Using readily available equipment, you can carry out a home experiment that illustrates one of the weirdest effects in quantum mechanics.

1) Gomme quantique (Quantum Eraser)
2) Interféromètre de Michelson
3) Interféromètre de Jamin
4) Holographie
Related Topics
Wave-particle duality, wave interference, quantum mechanics.

Principle
A Mach-Zehnder-interferometer is illuminated with a laser beam. Circular interference fringes appear on the screens behind the interferometer. If polarization filters with opposite polarization planes are placed in the two interferometer paths the interference patterns disappear. Placing another polarizer before one of the screens causes the pattern to reappear. Electromagnetic radiation can be described both in terms of propagating waves, as well as particles (photons). The experiment illustrates this duality by showing how interference patterns can be explained on the basis of both classical wave mechanics and quantum physics.

Equipment
Base plate in experimental case 08700.01 1
Laser, Helium-Neon, 0.2/1.0 mW 08180.93 1
Surface mirror 08711.01 4
Adjusting support 08711.00 4
Beam splitter 50 % : 50% 08741.00 2
Holder for diaphragm/beam splitter 08719.00 2
Screen 150 mm × 150 mm 09826.00 2
Glass lens in mounting, \( f = +20 \) mm 08018.01 1
Lens holder for base plate 08723.00 1
Polarization specimen, mica 08664.00 1
Diaphragm holder for base plate 08724.00 1
Polarisation filter for base plate 08730.00 3
Magnetic foot for base plate 08710.00 13

Fig. 1: Experiment setup.
Caution!
Laser radiation! DO NOT STARE into the beam or view directly with optical instruments! Wear protective goggles!

Tasks
1. Set up the experiment and observe the interference pattern on the screen.
2. Change the polarization of the beams with the PF1 and PF2 polarizers and observe the influence on the interference pattern.
3. Use the third polarizer PF3 to cancel the polarization of the light in the two beams, and observe the reappearance of the interference pattern.

Set-up and Procedure

In this experiment a Mach-Zehnder Interferometer is used to split a light beam into two parts, send them along two different paths where they can be subjected to individual treatment and then to reunify the two beams again and observe interference effects (See Fig. 2). Since the precise alignment of the Interferometer is crucial the individual steps will be described in the following and illustrated with photographs. In the final set-up shown in Fig. 3 the position of all the optical elements can been seen along with the names and abbreviations used for them in this set-up guide.
- Fix the laser (HeNe 0,2/1mW) to the optical base plate so that the beam path height is about 12,5 cm above the plate (Fig. 4).
- Direct the beam with the mirror M1 to the right corner in the front of the plate. Adjust the mirror M1 so that the beam path height there is the same as at the exit point of the laser (Fig. 5).
- In this step the mirrors M2, M3, M4 and the beam splitters BS1, BS2 will be preadjusted so that the beam height can be maintained. To achieve this, the respective elements are positioned in the right corner in the front of the plate. Their height is adjusted so that the beam coming from mirror M1 strikes them in the centre. The tilt should be adjusted so that the beam is reflected onto itself (Fig. 6).
- The mirrors M1, M2, M3, M4, the beam splitters BS1, BS2 and the screens are positioned as shown in Fig. 7 so that the indicated light-path forms. One should make sure that the coated side of the beam splitter BS1 is located on the side pointing towards mirror M2 and the coated side of beam splitter BS2 points toward mirror M4.
- The beams should preferably travel parallel to the lines on the base plate and strike the optical elements in the centre.
- The goal of this step is to achieve a perfect coincidence of the pairs of beams going from the beam splitter BS2 to the screens. For adjustment one uses the mirror M4 and the beam splitter BS2.
- One of the two screens should be quite close to the beam splitter BS2 the other one far away (Fig. 8).
Initially on both screens two bright points will be visible. With the adjustment screws at mirror M4 these points can be brought to coincide on one of the two screens. But the adjustment is only done when the points coincide on both screens (the close one and the far one) simultaneously. A twinkling of these points then already indicates interference effects. Typically the simultaneous coincidence of both pairs of points can not be realized with the adjustment screws on mirror M4 alone. Additionally the mirror M4 has to be moved to the left or to the right to achieve this. If the two dots appear in different heights on one of the screens while they coincide on the other one, this can be corrected by tilting the beam splitter BS2.

The expansion lens \( f = 20 \text{ mm} \) is brought into position. The interference pattern visible on both screens should be centred with the aid of the adjustment screws of the mirror M4 (Fig.9).

**Fig. 8:** Adjusting the beams.

**Fig. 9:** Centering the interference pattern
Now the λ/4 plate is brought into position. The role of this plate is to transform the linear polarized laser light into circular polarized light. This has the advantage that the orientation of the polarizers relative to the beam coming from the laser is of no importance. The λ/4 plate should be oriented so that the writing on it is in an upright position (Fig. 10).

Finally, the three polarizing filters PF1, PF2, PF3 can be placed. Fig. 11 and Fig. 12 show the complete setup.

Fig. 10: Correct set-up of the λ/4 plate.

Fig. 11: Complete experiment setup, side view.

Fig. 12: Complete experiment setup, top view.
Having set the experiment as described above, block one of the two paths in the interferometer: a relatively homogeneous spot is visible on the screens. If you now open the blocked path, the spot does not become brighter everywhere, but there are regions (fringes) where the brightness drops. If you block only half of one path, direct comparison is possible as shown in Fig. 13 and Fig. 14.

Shift the polarizing filter PF3 out of beam path. The polarizing filters PF1 and PF2 are oriented so that light passing them has the same polarization. Under these circumstances interference rings are visible on both screens.

If you rotate PF1 so that light passing it is polarized perpendicular to light passing PF2, the interference effect on both screens vanishes.

The next step is to introduce the polarizing filter PF3 and orientate it at an angle of 45 degrees with respect to PF1 and PF2. The interference pattern is visible again on the screen SC1 behind PF3.

Fig. 13: Blocking half of the beam.

Fig. 14: Pattern seen on the screen when blocking half of the beam.
Theory and Evaluation

1. Classical physics - wave interference

Wave interference is the superposition of two or more waves that results in a new wave pattern. The resultant displacement at a point is equal to the vector sum of the displacements of different waves at that point. To illustrate this principle, let us assume two sinusoidal waves of the same wavelength interfere with each other. If the phase-shift between them is zero, in other words, if at any given point their amplitudes are the same, the overall amplitude will be double that of each wave (constructive interference). If, on the other hand, their phases are shifted by half a period, they will cancel each other out (destructive interference). Fig. 15 illustrates this example.

Most electromagnetic waves can be well approximated by plane waves, that is waves with infinitely long and wide wavefronts. For such electromagnetic waves, it follows from Maxwell’s equations that the electric and magnetic field are perpendicular to the direction of propagation and to each other.

Fig. 15: Illustration of wave interference.

Electromagnetic waves exhibit a property called polarization, which describes the orientation of their oscillations. Conventionally, when considering polarization, only the electric field vector is described and the magnetic field is ignored, since it is perpendicular to the electric field and proportional to it. If we divide the electric field vector into x and y components, a polarization of a wave tells us how those components change in time. In other words, a polarization state of an electromagnetic wave is the shape traced out in a fixed plane by the electric vector as such a plane wave passes over it (Fig. 16).

Important fact is that electromagnetic waves of different polarization do not interfere with each other.

The laser in the experiment produces coherent electromagnetic radiation, i.e. electromagnetic waves with the same frequency, polarization and phase. The beam is split into two, and the polarization of each beam can be changed separately by adjusting the polarizers PF1 and PF2. Hence, if we set the polarization of both beams to be the same (equivalent to removing the polarizes from the beam paths), we observe the interference pattern on the screens. The bright fringes are the locations where the incoming beams interfere constructively, hence producing higher amplitude than without the interference effect, while the dark fringes are the locations where destructive interference takes place, and the radiation from the two beams cancels each other out. When we use the polarizers PF1 and PF2 to set different polarizations for each beam, the interference pattern disappears, since electromagnetic waves of different polarization do not interfere. We can now use the third polarizer, PF3, to recover the interference fringes by setting it at an angle of 45° with respect to the polarizers PF1 and PF2. In doing so, we again bring the two beams to the same polarization, and they interfere.
2. Quantum physics – the quantum eraser

The experiment can also be interpreted by a quantum theory. Hence, we now consider the electromagnetic radiation to consist of photons. Note, that this does not mean that we can think of photons as rigid spheres. Actually, in mathematical terms, a state of a system (a photon for example) in quantum mechanics is described by a complex wave function $\Psi(x,t)$ (also called a state vector in a complex vector space), belonging to a complex separable Hilbert space, and is governed by the Schrödinger equation (Eq. 1)

$$i\hbar \frac{\partial}{\partial t} \Psi(x,t) = \hat{H} \Psi(x,t) \tag{1}$$

where $i$ is the complex number, $\hbar$ is the reduced Planck constant and $\hat{H}$ is the Hamiltonian operator. The wave function $\Psi(x,t)$ is a rather abstract mathematical object and does not represent an observable, that is, a quantity we can actually measure. What we can obtain from the quantum theory is a probability density of an observable, which is given by the amplitude of the wave function. Hence, we can calculate the probability of finding a particle at a given position in space, or having a given momentum, or energy, etc. Therefore, even though we talk about particles, the quantum theory describes them as wave packets, and what we actually obtain are “clouds” of probability. For example, if we calculate a position of a photon, the result will be a region in space where the probability is non-zero, and not a single location, as in classical physics. What this means is that, from the quantum point of view, the particle is everywhere in the region where the calculated probability is non-zero. Additionally, the probability is given only by the amplitude of the wave function, while the phase encodes information about the interference between quantum states. This gives rise to the wave-like behavior of quantum states. For example, if there are two ways for a photon to travel, as in the quantum eraser experiment, and both are equally probable (we cannot measure which path the photon actually takes), both of these quantum states interfere with each other and result in the fringe pattern we observe.

Contrary to classical mechanics, the quantum theory does not allow for accurate simultaneous predictions of conjugate variables, like position and momentum, time and energy (frequency). This is known as the uncertainty principle (Eq. 2, for position and momentum)

$$\Delta x \Delta p \geq \frac{\hbar}{2} \tag{2}$$

where $\Delta x$ and $\Delta p$ are the uncertainty of position and momentum, respectively. Hence, a minimum exists for the product of the uncertainties, and the more precisely one property is measured, the less precisely...
the other can be measured.

Now let us interpret the experiments using quantum physics. Even though the laser produces many photons that travel through the setup simultaneously, the truly amazing fact is that the result is the same (interference pattern is formed) even when we sent one photon at the time. From the quantum-mechanical point of view, the photon has non-zero probabilities of travelling along both paths in the setup, therefore it travels simultaneously along both paths and interferes with itself! Both states (photon travelling along path a and path b) coexist and have the same probabilities, and the wave function is a superposition of those states, which results in the interference pattern. When we use the polarization filters PF1 and PF2 to prescribe polarization information on the photon (opposite polarizations for each path), the wave function changes (and hence the probabilities of finding the photon along the two paths) and removes the ability of the photon to interfere with itself. What it means is that, by polarizing the photon, we are able to tell which path it travelled (the probability becomes one for one path and zero for the other) and hence only one state exists. Thus the interference pattern disappears. When we erase the polarization information with the third polarizer (PF3), the probability of finding a photon at a given location at the detector (screen) results again from a superposition of the two equally probable quantum states (photon travelling along path a and path b), and hence forms the interference pattern. Thus the name “quantum eraser”.

Notoriously, the theory of quantum mechanics reveals a fundamental weirdness in the way the world works. Commonsense notions at the very heart of our everyday perceptions of reality turn out to be violated: contradictory alternatives can coexist, such as an object following two different paths at the same time; objects do not simultaneously have precise positions and velocities; and the properties of objects and events we observe can be subject to an ineradicable randomness that has nothing to do with the imperfection of our tools or our eyesight.

Gone is the reliable world in which atoms and other particles travel around like well-behaved billiard balls on the green baize of reality. Instead they behave (sometimes) like waves, becoming dispersed over a region and capable of criss-crossing to form interference patterns.

Yet all this strangeness still seems remote from ordinary life. Quantum effects are most evident when tiny systems are involved, such as electrons held within the confines of an atom. You might know in the abstract that quantum phenomena underlie most modern technologies and that various quantum oddities can be demonstrated in laboratories, but the only way to see them in the home is on science shows on television. Right? Not quite.

On pages 92 and 93, we will show you how to set up an experiment that illustrates what is known as quantum erasure. This effect involves one of the oddest features of quantum mechanics—the ability to take actions that change our basic interpretation of what happened in past events.

Before we explain what we mean by that and outline the experiment itself, we do have to emphasize one caveat in the
interest of truth in advertising. The light patterns that you will see if you conduct the experiment successfully can be accounted for by considering the light to be a classical wave, with no quantum mechanics involved. So in that respect the experiment is a cheat and falls short of fully demonstrating the quantum nature of the effect.

Nevertheless, the individual photons that make up the light wave are indeed doing the full quantum dance with all its weirdness intact, although you could only truly prove that by sending the photons through the apparatus and detecting them one at a time. Such a procedure, unfortunately, remains beyond the average home experimenter. Still, by observing the patterns in your experiment and by thinking about what they mean in terms of the individual photons, you can get a first-hand glimpse of the bizarre quantum world.

If you want to go straight to the home experiment, it is detailed on the next two pages. The discussion that follows here (and continues on page 94) delves into the science of quantum erasers in general. This explanation will help you understand what the do-it-yourself eraser demonstrates, but you might want to come back to it after seeing what that specific kind of eraser does.

What a Quantum Eraser Erases

One of the strange features of quantum mechanics is that the behavior that something exhibits can depend on what we try to find out about it. Thus, an electron can be in a superposition of behaving like a particle or like a wave, depending on which experiment we subject it to. For example, in some situations particle-like behavior emerges if we ascertain the specific trajectory that an electron has followed and wavelike behavior transpires if we do not.

A standard demonstration of this duality relies on what is called a two-slit experiment (your do-it-yourself quantum eraser is similar to this experiment in that it involves two pathways, but not two slits). A source emits particles, such as electrons, toward a screen that has two slits they can pass through. The particles ultimately arrive at a second screen where each one produces a spot. Where each particle lands is to some extent random and unpredictable, but as thousands of them accumulate, the spots build up into a definite, predictable pattern. When the conditions are right for the particles to behave as waves, the result is an interference pattern—in this case a series of fuzzy bars, called fringes, where most of the particles land, with very few hitting the gaps between them.

The particles will generate the interference pattern only if each particle could have traveled through either of the two slits, and there is no way of ascertaining which slit each one passed through. The two pathways are then said to be indistinguishable and each particle acts as if it actually traveled through both slits. According to the modern understanding of quantum mechanics, interference occurs when indistinguishable alternatives are combined in this way.

When two or more alternatives coexist, the situation is called a superposition. Erwin Schrödinger highlighted the oddity of quantum superpositions in 1935, when he proposed his now infamous concept of a cat that is simultaneously alive and dead, sealed inside a hermetic box where it cannot be observed. When quantum interference happens, something in the experiment is like a kind of Schrödinger’s cat. But instead of being alive and dead at the same time, the cat may be walking by a tree, passing on both sides of it simultaneously.

Schrödinger’s cat ceases to be in a superposition as soon as we look inside its box: we always see it to be either alive or dead, not both (although some interpretations of quantum mechanics have it that we become in a superposition of having seen a dead or a live cat). If a spotlight is shining near the tree, we see the quantum cat go one way or the other. Similarly, we can add a measurement tool to watch each particle as it passes the slits. One could imagine having a light shining on the slits so that as each particle comes through we can see a flash of light scatter from where the particle went. The flash makes the two alternative pathways distinguishable, which destroys the superposition, and the particles arrive at the final screen not in a pattern of fringes but in one featureless blob. Experiments analogous to this scenario have been conducted, and, as predicted by quantum mechanics, no interference pattern builds up.

We need not actually “do the looking.” We do not have to

What you will need for the experiment

- A very dark room.
- Polarizing film. Plain gray, high-quality film ("experimental grade") gives the best results; avoid film tinted with a color [see www.sciam.com/ontheweb for some places that sell film]. You need to cut it into six squares, each about two inches on a side. The box on page 94 describes what polarizers do to photons.
- A laser, such as a laser pointer. If yours emits polarized light, align its polarization at 45 degrees from the vertical. If your laser is not polarized, include a polarizer at 45 degrees immediately after the laser at every step.
- Use a rubber band to keep the laser turned on.
- A thin, straight piece of wire, such as from an unused twist tie or a straightened staple. The thinner the better.
- Some tinfoil and a pin to poke a hole in it. The light that goes through the pinhole will expand outward, forming a narrow, conical beam. The pinhole makes the patterns dimmer but may improve the results if the room is dark enough.
- Some stands to hold the laser and polarizers in place. These could be as low-tech as cereal boxes.
- A screen to display the final patterns. The bare wall will do if it is plain enough; otherwise use a sheet of paper.
Quantum Erasing in the Home

The steps presented here outline how to see quantum erasure in action. See www.sciam.com/ontheweb for a fuller description and additional information, such as the basics of how waves interfere and produce fringes.

SEEING INTERFERENCE

- Wrap the tinfoil around the business end of the laser and put a pinhole in it to let through some of the light beam.
- Set up the laser so it shines on the screen from at least six feet away. It should produce a circular spot of light on the screen.
- Position the wire vertically and centered in the light.

**WHAT HAPPENS:** As shown, you should see an interference pattern consisting of a row of fringes (bright and dark bands). The interference pattern arises because light passing on the left of the wire is combining, or "interfering," with light passing on the right-hand side. If you hold a piece of paper just after the wire, you will see a lobe of light on each side of the shadow of the wire. The lobes expand and largely overlap by the time they reach the screen. For each individual photon arriving at the screen in the overlap region, it is impossible to tell whether it went on the left or the right side of the wire, and the combination of the two ways it went causes the fringes. Although you are looking at trillions of photons, each of them is interfering only with itself.

LABELING THE PATH

- Take two polarizers and rotate one of them so that their axes are perpendicular; you have done this correctly if when you overlap the film temporarily, no light goes through the overlap region.
- Tape them together side by side with no gap or overlap. Do the taping along the top and bottom so the tape will not block the light. We will call this the path labeler.
- Position the labeler in the beam so that its join is right behind the wire. Attaching the wire to the labeler might be easiest. Wire and labeler will not be moving for the rest of the experiment. We will say that the left-hand polarizer produces vertically polarized light (V), and the right-hand one horizontally polarized (H). It does not matter if we have these labels reversed.

**WHAT HAPPENS:** Even though the light is again passing on both sides of the wire, the fringes should be gone. If a photon reaches the screen by passing to the left of the wire, it arrives V-polarized; if to the right of the wire, H-polarized. Thus, the labeler has made available the information about which way each photon went, which prevents the interference.
SELECTING THE LEFT-PASSING PHOTONS
- Position a third polarizer (the “analyzer”) between the labeler and the screen in the V orientation.

WHAT HAPPENS: The analyzer will block all the right-passing photons (which became H-polarized at the labeler) and will let through all the left-passing ones. The pattern will be nearly the same as in the previous step—just dimmer and not extending quite so far on the right, because it is only the left lobe of light. With the analyzer, you are accessing the information that the labeler made available: you know that all the photons hitting the screen passed to the left of the wire.

SELECTING THE RIGHT-PASSING PHOTONS
- Put the analyzer in the H orientation.

WHAT HAPPENS: The H analyzer blocks the left-hand lobe of light and lets through only the right-hand lobe. If you could measure intensities of light (or numbers of photons) at the screen, you would find that the light in step 2 was just the sum of the light in steps 3 and 4. Notice that the fringes were missing from step 2 even though you were not ascertaining the polarization of the photons; it was enough that you could have done so, as in steps 3 and 4.

ERASING THE PATH INFORMATION
- Rotate the polarizer 45 degrees clockwise from V, an orientation we call diagonal (D).

WHAT HAPPENS: The fringes reappear! Why? The polarizer is erasing the information about which side each photon used. Now each left-passing V photon has a 50 percent chance of getting through it to the screen, as does each right-passing H photon. In both cases, the photons that get through become D-polarized, so there is no way to tell which way each photon went. Once again, each photon apparently goes both ways at once and interferes with itself.

THE ANTI-ERASER
- Rotate the polarizer 45 degrees counterclockwise from V ("antidiagonal" or “A”).

WHAT HAPPENS: Again there are fringes—everything said in step 5 applies to an A-polarized eraser as well. But if you look very closely, you will see that the fringes are shifted slightly in the two cases. The A fringes are bright where the D ones are dark, and vice versa. If you could add up the intensities, or numbers of photons, for the D and A erasers, the sum would again be the shape from step 2, with no interference visible.

BOTH ERASERS AT ONCE
- Cut in half horizontally a D-oriented and an A-oriented polarizer.
- Join the top half of the D with the bottom half of the A.
- Put the hybrid analyzer in place.

WHAT HAPPENS: D fringes appear in the top half of the light and A fringes in the bottom half. The pattern looks a bit like misaligned teeth and makes clearer how the dark and bright fringes of each eraser correspond.

CONCLUSION
Think about what the photons were doing in each of the steps.
- In some steps (3 and 4), each photon went on one side or the other of the wire (no interference), but in others (4, 5, 6 and 7), they seemingly went on both sides at once (producing interference).
- Our interpretation of what the photons did at the wire depends on what they encountered later on in the setup—be it an analyzer or an eraser or nothing but the screen.
- Steps 6 and 7 revealed that the "which way?" information can be erased in more than one way, to produce either the original interference pattern or the inverse of it.
What polarizers do to photons

Polarizing film has an axis (in our diagrams we depict its direction with lines on the film), and the film allows passage of light that is oscillating parallel to the axis. You can think of light as being like a wave on a rope held between two people; the wave can make the rope move up and down or side to side or at any angle in between. The angle of the oscillation is the polarization of the wave.

Polarizing film is like a screen of parallel bars that the rope passes through: it lets through waves polarized parallel to it unhindered, blocks perpendicular ones completely and allows waves on other angles to get through with reduced amplitude. Most important, the wave (if any) that comes out the other side of a polarizer is polarized parallel with the polarizer’s transmission axis.

The quantum description of what happens to light going through a polarizing film sounds only slightly different: The light is made up of individual particles called photons, and like a wave, the photons can each have a direction of oscillation. A photon will get through every time when it hits a polarizer with the transmission axis parallel to the photon’s polarization. A perpendicular polarizer blocks the photon every time. At a 45-degree angle, the photon has a 50 percent chance of getting through (the exact probability varies as the angle is varied). Most important, when a photon does go through a polarizer, on the other side it will be polarized parallel with the polarizer’s transmission axis.

Light can also be unpolarized, which means the photons making up the light have random polarizations. That is another case in which half the photons will get through a polarizer, and, as always, those that do so become polarized parallel with the polarizer.

You can see how polarizers work by putting two of them together. As you rotate one of the polarizers, you can see through them clearly when their axes are aligned, barely at all when they are perpendicular and to some extent at other angles. Photons that make it through the first polarizer are polarized by it, and then their probability of getting through the second one depends on the angle between their polarization and the second polarizer’s axis.

An interesting effect happens if two polarizers are perpendicular and a third one is inserted between them on an angle (45 degrees is best): adding the third polarizer allows some light to get through, even though you might expect it to be an additional obstacle for the light. See if you can explain why that happens (the answer is at www.sciam.com/ontheweb). The do-it-yourself quantum eraser also relies on a polarizer at 45 degrees changing what the light does.

detect the light flashes and ascertain which way each particle went. It suffices that the information is available in the flashes and could have been observed in that way.

Now we finally get to the quantum eraser. The eraser is something that can erase the information indicating which path each particle has followed, thereby restoring the indistinguishability of the alternatives and restoring interference.

How might an eraser do that? Imagine that the “flash of light” that scatters from each particle is a single photon. For the photon to reveal the “which path?” information of the particle, it must be possible (even if only in principle) to tell which slit the photon came from. That means we must be able to measure the position of where each photon scattered accurately enough to tell the slits apart. Heisenberg’s uncertainty principle, however, tells us that if we instead measure the momentum of each photon with great accuracy, then the photons’ positions become less well defined. So if we pass the photons through a lens that makes their momentum information available, the information about their positions is erased. When that happens, the two paths the particles can follow are again indistinguishable and interference is restored.

We have omitted one last tricky detail, but we will come back to that. First, stop and think a bit more about what is happening in the erasing process we just described, because that is where the weirdness lies. When we detect the position where one of the photons scattered, we learn which slit its corresponding particle went through, which means the particle did go through one slit or the other, not both. If we instead detect the photon’s momentum, however, we cannot know which slit the particle went through. What is more, when we do many momentum measurements and see an interference pattern, we infer that in those cases the particles went through both slits (interference would be impossible otherwise).

In other words, the answer to the question, “Did the particle go through one slit or both slits?” depends on what we do with its corresponding photon long after the particle has gone through. It is almost as if our actions with the photons influence what has happened in past events. We can find out which slit the particle went through, or we can have our quantum eraser can delete that information from the universe.

Strangest of all, we can decide which measurement to make after the particle has passed through the slits—we can have the apparatus for both alternative measurements in place, with a switch that we flick one way or the other just before each pho-
ton arrives. Physicists call this variation a delayed-choice experiment, an idea introduced by John A. Wheeler of the University of Texas at Austin in 1978 that extends a scenario that Niels Bohr and Albert Einstein used in their arguments about quantum mechanics and the nature of reality in 1935.

At this point, some particularly clever readers will be worrying about a fundamental problem that seems to undermine what we have just described: Why can’t we delay the choice of our photon measurement until after we have seen if the particles form an interference pattern? We could, in fact, arrange to do just that by having the final screen not too far from the slits and the photon detector much farther away. So what would happen if we saw the particles form fringes but then chose to do photon position measurements that should prevent such fringes from forming? Wouldn’t we have created a paradox? Surely we would not expect the already registered interference pattern to vanish! Similar reasoning suggests we could use the delayed-choice effect to transmit messages instantaneously over arbitrary distances (thereby circumventing the speed of light).

That tricky detail that we omitted earlier is what saves the day: to see the interference of the particles after applying the quantum eraser, we first have to divide them into two groups and observe the groups separately. One group will display the original pattern of fringes; the other will display the inverse of that pattern, with particles landing on what were originally the dark bands and avoiding the places where the bright fringes were. The two groups combined fill in all the gaps, hiding the interference.

The paradox is avoided because we need data from the photon measurement to know which group each particle belongs to. Thus, we cannot observe the fringes until after we have done the photon measurements, because only then do we know how to split the particles into groups. In the home experiment, dividing particles into groups is done for you automatically because one group gets blocked by a polarizing filter, and you can therefore see the interference pattern of the group that gets through with your own eyes. In the final step you can see the interference patterns of the two groups right next to each other.

From a practical standpoint, the inability to send messages faster than the speed of light and create a paradox is perhaps disappointing, but physicists and logicians consider it to be a very good feature.

For more discussion about quantum erasers, go to www.sciam.com/ontheweb, where you will find:

- A list of cutting-edge interference and quantum eraser experiments carried out in recent years.
- A short discussion of what quantum erasers have to do with how the ordinary world we are familiar with emerges from the weird underlying quantum reality.
- More information about delayed-choice experiments and the impossibility of superluminal messages.
- A few other related experiments you can do at home.

How a Quantum Eraser Works
How quantum particles behave can depend on what information about them can possibly be accessed. A quantum eraser eliminates some information and thereby restores the phenomenon of interference. The eraser’s action is most easily understood by considering a "double-slit" experiment [below].
Michelson Interferometer
for Demonstrating
the Wave-Particle Duality of Light
and Quantum Erasing

OPERATING MANUAL
version 2.01

Apparatus developed by

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February 2011
NOTE

This demonstration module is closely related to the devices described in

T.L. Dimitrova and A. Weis
*The wave particle duality of light: A demonstration experiment*,

T. L. Dimitrova and A. Weis
*Lecture demonstrations of interference and quantum erasing with single photons*

T. L. Dimitrova and A. Weis
*Single photon quantum erasing: a demonstration experiment*

Reprints of these papers are given as Appendix in the Manual.

In contrast to the Mach-Zehnder interferometers described in those papers the device presented here is based on a Michelson interferometer (*MI*) and is operated with a single laser beam only.
1. Optical setup

Fig. 1 shows the optical layout of the experiment. It is based on a Michelson interferometer (MI). All components are mounted on an optical breadboard using M6-threaded mounting holes.

**Figure 1:** Photograph and scheme of the optical layout of the Michelson interferometer.

The beam from the laser (green diode laser, $\lambda=532$ nm, 5 mW nominal maximal power) is directed to the interferometer via the mirror $M1$. Prior to entering the interferometer the intensity of the laser beam can be adjusted by two filters which can be moved by sliding their table mounts via rods ended by black balls that extend from the enclosing box. The two screws that hold down each filter mount should be fully screwed down (avoid excessive force). The taps that hold the sliding bases in place are precisely
machined so that a smooth translational motion of the filters is assured. The first filter (BF) is a blocking filter with an optical density that can be adjusted by adding/removing individual neutral density filters. Make sure to have at least an optical density of 3 mounted when operating the photomultiplier. Note: the individual filters are marked NE10A, NE20A, etc, which corresponds to optical densities of 1, 2, etc, i.e. attenuations of $10^1$, $10^2$, etc. The BF is inserted for performing experiments with single photons. The second filter (VF) is variable filter which allows the continuous attenuation of the beam intensity by a factor ranging from 1 to 100. Two detectors: a photodiode (PD) and a photomultiplier (PM) are mounted behind an aluminum screen with two small apertures before the relative detectors.

2. Electronics

2.1. Control box: Front panel

Figure 2 shows a photograph of the front panel controls of the electronics control box.

![Figure 2: Front panel of the electronics control box.](image)

2.1.1 Laser

Power on/off switch with LED indicated status. Potentiometer (power) regulating the voltage applied to the laser. Maximum setting for the laser is +3.0 V. Allow the laser to stabilize for 15 minutes (its longitudinal mode structure drifts during this time). The laser can be switched on and off using the switch without need to reduce the potentiometer setting to its minimal value.

2.1.2 Photomultiplier

Power on/off switch with red LED indicating the status.

*HV level*: potentiometer control of the high voltage applied to the photomultiplier. The amplitude of the analog pulses is given by a power law of the applied high voltage. The high voltage generator is contained in the photomultiplier housing and is adjusted by a variable (low) control voltage generated in the electronics box.
**Discr. level:** Potentiometer allowing to vary the discriminator level. Analog photomultiplier pulses larger than this level produce a TTL pulse that is output on the back panel. These pulses also flash the green LED marked *photon* and produce pulses at the *speaker out* connector and at the *PHOTOMULTIPLIER TTL OUT* connector on the back panel.

The red and yellow banana jacks above the *discr. level* and *HV level* potentiometers deliver voltage levels (referred to the black jack) proportional to the two potentiometer settings.

The photomultiplier aperture on the screen is equipped with an electronically controlled shutter. It closes the photomultiplier aperture when the blocker filter (*BF*) is open. When the *BF* is inserted such that it closes the *interlock* switch, the aperture is opened and high voltage is applied to the photomultiplier.

### 2.1.3. Piezo control

A five-position control knob allows you to choose the source of the voltage applied to the piezo ceramic controlling the mirror *M3*.

- **Position remote:** Control of the DC voltage applied to the *PZT* by the remote control box, connected to the remote piezo control on the backpanel of the electronics control box via a long cable.
- **Position manual:** Control of the DC voltage applied to the *PZT* by the potentiometer *man. level* on the front panel.
- **Position ramp:** A periodic linear ramp is applied to the *PZT*. The ramp’s amplitude is controlled by the potentiometer *scan. ampl.* on the front panel.
- **Position lock:** A feed-back voltage is applied to the piezo such that a half-width point of an interference fringe is locked to the position of the photodiode’s aperture. The controls *P*, *I*, offset and *PD gain* used in connection with locking the MI and are described below.
- **Position open:** A constant voltage of +15 volts is applied to the *PZT*.

### 2.1.4. Fringe lock

Two potentiometers for controlling the proportional (*P*) and integral (*I*) parts of the feedback amplifier used in the fringe lock mode described below.

### 2.1.5. Photodiode

The upper potentiometer controls the amplification (gain) of the photodiode signal output on the backpanel. The lower potentiometer allows the adjustment of a constant voltage offset of the photodiode signal, a feature used for fringe locking.
2.2 Control box: Back panel

Figure 3 shows a photograph of the back panel connectors of the electronics control box.

![Back panel of the electronics control box.](image)

**Figure 3: Back panel of the electronics control box.**

2.2.1 DETECTOR UNIT

The wide multi-pin connector **DETECTOR UNIT** connects the electronics box to the detector unit by the corresponding cable. This cable carries signals to/from the photomultiplier, the photodiode and the shutter.

2.2.2 INTERFEROMETER

The small multi-pin connector **INTERFEROMETER** connects the electronics to the interferometer board by the corresponding cable. This cable carries signals to/from the laser, the piezo and the interlock switch.

2.2.3 PHOTODIODE OUT

The connector **PHOTODIODE OUT** delivers a voltage proportional to the light power detected by the photodiode plus a constant voltage offset (gain and offset can be controlled on the front panel). It is used for oscilloscope display. Note that on some versions of the electronics box the output signal may be reversed, i.e., increasing laser power will lower the signal.

2.2.4 PIEZO RAMP OUT

This connector **PIEZO RAMP OUT** delivers the same voltage that is applied to the piezo. The delivered voltage depends on the selector switch setting on the **Piezo control** unit on the front panel. The output is used for oscilloscope display.
2.2.5 PIEZO TRIGGER OUT

This connector delivers a TTL signal which is high during the rising slope of the piezo ramp and low during its falling slope.

2.2.6 PHOTOMULTIPLIER

The connector ANALOG OUT delivers the analog photomultiplier pulses as they come from the photomultiplier.

The connector TTL out delivers TTL pulses that are synchronous with each analog pulse whose amplitude is larger than the voltage set by the \textit{discr. level} potentiometer on the front plane.

2.2.7 SPEAKER

A small loudspeaker driven by (stretched) pulses that are synchronous with the \textit{PHOTOMULTIPLIER TTL OUT} pulses. The volume of the pulses can be adjusted by the small \textit{volume} potentiometer (requires screwdriver).

The \textit{internal/external} switch allows you to switch between the internal speaker and the external active speaker system connected to the \textit{ext. out} jack.

Figure 4 shows the connection of the interferometer to the electronics control box.
Figure 4: Wiring of the interferometer experiment.
3. Locking the interferometer

Fringe locking is an electronic feedback feature which allows you to lock the (spatial) position of the fringe pattern with respect to the photodiode aperture in the detector block.

We only briefly touch upon the procedure for actively stabilizing the fringe position in space which is not needed for the wave-particle and the quantum erasing demonstrations.

If fringe locking is required, proceed as follows:

- Set the piezo control switch on the front panel to scan and display the photodiode signal on the oscilloscope.
- Adjust the PD offset potentiometer such that the amplitudes of the displayed fringes are symmetric with respect to 0 V.
- Set the piezo control switch on the front panel to manual and adjust the man. level potentiometer such that the photodiode signal is near to 0 V. You will see a slight variation around 0 V due to fluctuations of the path length difference in the interferometer. Gently push on the optical breadboard and watch the reaction of the photodiode signal.
- Set the control switch on the front panel to lock and watch the photodiode trace signal on the oscilloscope. The lock operates correctly if the oscilloscope trace of the photodiode signal remains near 0 V, even when applying a gentle pressure on the MI breadboard.
- If the photodiode signal shows a periodic oscillation, reduce the PD gain until the oscillation ceases.
- Optimize the P and I setting of the PID controller to achieve the tightest possible lock.
- If the interferometer has a large drift, the integrator may charge up to its maximal voltage. Reset the integrator then by pushing the reset button.
4. Demonstrations of the wave nature of light.

Laser control
Prior to performing any demonstrations the laser should be allowed to warm up for 15 minutes.

Experiment W1: Fringe pattern by projection
PREPARATION:
- Set the scan mode control to open.
- Remove the blocking filter BF.
- Set the variable filter VF to full intensity.

Distant projection (useful for auditorium demonstrations)
- Insert the mirror M4 (mounted on a repositionable magnetic base) at the position shown in Fig. 1 to project the interferometer output to a distant screen/wall. If the interferometer is well aligned you should see an interference pattern onto the wall (see Figure 5).
- Adjust the orientations of mirrors M2 and M3 such as to see 4 to 5 vertically oriented bright fringes.
- Use the micrometer screw to maximize the fringe contrast.

On board projection (useful for demonstrations to people standing near the system)
- Remove the mirror M4 (see Fig. 1) to project the interference pattern onto the detectors screen.
- Remove the projection lens L and adjust the height of the detector block so that the outgoing beam hits the screen at the height of the apertures of the detectors. Reinsert then the lens L and adjust its height and transverse position so that the blown-up fringe pattern is well centered on the projection screen.
- Readjust, if necessary the micrometer screw to optimize the contrast.

DEMONSTRATIONS:
- Block either one of the paths of the interfering beams and show that the interference disappears.
- Demonstrate that the fringe pattern is sensitive to perturbations that affect the relative path difference of the interfering beams by gently pressing the breadboard with your finger, by gently shaking the mounts of the MI components, or by holding your hand under one of the interfering beams (warm air mounting from your hand will affect the air’s index of refraction). Body heat will produce similar
effect when standing close to the interferometer. You may also send a stream of
gas from a (non-burning) gas lighter through one of the beams.

- Show that the gas related effects are much less pronounced when performed on
  the beams after the beam splitter BS.

- Demonstrate how the contrast can be adjusted by the micrometer screw and
  explain the underlying physics (multimode structure of the laser spectrum).

- Show that the number of interference fringes increases with the angle under which
  the interfering beams intersect.

Figure 5: The wave experiment operated in fringe projection mode.
Experiment W2: Fringes in automatic scanning mode

PREPARATION:

- Prepare the interferometer as described in experiment W1.
- Connect the outputs PIEZO RAMP OUT and PHOTODIODE OUT of the electronics box to an oscilloscope as shown in Fig. 4. Trigger the oscilloscope on the ramp signal.
- Set the scan mode control to ramp. Adjust the scan amplitude to its maximal value (fully clockwise). In this mode a periodic linear voltage ramp with a (positive) amplitude of approx. 30 V is applied to the piezo-driven mirror M3, thereby changing the path length of one of the interfering beams in a periodic way.

DEMONSTRATIONS:

- Activate the ramp scan mode and show the voltage ramp on the oscilloscope.
- Demonstrate, as in Experiment 1, the sensitivity of the fringes to perturbations of the interfering beams.
- Show the PD fringes on the oscilloscope and the dependence of their number on the scan amplitude.
- Demonstrate the contrast of the fringes. Not that the voltage shown by the PHOTODIODE OUT channel depends on the electronic offset voltage added through the control offset level, so that the “no light” level does not necessarily corresponds to 0 V. Determine the “no light” voltage level by blocking the photodiode aperture with your finger. If your oscilloscope has a horizontal cursor, adjust it to correspond to this level. Unblock the photodiode and demonstrate that the signal level in the dark fringes is close to a complete absence of light. Note that on some versions the voltage level may be inverted (increasing light yielding decreasing voltage). Invert the signal on your oscilloscope if it has an inversion feature.
- Measure the DC power level when blocking either one of the interfering components. Compare it to the fringe amplitude and explain the result.
Figure 6: The wave experiment operated in scanning mode.
Experiment W2: Manual/remote scanning mode

PREPARATION:

- Prepare the interferometer as described in Experiments W2.
- Show that changing the voltage on the piezo leads to a fringe displacement.
- Connect the MI to the electronics and an oscilloscope as shown in Fig. 4.
- Set the scan mode control to manual or to remote. In this mode no internal periodic ramp is applied to the PZT, but the PZT voltage can be adjusted manually by either using the man. level potentiometer on the front panel or the remote control potentiometer attached to the remote piezo control on the back panel.

DEMONSTRATION

- Demonstrate that the position of the fringes on the detector’s screen can be moved manually by this control.
- Demonstrate the correlation of the fringe motion seen on the projection screen and the photodiode signal seen on the oscilloscope.
- For student labs: Determine the voltage necessary to displace the interference pattern by one fringe and determine from this the piezoelectric constant $\Delta L/dV$ (in $\mu m/V$) of the piezo ceramic. Do this study in the manual scan mode. Study the nonlinearity of the piezo response by determining the voltages $V_i$ necessary to induce a pattern displacement by $i = 1, 2, 3, \ldots N$ fringes. Plot $V_i$ as a function of $i$ and see the non-linearity.
5. Demonstration of the particle nature of light

General preparations

- Prepare the interferometer as described in Experiment W2.
- Set the variable filter (VF) to full intensity (see Fig. 5)
- Connect the outputs PIEZO RAMP OUT and PHOTOMULTIPLIER ANALOG OUT of the electronics box to an oscilloscope as shown in Fig. 4. Trigger the oscilloscope on the ramp signal. Choose the highest vertical oscilloscope sensitivity for the PHOTOMULTIPLIER ANALOG OUT signal.
- Set the scan mode control to ramp. Adjust the scan amplitude to its maximal value (fully clockwise).
- Center the photomultiplier on the fringe pattern (which appears blurred because of scanning).
- Turn the high voltage control knob to its minimal setting (fully counterclockwise).
- Insert the blocking filter (BF). Make sure that the interlock switch is closed. You will hear the sound of the shutter (in front of the photomultiplier) opening when the interlock switch is closed. You also hear a relay switching in the electronics control box.
- Turn on the photomultiplier control. Slowly increase the high voltage level while observing the photomultiplier trace on the oscilloscope (choose initially a high vertical sensitivity on the oscilloscope trace displaying the photomultiplier pulses. At some point you should see positive pulses coming from individual photons. The fact that not all photons yield pulses of the same height is normal and due to the statistical nature of the amplifying process within the PMT.
- Connect the speakers to the output jack on the back panel of the electronics and switch them on (make sure the switch is set to external).
- Lower the discr. level voltage on the front plane until you hear a reasonable rate of photon clicks. If the detector block is strongly misaligned you will hear very few photons.
- Use the tilt adjustments of the detector block to maximize the photon count rate (you may eventually have to rotate the whole block by loosening the holding screw in its post mount.
- Increase the PMT voltage to its maximal value. You should now see a periodic modulation of the photon density on the oscilloscope screen. If necessary, do further optimizations of the PMT fringe signal via the tilt adjustment of the PMT mount. The system is now ready for single photo demonstrations.
Experiment P1: Hearing photons

PREPARATION:

- Perform the preparations described under General preparations above.
- Set the Piezo control to open.
- Block one of the interfering paths in the interferometer by a sheet of paper.
- Insert the blocking filter. Make sure the interlock switch closes (see Fig. 4 and 7).
- Adjust the variable filter to some intermediate position.
- Power the photomultiplier and adjust the high voltage to some intermediate value. Turn the discr. level fully clockwise. Power the active loudspeakers. Lower the discriminator level until you can hear the photons (rate $R_{upper}$). Block the laser beam after it exits from the laser and lower the discriminator level to a value before the click rate starts to increase dramatically (rate $R_{lower}$). Chose some setting of the discriminator between the values $R_{lower}$ and $R_{upper}$.

![Figure 7: The experiment operated with single photons.](image)

DEMONSTRATION:

- With one of the interferometer arms blocked, demonstrate how the photon click rate depends on the laser intensity by moving the variable filter.
- Demonstrate that with the laser blocked the count rate is very low.
- Show the PMT oscilloscope trace while you do these acoustic demonstrations.
- Remove the sheet of paper, so that the two beams can interfere. Set the PMT control knob on the back panel to remote. Use the potentiometer on the remote control box to move the fringes as described in Experiment W3. Demonstrate
(acoustically and via the oscilloscope signals) that the click rate is modulated periodically.

**Experiment P2: Two path interference on a photon-by-photon basis.**

**PREPARATION:**
- Do the *General preparations* as described above. Turn off the photomultiplier.
- Remove the blocking filter $BF$.
- Set the variable filter $VF$ to minimal intensity.
- Perform the strong light experiment (Experiment $W2$) to show again the fringe period.
- Turn the loudspeaker off for this demonstration.

**DEMONSTRATIONS:**
- Insert the blocking filter $BF$ and power the photomultiplier. Display the photomultiplier signal on the oscilloscope together with the piezo ramp (Fig. 8).
- Slowly increase the intensity by moving the variable filter $VF$. Demonstrate how the photon pulse density slowly increases on the photomultiplier trace, and how a fringe pattern starts to emerge from the individual photon pulse as the light intensity is increased. Show that the relative noise (shot noise) on the photomultiplier decreases with increasing light power. If your oscilloscope has an averaging mode, activate it and demonstrate how the fringes become smoother with increasing averaging time. Use this for a discussion on the concept of shot noise.

*Figure 8: The experiment operated with single photons in scanning mode.*
Experiment P3: The photon interferes with itself.

PREPARATION:
In order for this demonstration to be as spectacular as it can be you should prepare it carefully.

- With strong light adjust the micrometer to have a maximum contrast. The success of this demonstration depends on how “dark” the fringe pattern becomes in the region between the bright fringes.
- Now insert the blocking filter $BF$ and adjust the variable filter $VF$ to maximal intensity.
- Set the piezo control mode to remote.
- Use the remote control box to scan the piezo. The remote control allows you to stand at a larger distance from the interferometer, thereby avoiding that your body heat induces interferometer drifts.
- Adjust the discriminator level such that you can hear a maximal contrast between the interference minimum and the interference maximum.
- Use the remote control to adjust the $PZT$ voltage so that the photomultiplier is located in a fringe minimum. Adjust the discriminator level to have a very low counting rate.
- Use the remote control to set the interferometer to an intensity maximum. The audible and visible difference between the count rates in the minimum and maximum should be as large as possible. If necessary repeat the three last steps iteratively.

NOTE: For the effect to be most spectacular you may want to reduce the optical density of the blocking filter. By removing one of the $NE10A$ filters in the preparation phase. Do this with great care by making sure that the photomultiplier is turned off during this manipulation.

DEMONSTRATIONS:
- Demonstrate by remote control that the (acoustic) photon click rate (and the corresponding oscilloscope pulse rate) can be varied between maxima and minima. You may want to use the discriminated TTL pulses from the PMT rather that the analog pulses. Just play to see which one you prefer. Note: the TTL pulses avoid the important (but distracting) discussion of why all analog pulses have different amplitudes. Note also that the TTL pulses reflect what is heard on the loudspeaker.
- Manually adjust the $PZT$ voltage so that the photomultiplier is located in a fringe minimum.
- Now block one of the interfering beams. Use a cardboard of at least A4 size (rather than your hand) for blocking, since hot air brought by your hand may
perturb the path length in the interferometer and ruin the effect. Insert the cardboard in one of the paths, being careful not to touch any of the components and not to produce air turbulence (do not forget that the path length difference has to be kept stable at the level of a fraction of a wavelength in order to stay near the minimum of interference). When the cardboard is inserted you should see and hear a distinct increase of the click rate. This is the most spectacular demonstration to be performed with the module: When 2 paths are offered to an individual photon it does not reach the detector (ask the students about energy conservation). However, when one forces the photon to take a specific path it does reach the detector!
6. Quantum erasing

Interference is a consequence of the fact that one does not know which path each photon takes in the interferometer. Any attempt to determine the path by putting specific labels on the photon in each path leads to a destruction of the interference. It is, however, possible to erase this path information after the photon has emerged from the interferometer, thereby restoring the interference pattern. This phenomenon is called quantum erasing.

In the first experiment one demonstrates the effect with strong light. The individual paths are labeled by orthogonal linear polarizations that are imposed by the polarizers $P1$ and $P2$. In order to keep a maximal contrast the light is polarized at 45° by a prepolarizer (Fig. 9) before entering the interferometer.

**NOTE:** The laser module is rotated in its holding mount so that its polarization is at 45° in order to avoid any loss of intensity. Please remember to perform this alignment should the laser head need to be replaced or dismounted! Since the direction of the laser beam is not perfectly aligned with the axis of its cylindrical housing, a rotation of the laser will displace the beam and require a realignment of the optics. Note however that if the interferometer components ($M2, M3, BS$) had been well aligned previously they will need no realignment during this procedure. In that case, only the pointing direction (and eventually the height) of the laser and the mirror $M1$ should be used for this realignment.

If the polarizers are well oriented the interference pattern will disappear on the relative (projection or detector) screen. Inserting now an ERASING polarizer after the exit of the interferometer will make the fringes reappear, when the ERASER is oriented at $\alpha=\pm45^\circ$. This wave erasing phenomenon can be easily explained by classical wave mechanisms and is a good exercise in polarization calculus.

The interference becomes more intriguing when the experiment is performed with single photons. The wave function of the photon in the interferometer is described by a state vector of the general form

$$|\Psi\rangle = a |\text{path1}\rangle |H\rangle + b |\text{path2}\rangle |V\rangle,$$

which represents a (single particle) entangled state, in which the photon’s internal degree of freedom (polarization) is entangled with its external degree of freedom (the path it takes).
Experiment E1: Wave erasing by projection

PREPARATION:

- Remove the blocking filter $BF$.
- Set the variable filter $VF$ to full intensity.
- Insert the polarizers $P1$ and $P2$ and make slight adjustment of the polarizer orientation until the interference pattern disappears (Figure 9). Put the polarizers back to their parking positions.
- Note that the polarizers are not perfect optical flats, so that their insertion will distort the fringe pattern, requiring a slight readjustment of the interferometer via the mirrors $M2$ and $M3$.

![Diagram](image)

Figure 9: Optical layout for demonstrating erasing with waves.

DEMONSTRATIONS:

- Insert the polarizers $P1$ and $P2$ and show that the interference disappears.
- Insert the $ERASER$ polarizer and show that the interference disappears when it is oriented at $\alpha=\pm45^\circ$.
- Show how the contrast varies smoothly when the orientation of the $ERASER$ is varied.
- Show that the fringe patterns in the positions $\alpha=+45^\circ$ and $\alpha=-45^\circ$ are complementary.
Experiment E2: Wave erasing by scanning

PREPARATION:
- Do all preparation as in experiment E1.
- Set the electronics to scanning mode and show the photodiode signal with the ramp on the oscilloscope.

DEMONSTRATIONS:
- Insert the prealigned polarizers $P1$ and $P2$ and that the interference disappears.
- Insert the ERASER polarizer and show that interference is restored when it is oriented at $\alpha=\pm45^\circ$.
- Show how the contrast varies smoothly when the orientation of the ERASER is varied.
- Show that the fringe patterns in the positions $\alpha=+45^\circ$ and $\alpha=-45^\circ$ are complementary.
Experiment E3: Quantum erasing

PREPARATION:

- Prealign the polarizers as in experiment E1 and put them back to their parking positions.
- Insert the blocking filter $BF$.
- Set the electronics to scanning mode and show the photomultiplier signal together with the ramp on the oscilloscope.
- Check that the detector block is well aligned when the polarizers are inserted. Realign if necessary to get maximal signal on the oscilloscope.

DEMOnSTRATIONS:

- Insert the prealigned polarizers $P1$ and $P2$ as shown in Fig. 10 and show that the interference disappears.
- Insert the ERASER polarizer and show that the interference is restored when it is oriented at $\alpha=\pm 45^\circ$. Use the averaging mode of the oscilloscope to demonstrate the transition from the photon picture to the wave picture.
- Show how the contrast varies smoothly when the orientation of the ERASER is varied.
- Show that the fringe patterns in the positions $\alpha=+45^\circ$ and $\alpha=-45^\circ$ are complementary.

Figure 10: Optical layout for demonstrating quantum erasing with single photons.
7. Trouble shooting

7.1 Interference lost, slight misalignment

In case the interference pattern gets lost during manipulations, proceed as follows: remove the lens $L$ and place a white paper sheet in front of the detector screen. You will typically see two spots coming from the two interfering components. Making the two spots overlap on the detector screen is generally not sufficient to restore fringes since the interfering beams have to overlap over their whole propagation direction. For this it is necessary to make the two beams overlap at two distinct positions in space (a consequence of Euclid’s axiom!) besides the point near the screen the second point of choice is located on the beamsplitter $BS$.

Use the controls of mirrors $M2$ and $M3$ to ensure that the two beams overlap on the detector screen as well as on the reflecting surface of the $BS$. Use a thin sheet of lens cleaning tissue that you gently press onto the beamsplitter as a visual guide for the alignment. For this, identify first the surface of the (several mm thick) beamsplitter that acts as the semitransparent mirror, and apply the paper to that surface (upon delivery of the apparatus that surface points to the inside of the interferometer). Control the beam overlap iteratively on the $BS$ and on the detector screen until a complete overlap is achieved.

Adjust the height of the detector block so that the spot is at the height of the two detector apertures. Insert the lens and check whether you see a nice fringe pattern. Insert the lens $L$. You should see interference fringes. In case you see two large spots with fringes only in their overlap region, remove the lens and redo the alignment described above. Repeat this until the (lens-magnified) pattern shows a full fringe pattern. Make fine adjustments of $M2$ and $M3$ to tilt the fringe pattern to the vertical (or horizontal) and to adjust the desired number of fringes. Do not attempt to perform the coarse alignment above with the lens in place! Adjust the lateral position and height of the lens so that the interference pattern is centered (with respect to the two apertures) on the detection screen.

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APPENDIX

Reprints of papers by Prof. Antoine Weis and Dr. Todorka L. Dimitrova on the Wave-Particle Duality of Light and Quantum Erasing.

1) T.L. Dimitrova and A. Weis
The wave particle duality of light: A demonstration experiment,

2) T. L. Dimitrova and A. Weis
Lecture demonstrations of interference and quantum erasing with single photons

3) T. L. Dimitrova and A. Weis
Single photon quantum erasing: a demonstration experiment
The wave-particle duality of light: A demonstration experiment

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The wave-particle duality of light plays a fundamental role in introductory courses on quantum mechanics. Traditionally the wave and particle aspects of light are demonstrated in separate experiments which makes it difficult for students to understand their complementary nature. We present an experiment using a single apparatus that demonstrates the wave aspect, the particle aspect, and most importantly, their coexistence. The apparatus is based on a Mach-Zehnder interferometer in which a light beam is attenuated so that at each instant there is only a single photon in the interferometer. In this way the observation of single photon interference becomes possible. By integrating the single photon events in a storage oscilloscope the evolution toward classical interference fringes can be shown in real time. A second strong laser beam, derived from the same pointer, but slightly displaced, traverses the interferometer at the same time, allowing the simultaneous demonstration of wave aspects. Special features of the setup are low cost, simplicity, didactical power and suitability for presentations in large lecture halls using both multimedia projections and audible signals. © 2008 American Association of Physics Teachers. [DOI: 10.1119/1.2815364]

I. INTRODUCTION

The historical debate on the particle versus wave interpretation of light is well known. The debate between Newton and Huygens seemed definitely settled in favor of the wave nature by the work of Young, Fresnel, Maxwell, Hertz, and others. The discussion was revived by Einstein’s interpretation of the photoelectric effect in terms of light being a stream of particles, later called photons. The wave and particle aspects were unified by Bohr and Heisenberg who introduced the concept of complementarity, which was later identified as a distinguishing characteristic of quantum mechanics: contradictory properties of a physical system, here particles and waves, are interpreted as complementary properties, and a complete description of the system is obtained only when considering both properties (duality). Later the wave-particle duality was given a simple interpretation by stating that light propagation is described by a quantum mechanical wave function with the same superposition and interference properties as a classical wave. The particle nature is revealed at the moment of detection when the wave function collapses. Put simply, light behaves as a wave when it propagates and like a particle when it is detected.

First year students can grasp the alternative manifestations of light as either particles or waves, depending on different experimental conditions, but usually have problems understanding the simultaneous existence of both properties. At this point lectures usually discuss a Gedanken experiment, in which we imagine classical two-beam interference with light waves so weak that at each moment there is only a single photon in the apparatus. However, there are no standard demonstrations that illustrate the simultaneous visualization of the wave and particle aspects of light.

Single particle interference experiments have been performed with massive particles such as electrons (for example, Ref. 1), neutrons (for example, Ref. 2), atoms and molecules (Ref. 3 and references therein) up to molecules as large as C_{60}F_{48}·4. Beautiful as these experiments are, they are not suitable for lecture demonstrations of wave-particle duality. This difficulty is often bypassed by presenting simulations. The web site of Physics 20005,6 provides an interactive applet which simulates the double slit experiment with single electrons together with a detailed discussion between students and teachers following the Socratic method.

Following earlier recordings of single photon interference by photographic plates2 and even the unaided eye,8 the Gedanken experiment we will discuss was realized as a practical demonstration experiment in 1996 using a video camera9 and in 2003 using a charge coupled device (CCD) camera.10 In both experiments the interference pattern from a double slit illuminated by a strongly attenuated red laser was recorded on a photon by photon basis. The attenuation was so strong that at each moment only a single photon was in the vicinity of the double slit. Each frame recorded by the camera shows an apparently random distribution of photons, illustrating the particle nature of light. After the integration of a sufficient number of frames, the classical wave interference pattern emerges. The German version of Physics 20009 shows a movie of this process recorded by the authors of Ref. 10. In the context of events related to the World Year of Physics (2005) one of us (A.W.) built an improved version of this experiment using light from a green laser pointer and a camera with a higher pixel resolution. Figure 1 shows a series of interference patterns recorded with this device.

The purpose of the work we report here is to propose a similar, but lower cost experiment which avoids the prohibitively high cost (=20 000 EUR) of the CCD camera.

II. PEDAGOGICAL IDEA AND METHODOLOGICAL ADVANTAGES

The main aim of the experiment is to give students a convincing demonstration of the dual nature of light. Classical demonstrations of the wave and particle nature of light are usually performed using two distinct experiments and students might get the impression that the two properties of
light (waves and particles) are mutually exclusive because they appear independently in different experiments. To eliminate this conceptual difficulty we have designed an apparatus in which the particle and wave aspects can first be demonstrated individually. Then the same apparatus is used to visualize the real-time evolution of individual quantum events to a classical wave pattern. The use of the same light source and the same interferometer is important to convince students that we can investigate the two aspects of light with the same apparatus.

Two-beam interference phenomena are often explained on the basis of Young’s double slit experiment by displaying the well known interference pattern on a distant screen. Although this example is well suited for a theoretical discussion and most easily realized using a laser pointer and a double slit, it is not practical for advanced demonstration experiments because it does not allow the variation of system parameters in a simple way. In the present experiment we have chosen a Mach-Zehnder interferometer in which a large spatial separation of the two interfering beams can be easily realized, permitting several manipulations, such as the adjustment of the path length difference and the relative angle of the interfering beams, and, most importantly, the easy blocking of one of the two beams. The macroscopic dimensions of the Mach-Zehnder interferometer allow the observer to see all components from the light source via the generation and recombination of the interfering beams up to their detection.

A green laser pointer was chosen as the light source because it has a sufficiently long coherence length for the easy alignment of the interferometer. The intensity of the green beam and its wavelength near the vicinity of the eye’s maximum sensitivity ensure that even expanded interference patterns are easily visible in a large auditorium.

Our main design criterion was to have the apparatus as simple and pedagogical as possible while also offering the flexibility to vary certain parameters to illustrate several aspects of the phenomena. The equipment is designed for demonstrations in a large auditorium. The interferometer is mounted on an aluminum plate tilted by 45°, so that all components can be easily seen. If necessary, a webcam can be used to project a close-up of the interferometer table. As mentioned, the expanded fringe pattern using the full laser intensity can easily be seen from a distance without additional tools. Individual photon events can be seen as pulses on an oscilloscope, or heard as clicks using audio equipment. All relevant electronic signals (photomultiplier pulses and photodiode signals) can easily be projected using equipment such as a digital oscilloscope equipped with a video port or a USB-based oscilloscope. Attention was paid to obtain stable pictures and good visibility of all the components and projected signals. Last but not least, we have made an effort to reduce component cost as much as possible, and to give the apparatus a pleasant look.

### III. EXPERIMENTAL SETUP

The scheme of the experimental apparatus is shown in Fig. 2 and a photo of its main components in Fig. 3. The light source is a 5 mW green (λ=537 nm) laser pointer. The batteries in the laser pointer were replaced by electrical contacts so that the laser could be driven by an external power supply. We found that the spectral width of the laser radiation and hence its coherence length depends on the operating voltage and a randomly chosen pointer has its own optimal voltage for the highest fringe contrast. Once set correctly and after a warm-up time of several minutes this voltage gives reproducible results on daily basis.

The standard Mach-Zehnder interferometer has two beam splitters and two mirrors (all 1 in. optics) arranged in a 18 ×18 cm² square (see Figs. 2 and 3). One of the mirrors is mounted on a low-voltage piezotransducer that allows the voltage-controlled variation of the path length difference (∼5 V per fringe).
Prior to entering the interferometer, the laser beam is split into two beams (beams 1 and 2) of equal intensity; one of the beams can be strongly attenuated by an (insertable) stack of neutral density filters. The two beams are then sent through the interferometer and form two interference patterns on sandblasted aluminum screens. Each screen has a small central aperture behind which a photodiode PD (strong beam) and a photomultiplier PM (weak beam) are placed. The screens are mounted on their corresponding detectors and each unit can be displaced in the transverse direction on a common optical rail. The photomultiplier is equipped with a narrow collimator C and interference filters IF so that it only detects light at the laser frequency in a small solid angle similar to the one described in Ref. 10. By coincidence the strong green spectral line of Hg is transmitted by the interference filters and care has to be taken when operating the photomultiplier in a room equipped with standard fluorescent lighting. When properly adjusted, the narrow solid angle seen by the photomultiplier collimator permits operation of the system without dimming the room lights.

The photomultiplier (Hamamatsu, model H5784) has an integrated high voltage supply and preamplifier, and requires only a low voltage external power supply and a potentiometer for controlling the high voltage applied to the tube. The output pulses produced by individual photons have a decay time of 20 \( \mu s \) and can be displayed by an oscilloscope or, after discrimination and pulse shaping, rendered acoustically by a loudspeaker.

IV. DEMONSTRATIONS OF THE WAVE AND PARTICLE NATURE OF LIGHT AND OF THEIR COMPLEMENTARITY

A. Seeing waves and hearing particles

The wave nature of light can be shown classically as the interference fringe pattern produced by the unattenuated beam 2 on the screen P2 (Fig. 2). Alternatively, we can apply a voltage ramp to the piezotransducer and show the time dependent photodiode signal revealing the sinusoidal intensity modulation (lower trace of Fig. 4). The large spatial separation of the beams easily convinces students that two beams are involved in the experiment. Both beams can be manipulated conveniently including blocking, attenuating, and rotating the polarization, changing the angle between the interfering beams. In the piezotransducer-scanning mode, for example, we easily show that by blocking one arm the interference disappears and the intensity recorded by the photodiode becomes one quarter of the maximum intensity observed in the fringe pattern. Another readily implemented demonstration is the dependence of the fringe spacing on the angle between the interfering beams.

The particle nature of light can be shown by recording the strongly attenuated beam with the photomultiplier while one of the Mach-Zehnder interferometer paths is blocked (see Fig. 2). The photomultiplier pulses can be displayed directly as an oscilloscope trace, or can, after electronic discrimination and pulse shaping, be transmitted to a loudspeaker, so that the detected single photons can be “seen” and “heard.” When hearing the photon stream older scientists are often
reminded of the (now less commonly demonstrated) sound from a Geiger counter; a good starting point for an excursion into counting statistics.

B. Hearing single photon interference

Our original idea\textsuperscript{11} was to move the two detectors simultaneously through the respective fringe patterns (P1 for the photomultiplier and P2 for the photodiode) which would yield an oscillating current from the photodiode and a periodic oscillation of the click rate from the photomultiplier. When the optical rail carrying the detectors is mounted on the same table as the interferometer, the unavoidable mechanical vibrations associated with the detector motion perturb the interferometer and induce an uncontrolled jitter of the fringe patterns. Thermal drifts of the path length difference yield additional complications. For this reason we have designed an active stabilization of the path length difference and hence of the fringe pattern with respect to the photodiode. An electronic feedback system uses the photodiode signal to control the length of the interferometer arm B using the piezotransducer-mounted mirror (Fig. 2). For this purpose the photodiode is placed at a point in the fringe pattern at which the light intensity is equal to half of its maximum value. The difference between the photodiode signal and a reference voltage (chosen to make the difference null) provides an error signal which, after proportional-integral amplification, is fed to the piezotransducer in a servo-loop. In this way the path length difference can be stabilized and the spatial position of the fringe pattern becomes locked to the photodiode. With the locked fringe pattern a displacement of the photodiode will induce a controllable displacement of both fringe patterns. By keeping the photomultiplier position fixed the photodiode motion moves the pattern P1 across the photomultiplier and the audience can hear a periodic change of the click rate. With a suitably adjusted intensity of the attenuated beam this periodic change manifests itself as a periodic modulation of the sound’s pitch. In parallel to the acoustic signals an oscilloscope trace showing the photomultiplier pulses can be displayed.

This experiment is well suited for accompanying a Socratic discussion with students about the nature of light, addressing questions such as the relation between the classical fringe pattern and the periodic modulation of the pulse/click rate, the rectilinear motion of photons, and the dependence/independence of the interfering entities. For this purpose we can use to advantage the Mach-Zehnder interferometer’s ability to alter the fringe period. The discussion can lead students to the conclusion that the photon possesses unusual, that is, nonclassical properties.

C. From particles to waves

The experiment in Sec. IV B illustrated the simultaneous appearance of wave and particle aspects which might trigger the students’ curiosity about how the two aspects can be combined into a unified picture. We now present an elegant and convincing experiment that shows the evolution from individual quantum events to classical wave interference phenomenon. For this purpose we create a periodic modulation of the light path difference in the two interferometer arms by applying a periodic voltage ramp to the piezotransducer. The signals from the strongly attenuated beam 1 and the full intensity beam 2 are displayed simultaneously as oscilloscope traces. The lower curve in Fig. 4 shows the sinusoidally modulated photodiode signal which represents the interference fringes; the uppermost signal of the figure shows the simultaneously recorded photomultiplier pulses. We see that the density of the photomultiplier pulses is larger in the vicinity of the points of constructive interference, and still displays the quantum nature of the signal. By using the averaging function of the oscilloscope (Tektronix, model TDS20000B), the photomultiplier signal can be integrated as represented by the consecutive traces shown in Fig. 4 (averaging time increasing from top to bottom). For increasing integration times the quantum nature of the individual events is gradually washed out, and we observe a continuous transition to a smooth sinusoidal intensity distribution. After 128 averages the individual quantum events can hardly be distinguished, and the interference pattern becomes identical to the classical pattern detected with the photodiode. In this way we show in real time the transition from a two-beam interference experiment with individual particles to the familiar two-wave interference fringes.

Alternatively, we can produce a similar sequence of pictures as in Fig. 4 by continuously raising the intensity of the weak beam entering the interferometer with a variable attenuator. Due to the finite bandwidth of the recording system,
the pile-up of the individual pulses will converge to a smooth trace. The remaining structure from the individual pulses is a good starting point for discussing the shot noise of the detected signal.

It is also worth mentioning that the photodiode signal is the current produced by a very large number of (conduction band) electrons that were each produced by a single photon via the internal photoelectric effect in the semiconductor forming the photodiode.

We have shown this experiment at conferences, exhibitions, and lectures and have received a unanimous opinion—not only from students—on its unambiguous, convincing and spectacular nature.

D. The photon interferes with itself

This experiment is well suited to accompany a discussion of quantum mechanical “which-way” experiments. The demonstration, whose result is astonishing for students, is realized in the following way. First the fringe pattern is locked to the photodiode as explained in Sec. IV B, and the photomultiplier is moved to a fringe minimum, characterized by a low photon count rate [see Fig. 5(a)] which can also be displayed acoustically. If now path A of beam 1 is blocked inside of the interferometer, it is possible to hear (and see) a distinct increase of the click rate [Fig. 5(b)]. This result demonstrates that if we give each photon the choice of taking either path A or path B, it has a low probability to appear at the detector. In contrast, if we force the photon to follow a specific path by blocking the other path, then its probability to arrive at the detector is much higher. The puzzling fact that a two path interference pattern is only a single photon in the interferometer. The two interference patterns are detected by a photodiode and a photomultiplier, respectively, whose signals can be displayed as oscilloscope traces. In addition, the pulses produced by individual photons in the photomultiplier can be rendered acoustically. Besides demonstrations of the classical two-beam interference in wave optics, the apparatus makes possible the demonstration of different effects associated with the particle nature of light. The most impressive demonstration is an experiment that shows interference fringes in terms of single photon events, which, after integration in a digital storage oscilloscope, can be seen to evolve in real time to the classical interference pattern.

The apparatus discussed in this paper can be used for other demonstrations of quantum effects involving single photons, such as delayed choice experiments. We only mention the possible realization of what is known as the “quantum eraser,” a do-it-yourself version of which has recently been proposed by Hillmer and Kwiat. By implementing orthogonal polarizers in the two paths of the attenuated Mach-Zehnder interferometer beams we can imprint a which-way label to each photon, thereby destroying the interference pattern. A suitably oriented additional polarizer subsequently put in front of the photomultiplier will erase the which-way information and restore the interference phenomenon. In contrast to the strong light demonstration in Ref. 14 our apparatus will demonstrate the quantum nature of the erasing process on a photon by photon basis.

V. SUMMARY AND OUTLOOK

We have developed a lecture demonstration based on a Mach-Zehnder interferometer which makes possible different presentations related to the wave-particle duality of light. The interferometer operates simultaneously with two interfering beams from a strong laser beam and two interfering beams from the same laser, so weak that at each instant there is only a single photon in the interferometer. The two interference patterns are detected by a photodiode and a photomultiplier, respectively, whose signals can be displayed as oscilloscope traces. In addition, the pulses produced by individual photons in the photomultiplier can be rendered acoustically. Besides demonstrations of the classical two-beam interference in wave optics, the apparatus makes possible the demonstration of different effects associated with the particle nature of light. The most impressive demonstration is an experiment that shows interference fringes in terms of single photon events, which, after integration in a digital storage oscilloscope, can be seen to evolve in real time to the classical interference pattern.

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1 Electronic mail: antoine.weis@unifr.ch
7 The German translation of Ref. 5 is at (www.unifr.ch/physics/P2K/) and (www.iap.uni-bonn.de/P2K/).
11 A. Weis and R. Wynands, “Three demonstration experiments on the wave and particle nature of light,” Phys. und Didaktik in Schule und Hoch-
Diamond Jar. The diamond jar adds some drama to the process of charging up a Leiden jar. The tinfoil inner and outer coatings of the jar are made up of diamonds with small spaces between their points. As the jar is charged, sparks jump between the points of the diamonds. The device is also called a Spangled Jar. This example is at Case Western Reserve University. (Photograph and Notes by Thomas B. Greenslade, Jr., Kenyon College)
Lecture demonstrations of interference and quantum erasing with single photons

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Abstract

Single-photon interference is a beautiful manifestation of the wave–particle duality of light and the double-slit Gedankenexperiment is a standard lecture example for introducing quantum mechanical reality. Interference arises only if each photon can follow several (classical) paths from the source to the detector, and if one does not have the possibility to determine which specific path the photon has taken. Attaching a specific label to the photon traveling along a specific path destroys the interference. However, in some cases those labels can be erased from the photon between leaving the apparatus and being detected, by which interference can be restored, a phenomenon called quantum erasing. We present lecture demonstration experiments that illustrate the wave–particle duality of light and the phenomenon of quantum erasing. Both experiments are first shown with strong light and, in a second step, on a photon-by-photon basis. The smooth transition from the quantum to the classical case can be shown in real time by varying the incident light intensity.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

Wave–particle duality is a main feature of quantum mechanical concepts, offering a unified picture of seemingly contradictory classical representations of reality. Its most convincing manifestation is the phenomenon of single-photon interference. In recent years, the authors have developed two lecture demonstration experiments of single-photon interference: double-slit interference with detection by a single-photon CCD camera [1, 3] and two-path interference in a Mach–Zehnder interferometer (MZI) with photomultiplier detection [2, 3]. Both demonstrations show the simultaneous existence of wave properties and of particle properties of light. This illustrates that those complementary properties do not depend on the nature of the performed experiment, but are inherent properties of a quantum system.

In addition, the outcome of a quantum mechanical experiment may depend on how and when something is measured, and there is an inextricable link between information (the knowledge we have) of the investigated system and its real physical state. In the words of Paul Kwiat [4]: ‘Quantum information, in the end, describes not only what can be known, but the subtle effect that knowing has on nature.’ The ‘classical’ experiment that addresses this issue is the quantum eraser, proposed by Scully and Drühl [5] in 1982, and further refined in different realizations [6].

The experiments presented here are based on a two-path MZI, which is well suited to demonstrating quantum interference [2, 3, 7] and single-photon quantum erasing.

In the most widely accepted Copenhagen interpretation of quantum mechanics, the photon in the apparatus is described by a delocalized probability wave that evolves along the two classical trajectories. Interference arises as a consequence of the phase difference accumulated by the two coherent trajectories. Interference arises as a consequence of the phase difference accumulated by the two coherent trajectories. Interference arises as a consequence of the phase difference accumulated by the two coherent trajectories. The wavefunction description allows one to make only probabilistic statements of the photon’s state inside of the apparatus, whereas in the de Broglie–Bohm picture [8] the photon takes a well-defined path while being guided by a quantum mechanical pilot wave that follows both paths, thereby determining the interference. It is well known that any experimental feature (labeling mechanism) that would allow the determination of the photon path
inevitably destroys the coherence of the probability wave, and hence interference. In some cases, however, it is possible to erase that which-way information after the photon has left the apparatus, thereby restoring interference, a phenomenon called quantum erasing.

A simple way of marking the possible paths in the MZI is the insertion of orthogonally oriented linear polarizers in the two interferometer arms. As a consequence the interference pattern disappears. In practice, the erasing of the which-way information is realized by inserting before the (detecting) screen a third polarizer oriented at ±45°, called the ‘eraser’. This erasing polarizer destroys the which-way information imposed by polarization labels and makes the interference reappear, a phenomenon that, when observed on a photon-by-photon basis, is a manifestation of quantum erasing. In terms of classical wave superposition the phenomenon is readily understood, but its understanding at the single-photon level presents some difficulties for students.

From a didactical point of view, it is a nice example for introducing the concept of entanglement: while being in the interferometer the external degree of freedom (path) of each photon’s wavefunction is entangled with its internal degree of freedom (polarization). Although quantum erasing is even more puzzling in a version using entangled photon pairs, we believe that single-photon quantum erasing is most suited for a lecture introduction of the phenomenon.

Recently, we have extended our lecture demonstration experiment on the wave–particle duality of light for demonstrating the phenomenon of quantum erasing with single photons.

2. Single-photon interference

In our previous work [3] we have presented lecture demonstration experiments that show the wave–particle duality with quantum (single-photon) interference. The motivation for the elaboration of this experiment was to show in a single experiment the wave and the particle properties of light and to demonstrate the coexistence of these two contradictory aspects of light. We now use a simplified version (shown in figure 1) of the apparatus described in [3] that has only a single beam traversing an MZI. The light source is a 5 mW green laser module with a wavelength close to the maximum of the eye’s spectral sensitivity. As discussed in [3, 7] the use of an MZI rather than a double-slit presents some methodological and didactical advantages for demonstrating quantum interference. Its spatially well-separated beams facilitate light manipulations in the two paths.

Conventionally, the wave nature of light is presented by projecting the interference pattern on a screen (projection mode). Alternatively, one may displace one of the MZI mirrors by a piezotransducer (figure 1, left) controlled by a periodic linear voltage ramp (scanning mode). In this way the difference between the optical paths of the two arms of the interferometer undergoes a periodic linear change whose effect can be detected as a modulation of the light intensity recorded by a photodiode with a small entrance aperture. The interference pattern is represented via the sinusoidal variation of the photocurrent displayed by an oscilloscope.

For the single-photon experiments (figure 1, right), we insert strongly attenuating filters as well as a filter of variable transmission before the entrance of MZI. A single-photon detecting photomultiplier equipped with a collimator and filters that strongly suppress stray light allow the demonstration to be performed in an ambient light environment. The photomultiplier pulses are sent to an oscilloscope and to a loudspeaker so that single-photon events can be both seen and heard.

Strong light interference is first shown as oscilloscope fringes from the photodiode in the scanning mode (lower trace of figure 2). After insertion of the attenuating filters, single-photon interference is shown in the same way using the photomultiplier signal. The top three traces of figure 2 show the photomultiplier signals in a single sweep of the piezo and after multiple averages of subsequent sweeps.

In the top trace individual photons are seen as pulses on an oscilloscope time trace. While the individual pulses represent particle nature, their (temporal) density is a measure of light intensity. When the number of averaged traces is increased, individual pulses pile up and a periodic modulation of the pulse density appears. This modulation becomes smoother and smoother and approaches the photodiode signal asymptotically as more and more traces are added. In this way one sees how classical wave interference emerges gradually from single-particle interference events, convincing evidence for the wave–particle duality of light.

A most spectacular demonstration consists in adjusting the interferometer (in photon projection mode) such that

![Figure 1. Experimental setup. Left: classical interference with strong laser light in scanning mode with photodiode detection (M: mirror; BS: beam splitter; C/F: collimator–filter box). Right: single-photon interference with photomultiplier detection (BF: attenuating filter).](image-url)
Figure 2. From single-photon interference (top) to wave interference (bottom). The classical interference pattern emerges when many single-photon traces are averaged.

the photomultiplier is located in an interference minimum characterized by a very low click rate of the loudspeaker signal. When one of the paths of the MZI is then blocked by insertion of a large cardboard, the click rate increases in a dramatic way, thereby demonstrating that indeed each photon interferes with itself (according to the Copenhagen interpretation).

3. Quantum erasing

For labeling of the which-path information required in the demonstration of quantum erasing, orthogonal linear polarizers P1 and P2 are inserted in the two paths as shown in figure 3. The experiment would be ideally performed with unpolarized light. However, since laser light is always strongly (albeit not perfectly) polarized we insert a prepolarizer oriented at ±45° with respect to the horizontal. The erasing polarizer P3, mounted on a rotation stage, is inserted at one of the exits of MZI. This arrangement allows the demonstration of quantum erasing both with classical waves (strong light) and with single photons in a strongly attenuated beam. We use both exits of the interferometer. The erasing of the labels is performed on one of them, while the labeling effect remains visible on the second exit throughout the experiment (figure 3).

We begin the demonstration by showing quantum erasing with strong light. The path labeling by the polarizer destroys the interference, which is well seen by screen projection. After insertion of the eraser oriented at +45° or −45° the interference pattern reappears with full contrast (figure 4, top), although its overall intensity is reduced by a factor of 2. By rotating the erasing polarizer away from the ±45° orientation, the contrast is reduced and disappears completely at 0° (figure 4, top) and 90°, in which case only light from one of the paths reaches the detector. This wave erasing phenomenon can be easily explained by classical wave mechanics which yields for the intensity on the screen

\[ I = \frac{I_0}{4} (1 - \cos \Delta \phi \sin 2\alpha), \]

where \( \alpha \) is the angle of the eraser’s axis with respect to the horizontal and \( \phi \) is the phase difference of the interfering beams, which is proportional to the coordinate of the fringe position on the screen.

Wave erasing can also be shown in scanning mode. Without labeling polarizers in the MZI, one sees a sinusoidal

Figure 3. Top: wave erasing with strong light. Bottom: quantum erasing with single photons.

Figure 4. Top line: wave erasing in screen projection mode. Middle line: quantum erasing with photons, recorded as a single oscilloscope trace of the photomultiplier pulses. Bottom line: averaged oscilloscope traces.
fringe pattern on the oscilloscope. When the prealigned polarizers $P1$ and $P2$ are inserted, the interference disappears and the oscilloscope displays a flat trace without structure. After inserting the erasing polarizer, one sees the restored interference pattern for the $\pm 45^\circ$ orientations, and one can show the change of contrast when the eraser is rotated away from those orientations.

The demonstration of quantum erasing on the photon-by-photon basis is done in the scanning mode with strongly attenuated light, in the same way as in the wave–particle demonstration described above.

After having shown that single-photon interference with no inserted polarizers yields a sinusoidally modulated pulse density (as in figure 2), one readily shows that the interference is made to disappear by insertion of the orthogonal polarizers $P1$ and $P2$, as is evidenced by a uniform density distribution of photon pulses. Like in the classical case, the insertion of the erasing polarizer oriented at $\pm 45^\circ$ makes the modulation (interference) reappear with decreasing contrast as the eraser orientation is rotated away from $\pm 45^\circ$ (figure 4, middle line).

In all demonstrations one first shows a single trace and then subsequently averaged traces (figure 4, bottom line) to make the contrast of the interference structure apparent. The disappearance of the contrast in the extreme cases of $0^\circ$ and $90^\circ$ orientation of the eraser is trivial in the sense that only light from one of the labeled paths reaches the detector in those configurations, which yields a (trivial) full knowledge of the which-way information. The increase of the contrast observed from rotating the eraser away from $0^\circ$ or $90^\circ$ can be interpreted as the gradual disappearance of the which-way information.

4. Summary

We have presented two novel lecture demonstration experiments for the wave–particle duality of light and for the phenomenon of quantum erasing. The experimental setup allows demonstrations both with strong laser light (by screen projection or by photodiode detection) and on a photon-by-photon basis (photomultiplier detection). The wave–particle duality is shown on the basis of single-photon interference in an MZI. The which-way information in the quantum erasing experiment is applied by orthogonal linear polarizers in the two arms of the interferometer. The erasing tool is a rotatable linear polarized, placed after the exit of the interferometer.

The experiments are well suited to accompanying introductory lectures in quantum mechanics for which demonstration experiments are generally scarce. By their impressive visualizations these demonstrations help the students develop a better feeling for specific features of quantum mechanics, such as wave–particle duality, superposition and delocalization of quantum states, which-way measurements, entanglement and quantum information.

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Single photon quantum erasing: a demonstration experiment

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Abstract
In the conventional interpretation of quantum mechanics the interference of particles in a two-beam interferometer is closely related to the problem of which-way information. One of the mysteries of quantum mechanics relies on the assumption that the wavefunction of each photon propagates simultaneously along both classically allowed paths, and that interference arises as a consequence of the indistinguishability of those paths. Any attempt to obtain which-way information by putting individual labels on the photons in each pathway inevitably destroys interference. However, even in cases in which the photons carry which-way labels, it is possible to erase those labels after the particle has left the interferometer. The erasing process (partly or completely) destroys the which-way information, and thereby restores interference. This phenomenon is known as quantum erasing. Here we present a lecture demonstration experiment of quantum erasing based on a Mach–Zehnder interferometer operated with single photons.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In introductory quantum mechanics, university students are faced with abstract novel concepts such as quantum mechanical states represented by state vectors, state superposition, coherence, interference and entanglement, to name just a few. The students learn basic mathematical rules to transform those entities and to describe their evolution in space and time. From earlier classes on classical physics, students are used to seeing physical phenomena visualized by lecture demonstration experiments or in student laboratories. They often experience difficulties with the abstract world of quantum mechanics, in which demonstration experiments are scarce. Since quantum mechanics is mainly applied to describe the phenomena at the
atomic and sub-atomic scale, students may erroneously believe that there are no convincing demonstrations of quantum effects in macroscopic setups. Superfluidity and superconductivity are well-known counter-examples that show quantum behaviour at the macroscopic scale. The single photon interference experiments presented here are another beautiful way to discuss macroscopic quantum phenomena. The discussion of quantum interference in Young’s double slit experiment is a standard topic in any introductory quantum mechanics lecture. However, due to the small separation of the slits, the spatial separation of the interfering beams is hardly visible by the unaided eye. This difficulty can be circumvented by the use of a two-beam interferometer, such as the Mach–Zehnder interferometer (MZI), which allows realizing table-size beam separations and interference of quantum states. The specific didactical advantages of such interferometers were addressed before [1, 2].

In a recent publication [2] we have described a MZI-based lecture demonstration experiment of single-photon interference which illustrates the wave–particle duality of light by demonstrating the transition from the particle aspect of light to its wave aspect. The experiment also demonstrates in a convincing way that each photon ‘interferes with itself’ (phrasing of Dirac [3]). In the present paper we describe an extension of the latter apparatus for demonstrating the intriguing phenomenon of single-photon quantum erasing.

2. Interference of polarized waves and wave erasing

We start by discussing the interference of classical waves in the two-beam Mach–Zehnder interferometer shown in figure 1(a). A first beamsplitter separates a monochromatic wave of intensity $I_0$ into two coherent waves which are recombined by a second beamsplitter after having propagated along different paths. Two pairs of beams emerge from the interferometer at the exit ports $A_+$ and $A_-$. The two beams in each exit port interfere in a constructive or destructive manner depending on the relative phase $\Delta \phi$ that they have accumulated during their propagation through the interferometer. If the interfering beams propagate along the same direction, the (complementary) intensities emerging at $A_+$ and $A_-$ are given by

$$I_\pm(\Delta \phi) = \frac{I_0}{2}(1 \pm \cos \Delta \phi). (1)$$

The relative phase $\Delta \phi$ of the interfering beams is determined by the difference of the path lengths they travel, which can be controlled by translating the upper-left mirror with the help of a piezoelectric transducer (PZT).
In practice one adjusts the interferometer such that the interfering beams propagate along slightly different directions, in which case the uniform transverse intensity distribution of the emerging light changes into a system of equidistant bright and dark fringes. The number of fringes is proportional to the angle formed by the interfering beams. The intensity at each position in the fringe pattern varies periodically with $\Delta \varphi$, according to (1) with a position-dependent phase offset. As a consequence the fringe pattern moves uniformly in its transverse direction when $\Delta \varphi$ is varied by applying a linear voltage ramp to the piezo.

If one inserts orthogonal linear polarizers (horizontal and vertical, respectively) in the two paths of the MZI in figure 1(b), the fringe patterns at both exit ports become homogeneous spots, each of intensity $I_0/4$. Since orthogonally polarized beams do not interfere, the spot intensities represent the incoherent sum of the intensities of the individual beams, each beam losing half of its intensity at each beam splitter and at the polarizer. Interference can be restored by the insertion of a third polarizer (eraser) after one of the exits, which yields the fringe pattern (derived in appendix A),

$$I_\pm(\Delta \varphi, \alpha) = \frac{I_0}{8}(1 \pm \sin 2\alpha \cos \Delta \varphi),$$

(2)

where $\alpha$ is the orientation of the eraser with respect to the horizontal. For reasons that will become evident in the following section the polarizer at the exit is called the ‘eraser’, and we speak of classical erasing when referring to the restoration of interference by that polarizer. Figure 2 shows a contour plot diagram of equation (2), in which the cuts indicated by the dashed lines correspond to the eraser settings used in figure 5.

The erasing phenomenon with classical waves can be readily understood: two orthogonally polarized beams cannot interfere and, hence, produce no fringes. When the erasing polarizer is inserted with an orientation that differs from the horizontal ($\alpha = 0^\circ$) or the $\Delta \varphi$.

\footnote{The factor $I_0/8$ in equation (2) is only valid when the incident light is either unpolarized or polarized at 45° with respect to the horizontal.}
vertical ($\alpha = \pm 90^\circ$), the optical fields of both beams have interfering polarization components along the eraser direction, and can thus interfere. The (signed) fringe visibility $V_\pm$ given by

$$V_\pm = \frac{I_\pm(0, \alpha) - I_\pm(\pi, \alpha)}{I_\pm(0, \alpha) + I_\pm(\pi, \alpha)} = \pm \sin 2\alpha$$

becomes maximal for $\alpha = \pm 45^\circ$. It is complementary at the two outputs and changes sign for $\alpha \to -\alpha$.

Hillmer and Kwiat [4] have presented a do-it-yourself realization of the wave-erasing phenomenon using diffraction of an (unattenuated) beam from a laser pointer by a thin wire. When the partial waves passing on either side of the wire are marked by orthogonal polarizers, the diffraction, i.e. interference pattern, disappears. The interference can be restored with maximal contrast when a polarizer oriented at $\pm 45^\circ$ is inserted in the far field. Although the experiment is presented with strong light only (wave erasing), [4] contains a valuable discussion of the underlying quantum mechanical aspects (quantum erasing) addressed below.

### 3. Single photon interference

The discussion of the erasing phenomenon at a single particle level (quantum erasing) is more intriguing, since it is related to the quantum mechanical question of which-way information. Let us first consider the case in which a single photon traverses the MZI of figure 1(a). The photon’s wavefunction is coherently split by the first beamsplitter and evolves along both classical paths. The wavefunction of the photon inside the interferometer is described by

$$|\Psi_{\text{inside}}\rangle = r|1\rangle e^{i\Delta \varphi} + t|2\rangle,$$

where the state vectors $|1\rangle$ and $|2\rangle$ refer to the two paths, and $\Delta \varphi$ is the phase difference introduced above. The factors $r$ and $t$ are the amplitude reflection and transmission coefficients imposed by the first beamsplitter. The second beamsplitter further splits the wavefunction into four components, so that the wavefunction of the photon exiting the interferometer is given by

$$|\Psi_{\text{out}}\rangle = r^2|-\rangle e^{i\Delta \varphi} + t r |+\rangle e^{i\Delta \varphi} + r^2 |-\rangle + r t |+\rangle,$$

where the state vectors $|\pm\rangle$ refer to the propagation directions in the output ports $A_{\pm}$. The probabilities $w_+$ and $w_-$ for detecting the photon at either $A_+$ or $A_-$ are then given by

$$w_{\pm} = |\langle \pm |\Psi_{\text{out}}\rangle|^2 = \frac{1}{2}(1 \pm \cos \Delta \varphi),$$

which agree with the intensities (1) derived for wave interference. The amplitude transmission and reflection coefficients are $t = 1/\sqrt{2}$ and $r = i/\sqrt{2}$, respectively.

The number of photons per second detected at each output is given by $R_{\pm} = R_0 w_{\pm}$, where $R_0$ is the rate of photons (number of photons per second) entering the interferometer. The single photon events can be rendered visually (showing pulses from a single photon detector on an oscilloscope) or acoustically (transforming the single photon detector pulses to clicks rendered by a loudspeaker). Quantum interference of individual photons can thus be visualized [2] as a periodic modulation of the single photon event rate (average frequency of pulses or clicks) when $\Delta \varphi$ is varied. The ‘weirdness’ of single photon interference lies in the fact that each photon behaves differently when both paths are open and when one path is blocked, as discussed in [2].

### 4. Quantum erasing

Single photon interference is a consequence of the indistinguishability of the interfering paths shown in figure 3(a). Any attempt to obtain which-way information leads unavoidably to
the destruction of interference. Classical gedanken experiments for obtaining which-way information have considered the detection of a ‘trace’ left by the photon in each path, such as the recoil of one of the path direction changing elements (mirror, double slit) or the interaction of the photon with an atom placed near one of the paths. An alternative way to obtain which-way information after the photon has left the interferometer is the application of path-specific labels on the photons in each path. This is represented in figure 3(b), where the photons in each path are symbolically labelled by a specific colour. By inserting a specific (‘blue’ or ‘red’) colour filter into the recombined beam, one can, in principle, gain a posteriori knowledge on the path taken by the photon. As a consequence, no interference will be observed on the projection screen. It is not necessary to actually insert the label-identifying filter to see the interference disappear. The mere fact that which-way information is carried by the photons suffices to destroy interference.

In some circumstances, however, it is possible to wipe out the specific path labels by a suitable device (shown symbolically as a colour eraser in figure 3(c)), so that the photon no longer carries which-way information. In that case interference will be restored with full contrast. In our experiment we have opted for a labelling by mutually orthogonal (horizontal \( H \) and vertical \( V \)) linear polarizers (figure 3(d)). The erasing element in that case is a suitably oriented linear polarizer inserted after the interferometer. Since the information erasing is done on individual light quanta, the process is called quantum erasing. The quantum eraser setup is identical to the wave erasing setup shown in figure 1(b) and discussed in section 2.

The quantum mechanical treatment of the single photon quantum-erasing experiment involves the delocalized wavefunction of the photon. As shown in appendix B, the wavefunction of the photon in the interferometer after having passed the \( H \) and \( V \) polarizers is given by

\[
|\Psi_{\text{after } H/V}\rangle = \frac{1}{\sqrt{2}} (r|1\rangle|H\rangle e^{i\Delta \psi} + t|2\rangle|V\rangle).
\]  

This wavefunction represents a single particle entangled state in which the photon’s internal degree of freedom (polarization) is entangled with its external degree of freedom (direction

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\( ^3 \) The labels ‘red’ and ‘blue’ chosen here are to be understood as symbolic labels. However, one might think of a quantum eraser variant in which the light frequencies in both arms are shifted to the blue and red, respectively (for instance by acousto-optic modulators), and where a tunable mixer would serve as eraser.
of propagation). As shown in appendix B, the eraser action on this state after it has left the interferometer yields the photon detection probabilities

\[ w_{\pm} = \frac{1}{4} (1 \pm \cos \Delta \phi \sin 2\alpha), \tag{8} \]

which are identical to the corresponding expression (2) for the intensities of classical waves.

We draw the reader’s attention to further useful discussions [4, 5] of the relation between quantum interference and which-way measurements.

5. Experimental setup

Figure 4 shows a photograph of the Mach–Zehnder interferometer that we use to demonstrate quantum erasing. It is similar to the apparatus that we used previously to demonstrate the wave–particle duality [2]. The beam from a green laser module (\( \lambda = 532 \text{ nm}, 5 \text{ mW} \)) is directed to the interferometer. Prior to entering the interferometer, the intensity of the laser beam can be attenuated by an insertable blocking filter (BF) with an optical density of 4–5. A variable filter (not shown in the photograph) placed after BF allows a smooth variation of the light intensity by a factor of 100.

The particular laser used for the experiment emits two modes (intensity ratio 5:1) spaced by typically 30 GHz, giving the beam an overall coherence length of 1 cm, more than the path length difference \( \Delta L \) of the two interfering beams. The coherence length associated with each mode was approximately 40 cm, which corresponds to the MZI dimensions. The quantum interference experiments can be performed under conditions where the average spatial separation of consecutive photons is larger than the individual photon’s coherence length, thereby assuring that there is, at each moment, only a single photon in the apparatus.

The Mach–Zehnder interferometer consists of two (non-polarizing) 50/50 beam splitters (BS) and two mirrors (M). One of the mirrors is mounted on a PZT by which the path length difference \( \Delta L \) of the two interfering beams, and hence \( \Delta \phi \), can be varied. At the
exits of the MZI, the interfering beams are expanded by lenses (L) and projected onto metal discs for visualizing the interference patterns. Both projection screens have small central apertures, behind which a photodiode and a photomultiplier are mounted, respectively. The photomultiplier is equipped with two interference filters and a set of narrow collimating apertures that suppress ambient light at a sufficiently low level for permitting demonstrations with single photons in a fully lit environment [2]. The labelling polarizers (P1 and P2) are mounted in rotation stages and are oriented horizontally and vertically, respectively. In order to ensure a maximal contrast, a pre-polarizer (PP) oriented at 45° with respect to the horizontal is inserted before the MZI. The erasing polarizer (eraser), also mounted on a rotation stage, can be inserted at one of the exit ports of the MZI.

The MZI can be operated in two modes. With strong light we use projection on the screens for demonstrations to small groups of students, or wall projection for large auditorium presentations. In the scanning mode of operation we display the signals of the photomultiplier (or photodiode) on an oscilloscope while scanning the path length difference through a linear voltage ramp applied to the PZT. In an auditorium the oscilloscope traces can be shown by means of a multimedia projector.

6. Demonstration experiments

Prior to demonstrating the quantum-erasing phenomenon, it is necessary to present the main features of Mach–Zehnder interferometry with waves and photons introduced above. For this purpose one removes the BF, the polarizers P1, P2 and the eraser. Once the students are acquainted with the projection and scanning modes, the quantum-erasing demonstration can be shown. When inserting the (pre-aligned) orthogonal polarizers P1 and P2 the projected patterns are seen as light spots with a uniform intensity distribution which show no interference fringes. The lost interference is recovered when the eraser is inserted after one of the exit ports of the MZI. First, wave erasing with strong light is demonstrated. When the eraser is pre-oriented to \( \alpha = +45° \) or \( \alpha = -45° \) the projected fringe pattern reappears with maximal contrast. The photograph in figure 4 shows simultaneously the uniform pattern of the unerased exit port (centre, top) and of the erased beam (right). The degree of erasing can be varied by changing the eraser orientation. Typical results are shown in figure 5 both in projection mode and in scanning mode. The fringe contrast is seen to vary smoothly as the eraser orientation \( \alpha \), measured with respect to the horizontal plane, is varied. Interference disappears for the trivial cases of \( \alpha = 0° \) (and \( \alpha = 90° \), not shown) and becomes maximal for \( \alpha = \pm 45° \). The contrast variation obeys the \( \alpha \)-dependence given by (1). In particular, the inversion of dark and bright fringes when going from \( \alpha \) to \(-\alpha\) (figure 2) can be observed in figure 5. The slight shift of the fringes in the series is due to thermal drifts of the interferometer during recordings with different settings of \( \alpha \).

After insertion of the BF quantum erasing can be shown to occur in single photon events. The experiments are performed in the scanning mode, and the results are shown in columns 3 and 4 of figure 5. The interferograms in column 3 represent recordings of single time traces, in which the pulses produced by individual photons can be distinguished. In the cases of maximum contrast (\( \alpha = \pm 45° \)) one clearly recognizes a modulation of the photon pulse density that is correlated with the strong light fringe patterns of columns 1 and 2. The contrast of the recordings for \( \alpha = \pm 15° \) is weaker and the signal modulation is difficult to see in the single-shot time traces. However, when several scans are averaged with the help of a digital oscilloscope (column 4), one clearly observes the reduced contrast for \( \alpha = \pm 15° \), and the absence of fringes for \( \alpha = 0° \).
Columns 1 and 2 show the erasing phenomenon with classical waves, while column 3 shows the phenomenon of quantum erasing with single photons. The time-averaged data in column 4 represent an intermediate case, in which both the wave aspect (sinusoidal modulation) and the particle aspect (granularity of the signal) of erasing are visible.
A similar quantum-erasing experiment using a MZI was presented by Schneider and LaPuma [5]. The experiment used a fixed path length difference $\Delta L$ and low light level signals were recorded with a consumer-grade CCD camera. In that experiment the average photon number in the interferometer was $10^{-2}$. However, the CCD camera did not permit them to show the results on a photon-by-photon basis. In our experiment, the trivial, albeit powerful use of the piezo-driven mirror, together with photomultiplier detection permits the demonstration of quantum erasing with single particle detection via the rapid scanning between constructive and destructive interference.

7. Summary and discussion

We have presented a lecture demonstration experiment for the phenomenon of quantum erasing based on two-path interference in a Mach–Zehnder interferometer. A preliminary account of the present results was presented in [6]. When which-way labelling information is imposed by orthogonal linear polarizers in the two paths, interference disappears at both interferometer exits. Interference with a very high visibility is recovered when the exiting light is made to pass an erasing polarizer oriented along the bisectrix of the labelling polarizers.

The apparatus allows a demonstration of several features of the erasing process both with strong light and with single photons. While the erasing phenomenon is readily understood when the light is treated as a classical wave, a lecture demonstration of quantum erasing with single photons is well suited to introduce and discuss various aspects of quantum mechanics, such as the wave–particle duality, since the apparatus produces a real-time demonstration of the gradual build-up of a smooth (wave) interference pattern from superposed single photon events. The apparatus is also well suited—and probably represents the simplest way—to introduce the fundamental concept of (single particle) entanglement, described by (7).

As discussed by Kwiat and Englert [7] the role of the erasing polarizer is to partition the photons from the MZI in two subsets: transmitted photons and blocked photons. For any two orthogonal orientations $(\alpha, \alpha + \pi/2)$ of the eraser at a given exit port, the resulting fringe patterns are therefore shifted by half a period. This can also be seen from (2) and (8), which imply that $I_{\pm}(\Delta \varphi, \alpha + \pi/2) = I_{\mp}(\Delta \varphi, \alpha)$. The patterns are thus complementary and the sum of their intensity distributions produces patterns with no fringes. A similar property is seen when comparing the fringe patterns at both exit ports after erasers with identical orientations. Here too the patterns are complementary, as implied by the $\pm$ sign in (2) and (8), and the fringes add to a homogeneous pattern.

The dual nature of light is reflected in the fact that perfect fringe visibility (wave nature) and full which-way information (particle nature) are mutually exclusive. The former is obtained for $\alpha = \pm 45^\circ$ and $\alpha = -45^\circ$, while the latter occurs for $\alpha = 0^\circ$ or $90^\circ$. Any eraser orientation that differs from those four values relaxes on both aspects, and it was shown (e.g. by Englert [8]) that the degree of fringe visibility and the degree of which-way information obey an inequality. The visibility of the fully erased single photon interferograms (rightmost traces for $\alpha = \pm 45^\circ$ in figure 5) does not reach 100% because of background photons and interferometer drifts during signal averaging. Improving our apparatus from a demonstration device to a research grade device should allow a quantitative study [8] of the wave–particle duality as reported by Schwindt and co-workers [9].

One of the strange aspects of quantum erasing is the fact that the choice (via the orientation of the eraser) of whether one wants to observe wave-like properties (via interference) or particle-like properties (via which-way information) can be taken after the photon has left the interferometer. Unfortunately, the random time distribution of individual photons does not allow one to know the instant at which the photon leaves (enters) the interferometer. However,
by using a sufficiently fast polarization switching device at a sufficiently large distance after the MZI, one can always ascertain that the photon will have left the interferometer at the moment of decision taking. For this one would only count photons during a sufficiently short time interval following the setting of the eraser. This timing difficulty can also be circumvented in more elaborate experiments that use entangled photon pairs produced by parametric downconversion (as discussed, e.g., by Herzog et al [10]). By measuring photon correlations it is then even possible to decide whether to read out or to erase the which-way information after the actual detection of the photon [11].

The concept of erasing which-path information was coined by Scully and Drühl [12] in 1982 and quantum erasing has since been studied in many experiments using mainly entangled photon pairs4. The experiment presented here shows quantum erasing in its simplest form—using single photon entangled states—in a way that is adapted to lecture hall demonstrations.

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Appendix A. Derivation of equation (2)

The wave erasing expression in equation (2) can be most easily derived using the Jones vector formalism, in which two component vectors (spinors) $\Psi$ describe the state of polarization of the light. The basis vectors are chosen to be the horizontally and vertically polarized waves. The optical field of the laser beam after the prepolarizer oriented at 45° is given by

$$\Psi_0 = \frac{E_0}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}. \quad (A.1)$$

The BS split each incident beam into a reflected and a transmitted beam of equal intensity. The effect of an ideal beam splitter is described by multiplying the incident spinor by the amplitude reflection and transmission factors [14]:

$$r = \frac{i}{\sqrt{2}} \quad \text{and} \quad t = \frac{1}{\sqrt{2}}, \quad (A.2)$$

which follow from the Fresnel laws. Figure A1 shows the amplitudes of the optical fields at different positions along the possible paths 1 and 2.

The horizontal and vertical polarizers are described by the matrices

$$M_H = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad \text{and} \quad M_V = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \quad (A.3)$$

respectively. The erasing polarizer is oriented at an angle $\alpha$ with respect to the horizontal, so that its matrix is given by

$$M_\alpha = R^{-1}(\alpha)M_H R(\alpha) = \begin{pmatrix} \cos^2 \alpha & \sin \alpha \cos \alpha \\ \sin \alpha \cos \alpha & \sin^2 \alpha \end{pmatrix}, \quad (A.4)$$

where

$$R(\alpha) = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \quad (A.5)$$

is the rotation matrix in two dimensions.

4 A discussion of various undergraduate experiments using entangled photon pairs is given, e.g., by Galvez et al [13].
Each beam in the interferometer acquires a spatial phase $e^{i\phi_i}$ with

$$\phi_1 = 2\pi \frac{L_1}{\lambda} + \delta \phi$$

and

$$\phi_2 = 2\pi \frac{L_2}{\lambda},$$

where $L_i$ are the lengths of the paths ($i = 1, 2$) travelled by each beam, and

$$\delta \phi = 2\pi \frac{\Delta L}{\lambda} = \beta V,$$

is the additional (voltage controlled) phase shift due to the piezo-controlled displacement of the mirror, $V$ being the voltage applied to the piezo. In order to simplify the mathematical expressions in figure A1, we have omitted those phase factors and write them only in the final expressions at the exit ports.

The intensity $I_-$ at the (erased) exit $A_-$ is given by squaring the sum of the amplitudes shown in figure 5, which yields, after some algebra

$$I_- = |\Psi_{A,-1} + \Psi_{A,-2}|^2 = \frac{I_0}{8}(1 - \cos \Delta \phi \sin 2\alpha),$$

where

$$\Delta \phi = 2\pi \frac{L_1 - L_2}{\lambda} + \delta \phi \equiv \Delta \phi_0 + \beta V.$$

Changing the voltage $V$ by a linear ramp thus yields an oscillatory variation of the intensity whose amplitude depends on the orientation $\alpha$ of the eraser.

In a similar way one finds the intensity at the output $A_+$ to be given by

$$I_+ = |\Psi_{A,+1} + \Psi_{A,+2}|^2 = \frac{I_0}{8}(1 + \cos \Delta \phi \sin 2\alpha).$$

The complementarity of the two output intensities implies that the total intensity

$$I = I_+ + I_B = \frac{1}{4}$$

is independent of $\Delta \phi$.  

Figure A1. The field amplitudes of the various beams in the quantum erasing setup. The spatial phases acquired by the individual beams are only given for the expressions of the four fields at the exits.
Appendix B. Derivation of equations (7) and (8)

In the case of single photon erasing we use the Dirac bra and ket notation to denote the quantum mechanical state of the system. The state after the prepolarizer is given by

$$|\Psi_0\rangle = \frac{1}{\sqrt{2}} (|H\rangle + |V\rangle) |in\rangle,$$

where $|H\rangle$ and $|V\rangle$ denote horizontally and vertically polarized states, and $|in\rangle$ refers to the propagation direction of the incoming photon. The action of the first beamsplitter is described by the projection operator

$$P_{BS1} = r|1\rangle\langle in| + t|2\rangle\langle in|,$$

where $|1\rangle$ and $|2\rangle$ refer to the propagation directions of the reflected and transmitted beams; $r$ and $t$ are the reflection and transmission coefficients introduced in appendix A. The wavefunction of the photon after the prepolarizer is then given by

$$|\Psi_{BS1}\rangle = P_{BS1} |\Psi_0\rangle = \frac{1}{\sqrt{2}} (r|1\rangle|H\rangle + t|2\rangle|V\rangle + r|1\rangle|V\rangle + t|2\rangle|H\rangle).$$

Introducing the spatial phase difference $\Delta \varphi$ acquired by the beams we obtain the wavefunction before the $H$ and $V$ polarizers:

$$|\Psi_{before H/V}\rangle = \frac{1}{\sqrt{2}} (r|1\rangle |H\rangle e^{i\Delta \varphi} + r|1\rangle |V\rangle e^{i\Delta \varphi} + t|2\rangle |H\rangle + t|2\rangle |V\rangle).$$

The $H$ polarizer in beam 1 and the $V$ polarizer in beam 2 pass only the corresponding polarization states, and the action of the polarizers is therefore described by the projection operator

$$P_{H/V} = |H\rangle\langle H| |1\rangle\langle 1| + |V\rangle\langle V| |2\rangle\langle 2|,$$

After the polarizers the (intra-interferometer) state vector is reduced to

$$|\Psi_{after H/V}\rangle = P_{H/V} |\Psi_{before H/V}\rangle = \frac{1}{\sqrt{2}} (r|1\rangle |H\rangle e^{i\Delta \varphi} + t|2\rangle |V\rangle).$$

The second beam splitter splits each subcomponent of the wavefunction (B.6) into reflected and transmitted parts yielding outputs along the directions $|+\rangle$ and $|−\rangle$. Its action is thus described by the projection operator

$$P_{BS2} = r|−\rangle\langle 1| + t|+\rangle\langle 1| + r|+\rangle\langle 2| + t|−\rangle\langle 2|.$$

The wavefunction of the photon that has left the interferometer, but has not yet passed the eraser is then given by

$$|\Psi_{before eraser}\rangle = P_{BS2} |\Psi_{after H/V}\rangle$$

$$= \frac{1}{\sqrt{2}} (r^2 |H\rangle |−\rangle e^{i\Delta \varphi} + r t |H\rangle |+\rangle e^{i\Delta \varphi} + r^2 |V\rangle |+\rangle + t^2 |V\rangle |−\rangle).$$

Let us now consider only the part of the wavefunction that appears at the exit port $A_−$, i.e. which propagates along the $|−\rangle$ direction. It is obtained by applying the projector $P_− = |−\rangle\langle −| on the last expression, yielding

$$|\Psi_{−}\rangle = P_− |\Psi_{before eraser}\rangle = \frac{1}{\sqrt{2}} (r^2 |H\rangle |−\rangle e^{i\Delta \varphi} + r^2 |V\rangle |−\rangle)$$

$$= \frac{1}{\sqrt{2}} [−|H\rangle e^{i\Delta \varphi} + |V\rangle] |−\rangle.$$

Let the eraser after the output $A_−$ be oriented at $\alpha$ with respect to the horizontal. It passes only the state

$$|\Psi_\alpha\rangle = \cos \alpha |H\rangle |−\rangle + \sin \alpha |V\rangle |−\rangle,$$

so that its action is described by the projection operator

$$P_\alpha = |\Psi_\alpha\rangle \langle \Psi_\alpha|$$

$$= [\cos^2 \alpha |H\rangle \langle H| + \sin^2 \alpha |V\rangle \langle V| + \sin \alpha \cos \alpha (|H\rangle \langle V| + |V\rangle \langle H|)] |−\rangle \langle −|. $$

$$= [\cos^2 \alpha |H\rangle \langle H| + |V\rangle \langle V| + \sin \alpha \cos \alpha (|H\rangle \langle V| + |V\rangle \langle H|)] |−\rangle \langle −|. $$
The wavefunction after the eraser is then given by
\[
|\Psi_{\text{after eraser}}\rangle = \frac{1}{\sqrt{2}} \left[ -\cos \alpha |H\rangle \cos \Delta \phi + \sin \alpha |V\rangle + \sin \alpha \cos \alpha (|H\rangle - |V\rangle) \right]
\]
and the probability of detecting the photon after the eraser at the output \(A_-\) is obtained from
\[
w_- = \langle |\Psi_{\text{after eraser}}\rangle | |\Psi_{\text{after eraser}}\rangle \rangle,
\]
which, after some algebra, yields
\[
w_- = \frac{1}{8} (1 - \cos \Delta \phi \sin 2\alpha),
\]
i.e. the same result as (A.8) obtained in the wave-erasing calculation. The probability for the photon to be detected at the other output is found to be
\[
w_+ = \frac{1}{8} (1 + \cos \Delta \phi \sin 2\alpha).
\]

References

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Interféromètre de Jamin

Mesure de l’indice de réfraction d’un gaz

L’interféromètre de Jamin est un dispositif optique interférentiel qui se base sur la séparation d’amplitude en deux faisceaux d’un faisceau provenant d’une source lumineuse étendue. Il est constitué de deux plaques de verre épaisse dont les faces extérieures sont recouvertes d’une couche réfléchissante argentée. La figure ci-dessous illustre le chemin des rayons lumineux interférant au point d’observation (P).

Cette expérience permet de mesurer précisément l’indice de réfraction d’un gaz en observant le défilement des franges brillantes de la figure d’interférence lorsqu’un des deux tubes est progressivement rempli par un gaz tout en maintenant le vide dans l’autre tube. Le principe de la mesure consiste à déterminer la variation de l’indice de réfraction lors d’une variation de pression lorsque le tube est lentement rempli de gaz. Il a été établi que la différence entre l’indice de réfraction du gaz et celui du vide est proportionnelle à la polarisabilité atomique ou moléculaire du gaz et à sa densité à travers la relation de Lorentz-Lorenz ; si le gaz suit la loi des gaz parfaits, cette différence est proportionnelle à la pression et inversement proportionnelle à la température.

Objectifs du travail :
1. Comprendre et expliquer la distribution d’intensité à la sortie de l’interféromètre lorsque les faces des plaques de verre sont parfaitement parallèles.
2. Décrire la formation d’une figure d’interférence lorsque l’une des plaques de verre est légèrement inclinée de sa position verticale (vous pouvez décrire la situation symétrique lorsque les deux plaques sont inclinées dans des directions opposées et que les angles d’inclinaison sont égaux formant ainsi un coin en forme de triangle).
3. Décrire le déplacement de la figure d’interférence lorsque la différence de chemins optiques entre les deux faisceaux varie d’une valeur donnée. Evaluer le nombre de franges brillantes défilant à travers un repère fixe lorsque le gaz contenu dans l’un des deux tubes est entièrement évacué (la longueur du tube est de 200 mm).
4. Mesurer la variation d’indice de réfraction des gaz à disposition en fonction de la pression. Corriger vos valeurs pour obtenir l’indice de réfraction du gaz dans les conditions standards de pression (760 Torr) et de température (0 °C). Faites une comparaison critique de vos résultats avec les valeurs tabulées dans un Handbook de chimie et expliquez les tendances observées en vous référant à la position des éléments dans le tableau périodique de Mendeleïev. Notez que l’indice de réfraction est une grandeur physique possédant une grande dispersion spectrale.
**Figure** : Schéma illustrant le trajet des rayons lumineux interférant sur un écran placé en position (P). Les rayons lumineux parasites n’ont pas été représentés sur le schéma.

**Bibliographie** :

- Eugene Hecht, « Optics » publié par Addison Wesley (4ième édition, 2002).
- M. Born et E. Wolf, Principles of Optics, 7ième édition, Chapter II (Cambridge University Press, 1999).
- Table des indices de réfraction: https://refractiveindex.info

**Recommandation** :

Avant d’enclencher la pompe à vide, assurez-vous toujours que les cylindres de gaz soient tous fermés hermétiquement et que la vanne de remise à l’air soit également fermée!

**Notice : interférométrie** | **TP avancés de physique**
--- | ---
Daniel Oberli
Recording and reconstruction of holograms

Related topics

Principle
The laser beam is divided into an object beam (illuminating beam) and a reference beam by using a beam splitter. The expanded illuminating beam is diffusely reflected by the surface of the object and then interferes with the reference beam in the plane of the hologram.

A laser light hologram is recorded and reconstructed by using the same laser light as for recording. In the second part of the experiment the object beam and the reference beam strike the hologram plate from opposite sides. This results in an interference pattern which is structured in the depth of the light-sensitive emulsion and forms semi-transparent silver layers or layers of different refractive index when the hologram is processed. For the purposes of reconstruction, the hologram can be illuminated with white light and viewed in reflection. The virtual image is due to Bragg reflection on the layers, and is monochromatic.

A white light reflection hologram is recorded by using laser light and reconstructed by using a point white light source at distance.

Equipment

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<th>Quantity</th>
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<td>thermometer, offset, +40°C; Roller squeegee; Clamps, 2 pcs.; Film</td>
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<td>tongs, 2 pcs.; Darkroom lamp with green filter; Light bulb 230 V/15</td>
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Tasks

1. Record a laser light hologram and process it to get a phase hologram. Reconstruct it by verifying the virtual and the real image.

2. Record a white light reflection hologram and process it to get a phase hologram. Laminate it for reconstruction by a white light source.

Fig. 1: Experimental set-up for recording a transmission hologram.
Transmission hologram
- Perform the experimental set-up according to Fig. 7. The beam path height is 13 cm.
- Since this set-up is a two beam arrangement in which the reference and the object beams follow different paths after passing through the beam splitter BS [1,2], particular care must be taken to ensure the set-up’s mechanical stability.
- Allow the laser to warm up for approximately one hour before beginning the experiment in order to avoid oscillations in the wavelength.
- The laser beam (initially without the E20x expansion system [1,4]) is adjusted with the mirrors M1 [1,8] and M2 [1,1] in such a manner that the object O [10,5] is well illuminated. Then insert the beam splitter BS [1,2] (metallized side toward mirror M1), which splits the laser beam into the reference (R) and object beams (O). Half of the object beam, which has already been adjusted, passes through the splitter; whereas the other fraction is deflected to the large mirror M2 [4,5, 6,5]. This large mirror is now adjusted in such a manner that the beam strikes the centre of the hologram plate H [10,3] (or the holographic sheet film between the glass plates) at the height of the beam path.
- Now move the E20x expansion system [1,4] without the objective and the pinhole diaphragm, but with the adjusting diaphragms, into position. Align it in such a manner that the beam passes unimpeded through the adjusting diaphragms. Now replace these diaphragms with the objective and the pinhole diaphragm. Move the pinhole diaphragm toward the focal point of the objective. Initially ensure that a maximum of diffuse light is incident on the aperture diaphragm and subsequently, consider the expanded beam. Successively shift the positions of the objective and the pinhole diaphragm laterally while approaching the focal point in order that an expanded beam without diffraction phenomena is subsequently provided.
- If sheet film is used, the film is tightly pressed between two glass plates in the plate holder. To avoid undesirable interference phenomena and multiple reflection between the glass plates, it is advisable to press the upper edges of the glass plates together with an additional clamp or clip. Before exposing the film, wait approximately 1 to 2 minutes until the pressure and temperature equilibrium between the sheet film and the glass plates has taken place.
- The photosensitive layer faces the object during the image-capture process.
- Immediately after removing a piece of film or a plate from the storage box, reclose the box.
- The exposure time of approximately 10 to 20 seconds is set on the laser power supply.
- The development and bleaching of the phase hologram is performed according to the procedure given below.
- The hologram can be reconstructed according to Fig. 7 if the object beam is blocked directly behind the mirror M2 with blackened cardboard.

Attention
Never look directly into the laser beam! The He/Ne laser has a power of 5 mW and can cause permanent damage to the retina. When tracing the path of the beam, use only absorbing or strongly diffusing materials.

Development and bleaching
Only phase holograms are dealt with in the following, because of their better appearance in reconstruction. Therefore the following agents have to be prepared before to process the photographic plates after exposure.
1) Developer
Mix 100 ml of holographic developer with 400 ml of deionized water and keep the mixture ready in one of the plastic dishes.
2) Stop-bath
Mix 12 ml of stop-bath solution with 468 ml of deionized water and keep the mixture ready in a second plastic dish.
3) Bleaching
Dissolve 5 g of potassium dichromate in 1000 ml of deionized water. Add 5 ml of concentrated sulphuric acid. Keep the solution ready in a third plastic dish.
Caution: Never pour water into a vessel containing sulphuric acid.
4) Rinsing
A fourth plastic dish is filled with deionized water to rinse the bleached holograms. The photographic plate is processed by developing it for two minutes. After a stop-bath of 30 seconds the plate is bleached for two minutes. Finally it is rinsed for about five minutes and dried.

Avoid all skin contact while working with the developing and bleaching agents. Always wear the recommended gloves. Before recording holograms, clean all the optical components by using lens-cleaning paper and acetone. Make sure that the base plate is in a rather vibration-free position.

Only work in green light in the laboratory.

Theory and evaluation
In normal photography only the two-dimensional projection of a recorded three-dimensional object is obtained. Holography supplies a truly three-dimensional image of the object when reconstruction is carried out. This can be done by storing the three-dimensional wave field emitted by the object using a coherent reference wave (coherent background) (Fig. 2).

The object wave and reference wave produce an interference pattern at the position of the hologram which is stored as optical density (amplitude hologram) or as a change in refractive index (phase hologram). When the developed hologram is illuminated by the same reference wave, the reconstructed object wave as was previously emitted from the actual object appears behind the hologram. The observer therefore sees the image where the object was previously situated. In qualitative terms this phenomenon can be explained as follows: the spherical wave emanating from a point on the object interferes with the (in the simplest case plane) reference wave (Fig. 3). The recorded interference pattern consists of concentric circles (Fresnel zone plate).

When reconstruction is carried out (Fig. 4), a plane wave is diffracted at the Fresnel zone plate. This creates, in addition to the light which passes through (0 = order diffraction), a divergent spherical wave (1st order diffraction) and a convergent
Recording and reconstruction of holograms

Fig. 2: The principle of holography: interference of object wave \( O \) with coherent reference wave \( R \). \( H \) is the hologram plate.

a) Recording  b) Reconstruction

spherical wave (-1st order diffraction). Besides the virtual image at the original position of the object, there is also a real image on the other side of the hologram.

For the quantitative treatment of holography, the light source is described by a complex function.

\[
E(x, y, z, t) = E_0(x, y, z) e^{i \omega t} (1)
\]

The real part of this complex function is the electrical vector of the light wave.

Intensity is obtained by time averaging (denoted by \(< >\)) and apart from a constant factor is:

\[
I = < E \cdot E^* > (2)
\]

A number of simplifying assumptions are made for the following calculations in order to reduce the calculating effort required and to emphasize the results which are of essential importance for holography. The following initial assumptions are firstly made:

- The time-dependent factor \( e^{i \omega t} \) is equal for all waves and is therefore omitted, and it is also left out of the calculation of intensity as a result of averaging (\( \omega = 2 \pi f, f = \text{frequency} \)).
- The hologram is regarded as an “area hologram” (i.e. thickness of photographic layer \( \ll \) length of light wave). It is regarded as being in the plane \( z = 0 \).

A far more complicated calculation for “volume holograms” leads to similar results.

Fig. 3: Overlapping of a spherical wave emanating from \( O \) and a plane reference wave \( R \).

Recording of holograms

Object wave \( O \) and reference wave \( R \) overlap in the plane of the hologram \( (z = 0) \) and supply a position-dependent interference pattern with intensity \( I \).

\[
O = O_0(x, y) e^{i \varphi(x, y)} (3)
\]

\[
R = R_0(x, y) e^{i \varphi(x, y)} (4)
\]

\[
I = (O + R) \cdot (O + R)^* = O^*O + R^*R + O^*R + O^*R^* = I_0 + I_R + O_0R_0 e^{i(\varphi - \varphi)} + O_0R_0 e^{i(-\varphi + \varphi)} (5)
\]

The developed hologram then has a (complex) position-dependent transmittance:

\[
\tau(x, y) = T(x, y) e^{i \varphi(x, y)} (6)
\]

If the phase \( \varphi(x, y) = \text{const.} \), we speak of an amplitude hologram (optical density fixed after developing). On the other hand, if \( T(x, y) = \text{const.} \) (by bleaching the hologram) we have a phase hologram.

The transmittance is dependent on energy density \( W \), the product of light intensity \( I \) and exposure time \( t_0 \) (Fig. 5).

The exposure time and also the ratio of the intensities of the object and reference waves should be chosen so that the transmittance is in the linear range of the characteristic shown in Fig. 5, e.g. between \( W_1 \) and \( W_2 \) respectively between \( W_3 \) and \( W_4 \).

Fig. 5: Amplitude and phase transmittance in relation to energy density \( W \) for amplitude and phase holograms.
We therefore assume for the transmission of the holograms:
- the intensity of reference wave \( I_R \) and the exposure time are chosen so that the transmittance is in the linear range of the characteristic.
- \( I_O \ll I_R \) for the intensity of object wave \( I_O \), so that intensity modulation remains in the linear range of the characteristic.

Under these simplifying conditions we obtain for an amplitude hologram (\( \varphi = \text{const.} \)):

\[
\tau (x,y) = a T_O + b I (x,y) \quad (7)
\]

\( a, b = \text{const.} \)

and for phase hologram (\( T = \text{const.} \)):

\[
\tau (x,y) = \alpha \cdot e^{i \varphi} + i \beta I (x,y) \quad (8)
\]

\( \alpha, \beta = \text{const.} \)

the series

\[
e^{i \varphi} = \sum_{n=0}^{\infty} \frac{i^n}{n!} \varphi^n
\]

for \( I_O \ll I_R \) being interrupted after the first term. The relationship between \( \tau \) and \( I \) is also approximately linear for phase holograms. The factor \( i \) means that the reconstruction wave additionally undergoes a constant phase shift on passing through the hologram.

**Reconstruction of a hologram**

For the purpose of reconstruction the hologram is generally illuminated again by reference wave \( R \). The wave front appearing behind the hologram (according to (7) and (5)) contains the following:

\[
H = \tau \cdot R
\]

\[
= (a T_O + b I_O + b I_R) \cdot R \quad \text{reference wave}
\]

\[
+ b I_R \cdot O \quad \text{object wave (virtual image)}
\]

\[
+ b R^2 \cdot O^* \text{conjugate object wave (real image)}
\]

The first term essentially reproduces the reference wave, slightly modified by \( I_O \).

The second term describes the object wave, i.e. it appears to the observer as if the object were still at the same point as for the recording. \( I_O \) is constant and the image is therefore undistorted provided \( R \) a plane wave.

The third term supplies a real image, known as a conjugate image, because \( O^* \) has the negative phase \( -\varphi \) of \( O \).

A divergent light beam becomes convergent.

**The real image**

The position of the real image is studied in greater detail in the following example. Let the reference wave be a plane wave which hits the hologram at an angle \( \beta \). The object is at angle \( \alpha \) when the recording is made (Fig. 6).

![Figure 6: Position of image points with oblique reference wave.](image)

For small angles \( \alpha \) and \( \beta (\alpha, \beta \ll 90^\circ) \) the virtual image is in mirror symmetry to the real image in relation to the dash-dot line which is vertical to the direction of the reference wave.

The following relationship is obtained by calculation: Reference wave in the hologram plane \((z = 0)\)

\[
R = R_0 e^{i k x \sin \beta} \quad (10)
\]

Object wave in the hologram plane

\[
O = O' e^{i k x \sin \alpha} \quad (11)
\]

where \( O' = \text{object wave at angle } \alpha = 0 \).

In reconstruction we obtain for the conjugate image

\[
R^2 \cdot O^* = R_0^2 \cdot O'^* \cdot e^{i k x (2 \sin \beta - \sin \alpha)} \quad (12)
\]

it therefore appears at angle \( \gamma \) with

\[
\sin \gamma = 2 \sin \beta - \sin \alpha \quad (13)
\]

No real image exists at particular angles \( \alpha \) and \( \beta \). If

\[
2 \sin \beta - \sin \alpha > 1 \quad (14)
\]

there is no solution for \( \gamma \). This is already the case at \( \alpha = 0^\circ \) for angles of the reference beam of \( \beta > 30^\circ \).
Reconstruction of hologram with $R^*$

If it is the real image which is of particular interest in reconstruction, e.g. in producing hologram copies of a master hologram, the hologram is reconstructed with $R^*$, i.e. the hologram plate is illuminated from precisely the opposite direction. Instead of (9) we then obtain:

$$H = \tau R^*$$

$$= (aT_{o} + bI_{o} + bI_{R})R^*$$

$$+ bR^2O$$

$$+ bI_{R}O^*$$

The observer looks in the direction in which the virtual image appears in reconstruction with $R$. The real image is at the corresponding position in front of the hologram plate.

For reconstruction the processed photographic plate is brought back into the same position as for recording and illuminated with the same laser light. The object is eliminated and the object beam is blocked directly behind the mirror $M_2$ with blackened cardboard. For the observer in front of the photographic plate a clear virtual image is created in the position where the object has previously been. Turning the photographic plate by 180° allows the observer to see the real image in front of the plate (see theory for reconstruction with $R^*$).

Recording a white light reflection hologram

The experiment is setup as shown in Fig. 8. The photographic plate (or film) is fixed on the holder and put into the position shown in Fig. 8 [10, 3]. The object is positioned directly behind the photographic plate. The beam expanding system E20x is introduced and adjusted as described before. The exposure time is approximately 2 seconds.

After processing and drying a dark laminate is applied to the emulsion layer of the photographic plate with the squeezing roller.

For the reconstruction of the hologram it is sufficient to have a point white light source emitting a parallel beam, e.g. a halogen spot light at 1 m distance or more or even sunlight. The best image quality is achieved if the hologram is illuminated from the same side and at the same angle as the reference beam during recording. From the continuous white light spectrum only one wavelength (here the red light of the He/Ne laser) is filtered out for the reconstruction while all the others are removed. If the emulsion layer has shrunk, the colour of the reconstructed image will shift towards shorter wavelengths while expansion will cause a shift towards longer wavelengths.
| LEP 2.6.03 -00 | Recording and reconstruction of holograms |