Observation of two truly independent laser interference made easy

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Abstract

An interference of two beams coming from one laser is a well-known and popular experiment. But is it possible to obtain interference fringes using two completely independent laser sources? If the answer is 'yes', is such an observation available in a typical optical laboratory? We show a simple but spectacular method of observing such an interference, using very common continuous wave He–Ne lasers as well as diode lasers often found in atomic physics laboratories. The contrast of the fringes ranges from 27% to 87%, depending on the laser properties. The method works for both single and multi-mode unstabilized He–Ne lasers. The fringes are visible on a scientific as well as on a common security camera.

Keywords: two laser interference, Mach–Zehnder interferometer, modern experiments for students

Supplementary material for this article is available online

(Some figures may appear in colour only in the online journal)

1. Introduction

There is a popular notion saying that the only 'true' or 'legitimate' interference takes place when interfering beams are derived from one laser source, as in a Michelson or Mach–Zehnder interferometer. It surely is a convenient scenario, as the beams have identical frequencies and are coherent, but one should never forget, that it is not the only possible one. Although not

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as simple to implement, interference of independent sources may be more educational, as it counters this common—and erroneous—belief.

We demonstrate a relatively simple method of observation of the interference fringes for two truly independent lasers. To our best knowledge, there are very few published demonstrations of independent lasers interference in the sense of photographic recording of interference fringes. The first and the best known is the experiment reported by Magyar and Mandel, performed using two ruby lasers in the optical region [1]. Another one, somehow forgotten in our opinion, is the demonstration shown by Radloff for two single-mode helium–neon (He–Ne) lasers, enclosed in the same quartz block to improve their stability [2]. An interesting setup is presented in reference [3], where the fringes are seen directly to the naked eye, but at a cost of implementation of two dye lasers pumped synchronously by a pulsed laser. Our previous approach offered observation of static fringes of very high contrast, visible to the naked eye (see [4, 5]) but the involved diode lasers were not independent—their relative frequency and phase were electronically stabilized by means of an optical phase-locked loop system. Other demonstrations of the two laser interference rely on a purely electronic detection by a photodiode with visualization on an oscilloscope only (see e.g. [6, 7]). From the scientific point of view, a direct imaging of the transient interference pattern in the classical and quantum regime is continuously an area of interest (see e.g. [8–10]), although these experiments require sophisticated equipment such as streak cameras or modulated light cameras.

Here our approach relies on off-the-shelf components, usually found in scientific laboratories but also in student ones. As for the laser sources we have chosen different pairs of He–Ne lasers as well as a pair of external cavity diode lasers. The motivation for using two different types of lasers was twofold. First of all, He–Ne lasers are very common as both scientific and demonstration apparatus, whereas the diode lasers are a workhorse in atomic physics laboratories. Secondly, these two types of lasers have different longitudinal mode structure and it was very interesting to find a way to demonstrate the interference fringes for both of them. We comment on this later on.

The photographic detection of the interference fringes was realized with a very basic CCTV (‘security’) camera or a scientific grade CCD camera. The setup is completed by acousto-optic modulators (AOM) and a fast photodiode. As we explain in the next section, the role of the AOMs is crucial in our approach.

Our method provides a valuable extension to student laboratories in physics but also possibly to lectures, allowing one to dive deeper in the field of first order coherence, photon labelling and photon path distinguishability. The demonstrations described in this article are devoted mainly to undergraduate students of all physics related programs. But may be also a part of student advanced laboratory in physics for graduate students. We believe that our approach will help students to understand the nature of light in the classical regime, especially when the recent technological progress has allowed the introduction of ready-to-use kits for studying light properties at the quantum level [11].

The article is organized as follows. In section 2 we present the physical background of the observation of two laser interference, in section 3 we provide the detailed description of the experimental setups, whereas in section 4 we focus on the procedures of taking photos of the fringes. Section 5 is devoted to the results of our observations and at the end of the article there is a short list of files provided as a supplementary material (https://stacks.iop.org/EJP/42/055305/mmedia).
2. The idea of the measurements

The generic configuration used to observe interference fringes is shown in figure 1(a), where both beams usually originate from the same laser source. When it comes to independent light sources, there are two main factors that prevent observation of static interference fringes in standard experiments. The first one is (usually unstable) frequency difference of the lasers and in addition—their longitudinal mode structure, i.e. the presence of several different frequencies within a single laser beam. The second factor is the nonzero spectral linewidth of the lasers leading to rapid random changes of their relative phase.

Firstly we focus on the issue of the frequency difference of the interfering beams. A basic mathematical description of the two wave interference is provided in many textbooks and articles (see e.g. [1, 3, 12, 13]). In general, the two beams do not necessarily have identical frequencies—is it possible to obtain interference fringes in this case? Let us consider a resultant light intensity $I$ on the camera sensor, where we assume that the polarization of the beams is parallel (i.e. vertical in figure 1(a)):

$$I(\vec{r}, t) = \varepsilon_0 c \left( E_{0,1} \cos(\vec{k}_1 \cdot \vec{r} - 2\pi \nu_1 t) + E_{0,2} \cos(\vec{k}_2 \cdot \vec{r} - 2\pi \nu_2 t) \right)^2$$

$$= 2I_1 \cos^2(\vec{k}_1 \cdot \vec{r} - 2\pi \nu_1 t) + 2I_2 \cos^2(\vec{k}_2 \cdot \vec{r} - 2\pi \nu_2 t) + 2\sqrt{I_1 I_2} \times \left( \cos((\vec{k}_1 - \vec{k}_2) \cdot \vec{r} - 2\pi(\nu_1 - \nu_2) t) + \cos((\vec{k}_1 + \vec{k}_2) \cdot \vec{r} - 2\pi(\nu_1 + \nu_2) t) \right),$$

where $\varepsilon_0$ is the vacuum permittivity, $c$ is the speed of light, $E_{0,1}$ and $E_{0,2}$ are amplitudes of the electric field of both beams and the horizontal line denotes the time average. We have used the relation $I_i = \frac{1}{2} \varepsilon_0 c E_{0,i}^2$. We can safely assume $\nu_1$, $\nu_2$ and $\nu_1 + \nu_2$ to be too fast for any detector, so averaging is performed over a period of the optical oscillations. The only remaining terms are beam intensities and one term with frequency difference $\nu_1 - \nu_2 = \Delta \nu$ of a relatively small value (and thus not influenced by short time averaging):

$$I(x, t) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \left( \frac{2\pi}{\lambda} \frac{\sin(\varphi/2)}{\xi} x - 2\pi \Delta \nu t \right),$$

Figure 1. (a) Principle of the interference image formation. $\nu_1$ and $\nu_2$ are frequencies of the beams, $\vec{k}_1$ and $\vec{k}_2$ their wave vectors, (b) contrast of the fringes as a function of the product of the exposure time $t_{exp}$ and laser frequency difference $\Delta \nu$ (see text).
Above we have used the facts that: (a) \( |\vec{k}_1| \approx |\vec{k}_2| \approx k = 2\pi/\lambda \), (b) \((\vec{k}_1 - \vec{k}_2) \cdot \vec{r} = 2k_x x\), and (c) \(k_x = k \sin(\phi/2)\). From the argument of the cosine we see that when the frequency of both beams differs by \(\Delta \nu\), then the fringes move (here—horizontally, along \(x\) axis) with the speed equal \(d\Delta \nu\), where \(d\) is the spatial period of the fringes and \(d = \frac{\lambda}{2\sin(\phi/2)}\). We stress here that the period \(d\) of the fringes on the camera sensor depends on the angle \(\phi\) between the beams. Assuming that a single fringe should span a few dozens of camera sensor pixels, the angle \(\phi\) should be not greater than 2 mrad.

Since we are interested in the possibility of recording a sharp image of the moving fringes, we focus on the characteristic time \(t\) during which a single fringe shifts on the camera by its width \(d\). It is easy to see that this time equals just \(1/\Delta \nu\) [12, 14]. Intuitively, time of exposure \(t_{exp}\) should be roughly 10 times shorter than \(1/\Delta \nu\). According to our experience, the lowest frequency difference between the lasers \(\Delta \nu\) we can effectively catch is on the order of 100 kHz. Thus, to get high quality images, the camera exposure time \(t_{exp}\) should be at most 1 \(\mu\)s. To get a more quantitative understanding, we have integrated the intensity profile of the moving fringes from equation (2) over time \(t_{exp}\) and calculated the fringes contrast \(V\), commonly defined as:

\[
V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}},
\]

where \(I_{\text{max}}\) is maximum fringe intensity and \(I_{\text{min}}\) is its minimum intensity. The predicted contrast as a function of the product of \(t_{exp}\) and \(\Delta \nu\) is shown in figure 1(b) for the case of beams of equal intensity—see also equation (7) in reference [1]. It appears that decent images are expected when the exposure time is just a few times shorter than \(1/\Delta \nu\).

In case of He–Ne lasers, because of temperature changes and thus laser cavity elongation, laser modes continuously wander, meaning that the relative frequency of the lasers is not constant. The observed rate of change of the relative frequency was 1–20 MHz s\(^{-1}\) in our case. The frequency difference of the diode lasers was on average more stable but at the same time chaotic, with amplitude of the changes of 10 MHz within 10 s. Thus in practice, in both cases one has to wait for the frequency coincidence of the lasers within, say, \(\pm 100\) kHz accuracy, to have a chance of capturing the fringes using exposure time of about 1 \(\mu\)s.

In the case of multi-mode lasers, the expected contrast of the fringes is lowered since only part of the light contributes to the generation of quasi-stationary fringes, seen using our method. The rest of the light (from the other modes) produces very fast moving fringes, integrated to a plain spot even during the very short time of exposure used in our approach.

The second obstacle on the way to observation of the interference fringes, mentioned at the beginning of this section, is relative phase instability. Even if the central wavelengths of both lasers were precisely the same, the rapid relative phase changes would average the interference pattern to a plain spot since the fringes would jump randomly in the plane of a screen. Fortunately, the linewidth of a single longitudinal mode of probably the most popular lasers—He–Ne ones—is a few kilohertz only. This means that our very short laser pulses also overcome the problem of relative phase changes. The linewidth of scientific grade external cavity diode lasers is, on the other hand, quite large—on the order of 100 of kilohertz. Interestingly, even in this case, as we show later on, the high quality images are also achievable in our setup. In this case, an important factor is the fact that these lasers are single-mode, so the whole light may take part in formation of the fringes, instead of partially contributing to the background, as in the case of multi-mode He–Ne lasers.

To achieve the goal of capturing interference fringes of two lasers on cameras with a typical exposure time of 3–15 ms, we used very short (140 ns–1 \(\mu\)s) laser pulses instead, generated using common AOMs. Therefore, our main idea is to take ‘classical’ photos lasting several milliseconds (due to camera construction), while carefully keeping the camera sensor in the
Figure 2. Experimental setup with two AOMs for two He–Ne lasers interference. Three types of laser II were used: single-mode one and multi-mode ones, both ‘compatible’ and ‘incompatible’ with laser I. In case Y the interference was captured on a CCD camera, whereas in case X—on a common CCTV one. The length of a common path for interfering beams was 127 cm. The polarization of the beams was perpendicular to the plane of the image. Distances are not preserved in the picture. AOM—acousto-optical modulator, PD—photodiode.

dark most of that time. The light from the continuous wave lasers is sent to the camera for a short time only, using AOMs. We can say that in reality the exposure time $t_{\text{exp}}$ effectively meets the criterion of being shorter than $1/\Delta \nu$, as discussed above. This way we turned the need for a fast detection system into the need for much cheaper and easily available fast light modulation devices.

It is also worth to note that unavoidable imbalance in the intensity of both beams has minor influence on the fringes’ contrast. For example, for the intensity ratio of two interfering modes as high as 4, the contrast may still be very high—at the level of 80%. Thus, the main concern here is the difference in lasers’ frequency, not their intensity.

The details of the implementation of the AOMs in the experimental setups are provided in the next section.

3. Experimental setups

Our approach allows one to record interference fringes between lasers of various mode structures. We used a combination of four He–Ne lasers ($\lambda = 633$ nm) in such a way that we kept one (multi-mode) in place (we call it laser I) and interchanged the three remaining ones (calling them jointly laser II). We also used two single mode diode lasers operating at $\lambda = 780$ nm. In total, the following laser configurations resulted:
Figure 3. Experimental setup with one AOM for two diode or He–Ne lasers interference. The length of a common path for the beams was 174 cm. Distances are not preserved in the picture. AOM—acousto-optical modulator, PD—photodiode, $\lambda/2$—half-wave plate.

(a) Multi-mode + multi-mode laser with the same mode separation (we call it ‘compatible’ laser);
(b) Multi-mode + single-mode laser;
(c) Multi-mode + multi-mode with different mode separation (we call it ‘incompatible’ laser).
(d) Single-mode + single mode diode laser.

We recorded interference fringes with two setups, both reminding a Mach–Zehnder interferometer, but with two laser sources, instead of one source with a split beam:

Both beams had their own 80 MHz AOM, as shown in figure 2. While both AOMs being turned off, 0th orders were mixed on a glass plate to reach coaxially a fast photodiode. After turning AOMs on, 1st orders were directed with minuscule angle difference towards common mirror, and then to the camera. We used this setup for He–Ne lasers only;

Beams, first mixed on a glass plate, were passing through common AOM, used to turn on/off 1st diffraction order directed towards a CCD camera (see figure 3). A fast photodiode was fed by the second beams intermixture from the glass plate. We used this setup for the diode lasers as well as for the He–Ne lasers (multi-mode and single mode ones). The lenses L1 and L2 in figure 3 (L2 mounted on a translation stage) were used optionally, only with diode lasers to modify the wavefronts of the interfering beams to get various geometries of the fringes. The L4 lens was optionally used with He–Ne lasers to increase the light spot on the camera sensor.

0th orders in figures 2 and 3 illuminated a fast photodiode in order to obtain lasers spectra on a Rigol DSA1030A spectrum analyzer. A photodiode signal was also sent to the oscilloscope, along with an AOM steering signal from the generator as a reference. In both setups the residual 2nd orders of both beams were usually blocked by shutters. Chosen pictures involving 2nd order are provided as a supplementary material.

A digital signal generator was responsible for turning on/off AOMs and triggering the CCD camera (the latter signal lasted about 200 $\mu$s and its exact duration is of no importance here). AOM signal was switched on a few dozens of $\mu$s (found experimentally) after camera triggering to allow it to prepare internally for image acquisition. The typical photodiode signals together with AOM steering signal and camera trigger are collected in figure 4.
Figure 4. Waveforms from the oscilloscope: (a) fast moving fringes (red dense oscillations on a photodiode) are a sign of no quasi-stationary interference. (b) A zoomed central part of (a), but in case of a quasi-stationary interference presence. Only a relatively flat part of a single wave period (blue line) suggests interference pattern in the photo, while red wave’s frequency is still too high to result in a visible interference—compare the attached images. The indentation on the right side of an AOM on/off signal indicates the exact time of the light pulse (see text for details).

We set AOM signal durations in such a way to not to overilluminate the camera. Approximately, the lasers power reaching the camera during the pulse were up to 6 mW and AOM efficiencies were between 50% and 70%. Data from the CCTV or scientific CCD camera was collected on a computer and processed as described later on. The detailed information about the lasers, AOMs, cameras and the photodiode is collected in technical details supplement.

The noticeable dip in the photodiode signal in figure 4(b) appears (in the configuration from figure 2) when the AOMs are momentarily switched on and are diffracting light from the 0th order (photodiode signal) into 1st order (towards the camera). In other words, the light normally falling on a photodiode is temporarily directed onto a camera by the AOM. The time shift between AOMs activation signal and the apparent dip is a measure of a total delay introduced by the electronics and the geometry of the AOM. The delay comes mainly from
the fact that the ultrasonic wave, generated in a crystal of the AOM by a transducer, reaches the laser beam passing this crystal after about 1.2 $\mu$s. This means that the laser beam may be diffracted by the AOM only after 1.2 $\mu$s after the AOM is switched electronically. The shape of the dip reflects the fact that the ultrasonic wave passes the laser beam cross section with a finite velocity and in reality the AOM operation is smooth in time.

A common drawback of some of the AOM systems is the presence of residual diffracted beams even when the AOM driver modulation input is set to ‘off’, caused by imperfect damping of the radio frequency signal being sent to the AOM transducer from the power amplifier. If one compares the duration of the light pulse and the camera exposure time, one sees that the problem is not marginal. For instance, for the pulse of 400 ns, captured within exposure time of 3 ms in the continuous presence of the leaking light at the realistic level of 0.04%, the energy deposited on the sensor from the leaking light is three times greater than that from the main pulse. Fortunately, since the leaking light is present for the whole exposure time, it forms part of the background and as such is efficiently removed during image processing. Nevertheless, the leaking beam presence may lead to camera sensor saturation. It also slightly decreases the quality of the interference images, presumably due to the fact that the leaking light is captured by the sensor also before the camera is triggered (see technical details supplement).

To reduce the problem of leaking light when using the setup with two AOMs with homemade AOM drivers, for some of the measurements we have employed power amplifiers driving the AOMs with additional regulated electronic dampers, allowing us to further decrease the power of the leaking laser beams dozens of times. The additional damping of the leaking light improved our results, leading to $\approx 90\%$ contrast of the fringes, as described in the results section.

The setups described above allowed us to catch high quality images of interference fringes in an easy way, especially when using a cheap, simple ‘security’ camera. The best results are obtained using a scientific grade CCD camera, but at a cost of a slightly more complicated procedure. Both approaches are described in the next section.

### 4. Image recording

In case of the CCTV camera the procedure of image recording was very simple. The AOMs were switched on for 400 ns periodically by a generator at a rate of 10.7 Hz or 13.4 Hz. At the same time, the camera signal was continuously captured on the computer at a native rate of 30 frames per second (fps). Since camera internal triggering (and thus frame synchronization) was not directly available, some of the laser pulses arrive during the inactive state of the sensor. We have found that about half of the shots were recorded in our configuration. If the shot was successfully captured during the short time of coincidence of the laser frequencies, the fringes were present in the image.

When using the scientific CCD camera, the procedure was as follows. First, the camera had to be ‘armed’ manually in the software, i.e. the ‘wait for the external trigger’ mode had to be activated. Then, the camera trigger and the AOM pulse were triggered manually when the stationary interference was expected, basing on the oscilloscope waveforms (compare red and blue lines in figure 4(b); see also technical details supplement). The best photos were those, for which the photodiode signal was the flattest during the time when the AOMs where switched on. The signal flatness ensured that there was a quasi-stationary interference captured by the photodiode, so—simultaneously—by the camera as well. Most of photos taken this way were successful. The exact exposure time of our CCD camera is unknown for any settings shorter than 10 ms. We estimated it to be effectively not shorter than 2–3 ms. The AOM pulses were between 140 ns and 1000 ns.
To anticipate the instant of both lasers frequency coincidence, it was very helpful to follow in real time spectra of the photodiode signal seen on a spectrum analyzer. Firstly, in figures 5(a) and (b) we present for reference the beatnote spectra and mode separations in our multi-mode lasers (mode ‘compatible’ and ‘incompatible’, respectively), recorded separately on the spectrum analyzer. Note that the pronounced peaks (in blue and brown) come from the interference of the longitudinal modes within a single laser. In figures 5(c) and (d) we show the richest inter-laser mode beating structure, i.e. the one for two mode ‘incompatible’ lasers. In case (c) the laser frequencies coincide in the sense of two given modes (there is a peak at zero frequency, not directly seen here), whereas in case (d) none of the frequencies overlap, producing a rich ‘comb’ of beatnotes. For all other laser combinations the spectral structure is far simpler. The measured spectral width of the beatnote signals for the He–Ne lasers was not greater than 20 kHz, so its influence on the fringes’ contrast was negligible in the case of our short pulses.
5. Results

The fringes were immediately seen on a computer screen without any processing, especially in the case of the setup with two AOMs. Nevertheless, to evaluate fringes distinctness and overall visibility, but especially—contrast, we performed a standard analysis (widely used e.g.
Table 1. Results of interference in various setups and He–Ne laser configurations.

| Laser II | He–Ne laser |
|----------|-------------|
| Single-mode | Multi-mode |
| Configuration | One AOM and L4 lens | Two AOMs + leaking light damping system | Two AOMs |
| Laser I | Contrast | 55% | 87% CCD/74% CCTV | 27% |
| Multi-mode | Reference | Figures 3 and 6(e) | Figures 2 and 6(a) and (b) | Figures 2, 6(f) and 5 |
| He–Ne laser | Configuration | Two AOMs | Two AOMs |
| | Contrast | 51% | 69% |
| | Reference | Figures 2 and 6(d) | Figures 2 and 6(c) |

in cold atom physics or visual astronomy), as described below. Typical processed results are put together in figure 6. We set the same intensity scale for all presented photos. Every final photo from the CCD camera is a composite of three separate ones: a raw interference fringes photo (with subtracted background) is divided by no-interference photo (with subtracted background as well). The no-interference image was recorded for the case of washed-out fringes (see figure 4(b), red line). This way, the final images were virtually free of the influence of the laser beams intensity distribution. In other words, thanks to this method, the Gaussian shape of the beams intensity profiles as well as local beam imperfections (like diffraction patterns formed by dust) were eliminated. In case of the CCTV camera, we have only subtracted the background image. The contrast was computed according to its definition in equation (3). We have calculated $I_{min}$ as an average intensity of two adjacent minima.

As expected, contrast of the fringes depends crucially on the mode structure of the lasers. In the configuration of two multi-mode but ‘mode-compatible’ lasers virtually all modes take part in formation of a stationary interference and contrast is indeed the greatest. It reached 87% (figure 6(a)) on the CCD camera and 74% on a CCTV camera (estimated exposure time: 15 ms; figure 6(b)) when using additional damping of the leaking light. In the same setup but with no damping system, the contrast reached 69% (figure 6(c)). In case of the multi-mode and single-mode laser, only two modes interfere stationarily, so the first laser introduces additional ‘offset’ light from the remaining modes, resulting in the contrast of 51% (figure 6(d), two AOMs) or 55% (figure 6(e), one AOM). Finally, in case of two multi-mode, but ‘mode-incompatible’ lasers, again only two modes may interfere stationarily, while all the remaining ones from both lasers contribute to the ‘offset’ signal, leading to the contrast of 27% (see figure 6(f)). A typical processed movie from the CCTV camera with the original and three times lowered frame rate is included as a supplementary material.

For the diode lasers, we used only single AOM setup with lenses (see figure 3) and we got contrast of 45% for the AOM switched on for 1 $\mu$s. The results are shown in figure 6(g), where we present two different phases of the interference pattern. This is a good result from the perspective of the demonstrations themselves, however it is a relatively low contrast, as for the case of two single mode lasers. The measurement of the beatnote spectrum within 3 GHz bandwidth reveals that the contrast value cannot be explained only on the basis of the spectral profile of the beatnote signal. This conclusion follows from equations (5) and (11) from reference [15] but for the case of a finite measurement time. One of the explanations might be
a presence of another spectral component in the laser light, within a few nanometers range, not seen on an electronic spectrum analyzer. Such light would contribute to the background light, similarly to the ‘unwanted’ modes of the multi-mode He–Ne lasers.

The measured contrasts are summarized in tables 1 and 2 for He–Ne and diode lasers, respectively.

6. Supplementary material

We have provided the following supplementary files:
- technical_details.pdf file containing detailed information on the equipment we used;
- a typical movie recorded with the CCTV camera with subtracted background, with a native frame rate as well as slowed down three times (CCTV_30fps.gif and CCTV_10fps.gif, respectively);
- a short movie consisting of five post-selected frames with an interference pattern recorded for two He–Ne lasers in the single AOM configuration, seen both in 1st (left spot) and 2nd (right spot) AOM diffraction order (1st_and_2nd_order.gif).

7. Summary

Our research refers to a common misconception about one and only possibility of light interference for two beams coming from one laser source. Although not unprecedented, our demonstration provides a relatively easy approach and utilizes mainly popular, unsophisticated equipment, making it accessible and affordable.

In particular, we presented an easy way to capture and process interference fringes photos for two truly independent lasers in various configurations with profound explanations of the results. We used widely available He–Ne lasers and a cheap CCTV camera, optionally expanding our setup with a scientific grade CCD camera and diode lasers. The best results we obtained were in a configuration with two virtually identical multi-mode He–Ne lasers, reaching the contrast of 74% on a CCTV camera and almost 90% on a CCD camera. Due to availability of used elements, simplicity of our method and its potential for inquiry-based learning, it can be successfully employed as one of the modules in both undergraduate and graduate students’ laboratories or during lectures.

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