# Notes for teachers

**on module 07:**

# Diffraction and Interference

*Diffraction offers a variety of visually appealing experiments to demonstrate the wave character of light. But more than that, it gives students a unique opportunity to measure on a nanometre scale – with very simple means.*

**Summary:** Students will generate diffraction patterns and use them for measurements.

The module is structured in 3 chapters:

- Diffraction on a double slit is used to measure the wavelength of the laser light.
- Diffraction on a single slit and bar are compared. Students then measure the thickness of a hair, based on the diffraction pattern.
- Diffraction on a grating is demonstrated on a CD. Students then build their own spectrometer and measure the spectrum of a fluorescent light bulb.

**Designed for:** upper secondary level (age ca. 16 to 18)

**Duration:** The first chapter requires one and a half lessons (20 + 40 min),
the second and third chapter one lesson of ca. 40 min each.

**What students should already know:**

- constructive and destructive interference of waves
  illustrated e.g. in a ripple tank or with sound waves
- light behaves as waves
- Huygens principle

**What students will learn:**

**Facts**

- To measure the wavelength of light with the double slit (Young) experiment
- Diffraction on a single slit and Babinet's principle
- How to measure the width of a hair, based on a diffraction pattern
- How the diffraction pattern of DNA lead to the discovery of its structure
- Diffraction on gratings in reflection and transmission
- How spectrometers work
- That the spectrum of energy-saving light bulbs consists of discreet colours – in contrast to the continuous spectrum of sunlight.

**Skills**

- How to handle lasers safely (Laser safety)
- Experiment in teams
- Design experimental setups for accurate measurements

**This module includes:**

- 3 worksheets
- 3 fact sheets
- Laser safety rules

## Chapter 1 | Diffraction on a double slit

### Suggested lesson outline for a double slit

Students will conduct Young's experiment on diffraction on a double slit. They first will learn about the responsible use of laser sources and then use the diffraction pattern to measure the wavelength of the laser light employed in the experiment. Based on Huygens principle and geometrical arguments, the students will derive the necessary equations themselves.

| **Timing** in minutes | **Activity** | **Material** |
|---|---|---|
| | **First lesson (part)** | |
| **0 – 15** | Laser safety | Laser safety document |
| **15 – 30** | Group work on the first page of the worksheet "Light waves" | WS07.1<br>laser<br>slide with diffraction patterns<br>*Not included in the kit:*<br>batteries for laser, screen,<br>clothes pegs to hold slide |
| **Homework** | Point 4 of worksheet "Light waves" | WS07.1 |
| | **Second lesson** | |
| **0 – 10** | Continue group work on the worksheet "Light waves" (second page) | WS07.1<br>laser<br>slide with diffraction patterns<br>*Not included in the kit:*<br>batteries for laser, screen, ruler<br>clothes pegs to hold slide |
| **30 – 39** | Discussion of measurement results | |
| **39 – 40** | Handout fact sheets | FS07.1 |

### Description of suggested lesson

#### Preparation

Please remember to test the batteries for the lasers before the lesson.

#### Laser safety

Please ask students to read the laser safety instructions to the class. Discuss with your students the necessity of these rules. The safe handling of laser sources is an essential part of the skills to be learned during this module. Let all students sign the declaration on their laser safety sheet. Although this has not legal value, it conveys the important message that your students are personally responsible for the safe handling of the lasers.

#### Introduction

To have the maximal benefit from this lesson, students should be familiar with wave interference. To remind them, you could use the example of a rock concert, where the bass sounds from the speakers to the right and to the left of the stage interfere in front of the stage, so that, in one spot, the bass is louder than a few steps to the left or right (if necessary, explain with a drawing on the board). This is typical wave behaviour, which can also be observed with light, interestingly. Please do not give away much more information than that, since your students are meant to find out for themselves.

#### Worksheet "Light waves"

Please go through the introduction of the worksheet (WS07.1) with your students. If you wish, you may tell the students how Young performed his experiment (see section 'Background'). Continue up to the subtitle 'Preparation' and then hand out the laser sources. If some students are not handling the laser responsibly, in accordance with the rules laid out in the instruction sheet, please do not allow them to use the lasers. Students may still participate actively in the group work without touching the lasers.

If you have no suitable screens available, you may use post-it notes instead. Cut off the sticky area of the sheet and stick it on a stable standing object with a flat vertical surface (e.g. the chalk-box). This offers an additional advantage as students can write or mark directly on the paper.

When everyone has set up a suitable screen and tested the laser, please hand out the slides. From here on the students should be working on their own as much as possible. Go from one group to the other and help when the students have difficulties. Do not stand for more than a few minutes with the same group, but try to visit all of them. Commend good ideas and show interest in why students have chosen a particular solution, e.g. to build their experimental setup. Keep an eye on the secure handling of the lasers.

When you see that most groups have progressed with the work on point 3) of the worksheet, discuss the students' observations in class. Please give them the opportunity to experiment freely, such that they can get a feeling for the crucial parameters of this experiment.

#### Homework

*Optional:* You may want to compile a list of the factors your students name in reply to point 3), e.g. on the blackboard. Let your students copy this list and, for homework, ask them to write a short comment on each of the factors about *how* and *why* they change the appearance of the diffraction pattern. Obviously, they will not have all the answers at this point, but they will find (some) answers later in the chapter. It is recommended that this homework be made voluntary and not obligatory.

To save time at the beginning of the second lesson, ask you students to answer the question raised in point 4 on the second page of the worksheet. This should cause them to look up some of the basic theory of oscillations, waves and interference.

#### Second lesson

Please begin the second lesson with a short discussion on the text at the top of the 2$^{nd}$ page of the worksheet. The description there is meant as a mere reminder – depending on how much you already explained to your students about interference, you will need to reserve more or less time for this part. Then discuss the homework with your students. Make sure that all class members have understood the answer to question 4.

Please help your students to understand the meaning of the drawings above point 5. If your students are not yet familiar with Huygens principle, you will need to explain it at this point.

To see if your students understand the concept, ask them to predict what would happen if they changed the wavelength. If you use the drawing on the right, this would correspond to changing the radius of the half-circles (wavefronts) and thus to changing the angle of diffraction and positions of the diffraction orders.

From point 5) on, let your students work independently in their groups again. As the measurements are being made for point 6), please ensure that the students are measuring the distances between the small spots, not the long-range modulation (also see, "What students might ask", question 2).

#### For your faster students

In case some of your students are still busy with measurements, while others have already completed the whole worksheet, you could offer the faster students the following experiment: Please give them a piece of the thick black aluminium foil you find in the Photonics Explorer kit. Ask them to lay it on a piece of cardboard and use a fine needle to make a small hole into it. When they see the diffraction pattern of the hole, you may ask them: 1) What does the light in this experiment interfere with, since there is only one hole and not two slits; 2) How would they explain the shape of the diffraction patterns; and 3) How would the shape of the diffraction pattern change if they change the size or shape of the hole (e.g. to an oval)? Let them try.

#### Discussion of measurement results

Collect the different results on the board. Ask the students to quantify how precise they believe their measurements to be, e.g. by estimating how many nanometres their result might differ from the true value. Then compare the results with the true wavelength of around 655 nm. Due to manufacturing issues, the emitted wavelength may vary some 3 or 4 nm from one laser to another.

To give the students an idea of the dimensions, compare it with the thickness of common paper (0.1 mm) and make the students aware that they just calculated the size of something that is more than 100 times smaller. Ask them where such a precise measurement might be needed in real-life applications.

Ask the students what they have done to increase the accuracy of their measurements. Possible answers might include:

- to make an average of several measurements;
- to measure instead of the distance between the first and the zeros order ('a'), the distance between the two first orders ( 'a' and '-a'; to the left and right, respectively) and then to divide it by two;
- to increase the distance between slide and screen;
- to make a small black spot on the screen where the zeros order is, such that the other diffraction orders are better visible;

etc.

At the end of the lesson, hand out fact sheet FS07.1.

## Background information

### Young's experiment

In order to prove that light is a wave, Young reported his experiment "which may be repeated with great ease, whenever the sun shines, and without any other apparatus than is at hand to every one." It is a good example of how, with simple means, important scientific progress can be achieved.

Young writes: "I made a small hole in a window shutter, and covered it with a piece of thick paper, which I perforated with a fine needle." He then placed a playing card in the beam, thus cutting effectively the beam into two parts. In the shadow of the card, he saw interference fringes that disappeared if he blocked the light passing on one side of the card.

He reported his experiment in 1803 in "The philosophical transactions of the Royal Society of London," pages 1 to 16.

### Coherence

Interference and coherence are directly linked: Interference is only possible due to coherence; and the degree of coherence is measured based on the contrast of the interference pattern. Technically speaking, coherence describes the correlation of the physical properties between two waves.

In a bit more in detail: Light consists of oscillating electric and magnetic fields. These fields can pass each other in vacuum without interacting – that's why nothing happens to light beams that cross in vacuum. However, at the intersection – as everywhere else – the local electric (and magnetic) field is the sum of all the electric (and magnetic) fields that are present at a certain moment. For instance, two fields of the same strength, but opposite directions, will add up to zero, meaning they annihilate each other. If, however, the two fields are oriented in exactly the same direction, the resulting field will be twice as strong, and the intensity of the light even four times stronger (The intensity is proportional to the square of the electric field).

Normally, the sum of the fields changes so fast that we can't see it. Only if the overlaying fields remain synchronised over a long period of time – in the range of at least a tenth of a second – can we see the effect with our eyes. This can happen if the two interfering light beams are exactly the same, e.g. because they originate from one laser beam. Due to the way light is generated in a laser, the fields in a laser beam oscillate synchronously in the same direction with the same frequency.

Sunlight, on the other hand, consists of many short wave fragments that are not related to each other. In principle, these fragments interfere with one another too, but they cannot produce a steady interference pattern. Sunlight is therefore considered to be incoherent, while laser light is referred to as coherent light (also see "Students might ask," Question 3).

## Students might ask

#### 1) If all these researchers mentioned in the introduction later were proven wrong, why are we learning this?

Science is not about delivering the truth. Science is a process of observing and constructing models that describe observed behaviour as accurately as possible. As science advances, today's models may become outdated, or at least more refined. It is therefore even more important to know and understand the process of scientific work than to remember all details of its current results.

#### 2) Where does the long range modulation in the diffraction pattern come from?

If you close one of the two slits in the experiment, this long-range modulation would remain, while the small spots disappear (let your students try with field ②). It is thus the result of the interference of light passing through the single slit at different places. In contrast, the small spots are the result of interfering light from both slits.

In the next chapter, the diffraction on a single slit is discussed in more detail.

#### 3) How could Young perform this experiment without a laser?

Only coherent light can generate fringes. While, in almost all cases, lasers emit highly coherent light, sunlight has a very low coherence by nature. Young overcame this problem by experimenting with sunlight passing through a very small hole. The greater the distance from the hole, the more the light becomes coherent: it appears to come from a single point (thus all being in phase) rather than an area (where light from different points on the area may be out-of-phase). The light in Young's experiment was therefore 'spatially coherent'.

Sunlight is composed of many different wavelengths. Since light with longer wavelengths (e.g. red) diffracts stronger on the same object (in Young's experiment a playing card) than light with shorter wavelengths (e.g. blue), Young saw coloured fringes. It is, however, much easier to perform this experiment with a single wavelength.

## Chapter 2 | Diffraction on single slit (optional)

### Suggested lesson outline for single slit

Students will compare the diffraction pattern on a single slit with that of a bar of the same width (inverted mask, Babinet's principle). They will then use the diffraction pattern of their own hair to measure the thickness of this hair. Faster students will also see how the diffraction pattern of DNA was used to deduce the structure of this important molecule.

| Timing in minutes | Activity | Material |
|---|---|---|
| **0 – 5** | Introduction | |
| **5 – 30** | Group work on the WS "Light – ruler of the nanoworld" | WS07.2<br>laser<br>slide with diffraction patterns<br>*Not included in the kit:*<br>batteries for laser, screen, ruler, holder for slide, hair |
| **30 – 40** | Hand out and discuss fact-sheet | FS07.2 |

### Description of suggested lesson

#### Introduction

This lesson builds on the previous lesson on the double-slit, and can be used in the second part of a double period (2 lessons block), for example. It is therefore expected that the students are familiar with the laser safety regulations. However, the worksheet is designed such that it can also be used on its own. In this case, you will have to discuss the laser safety regulations before beginning the experiments (see chapter 1).

In the previous lesson, some of the students might have tested one of the double slits. If so, please remind them of what they have seen, and let them share their observations with the other students. Explain that not only light coming from two different slits can interfere, but that the light passing through one slit can interfere also with the light passing through another part of the same slit. The details are explained on the factsheet, which students will receive after the lesson.

#### Worksheet "Light – ruler of the nanoworld"

Please let your students know that the goal of this worksheet is to demonstrate how interference patterns can be used to analyse very small things. If you have discussed the worksheet on double slits with your students, you may invite them to have a closer look at fields ③ and ④ on the slide they might still have before them. You can thus skip the introduction of the worksheet and go directly to point 1).

#### Babinet's principle (1 and 2 on worksheet)

Points 1) and 2) of this worksheet are intended to let students find out that the diffraction pattern of a slit and a bar with the same width are the same. Due to the limitations of the production technique, the width of the slit is between 53 and 57 µm, while the width of the bar is between 57 and 61 µm. The two diffraction patterns will therefore not match exactly - yet sufficiently to demonstrate the effect.

#### Measuring the thickness of a hair

In point 4) of the worksheet, the students apply the formula given in point 3) to measure the breadth of their hair. This task is primarily meant as an exercise in preparing and making an exact measurement – an essential part of scientific work. Therefore, encourage your students to discuss what they can do to improve the accuracy of their measurement in their groups.

As an orientation: a typical scalp hair has a width of about 60 to 80 µm. As you go from group to group, please help your students to get an idea of what that means, e.g. by comparing it to one millimetre and the wavelength of the laser light they use.

#### Discovery of the DNA structure

The remainder of the worksheet is intended for faster students who have already completed the measurement of their hairs. The experiment demonstrates how Franklin, Crick and Watson could derive the 3 dimensional structure of DNA from a diffraction pattern.

Point 7) poses an apparently simple question. But it requires your students to have a good understanding of diffraction and to include the practical experiences they just gained to find a feasible answer.

Rosalind Franklin used electromagnetic waves with a much shorter wavelength. The method applied is called 'X-ray fibre diffraction' and the radiation she used had a wavelength of somewhere between 0.1 and 5 nm.

#### Fact sheet

After you collected the experimental materials, hand out and explain fact sheet FS07.2.

The drawings on the fact sheet should make it easier for you to explain how the formula given in point 3 of the WS was derived. Basically, it is the same geometrical argumentation, based on equivalent triangles, as in the case of the double slits (see WS07.1).

It is very unlikely that, in real life, your students will ever need to remember the exact formulae for the diffraction on a single slit by heart. But they should remember that diffraction is a useful tool to analyse and measure very small things.

## Background information

### Babinet's principle

The exact physics behind the phenomena are difficult to explain and require advanced maths. All we would like students to remember is that objects with complementary transmission properties (where one is transparent, the other is opaque, and vice versa) produce the same diffraction pattern – with the exception of the diffraction pattern centre and the overall intensity. The overall beam intensity after the mask will depend on how much of the original beam is blocked by the object.

The more precise formulation of Babinet's principle is that the sum of the field behind a mask and the field that a complementary mask would produce is again the original beam – just as if there was no mask. That might sound trivial at first sight. But students will ask you what happens to the light that spreads after the mask away from the centre. For both diffraction patterns from the mask and its inverted counterpart, the bright areas are the same. Intuitively one would therefore estimate that the sum of the two can never match the single spot that the original beam produces on the screen without any mask. Yet, if you add up the two fields (after the mask and it's inverted complement), all the light in these bright outer areas interferes destructively and these areas thus become dark while the spot in the centre remains. From this you can conclude that in fact the two diffraction fields are not identical: their electric fields are opposed in their orientation.

## Chapter 3 | Diffraction on gratings and optical spectroscopy

### Suggested lesson outline for diffraction on gratings

Students get to know two types of diffraction gratings: in reflection and in transmission. They use both types to analyse the spectra of an energy saving light bulb. In the end of the lesson diffractive optical elements are demonstrated as an example for the versatile applications of controlled diffraction.

| Timing in minutes | Activity | Material |
|---|---|---|
| **0 – 5** | Introduction | CD's |
| **5 – 35** | Group work on the WS "The colours of white " | WS07.3<br>slide with diffraction grating<br>*Not included in the kit:*<br>sunshine, energy saving light bulb, translucent sticky tape, CDs, scissors |
| **35 – 39** | Demonstration of diffractive optical elements | plastic card with diffractive optical elements |
| **39 – 40** | Hand out fact-sheet | FS07.3 |

### Description of suggested lesson

#### Preparation

When you print the worksheets, please take care that all scaling options in the printing menu are deactivated. If you have the opportunity to print the third page on slightly stronger paper, it is certainly worthwhile doing so.

Please prepare several lamps with compact fluorescent light bulbs before the lesson, Ideally, the lamps should have no lampshade and the light bulbs should be just a bit above table height. This will make it significantly easier for your students to make an accurate measurement in the last experiment.

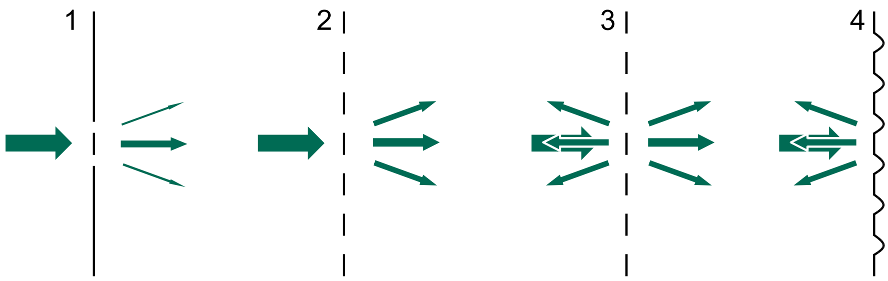
#### Intro

Use the first few minutes to remind your students of the double-slit experiment. Guide them with questions to the understanding that the diffraction angle depends on the wavelength, and that this effect can be used to separate the different wavelengths of light.

Hand out CDs to your students and give them one or two minutes to observe the colour fringes that a CD produces. Can your students make a link between this effect and the double slit experiment you just discussed?

#### Worksheet “The colours of white”

Hand out WS07.3 and discuss the introduction with your students. You can then illustrate the link between the double slit and the diffraction on a CD with a couple of fast drawings for them:




1) Diffraction on double slit: Only a small amount of light passes the mask and the diffraction orders are very weak;
2) Diffraction on a grating: More light passes through the mask and the diffraction orders are brighter;
3) If the surface of the diffraction grating is reflective, diffraction orders can also be seen in reflection; and
4) A CD has little dents along a very long spiral with exactly 1.6 µm pitch between two tracks. The dents are designed such that less light of the read out laser beam is reflected from an area with a dent than from an area without a dent (this difference in the reflected light intensity contains the digital information). Due to the strict regularity of the tracks, a CD acts as a circular, reflective diffraction grating.

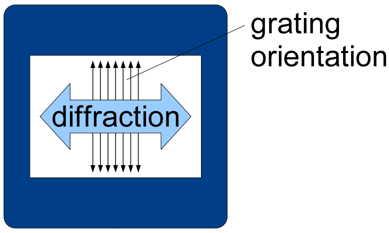
#### Using a CD as a spectrograph

Show the students how a CD can be used to qualitatively analyse the spectrum of a light source. In point 2) of the worksheet, the students should notice that the spectrum of sunlight (and, if you still have one, of an incandescent light bulb) is seemingly continuous, while the spectra of an energy-saving light bulb consists of discrete colour bands. The number of colours and their central wavelengths depend on the specific model you use; quite often you will find the colours red, orange, green, turquoise and dark blue.

#### Building a spectrometer

The figure in point 8) illustrates constructive interference in the direction of the first diffraction order. In the middle of the left drawing you can see how the wavefront is delayed where the light has to pass the thicker parts of the foil. The drawing on the right illustrates the same situation at a larger wavelength, leading to a larger diffraction angle.

The question in point 9) is meant to make your students remember a simple yet useful piece of information: for a linear grating, the diffraction pattern is orientated perpendicularly to the grating. To apply this example to the CD, you could ask your students how the lines with the dents are oriented on a CD (as a long spiral like on a LP, just smaller).




The 3rd page of the worksheet allows your students to build their own spectrometer. This experiment is primarily developed to achieve didactic goals. It illustrates the functioning of a spectrometer and allows your students to apply what they have learned about diffraction in quantitative measurements. The design – in particular the geometry – is chosen to keep physical and mathematical aspects as simple and clear as possible. Therefore the resolution of the device is limited, and even a very accurate measurement might differ from the true value by about 10 nm.

Ideally, the compact fluorescent light bulb is mounted just a few centimetres above table height. Ask your students to lay their spectrometer sheet flat on the edge of the table. If there was no translucent tape behind the triangle cut-out, the light from the lamp passing through the cut-out should go towards the 7cm mark at the scale. The students should then look through the diffraction grating at about table height and see triangles in the colours they identified already with the CD in point 6). For an accurate measurement, good teamwork is mandatory.

#### For your faster students

Your faster students can estimate the accuracy of the measurement. What might influence it? Which of those influences can and cannot be reduced by taking the average of several measurements? Can they quantify the typical measurement uncertainty in percent and/or nanometers?

#### Diffractive optical Elements

A diffractive grating, as used in the previous experiment, is a simple example of a diffractive optical element. Inside the DVD package of the Photonics Explorer you will find two plastic cards with several other diffractive optical elements. Just as the laser light passing the grating is distributed in bright spots along a line (the diffraction orders), these elements distribute the laser light into more complex two-dimensional patterns. By shining it through different elements on a white wall or screen you can demonstrate this eye-catching technology to your students as one of the many applications of the physical effect they just studied.

At the end of the lesson, please hand out the fact sheet FS07.3.

## Background information

### The ‘white’ of energy saving light bulbs

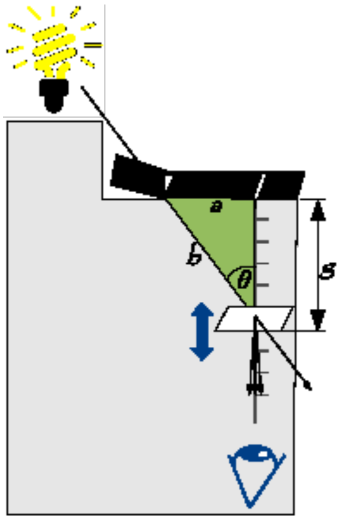
Compact fluorescent light bulbs generate light by a gas-discharge: free electrons are accelerated by an applied electric field in an ionized gas. When these accelerated electrons collide with ions, their kinetic energy excites the ions, which reemit the energy as electromagnetic radiation. However, this radiation is in the ultraviolet (254 nm wavelength). It is and not useful for illuminating a room but harmful for the eye. Therefore, the inside of the tube is coated with fluorescent phosphors that absorb the ultraviolet light and reemit the energy in form of visible light. Different phosphors reemit at different discrete wavelengths, namely those observed by your students in point 6). The mixture of phosphors determines the colour of the lamp, e.g. a ‘warmer’ (more orange) or ‘colder’ (more blue) white.

Each manufacturer has its own ‘recipe’ for mixing phosphors, which may even vary between different product lines. Therefore, the spectra of different lamps will not be the same either. The following measurement on one lamp can therefore only serve as a rough orientation (measured with a professional spectrometer):

| Colour | Central wavelength |
|---|---|
| red | 612 nm |
| orange | many weak lines, ca. 575 – 595 nm |
| green | 546 nm |
| turquoise | 487 nm |
| dark blue | 436 nm |

#### Calculating the wavelength with the formula given in point 11)

You might be wondering if the formula used in point 11) is just an approximation, especially since the incident of the light is not normal to the grating. As the following explanation shows, the formula actually produces an accurate result.




A really precise model would require advanced maths (solving the Fresnel-Kirchhoff integral). However, for most situations, the geometrical model – as you find it in school books – gives sufficiently precise results. According to this model, the grating equation for the maxima in the diffraction pattern for light under the angle of incident is:

$$\sin(\alpha_m) = \sin(\theta) + m\frac{\lambda}{d}$$

where is the grating period (in school books often ; we use to maintain consistency with double slit experiment), the wavelength of the light, the number of the diffraction order and the angle of the th diffraction order towards the normal of the grating. In our configuration, we are looking at the 1st diffraction order along the normal to the grating, so that . The form is thus reduced to:

$$\frac{\lambda}{d} = \sin(\theta) = \frac{a}{b}$$

where is simply the ratio of opposite (a: distance between the axis of the triangle cut-out to the white line) to the hypotenuse (b: the distance between the axis of triangle cut-out and the point where the grating crossed the scale for ).

## Students might ask

#### 1) What is the difference between a diffractive optical element (DOE) and a hologram?

A hologram is a DOE, but not all DOEs are holograms. Holography is one technology to generate a DOE, namely by recording the interference of light waves in a medium like a photographic film.

The DOEs on the plastic cards you find in the Photonics Explorer are fabricated using another technique: They have been calculated with the help of a computer and then were written with a very precise device (focused ion or electron beam) into a hard material. The result is a kind of stamp with an extremely fine, structured surface. This stamp is then embossed at a hot temperature into plastic in order to generate the DOEs you find on the plastic cards.