Modular and extensible lesson on optical fibre communication for youths

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Abstract.   Optical fibre communication enables the global internet, but few youths ever learn about how it works, even at a basic level, until tertiary education. While some middle school curricula might include simple geometrical optics concepts like reflection and refraction, they often lack contextual linkage to worldwide telecommunications. Through our studies, we have found that students are more engaged in the learning process when the material directly relates to real life. To address this gap, and moreover to tackle the issue of the STEM skills shortage, we have designed a self-contained lesson to introduce youths to this topic. It is modularised into three parts, beginning with using light to communicate Morse code, and then covering advanced themes such as multiplexing and fibre guidance based on total internal reflection. The modules can be taught sequentially or individually depending on educational level. They emphasise a more phenomenological than theoretical approach and include hands-on activities using easily obtainable materials. We outline the lesson and pedagogical guidelines for classroom settings, as well as evaluate actual classes run. This lesson can be flexibly implemented in formal classes or through educational outreach programmes.

1. Introduction

In addressing skill shortages in science, technology, engineering, and mathematics (STEM) fields, studies have shown that life aspirations of youths typically begin to materialise before the age of 14 years, and thus suggest early intervention as a solution [1]. With appropriate tools and pedagogy, a seemingly advanced topic like fibre optics can appeal even to young students [2]. The Active Learning in Optics and Photonics (ALOP) framework [3] introduced by UNESCO emphasises an interactive and hands-on approach to learning, and has seen positive demonstrations at high school levels (ages 15+) [4, 5].

Here, we apply ALOP principles at middle school levels (ages 11 to 14 years) and outline a lesson in optical fibre communication. It consists of three interactive modules covering different topics, each of which can be delivered alone or in succession depending on student level. Meant as an introduction, the modules assume no prior physics or engineering knowledge.

Module 1, which introduces encoding and basic communication using torchlights, can be taught to younger ages as a self-contained primer. For higher levels, Modules 2 and 3 cover multiplexing and refraction, respectively, and can function as individual or consecutive extensions or even standalone topics. Experimental exploration is encouraged and the modules use equipment that is easily obtainable, craftable, and hence replicable.

This lesson was first presented at the 2017 Conference on Education and Training in Optics and Photonics [6]. This paper extends the exposition and evaluates the module implementation in several class workshops.

2. Modules

To set the context, it is useful to introduce a communication system as a sequence of functional blocks depicted in Fig. 1 [7, 8]. A message originates from a source and is encoded and sent by a transmitter as a modulated signal. The signal travels through a channel, which can take any form (e.g. optical fibre, copper cable, the atmosphere, etc.), to reach a receiver, which subsequently decodes the message for the destination. In multichannel systems, multiplexing (demultiplexing) occurs after (before) encoding (decoding) at the transmitter (receiver). As indicated, the coverage of the various modules relate to different parts of the system.

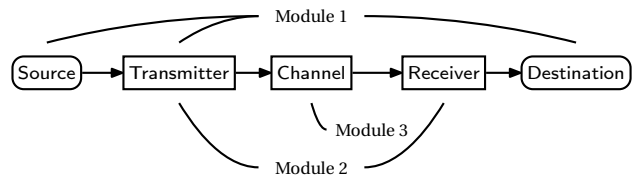The following subsections outline each module, which includes some basic theory (as would be delivered

Figure 1: Block diagram of a communication system.

to pupils) followed by one or more hands-on activities. Target ages are listed in parentheses.

2.1. Module 1: information (for ages 10+)

2.1.1. Coding and modulation Information is represented as a sequence of binary bits, each of which can take one of two logical states. Computers use digital 1 and 0 to represent TRUE and FALSE, respectively. Two things are necessary to communicate information. Firstly, a system is needed to assign meaning to bit sequences. This is known as *encoding*. A well-known system probably familiar to youths is Morse code [9]. Here, the binary states are represented as dots • and dashes —, and each letter, numeral, and symbol is encoded as a distinct sequence of these. Table 1 lists the internationally used Morse codes. As an example, the universal distress signal "SOS" is encoded as • • • — — — • • •.

Table 1: International Morse code chart.

A	•—	S	•••	.	•—•—•—
B	—•••	T	—	,	——••——
C	—•—•	U	••—	:	———•••
D	—••	V	•••—	?	••——••
E	•	W	•——	'	•————•
F	••—•	X	—••—	-	—••••—
G	——•	Y	—•——	/	—••—•
H	••••	Z	——••	(	—•——•—
I	••	1	•————	)	—•——•—
J	•———	2	••———	"	•—••—•
K	—•—	3	•••——	=	—•••—
L	•—••	4	••••—	+	•—•—•
M	——	5	•••••	&	•—•••
N	—•	6	—••••	@	•——•—•
O	———	7	——•••	!	—•—•——
P	•——•	8	———••	;	—•—•—•
Q	——•—	9	————•	_	••——•—
R	•—•	0	—————		

Secondly, a physical means of conveying the binary states is required. This can be conveniently actualised, in the optical context for example, by turning a torchlight on or off, or in Morse code protocol, by turning a torchlight

on briefly (e.g. 1 second) for a dot and turning it on for longer (e.g. 3 seconds) for a dash [10]. In this way, a person sending a Morse coded message would be transmitting a sequence of long and short flashes. This is *modulation*. That is, the (encoded) message modulates the communication signal (e.g. light flashes) which then travels through a channel (e.g. the air) to be perceived by a receiver (e.g. another person seeing the flashes).

2.1.2. Class activity: Morse code In this activity, students work in pairs to send Morse coded messages to one another. Each pair is provided with a torchlight, a cardboard tube, a Morse code chart such as table 1, a Morse code decoding tree chart as shown in figure 2, pens or pencils, and some paper.
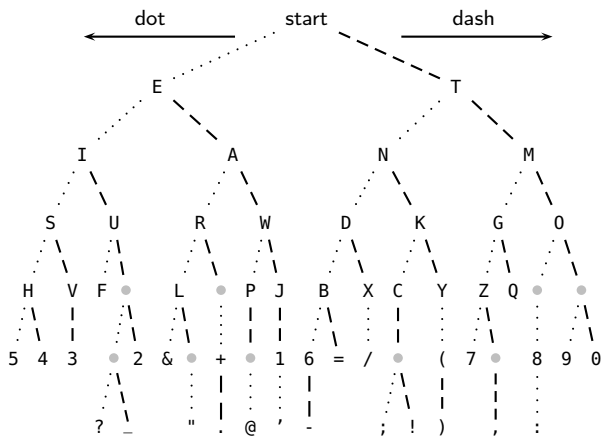
Figure 2: Morse code decoding tree.

In each pair, one student is assigned as the sender and the other, the receiver. The sender decides on a message unbeknownst to the receiver. S/he encodes the message in Morse code referring to table 1, then transmits the encoding by turning the torchlight on and off accordingly and shines the beam through the cardboard tube, which acts as a fibre channel, as depicted in figure 3a. The receiver observes and records the sequence of flashes from the tube's output. S/he then uses the dichotomic search chart in figure 2 to decode the message and verify it with the sender. For each encoded sequence, the receiver begins at start and descends the tree. Each dot or dash is a left or right traversal, respectively, to the next lower level. The node on which the traversal ends is the decoded character. For example, a "D", encoded as — • •, has a traversal beginning at start and moving right→left→left. Although it is possible to use table 1 for decoding, the reverse lookup is unsorted and cumbersome. The chart in figure 2 is recommended as an easier alternative. After a round, the sender and receiver can swap roles if time permits.

A number of tips can be considered. Firstly, the students should observe a no-speaking rule. This ties the
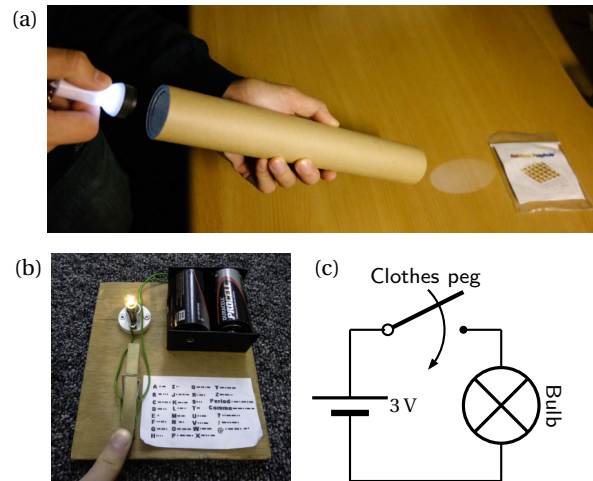
Figure 3: (a) Morse code class activity using a torchlight and cardboard tube. (b–c) Morse code circuit and schematic.

activity closer to reality, where direct verbal communication is not possible over long distances. Secondly, situations where the receiver incorrectly decodes a message can be used as opportunities to introduce students to the existence of errors and their associated challenges. For instance, a receiver mistaking a dot for a dash is analogous to a bit error in digital systems. It is also useful to stress the importance of accurate clocks as integral components for robust bit discrimination. In this exercise, stopwatches could be used instead of having students mentally count seconds. Thirdly, students may discover that the manual process of sending dots and dashes is slow and tedious. This is a chance to highlight the need for ever faster transceiver systems, especially with exponentially growing internet traffic [11]. Lastly, it is helpful to let students interact with a simple home-built Morse code circuit, such as in figures 3b–c, for them to appreciate how telegraphic Morse code was historically transmitted.

2.2. Module 2: multichannel systems (for ages 13+)

A useful question to pose to students is, "how can multiple people each communicate using the limited fibre resources at the same time?" The answer is *multiplexing*, which is the transmission of information streams through a single medium by dividing it into multiple channels [8, 10]. This module covers *wavelength-division multiplexing* (WDM), where different channels are represented by different optical wavelengths (colours)‡ and travel simultaneously through the same fibre.

2.2.1. Optical multiplexing Figure 4 portrays a simplified WDM picture. Each sender, who may be communi-

‡ Here, knowledge of the concept of *wavelength* is not strictly required. For uninitiated students, the term *colour multiplexing* suffices.

cating different types of data as illustrated by the various icons, uses a separate wavelength as indicated by the different coloured lines. These are all multiplexed (MUX) and transmitted simultaneously through the same fibre link. At the receiver side, the signals are demultiplexed (DEMUX) to separate each channel, and subsequently routed to the respective recipients.
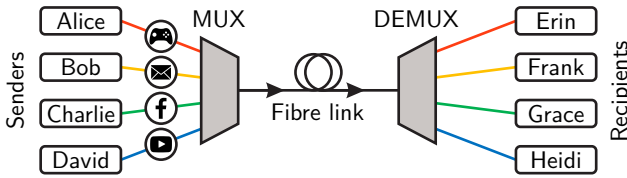

Figure 4: Multiuser system utilising WDM on a single shared fibre link.

One way to think of multiplexing is colour addition. Combining the primary colours, red, green, and blue, produces white [12]. So a white beam can be envisaged to contain all the information from the different coloured beams, as demonstrated in figure 5a. It is the basis for energy-efficient white light-emitting diode (LED) sources, the contributions to which won the 2014 Nobel Prize in Physics [12]. Inversely, that white light is composed of the rainbow spectrum can be demonstrated via diffraction gratings, as in figure 5b.
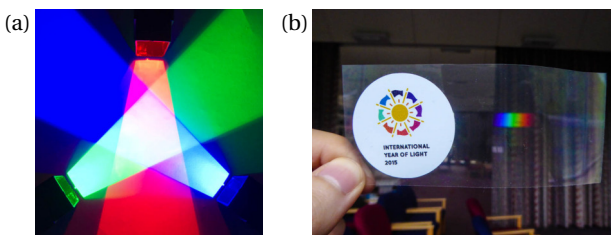

Figure 5: Analogising WDM. (a) Combining coloured beams to give white represents *multiplexing*. (b) Separating white light into its constituent colours (via a diffraction grating) represents *demultiplexing*.

2.2.2. Class activity: wavelength-division demultiplexing through filtering Demultiplexing is the process where the individual channels that were multiplexed together are separated at the receiver [13]. Students learn about colour separation through filtering. They can be divided into small groups, with each group having a transparent container prepared with clear gelatin, a low-cost household material [14]; three other transparent containers, each with a different coloured jelly;§ and

§ We used strawberry, lemon & lime, and blackcurrant flavoured jellies corresponding to red, green, and purple, respectively. These choices were influenced by the use of correspondingly coloured light sources, as well as store availability.

three slitted LED sources emitting red, green, or blue.‖

In this activity, which was inspired by the "Laser Jello" experiment from the Exploratorium® [15] and the "Transmission with Gummy Bears" activity from LASER Classroom™ [16], students first shine all three LED colours into the clear gelatin, noting that they are all transmitted, as shown in figure 6a. Thereafter, they experiment with the coloured jellies to observe them acting as wavelength (channel) filters that transmit only the like-coloured beams. Figures 6b–d depict this effect, where switching among the coloured jellies resembles the action of a tunable optical filter [8]. Laser pointers may be substituted for LEDs, though proper teacher supervision is advised and laser safety guidelines should be followed.
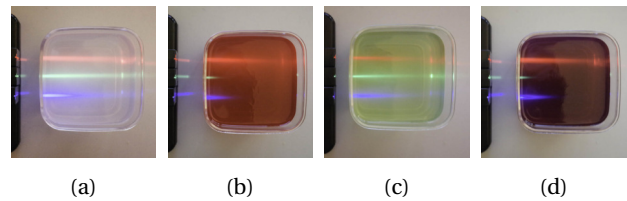

Figure 6: Multiple wavelength transmission through (a) clear gelatin, and selective filtering using (b) red, (c) green, and (d) purple jellies.

To make the experiment analogous to a fibre WDM system, the beams can be shone through a cascade of the clear gelatin followed by a coloured jelly, with the former representing a fibre link, as exemplified in figure 7b. Likening the clear gelatin to an optical fibre and visually demonstrating all-colour transmission illustrates the fact that fibres can support WDM. While we acknowledge that this set-up does not exactly model actual multiplexed systems, since the beams are spatially separated, it nevertheless suffices as an analogy to real systems [17]. An alternative is to shine a (ray box) white beam into each coloured jelly and inspect the transmitted colour using a white screen placed *after* the jelly [18].
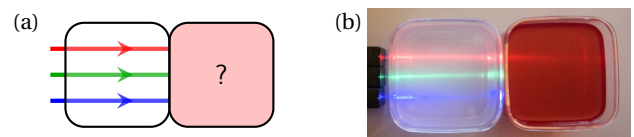

Figure 7: Clear gelatin and coloured jelly used to simulate a fibre and demultiplexer set-up. (a) A sample worksheet question and (b) the experimental result.

Worksheets asking which beams are transmitted through each coloured jelly, e.g. figure 7a, can be used for students to record their findings.

It should be noted that because the jelly colours are not purely composed of the exact wavelengths of

‖ We used the Light Blox Kit by LASER Classroom™ (http://laserclassroom.com/lightblox/).

the corresponding beam colours, all beams are neither completely transmitted nor completely filtered out [19]. Rather, it is the relative degree of transmission and filtering that matters for this pedagogy. For instance, the red jelly in figure 6b *mostly* transmits the red beam and *mostly* filters out the green and blue beams. In figure 6d, the purple jelly is actually closer in colour to the red beam than the blue one and therefore transmits red more.

For advanced students, a more rigorous explanation can be given. Each jelly has an absorption spectrum which determines the ranges of wavelengths that are absorbed or transmitted [20]. Such can be measured using a spectrophotometer as in [21], which shows the absorption for different flavours (colours) of jelly. For example, lemon & lime (green) jelly has low absorbance at green wavelengths (495 nm to 570 nm) as expected, but only moderate absorbance at red wavelengths (620 nm to 750 nm). Hence, some red light is transmitted.

2.3. Module 3: light guidance (for ages 14+)

Modules 1 and 2 concerned the transmitter and receiver. Following figure 1, here we explore the physics of how optical signals travel through the channel (i.e. the fibre). While the theory in sections 2.3.1 and 2.3.2 is didactically sufficient, the reader is referred to most physics or optics textbooks, e.g. [8, 10, 13, 22], for more details.

2.3.1. Reflection and refraction Whereas *reflection*, e.g. in bathroom mirrors, should be a recognisable concept, students may be less familiar with *refraction* and its physics. The perceived bending of a straw in water as in figure 8a is a real-world example.
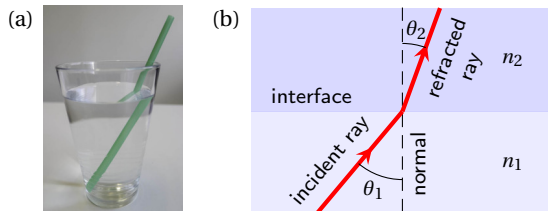

Figure 8: (a) Refracted straw image. (b) Refraction of light travelling through two refractive indices $n_1 < n_2$.

Refraction is explained as a change in the speed of light as it travels between materials of different *refractive indices*. For young students, it is unnecessary (and inadvisable) to elaborate on the microscopic particle interactions causing this change. Rather, it suffices to mention that light slows down when travelling through an *optically denser* material, which has a higher refractive index. As shown in figure 8b, this change in the light's propagation speed causes it to bend at the interface. The indices n are related to the incidence (θ_1) and refraction (θ_2) angles of light by Snell's law of refraction [10]:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2. \tag{1}$$

2.3.2. Total internal reflection Converse to figure 8b, figure 9a shows light travelling from a higher to a lower refractive index, with $\theta_1 < \theta_2$ since light travels faster in n_2. As θ_1 is increased, so too will θ_2 until it is perpendicular to the normal, as in figure 9b. Here, the incidence angle is known as the *critical angle* θ_c. If θ_1 is increased beyond θ_c as in figure 9c, then no light is refracted and all light is instead internally *reflected* [13]. The interface resembles a mirror and the reflection angle θ_2 is equal to θ_1. This is *total internal reflection* (TIR) [22]. It is emphasised that TIR can only occur for light travelling from within a material of higher refractive index to one of lower refractive index. Light guidance in optical fibres is possible via multiple longitudinal TIRs [8].
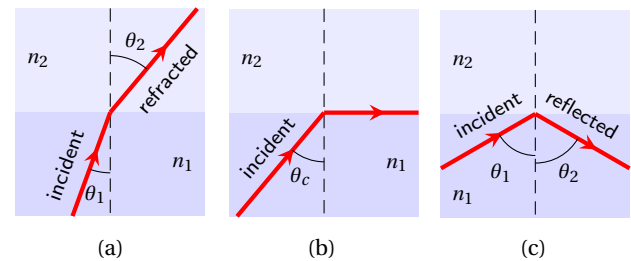

Figure 9: Light at a refractive index interface with $n_1 > n_2$: (a) refraction, (b) critical refraction, and (c) TIR.

2.3.3. Class activity: measurement of refractive index The objective is to measure the refractive index of gelatin. Students can work in groups, each given a transparent square container with clear gelatin as per section 2.2.2, a 360° protractor, a slitted LED source, a scientific calculator, pens or pencils, and an associated worksheet.

The experiment is set up with light passing between air and gelatin. From (1), the unknown refractive index of gelatin n_{gel} can be determined from the known index of air ($n_{\text{air}} \approx 1$) as well as the angles of incidence θ_{air} and refraction θ_{gel} which are to be measured. This is done by aligning the container's edge to the protractor's 0° to 180° axis. A narrow LED beam is shone angularly through the edge of the container, at the protractor's origin, as depicted in figure 10a. $n_{\text{gel}} > n_{\text{air}}$ causes the light to slow down and refract through the gelatin. By measuring θ_{air} and θ_{gel}, and rearranging (1), n_{gel} can be calculated via

$$n_{\text{gel}} = \frac{\sin \theta_{\text{air}}}{\sin \theta_{\text{gel}}}. \tag{2}$$

Depending on whether the students are familiar with trigonometry, it may be necessary to assist them with calculating the sines of angles using the scientific calculator.
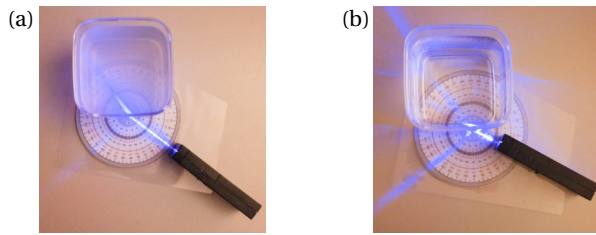
Figure 10: Refractive index measurements using (a) clear gelatin and (b) water.

A simple extension to the activity is for the students to measure the refractive index of water, as pictured in figure 10b. The indices of water (~1.33) and gelatin (~1.34–1.40) can then be compared and a discussion can follow about how gelatin, being a solid, has an index closer to that of the glass in optical fibres (~1.45 [8]). Although any LED colour can be used for the measurements, it is important to use the same colour for both the gelatin and water cases, since different colours (wavelengths) travel at different non-vacuum speeds [10, 22] and will refract at slightly different angles.

2.3.4. Class demonstration: light guidance using TIR
Continuing from the refraction topic, the effect of TIR as discussed in section 2.3.2 is explored. Either the students can examine this themselves by manipulating the incidence angle on the gelatin set-up as in figure 11a, or a teacher can demonstrate the Tyndall/Colladon experiment [23], where laser light is guided through a water stream as in figure 11b. The latter requires a large transparent water-filled tank with a faucet, a laser pointer, and a water collection bucket. A combination of both demonstrations is encouraged.
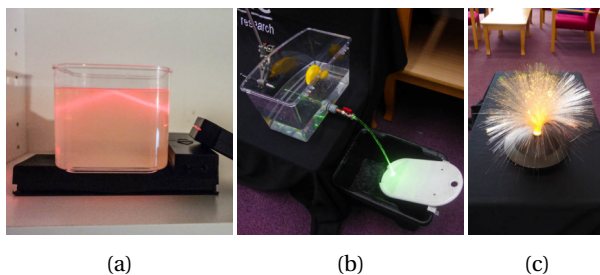

Figure 11: TIR demonstrations using (a) a container of clear gelatin, (b) a home-built Tyndall/Colladon experiment set-up, and (c) a fibre fountain.

An additional useful teaching tool is a fibre fountain, shown in figure 11c. The hairlike plastic strands provide a safe emulation of real glass fibres.

3. Evaluation and Discussion

The modules were implemented in formal classes, delivered by graduate student demonstrators through our university's *Lightwave Roadshow* educational outreach programme [23]. For each module, a set of learning objectives was identified, and worksheets or quizzes were used to assess the quality of learning and the practical skills demonstrated. Surveys were also conducted to gauge enjoyment and attitudinal changes, using the methodology in [24].

With reference to table 2, this is a summary of activities undertaken:

- **Module 1** was conducted with 86 10–11-year-olds as part of a larger class on fundamental optics, including other activities on the electromagnetic spectrum and mirrors. Students were split into groups of 12–15 and moved around each activity station in 20-minute rotations. For the Morse code exercise, 98% correctly decoded "SOS", indicating suitability for this age group.

- **Module 2** was carried out in an extended lesson with Module 3 with 39 14–15-year-olds. Students experimented passing coloured LED beams through various jellies. They earned 1 mark for making an observation, 1 mark for noting selective filtering, and an additional ½ mark for further comments about imperfect filtering (e.g. green jelly not completely blocking red and blue).

- **Module 3** was implemented in two separate sittings; in a combined lesson with Module 2 (previous bullet), and on its own with 9 11–16-year-olds. Both sittings included the gelatin index measurement exercise. In the latter, it was observed that the younger students (11–14 years) required extra guidance working with Snell's law and trigonometric calculations. Nevertheless, all were able to complete the exercise. Students scored 1 mark for angle measurements, 1 mark for correct application of (2), and ½ mark if their answer was within the reasonable range.

Table 2: Average student scores for each module. N_{pu} = number of pupils.

Module	N_{pu}	Activity	Marks per criteria	Average Score
1	86	Morse decoding	Decode "SOS" correctly: 1	98%
2	39	Coloured beams through coloured jellies	• Observations: 1 • Note filtering: 1 • Note imperfect filtering: ½	88%
3	48	Refractive index of gelatin	• Measure angles: 1 • Calculate index: 1 • $1.2 \leq n_{gel} \leq 1.6$: ½	92%

The average scores in table 2 were computed via

$$\text{average score} = \frac{1}{N_{\text{pu}}} \sum_{i=1}^{N_{\text{pu}}} \left(\frac{\text{marks}_i}{\text{full marks}} \times 100 \right), \quad (3)$$

and indicate strong achievement of the learning objectives. Determination of appropriate age ranges was also informed by demonstrator observations and student feedback. Particularly, some 14-year-olds doing Module 2 found the filtering activity rather easy. Thus in relation to our previous paper [6], we have reordered Modules 2 and 3 and lowered the target age of Module 2 (previously ages 16+).¶

In classes covering Modules 2 and/or 3, students were asked, both before and after the classes, about their likelihood of recommending studying photonics or electronics. As figure 12 shows, whereas most 'pre' responses were predominantly negative, reflecting stereotypical STEM perceptions, there were consistent favourable shifts in attitude post-class.
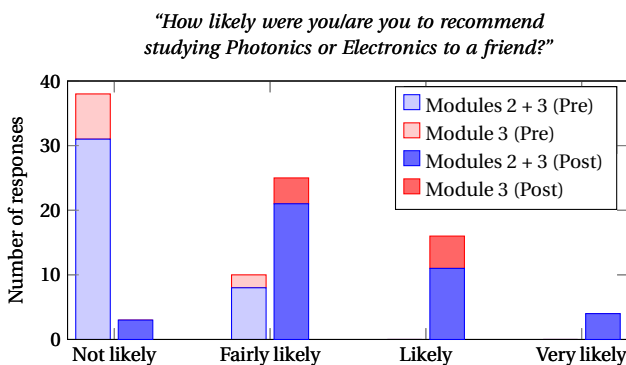

Figure 12: Pre-to-post-class changes in attitude for Modules 2 and 3.

4. Conclusions and Future Work

We have outlined a modular hands-on lesson covering en/decoding, multiplexing, and fibre guidance. While the modules, designed for primary levels and up, can be taught individually (within 30-minute sessions) or in succession, they all serve to introduce youths to optical fibre communication and spark interest in STEM. The practical materials required are cheap, easily sourced, and can be prepared or built at home.

Future improvements can include adding modules on other topics, such as polarisation, as well as adding more challenging concepts to tailor earlier modules for older ages, e.g. diffraction for Module 2. More evaluation data can also be obtained, including for running all modules consecutively.

¶ Module 2 (previously called Module 3) had not been trialled in a classroom prior to [6].

It is hoped that this lesson may be helpful to other educators.

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