AC 2011-1682: VISUALIZING CONCEPTS IN ELECTROMAGNETIC FIELDS: HANDS-ON EXPERIMENTS USING STUDENT-OWNED LABORATORY KITS

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Visualizing Concepts in Electromagnetic Fields: Hands-On Experiments Using Student-Owned Laboratory Kits

The concepts of Electromagnetic (EM) fields serve as the foundation for many key principles of electrical engineering. Given its significance, EM fields has been a core subject taught to Electrical Engineering (EE) undergraduate students, both in the U.S. and abroad. Yet, interest in the required junior level EM courses and the subsequent EM technical electives is waning at Virginia Tech. The percentage of seniors enrolled in the technical electives in the EM area is the lowest of all technical electives offered by the Bradley Department of Electrical and Computer Engineering (ECE). Unfortunately, lack of student interest in EM courses has also been observed at other universities in the United States. This is disturbing as many of the upcoming technologies in electronics, communications, biomedicine, and imaging require greater application of concepts from EM. Hence, it is critical that the methods used to teach EM concepts change to improve the understanding of the fundamental concepts in EM and to attract more students into the field to insure that our students can participate in the technological advancements.

Traditionally, instruction in the required EM courses tends to concentrate on abstract theory and translation of theory to practice occurs in the senior technical electives. However, the emphasis on the theoretical concepts without mention or demonstration of their applications in the introductory courses fails to engage our students. While computer simulations can be useful to visualize EM concepts, studies have shown that students who gain the most from simulations already have a good grasp of the fundamental concepts, i.e., abstract learners.[1,2] Thus, the use of simulations in core EM courses does not support learning by visual learners, a group with a large distribution of women and underrepresented minority students. Providing a stronger connection between theory and practice has been shown to assist visual learners to develop a deeper understanding of abstract theoretical concepts without harming the learning of the abstract learners.[3,4]

To achieve our goal to promote a deeper understanding of EM concepts by all students, we have developed a set of hands-on experiments that the students can be perform using a low-cost electronics kit and USB-powered oscilloscope, collectively referred to on campus as Lab-in-a-Box (LiaB). The experiments are designed to promote student comprehension, depth of learning, and application of the fundamental concepts in electromagnetic fields using series of optical experiments with eye-safe optoelectronic devices, which enable the students to <u>see</u> the application of the concepts. The electronics breadboard serves as an optical table with plastic optical components mounted and aligned to optoelectronic and electro-optical devices using simple optomechanical fixtures positioned in the 0.1” spaced holes. Instructional materials have been created to provide background on associated technologies, applications, laser safety, and the processes used to fabricate some of the custom optical and optomechanical components used in the experiments. This paper will describe the pedagogical approach to incorporating LiaB into the EM course, assessment outcomes, and lessons learned.

Background on the Lab-in-a-Box

In 2004, the Virginia Tech Bradley Department of ECE began to offer a d.c. circuits laboratory course to accompany the d.c. circuits lecture course to provide an opportunity earlier in the

Electrical Engineering and Computer Engineering (CpE) curricula for students to apply the concepts taught in the circuits lecture courses. A unique feature of this laboratory course is that the students conduct much of their work using set of equipment, known as Lab-in-a-Box (LiaB), outside of a traditional classroom environment. The assignment of experiments performed at home is a core pedagogical approach taken in all four of the courses that now use the LiaB kit – the d.c. and a.c. laboratory courses taken by our EE and CpE undergraduates and the circuits and electronics laboratory courses taken by our mechanical engineering undergraduate students. The goals when developing each of the assignments are to provide a demonstration of one-to-two theoretical concepts in practice, to provide an increasing level of experimentation and design content in the exercises, and to develop a sense of self-confidence and motivation for the students to complete the experiments with minimum guidance from graduate teaching assistants (GTAs), the laboratory staff, and course instructor.

The LiaB kit contains an analog/digital trainer (ANDY board), shown in Figure 1, a digital multimeter (DMM), electrical components that include a set of 5% resistors, capacitors, inductors, light emitting diodes, several operational amplifiers and a few 555 timers. A recent addition to this set of equipment is a USB-powered oscilloscope, which was replaced a software oscilloscope and sound card interface. A two channel oscilloscope with arbitrary function generator (Velleman PCSGU250) was adopted in Spring 2009. A laboratory manual, now in its 3rd edition, contains background information on the operation of the powered ANDY board and the components and the experimental procedures with circuit schematics and step-by-step instructions on the analysis, simulations, and measurements that the students are to perform.[5] Online instructional materials and tutorials have been developed to provide support to students as they work on each of the assigned experiments.[6] We have obtained very positive results during an early assessment for the initial d.c. experiments via a survey instrument[7] in addition to positive feedback from the department faculty members. Another survey has recently been conducted to assess both the d.c. and a.c. circuits experiments as well as the associated online instructional materials and tutorials. Preliminary analysis of the data is again very positive with the comments from the students aligning well with our pedagogical goals.

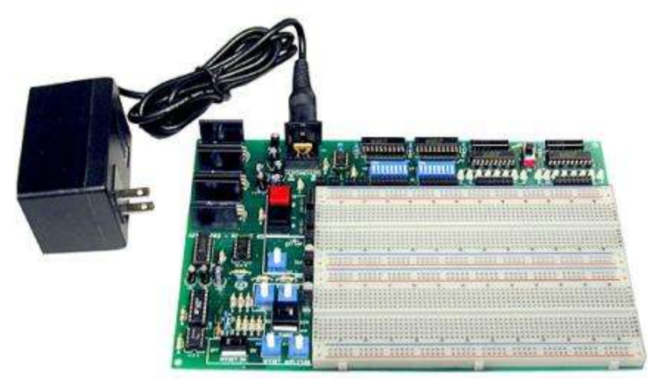

Figure 1: The RSR/VT A and D trainer.

Motivation for the EM LiaB Experiments

It is a rare EE undergraduate student that looks forward to taking the EM fields courses required during the junior year at Virginia Tech. Even more unusual is having a CpE student decide to enroll in one of the EM courses, which can be used as a technical elective in the senior year of the bachelor's degree in CpE. A review of the courses, exit interviews of our seniors, and informal conversations with students has lead to a hypothesis on why student interest in EM is so low. To achieve the core learning objectives, the topics taught in the introductory courses on EM fields are abstract in nature and translation of theory to practice generally occurs in the subsequent senior undergraduate technical electives. However, it is the emphasis in these courses on the instruction of the theoretical and mathematical foundation without concrete applications that fails to engage our students. These juniors tend to view the first two courses on electromagnetic fields as rigorous math courses without a useful purpose in the technical electives that they have started to identify to take during their senior year or in their future careers. It is clear that this instructional approach is not spurring student interest at Virginia Tech as the percentage of senior undergraduate enrolled in the technical electives in the EM area is the lowest of all of the technical electives offered by the ECE department. This is disturbing as many of the trends for future technologies in electronics, communications, biomedicine, and imaging require the integration of concepts from EM.[8,9] For example, optoelectronic, electro-optic, plasmonic, and passive optical devices and circuits are under investigation as one of the alternatives to Si-based nanoelectronics in addition to their use as high speed inter- and intra-chip interconnects.[10] The integration of optical computing with traditional electronics offers the means to perform large scale, complex, and reconfigurable calculations that would support the establishment of secure ad hoc communications networks and is needed for real-time parallel processing. Furthermore, the applications of wireless technologies have expanded rapidly over the past twenty years with the consumer acceptance of cell phones and wireless internet connectivity, providing a technology platform from which other products have been launched. Hence, it is important that our engineering students have a solid foundation in electromagnetic fields so that they can participate in the technological advancements of the future.

Several of the faculty members who were heavily involved in the development of the LiaB courses have participated in discussions with the faculty members who are responsible for supervising the instruction of the core EM undergraduate courses. The concerns expressed about the student interest and depth of learning in the EM courses are almost identical to the concerns raised about the undergraduate circuits courses prior to the introduction of the LiaB-based lab courses. One of the authors (Y. Xu) proposed developing hands-on activities that the student can perform to demonstrate EM concepts, using the student-owned LiaB kit.

The cliché – seeing is believing – is one of the fundamental principles that underpin the project; visible light-emitting diodes and low-power vertical cavity surface emitting lasers are key components in a number of the experiments that have been developed since his proposal. The electronics breadboard serves as a miniature optical table and plastic optical components can be mounted on the solderless breadboard surface and aligned to optoelectronic and electro-optical devices with simple optomechanical fixtures positioned in the 0.1” spaced holes on the breadboard. The students perform experiments that demonstrate basic concepts in EM and <u>see</u> the application of these concepts using eye-safe optoelectronic devices at home and in the classroom. We note that radio frequency (RF) experiments can also be developed using the LiaB platform, keeping in mind the maximum frequency of operation of the breadboard itself (~4 MHz) and the Federal Communications Commission’s regulations on power and broadcast frequencies.

Design of Experiments

The first step in the process to design the experiments was the identification of the topics for the experiments. Informal discussions were held with the faculty members who regularly taught the introductory and senior-level EM classes to obtain their input on the central concepts in each course and to determine which concepts were most difficult for the students to comprehend and retain. A list of these topics was reviewed and ideas were generated on how students could experimentally verify and apply the concepts. We then selected a subset of these topics to begin the development of the hands-on activities. Unlike the LiaB circuits experiments, which are performed outside of the classroom, we were open to all venues. While some experiments would be conducted by students at home, others would be performed in the classroom as a hands-on activity during the lecture and certain experiments would be carried out in one of the traditional laboratory classrooms so that other measurement equipment could be used in the experiment.

As with the experiments developed for the circuits courses, the experiments on EM concepts are constructed based on instructional events:[11] gain attention, state objectives, activate prior knowledge, present material, provide learning guidance, motivate practice, and provide feedback. A template based upon these events has been developed and is completed during the design of the experiment so that each event is presented to the students in a systematic manner. The template, which becomes the experimental procedure, has the following sections.

(a) Learning Objectives: The expected knowledge that the students will gain from the experiment including a deeper understanding of one-to-two concepts explored in the experiment.

(b) Preparation: The sections of the textbook in which the concepts are discussed are identified.

(c) Background: A brief explanation of the theory is presented along with a short discussion of the practical applications of the theory in day-to-day life, products used commonly by students, and/or in areas of research that undergraduate students would be aware of. In addition, the experimental set-up is explained. Schematics of the circuits and images of students performing specific measurements are included. Ties between the current experiment with experiments performed previously are also made.

(d) References: Books other than the course textbook, technical papers, and websites are provided so that interested students can read further on the topics covered in the Background section.

(e) Materials: The components required to perform the experiment are listed.

(f) Experimental Procedure: A step-by-step set of instructions are provided in the following order – (1) Analysis, which are hand calculations and MatLAB programs that are expected to be done before the student start the hands-on section of the experiment, (2) Modeling, which are any simulations that the students are expected to perform using software packages, (3) Measurements, which cover the set of instructions on how the components should be assembled and what measurements are to be made as well as questions interspersed in the instructions that are intended to guide the students as they analyze the results of the measurements and to spur them to consider why differences may exists when the students compare the results from the measurements with those obtained from the steps performed in the Analysis and Modeling.

The students are required to submit a lab report, which is graded and returned to provide feedback to the students.

Concepts to Experiments

The concepts integrated into the first four experiments are: far-field angle, numerical aperture, collection efficiency, Malus' Law, Beer-Lambert Law, and total internal reflection. The experiments that cover these concepts are: Propagation in Free Space and Detector Responsivity; Coupling Efficiency; Polarization and Vector Dot Product; and Total Internal Reflection and Absorption Coefficient. The experimental procedures for three of the four experiments have been finalized and are described below. An experiment on diffraction and interference, in which students will map the intensity of light after it passes through a single slit and then through a double slit, will be developed in the near future.

The components needed by each student for use in the three experiments developed to date are four different light emitting diodes, three of which have different emission wavelengths (white, green, and red) and an additional red LED that had a significantly different far-field angle from the first; a Si photodetector with integrated amplifier; a resistor to control the current through the LEDs and trim the gain of the photodetector amplifier; a plastic core fiber; and two polarizers. In addition to these off-the-shelf components, an inexpensive filter housing was designed, which could be used on the breadboard with the optoelectronic components. The housing held the two polarizers parallel to one another, but permitted rotation about the plane from 0 to 90 degrees in increments of 30 degrees. A prototype of the fixture was fabricated using a computer numerical controlled machine; however, we intend to have larger quantities fabricated using injection molding to minimize the long-term cost. The first two experiments were piloted in a senior technical elective in Fall 2010. The third experiment will be piloted in Spring 2011 after we revise the design of prototype to simplify manufacturability.

Experiment 1: Propagation in Free Space and Detector Responsivity. The students, working in teams of two, construct circuits to drive specified currents through the LEDs and measure the output voltage from the amplifier integrated photodetector package. Students then performed several measurements that included measurement of the response of the detector to changes in the current of a single wavelength LED, the output of the photodetector as a function of LED wavelength, measurement of the change in detector response as the distance between LED and detector is increased, and mapping of the variation in intensity of the LED output versus angle. Examples of the data collected by the students are shown in the figures below.

Experiment 2: Coupling Efficiency. Students constructed a simple lens system. They focused the light generated by an LED through a lens into a multimode fiber and used the photodetector to measure the output intensity of the fiber. They determined the coupling coefficient of the optical power into the fiber experimentally and compared the result with the value that they calculated using the information provided on datasheets for the LED far-field angle, the focal length of the lens, and the numerical aperture of the multimode fiber. Given the alignment tolerances of the LED-to-lens and lens-to-fiber and requirement to accurately translate the multimode fiber laterally through the far-field pattern of the LED, this experiment was conducted in a laboratory classroom so that students had access to micropositioners. Figure 3 is a photograph of half of the experimental set-up – the alignment of the LED to multimode fiber using two micropositioners on an optical bench.

Experiment 3: Polarization and Vector Dot Product. The third experiment involved the rotation of one polarized filter with respect to another to demonstrate Malus' Law. A surface emitting LED is used as a random polarized light source and the photodetector with amplifier is used to detect the intensity of the light that passes through both polarizers. Students rotate one polarizer with respect to the other while monitoring the detector output. They plot the measured signal as

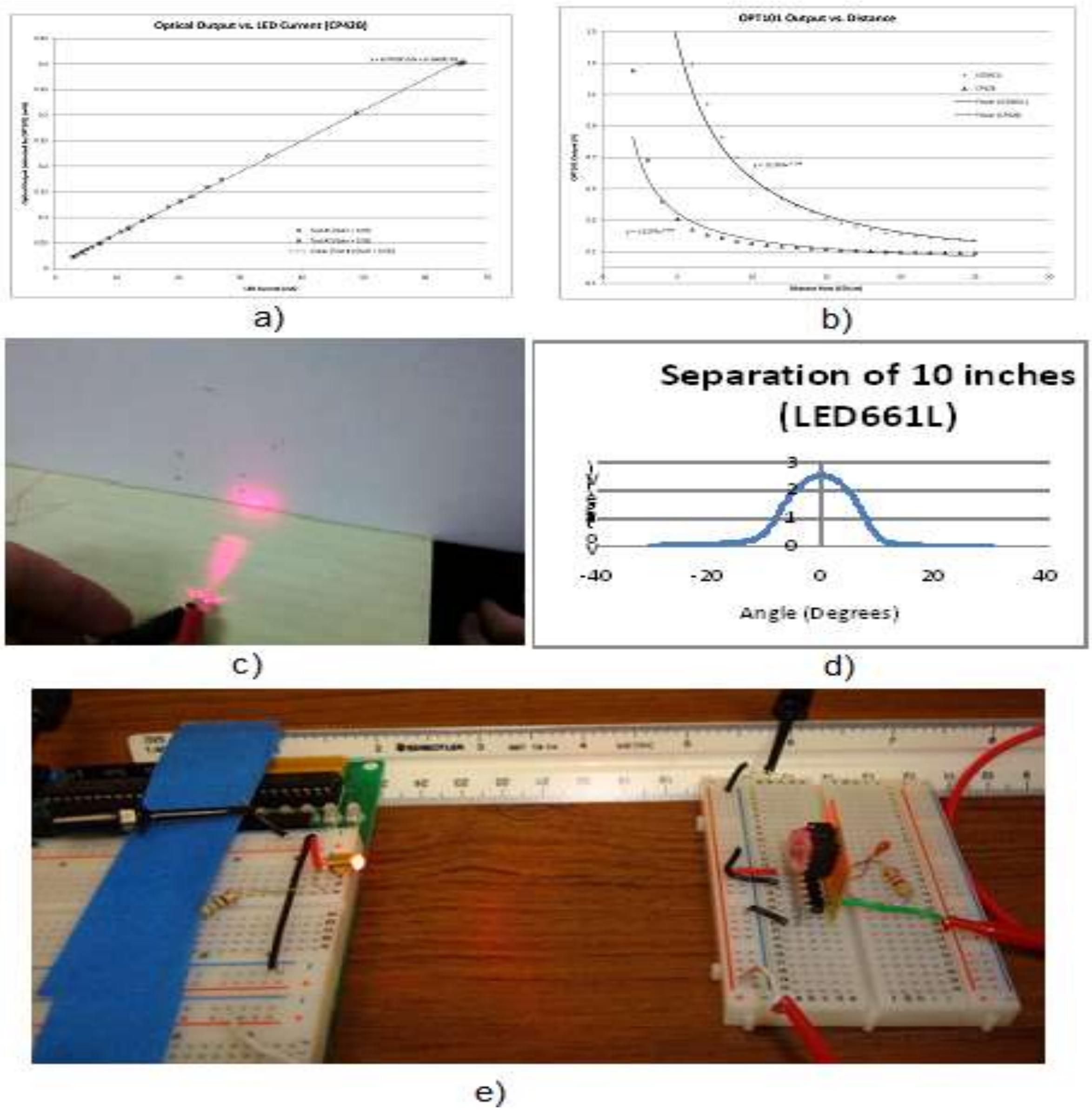

Figure 2: Images submitted by the students in the lab report on Free Space Propagation and Detector Response: a) plot of the data collected on the change in LED emission intensity, as determined by the change in the detector output, as a function of current, b) plot of the data collected on the change in the detector response as the distance between the LED and photodetctor is increased, c) experimental verification of the LED far-field pattern, d) plot of the emission intensity of the LED as a function of angle with respect to the photodetector, and e) an experimental set-up used to collect the data shown in b).

a function of rotation angle and compare the results with calculations from Malus' Law. They also calculate the degree of polarization to obtain a measure of how well the polarizing filters are at discriminating between the two polarizations of light. The fixture that has been designed for this experiment permits students to perform the experiment without requiring specialized optomechanical positioners (Figure 4); thus the experiment can be conducted at home or during a lecture in a standard classroom environment.

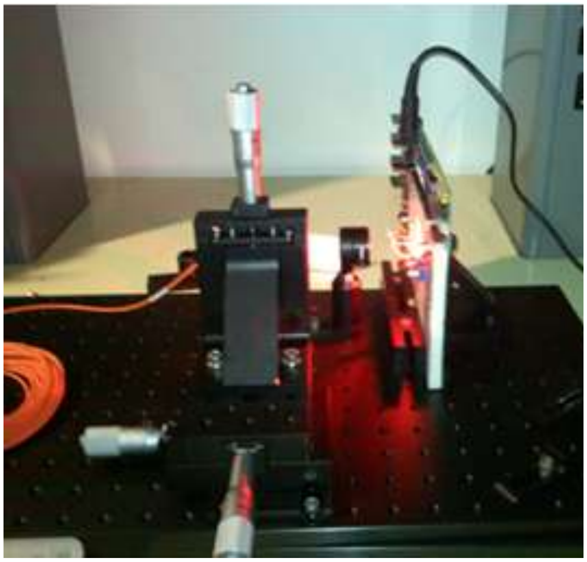

Figure 3: Photograph of the LED, lens system, and multimode fiber with optomechanical mounts and micropositioners.

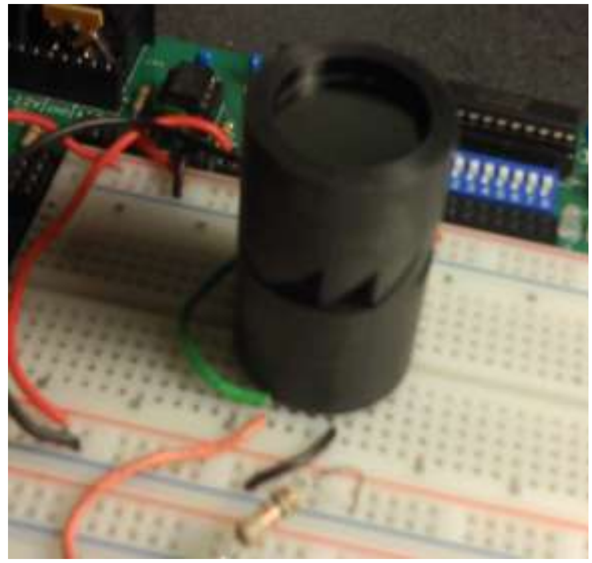

Figure 4: Photograph of the fixture used to rotate the polarizers. The serrated teeth on the upper half of the fixture lock in place with a notch in the lower half at 0^{o}, 30^{o}, 60^{o}, and 90^{o} positions.

Results from the First Assessment Cycle

Students were asked to complete two surveys, one before the two experiments, Propagation in Free Space and Detector Responsivity and Coupling Efficiency, were assigned and the second after the final lab report was submitted at the end of the semester. The first survey was opened approximately halfway through the semester. The purpose of the surveys was to determine whether the students thought that the experiments helped them understand the concepts presented during the classroom lectures. The survey was broken into five parts. The questions in Part 1 were designed to collect information on the students' experience in optics and the hardware and software tools used in the experiments. Part 2 questions solicited input from students on their confidence to perform several of the tasks that were required to complete the experiences; for example, where they confident that they could design and construct an LED driver circuit or calculate the amount of light emitted by an LED into a fiber. Student opinion on the importance of the prerequisite course, an introductory electronics course, and the introductory course on communication theory to their ability to understand the material presented in the current course was requested in Part 3. Self-confidence in completing the hands-on activities and the value that such activities have on the immediate learning and on their careers as electrical engineers formed the basis for questions in Part 4. Students had the opportunity to enter comments on the advantages and disadvantages of EM hands-on activities in Part 5. Ten of the fourteen students enrolled in the course participated in both surveys.

The analysis of the students' answers in Parts 1-3 indicated that the students had extremely limited or no prior experience in optics and the hardware and software tools that were mentioned in the survey questions. Their level of confidence to perform the optical tasks listed was slightly negative and neutral concerning their ability to construct the circuits needed to drive the LED and power the photodetector with amplifier. The consensus was that neither the first electronics course nor the communications course was important and that the junior EM course was acceptable. The students were overwhelming positive about the inclusion of the hands-on experiments in the course before the experiments were assigned, that the activities would help with their understanding of concepts in the course as well as in their careers. As an example, one student commented that "Our courses thus far in electromagnetics are very theoretical. Especially considering that an EMF is not something that you can see. Doing experiments would be a good way of filling in the disconnect between theory and real life." Another student commented that "Hands-on experiments in electromagnetics have the advantage of realizing theory that otherwise remains abstracted as dusty equations on a chalkboard. A full appreciation for electromagnetics can only be achieved by setting these equations to work in design projects that pull all the concepts together." Two concerns were raised before the assignment of the experiments. The first issue was a concern about the time and effort associated with hands-on experiments, particularly if the set of instructions were not written clearly. The second was whether the pedagogical approach was appropriate to apply in an electromagnetic course. One student expressed his concern in the following statements. "The weakness of hands-on experiments in electromagnetics is complexity. The physical demonstration of certain theories that can be derived can be exceedingly challenging. When choosing lab experiments, a line needs to be drawn that separates what's just fancy and what's really feasible during the time allotted."

Students were asked the same questions in the second survey after completing the second experiment. In general, the students' answers to the questions in Parts 1-2 were more positive after the hands-on activities than they were prior to the assignment of the experiment; however, the average of the responses to each question was neutral. There was a slight increase in appreciate for the contribution that the three courses (the junior-level EM course, the introductory electronics courses, and the course on communication theory) as well as a small increase in their confidence to complete an EM hands-on activity. Despite the overall neutral to negative responses to the first sets of questions, the students remained extremely positive about the value of the hands-on activities after the completion of the second experiment when asked about them in Parts 4 and 5 of the survey. One student stated that "I loved the hands-on portions of this class. You can actually see things working. So often we get bogged down in all the math and virtual possibilities on the board but it doesn't come together until you actually work with the fiber optics and sensors." Only one student indicated that the concern which was raised before the experiments were assigned – the course material was too complex and mathematical for a hands-on activity, remained a concern. Unfortunately, a number of students did comment that the instruction set for the experiments were vague and should be more structured. Given these comments, the experiments will be revised to present clearer instructions.

In addition to the assessment obtained from students who participated in the EM hands-on activities, feedback was solicited from other faculty members who regularly teach the core courses in electromagnetics. The major concern expressed was that the experiments developed thus far did not include any activities on RF or microwaves. The underlying issue was that the electromagnetic fields cover a large spectrum and the experiments concentrated only on the visible wavelength region. However, the faculty members understood that the limitations of the LiaB platform, which prevented the operation at high frequencies. Efforts will be made in the background section of the experimental write-up to include examples of how the concepts demonstrated in the visible wavelength region also are applied in other frequency regions.

Conclusions

Several experiments on concepts in electromagnetic have been developed using the LiaB kit and the pedagogical approach that has formed the foundation of the nontraditional laboratory courses at Virginia Tech. Two of the experiments were introduced into a senior technical elective. Assessment from students and fellow faculty members were collected. The results of the assessments show that there is an improvement in the students' confidence that they understand and can apply the concepts demonstrated in the hands-on activities. Suggested improvements are to clarify the instruction in experimental procedure and include material that demonstrates that the concepts can be applied over the entire frequency range.

Acknowledgements

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