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Inexpensive Hands-On Activities in Solid State Lighting

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Inexpensive Hands-On Activities in Solid State Lighting

Hands-on activities were developed as part of an overseas immersion programme (OIP) run by the School of Engineering at the University of Glasgow (UoG). The two-week OIP was a combination of academic and cultural experiences where the academic experience was a 10 credit course on solid state lighting. The course was taught for the first time in the summer of 2015 to a cohort of 32 Year 1 and Year 2 students in the undergraduate electronics and electrical engineering programmes offered at the University of Electronic Science and Technology of China (UESTC) and the Glasgow College, UESTC (formerly known as the UoG-UESTC Joint School). Both institutions of higher learning are located in Chengdu, China. The students were Chinese nationals who were in the process of building their knowledge of technical English. Three laboratory exercises and one design project were developed to provide opportunities for hands-on learning and to allow the students to explore their own ideas on solid-state lighting applications. The labs and project assigned are described along with the intended learning outcomes and a summary of student evaluations. Planned improvements to the labs and project, which will be incorporated in the when the course is offered again in the summer of 2016, will also be discussed.

I. Background

The University of Glasgow (UoG) and the University of Electronic Science and Technology of China are partners in a joint educational programme (JEP) in Electronic and Electrical Engineering (EEE). The Glasgow College, UESTC in which the JEP in EEE is housed is now in its third year of operation. The JEP in EEE has an enrolment of 600 students in the first three years of the four year undergraduate programme with a planned enrolment of 960 students in steady-state. As part of its mission, the Glasgow College, UESTC has organized several summer overseas immersion programmes (OIP) to enable all students in the programme to have an international experience prior to graduation. One of the OIP is a trip to the United Kingdom and Ireland. The students spend a long weekend in London sightseeing, a week in Ireland where they visit the Dublin Institute of Technology, and two weeks in Glasgow. During their stay in Glasgow, the students participate in a course on solid-state lighting, which is designed to provide them with an experience as students at the University of Glasgow, to visit the Intelligent Lighting Centre at the University of Strathclyde, and to explore how various companies and tourist sites employ solid-state lighting throughout Scotland. Time is also allocated to allow the students to gain an appreciation for the culture and history of Scotland during each of the visits.

The students' conceptual knowledge about solid state lighting prior to the summer OIP was limited. Most of the students knew the application of piecewise models and load line analysis to determine diode currents and voltages in circuits, including power electronic circuits. In a number of laboratory exercises and design projects assigned during the previous academic year, the students had made use of visible light-emitting diodes (LEDs), although none of these were white light LEDs. Furthermore, most of the students had some experience with the microprocessor platform that they were asked to employ in the design project during the second week of the OIP. However, students were unfamiliar with many of the topics related to the design of solid state lighting products such as the spectral and frequency response of the human eye. The goals of the laboratory component integrated into the academic experience were to provide students with opportunities to explore some of the device parameters and the response of humans to light and to use the knowledge that they gained from these hands-on activities as well as material from lectures and industrial visits in a short design project.

While the University of Glasgow has a strong research programme in optoelectronic devices, no laboratory experiments existed that were tailored for undergraduate students. The characterization equipment that was available was research-grade instruments in limited quantity, unsuitable for use by a large number of students who had only two weeks in Scotland. The tuition generated by the summer OIP had to cover all of the costs associated with the course as well as field trips to cultural sites in the region. No capital expenditures could be covered by the tuition without severely impacting the number of students who could afford to participate in the OIP. It was decided that the costs for components and equipment had to be limited to £150 or roughly $225 per student. While there are a number of commercially-available, inexpensive optical experiment kits such as the Optics Discovery Kit[1], the kits were generally designed to support instruction on physical optics rather than the optical and optoelectronic concepts applied in solid state lighting. Experiments developed by other educators tended to be orientated, again, towards physical optics[2] or towards optical communications[3 - 6].

After reviewing the concepts that were to be covered in the lectures, it was decided that experiments in which students explored the eye response in the time domain and the spectral content of light as well as measure the far-field angle of several light-emitting diodes to reinforce the learning of the associated concepts. It was also expect that these experiments would provide practical experiences that could then be applied in the open-ended projects that the students would design later in the course.

II. Hands-On Experiments

Three experiments were conducted by the students during the first week of the OIP. In these experiments, students measured the far-field angle of light-emitting diodes (LEDs) and the spectral content of single colour and white light LEDs using an inexpensive spectroscope. They constructed a white light source using three single colour LEDs, and observed the frequency response of their eyes to white light LEDs powered by a variable duty cycle/variable frequency square wave generator and compared the response to that of a photodetector. During the second week of the OIP, students designed and constructed a wearable circuit using various optoelectronic and electronic components and an mbed microprocessor, which they demonstrated during a fashion show on the last day of the OIP.

The laboratories were designed to couple with topics from the lectures, but function more or less stand-alone as some of the topics were discussed in lectures that followed the labs due to constraints on the schedules of external speakers and industrial and cultural visits. A description of the experiments including a bill of materials is provided in Table I. An

Table I: Description of Experiments and the Bill of Materials

Experiment	Activities	Bill of Materials
Properties of Narrow and Wide Angle LEDs	1. Construct a circuit to power an LED in pulsed operation and a second circuit to detect output of an integrated photodetector-amplifier. 2. Measure the light output at two different current levels of four different LEDs 3. Determine the far-field angle of one narrow- and one wide-angle LED of the same colour. 4. Repeat the measurement of the far-field angle of the two LEDs, but locate the light-to-voltage sensor 2-4 cms further away from the LEDs.	Arbitrary function generator DC voltage supply Oscilloscope 2 solderless breadboards (400 tie) 1 each: red LED with 2 $\theta_{1/2} = 15^{o}$ far-field angle, red LED with 2 $\theta_{1/2} = 45^{o}$ far-field angle, green LED with 2 $\theta_{1/2} = 15^{o}$ far-field angle, green LED with 2 $\theta_{1/2} = 45^{o}$ far-field angle 1 BCS47 npn transistor BC547 1 TSL14S sidelooker light-to-voltage sensor 1 each: 68Ω, 130Ω, 1 kΩ and 10 kΩ resistors Protractor Ruler
Human vs. Machine	1. Construct a circuit to power an LED in pulse operation, limiting the current to 20 mA. 2. Slowly sweep the frequency of the pulses from 1 Hz to 500 Hz and monitor the output of the LED by eye. 3. Again, sweep the frequency of the pulses and monitor the output of the amplified photodetector. 4. Set the frequency to 1 kHz, and sweep the duty cycle from 20% to 80% while monitoring the output of the amplified photodetector.	Arbitrary function generator DC voltage supply Oscilloscope 2 solderless breadboards (400 tie) 1 LED, colour and far-field angle was students' choice 1 BC547 npn transistor 1 TSL14S sidelooker light-to-voltage sensor Set of 92Ω, 130Ω, 910 Ω, 9.1 kΩ and 91 kΩ resistors 91Ω
Properties of Red, Green, and Blue LEDs	1. Using a light diffuser, observe the colours that are generated as one or more of the LEDs is first operated at a proscribed current level and then as the currents to the three LEDs is altered. 2. Using a spectroscope, observe the spectrum of light emitted from each LED individually and in various combinations.	Arbitrary function generator DC voltage supply Oscilloscope 1 solderless breadboard (400 tie) 1 three-colour LED lamp 3 BC547 npn transistors 3 trim potentiometers Set of 47 Ω and 110 Ω resistors 4 single-throw single-pole switches 1 ping-pong ball with three holes drilled into it 1 economy spectroscope (Carolina Biological Supply Company)

explanation of the learning outcomes that the students were expected to achieve by the end of each experiment is provided in Table II. Students conducted the experiments in teams of two. Student learning was assessed via two lab reports and an oral presentation on their design project.

Table II: Intended Learning Outcomes for Each Experiment

Experiment	**Intended Learning Outcomes – Students will:**
Properties of Narrow and Wide Angle LEDs	• Calculate the full-width half-maximum of the emission pattern(s) from: ○ LEDs that differ in colour, ○ an individual LED emitting different amounts of optical power, and ○ an individual LED positioned at two distances to observer. • Analyse the calculated far-field angle with respect to the experimental variables. • Compare the experimental far-field angles with the expected values documented in the component datasheets. • Theorise why the measurements were made while pulsing the LEDs. • Reflect on the accuracy of the calculated far-field angle and the changes in light intensity with angle as observed by eye.
Human vs. Machine	• Compare the linearity of response of the optical sensor and the human eye as the optical power emitted by an LED is increased. • Estimate the frequency response of the human eye. • Measure the frequency response of the LED-optical sensor system and determine which component limits the response using information in the datasheets. • Translate the knowledge about the linearity of response to explain the observed vs. measured intensity of the LED as the duty cycle is changed from 20-80 %. • Describe advantages of pulse width modulation as compared to varying resistor values to alter the optical power emitted by an LED.
Properties of Red, Green, and Blue LEDs	• Explain how colours, observed by eye, are generated by mixing the output of three LEDs. • Compare the colours observed by eye with the spectral content of the light as displayed by the spectroscope. • Write a program for an mbed microcontroller to create 15 different colour variations using the three-colour LED lamp and power the LEDs using the PWM outputs of the mbed and demonstrate its operation.

Experiment 1: Properties of Narrow and Wide Angle LEDS

The first experiment is similar to the far-field measurement experiment described in Ref. 5. As can be seen from the intended learning outcomes in Experiment 1, students were expected to discover that the far-field angles of the light emitted by LEDs were independent of the colour of the LED, the current flowing through each LED, and the distance between the LED and photodetector. They were also expected to evaluate their ability to judge accuracy of their measurement of the far-field angles after a review of the datasheets as well as begin to develop an understanding that the light intensity seen by eye and measured using the photodetector are not equivalent. Lastly, the students were to speculate on the reasons why a pulsed source was used to power the LED.

The protractor used was a print-out of an array of concentric semicircles with increasing radii on A3 paper. Lines emanating around the origin were spaced at 5^o. The pattern was sufficient large to allow the students to place the two breadboards on it and enabled reasonably accurate measurement of angle. The students were instructed to place at the edge of one of the breadboard and position the breadboard such that the LED was located at the origin of the semicircles and pointed along the 0^o line. First, the students were to estimate the far-field angle by eye. Then students moved the second breadboard, on which the optical sensor circuit was constructed, along one of the semicircles around the LED, taking voltage measurements at every 5^o. The far-field angle for each LED was then calculated by applying the definition that the far-field angle $\theta_{1/2}$ is the subtraction of the angle at which the maximum intensity is measured (0^o) from the angle at which the intensity has dropped to 50 % of the maximum intensity.

The resolution of the paper protractor was satisfactory for the purposes of the experiment. A majority of student teams found far-field angles that were within an acceptable range of accuracy, though the accuracy of the far-field angles of the narrow angle LEDs was less than that of the wide angle LEDs. Several students were observed to scribe additional lines on the printout to obtain a more accurate determination of the far-field angle. As this will not make the grid unreadable, a new grid will be produced with a finer array of lines.

Despite the information provided to the students at the beginning of the lab session, a number of teams made an error by placing the photodetector on a semicircular path that was too close to the LED, causing the photodetector output to saturate at some angle well before 0^o. The top-hat shape of the graph of photodetector voltage versus angle was a signature of this error. Due to this error, these teams did observe a correlation between far-field angle and LED colour (due to the lower optical efficiency of the red LEDs as compared to that of the green LEDs), LED current, and distance between the LED and optical sensor. The error could have been a result of lack of attention during the oral presentation, lack of notes taken during the presentation/forgetting the information, or lack of comprehension due to the technical language used or the (Scottish) accent of the presenter. An effort to determine the exact cause will be studied during the next offering of this course. An area for note taking will be added to the printed laboratory procedure. The undergraduate laboratory teaching assistants will be asked to observe whether students use this area during the presentation and to informally assess the accuracy of the notes that are taken during the lab session.

The interference caused by sunlight was observed by several teams who were conducted their experiment while seated at lab stations near an outside window. As the students circulated among teams, the information about this interference was rapidly communicated to the rest of the cohort, some of whom then realised that the fluorescent lights in the room could also create interference, however, with a characteristic 50 Hz frequency.

Experiment 2: Human vs. Machine

The second experiment was designed to guide students to an understanding of the limitations of the eye response, i.e., the lack of linearity with respect to linear changes in optical intensity and the maximum frequency of optical pulses in the time domain. A second aim was to demonstrate pulse width modulation (PWM) as a means to adjust the optical power outputted by an LED. Rather than having the students use the PWM output from the mbed microcontroller, which could be used in the design project, or an operational amplifier circuit as the PWM generator, students pulsed the LEDs using a transistor switch with an arbitrary function generator as the input. Each team of students observed the operation of the LED as they altered the frequency of the arbitrary function generator, which had been set to output a 50 % duty cycle square wave. The students were asked to determine the maximum frequency at which they could detect pulsed emission from the LED. They then measured the output of a photodetector aligned to the LED to determine the maximum frequency of operation. The students then set the frequency of operation on the arbitrary function generator to 1 kHz and varied the duty cycle, repeating the measurement by eye and using a photodetector. They were also asked to comment on the brightness of the LED as observed by eye and as measured by the photodetector.

Understanding the eye response and the value of pulse width modulation as a technique to power LEDs will be important to the project that the students would design during the second week of the OIP. While most of the student teams identified frequencies for the visual detection of the limit to the pulsed operation of LED that were well beyond the maximum frequency of the eye response[7], all teams found that the signal from the photodetector was modulated by the LED signal up to frequencies approaching 1 MHz, at least 100 times larger than the maximum frequencies observed by eye. Several teams reviewed the datasheets for the LED, photodetector, and bipolar transistor and realized that the maximum frequency of operation was not limited by any of the three components, although none of the teams realized that the parasitic capacitance of the breadboard was the culprit. All of the teams realized that the observed change in brightness of the LED as the duty cycle was increased was a result of the integration of light by the eye rather than an actual increase in the instantaneous optical power emitted by the LED.

The experiment was designed to introduce students to common techniques used in solid state lighting to reduce power consumption and to dim the output of the LED without having to address the electrical nonlinearities of a diode. Unfortunately, knowledge about PWM was not incorporated into the design of one of the projects, resulting in rapid discharging of the most of the battery power supplies during the project presentations. To emphasize the desirability of pulsed operation of LEDs, the laboratory procedure will be rewritten to include calculations of electrical power dissipation by LEDs operated in continuous wave (cw) and pulsed mode. In addition, the undergraduate laboratory teaching assistants will be asked to prompt students to consider methods to reduce power consumption during the laboratory sessions during Week 2.

Experiment 3: Properties of Red, Green and Blue LEDs

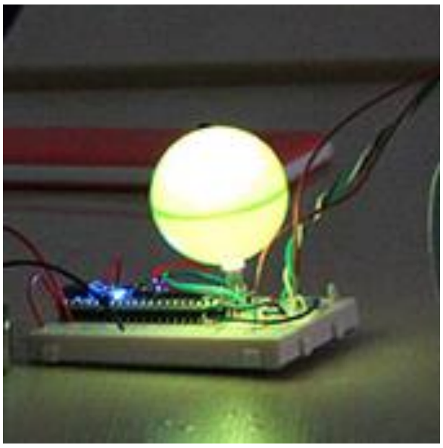

Fig. 1. Three-colour LED with ping-pong ball diffuser driven using the digital outputs from an mbed micrcontroller[9].

The third experiment was based upon an experiment described in a paper written by G. Planinšič[8]. A three-colour LED lamp was used instead of three individual LEDs so only one hole in the diffuser, a ping-pong ball, had to be made. Unlike what was done to the individual LEDs in Ref. 1, the lens of the three-colour LED lamp was not eroded. The far-field of the emission was sufficiently wide that most of the diffuser is illuminated. It was decided to use resistors to limit the current to each of the three LEDs packaged in the three-colour LED lamp and a DC power supply rather than PWM so that students would more easily see the correlation between the power outputs of the individual LEDs, the colour of diffused light, and the spectrum observed using the spectroscope.

During the second half of the lab session, students were asked to write a program for the mbed to create fifteen colours using the data collected in the first part of the experiment. Instead of varying the DC currents to the individual LEDs, the students were asked to use the PWM outputs of the mbed to control the amplitude of the optical power emitted by each LED. This part of the experiment served to introduce the students to some of the capabilities of the mbed microcontroller, which the students were expected to incorporate into their design projects.

The course instructor concluded that the learning outcomes were met and that it provided a good segue into the design project, which the students were to complete in the following week. Students did not require the entire three hour session to complete the experiment, which allowed the undergraduate lab teaching assistants time to work with the three UESTC students who were unfamiliar with the mbed platform. This instruction did not take much time as the UESTC students had experience with another microcontroller platform as well as with C programming. Furthermore, there was sufficient time during the lab session for the course instructor and the lead electronics laboratory staff member to discuss ideas for projects with the students. There are no plans to modify the experiment.

III. Design Project

The students had been given information about the design project during the first lecture session. The students were given an open-ended assignment to design a wearable optoelectronic circuit that incorporated an mbed microcontroller and was powered by a 9 V battery. They were allowed to select a small number of components that were not readily available in the electronic store if they provided component part numbers to the lead electronic laboratory staff member by the end of Experiment 3 with the caveat that the components must be in stock at one of the suppliers used by the School of Engineering and that the total cost of the components to be purchased was reasonable. The exact limit on the cost was dictated by the total cost of all of the requests. In fact, the number of requests for component purchases was small and no requests were denied except for one case where the component was not actually in stock at the time of the order. Students were also asked to submit requests for items of clothing on which the circuits would be placed, which were then purchased from local charity shops.

The work on the design projects was scheduled for the afternoons of Tuesday and Thursday of the second week of the OIP. Presentations of the designs were scheduled on Friday of that week with awards given for the top three projects as determined by scores on the projects from the undergraduate laboratory teaching assistants. Several of the student teams worked on the projects in their dormitory rooms in the evenings, though this was not suggested or encouraged by the course instructor. First place was awarded to two Year 2 students who designed a coupled optoelectronic system in which displays embedded in two shirts flashed simultaneously when an optical signal emitted by an electronic wristband was sensed by a photodetector in a second electronic wristband. The second and third prizes were awarded for a bookbag clock with an optically swept second, minute, and hour “hand” and a wearable hot/cold beverage detector, respectively. Examples of the projects were described in a campus newsletter[9].

All of the design projects worked in some fashion. As previously mentioned, some of the concepts introduced during Experiments 1 – 3 were not incorporated into the projects. For example, most of the projects required the use of a large number of LEDs; the project shown in Fig. 2. was a typical example of the quantity of LEDs used in each project. In 14 of the 15 projects, the LEDs were operated in a constant current mode rather than in pulsed operation, even though students were required to incorporate an mbed microcontroller in their designs and, thus, had ready access to a PWM signal to drive the LEDs as they had done in Experiment 3. Thus, the knowledge transfer from the experiments to the project did not occur as had been expected.


Fig. 2. Wearable optoelectronic design project in which a Doraemon image was outlined with blue and red LEDs operated in CW mode[9].

The complexity of supporting a very diverse range of designs placed significant demands on the course instructor, the lead electronics laboratory staff member and the two undergraduate laboratory teaching assistants. Furthermore, the amount of time invested in the projects by some of the students was considerably more than had been expected and was thought to detract from their willingness to participate in some of the cultural and industrial visits that were scheduled during the second week of the OIP. At least two of the teams underestimated the challenges associated with their design and spent much of the night before the scheduled presentations working to make a part of their project function. Two other teams were driven to complete fairly complicated designs, which they began on the weekend between weeks 1 and 2 of the OIP and again on the Thursday evening. Thus, the design project that will be incorporated into the summer OIP in 2016 will be more focused in scope to reduce the time required to complete team designs while still allowing for some individual/team creativity. This will also enable the staff to stock components that will likely be needed for student designs, reducing the support needed to purchase components on short notice. In addition, the course instructor and electronic laboratory staff member will be able to work with the undergraduate teaching assistants to identify possible design errors and to discuss how to guide students to solutions before the design project is assigned. Lastly, a more constrained design project may reduce the student indecisiveness so that they settle on a design of their own more rapidly.

31 of the 32 students voluntarily completed an evaluation of instruction prior to the project demonstrations on the final day of the course. However, only two-third of these students provided answers to each of the survey questions, which are listed in Table III. 20 out of 21 students strongly agreed (68.2 %) or agreed (27.3 %) that they were satisfied with the course. Similarly, 21 out of 22 students strongly agreed (71.4 %) or agreed (23.8 %) that the project allowed for creativity and imagination. All 19 responses to the statement “The project has been intellectually challenging and stimulating” were positive. In general, the comments in the open response portion of the survey were positive, though six students commented on the limited time available to complete the project. None of the students wrote comments about the three laboratory experiments.

IV. Summary

A two-week course on solid-state lighting was taught in the summer of 2015. Three laboratory experiments and one design project were developed and successfully delivered as part of the overseas summer immersion programme. The total cost of the experiments and design projects was approximately $225 per team, which included the cost of a mbed microcontroller ($49) and the purchase of one spectroscope ($9.65) per team. Student feedback collected at the end of the summer OIP indicated that they enjoyed the laboratory experiments and the opportunity to design wearable electronics, but some were unhappy with the amount of work that the project entailed. Informal assessment of student learning indicated that most of the learning outcomes from each laboratory experiment were achieved. However, there were exceptions – specifically the measurement of far-field angle and the adoption of pulse width modulation of the LED to limit the rate of discharge of the 9 V battery used to power the wearable optoelectronic design project. Changes to two of the experimental procedures to promote the achievement of these two learning objectives were described. In addition, revisions to the design project to make the project more manageable for the staff and less time-intensive for the students so that they are able to gain as much as possible from all of the experiences during the OIP.

Table III: Questions in Evaluation of Instruction Survey

1.	**Individual Project-Based Learning**
1.1	The course has improved my ability to manage individual project work.
1.2	The project work has allowed for creativity and imagination.
1.3	The supervisor is helpful and approachable.
1.4	The project has been intellectually challenging and stimulating.
1.5	Overall, I am satisfied with the supervision provided.
2.	**Assessment and Feedback**
2.1	It was made clear to me what I was expected to achieve in this project.
2.2	The assessment scheme for this course is clear to me.
2.3	I have received sufficient feedback during this project.
2.4	Feedback from staff has helped me understand how well I am doing and how I could do better.
3.	**Organisation and Management**
3.1	The course is well organized.
3.2	Course information has been effectively communicated.
3.3	Timetabling and administrative support works well for this course.
4.	**Learning Resources**
4.1	Access to IT facilities and online learning resources are sufficient for this course.
4.2	Access to lab facilities and other resources are appropriate for this course.
5.	**Overall Satisfaction**
5.1	Overall, I am satisfied with this course.
6.	**Free Form Questions**
6.1	What is good about this course?
6.2	What could be improved in this course?
6.3	Any other comments about this course?

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