Demonstrations of wave optics (interference and diffraction of light) for large audiences using a laser and a multimedia projector

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Abstract
This article presents a new technique for performing most well-known demonstrations of wave optics. Demonstrations which are normally very hard to show to more than a few people can be presented easily to very large audiences with excellent visibility for everyone. The proposed setup is easy to put together and use and can be very useful for high-school physics teachers and even university professors.

Online supplementary data available from stacks.iop.org/physed/46/705/mmedia

Introduction
Wave optics demonstrations are often hard to perform to more than a few people due to the small size and insufficient brightness of the diffraction and interference patterns involved. This is especially true for the more basic diffraction phenomena—single- and double-slit experiments, pinholes, thin wires/hairs, diffraction from an edge, etc. And while interference can be shown with different colourful phenomena in soap bubbles, oil films (on wet asphalt, for example) or in other ways [1] and diffraction can be shown with diffraction gratings (traditional or otherwise [2]), the most basic diffraction phenomena that lie at the methodological foundation of much of wave optics remain hard to perform as demonstrations. Increasing the size of the corresponding pictures requires special technical solutions, large distances between the elements of the experimental setup, darkening of the room and time for the eyes to adapt. All of this makes the job of the demonstrator relatively hard and so these demonstrations are rare in everyday practice. This is so prevalent that compilations of large numbers of demonstrations across all physics will only feature geometrical optics in the optics section ([3] is a good example—an otherwise very good book with no wave optics whatsoever).

Using a camera to shoot small objects and show them enlarged is a known technique but until recently was not very widespread because of the limited availability of the equipment required. The wide introduction of digital projectors in education has opened the doors to using that technique to perform wave optics demonstrations to large audiences with excellent quality and visibility of the pictures.

This article is dedicated to a new technique for performing wave optics demonstrations
Figure 1. The general setup.

Main demonstration setup

The principal setup is presented in figure 1. The first part of the setup consists of a laser L, laser beam expander E, optical object O and a semi-transparent screen S1. The expanded beam falls on the object O which can be a thin slit, a hair, a circular opening etc. The corresponding picture is projected on the semi-transparent screen and can be seen close up with the naked eye. The distances between the elements are set according to the specific situation to achieve the best picture quality possible. It is advisable to have at least two metres between the laser and S1. More is generally better but not necessary.

We used a 5 mW He–Ne laser set on a stand that allowed us to vary its vertical position. The expander E is a converging or diverging lens with a short focal length of about 10 mm. It could be the lens of a door’s peep-hole. For the sake of convenience the lens can be attached directly to the laser tube with a magnetic holder. The screen was made with tracing paper. The object is put on a stand and its position can be regulated by micrometric screws. It is convenient to put the laser and object on an optical rail.

The second part of the experimental setup consists of a video camera C, a digital projector P and a projection screen S2. The camera is set on a tripod behind the semi-transparent screen S1 and used to observe the picture. It is put at such a distance so that only the respective picture is in its viewing field. The image from the camera is sent to the projector P and is projected for the audience onto the big screen S2. There is no specific requirement for the camera and projector—any widely available models can be used, as long as they are compatible with each other.

A quick note should be made about affordability—while it may not be exactly cheap to put this rig together from scratch, the intention is not really to obtain and use it as a stand-alone. All elements of the setup can (and indeed should) be used for many other purposes. The second part of the setup in particular (the camera–projector combination) can be used to show to large audiences all kinds of demonstrations that would normally be observable by only a few people for whatever reason—small size, limited field of view etc.

It should also be noted that the light beam we use is divergent. In reality, every light beam is more or less divergent so it is never a question of parallel versus divergent but rather a question of how divergent the beam is and how much it deviates from the ideal parallel beam model. In our experience, the proposed setup gives pictures that are indistinguishable from the traditionally performed experiments with unexpanded laser beams or with lasers that are expanded with two lenses to give a ‘parallel’ beam. So while this setup does not use a theoretically ‘proper’ light beam it does provide practically the same pictures while being much more simple and robust than the generally better two-lens way of expanding the laser beam. Since we do not use the setup for actual experiments and measurements but only for demonstrations, the one-lens expansion is well suited to the task.

Using this experimental setup we were able to perform for very large audiences all the well-known demonstrations of diffraction and interference of light with excellent picture quality and good visibility for everyone.

Experiments

We will illustrate the capabilities of the setup by looking into some of the demonstrations we performed. We will not go into theoretical explanations of the phenomena involved. There are good optics textbooks (we used mainly [4, 5] and have recently come across the excellent [6]) that discuss them in great detail and most are really very basic wave optics anyway.

The pictures in the article were taken with a good photo camera at the best settings possible. On occasions even over-exposure was used to bring out some of the dimmer details or for artistic purposes (this leads to some yellow coloration in
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It should also be noted that cameras generally have a better sensitivity to the red light of the He–Ne laser than the human eye. The pictures are clearly visible with the naked eye but a camera (photograph or video) makes it much easier to observe them in addition to making them available to more people, as already mentioned.

Poisson/Arago’s spot

Demonstration of the Poisson’s spot (also called Arago’s spot) has historical importance due to its role in the establishment of the wave theory of light.

In 1818, the Paris Academy of science proposed ‘light diffraction’ as the topic for their annual award. The organizers were proponents of the corpuscular theory and were hoping that the papers presented would bring a final victory for that theory. However, Augustin-Jean Fresnel presented a paper that explained all known optical phenomena with the wave theory of light. Simeon Poisson, a former member of the award committee, derived from Fresnel’s work on wave theory the ‘absurd’ conclusion that there should be a bright spot in the centre of the shadow of a small circular object. Francois Dominique Arago immediately set out to devise an experiment and managed to demonstrate the bright spot. This was an important argument in favour of the wave theory and greatly contributed to its wider acceptance. It turns out that the phenomenon was observed by Giacomo Maraldi as early as 1723 but remained unnoticed.

To conduct the experiment it is necessary to have an opaque object with a good circular shape and relatively small size. We tried different approaches.

Ink drops. Relatively satisfactory results were obtained using small (diameter 1–2 mm) dried droplets of black ink. The droplets are deposited with a small syringe or a thin piece of wire onto a well-cleaned plexiglas (or glass) plate. It is advisable to use a relatively thick plate (1–2 cm) to avoid interference effects from multiple reflections within the plate which could deteriorate the quality of the main picture. The widened beam is shone on one of those droplets or on several of them simultaneously (by moving the plate further from the laser). Good quality patterns featuring Poisson’s spot are observed (figure 2). One problem of this approach is that droplets tend not to be perfectly circular. Because of this we applied more of them on the plates so that at least some were sufficiently round. The ‘imperfect’ ones also provide interesting diffraction patterns.

Ball bearings. Another object that can be used is a small ball bearing (ours were 2 mm in diameter) because they are produced with great precision and as such have an excellent spherical shape (and thus excellent circular cross-section). The problem in this case is to put the ball in the beam path without other opaque objects to hold it, because they create their own diffraction patterns. In order to achieve this we glued the balls to a plexiglas plate. A small amount of glue was applied with the tip of a pin on the horizontally placed plate and the ball was gently pressed onto it so that the glue did not smear onto the sides of the ball. After the glue dried the balls were sufficiently stable on the plate so that it could be put upright and moved around without the balls falling. The diffraction patterns from the balls are virtually indistinguishable from the ones from ink droplets (so we will not show one from an ink drop).

Pin head. A spherical pin head can also be used as the diffraction object. A very impressive picture is obtained (figure 3) that shows Poisson’s spot along with some other beautiful diffraction effects.
**Diffraction from a pin head**

The picture is seriously overexposed (hence the yellow colour) for artistic purposes as well as to bring out some hard-to-see details.

**Diffraction from a razorblade**

We have always admired the impressive diffraction patterns from the edges of a razor blade that can be seen in some optics textbooks and Internet resources. It turns out that this beautiful demonstration can very easily be done with our setup. The blade has to be set relatively far away from the laser so that most of it is located within the expanded laser beam. The beautiful pattern of diffraction and interference can be seen in figure 4. Objects other than razor blades can be used (as shown in [7]) to produce other beautiful pictures.

**Interference from a thin glass plate**

This extremely attractive demonstration of light interference can be easily realized with our proposed setup. We used thin glass plates from the cover slip of a microscope slide (size 35 mm × 38 mm × 0.45 mm) because they are of relatively high optical quality while being easy to obtain and relatively affordable. It is important that the plate be flat and the surfaces sufficiently parallel—the microscope slides we used were satisfactory in that regard. The plate is placed very close to the laser so that the beam falls on only a small part of the plate (thus further avoiding any large imperfections that may distort the image) and at a very small angle to the plate. Two interference patterns appear on the screen—one from the reflected light and one from the transmitted light. The two pictures are supposed to be phase shifted by half a wavelength according to theory and this is easily demonstrable in the pictures on the screen—where one pattern has a bright region, the other has correspondingly a dark one and vice versa (figure 5). Moving the plate away from the laser so that it falls completely...
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within the widened laser beam, we can observe an interesting interference pattern (figure 6) that clearly shows the small imperfections in the glass plate—variations of the physical thickness and optical density. Heating the plate with a soldering iron from behind can be used to demonstrate thermal deformations in a very visual way.

Others
Some other phenomena that we successfully demonstrated using the same basic setup are two-slit interference (Young’s experiment), interference from a Fresnel biprism, diffraction from an edge, diffraction from a wire, diffraction from a single slit, diffraction from a circular hole, diffraction from a needle point etc. Example pictures of some of these are included in an online supplement to this article as figures 7–13 (available at stacks.iop.org/physed/46/705/mmedia). Also included as figure 14 (available at stacks.iop.org/physed/46/705/mmedia) is a picture from a plate with ink droplets placed farther from the laser so that more droplets are illuminated—virtually all feature a Poisson’s spot in a spectacular display of the beauty of wave optics.

Conclusion
The proposed demonstration setup is simple and easy to use, the necessary equipment is relatively affordable (usually already available) and easy to obtain (the complete first part of the setup can be found at [8] for example, featuring even more demonstrations and experiments than the ones mentioned here) and the results are quite spectacular. We performed demonstrations with this setup at physics conferences and some participants (professional physics teachers) said they had never seen those phenomena live before. With this new technique of doing wave optics demonstrations, large groups of people (even more than 100) can be shown some fundamental (and very attractive) phenomena that are otherwise rarely shown in common teaching practice. This helps bring physics out of its highly abstract theoretical mould, and noticeably improves the learning experience and increases the motivation of the students.

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Figure 6. Interference from a thin glass plate placed far from the laser.

References

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