Teaching an introductory optics lab course for mechanical engineering students

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ABSTRACT

We have developed an optical engineering laboratory course that highlights the connections between mechanical and optical engineering, in an effort to attract mechanical engineering students to make the shift to optical engineering for their graduate studies.

Keywords: optics education, mechanical engineering, schlieren, interferometry, fiber optical sensing

1. INTRODUCTION

Although the Center for Optical Research and Education (CORE) at Utsunomiya University was founded in 2007, it began as a research institute attached to the university's graduate faculty of engineering. Thus, graduates were given degrees in engineering but not in optical engineering specifically. As the number of optical engineering faculty steadily increased, the Japanese Ministry of Education agreed in 2016 to create Japan's first-ever master's degree on optical engineering. In 2020, this was further reinforced by adding the first optical engineering PhD degree program.

While the success of the optical engineering department has been a source of pride for Utsunomiya University, it continues to face a problem common to optical science departments worldwide — the recruiting of undergraduates to the department. In Japan, fourth-year engineering students must choose a research laboratory to attach themselves to in order to gain basic experimental experience. For most students, this is their first experience with self-directed learning, and also their first extended study project. And since it is difficult to recruit high school students directly into the optical engineering department — there remains a limited awareness of optics as an independent field — our students must be recruited from the other engineering departments.

A problem with this approach is that the optical engineering faculty at Utsunomiya University have had difficulty in convincing Mechanical Engineering undergraduates to select optics-associated faculty for their senior thesis advisors. The students are not familiar enough with optical topics to have confidence in that choice. While students have little difficulty in imagining (whether or not their imaginings closely reflect reality) how mechanical engineering links to their future employment opportunities, the same is not yet the case for optical engineering. As a result, student recruitment from among the pool of mechanical engineering students has been poor. Starting in 2022, however, Profs Otani, Hagen, and Kondo collaborated to create an introductory optics lab course for second-year mechanical engineering students. This has helped to expose mechanical engineering students to the many connections between optical and mechanical engineering, and seems at least partly responsible for the improvement in mechanical engineering student recruitment that occurred at the beginning of the 2023–2024 academic year.

In the discussion below, we give an outline of the laboratory class and comment on its successes and failures so far in achieving our goals.

2. LABORATORY CLASS OUTLINE

During each Mechanical Engineering student's second year, one required element is a year-long laboratory course in which the student passes through a sequence of topics rotated among the entire body of 2nd year MechE students. Many of the laboratory topics require two class periods (one three hour period per week, for two weeks), several of the available topics — such as the new optical engineering segment — are given a longer period of four weeks. The total number of students passing through the program total about 100, and the

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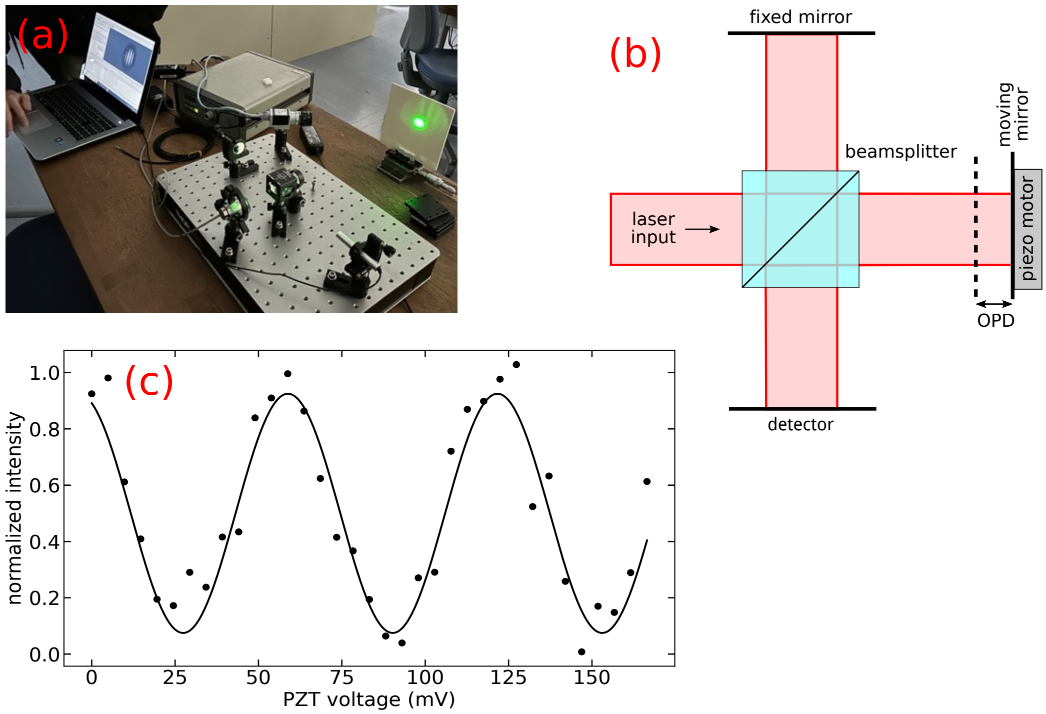

Figure 1: (a) Interferometer experiment, (b) optical layout, (c) example measurement and fitted curve.

laboratory sessions are separated into six Wednesday and six Thursday groups, with each group containing 8–9 students. Thus, there are 12 total groups rotating through each laboratory topic each year.

The optical engineering laboratory segment starts with a lecture introducing the background and details of the three experiments covered there. A student therefore experiences the optical engineering segment as something like:

week 1: Introductory lecture

week 2: Interferometry (precision metrology)

week 3: Schlieren imaging (visualization of flow)

week 4: Optical fiber sensing

However, rather than have 8 or 9 students grouped around a single experiment topic, and switch topics each week, we instead further divide the students into partners of two or three, which then rotate among the three optical experiments. Thus, the students experience the three experiments (interferometry, schlieren imaging, fiber sensing) in a different order depending on how the partners are divided up.

2.1 Lab topic 1: distance metrology using a Michelson interferometer

In the first optical experiment, the students start by aligning a laser-based Michelson interferometer (using a 532 nm laser). A photodiode detector is place at the interferometer output to measure the intensity. While students adjust the voltage on a piezoelectric motor drive, they record the detector voltage at each step, as indicated in Fig. 1. Fitting a sinusoid to the resulting data, they can estimate the bias, amplitude, fringe wavelength, and initial phase of the sinusoid. At first, the fringe wavelength (the distance between peaks in the fitted sinusoid) are given in units of millivolts, since they are measured via the piezoelectric motor. However, since we know the laser wavelength *a priori*, and the interferogram equation, we can convert the piezoelectric

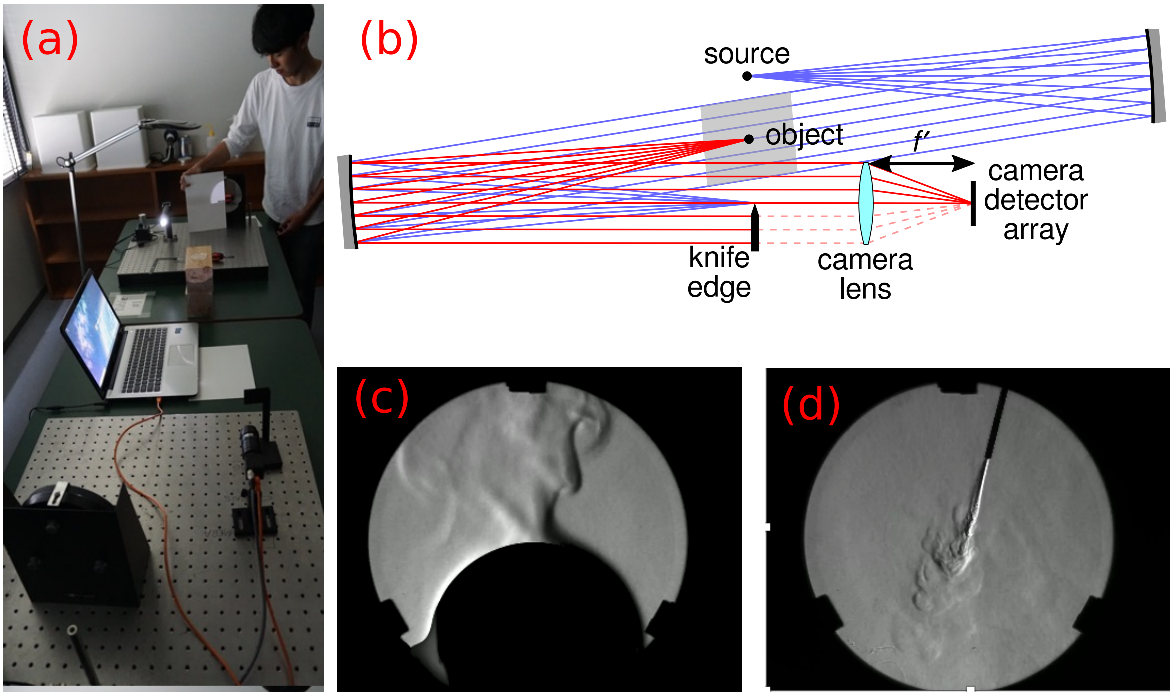

Figure 2: (a) The schlieren experiment setup, (b) optical system layout, and example flow images for (c) a black-painted light bulb and (d) HFC-152 gas.

motor's voltage settings into distance. Given the noise in the measurements, the students are able to estimate the metrological distance (in nm) that this system is capable of measuring.

In the second step of the experiment, a lens is placed between the interferometer output and a white screen magnifies the interferogram pattern so that students can see it easily with the naked eye. This pattern is imaged onto a camera detector array, allowing for the students to see the spatial interferogram profile. From the first step in the experiment, they can estimate the appropriate piezoelectric motor voltage required to induce a phase shift of 90°, 180°, and 270° (in addition to the initial 0° image taken at zero-voltage). Therefore, the students collect four images, and use the conventional four-phase-shift equation

$$\phi = \arctan\left(\frac{I_{270} - I_{90}}{I_0 - I_{180}}\right)$$

to obtain the (wrapped) phase interferogram image. This wavefront phase is then easily converted into the quantitative shape of the not-quite-flat fixed mirror, using the interferogram equation and laser wavelength.

2.2 Lab topic 2: visualizing flow with schlieren imaging

The schlieren imaging experiment involves aligning a pair of 150 mm diameter mirrors (and 150 mm focal lengths), a "knife-edge" flag, and a camera to view the mixing flow of materials with different refractive indices, such as hot and cool gas. After aligning the system so that the flow images are visible, the students set up the camera and capture digital images of the three example objects: the evaporation from a dish of ethyl alcohol, the hot air flowing across a black-painted light bulb, and the gas emitted from an air duster can (HFC-152 gas). See Fig. 2 for a photo of the system, a system layout, and example images.

After collecting the data with the air duster can, students begin the quantitative aspect of the experiment. The experiment manual walks them through a sequence of steps, calculating the estimated deflection angle of the optical rays passing through the gas, and converting this into an estimated refractive index gradient. While schlieren is widely known to be a difficult technique to yield accurate quantitative results, the steps here adopt an approximate physical model for the deflection angle of light passing through the "schliere", and the conversion

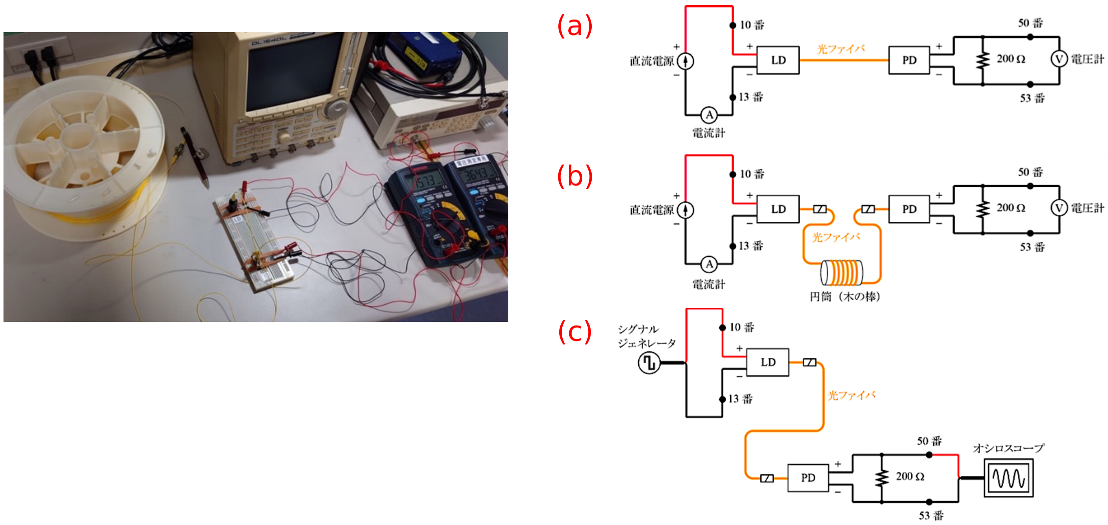

Figure 3: Experimental setups used to (a) measure threshold current of a laser diode; (b) measure bending loss; (c) make an optical communication system.

of this deflection angle into a change in intensity at the image. This provides insight into the connection between the physical system and the raw images that they see at the camera.

2.3 Lab topic 3: fiber optic sensing and optical communications

The third optical experiment (Fig. 3) involves the use of optical fiber for sensitive optical communications measurements:

1. Measure the current-intensity characteristics of the LD. Confirm that the laser oscillates when the injection current exceeds a threshold value.
2. Calculate the optical loss per bending circumference of the optical fiber.
3. Find the optical loss per rotation of the optical fiber (wrapped many times around a cylinder) in relation to the bend radius of the optical fiber.
4. Measure the modulation bandwidth (operating speed) of the laser diode (LD) from the waveform of the optical signal. By modulating the current injected into the LD, an intensity-modulated optical signal is generated, which is received by the photodiode.

3. CONCLUSION

By developing a laboratory class that highlights the connections between optical engineering and mechanical engineering, we hope to attract more students from the mechanical engineering student body and show to them that optical engineering can be relevant to their own future goals, in employment and in research.