Research Article in Physics Education Research

Teaching Double-slit Experiment with Modular Optical Experimental Instruments

Xiujun He[1], Yubin Xu[1], Guangtian Zhu [1*], and Weiqing Pan[2*]

[1] East China Normal University; College of Teacher Education, Shanghai, Shanghai 200062, China

[2] School of Science, Zhejiang University of Science and Technology, Hangzhou 310023, China

[*] Corresponding Author: gtzhu@phy.ecnu.edu.cn, pan_weiqing@163.com

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Abstract: The Modular Optical Experimental Instruments (MOEI) are newly-designed laboratory demonstration tools which integrate a whole set of optical devices on a single board. The instructors can easily bring the MOEI to classrooms and demonstrate optical phenomena on projector screens. In order to investigate the impact of MOEI on the instruction of double-slit experiment, we investigated 134 undergraduate students with an open-ended experiment designing task. The Primary Trait Analysis (PTA) score suggested that students learning double-slit experiments with MOEI had better performance in selecting equipment and understanding the nature of science and showed more engineering thinking. The results also showed that students had a common misconception about the width of interference fringes, and MOEI was helpful to avoid it.

Keywords: Physics education research; Optical demonstration experiment; Modular optical experimental instruments

1. Introduction

1.1 Dilemma of demonstrating optical experiment

In introductory physics, wave optics includes light interference, diffraction and polarization. Observation of interference and diffraction phenomenon usually relies on demonstration experiments. However, traditional optical experimental instruments are sensitive to position and arrangement (Li et al., 2018). If an instructor brings the optical experimental instruments to his/her classroom, he/she may spend a lot of time relocating and adjusting these instruments.

In order to enrich the form of optics teaching, virtual simulation technology is brought into classrooms. Many interactive virtual simulation software can help students efficiently perform the double slit experiment. However, the simulation always provides perfect phenomenon (e.g., clear and bright interference pattern) so that the students can hardly experience the possible errors existing in real optical experiments. Moreover, students may consider the phenomenon of interference as a result of “computer calculation” instead of superposition of “real light”. Most students think that the real experiments are better than virtual simulation, virtual technology may not be a good substitute for real experiments (Chang et al., 2005). Hence, it is a dilemma in selecting the efficiency or effectiveness of demonstrating double slit experiment in class.

1.2 Modular experiment instruments

In order to find a balance between the efficiency and effectiveness of demonstrating optical experiments to students, we incorporate the Modular Optical Experimental Instruments (MOEI) in our class. The MOEI includes various modules such as double-slit interference, grating diffraction, Marius' law, Brewster's angle, etc., as shown in Figure 1. The MOEI integrates different optical devices (e.g., laser emitters and adjustable double slits) on a baseboard which can be easily carried to the classroom. It also uses a CCD signal processor to convert the light signal into an image grayscale signal. The interference pattern can be presented on the computer screen so that the whole class can observe the real-time phenomenon together.

Compared to traditional optical instruments, it is easier for instructors to carry the MOEI to their classrooms and let the students pass the equipment around. The students can observe the structure of the optical instruments, which help to enrich their engineering thinking. Figure 2 shows the structure of Young's double-slit interference module of MOEI. A turntable (structure ④) is engraved with six sets of double-slits with different widths. We can change the width of double-slits with a slight twist. A dichroic mirror (structure ②) can transmit light of certain colors and reflect light of other colors. For example, the rightmost dichroic mirror can transmit the green and red light emitted by the two lasers on the left, and reflect the blue light emitted by the laser on the right. The dichroic mirrors are placed in parallel at 45° so that laser light of different colors can reach the same position on the screen (structure ⑥).

Figure 1. Modular Optical Experimental Instrument

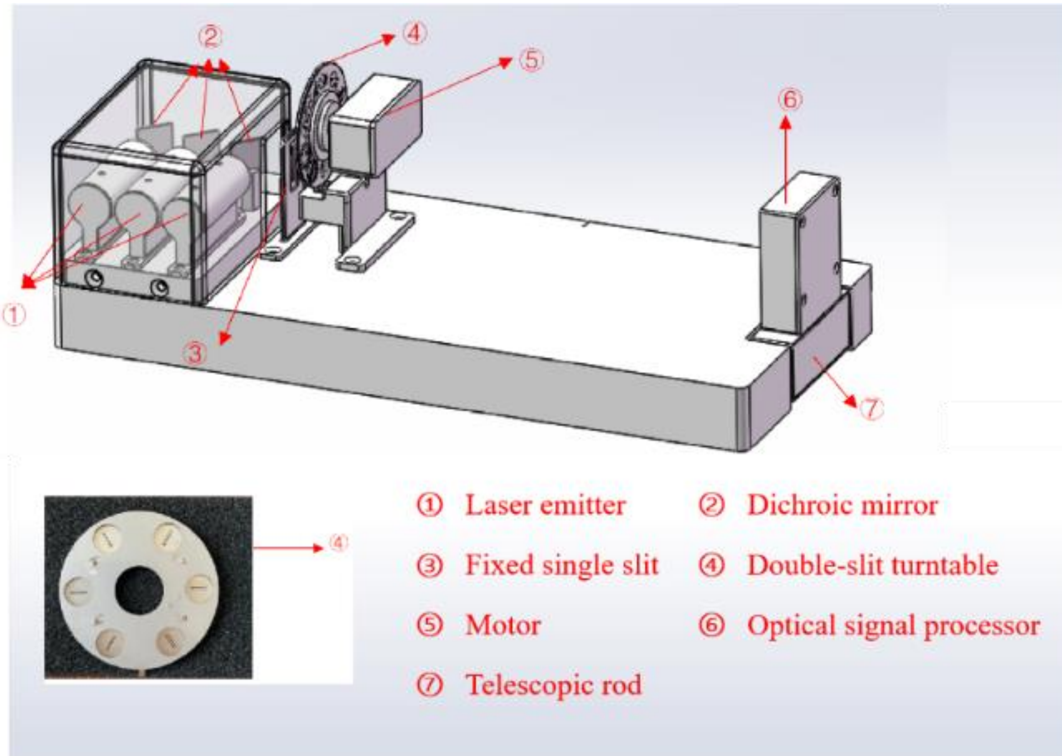

Figure 2. Young's double-slit interference module

2. Research Design

In order to test the effect of using MOEI in class, we designed a controlled study with an open-ended experiment designing task. Altogether 134 sophomore students in a calculus-based introductory physics curriculum participated in our study, including 46 students in the experimental group and 88 students in the control group. The experiment group and control group are taught by different instructors with similar teaching experience (10 years teaching experience in introductory physics). The students in the experimental group used the MOEI when learning the content of double-slit interference in class. The control group students learned double-slit interference with video clips and PowerPoint slides in class.

We used an experimental designing task to examine the difference between experimental group and control group students as shown below. In this task, students were required to use limited components to design an equipment which can present interference patterns of light with different colors. Students also need to describe the experimental scheme and predict possible outcomes and difficulties.

Experimental Design of Light Interference

In light interference, a teacher wants to show his students the phenomenon that "the interference fringes formed by different colors of light have different spacing". The teacher hopes you can help him to design an experiment equipment that can compare interference fringes formed by red and green light. Please complete the following questions:

1. In the lab, there is only one light screen, one green laser emitter and one red laser emitter. You can select other optical components as needed. Please list the necessary equipment you need to set up the experiment.

2. Please describe your experimental design in detail. (Your elaboration should be clear enough so that high school students can replicate the experiment according to your description.)

3. In your experiment, which of the following fringes have the same spacing or width?

(a) All red fringes are of the same width

(b) Green and red fringes are of the same width

(c) Red and dark fringes are of the same width

(d) The spacing between adjacent red fringe centers is the same

4. Describe the possible distribution and characteristics of the interference patterns of red and green light in your experiment.

5. What should you do if you want to observe overlapped red and green fringes? What difficulties mav vou encounter?

We use the method of Primary Trait Analysis (PTA) to score the experimental design task. PTA is an evaluation method for open-ended test. Since the answers to open-ended questions are not fixed, the evaluation of the answers relies heavily on subjective preference of the graders. It suggests graders to establish a standardized quantitative evaluation process for open-ended tasks by extracting elements of a task and setting scoring criteria for each element (Baughin et al., 2002). PTA has been widely used in evaluating open-ended tasks such as practical activities (Lin, 2019) and scientific experiment design（Tian et al., 2022; Xiao et al., 2018). In our study, we extract five evaluation elements for the experimental design task. The scoring criteria of each element are shown in Table 1.

Table 1. PTA scale of light interference experiment design

elements	scoring criteria	Score
Experiment Design	1.the experimental principles should be scientific 2.the experiment equipment should be available 3. steps should be complete	3 2 1 0
Equipment Selection	1.using new equipment out of textbooks 2.using new operation methods out of textbooks	2 1 0
Expression	1.express definitely and clearly 2.using concise language	2 1 0
Reasoning and Prediction	1.predict the exact experimental results 2.explain the results reasonably	2 1 0
Nature of Science	1.understand the differences between theory and practice 2.understand the high precision needs of optical instruments	2 1 0

3. Results

The experimental design task was assigned to both control group and experimental group students in class as a quiz. All students finished the task and most of them clearly expressed their operation steps. Two graduate students of physics education first cross-checked the PTA scale with a small sample and then graded all control group and experimental group students' answers.

We compared the experimental group (with MOEI) and control group (with video-clips) students' performance in the experimental design task. The t-test suggests that there is no significant difference between the two groups in the elements of "experimental design", "expression", and "reasoning and prediction". However, students in the experimental group had better performance in the elements of "equipment selection" and "nature of science". The descriptive statistics results are shown in Table 2.

Table 2. Descriptive statistics for experimental and control group

	Experimental group	Control group		
	M±SD	M±SD	p value	Cohen's d
Experiment Design	2.59±0.65	2.60±0.56	0.89	-0.02
Equipment Selection	1.54±0.59	1.34±0.50	0.049**	**0.37**
Expression	1.5±0.59	1.55±0.52	0.65	-0.09
Reasoning and prediction	1.46±0.55	1.45±0.57	0.99	0.02
Nature of Science	1.43±0.58	1.10±0.56	0.001***	**0.58**

Learning double-slit interference with MOEI indeed help students to notice the modern measurement tools such as computer image processing techniques. The experiment group students frequently mention CCD or other image processing sensor when selecting necessary equipment. Some students also select dichroic mirrors in their design in order to display red and green lights on screen simultaneously. In contrary, the traditional Young's double-slit experiment use only one light source. Hence, in order to compare the interference patterns generated by red and green lights, most students in the control group choose to record the patterns on screen by pencils or shooting cameras and then switch the laser emitter manually.

Students in the experiment group with MOEI also show better understanding in the nature of science. They are more aware of the difference between theoretical result and real observation. For example, question 3 in our task is a multiple-choice question about students' misconceptions of interference pattern. The distance Δx between the two adjacent lines of maximum brightness (the center of the two fringes) is a fixed value, i.e., $\Delta x = L\lambda/d$, where L is the distance between the slit and screen, λ is the wavelength and d is the slit separation. Based on this equation, many students think they would observe fringes of equal width on the screen. However, for the visual effects in reality, the width of each fringe narrows as the fringe's order increases. Compare to the students in the control group, more students in the experiment group noticed that the visual width of each fringe is not the same. About 20% students in the experiment group selected the correct answer (d) to question 3 while only 15% of the control group students made the same choice.

Moreover, students in the experimental group with MOEI are more aware of the factors influencing optical experiments. Question 5 asked students about the possible difficulties if they want to observe overlapped red and green fringes. Many students in the experimental group mentioned that red and green patterns may mismatch because the red and green laser emitter can hardly be arranged parallel. A slight shift in the position of the laser emitter can be amplified on the position of the inference pattern on screen. In contrary, none of the control group students noticed this issue of sensitivity of optical devices.

4. Summary

In our study, we applied the Modular Optical Experimental Instrument (MOEI) to demonstrate double-slit experiment in class. Compare to the traditional instructional method of teaching double-slit experiment with video clips, the MOEI improves students' experience of practical experiment without sacrificing the efficiency of class demonstration. When learning with the MOEI, students pay more attention to the structure and functions of each optical component. The open-ended experiment design task reflects that the experiment group students are more aware of the difference between theoretical results and practical observation in an optical experiment.

Besides the double-slit experiment as illustrated in this manuscript, the MOEI also support other optical experiments such as single-slit diffraction, Newton's rings, wedge interference, etc. Further studies of the MOEI will be carried out after the corresponding educational practice has been completed.

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Conflicts of Interest: There isn't any conflict of interest.

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