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HQBIT: PERFORMING QUANTUM OPTICS PRACTICAL WORK IN A HYBRID ENVIRONMENT

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Abstract

Active learning based on experiments and practical work helps students understand concepts that challenge our conception of the physical world. However, such experiments can be hard to execute in a classroom context, due to their complexity, difficulty to set up and manipulate, and high cost. The development of digital materials dealt with some of these issues but also brought their own set of drawbacks and do not fulfill what a student is supposed to experience with a real experiment. To combine the advantages of both digital and physical approaches, we developed a hybrid optical bench based on numerical simulation, tangible manipulations, and pedagogical augmentations. In this paper, we present the design of the project and focus on two experimental scenarios.

Keywords: Quantum Physics, Practical Work, Augmented Reality, Optics, Tangible Interactions.

1 INTRODUCTION

Learning quantum optics is a challenging task for students in higher education, due to the difficulty for them to associate mathematical notions to real-world phenomena that may appear counterintuitive [1]. Demonstrating and explaining historical experiments that built all the theoretical part of quantum physics, is beneficial to the students to leverage these difficulties [2].

At this end, practical work is commonly used in physics curricula to engage students in an active learning and observation process [3]. The problem with quantum optics experiments is that they are difficult to deploy in a classroom because of their high complexity, sensitivity to optical adjustments and can pose safety issues due to the use of electro-optical systems and lasers. They are generally very expensive and deployed in a 'research' environment far from the classroom. In an experiment session, student's manipulations are thus often limited to fine tuning of selected parts of the optical assembly to mitigate the complexity of the task. The general picture of the experiment is often lost because students experiment only with a small part of the whole phenomena. Furthermore, in real installations, the multiplicity of power cables and signals, and all the measuring/control instruments that clutter up the visual space can disrupt the overall understanding of the fundamental concept to be grasped.

Digital materials are often used to mitigate these problems by offering tools to simulate experiments on online platforms. [4, 5, 6]. They present the advantage of high accessibility and flexibility. On the other hand, experiencing on a desktop computer, or even a VR simulation, is far from what it is supposed to be experienced on a real physical setup. To overcome these problems, we propose HQBIT (Hybrid Quantum Bench for Innovative Teaching), a tangible and AR (Augmented Reality) optical bench to perform Quantum Optics experiments, based on the HOBIT (Hybrid Optical Bench for Innovative Teaching) project [7]. HQBIT is a hybrid system that allows the user to reproduce quantum optics experiments in a real-time simulated environment, using tangible reproductions of optical elements, and augmented reality that provide pedagogical supports within the experiment. The optical model of the tangible experiment is digitally simulated. This model integrates the response of optical components, detectors, non-linear crystals, pulsed lasers, etc., as well as the wave/corpuscle characteristics of light (photon statistics, entanglement) required to recreate quantum optics phenomena. This system has been designed in direct collaboration with physicists working in the field of quantum optics to guarantee realistic simulations consistent with experimental results but simplified to deliver real-time results. Using HQBIT, students can reproduce from scratch, key quantum optics experiments such as Bell Inequality Violation, which demonstrates the entanglement between a pair of photons, or the Mach-Zehnder Interferometer, which illustrates wave-particle duality. Both notions enter in conflict with the perception of our world and pose conceptual difficulties for students [1, 8].

With HQBIT, we offer a range of pedagogical materials designed to help students meet the challenges of understanding quantum physics. They assist the student during the practical setup and manipulation

of the optical components, and they help building the link between the observed results and the underlying concepts through dedicated visualizations that react in real-time to the students' manipulations.

2 METHODOLOGY

To explore the potential of a simulated and augmented platform to help students learning quantum optics, we have worked on an evolution of our initial platform dedicated to wave optics, HOBIT. We added new tools and techniques that are specifically related to quantum physics. This gave birth to the HQBIT platform (Hybrid Quantum Bench for Innovative Teaching).

2.1 HOBIT

The HOBIT platform, illustrated in Fig.1, is composed of a physical table on which users can plug and tune 'fake' optical elements, which are reproductions of real optical elements such as lenses, mirrors, or light sources. A vertical projection screen displays in real-time the results of the corresponding simulation. Hence, users interact with the platform as if they were manipulating a real optical bench.

The numerical simulation runs on a computer that is located inside the table. This simulation is connected to a set of microcontrollers used to retrieve the information about all the elements plugged onto the table. For example, when a user adjusts the knob on a mirrored optical mount, the related information is sent to the computer to update the simulation. The result of the simulation is displayed on the projection screen by way of a projector located at the rear of the table. Additionally, we also display tools such as a power-meter, or pedagogical supports, on the projection screen. A second projector, fixed on the side and combined to an upside-down mirror, allows us to augment the experiment with additional information. For example, it is possible to display the current state of an optical element next to it, or to display the light path.

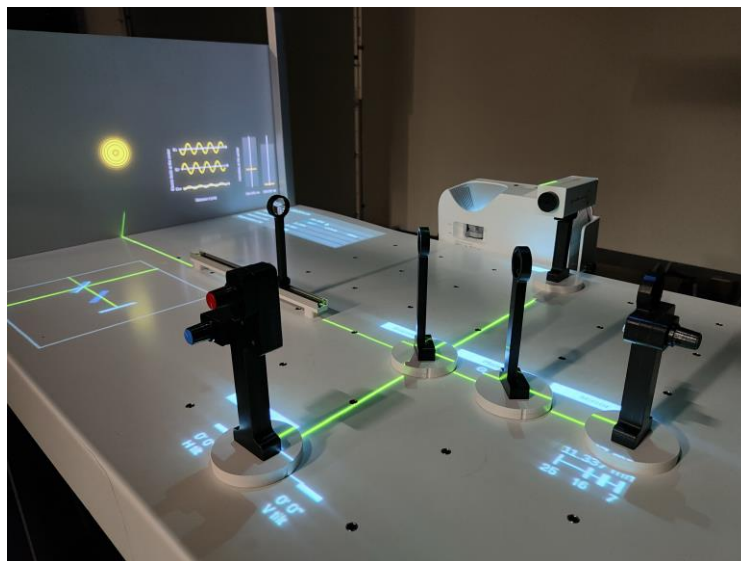


Figure 1. A Michelson Interferometer experiment on a HOBIT platform.

2.2 Quantum Optics

To cover a variety of quantum optics concepts, we aim to reproduce experiments that are commonly introduced in quantum physics curriculum.

HOBIT in its original state is not able to perform quantum optics experiments both in terms of software and hardware capacity. Some concepts of quantum optics, such as the duality wave-particle, can only be noted if light is simulated at a photon level. HOBIT does not make this distinction between a beam and a photon. Therefore, we have implemented all these missing parts of the light models to make HQBIT, an engine that simulates light in real time both for classical electromagnetic behaviors and quantum ones. It includes new additions such as photon statistical model or entanglement, and

modifications of existing part of the simulation such as propagation of light through various elements to include single photon light source propagation.

In terms of hardware, some optical components were missing on HOBIT. Single photons detectors for example, are often used to measure the numbers of photons in the output of an optical experiment. They are a key part of numerous experiments used to explain core mechanics of quantum optics like the Mach Zehnder interferometer [9]. Other additions include Polarizing Beam Splitter, Attenuators. Detectors and Correlator also comes with their own result visualization pedagogical tool.

As for the software, pre-existent components also had to undergo modifications to incorporate the addition of photon statistical model discussed earlier. This is the case for the Light Source element, that could already be reconfigured in wide range of source (lasers, lamp) but now that also exhibit a different photon statistic according to its type (coherent, thermal or quantum). Light Sources can also be pulsed instead of emitting continuous light.

All these novelties make HOBIT not simply an upgraded version of HOBIT, dedicated to quantum physics, but, a real platform of experimentation that can be used in multiples contexts, levels of education and fields of physics.

2.3 Pedagogical Tools

HOBIT is not simply a simulated representation of real-life conditions of experimentation. It is also important for us to ensure an enhanced experience for students to focus on the understanding of the concepts underlying their practical work. This ranges from providing supplementary information while performing the experiment, to being able to manipulate some parameters of it more easily and safely.

As mentioned earlier, an example of these pedagogical tools is the Detector result augmentation (Fig 2.). This tool allows student to directly visualize the photons arrival in time that hit the detector at activation (via a button press or a sequence mode). This information is particularly useful in context such as the light source characterization experiment or to explain the wave-particle duality (see Results section). Additionally, the tool not only provide insight on the time of arrival of each individual photon, but also to its spatial position. That way, the accumulation of photon on the detector gradually reproduces the projection that the student could observe on a simple projection screen. It makes a link between what he or she can usually observe at beam scale and now, at photon scale. Detector augmentation can display result for as many detectors as plugged on the table. It makes it possible to draw direct comparison between their results, and it is especially useful in experiment like the Hanbury Brown Twiss Experiment (see Results section).

As for the other optical components, all the detectors' characteristics can be modified by using a menu, displayed on the table. Users are not tied to use the specific characteristics of the detectors available in their practical class room, but instead can easily experiment with multiples configurations without any additional cost.

In the similar way, users have a direct control over the photon flux output by a light source component. It can be redefined directly on the component menu, or, if the teacher wants to dive a bit more in detail on the process of control of the photon flux can simply plug an Attenuator in front the light source.

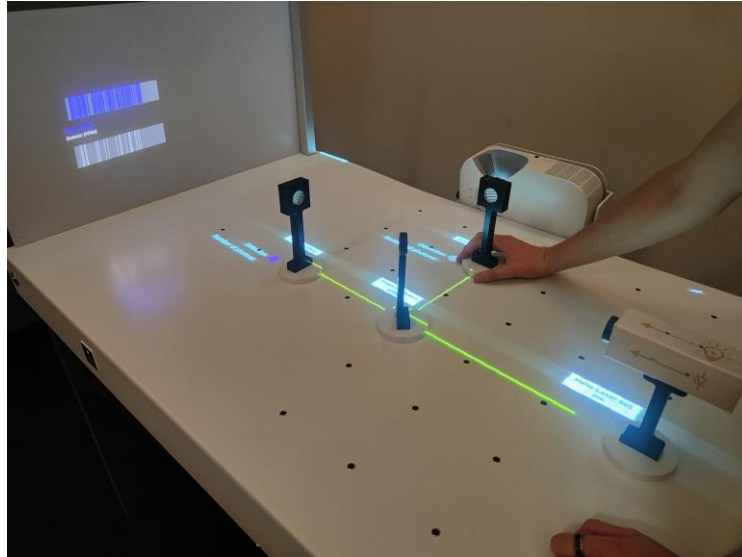


Figure 2. A setup with two detectors on HQBIT. On the table, an augmentation, at the base of each detector, display if a detection event occurs, as well as the number of photons detected. On the projection screen, an interactive figure displays the sequence of photons arrivals in time for each detector.

3 RESULTS

To cover a variety of quantum optics concepts, we reproduced two experiments that are commonly introduced in quantum physics curriculum using HQBIT.

3.1 Hanbury Brown Twiss Effect

3.1.1 Hanbury Brown Twiss Experiment

This first experiment explains a concept known as the Hanbury Brown Twiss Effect, or the photon bunching. It describes that, depending on the type of light source, photons can travel grouped (bunched), randomly (coherent) or equally spaced (anti-bunched). This last possibility is only exhibited in quantum (or rather, nonclassical) light. In 1956, Hanbury Brown and Twiss conducted an experiment to demonstrate this principle and characterize a light source in one of these three categories [9].

This historical experiment is a good entry point to quantum concepts as it points the difference between classical and non-classical light. The montage does not involve a lot of elements, but it requires to switch between three light sources (one for each type of light). The beam of light will cross a beam splitter, splitting the light in two perpendicular parts. Detectors are placed at equal distance of each output path of the beam splitter. They are linked to the correlator to control its activation. When a photon hit the detector linked to the “start” function of the correlator, it activates and begin to count time until a photon hit the detector linked to the “stop” function of the correlator.

This process is repeated a certain amount of time to quantify the data. If the light source is anti-bunched, photons does not arrive grouped on the beam splitter and thus, there should be a delay between the start and stop activation of the correlator, in most observations.

However, if light is bunched, photon arrive grouped on the beam splitter and are split at the same time through both paths, resulting in the simultaneous action of start and stop on the correlator.

3.1.2 HQBIT Experiment

On HQBIT, the user has at his disposal the light source, the beam splitter, the two detectors and the correlator. This last one can be plugged at any place of the table as it gathers automatically all the other detectors plugged on the table or any new detector that will be plug after him. Users can decide which detector is going to get linked to the start and the stop feature. Once the correlator is started by pressing the button on it, they can follow the process progression on an augmentation on the projection screen and directly on the element itself. Visuals indicators placed at the base of each detector display if it received an event (detection). Another indicator, at the base of correlator display the time progression between the last start detector activation and the subsequent stop detector activation. On the projection screen, results of the observations are aggregated in real time on a bar

chart. Like this, users can understand how the experimental results are obtained and get a better grasp at their meaning (Fig 3).

Different types of light sources of all three types are available on the source element and can be switched during the experiment via a simple click on the interface. It makes the transition less tedious, while making it easier to draw comparisons between them. Something also worth noting, is that students can have access to the whole manipulation without any constraint of security and any risk of breaking expensive optical materials, as they are only reproduction, and all the light model is simulated. This claim is valid for this experiment but also for the following one.

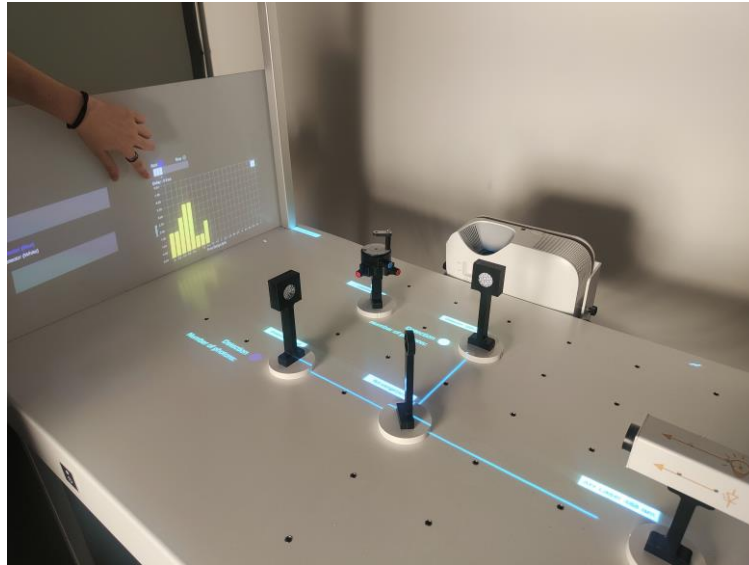


Figure 3. Hanbury Twiss Experiment on HQBIT. On the table, the simulation displays the beam propagation through all the elements. On the right, another augmentation displays a bar chart visualisation of the correlation process, updating in real time.

3.2 Superposition and Wave/Particle Duality

3.2.1 Mach Zehnder Interferometer

This experiment demonstrates the superposition principle and the wave/particle duality of photons [10].

A light source will send photons to a PBS (Polarizing Beam Splitter) that will transmit or reflect them in different polarization state (respectively horizontal and vertical) at a fixed probability depending on the initial polarization of the beam. After bouncing on mirrors, the two light beams cross again in another PBS that will recombine them. This setup is known as the Mach-Zehnder interferometer and is commonly used in quantum optics experiments. In the end of the second beam splitter, we add a single photon detector to detect the polarization state of each photon.

If we add a polarizer in front of the light source, to polarize the beam at 45° , it will split evenly on the first PBS, then recombine on the second to form a new beam. Furthermore, if we block one of the paths after the split, we observe on the detector, single photons polarized horizontally or vertically (depending on the blocked path). Now, if we do not block the light, and look at the clicks on the detector, we should observe photons in one state of polarization or the other. Instead, we observe photons that are polarized at 45° .

This result can only be expected if light behaves as a wave and not as particles that are distributed randomly on the first PBS. However, we can detect single particles on our detector. This is the wave/particle duality. Another concept that can explain this result is the superposition principle. In fact, after the first PBS, photons are not in a fixed polarization state but rather, in a superposition of both states. This becomes concrete only when observed.

3.2.2 HQBIT Experiment

As for the Hanbury Brown Twiss experiment, the setup is quite straightforward on HQBIT and all the optical components are available to perform this experiment with realistic conditions, from the PBS to

the single photon detector. Any component that absorbs a beam can be used as a blocker for the paths. After the setup of the Mach-Zehnder Interferometer, the user can adjust the initial polarization of the beam using the optomechanical component that host the polarizer as it would do on a real optical bench. Our main pedagogic contribution to this experiment comes in the form of a new element called the Polarimeter. This device does not have a real counterpart and allows the experimenter to interrogate the state of polarization at the position of the Polarimeter, in 2D or 3D, without destructing the beam (Fig 4.). This component was already present on HOBIT but was only able to output the state of polarization of the whole beam. As we saw previously, it is the state of polarization for each individual photon that is relevant to this setup. So, for the means of this experiment, we have upgraded it to output the state of polarization, not only at beam level, but also at photon level, and being able to switch easily between these two states. It offers a good support for the teacher to gradually introduce the theoretical and mathematical part of the wave/particle and superposition principle and using the Polarimeter to display the polarization state.

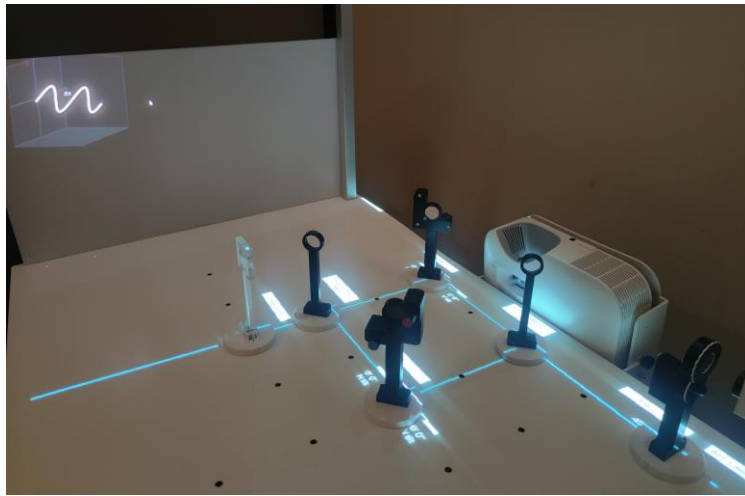


Figure 4. A Mach-Zehnder interferometer experiment on HQBIT. On the projection screen, the user can see the polarization state of the light crossing the Polarimeter in 2D or in 3D.

4 CONCLUSIONS

In this article, we have presented the HQBIT concept both from the point of view of quantum optical simulation developments and, all the augmentations developed for pedagogical purposes.

The first results obtained with the HQBIT prototype cover two historical curriculum experiments for students enrolled in quantum physics courses. The Hanbury Brown Twiss experiment benefit from multiples augmentations all around the table (embedded on a component or displayed on the projection screen) that unravel hidden steps of the experimentation while providing an easier access to a large variety of optical elements. The Mach-Zehnder Interferometer take full advantage of the Polarimeter component as a pedagogic tool to understand and make a link between notions seen in theoretical classes and real-life experiments.

To cover a wide variety of study curriculum, from bachelor's to master's degrees in quantum optics, we will continue to develop other pedagogical tools to help students gain a better understanding of these non-intuitive phenomena.

Of course, we also plan to conduct user studies to better quantify to what extent HQBIT helps understanding complex concepts of quantum optics. We will also study how much the skills acquired by using HQBIT can transfer to quantum optical experiment that can be less easy to operate and do not provide additional tools such as the Polarimeter or other augmentations.

5.ACKNOWLEDGEMENTS

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