple measured values can be displayed in the form of a graph.

To investigate Malus' law, two polarization filters and an LED are used in addition to the brightness sensor. An LED is used here because, unlike a laser, it emits unpolarized light. An example measurement result showing the typical curve of Malus' law can be seen in **Figure 3**. The results can also be transferred to polarized single photons interacting with a polarization filter, whereby the transmitted intensity must then be converted into a transmission probability.

Rotating Polarization

The set presented here also elegantly demonstrates that polarizing filters not only absorb part of the intensity of the incident light but can also change the direction of polarization. To do this, the setup in **Figure 4** is first constructed without polarizing filter B. If filter A and filter C are set to 0° and 90°, filter C no longer transmits any light according to Malus' law. If polarizing filter B is now added in the middle and set to 45°, it can be observed that light is transmitted again. This is because the polarization of the light is rotated by 45° by filter B. The remaining intensity is determined by applying Malus' law twice: $I = I_0\,(\cos^2(45°))^2 = \frac{1}{4}I_0$. In the context of teaching quantum optics, this provides a good opportunity to discuss the concept of quantum state preparation (Rainer Müller, n.d.-a).

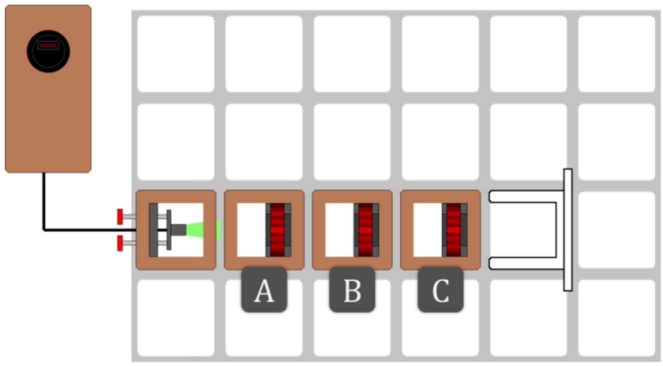

Figure 4. This setup demonstrates that the polarization of light can be rotated using polarizing filters (the authors' own illustration)

MICHELSON INTERFEROMETER

The Michelson interferometer, which became famous as a basis for the Michelson-Morley experiment, is still used today in fundamental physics research (e.g., The LIGO Scientific Collaboration et al., 2015) as well as in medicine (e.g., Drexler et al., 2001) and technology (e.g., Dandridge, 2024).

To use a Michelson interferometer as a measuring device, light with sufficient coherence length is split into two partial beams at a beam splitter. Both partial beams are reflected back to the beam splitter by mirrors and superimposed there. Depending on the difference in distance between the mirrors and the beam splitter, the superimposed partial beams interfere. The specific interference behavior can be observed either with a detector or on a screen.

Basic Setup with Qualitative Results

The basic setup of the Michelson interferometer is shown in **Figure 5**. As is common in educational contexts, a lens has been added behind the laser to widen the two partial beams. This results in a circular interference pattern on the screen, as shown in **Figure 5**, rather than just constructive or destructive interference.

Advanced Setup with Piezoelectric Element

When used as measuring instruments, a Michelson interferometer can be used to determine how the path

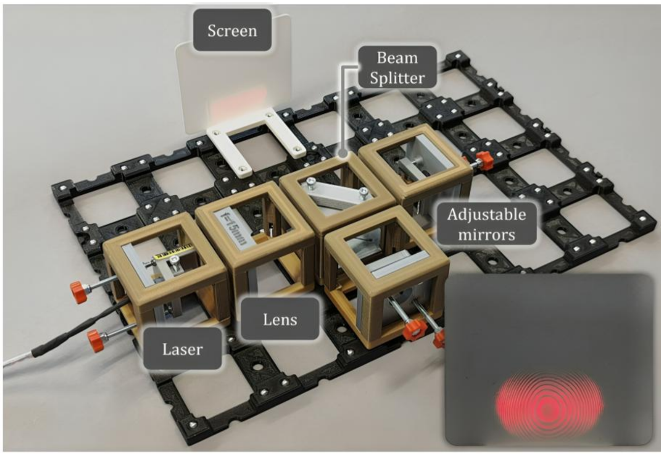

Figure 5. Michelson Interferometer setup with typical interference pattern (the authors' own illustration)

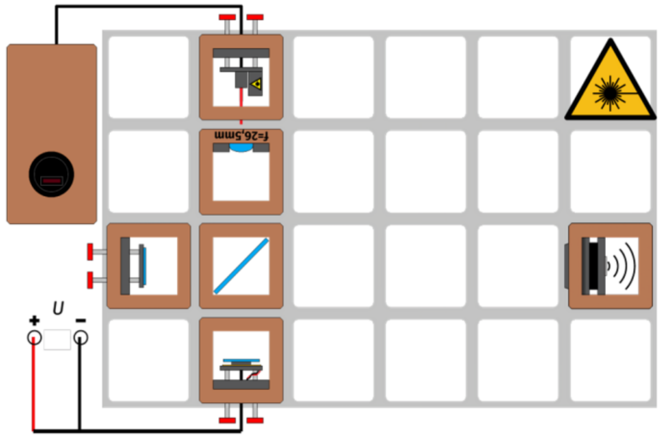

Figure 7. Setup for time-resolved interference (the authors' own illustration)

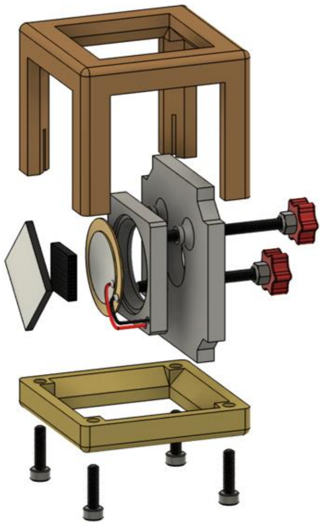

Figure 6. Exploded view of the piezoelectrically movable mirror (the authors' own illustration)

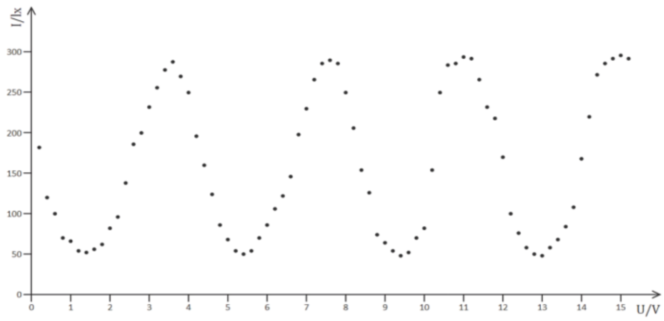

Figure 8. Exemplary measurement series for time-resolved interference (the authors' own illustration)

length between the mirror and the beam splitter changes. This movement leads to a change in the path difference and thus to cyclical changes in the interference pattern. In particular, the interference behavior in the center of the interference pattern alternates between constructive and destructive interference. Because this change goes through exactly one cycle while the path difference changes by one wavelength, the displacement of the mirror can be determined. For the tiny wavelengths of light, this variant can be used to measure very short distance changes.

In school practice, the experimenter is faced with the challenge that the mirror may only be moved a very small distance, otherwise the change in the interference pattern cannot be observed. In the setup presented here, this is solved with a piezo element to which the mirror is attached (**Figure 6**). When a voltage is applied, the piezo element deforms and thus displaces the mirror. With standard adjustable voltage sources between 0V and 30V, displacements in the range of 2-3 micrometers can be achieved.

Time-Resolved Interference in the Michelson Interferometer

When the Michelson interferometer is used as a measuring device in real-world contexts, it is obviously not practical to observe an interference pattern on a screen and evaluate it by hand. Instead, the interference behavior is normally measured using a sensor.

For the experiments presented here, the brightness sensor can be used to replicate this measurement method. Using the setup shown in **Figure 7**, for example, the intensity can be plotted against the voltage at the piezo element. A measurement can be seen in **Figure 8**.

For the experiments presented here, the brightness sensor can be used to replicate this measurement method. Using the setup shown in **Figure 7**, for example, the intensity can be plotted against the voltage at the piezo element. A measurement can be seen in **Figure 8**.

Such a measurement result is typically referred to as a time-resolved interference pattern, in contrast to the spatially resolved interference pattern shown in **Figure 5**. It is typical that time-resolved interference patterns are also recorded in the context of single-photon experiments (e.g., Kwiat et al., 1990). In particular, such a measurement was also carried out in the famous experiment on photon anti-correlation at the beam splitter, which provided the first direct experimental evidence of photons (Grangier et al., 1986).

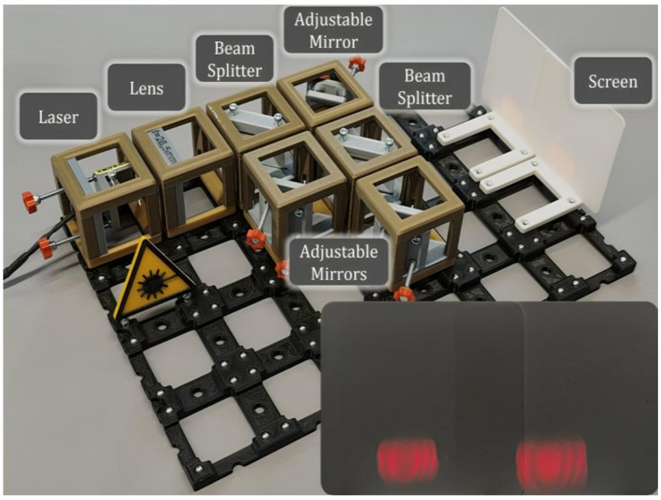

Figure 9. Mach-Zehnder interferometer with resulting inverse interference patterns (the authors' own illustration)

MACH-ZEHNDER INTERFEROMETER AND QUANTUM ERASER

As with the Michelson interferometer, coherent light is split at a beam splitter in the Mach-Zehnder interferometer. Unlike the Michelson interferometer, however, the resulting partial beams are then reflected by mirrors at a 90° angle onto a second beam splitter. This has the advantage that both partial beams are easier to manipulate. In addition, due to its design, the Mach-Zehnder interferometer has two outputs at which interference patterns are created. (The Michelson interferometer actually also produces two interference patterns, but one of the patterns is created where the laser diode is located, so it cannot be observed using the typical setup.)

Due to its layout, the Mach-Zehnder interferometer has many applications in the field of quantum physics. For example, quantum gates can be built based on the interferometer (e.g., Sajeed et al., 2006), it forms the basis for imaging with undetected photons (Lemos et al., 2014) and it can be expanded into a variant of the quantum eraser by adding polarization filters.

Basic Setup and Results

The setup of the Mach-Zehnder interferometer can be seen in Figure 9. As with the Michelson interferometer, a lens has been added to widen the laser beam and obtain a ring pattern. In addition, a third mirror is positioned in front of one of the interferometer's outputs, ensuring that the two interference patterns can be viewed side by side as seen in Figure 9. It is easy to see that the patterns are inverse to each other. For example, it is clear to see that in Figure 9 there is destructive interference in the center of the left-hand pattern, while constructive interference can be seen in the center of the right-hand pattern. The inversity results from phase shifts at the beam splitters.

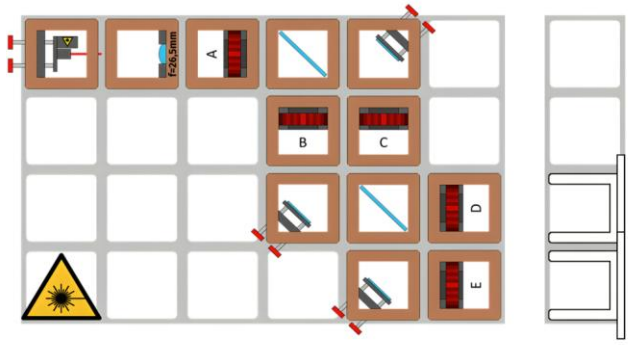

Figure 10. Setup of the quantum eraser analogy (the authors' own illustration)

Quantum Eraser Setup and Results

Interesting observations can be made on the Mach-Zehnder interferometer when polarization filters are added to the two beam paths. An example setup is shown in Figure 10. A polarizing filter at position A ensures that the light entering the Mach-Zehnder interferometer is linearly polarized at 0°. Filter B and filter C can be used to adjust the polarization of the partial beams that are superimposed at beam splitter 2. Without filter D and filter E, the contrast of the interference pattern depends on the angle between the two filters. The maximum contrast is achieved when both filters are set to the same position. If both filters are adjusted at an angle of 90° to each other, no interference pattern can be observed. However, if polarizing filters are added in front of the interferometer outputs (filter D and filter E in Figure 10), interference can be observed again in both partial beams even with orthogonally aligned filter B and filter C.

The use of polarization filters to rotate the polarization in this setup has the disadvantage that, according to Malus' law, some of the intensity is lost. However, this is still common in educational settings because alternative components such as wave plates are more expensive and conceptually more difficult to understand. The intensity of laser diodes is still typically sufficient if some intensity is lost.

Similar experiments can also be carried out with individual photons (Ma et al., 2016). These are referred to as quantum eraser trials. What is interesting here is that interference can also be measured when there is a maximum of one photon in the interferometer at any given time. Furthermore, the measurements are largely analogous to the setup presented here. In particular, the 'which-path information' can also be erased for the single-photon case by a polarizing filter at the outputs of the setup. This erasure of information on individual quantum objects also gives rise to the name 'quantum eraser'. The setup presented can be used as an analogy to discuss quantum eraser experiments in teaching and learning settings. The connection to experiments with single photons can then be established, for example, based on simulations (Rainer Müller, n.d.-b).

CONCLUSION

While hands-on experiments are common in lower secondary education, they are often not feasible in upper secondary education (Sek II) due to high costs. As a result, teachers rely on simulations or demonstration experiments not as a didactical choice, but due to a lack of alternatives. Considering the growing importance of quantum physics in education, expanding the spectrum of instructional options is therefore crucial to enable context-sensitive teaching decisions. We hope that the experiments presented in this contribution help to fill this gap.

The experimental set enables a wide range of hands-on experiments covering core concepts of wave optics and introducing key aspects of quantum optics, as typically addressed in secondary school physics education. Its low-cost and versatile design supports effective teaching and student engagement and allows for exploratory learning. This makes it a valuable addition to teaching and studying wave and quantum optics, because it not only helps to make experimental setups easier to understand and enables experimental skills to be developed, but also provides the opportunity to obtain real experimental results.

The set can be built yourself using a 3D printer for around €200. This makes it possible to build a few sets, so students can experiment in groups of two or three. For schools with very low budgets, it's at least possible to afford one interferometer, so it can be used for demonstration. The 3D files, parts lists, elaborate manuals and further experiments are available free of charge on the project website (Open3Quantum, n.d.). The website also contains documentation of further experiments, such as an analogy to the BB84 protocol. Illustrations, brief instructions and workbooks are also provided in German and English.

The materials have already been successfully tested in various German upper secondary school courses. It was found that, with adequate guidance, students are able to adjust the interferometers included and carry out measurements. In future research the impact on teaching quantum physics should be addressed in more detailed empirical studies.

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Ethical statement: This paper presents a new experimental setup designed for use in school classrooms. As this is a technical description of a method and does not involve any human participants or empirical data collection, no ethical approval was required.

AI statement: The authors stated that generative AI tools (e.g., ChatGPT by OpenAI) were used to check the English language clarity of the manuscript.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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