Reviewing the Link Between Young and Michelson Under COVID Lockdown

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Physics II is an undergraduate course on basic electromagnetism that I teach for engineers, and it includes topics from optics as a natural application. Among the many challenges of conducting video lectures during the local restrictions of the SARS-CoV-2 epidemic was finding demonstration material.[1–3] In this article, I describe how these restrictions led me to develop my home version of Michelson's experiment as an alternative to Young's, and how I was able to highlight the circumstances in which both experiments turn out to be two particular cases of the same underlying idea.

Without access to the faculty's collection of instruments due to the lockdown, I set out to generate as many demonstrations for the virtual course as possible with the material available at my home or that I could get at my neighborhood hardware store. For the lecture on interference, my initial objective was to produce Thomas Young's experiment with two slits (cylindrical waves), but I was not able to reach an acceptable precision and accuracy in its homemade construction despite consulting the traditional bibliography[4–6] (within the time I had available to prepare it). I also tried the two-pinhole version that reduces the problem to two point sources (spherical waves), but it was not satisfactory due to relative hole sizes and distance parameters achievable at home. The pinhole version reminded me that, as a previous personal project, I had the basic elements to assemble a simple version of Albert Michelson's interferometer with point sources. After preparing it as an alternative and analyzing the topic, I took the opportunity to review in class the interference of coherent point sources and how the point sources' relative position to the observer reveals both experiments (Young with point sources and Michelson with point sources) as two extremes of the same basic principle.[7] Indeed, these circumstances led me to consider the possibility of approaching a unified discussion of two topics that are generally treated separately.

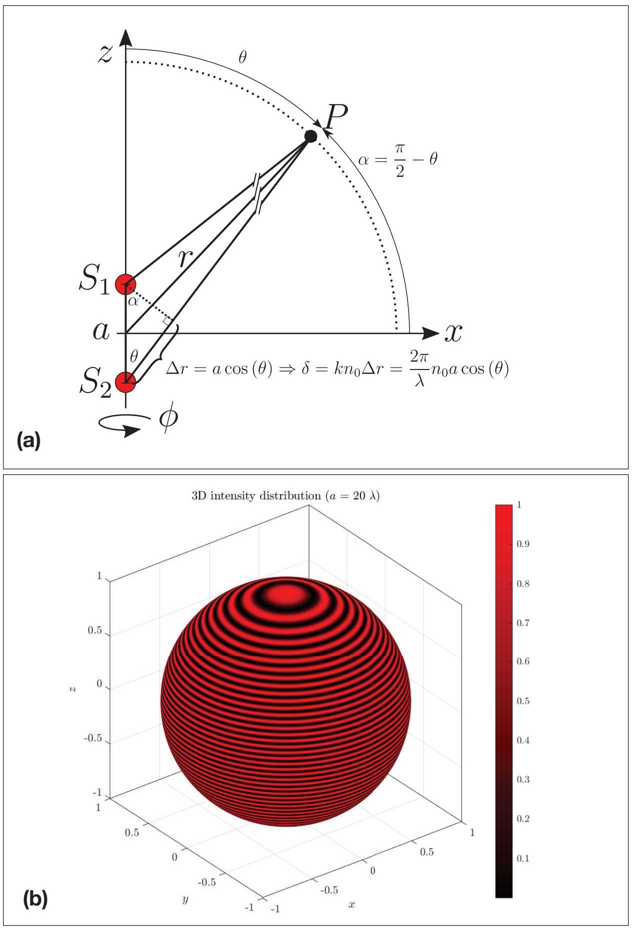

Fig. 1. (a) Interference diagram of two point sources. Under Fraunhofer conditions ($r \gg a^2/\lambda$), the rays S_1P and S_2P are essentially parallel; δ is the phase difference between light waves from the sources to the observation point P ($n_0 = 1$ is the index of refraction of air). (b) Representation on the sphere of the normalized luminous intensity as a function of the azimuthal angle, Eq. (1) (just for a greater visibility of fringes, a separation $a = 20\lambda$ has been chosen for this plot). A view from the poles shows rings (Michelson zones), while an equatorial view shows bands (Young zone). Note that under the actual parameters of the experiment, the number of fringes becomes very large (see "Construction and assembly").

Young and Michelson inhabit the same planet

The basic explanation for this connection is the one reviewed in any class on electromagnetic wave interference.[8,9] Suppose that two point sources S_1 and S_2 are coherent, of the same wavelength λ and intensity I_0 [see Fig. 1(a)]. Let a be the separation between them and suppose that both are symmetrically arranged and resting on the z-axis. If we observe everything at a point P, intensity is well known to be

$$I(P) = 4I_0 \cos^2(\delta/2),$$ [8]

where δ is the phase difference between beams at P. If the observation is at a large distance r from the origin of coordinates, namely, $r \gg a^2/\lambda$ (Fraunhofer conditions), rays may be considered essentially parallel, and the phase difference will be $\delta = (2\pi/\lambda)n_0 a\cos(\theta)$, where $n_0 = 1$ is the index of refraction of air [Fig. 1(a)]. The intensity at P therefore is

$$I(\theta) = 4I_0 \cos^2[(\pi a/\lambda)\cos(\theta)], \quad (1)$$

where θ is the angle from the z-axis in spherical coordinates ($0 \le \theta \le \pi$); and there is symmetry around z since the angle ϕ is not in the equation. In Fig. 1(b), the light intensity is shown normalized as a function of angle θ.

Equation (1) is general for two point sources seen at a sufficient distance. Now we can consider what is obtained in two very different relative positions of these sources with respect to the observer:

DOI: 10.1119/5.0050814

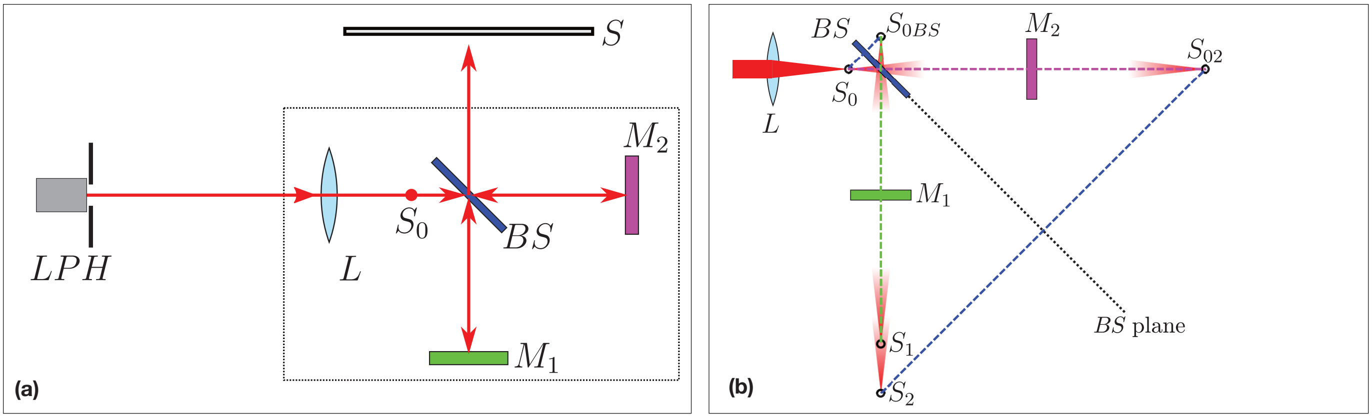

Fig. 2. (a) Diagram of Michelson's experiment: laser with a pinhole (LPH), converging lens (*L*) with focal point S_0, a beam splitter BS (blue), first surface mirrors M_1 (green) and M_2 (magenta), and observation screen (S). (b) Diagram of the determination of the position of virtual point sources S_1 and S_2 when the arms of the interferometer have different lengths [sources end up as considered in Fig. 1(a)]. Every reflection is indicated with a dashed line following the corresponding reflecting element color stated in (a). Lens *L* is illuminated with a plane wave. S_0 is the focal point of the lens and is the 'original' source: S_{0BS} is its image through the beam splitter, and in turn, S_1 is its image through the mirror M_1. On the other hand, S_0 has an image S_{02} by the mirror M_2, and this, in turn, has an image S_2 by the beam splitter.

- If the observation is made at points at which $\theta \approx 0$ or π rad (along the z-axis), the sources are one behind the other, and rings of interference will be observed; we will call these polar zones *Michelson zones* [see Fig. 1(b)].
- If the observation is made at points where $\theta \approx \pi/2$ rad, the sources are next to each other, and interference fringes will be observed; this equatorial (or parallel) zone will be called the *Young zone* [see Fig. 1(b)]. Indeed, if α is the complementary angle of θ, then $\cos(\theta) = \cos(\pi/2 - \alpha) = \sin(\alpha)$, and Eq. (1) is reduced to the well-known expression on the axis of symmetry from Young's experiment: $I(\alpha) = 4I_0 \cos^2[(\pi/\lambda)\sin(\alpha)]$.

It is interesting to note that near the equator of Fig. 1(b) (Young's zone), Eq. (1) produces the well-known pattern of equidistant linear fringes ($\alpha \approx 0$), while observing that in the Michelson zone the circular fringes [Fig. 4(a)] are not equally separated.[7] This connection is hinted at but not exploited in the traditional course bibliography.[8,9] Therefore, it is worth building a simple Michelson interferometer to demonstrate in class in order to discuss both topics (see next section).

Construction and assembly

Regarding the Michelson interferometer itself, it is widely described in the traditional literature.[5,8,10,11] However, details about fine-tune setup are only found in articles[12–14] and lab kit resources.[15,16] The basic setup of the interferometer as used on this occasion is shown in Fig. 2(a). Mirrors set normal to light beams set point interference sources one behind the other; however, sources can be set in parallel as in Young's experiment by properly tilting the mirrors, but the demonstration of the modified setup got to be beyond the scope of my intended discussion.[17] The determination of the position of virtual point sources S_1 and S_2 when the arms of the interferometer have different lengths is shown and described in Fig. 2(b) [in this case, both sources lie on the z-axis as considered in Fig. 1(a)].

Fig. 3. (a) Close-up of the interferometer. (b) General arrangement: laser with pinhole, interferometer, and screen.

The experiment was set up as shown in Fig. 2(a) (see description). The distance LPH – L was 1.16 m; the distance L – BS was 4.5 cm; distances BS – M_1 and BS – M_2 were both

~8 cm (we may assume that *a* is at most in the order of millimeters), and the distance to the screen BS – *S* was 1.3 m. As a light source, I used a red LED laser (generic unpolarized diode, λ = 632 nm) rated at 5 mW power (a common laser pointer may be used too). As the intensity profile is uneven in this case, I put a pinhole at the exit of the laser (aluminum foil with a small hole made with a pin). The lens *L* was a generic 4.25-cm focal length lens (any equivalent common magnifying glass may be used). The display screen *S* was a sheet of tracing paper at the bottom of a box, which allowed the array to be calibrated without much disturbance from ambient light.

Interferometer pieces were screwed on a 2-cm-thick plywood base (Fig. 3). Optical mounting parts were, of course, required for the construction. Using Autodesk Inventor (educators' license), I designed the necessary optical assembly parts on my own in a way compatible with those used in the laboratory (many free programs allow you to do the same work). The prints were made in PLA plastic with my 3D printer. The parts developed were mounting bases, post holders, posts, lens mount, beam splitter mount, kinematic mirror mounts (with two adjusters), and laser diode holder with mount. For the parts that required screws, the measures M6 and M4 were used because they were the ones I could easily get in my neighborhood's hardware store. The two first-surface mirrors were made by grinding an out-of-service hard drive platter, protecting its surface with tape during cutting (a mirror-polished flat piece of metal could be used too). The beam splitter used was a microscope slide (1 in × 3 in). Although the reflectance for this element is ~10% at 45°, the intensities of the two interferential sources still end up being similar (<~9% of the laser intensity), but not equal. It is interesting to note that the non-negligible thickness of the beam splitter (1 mm) produces high-frequency vertical interference lines (see "Results").

Results

Darkening the room, on the other side of the box and with a tripod, the images of the rings were captured with my cell phone in manual mode (Samsung Galaxy S21+). In Fig. 4(a) are shown the typical rings that can be projected onto a screen with this setup. Due to the high-frequency vertical fringes due to the splitter mentioned above, the simplest way to make an intensity profile is by taking a vertical section of the image [Fig. 4(b)]. The mentioned profile was obtained with the free software ImageJ.[18] Since the virtual point sources have different intensities, the observed contrast deteriorates.[8,11] However, by making the arms of the interferometer similar in length and converging both most-illuminated areas on the screen, Michelson rings can be seen clearly.

Although the assembly is rudimentary in terms of the solidity of the surfaces (in this case, everything was mounted on a wooden table), I have been able to achieve stability of the order of $\lambda/4$, with slow variations. The device as shown is sensitive enough to detect someone walking a few meters away from the experiment.

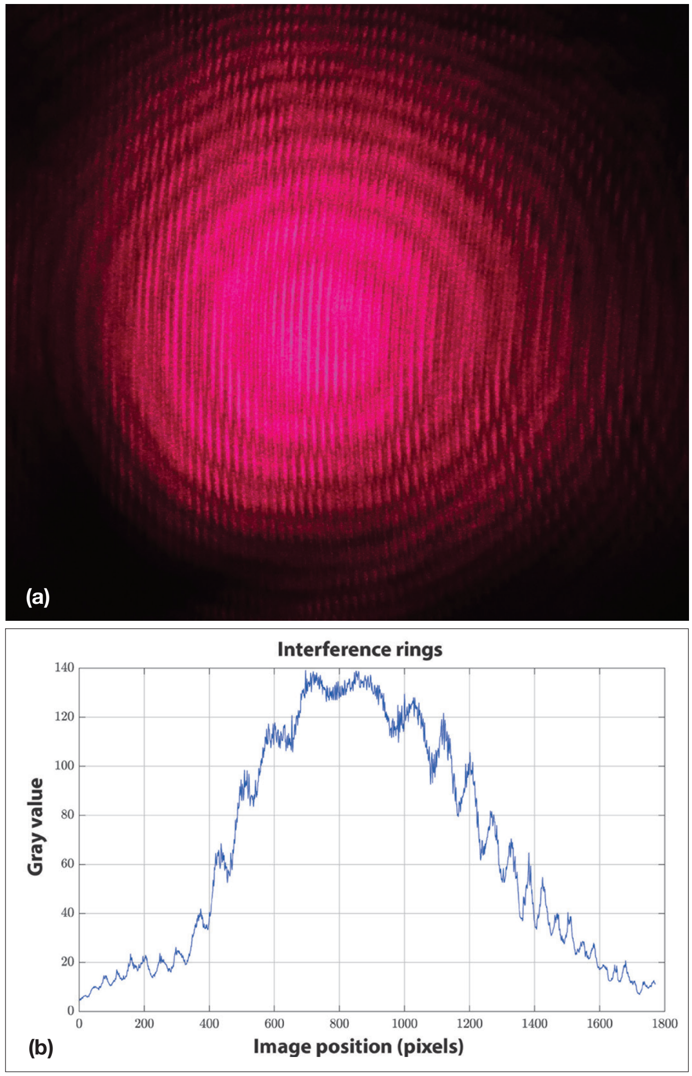

Fig. 4. (a) Typical observed interference rings on the screen. (b) Intensity profile of the vertical central section (data extracted with ImageJ). The considered (narrow) section is wide enough to average the vertical high-frequency interference pattern due to the splitter.

Conclusions

Although the device was only shown as an example in my video lectures, all the analysis of the subject was left for the consultation and live Q&A meetings. This was very well received by the students and generated interesting discussions about electromagnetic wave interference. Among some interesting points asked by the students are the limits of approximation to the point source with pinholes and lens foci, conical sections of spherical waves, intensity distribution in a laser beam, the current applications of interferometers (i.e., the Laser Interferometer Gravitational-Wave Observatory), and even the historical implications of this experiment. This demonstration brings a good opportunity to try a unified discussion of two topics that are generally treated separately.

This work has the potential to be taken as a basis for initiation projects in optics research in which you may take into account such diverse topics as assembly, setup, design and construction of elements, image capture, image analysis, model fitting, stability, etc. Likewise, this construction can be taken as a reference for instructors with limited resources beyond the public health situation. Three-dimensional printers can already be regarded as accessible equipment in institutions and even homes (as in my case) and allow the necessary parts to be made, although, in the absence of one, equivalent components can always be produced in wood or metal with some skill even at home.[4,14] Finally, this contribution hopes to show students that what could be done by a leading scientist of the 19th century may well be reproduced by an enthusiast in the 21st century.

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