A simple modular kit for various wave optic experiments using 3D printed cubes for education

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Abstract

Quantum technology is an emerging field of physics and engineering and important applications are expected in quantum computing, quantum sensing, quantum cryptography, quantum simulation, and quantum metrology. Thus the need for education in this field is increasing, while still remaining challenging. While the need for basic education in quantum physics is accepted in many countries, the possibilities still are limited. Concerning fundamental topics such as the superposition principle and complementarity, on the one hand, a large variety of simulations and animations are available. However, single-photon experiments are still beyond reach for any school, due to costs and technical difficulties. A promising approach seems to be a combination of cheap, easy-to-use and modular experimental kits for school which allow for wave optical experiments, in combination with quantum optical simulations. In the present article, we focus on the modularity and accessibility of an experimental kit based on 3D-printed ‘Optic Cubes’, which allow for a large variety of experiments in high school.

Keywords: quantum optics, interferometer, 3d-printed, low-cost, wave optics, polarization, experiments

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1. Introduction
Quantum technology is an emerging field of physics and engineering, which relies on the preparation and manipulation of single qubits. Important applications are expected in quantum computing, quantum sensing, quantum cryptography, quantum simulation, and quantum metrology. The so-called ‘second quantum revolution’ brings quantum physics and in particular quantum entanglement to a new level of applications which will have a significant impact on society. In turn, the need for education in this field is increasing, while still remaining challenging [1].

While the need for basic education in quantum physics is accepted in many countries [2], the possibilities still are limited. Concerning fundamental topics such as the superposition principle and complementarity, on the one hand, a large variety of simulations and animations are available [3, 4], in particular, for quantum optics. However, single-photon experiments are still beyond reach for any school, due to costs and technical difficulties [5, 6]. Thus, a promising approach seems to be a combination of cheap and easy-to-use and modular experimental kits for school which allow for wave optical experiments, in combination with quantum optical simulations.

Different approaches e.g. for the construction of a Mach–Zehnder interferometer with laser light have been reported. In addition to significantly more expensive commercial interferometer sets there are also other low-cost versions for the 3D printer [7, 8] and even setups using LEGO (R)-Bricks [9] or freely locatable components without any grid [10]. In the present article, we focus on the modularity and accessibility of an experimental kit based on 3D-printed ‘Optic Cubes’, which allow for a large variety of experiments in high school.

2. The optic cubes as toolbox for experiments
The concept of the ‘Optic Cubes’ was originally developed by IPHT Leibniz Institut Jena as a low cost microscopy toolbox (for example as a light sheet microscope [11]). It is designed as a modular system, where the individual optical components are placed in separate cubes, with an edge length of 5 cm. The experimenter can start by building various setups simply by placing the cubes on a magnetic grid of the baseplate. Many of the cubes can be reused in different settings, thus providing a high variety of experiments in a cost efficient manner. The rather simple possibilities of the variation of the experiments also encourages the learners to explore the physical effects of the cubes.

For example, a Michelson- and the Mach–Zehnder interferometer have been realized in such a modular way. However, our first tests of the Optic Cubes revealed potential for improvements regarding didactic criteria and operational aspects. In addition, we present more cube designs allowing for further experiments, both for learners at school and university. In the following sections, these extensions and improvements of the Optic Cubes are presented in detail.

2.1. Easy to modify
The modular structure of the optic cubes enables learners to experiment by easily trying out variations and correcting errors quickly. It turned out, however, that the original grid dimension of the original base plate was too narrow, and the cubes touch each other. For this reason we stretched the baseplate a little bit. This makes it even easier to remove the individual cubes and reposition them on the baseplate without moving other cubes, which is necessary for some experiments.

2.2. Easy to calibrate
Experiments with interferometry in particular require a high level of stability and—at the same time—precise adjustment in order to achieve good results. Since fine-tuning is necessary, the needed level of skill of the learners is higher than they are used to in experiments in ordinary geometric optics.

In order to make adjusting the setup as obvious and easy as possible, all adjusting screws have been provided with 3D-printed attachments (see figure 1), which allows easy operation by hand without additional tools.

2.3. Intuitive to operate
Especially when several groups of students are experimenting at the same time, intuitive and
**Figure 1.** Color coding of the cubes. The bottom of the cubes is clearly distinguishable. Red parts are meant to be touched and adjusted in order to perform the experiments.

Self-explanatory operation is important in order to assist the teacher. For this purpose, the cubes were given a color coding, as shown in figure 1: Since only the bottom of the cubes can be fixed at the magnetic grid, it is printed with a different color. Despite the symmetry of the cube, it is clear at first glance how the cubes have to be positioned on the grid. Furthermore, all components that can and should be adjusted are printed in red.

**2.4. Safety**

When experimenting and especially with a large group of inexperienced learners, special attention must be paid to safety. Therefore, a class 2 laser diode was built into a cube (see section 2.7.1). The installation in one of the cubes as well as the compact arrangement of the cubes ensures that the laser beam hardly leaves the setup uncontrolled.

3D printed screens can be used to ensure that possible light paths are blocked. Furthermore, the sensitive optical components such as beam splitters and front surface mirrors are protected from accidental contact, as the cube serves as a protection from direct contact.

**2.5. Low costs**

For use as a student experiment, the costs must be kept as low as possible in order to enable schools to purchase several sets. For this purpose, some of the components have been adapted to easily accommodate particularly inexpensive optical components. A set for carrying out all the experiments described below can be produced by yourself for around € 100. You can obtain the reworked .stl-files and list of used parts on [http://physikkommunizieren.de/o3q-waveoptics](http://physikkommunizieren.de/o3q-waveoptics).
2.6. General improvements

In order to improve the durability and overall precision of the experimental materials, metal nuts were embedded in the material at many points, as in the original design metal screws were screwed into plastic recesses (figure 2). This prevents components from having to be reprinted due to material wear and tear and at the same time the components are somewhat less dependent on precision set 3D printers.

2.7. Additional cubes

As explained above, most of the cubes have been adjusted or completely revised with regard to didactic criteria and operational aspects. The components originally provided by IPHT Leibniz Institut Jena already enable many experiments but for further experiments, e.g. with polarized light, necessary components such as an adjustable laser module and adjustable polarizing filters were missing. In the following, two cubes are presented that have been completely redeveloped.

2.7.1. Laser module. Instead of a mounted laser pointer, a cheap laser diode is introduced for the laser component (figure 3). Just like the mirrors, this module can be precisely adjusted due to the kinematic mount in two independent axes using the adjusting screws.

Compared to a bulky and heavy laser pointer, the diode has the advantage that the cube stays compact and is not loaded by bending moments compared to a bulky laser pointer that would protrude over the edge. The laser diode can also be switched on and off from outside the grid by the battery cube (see e.g. figure 5) via both button and switch, which has great advantages in terms of safety and usability. In the same manner as the laser module a Light-Emitting Diode (LED) module was constructed, which is used for experiments in section 3.3.

2.7.2. Polarizing filter module. A holder for polarizing filters was also designed (figure 4), which can be rotated freely in 360°. The rotation angle can be read from the scale on the red rotary wheel. In addition to simple experiments on the polarization of laser light and polarization through reflection, the setup of the Mach–Zehnder interferometer can also be expanded to an analogy experiment of the quantum eraser, which is shown in section 3.3.

Figure 2. Example for recessed nuts.
3. Experiments
The improvement described in section 2 made the experiments 3.1 and 3.2 on interferometry more accessible to learners. The experiments 3.3 and 3.4 extend the original setup, allowing for further experiments including the polarization.

3.1. Michelson interferometer
The Michelson Interferometer is a classic experiment dealing with the interference of electromagnetic waves [12]. In our experiment, a laser beam is split up at a beam splitter, and reflected back in order to superpose the amplitudes of the laser beam of both possible paths. In an educational context, a lens is usually integrated, such that the interference becomes visible as ring pattern or stripe pattern depending on the position of the lens. In figures 5–7 the lens is inserted so that a ring pattern is formed. The experimental setup can be seen in figures 5 and 6. As described, a laser module, a beam splitter module, two mirrors, a lens and a screen are used.

To adjust the setup, the laser is aligned so that it hits the center of the lens. Then both mirrors are adjusted with the lens removed so that they overlap on the screen. If the lens is then added again, an interference pattern, as shown in figure 7, can be observed if the adjustment is correct. Various tests are possible to ensure that the resulting pattern is actually due to interference. First of all, a single beam path can be covered, such that the interference pattern disappears. Second, a slight shock on the table makes the pattern disappear for a short while. In this way, learners can get an impression of the sensitivity of the interferometer as a measuring device.

3.2. Mach–Zehnder interferometer
The Mach–Zehnder Interferometer also uses a beam splitter to split a laser beam in order to generate an interference image [13–15]. A second beam splitter is used in the Mach–Zehnder interferometer for superposition. This has the advantage that the partial beams do not traverse any of the paths multiple times and can thus...
be better manipulated. The setup of the Mach–Zehnder interferometer can be seen in figures 8 and 9. As shown in figure 10, two complementing interference patterns emerge.

Again, it is also possible to check whether an observed pattern arises due to interference by covering one of the beam paths. The inversion of the interference pattern, which results from the
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Figure 6. Layout of the Michelson interferometer with optic cubes. The effect of the lens on the laser is not shown here.

Figure 7. Fringe pattern formed by the Michelson interferometer from optic cubes on the screen.
Figure 8. Mach–Zehnder interferometer with optic cubes.

Figure 9. Layout of the Mach–Zehnder interferometer with optic cubes.

3.3. Experiments regarding polarization

3.3.1. Polarization of laser beams. The additional Optic Cubes including polarization filters allow for several new experiments within this modular and flexible setup. It is most straightforward to examine the polarization of the laser itself. Cheap laser diodes are usually elliptically polarized. A polarizing filter is positioned behind the laser as shown in figure 11. By rotating the polarizing filter, it can then be determined at which angle transmission becomes maximal.
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Figure 10. Both fringe patterns of the Mach–Zehnder interferometer. At the center of the rings can be seen that the patterns are inverse.

Figure 11. Setup to investigate the polarization of laser beams.

This experimental setup can also be used to set the polarization of the laser diode to a specific angle, which is helpful in later experiments. An LED can also be examined using the same principle. It can be seen here that the light emitted by the LED is unpolarized.

3.3.2. Malus’s law. The setup allows to examine how the intensity of polarized light decreases when it is sent through a polarizing filter. This effect is described for completely polarized light and ideal polarization filters by the law of Malus as follows:
Figure 12. Setup to verify Malus’s law. The effect of the lens and the polarization filters is not shown here.

\[ I = I_0 \cos^2 \theta. \]

Here, \( I_0 \) describes the intensity of the incident light and \( \theta \) the angle between the original polarization direction and the axis of the polarization filter.

For the experiment, two polarizing filters are positioned behind the LED and one of the polarizing filters is rotated against the other (figure 12). It is advisable to focus the light of the LED with a lens in order to achieve an approximately parallel beam path. When rotating the polarizing filters against each other, the transmitted intensity can be observed on the screen.

3.3.3. Polarization by reflection. The polarization due to reflection can be investigated with the setup shown in figure 13. Complete polarization can be observed when light is reflected on dielectric materials if the light hits the reflective surface with the exact refractive index-dependent Brewster angle. Because the mirrors used are vapor-coated with aluminium, this is not a dielectric, but a weakened effect can still be observed. If the polarizing filter is rotated, it can be observed how the intensity changes on the two screens. In such a way, the angles of maximum intensity can be determined for transmission as well as for reflection, which are just shifted by 90° from one another.

3.4. Analogy experiment for quantum eraser

A Mach–Zehnder Interferometer is an important tool to investigate the fundamental concept of indistinguishability. It can be realized by adding polarizing filters in the two individual beam paths [16]. If these are aligned in the same orientation, the interference behavior can still be observed (with reduced intensity). However, if the polarizing filters are orthogonal (say, in horizontal/vertical basis), no more interference can be observed, as both paths become distinguishable. If in addition a third polarizing filter in \(+45°\)-basis is added behind the last beam splitter, interference can again be observed, as the polarization cannot be traced back any more to a specific path.

With the presented experimental material, the experiment can be realized for the case of multiple photons. The much more sophisticated
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Figure 13. Setup to investigate how light can be polarized by reflection. The effect of the lens and the polarization filters is not shown here.

Figure 14. Analogy experiment for a quantum eraser.

experiment with single photons can be made plausible using e.g. a simulation\textsuperscript{4}.

The experimental setup for this is based on the setup of the Mach–Zehnder Interferometer (section 3.2). After the setup has been adjusted so that an interference pattern can be observed, two polarizing filters (set to 0° and 90° with respect to the polarization of the laser) can be carefully added as shown in figure 14 and 15.

In an ideal setup, interference should no longer be observable. Often, on closer inspection, a slight residue can still be observed,

\textsuperscript{4}Simulation available at www.milq.info/en/materialien/simulationsprogramme/.
which among other things results from the elliptic polarizing properties of the beam splitter, which were determined in the experiment in section 3.3.3.

If a third polarizing filter is positioned behind the second beam splitter in 45°, the interference pattern can indeed be observed again.

4. Conclusions and outlook
Due to the modular nature of the ‘Optic cubes’, a large variety of applications can be imagined. For school, wave optic experiments can be realized as described in the present article). For university, even more sophisticated experiments can be tackled in future, for example, when replacing the light source by an NV-center [17]. Thus, possible applications of the ‘Optic cubes’ range from high school to quantum teaching labs at university. As the stl-files are open source, further improvements and extensions are welcome⁵. With the increasing needs in quantum education and at the same time the increasing accessibility of 3D-printing technology, we hope that this approach will improve experimental accessibility to important aspects of quantum physics such as the superposition principle and complementarity both at school and university.

Data availability statement
No new data were created or analysed in this study.

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⁵ The stl-files of the extended and improved set of ‘Optic Cubes’ can be downloaded from https://physikkommunizieren.de/o3q-waveoptics.
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