A Low-Cost Experimental Kit for Teaching Wave Optics Based on the CDIO Approach

Dinh Xuan Khoa and Nguyen Huy Bang, Vinh University, 182 Le Duan Street, Vinh City, Vietnam

We constructed a low-cost experimental kit consisting of a compact 532-nm diode laser, optics, and optomechanical components that arrange on a small honeycomb breadboard. The kit is flexible enough to construct five typical wave optic experiments, e.g., double-slit interference, Michelson and Mach-Zehnder interferometers, diffraction, and Malus's law of polarization. It is useful to use in both classrooms and laboratories to enhance experimental skills and creativity based on the CDIO (Conceive-Design-Implement-Operate) approach.

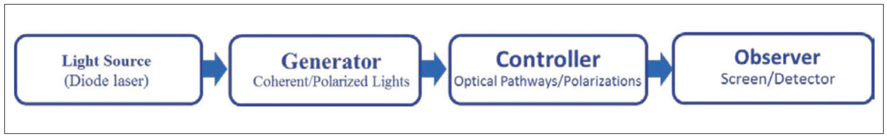

Fig.1. Block scheme of wave optic experiments.

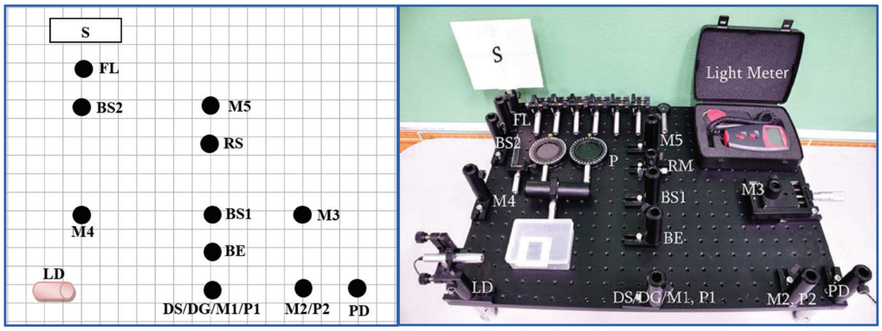

Fig. 2. Optical layout on a honeycomb breadboard, 45 cm x 60 cm (left) and experimental arrangement of the kit (right), where, LD – laser diode, M – mirror, PD – photodiode, BE – beam expander, BS – beam splitter, S – screen, P – polarizer, DS – double-slit, DG – diffraction grating.

Introduction

Historically, the properties of light have provided fundamental evidence to guide emerging quantum physics and gravitational theory.[1] Indeed, many phenomena such as interference, diffraction, and polarization of light have applications to technology.[2,3] Teaching wave optics, including experiments, is therefore an indispensible part of education programs to understand fundamental optical science and technological development. For instance, wave properties of light are often used to illustrate wave behavior of particles in teaching quantum physics.[4-6]

Experiments on wave optics, particularly interferometry, are often spatially sensitive so that the education setups fix their optical paths on a base or an optical rail.[7-12] Such permanent structures save setup time at the beginning, but they are somehow inconvenient in developing students' experimental skills and their creativity, particularly in developing applications based on interferometry.[13] On the other hand, coherent light sources used in the usual wave optics experiments are often delivered with 633-nm He-Ne lasers. This choice is useful due to stability of the laser line, which is often used as a secondary standard source for calibration of optical spectra and wavelength meters. Nevertheless, recent development of 532-nm semiconductor lasers is delivering many advantages, e.g., low cost, compact size, high lasing efficiency, and high visibility by human eyes. Such advantages are giving good opportunities for construction of low-cost and compact education experiments.

Recently we have witnessed a growing progress of technological applications based on fundamental science, including wave optics.[13,14] In order to meet demands for student competency under such progress without increasing duration of the syllabus, knowledge and skills should be taught simultaneously. Several models of integrated curriculum have been proposed to meet this goal. Among these, CDIO (Conceive-Design-Implement-Operate) is a promising and comprehensive approach.[15] It should be emphasized that the CDIO approach was initiated for engineering; nevertheless, its merit can be extended to non-engineering programs at different education levels.[16] Following this trend, we have recently adopted the CDIO approach to develop a teacher education curriculum of physics[17]; however, we have faced a difficulty due to the fact that most available experiments in wave optics are often designed to be implemented separately.[7-12] Furthermore, these experiments employ long optical rails to hold optomechanical elements in a long working space. Such features are obviously inconvenient to fulfill the standards of the CDIO approach for workspaces and integrated learning experiences.[15] Although some authors have proposed low-cost experimental setups with some developments,[18-22] these are still not tied to individual experiments.

In order to solve the above limitations of the available experiments, which are used in teaching wave optics based on the CDIO approach, in this work we propose a comprehensive kit integrating the five following experiments: the double-slit Young interference, Michelson and Mach-Zehnder interferometers, diffraction, and Malus's law of polarization. We use a small honeycomb breadboard to make the setup flexible. Furthermore, a 532-nm diode laser is used to significantly reduce

Table I. List of elements and prices.

Elements	Part number/model	Prices (USD)	Quantity
Diode laser	CPS532 – Thorlabs	$155	1
Mirror	ME1-G01 - Ø1" Thorlabs	13.40x4 = $53.60	4
Beam splitter	EBS1 – Thorlabs	31.40x2 = $62.80	2
Polarizer	LPVISE050-A – Thorlabs	75x2 = $150	2
Micro-translation stages	MS1 – Thorlabs	$178	1
Post holder	PH2 – Thorlabs	7.70x12 = $92.40	12
Post	TR50/M – Thorlabs	5.19x12 = $62.28	12
Continuous rotation mount	RP01/M – Thorlabs	$91.70	1
Light intensity detector	LX1010B	$40	1
Double narrow split	08523-00 – Phywe	$10	1
Honeycomb breadboard	MB18 – Thorlabs	$368	1
Kinematic mirror mount	KM100 – Thorlabs	38.70x6 = $232.20	6
Diffraction grating	08534-00 – Phywe	20	1
Thin film	~ 2 mm	1	1
Rule	2 m	1	2
Screen		1	1
TOTAL		$1518.98	49

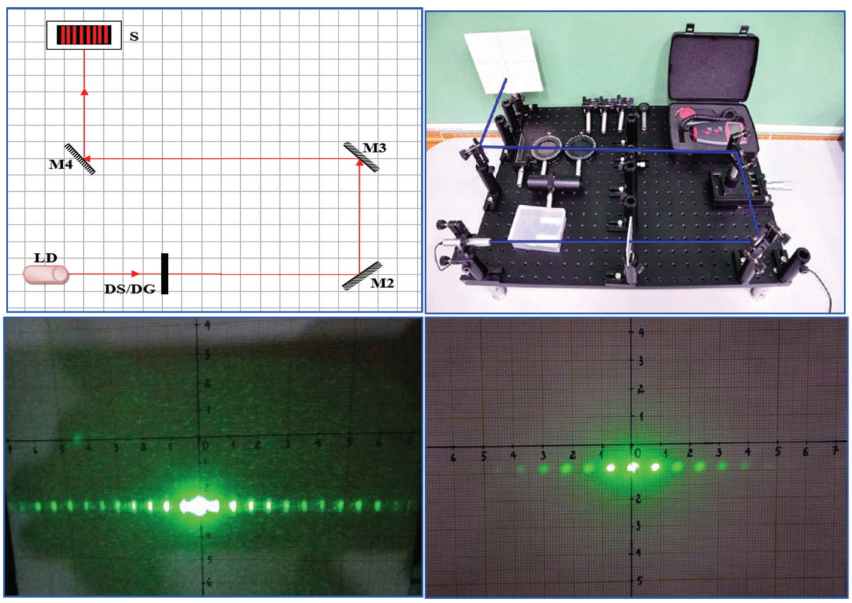

Fig. 3. Optical layout (upper left) and the setup arrangement of Young's experiment (upper right). The interfering fringes observed in the Young double-slit (lower left) and diffraction (lower right) experiments.

the dimension of the setup, lower cost, and enhance visibility.

Idea design of the integrated setup

In the usual experiments in wave optics (interference, diffraction, and Malus's law of polarization), the experimental structure can be categorized into the following main parts: light source, generator of coherent/polarized lights, controlling optical pathways/polarizations, and an observer (screen or detector), as shown in Fig. 1.

The generator can be a double slit (for Young interference), a transmitted diffraction grating (for diffraction), beam splitters (for interferometers), or a polarizer (for Malus's law of polarization). The controller can be nothing (for Young interference and diffraction of light), beam splitters and mirrors (for interferometers), or a second polarizer (for Malus's law of polarization).

In order to integrate the five experiments into a comprehensive setup, one has to accommodate the spatially different needs among them. Indeed, the Young, diffraction, and polarization experiments often need a long space (about 1.5 m) to ensure appropriate length of optical parts, whereas the remaining ones need only a small space (about 30 cm x 30 cm). We therefore use a honeycomb breadboard 45 cm x 60 cm (instead of the usual optical rail) and mirrors to extend and direct the needed optical paths. A 532-nm diode laser is also used as a light source (instead of the usual He-Ne laser) to reduce the dimension and weight of the setup, and to enhance the visual of interfering fringes. The optical layout and setup arrangement are shown in Fig. 2 with a detail of elements listed in Table I.

Experiments

In a first step of implementing the setup, we realize the simplest case, e.g., double-slit experiment. The optical layout and experimental arrangement are shown in Fig. 3. Here the laser diode shines on a double slit (DS), and emerging beams are reflected at mirrors M_2, M_3, and M_4 and directed on a screen. The optical paths can be tuned by moving the position of the DS between the laser and mirror M_3. The interfering fringes are observed sharply as in Fig. 3.

In the same manner, we replace the DS by a transmission grating (DG) to perform the diffraction experiment (Fig. 3, lower right). By analyzing fringes at different values of the optical part, we can determine the wavelength of the laser diode with a relative error of 1.2% and 1% for the double-slit and diffraction experiment, respectively.

In the next step, we perform experiments with Michelson and Mach-Zehnder interferometers. The optical layouts and experimental arrangements are shown in Fig. 4.

With the Michelson interferometer, we measure the wavelength of the diode laser and index of refraction of a transparent slab with relative error 3.8% and 3.4%, respectively. For the case of the Mach-Zehnder interferometer, a relative error of measurement of refractive index is 4%.

Finally, we use the setup to verify Malus's law of polarization of which arrangement is shown in Fig. 5. Here we see the experimental observation (bottom left in Fig. 5) matches the expected cosine^2 dependence of Malus's law.

Discussion

With the use of a small honeycomb breadboard and a compact green diode laser, one may construct a low-cost experimental kit that integrates five typical experiments in wave optics with readibly visible interfering fringes and attain the same accuracy as commercially available individual experiments. From an economic point of view, the kit is significantly less expensive compared to the total price of the five individual experiments (see Table I and compare to prices in Refs. 7-12). With a compact size of 45 cm x 60 cm, the kit can be used in the classroom for teachers or in lab for the students. Furthermore, one may increase the accuracy of the kit by using more mirrors to prolong optical parts.

From a didactical point of view, the kit can be used for three types of experiments in wave optics, namely, interference (three experiments), diffraction, and polarization. For the specific type of interferences, one may start from the simplest in the following hierarchy: double-slit Young interference, Michelson interferometer, and Mach-Zehnder interferometer. This way is easy for students to develop the kit into more complex interferometers and applications.[1-6,13,14,22] Therefore, the kit will be convenient to use in an integrated course, which is consistent with the CDIO standards for teaching.[15]

Conclusions

We have constructed a flexible and low-cost experimental kit for teaching wave optics based on standard optomechanical elements, a compact 532-nm diode laser, and a small honeycomb breadboard. The kit can be utilized to implement five experiments on interference, diffraction, and polarization of light, which can be used in classrooms or in laboratories. In addition to its low cost, the kit also has several advantages such as its compact size but very visually sharp fringes, high accuracy, simple arrangement, and flexibility to develop various experiments in wave optics. The kit is a valuable option for teachers to overcome low budget funding but still enhance students' comprehensive skills and creativity.

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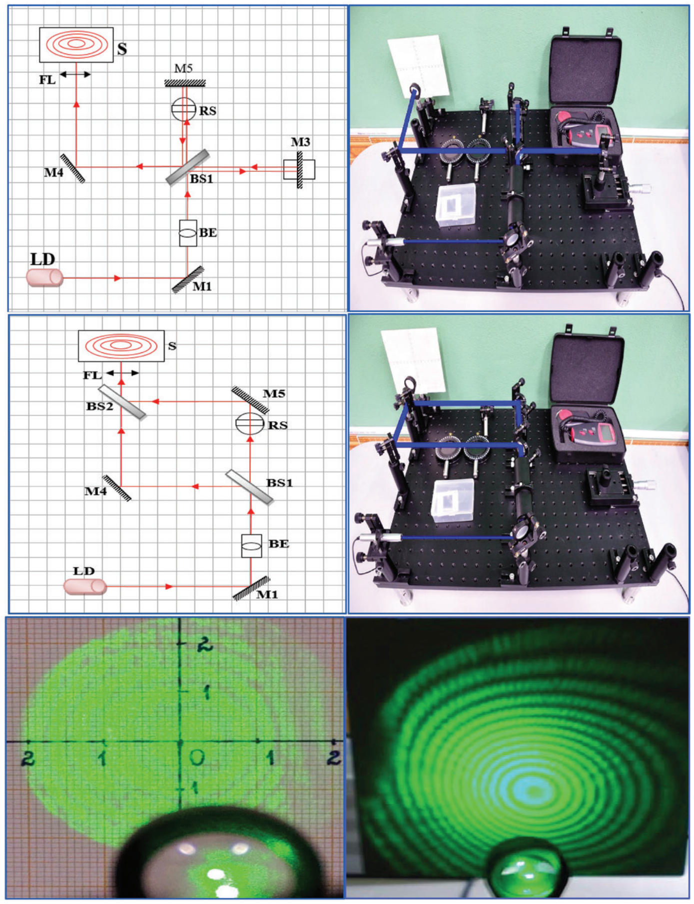

Fig. 4. Optical layouts (left) and experimental arrangements (right) of the Michelson (upper row) and Mach-Zehnder (middle) interferometers. The observing fringes of the Michelson (left bottom) and Mach-Zehnder (right bottom).

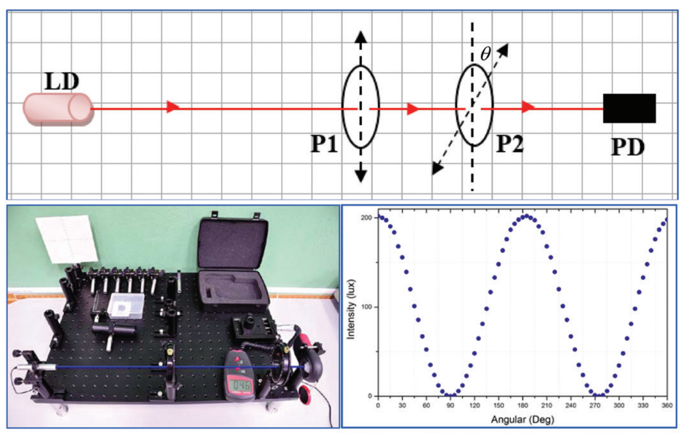

Fig. 5. The optical layout (upper) and experimental arrangement (lower left) of Malus's law with an interpretation of measured light intensity as a function of the angle θ (lower right).

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Vinh University, 182 Le Duan Street, Vinh City, Vietnam; bangnh@vinhuni.edu.vn