Designing interactive demonstrations of optics phenomena

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Challenge the future

Designing interactive demonstrations of optics phenomena

To be exhibited at the Science Center Delft

By

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Abstract

The United Nations and Unesco have declared 2015 to be the international year of light. The Optics department of the faculty of Applied Physics from the TU Delft has decided to contribute to this effort by designing optics experiments to be displayed at the Science Center Delft. The goal of this project was to manage first year students that helped design and explain these experiments. Another part was to design an experiment involving lithography. The students were split into three groups, each with a different subject, polarization, cloaking and light emitting diodes. The management part of the subject went well; ten experiments were designed and the principle behind them were explained on posters. I have learned that communication is very important in teamwork and that the group members need to be motivated in order get the proper results.

T. ten Bruggencate
Delft, July 2015

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1 Introduction

The United Nations and Unesco have declared 2015 to be the international year of light. They have chosen this year for several reasons. Around 1015 Ibn Al-Haytham wrote is book about optics, where the first experimental version of the Snell-Descartes law was presented. In 1815 Fresnel wrote down his theory that light is a wave. Maxwell created his theory of the electromagnetic properties of light in 1865. One hundred years ago, in 1915, Einstein formulated his theory about general relativity, in which light is also important. Finally 50 years ago in 1965 the cosmic microwave background radiation was discovered by chance. All of these events led to the decision to make 2015 the international year of light. Around the world events are organised to show the public the importance of light in our modern society. Examples of this are its use in the internet, global positioning system (GPS), astronomy, healthcare and culture.

In order to contribute to this event, the Optics department of the faculty of Applied Physics from the TU Delft has decided to design and build experiments for the Science Center Delft. The Science Center is the university museum of Delft, where the public can get to know the university and learn about the research that is done. A big part of its audience consists of elementary scholars, so the experiments must be explained in a simple manner. The plan was originally that this would be executed by two third year student and sixteen first year bachelor students of Applied Physics as their end projects. The third year students would each manage two groups of four first year students, with all a different subject, and guiding them towards proper designs for the Science Center. In the end I was the only third year student, and I decided to guide all students. Unfortunately, we also had only eleven students, but that worked out fine, since we dropped one of the four subjects and decided that I would design an experiment on that subject.

The four subjects are polarization, cloaking, lithography and light emitting diodes. The students were allowed to choose the subject of their liking and in this way three groups were formed and I would do the lithography subject myself.

This was quite an unorthodox Bachelor end project, since it does not consist of doing an experiment, getting results and writing a report about it. Instead, the project was all about managing the project and guiding the first year students during their five-week project. Designing an experiment about lithography and explaining it to the audience also became part of it.

In this report all the four subjects and the principles behind them will be explained. The designed experiments will be presented and discussed. Finally, the management part will be discussed and evaluated.

2

Experiments

2.1. LED

Basic principle

Light Emitting Diodes (LEDs) are semiconductor structures where a positively and negatively doped semiconductor are put next to each other. If a voltage is applied, light can be created at this interface, when electrons from the negatively doped layer (donor) recombine with holes from the positively doped layer (acceptor). In most commercially sold LED lighting, a blue LED is used. This blue light is sent through a phosphorescent layer, which converts some of the blue light into a spectrum from green to red, in order to create light that appears white to the human eye.
The reason that we perceive these colors as white light has to do with the photoreceptors in our eyes and the way our brain interprets the signals from the receptors. Our eyes have two main kinds of photoreceptor: rods and cones. Rods are more sensitive than cones and are mostly responsible for night vision and peripheral view, since they are placed at the edges of the retina. The rods cannot perceive colors. The cones work best at a relative higher intensity of light than the rods and are responsible for distinguishing colors. They are concentrated most at the center of the retina, which explains why our vision is the sharpest in the center of our view. There are three different kinds of cones, each sensitive to a different spectrum. One is more sensitive for the blue spectrum, the second for the green spectrum and the third is most sensitive for the red spectrum. These are designated S, M and L respectively and are abbreviations for Short, Medium and Long wavelengths. These spectra can be seen in figure 1.

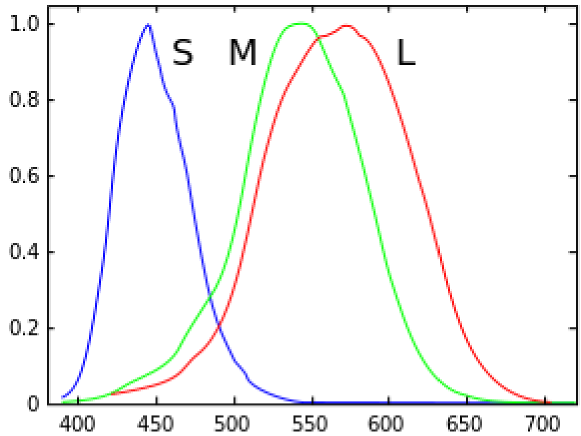

Figure 1. The normalized sensitivity of the three kinds of cones as a function of the wavelength in nm. [1]

Because our eyes are only sensitive for these main colors and our brains perceive white light as a correct mixture of these color spectra, we can trick the brain to see white with only these three colors. This is called the RGB system and is used for a lot of applications, but the main use is in (fluorescent) lighting and displays, like tablets and smartphones.

In order to compare LEDs with other light sources, one can measure the output spectrum and see the wavelengths that make up the light. A white light LED is most of the times a blue LED that is coated with a fluorescent layer. The fluorescent material absorbs some of the blue light when the photons collide with the electrons and bump them to a higher energy level. The excited electron then falls slowly to lower energy levels by emitting phonons, or lattice vibrations. Then the electron can fall back to its ground energy level under emission of a photon. This emitted photon has less energy than the original photon, because of the created phonons, and will therefore have a longer wavelength. In a fluorescent layer that consists of a mixture of fluorescent materials, there are a large number of possible energy transitions that results in a whole spectrum of light that is emitted. If the spectrum of a blue LED with a fluorescent layer is observed, one can see the whole visible spectrum, with the exception of a band between blue and yellow. Here the intensity of light is a lot lower. The blue light comes from the LED itself and is transmitted through the fluorescent layer, but because of the energy absorbed by the layer, the emitted light has to be less energetic than the original light. As quite a bit of energy is absorbed by the layer, the colors close to the original blue light are less often emitted. This manifests itself in the observed 'missing' part of the spectrum. This can be observed in figure 2. LEDs also have a very limited intensity in the deep reds, toward the infrared. Our own eyes do not see the difference, but if you are a photographer, this can be very important. If a picture would be taken from someone with a cyan or a deep red shirt and only a LED is used for lighting, these colors would not look good on the photograph, since the intensity of these colors is a lot lower than the surroundings.

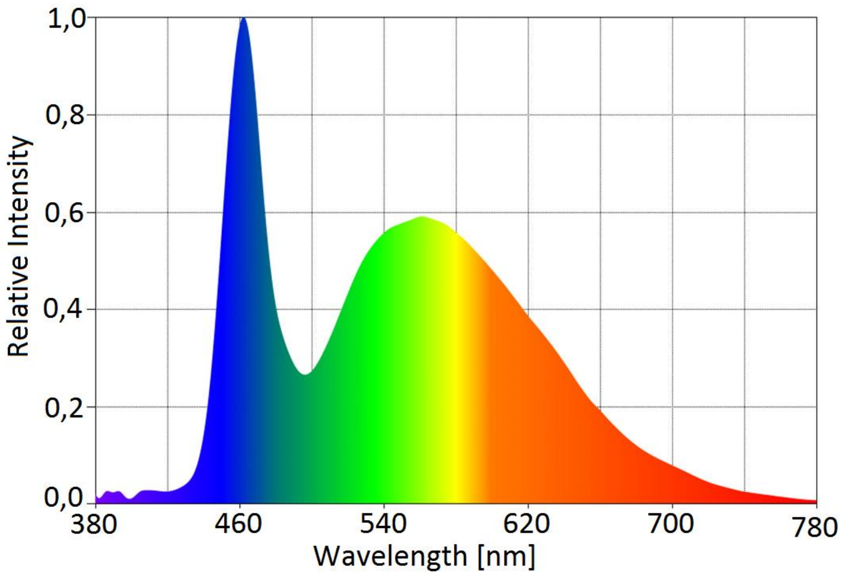

Figure 2. The spectrum of a typical LED that can be purchased in many hardware shops. One can clearly see that a band of cyan blue has a lot lower intensity than the other wavelengths. There is also no UV light created and almost no deep reds. So if you would want to take a picture of something with these colors, you would need another light source than the LED that is presents in your smartphone camera. [2]

Experiment 1 – RGB system

In the experiments that were designed by the PEP students, we wanted to learn the general audience more about LEDs and how 'white' light is produced. We also wanted to teach them a little more about all of the information that can be found on the package, when they buy an LED light. We will do this in the form of a poster and a setup.

The first experiment was created to show how the RGB system works and how you can create white light with a red, a green and a blue LED. The principle is very easy. We will place the three LEDs in such a way that they can shine on a white surface. Each of the LEDs is operated by a separate slide, so that people can mix their own light and create all of the complementary colors.

Experiment 2 – Benham disk

In a second experiment, we would like to demonstrate the same principle with a so called Benham disk. This disk is covered with different colored slices, red, green and blue. If this disk spins fast enough, the human eye cannot distinguish the separate colors and will perceive it as white.

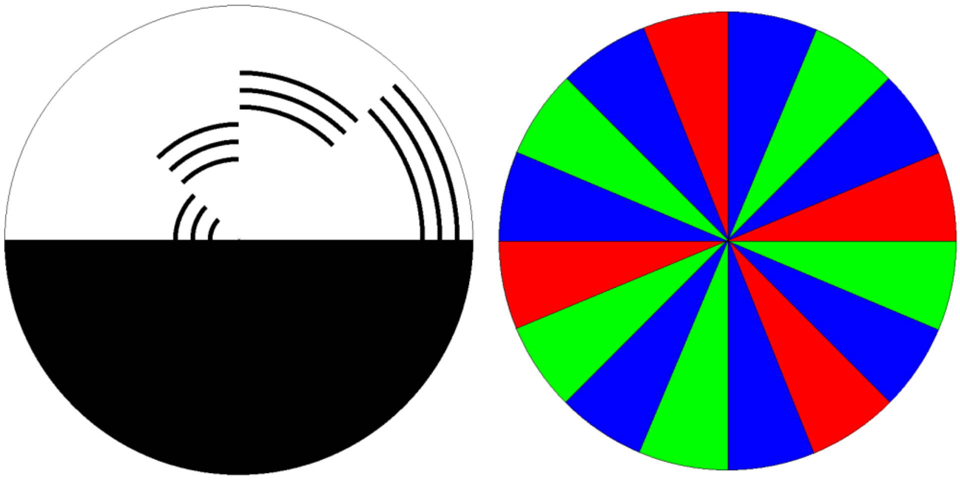

Figure 3. An example of a Benham disk on the right that appears white when it spins fast enough. On the left is another version where colors appear at the radii of the black lines when it spins. The funny things is that these colors are reversed when the disc is spun in the other direction.

Experiment 3 – spectra

In the third experiment we will demonstrate the difference between different light sources that are regularly used, such as an incandescent bulb, fluorescent lighting (TL), a gas discharge light and a LED, of course. We will display each of the spectra and provide background information about these light sources. We will also provide an economic balance to compare the price of each light source over a fixed period of time, to show people that LED lights are cheaper on the long run, despite the higher purchase price.

Experiment 4 – fluorescence

Finally, we want to let the audience play with a blue LED and different fluorescent layers, in order to really prove the concept to them. We want to use several different layers, which all create a different kind of 'white' light, for instance what we call 'warm white' and 'cool white' light. Examples can be found in figure 4.

Figure 4. Examples of the different kinds of 'white' light. The temperatures of the light correspond with the spectrum of blackbody radiation, which appears similar to these colors. [3]

2.2. Polarization

Basic principle

Light is an electromagnetic wave. A plane wave is a wave with its wave fronts forming infinitely large parallel planes. Its maximum amplitude is constant for the whole wave. The plane wave moves in one direction, this is called the z direction. The electric field vector is always perpendicular to the direction of movement, so it lies in the xy plane. This means we can describe the vector in the x and y components. The description of the length and orientation of the electric field vector over time is called polarization. There are several kinds of polarization. The simplest is linear polarization where the x and y components of the electric field are in phase. If the x and y components are not in phase you will have elliptical orientation, where the electric field will follow an elliptical shape over time. If the x or y component leads the other component by $\pi/2$, the axis of the ellipse coincide with the x and y axis. This is called well oriented elliptical polarization. If the amplitude in both directions is also exactly the same, the electric field will follow a circle and this is called circular polarization. Elliptical and circular polarization can be right or left handed, this depends on which component leads the other. The different kinds of polarization can be observed in the following figure.

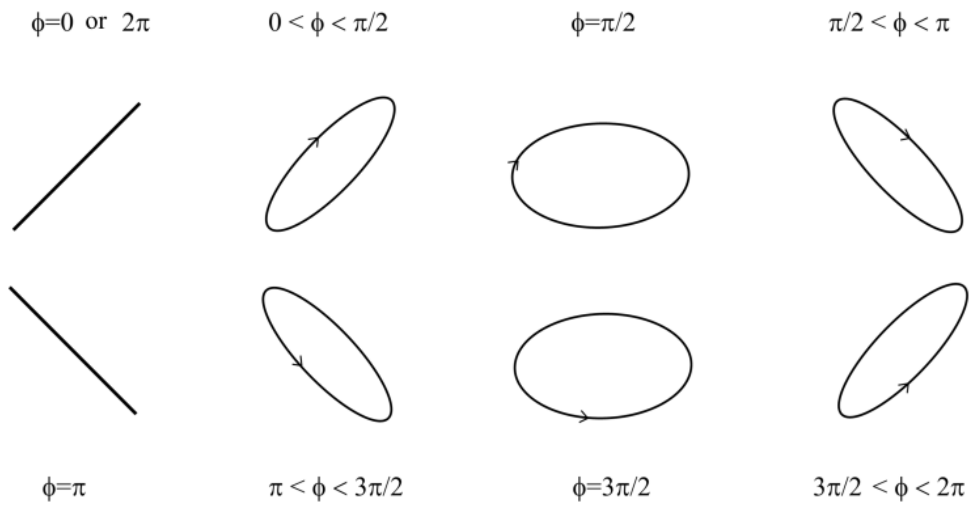

Figure 5. Different kinds of polarization that depend on the phase difference between the x and y components of the electric field. [4]

Brewster angle

Polarization is used in several commonly used items. One of these is the use of linear polarization filters in sunglasses. Since natural light is polarized evenly in all direction (or unpolarized), a linear filter will remove exactly 50% of the incoming light. Another advantage is that if the filter is positioned in the correct angle, a lot of reflections can be suppressed. This has to do with Brewster's angle (or polarization angle). If an unpolarized beam of light hits the interface between two media with a different index of refraction, the light will be partly reflected and partly refracted into the medium. In the case that the light hits the surface from the medium with the lowest index of refraction, something special can occur, where the reflected light is fully polarized. This happens when the reflected ray makes a right angle with the refracted ray and the angle of incidence is called the Brewster angle. The reason that this phenomenon occurs can be found in the way the light is reflected. As the electromagnetic wave hits the surface, the electric wave will affect electric dipoles in the medium, causing them to oscillate. This oscillation causes the electromagnetic wave to be both reflected and refracted. The electric field component perpendicular to the plane of incidence will oscillate dipoles that are also perpendicular to both the reflected and refracted rays. In the direction of the rays there is thus an oscillation of the electric field and this component will be found in both the reflected and refracted rays. One could say that if you look back from the direction of the rays, you can see oscillating dipoles and therefore the oscillation will continue in that direction. In the case of the component of the electric field that is tangent to the plane of incidence the electric field will also oscillate the dipoles, but now they oscillate exactly in the angle of the reflected ray. This means that there is no oscillation of dipoles perpendicular to the reflected ray, so the electric field cannot be transmitted in that direction. So all of this light is transmitted into the second medium. In figure 6 the effect of the reflection on polarization can be seen.

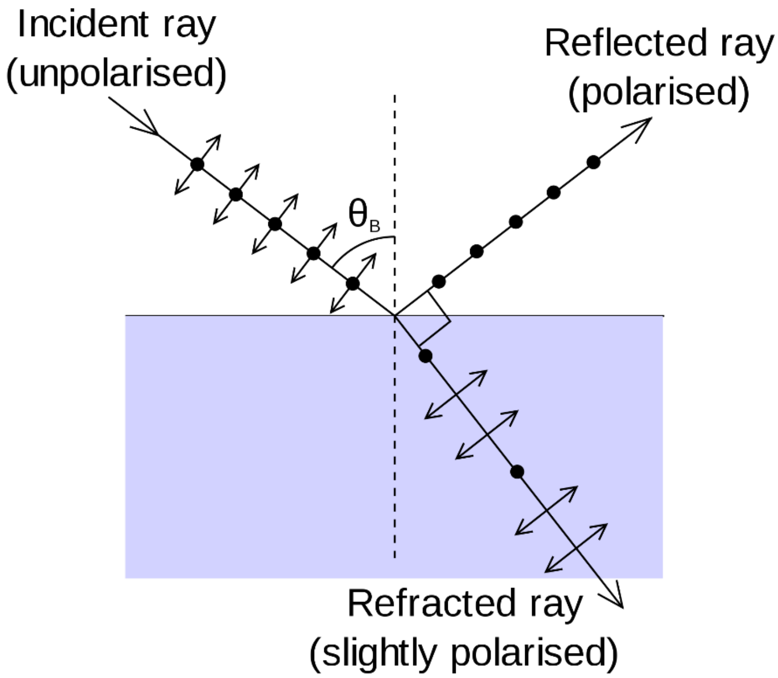

Figure 6. The Brewster angle. All of the electric field that is tangent to the plane of incidence is transmitted into the lower medium. Only the perpendicular field is reflected and transmitted. Therefore the reflected ray is fully polarized. [5]

The Brewster angle can be easily calculated from the Snell-Descartes law. Because of the right angle between the reflected and refracted ray, the angle of the transmitted ray can be put in terms of the incident angle:

$$\theta_t = \pi/2 - \theta_i,$$

where θ_t is the angle of transmission and θ_i is the angle of incidence, both measured with respect to the normal (the dashed line in figure 4). If we plug this into the Snell-Descartes law we get this:

$$n_i \sin(\theta_i) = n_t \sin(\theta_t) = n_t \sin(\pi/2 - \theta_i) = n_t \cos(\theta_i).$$

In this formula n_i is the index of refraction of the incidence medium and n_t is the transmitting medium. This formula can be rewritten into the following:

$$n_t/n_i = \sin(\theta_i)/\cos(\theta_i) \equiv \tan(\theta_B),$$

the formula for Brewster's angle, θ_B, that is also the angle of incidence.
The ratio in which fully polarized light is transmitted into and reflected from a surface as a function of the angle of incidence is given by the Fresnel equations: [6]

$$r_\perp \equiv \left(\frac{E_{0r}}{E_{0i}}\right)_\perp = \frac{n_i \cos(\theta_i) - n_t \cos(\theta_t)}{n_i \cos(\theta_i) + n_t \cos(\theta_t)}, \qquad r_\parallel \equiv \left(\frac{E_{0r}}{E_{0i}}\right)_\parallel = \frac{n_t \cos(\theta_i) - n_i \cos(\theta_t)}{n_i \cos(\theta_t) + n_t \cos(\theta_i)}$$

$$t_\perp \equiv \left(\frac{E_{0r}}{E_{0t}}\right)_\perp = \frac{2n_i\cos(\theta_i)}{n_i\cos(\theta_i) + n_t\cos(\theta_t)}, \qquad t_\parallel \equiv \left(\frac{E_{0r}}{E_{0i}}\right)_\parallel = \frac{2n_i\cos(\theta_i)}{n_i\cos(\theta_t) + n_t\cos(\theta_i)}$$

The subscript $\perp$ means we are looking at the electric field that is perpendicular and $\parallel$ means parallel to the plane of incidence. t denotes the transmission coefficient and r the reflection coefficient.

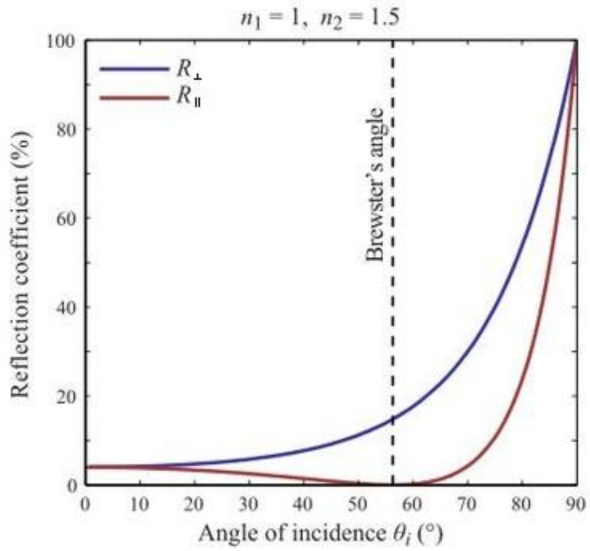

Figure 7. Reflection coefficients in percentage of the incidence light as a function of the angle of incidence for both polarizations. One can see that the parallel component goes to zero at the critical angle and the light is fully polarized. In this example an air-glass interface is examined. [7]

We cannot directly observe the electric field, but we can measure the intensity of the electromagnetic field. The intensity is the square of the electric field amplitude. Also the ratio of the intensity of reflection and transmission, R and T respectively, can be measured. We can look at the distinct polarized reflections, $R_\perp = {r_\perp}^2$ and $R_\parallel = {r_\parallel}^2$. Figure 7 shows these intensities. This reveals how the intensity of the reflection is dependent on the angle of incidence and polarization of the incident beam. At the Brewster angle, the intensity of the light that was polarized parallel to the plane of incidence is not reflected at all. This means all reflected light is polarized perpendicular to the plane of incidence. One can see in the figure that between 40 and 75 degrees the parallel polarized light is more than four times lower than the perpendicular polarized light. If the perpendicular polarized light would be blocked by a filter, the reflections will be significantly reduced and even completely removed at the Brewster angle.

Wave plates

Some materials, mainly crystalline structures, have anisotropic properties. One case is birefringence where the refractive index differs along the main axis of the material. Light polarized along the optical axis is unaffected by the crystal, while light polarized perpendicular to the optical axis is affected. This is caused by the fact that the material has a different crystalline structure along each axis, therefore interacting differently with the electromagnetic wave. If the refractive index is different for each polarization, it means that the wave propagates with a different speed through the material. This causes the phase difference between the two polarizations along each axis inside the material to change. If these materials are made with very precise thickness, they can act like so called quarter wave, half wave and full wave plates. In a half wave plate the electromagnetic wave along the secondary axis falls behind with a phase of π compared to the wave polarized along the optical axis. Basically, an extra half wave fits along the secondary axis over the length of the material, hence the name a half wave plate. In a quarter and full wave plate this is a quarter and full wavelength respectively, resulting in a phase difference of $\pi/2$ and 2π. Because of the exact number of wavelengths that fit in a wave plate, it is specifically designed for one wavelength and will not work properly for other wavelengths. In figure 8 the effect of a half wave plate on linear polarized light is shown for the case that the light is polarized under 45 degrees with respect to the optical axis. In this specific case the direction of polarization is changed by 90 degrees.

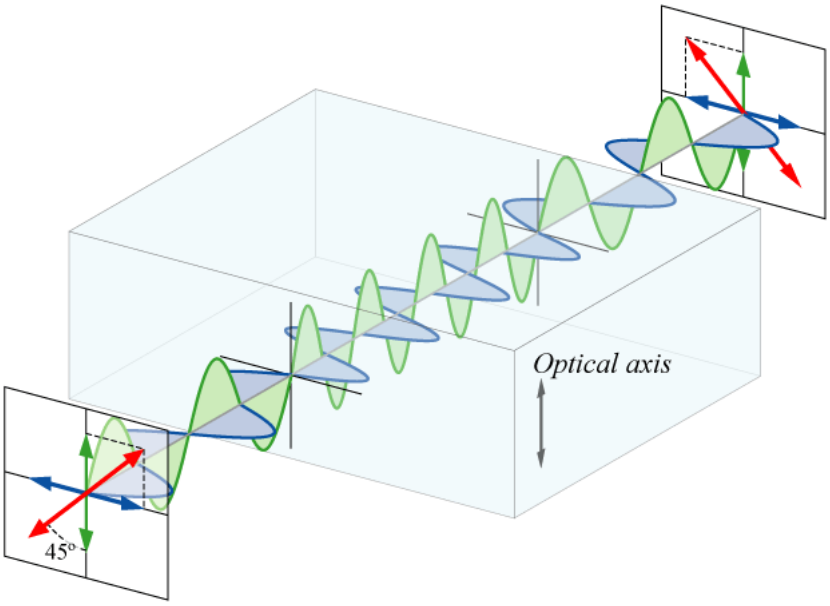

Figure 8. The effect of a half wave plate on linear polarized light that enters under 45 degrees with respect to the optical axis. Since exactly an extra half of a wave fits along the optical axis, this wave will fall behind by π. This causes the polarization to be changed from +45 to -45 degrees with respect to the optical axis. [8]

The polarization of the incoming wave can be split in its component vectors along the optical axis and the orthogonal axis. The polarized light along the orthogonal axis will propagate slower through the material than on the optical axis, causing in this case to fit half a wavelength more along the orthogonal axis than on the optical axis. This wavelength difference causes a phase difference of the polarization along each axis, which results in a different kind of polarization, again see figure 5.
A quarter wave plate can be used to change linear polarization into circular or elliptical polarization and vice versa. Whether it is changed in circular or elliptical polarization depends on the angle of polarization with respect to the optical axis, only if this angle is 45 degrees, linear polarization will change to circular.

Experiment 1 – wave plate

We designed several experiments based on polarization. The first experiment is designed to show the function of a polarizer. We will place a stationary polarizer in front of a light source. A secondary rotating polarizer is placed in front of the first one. We will let the spectator rotate the second polarizer so that he can really experience the effect of this combination, being able to block the light completely. We also want to show the effect of cellophane as a wave plate, by letting people slide a piece of it between the polarizers and letting them experience the effect. In figure 9 the setup is shown. This figure was made by the first year students, but slightly altered for this report.

Experiment 2 – Brewster angle

In the second experiment we will show the effect of the Brewster angle on the polarization of reflected light. We will place a photograph behind a glass plate on which light is reflected around the Brewster angle. A rotating polarizer will be placed between the photograph and the spectator. Again the spectator will be allowed to rotate the polarizer and see it effects. If the correct angle is found, most reflections should disappear allowing the spectator to observe the photograph through the glass plate. This setup is also shown in figure 9.

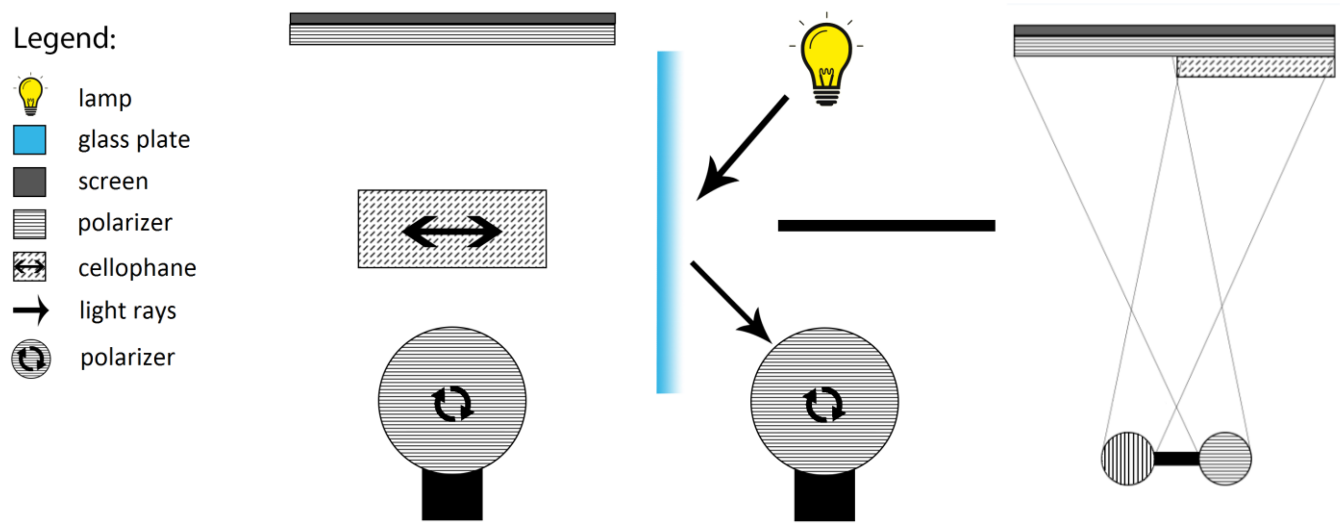

Figure 9. The first experiment on the left will show the effect of the angle between two polarizers and the effect of a halve wave plate on linear polarized light. In the second experiment in the middle the concept of the Brewster angle will be proven. On the right the proposed setup for the stereo photography can be seen. These figures have been made by the first year students.

Experiment 3 – 3D photography

The third experiment will show the basic principle behind 3D or stereographic pictures. With 3D photography two separate pictures will be taken simultaneously of the same object. This is usually done with two cameras that are separated by 8 centimeters. This distance is used most of the times, because it is the about the same separation as the human eyes. To create the 3D effect, each eye of the spectator should only see the picture destined for that eye. Our brain will translate the two different pictures captured by the eyes into a 3D image. One of the ways that this can be done is through polarization. If each picture is displayed in a different linear polarization, an appropriately angled polarizer in front of each eye allows the eye to see only the correct picture, while blocking the other. Polarization is also used by cinemas to display 3D movies. In this case left and right handed polarization is used instead of linear polarization, because the 3D effect will be unaffected if the spectator tilts his head. In this case the two different pictures are displayed on top of each other on a screen. A special silver screen is needed to preserve the polarization of each image, because the polarization is lost in normal scattering on dielectric surfaces. A silver screen, which are actually made with aluminum most of the times, have a metallic coating that reflect the polarized light without losing the polarization.

In this experiment we will display a 3D photograph with an LCD display. These kind of displays are already linearly polarized, making the setup easier. We will show two stereoscopic pictures next to each other, where the right image is meant for the left eye and vice versa. This is called cross eyed view. This is not an ideal method, but will show a proof of concept. We will place a sheet of cellophane on top one of the pictures, which will act as a half wave plate. If it is placed correctly, it will change the polarization of that image. Cellophane acts as a good half wave plate for a broad spectrum. Then two different polarizers in front of each eye will block one image while allowing the correct image to pass through it. The only drawback is that the spectator will have to use cross eyed view, but we may counteract this through the use of lenses.

2.3. Cloaking

Basic principle

Cloaking is all about hiding an object in plain sight. This is mostly done by bending light or electromagnetic waves around the object in such a way that it is unnoticeable by an observer. This is achieved by scientists in the microwave region using metamaterials and microstructures. Metamaterials are materials with properties that cannot be found in nature. The metamaterials associated with cloaking are materials with a negative index of refraction. This is accomplished by creating structures that interact with the electromagnetic wave and redirect it through, for instance, induction and resonance. These materials have to be specifically designed for a specific wavelength and generally only work at exactly that wavelength. One specific design has proved to be able to cloak a copper disc for one wavelength in the microwave spectrum. In this experiment a microwave frequency of 8.5 GHz was used, which corresponds with a wavelength of 3.5 cm. This structure can be seen in figure 7. It uses small copper loops placed on concentric cylinders that bend the electromagnetic wave around the cloaked circular disc. This design is shown in figure 10.

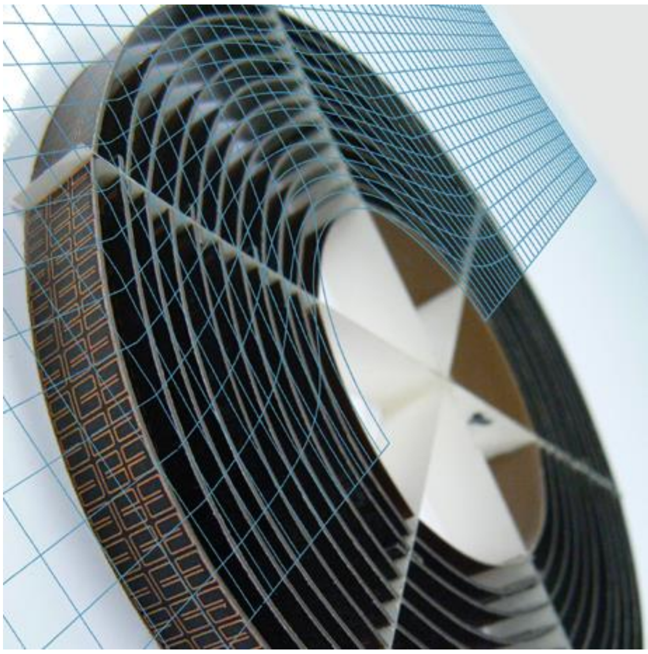

Figure 10. The metamaterial that has been produced to redirect the electromagnetic wave around the center. The design consists of concentric cylinders that are covered with small copper loops that interact with the electromagnetic wave. [9]

The biggest drawback of these metamaterials is that they only work at one specific wavelength and that this wavelength generally lies in the microwave spectrum. We would like to cloak objects in the visible spectrum as well, the whole visible spectrum, not just one specific wavelength.
Since we want to create some experiments that people can actually see with their own eyes, we will have to use some tricks in order to cloak some areas. We will do this by using reflection and refraction of light.

Experiment 1 – reflection

In the first experiment mirrors will be used to reflect the light around an area big enough to hide a human being. We will do this by placing four mirrors in two parallel V's. The two mirrors that make up each V are placed at a right angle with respect to one another. See figure 11.

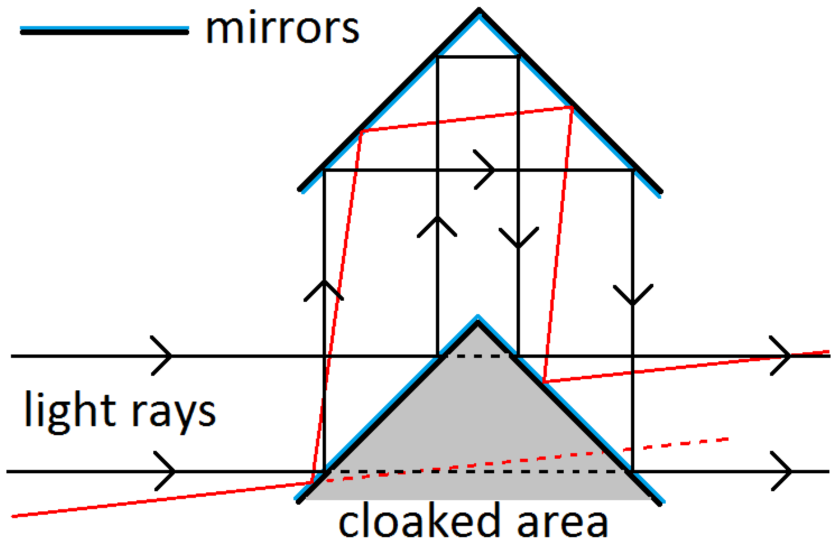

Figure 11.This setup of four mirrors reflect the light around the cloaked area behind the first V. The rays of light will ideally be reflected into their original trajectory, but in practice this is impossible, due to a difference in the angle of incidence. A ray of light incident under a different angle is also shown in the figure. One can clearly see that it is not reflected to its original trajectory.

Light rays that enter from the left hit the first mirror under a 45 degree angle, this will reflect the rays under 90 degrees into the second mirror. The light hits this mirror under a 45 degree angle as well, again reflecting it, but now back in its original direction. This happens again at the third and fourth mirror, which brings the rays of light back to their original trajectory. So it seems that the light continues along its original path as if the mirrors were not there. This means that the area behind the first V is effectively cloaked. Unfortunately this method is not ideal and only works perfectly if the all of the rays are parallel and enter under the correct angle. Rays entering under a different angle will not leave the setup on their original trajectory (see figure 11) or even hit the wrong mirror first. A spectator will always notice the illusion, since the edges are always visible, as well as the second pair of mirrors. One way to counteract this is to place the spectator far away from the setup, this way the rays of light that reach him are more parallel and have the correct angle. It would be ideal if the second V is hidden from view, for instance around a corner. Since we want to be able to cloak a human being, this will be a very large setup. Each mirror will be 2 meters high and 0.7 meters wide. To ensure safety of the spectators, each mirror will be glued to a wooden panel and tightly bound to a frame. Also all of the edges of the glass mirrors will be polished.

Experiment 2 – refraction

The second experiment will be based on refraction of light at an interface between two different media. The Snell-Descartes law is used to calculate the angle of transmission into a medium, given the angle of incidence and the refractive indices of both media:

$$n_i \sin(\theta_i) = n_t \sin(\theta_t).$$

In this formula n_i and n_t are the refractive indices, θ_i and θ_t are the angle of incidence and transmission, respectively, both measured from the normal. If light enters a medium with a higher refractive index than the medium it is currently in, the ray of light will be bend toward the normal. If the light then encounters a second interface that is parallel to the first and the same media are involved, the transmitted ray will be bend back into the same direction it entered the material, but it is translated by a small distance. See figure 12.

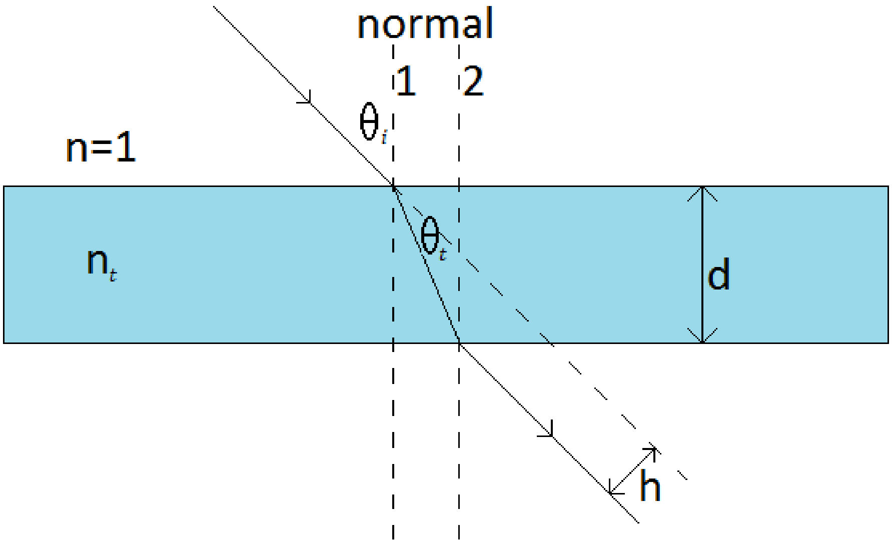

Figure 12. When a ray of light passes through a denser medium that has parallel interfaces, the light is refracted back in the same direction it was travelling in before it hit the medium, but it is translated by a small distance, *h*.

We can calculate the translated distance, h, as a function of the thickness of the plate, d, the angle of incidence, θ_i and the refractive index n_t. When we use goniometric relations and the Snell-Descartes law we can derive the following relation:

$$h = d\frac{\sin(\theta_i - \theta_t)}{\cos(\theta_t)}, \qquad \theta_t = \sin^{-1}\left(\frac{n_i \sin(\theta_i)}{n_t}\right).$$

We will use this effect in the following setup to bend light around a central area and then bend it back onto its original trajectory. In order to accomplish this we designed the following setup out of Plexiglas, see figure 13.

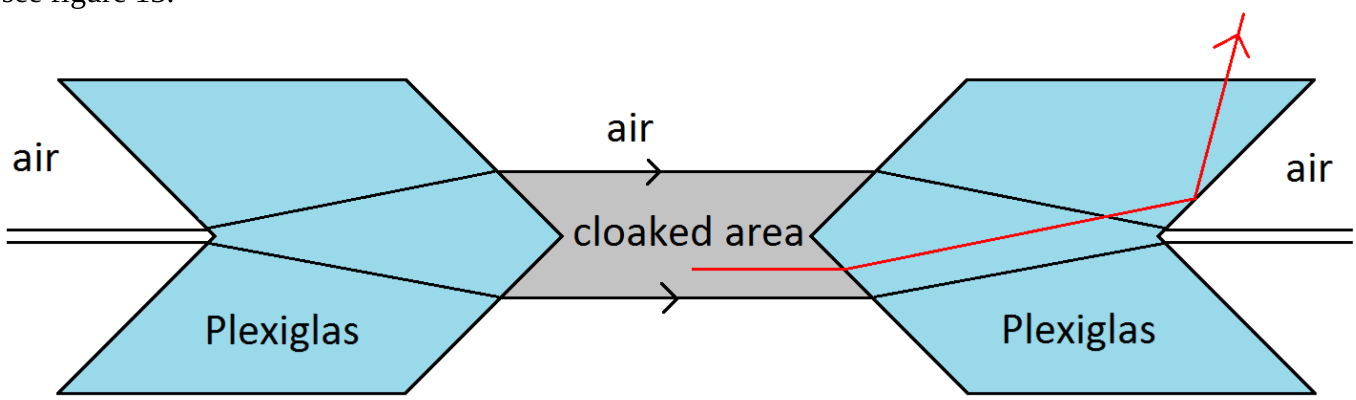

Figure 13. These specially designed shapes of Plexiglas, bend the light around the central area, creating a cloaked zone. Any rays of light that originated from the cloaked zone will exit through the side of the structure, due to total internal reflection.

Light rays emitted from the cloaked area entering the structures, will exit the structures from the sides, due to total internal reflection. This experiment is also very dependent on a correct viewing angle, which we will point out to the spectators. Therefore it is best viewed with one eye shut. For practical reasons we will use an angle of incidence of 45 degrees. Using the formulae above we can calculate that the thickness of the cloaked area is $2h = 2d \cdot 0.33$. The height and thickness of the Plexiglas will be 6 centimeters due to availability and costs. If we enter this in the formula we find that the cloaked area will slightly under 4 centimeter wide. This should be large enough to hide a toy car or something similar.

Experiment 3 – refractive index

We also designed a third experiment, which is not directly connected to cloaking, but can teach people something about refraction. The setup is very simple we will use a plastic lens (n=1.5) and a tank that is partially filled with glycerol (n=1.5). As a background we will use a checkboard pattern, which will show the effect of the lens. Initially the lens will be suspended above the liquid, distorting the view on the checkboard. We will than allow the spectator to lower the lens into the glycerol, which has the same refractive index as the lens. Therefore the effect of the lens will be countered and the spectator can observe the checkboard pattern without distortion. One could say that the lens disappears or is cloaked by the glycerol. See figure 14 for a picture of this setup.

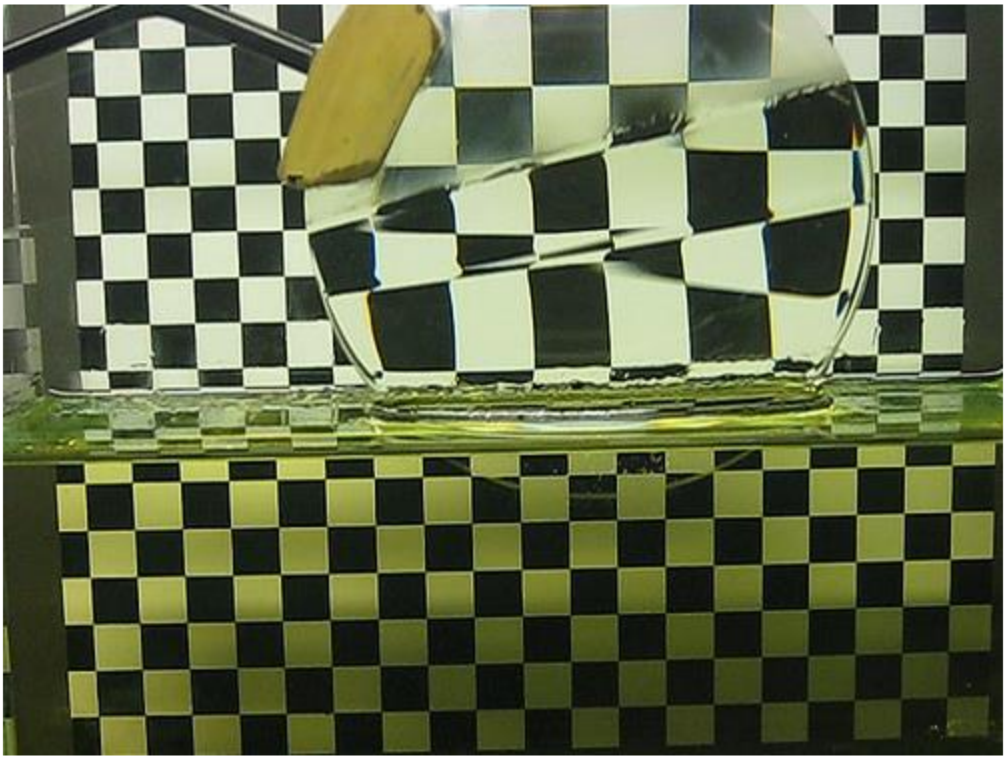

Figure 14. In this figure the effect of the lens can clearly be seen as the checkboard pattern is enlarged. Beneath the liquid with the same index of refraction, the pattern can be seen unaffected. Only the edge of the lens can be seen here. [10]

3

Lithography

Lithography is a word derived from two Greek words *lithos* and *graphein* and literally means writing on stone. The printing technique was created at the end of the seventeenth century and is nowadays more commonly known as etching, where a design is etched on a metal plate and later transferred onto a piece of paper. Nowadays the word lithography is used for another technique involving the production of computer chips, also called integrated circuits. Here patterns are etched into a layer that is deposited on a silicon disc, called a wafer. This technique involves light that is shone through a mask with the desired pattern and causes the pattern to be etched on the wafer. It is also called photolithography. This is the part of the process that I will try to explain to the audience.

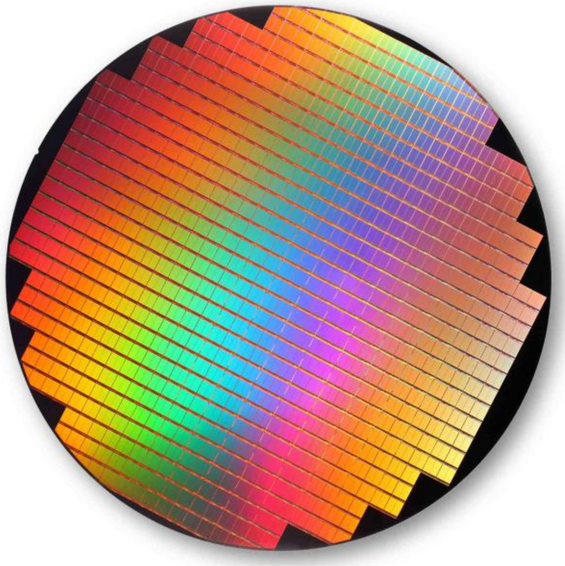

Figure 15. An example of a wafer containing square computer chips. [11]

3.1. How lithography works

In lithography a lot of computer chips are created at the same time. These chips are very small and are created in bulk on a thin silicon disc, called a wafer, with a diameter of 30 cm. Silicon is a metalloid and the eighth most common material on earth after for instance nitrogen, oxygen and carbon. It is most commonly found as silicon dioxide in sand, dust and rocks. Silicon is a semiconductor that is ideal to create extremely small transistors through the use of local doping by phosphor and boron. This are so called metal-oxide-semiconductor field-effect transistor or MOSFET for short. A transistor has three connections, a source, a drain and a gate. When a voltage is applied to the gate a current can travel from the source to the drain. It is basically an extremely small on and off switch. These extremely small transistors are created by doping specific small areas on the wafer. In order to make sure that only the correct areas are doped in this process, the rest of the wafer needs to be protected by a layer. Therefore the correct pattern must be etched out of this layer, which is called the resist. This etching is done through photolithography. The resist is a material that is sensitive to light. There are two different kinds of resist, one that hardens after exposure to light and another that is softened by it. Although these are quite different, the basic technique is the same. I will discuss the technique using a softening photoresist as example, it is also called a positive resist.

A wafer is first washed clean, as any pollution will ruin the chips, and then the remaining water is evaporated. After the cleaning process a layer of photoresist is applied to a wafer through a process called 'spin coating. See figure 13 for more details. With spin coating the resist is deposited onto the wafer, which is rotated at a high velocity (3000-6000 rpm). This way all the material will be equally distributed over the wafer's surface and any excess resist is simply spun off over the edges. A consistent thickness of this layer is very important in lithography, so this step is actually quite complicated to perfect.

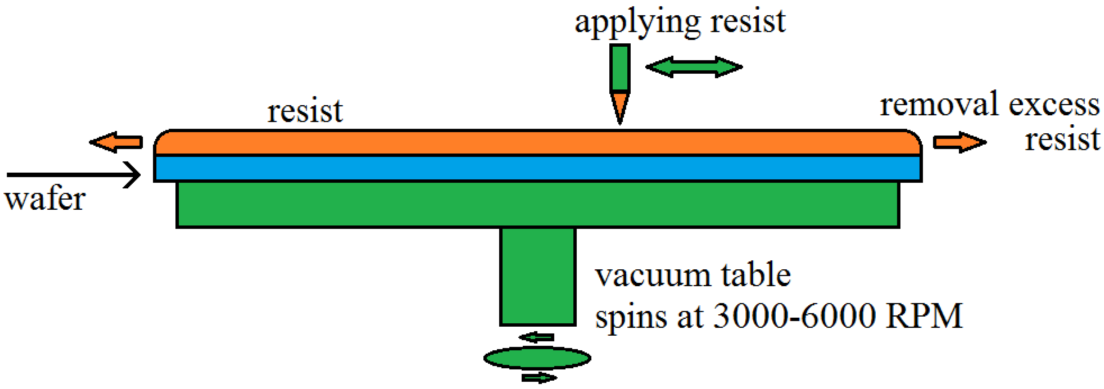

Figure 16. A schematic drawing of spin coating, where the resist is applied to the wafer.

A positive resist, used in lithography, becomes soluble in special liquids after it is irradiated with UV light. This means the irradiated resist can be washed away while the untreated photoresist will remain on the wafer. The next step is a process called etching. In the lithography industry plasma etching is commonly used. In this process plasma is used to remove the top layer of the substrate on all places that are not protected by the resist. The last step is the removal of the remaining resist using a chemical simply called the 'resist stripper'. The final product is a pattern on the wafer. This process is schematically illustrated in figure 17.

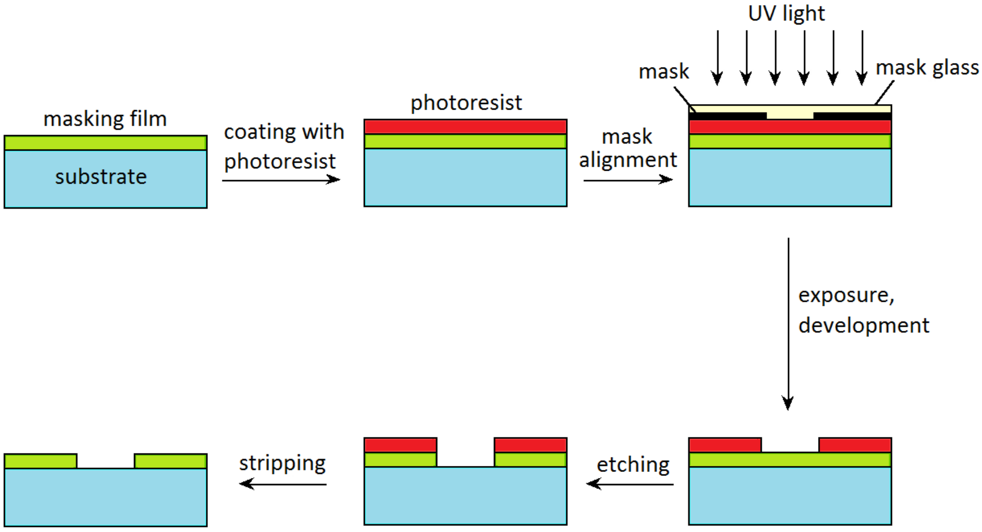

Figure 17. A schedule of the lithographic step in the chip production. [12]

The bottom layer consists of all the transistors, but on top of this all of the transistors need to be connected through electrical connections. Therefore another layer of metal is deposited on the first structure and this is processed through another lithographic step. This process is repeated over and over until a big structure of overlapping patterns is created which is the final product, the integrated circuit or chip.

3.2. The challenges

In the lithography industry the number of transistors on a chip has doubled roughly every two years and is known as Moore's law. It is named after Gordon Moore, co-founder of Intel, who predicted in 1965 that the number of transistors would double every year. In 1975 he changed this to every two years. Since then this has been the guideline for the computer industry. This law has driven the industry to new heights in performance and calculation power. It also meant that the products became better every year, but at the same time cheaper as well.
Because the size of chips remains the same, the transistors and therefore the patterns etched in the resist must become ever smaller, in order to fit on the chip. Since light is used in photolithography, this creates several issues. It is very hard to create an exact image of the pattern on the mask on the wafer. The industry uses an array of lenses to do this. The image created is four times smaller than the object. As the images need to get ever so smaller, the objects need to get smaller as well. This is not a big problem, but the way that light interacts with such a small object is. The resolution of the lens system starts to become an issue. The resolution is the ability of the imaging system to resolve different structures from one another. Objects that are closer to each other need more resolution to be distinguishable in the image. The angular resolution of two point sources that can still be resolved is given by the Rayleigh criterion for circular apertures:

$$\theta_{min} = \frac{1{,}22\lambda}{D}.$$

Here, θ_{min} is the minimal angular separation, λ is the wavelength of the used light and D is the aperture diameter. From this formula two solution can be found: using larger lenses, which increases the numerical aperture, or using light with a shorter wavelength. These things are done both in the industry, but the most is gained by going to light with a shorter wavelength. Currently deep ultraviolet, or DUV, is used by the industry. This has a wavelength of 193 nm and can be used to create structures as small as 32 nm. [13]. The state of the art in the industry is extreme ultraviolet light, or EUV, with a wavelength of only 13.5 nm, which is believed to be able to create structures of 7 nm or even smaller. [14] One of the problems with this technique is that EUV light is absorbed by most materials, even air. This means that the lithography needs to take place in vacuum, which is extremely hard since the intense light also excites atoms from the resist which need to be removed. Another challenge is to create mirrors for EUV, because EUV is absorbed by lenses. These mirrors are special mirrors with hundreds of coatings of 3 nm thick, which each reflect only a small part of the light, but work all together through constructive interference to reflect 60% of the light. [15]

3.3. The experiment

In this experiment we want to show the spectator how the resolution depends on the wavelength. A slide projector will be used to project an image using blue and red light consecutively. Or perhaps use two projectors that project the same image at the same time, one using blue light, the other using red light. This last option would allow the spectator to really compare the two. The size of the object is chosen in such a way that the structures will be imaged correctly in the blue light, but are blurry in the red light. The principle behind this is diffraction, where the wave characteristics of the light bend it around the object as well. This effect is reduced by smaller wavelengths. This should explain the spectator why the chip industry uses ever smaller wavelengths to create their chips. Next to this the basics of lithography will be explained on a poster. This will cover the production process of the integrated circuit as well as an explanation of the size of the transistors. In figure 18 a sketch of the setup can be seen.

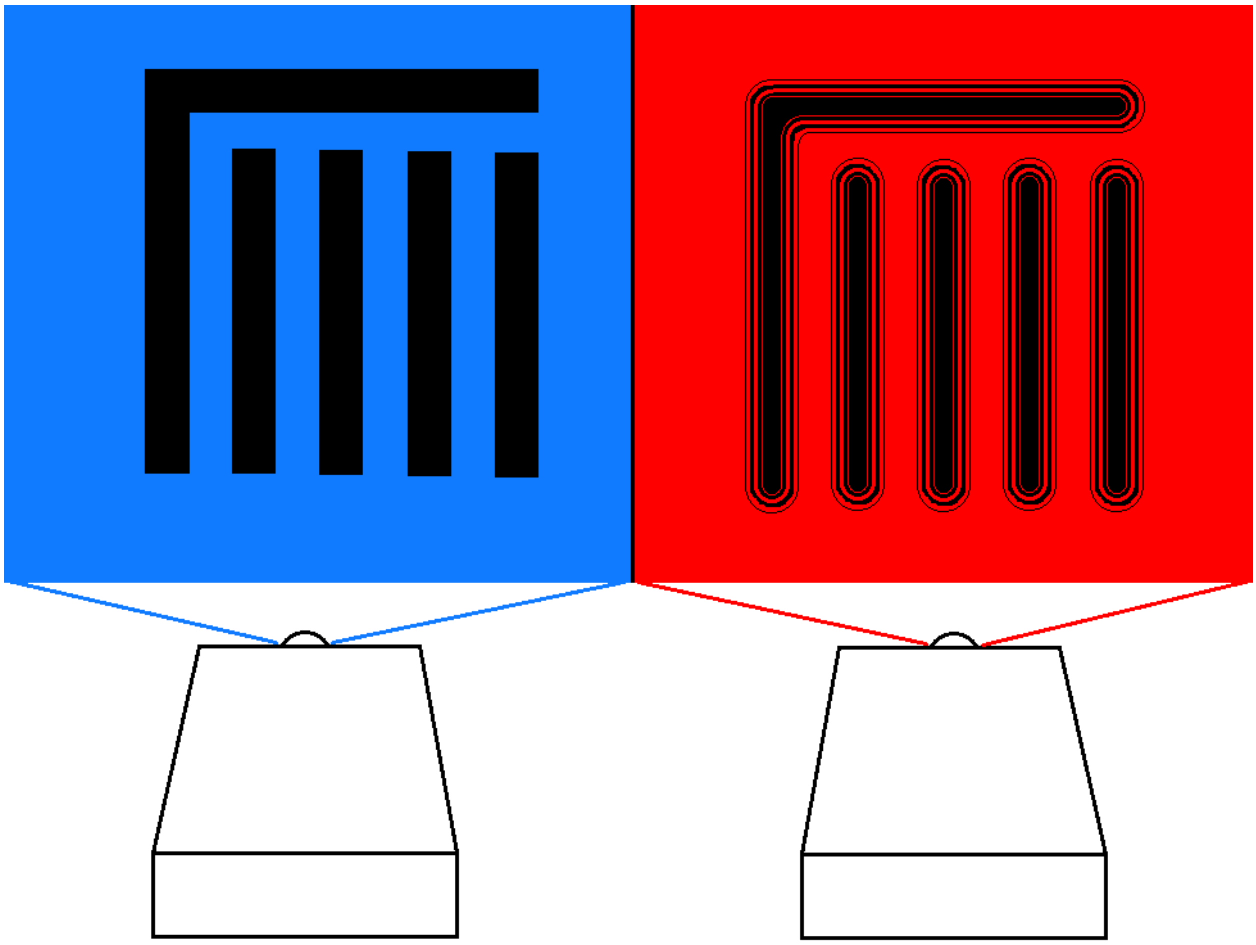

Figure 18. A sketch of the setup. The projector produces a sharp image with blue light, but the projector with the red light produces a blurry image due to diffraction.

4

Managing the project

4.1. Work description

Preparation

I started my project with some research in each of the subjects and tried to think of some simple experiments that could be done to explain the theory to a large audience of laymen. This would help me to guide the first year students during their PEP (propaedeutic end project), since I should have a clear picture of what they should accomplish.
At the welcome lunch in the week before their five-week project started, I presented the four subjects to the students, after which they were allowed to choose the subject of their liking. This presentation can be found in Appendix 1. We expected to have 16 students that we could divide into four groups of four, but we only had eleven students in total. After the students had chosen their favorite subjects, we found that nobody wanted to do lithography. My supervisors and I than decided to drop lithography as a subject for the students, so that they could do something they liked. We also decided that I would do lithography along with managing the students.

Guiding the students

On the first day of the PEP, I sat down with the students and supplied them with a work description and told them what I expected them to do in the first week of their PEP. For each of the subjects I made a handout to give them a clear idea what to do the first couple of days. These handouts can be found in appendix 2 till 5. Since we dropped the lithography subject, the fourth handout was not used. I planned the first week to be all about research and background information, I invited them to look for information in books and online to gain more insight in their subject.
It was clear to me that polarization was the hardest subject for the students, as they only had a very limited knowledge about this subject. I proposed to give them a lecture about it, which they took gladly. For this I used a lecture about polarization from the Optics course, which is taught by my supervisors. They gave me permission to use these slides. In about 90 minutes I tried to teach them the basics of polarization and after that, they understood the subject a lot better.

In the second week I instructed the students to start designing several experiments, which should show a specific aspect of the subject. I tried to let them think about possible practical issues and how to address those. I had a meeting with each of the groups to figure out how far they progressed in the first week and to redirect their efforts where necessary. Especially the LED group needed some more guidance as they did not accomplish enough in the first week and one of the students focused on an irrelevant subject. The cloaking group was quite quick to propose the same experiments that I already pitched to them during the welcome lunch, so I supplied them with more background reading about reflection and refraction. The polarization group now understood the theory, but struggled to design some experiments, so I supplied

them with a polarizer and cellophane so they could experiment for themselves. This and some suggestions I gave them helped to design several experiments.
In the third week I have sent the students an overview of the things they should keep in mind while designing their experiments, like costs and how to present them. This can be found in Appendix 6. After this I set up an appointment with one member of the supporting staff to talk to the students, to see if they needed to make any alterations to their designs and give them a realistic view on how it can be made. I also told the groups to do some research into the cost of the experiments and to get in touch with supplying companies to get an estimate price range for the most expensive components, i.e. the mirrors. This week was used to finalize their designs of the experiments and to start thinking about how to explain each of them to a general audience. I supplied the cloaking group with four small mirrors, so they could try to 'cloak' a small object and try to figure out possible issues for their large scale design.

In the fourth week of the PEP I got the students to work on the posters that explain each of their experiments. These posters should explain the theory and how the experiments work in a clear way, in order that the visitors of the Science Center are interested in reading them and can understand the basics of each subject. I decided to let them make a first draft of their poster for me to look at and give them feedback about it. The students also started to work on their final presentation.

In the final week for the students I let them present to me before their final presentation, so I could give them some feedback on it. I also gave them another round of feedback on their posters. After they had finished their presentation and poster, I prepared for a meeting with the supervisors to grade the students. I have added the posters of the groups in appendices 8 till 10.

Organizing the project

In the first week I made an appointment with an employee of the Science Center Delft to discuss the project and to find an appropriate room to place the exposition. I met with her in the second week, where I gave her an overview of the experiments that I envisioned. She was really excited about all of the ideas that I pitched. We than looked at several rooms that could be available for our exposition. During this appointment we also talked about what the Science Center organizes to attract attention. They give a lot of workshops to children, where they can build some things that are related to science. Since we want to look at the spectra of different light sources, I suggested a very simple workshop where you can build a basic spectrometer in only five minutes with some readily available materials. She liked this idea as well and asked if I could work this out on paper and send this to her. The workshop that I created can be found in Appendix 7.

During the second week I had several small conversations with my supervisors to update them and to see how we could better help the students. I also talked to two members from the support staff of the Optics section. I discussed the experiments that I had thought off to see if they had any practical suggestions for them. With these suggestions I could better guide the students and let them think about some practical issues.

In the fourth week I had further contact with the Science Center and went to inspect the room with the support staff from the optics department. This helped us to better plan the experiments and figure out what materials we need to create the exhibition. I contacted the director of the Science Center about some questions that arose from this visit. I also talked to Prof. Paul Urbach about the possible importation of several holographic plates from Russia, some of which could be displayed in the Science Center as well and would be a nice addition to our exhibition.

In August I will also assist the support staff of the Optics department with the realization of the experiments.

4.2. Evaluation

While looking at the results that each group has presented, I think the project as a whole went well. We have designed ten experiments to be displayed at the Science Center and made posters to explain the principles behind them. I think I have been able to teach most of the students something new about optics, especially the polarization group, which only knew the rudimentary basics. Looking at their understanding of the subject in their presentation, I think the course that I gave them was quite good. This group was the best of the three groups, because of the effort each of them put into the project and the fact that they were motivated. They also communicated very well with me and with each other. I thought they had the most difficult subject, but they did the best work. The fact that we communicated a lot with one another helped to achieve this goal and put them in the right direction. They also finished their draft and final posters a couple of days before the deadline, so I had the possibility to correct them a couple of times extra. The result was therefore very good and the subject clearly explained.

The cloaking group worked fast and were motivated, but one of the group put his effort in the wrong things for most of the time. I had to redirect him several times and then he would still do the thing that he had on his mind. This was sometimes a bit annoying to deal with for me, but especially to his teammates. In the end he did contribute and the group produced a good result. But it showed me that it is very important to make sure that everybody in a team works together instead of all doing their own thing.

I thought it was hard to motivate the LED group. They were the weakest group out of the three and their work progressed slowly in my opinion. I talked with them on several occasions to watch their progress and direct their efforts. I think most of them spend too little time on the subject, especially in the first two weeks of the project. In an evaluation form that I asked them to fill out, they complained that they did not know what was expected from them, while that was stated very clearly in the handout I presented them on the first day. They also said they thought the subject was too easy, and it was the easiest subject indeed, therefore I expected them to be very quick to finish their research. Unfortunately, they seemed to postpone their tasks instead of actually doing them. In the conversations I had with them I always ended by asking if it was clear what each of them had to do, so I thought it was strange that one of them commented that he did not know what to do until the last week. I would have liked that they had accomplished a lot more, but I could not get them to get to the job they had to do. Since only one member of the group was present enough and they did not communicate enough, I did not know how far they were with their part of the project. Only in the fourth week I really noticed that they were lacking behind and I had to push them quite hard to finish their poster and presentation. In the end the result was just barely up to par, but missed some of the tasks they were given.

At the end of the project I graded the students with my supervisors and it became clear that one of them thought that the students should have done a bit more experiments and report on that as well. Since that was not part of their assignment, it cannot be blamed on the students, but it clearly showed that I should have discussed the project more with all of the supervisors before the students started, instead of only one.

What I learned during this project is that it is very hard to have a group of students work independently towards a goal, without telling them exactly have to achieve it. I noticed that the students really looked at me for a day to day guidance, instead that they thought about this themselves. This made my job quite a bit more difficult as I had to guide and redirect them a couple of times a week. If I had known this beforehand I would have prepared myself better. I also learned that it is extremely difficult to motivate a group of students that just want to do enough to pass the project.

Communication is probably the most important part of such a project, where a lot of people work together. I noticed that in two of the three groups the communication went quite well and that their output was good as well. Those two groups communicated well amongst each other and to me as well. The third group communicated a lot less, both to me and one another, which caused a bit of friction and sometimes stagnation. One member of this group did not honour some agreements and did not communicate for a couple of days. This resulted in the fact that the cooperation suffered as it was sometimes unclear what was done already. This resulted in the fact that they did not submit a draft poster and that the final result was not that good and missed parts of the research that I had told them to do.

5

Conclusion

This project has been successful. The first year students designed ten different experiments for the Science Center and created posters to explain the physical principle behind them. The three groups of students performed each at a different level. The polarization group had good motivation, communicated well and put in a lot of effort. They performed the best. The cloaking group were all motivated and put in a lot of effort, but fell short on communication and direction of their efforts. They performed slightly worse than the polarization group. Finally the LED group were not motivated enough and only one of them really put in an effort. Their communication was quite bad and their final result was mediocre.

I have learned that in management it is very important to keep the groups motivated and make sure they communicate well within the group and to their supervisor as well. A point of improvement for myself is that I should communicate more with all of my supervisors to find out exactly what they all expect out of the project.

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Appendix 1 – Presentation

Wat gaan we doen?

- Keuze uit vier onderwerpen:
  - 'Cloaking'
  - Polarisatie
  - LED-verlichting
  - Fotolithografie
- Opzet:
  - Onderzoek
  - Bouwen experiment
  - Poster maken
  - Verslag schrijven
  - Presenteren

TUDelft Challenge the future 1

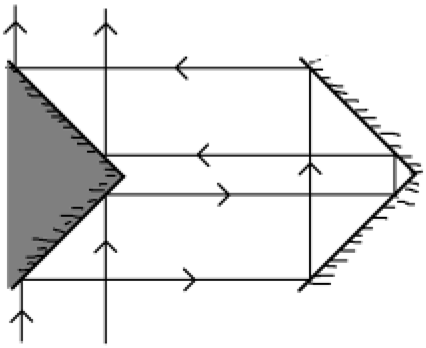
Cloaking

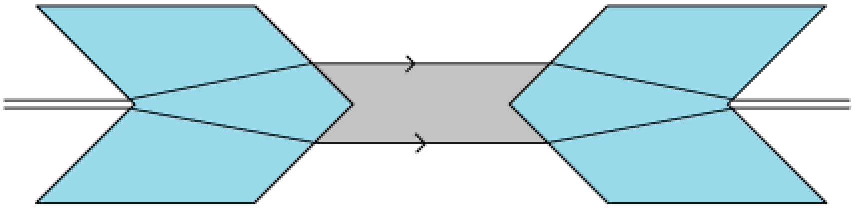
- Iets onzichtbaar maken
- Dit is (nog) niet mogelijk in het hele visuele spectrum
- Dus we gaan trucs gebruiken
- https://www.youtube.com/watch?v=oJb9RnAVDuE

TUDelft Challenge the future 2

Cloaking

- Wat wordt hier gedaan?
- Zijn er andere opties?
- Wat zijn de voor en nadelen?

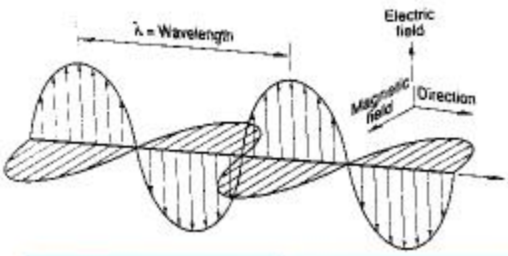




TUDelft

Polarisatie

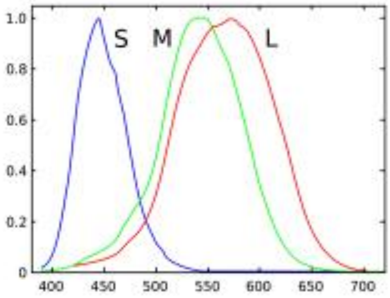
- Wat is polarisatie?
- Wordt gebruikt in:
  - LCD schermen
  - Zonnebrillen
  - 3D films
  - Reflecties verwijderen
- Hoe werkt dit precies?
- Wat kun je ermee?
- Wat is het verschil met holografie?

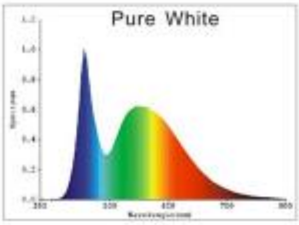


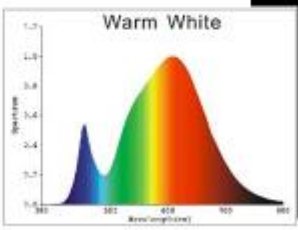
TUDelft

LED-verlichting

- Onze ogen zijn gevoelig voor drie spectra, rood, groen en blauw.
- RGB-systeem wordt gebruikt om wit licht te simuleren.
- Wit licht kan dus op verschillende manieren gemaakt worden







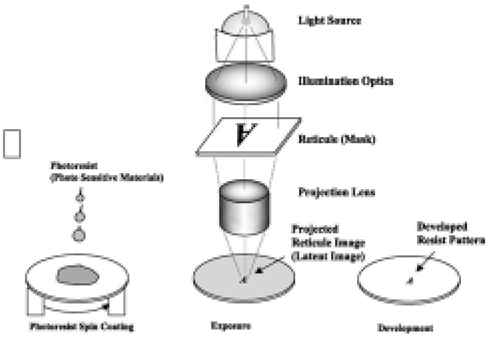
LED-verlichting

- In de huidige LED lampen worden blauwe LED's gebruikt.
- Door een fluorescente laag wordt dit omgezet in een spectrum die wij ervaren als licht

- Wat betekent alle info op de verpakking?

Fotolithografie (ASML)

- Wordt gebruikt bij het etsen van patronen op chips
- Door een lichtgevoelige laag bloot te stellen aan licht (of niet) kun je het gewenste patroon op de chip overbrengen.
- Hoe maak je de paronen zo klein mogelijk?
- Wat is het effect van:
  - de golflengte?
  - de vergroting?
  - de lens?



Wat lijkt jullie het leukste om te gaan doen?

- 'Cloaking'
- Polarisatie
- LED-verlichting
- Fotolithografie

Appendix 2 – Handout cloaking group

PEP – Cloaking

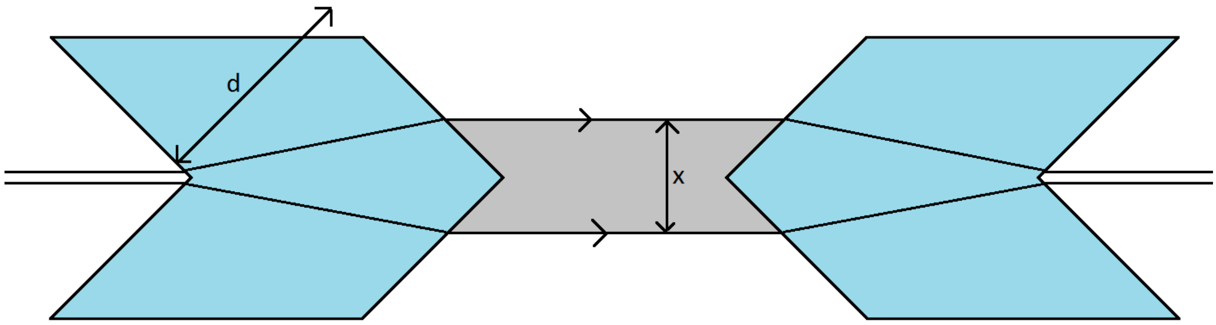
Bij dit project gaat het erom dat je een of meerdere experimenten ontwerpt waarbij cloaking duidelijk naar voren komt. Het belangrijkste hierbij is het ontwerp en de bijbehorende uitleg voor in het Science Center. Het bouwen zelf is van inferieur belang en er zijn technici aanwezig die dit voor een groot deel voor hun rekening zullen nemen.

Eigen input van jullie kant qua verschillende ideeën of ontwerpen wordt zeer gewaardeerd. Ga dus op internet kijken wat voor leuke experimenten gedaan kunnen worden, die gerelateerd zijn aan dit onderwerp. De inspiratie hiervoor kan overal vandaan komen: YouTube, Wikipedia, allerlei musea en natuurlijk de vele artikelen die hierover te vinden zijn (bv: Google Scholar)

Als achtergrondinformatie moeten jullie eerst hoofdstuk 30 en 31 lezen van Wolfson, over reflectie, refractie en optische instrumenten.

Bereken daarna de breedte van het 'onzichtbare' gedeelte, x, als functie van de dikte, d, van het water in de opstelling van figuur 1. Gebruik hiervoor ook example 30.2 uit Wolfson. De stralen komen onder 45 graden binnen en de brekingsindex van water is 1.33.

Hoe groot is d wanneer je een gecloakte ruimte van 50 cm wilt creeëren?



Figuur 1. Bereken x als functie van d.

Ga na wat de limieten zijn van de besproken technieken, denk aan de invalshoeken, zijwaarts en ook omhoog en omlaag. Hoe kun je ervoor zorgen dat dit effect wordt geminimaliseerd bij de uitvoering van het experiment? Denk hierbij aan bijvoorbeeld crowd control.

Appendix 3 – handout LED group

PEP – Light Emitting Diode

Bij dit project gaat het erom dat je een of meerdere experimenten ontwerpt waarbij het nut van LED verlichting duidelijk naar voren komt. Het belangrijkste hierbij is het ontwerp en de bijbehorende uitleg voor in het Science Center. Het bouwen zelf is van inferieur belang en er zijn technici aanwezig die dit voor een groot deel voor hun rekening zullen nemen.

Eigen input van jullie kant qua verschillende ideeën of ontwerpen wordt zeer gewaardeerd. Ga dus op internet kijken wat voor leuke experimenten gedaan kunnen worden, die gerelateerd zijn aan dit onderwerp. De inspiratie hiervoor kan overal vandaan komen: YouTube, Wikipedia, allerlei musea en natuurlijk de vele artikelen die hierover te vinden zijn (bv: Google Scholar)

Wij willen graag dat jullie een aantal dingen voor het publiek uit gaan zoeken:

- De geschiedenis van de elektrische verlichting, van gloeilamp via TL naar LED.
- Een uitleg van alles wat er aan info op een verpakking van een LED lamp te vinden is:
- Temperatuur van licht
- Wattage 3W → 23W
- A^+ energieklasse
- Hoeveelheid lumen (vergelijk met bv een zonnige dag buiten)

Daarnaast is het belangrijk dat jullie het RGB systeem gaan onderzoeken en hoe hieruit wit licht gemaakt kan worden.

Als vervolg daarop moeten jullie fluorescentie gaan onderzoeken om uit te kunnen leggen hoe je van blauw licht wit licht kunt maken.

Tot slot is het ook belangrijk om te weten hoe een LED licht produceert, dit is een gevorderd onderwerp, maar ik denk dat jullie dit wel kunnen.

Appendix 4 – handout polarization group

PEP – Polarisatie

Bij dit project gaat het erom dat je een of meerdere experimenten ontwerpt waarbij polarisatie het nut van polarisatiefilters duidelijk naar voren komt. Het belangrijkste hierbij is het ontwerp en de bijbehorende uitleg voor in het Science Center. Het bouwen zelf is van inferieur belang en er zijn technici aanwezig die dit voor een groot deel voor hun rekening zullen nemen.

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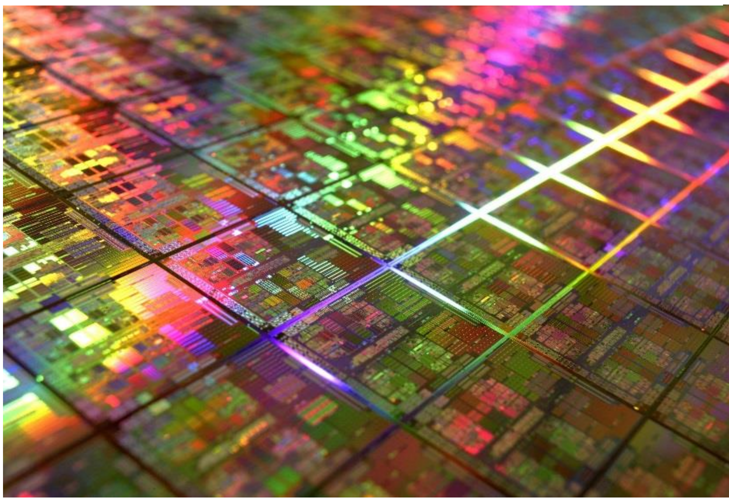
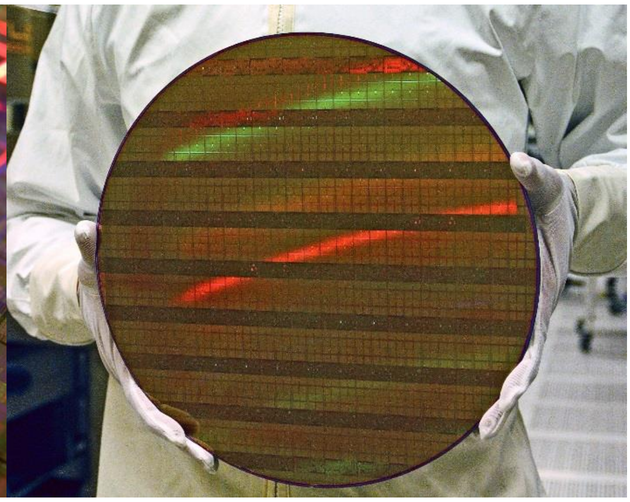
Allereerst is het aan te raden om hoofdstuk 29, elektromagnetische golven, en 30, reflectie en refractie, uit Wolfson te lezen, met name de delen over polarisatie.

Voor extra achtergrondinformatie zullen we voor kopieën uit het optica boek van Hecht zorgen. Hierin wordt een stuk dieper ingegaan op de verschillende soorten polarisatie, LCD schermen en ook een paragraaf over holografie. Dit laatste onderwerp is erbij gestopt om het verschil tussen hologrammen en 3D-fotografie uit te leggen.

Jullie kunnen ook veel informatie op internet vinden over de interessante dingen die met polarisatie worden gedaan. Probeer uit te zoeken hoe een polarisatiefilter werkt. Duik daarna wat dieper in de techniek van 3D-films in de bioscoop. Wat zijn de verschillen in materiaal die nodig zijn voor deze techniek? Zoek ook uit wat er in het plaatje bovenaan de pagina gebeurt.

Appendix 5 – handout lithography group

PEP – Lithografie

Bij dit project gaat het erom dat je een of meerdere experimenten ontwerpt waarbij de werking van lithgrafie duidelijk naar voren komt. Het belangrijkste hierbij is het ontwerp en de bijbehorende uitleg voor in het Science Center. Het bouwen zelf is van inferieur belang en er zijn technici aanwezig die dit voor een groot deel voor hun rekening zullen nemen.

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Om te beginnen lijkt het me handig om de optica hoofdstukken, 30, 31 en 32 in Wolfson, te lezen. Hierbij is het vooral belangrijk om te letten op interferentie en lenzen.

Hierna heb ik een rapport over lithografie uit mijn eerste jaar, om jullie een indruk te geven waar lithografie om gaat en hoe het werkt.

Als vervanging voor de ingewikkelde lenzensystemen die bij ASML worden gebruikt, gaan wij afbeelden met een enkele lens.

Probeer een lijst te maken van alles wat van invloed is op de kwaliteit van de afbeelding en hoe we dit kunnen gebruiken in een experiment.

Zoek extra informatie op internet over de algemeen gebruikte verkleining in lithografie.

Appendix 6 – handout experiments

Experimenten uitwerken

Welke experimenten willen jullie gaan doen?

Wat wil je duidelijk maken met het experiment?

Heeft het genoeg appeal of een wauw-factor?

Check de maakbaarheid en ook de kosten van elk experiment.

Is er een onderdeel te sponsoren?

Zijn bepaalde onderdelen al aanwezig?

Is het robuust genoeg? (kinder- en idiot-proof)

Denk na over een eventuele afscherming.

Bedenk hoe je elk experiment wilt gaan presenteren.

Geef exacte maten voor je ontwerp.

Beschrijf *alles* wat je nodig hebt. (Ook tafel/verhoging/lichtbron ed.)

Wil je alles uitleggen aan de hand van een poster of een andere manier?

Is het duidelijk genoeg voor een kind? (let ook op kijkhoogte)

Denk ook na over de ruimtelijke indeling van al jullie experimenten samen.

Begin ook al met het uitwerken van de uitleg icm plaatjes. Doe dit beknopt en per experiment.

Appendix 7 – Workshop Science Center

Workshop spectrometer maken (5 à 10 minuten)

Benodigdheden:

- Kartonnen koker van keukenrol (of wc-rol).
- Onbeschreven CD of CD-rom (hoe goedkoper, hoe beter).
- Duct tape.

Zo maak je het:

Knip de CD 3 keer doormidden, zodat je 1/8 CD overhoudt. (figuur 1)

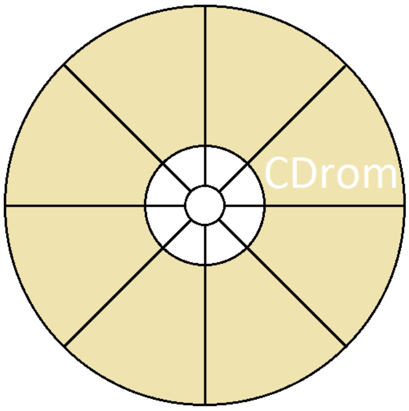
Pak een stukje duct tape en druk dit stevig op de folie van de CD (de kant waar het merk op staat).

Trek dit er vervolgens van af, de folie blijft aan de duct tape plakken, en dit kun je weggooien.

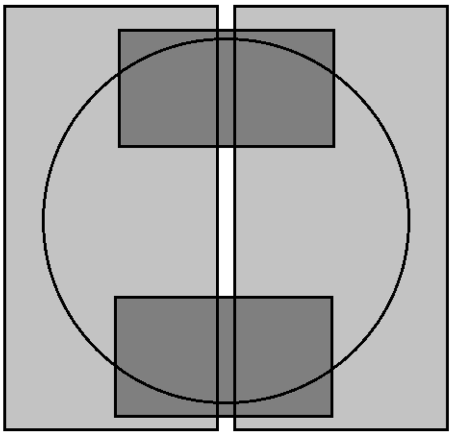
Plak vervolgens één kant van de keukenrol dicht met duct tape, maar laat een dunne spleet over (circa 1mm). (figuur 2)

Plak nu de CD met duct tape aan de andere kant van de koker. Zorg hierbij dat de CD correct is uitgelijnd met de spleet aan de andere kant van de koker. De spleet moet loodrecht staan op de straal van de CD. (figuur 3)

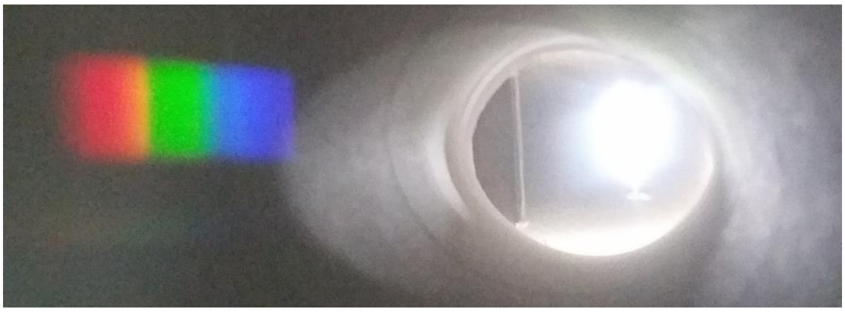
De spectrometer is klaar! Kijk door de koker naar een lamp of naar buiten en zie uit welke kleuren het licht bestaat.



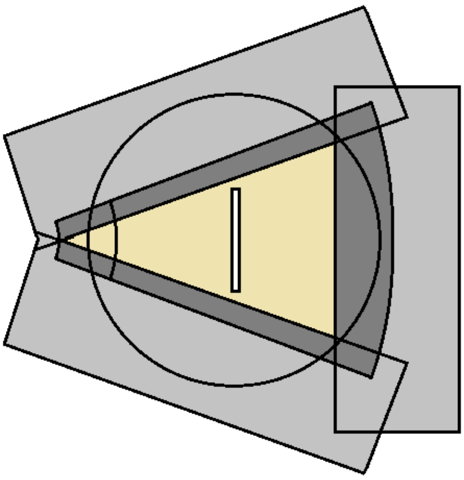
Figuur 2. knip de CD in 8 stukken



Figuur 3. Tape één kant van de koker dicht, op een smalle spleet na.



Figuur 4. Foto gemaakt van natuurlijk licht door een zelfgemaakte spectrometer.



Figuur 3. Zorg dat de CD correct met de spleet is uitgelijnd.

Figuur 5. Foto gemaakt van LED lamp met een zelfgemaakte spectrometer. Het grootste verschil met natuurlijk licht is de missende blauwe band.

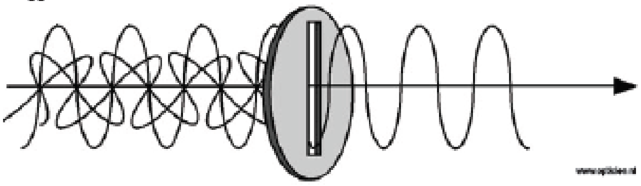
Appendix 8 – Poster polarization group

Hoe werkt een 3D TV?

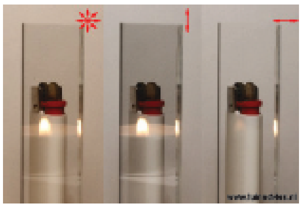
Amber Mozes, Jesper van Winden,
Rik Jansen en Vincent Heusinkveld

Polarisatie

Natuurlijk licht beweegt als golven die in alle richtingen trillen. Wanneer je licht door een polarisatiefilter laat gaan, trillen de golven nog maar één kant op. Dit komt doordat de gleuven in het filter maar één richting op staan. Op dezelfde manier kan reflectie weggefilterd worden.

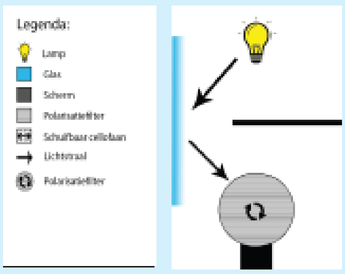


Er zijn verschillende soorten polarisatie: onder andere horizontaal en verticaal. Deze polarisatierichting wordt bepaald door de richting van de gleuven in het filter. Het wordt gebruikt in de foto-, film- en brillenindustrie om kleur in foto's een mooi effect te geven en om weerspiegelingen in glas en water weg te halen. Deze reflecties in glas kunnen met een horizontaal filter worden weggehaald zoals in de afbeelding hieronder te zien is.



Experiment 1 - Reflectie

Als je in de auto zit is kan de reflectie van de zon op het natte wegdek in je ogen schijnen. Dit kan natuurlijk gevaarlijk zijn. Het volgende experiment laat zien dat de reflectie met een polarisatiefilter weggehaald kan worden.



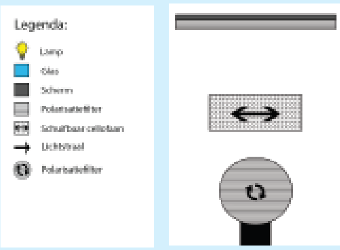
Door het filter te draaien kun je de weerspiegeling laten verdwijnen. Als je het goed doet zie je Teddy verschijnen! Op dat moment zijn de gleuven horizontaal gericht, waardoor de reflectie verdwijnt.

In het dagelijks leven zit dit ook in je skibril en zonnebril. Hierdoor schijnt de reflectie van regenwater of sneeuw op de skipiste niet in je ogen.

Cellofaan

Er zijn materialen die invloed hebben op de richting van polarisatie. Een voorbeeld hiervan is cellofaan, een folie dat vaak gebruikt wordt om bloemen en cadeautjes in te pakken.
Wanneer horizontaal gepolariseerd licht door een laag cellofaan gaat wordt het omgezet naar verticaal gepolariseerd licht en andersom. Dit kun je zelf ontdekken in het volgende experiment.

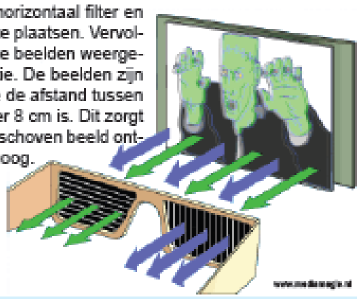
Experiment 2 - Cellofaan



Draai het polarisatiefilter zo, dat je niks meer ziet. Schuif vervolgens het cellofaan ertussen en kijk wat er gebeurt.
Een LCD-scherm is van zichzelf gepolariseerd. Op het moment dat je niks meer ziet werken het filter en het scherm elkaar tegen. Als je dan het folie ertussen schuift wordt de polarisatie weer omgedraaid en komt er weer licht doorheen.

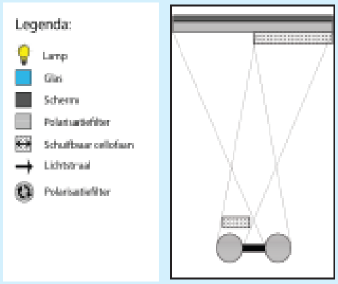
3D-Televisie

Polarisatie wordt ook toegepast in 3D-televisies. Dit werkt door voor het ene oog een horizontaal filter en het andere oog een verticaal filter te plaatsen. Vervolgens worden er op de televisie twee beelden weergegeven, met elk een eigen polarisatie. De beelden zijn met twee cameras opgenomen die de afstand tussen de ogen nabootsen welke ongeveer 8 cm is. Dit zorgt ervoor dat het ene oog een iets verschoven beeld ontvangt ten opzichte van het andere oog.
Je hersenen maken van deze 2D-beelden weer een 3D-beeld. Je ziet het beeld in 3D omdat je ogen diepte kunnen inschatten door de afstand tussen je ogen.



Experiment 3 - 3D-Beeld

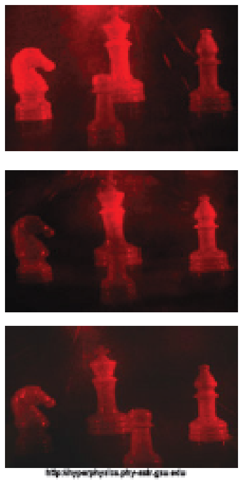
Het is mogelijk om met een polarisatiefilter je eigen 3D-TV opstelling te maken. Dit wordt in het voglende experiment gedaan. Het is zodanig opgezet dat je linkeroog het rechter gedeelte van het scherm ontvangt en je rechteroog het linkerdeel van het scherm.

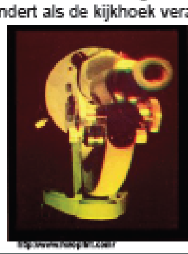


Het beeld gaat eerst door een horizontale polarisator, zodat het licht horizontaal gepolariseerd wordt. Door cellofaan voor de helft van het scherm te zetten wordt deze polarisatie omgedraaid naar verticaal. Zo komt het niet binnen bij het rechteroog. De cellofaanlaag voor het linkeroog draait de polarisatie weer naar horizontaal zodat het wel door het linkerfilter kan.

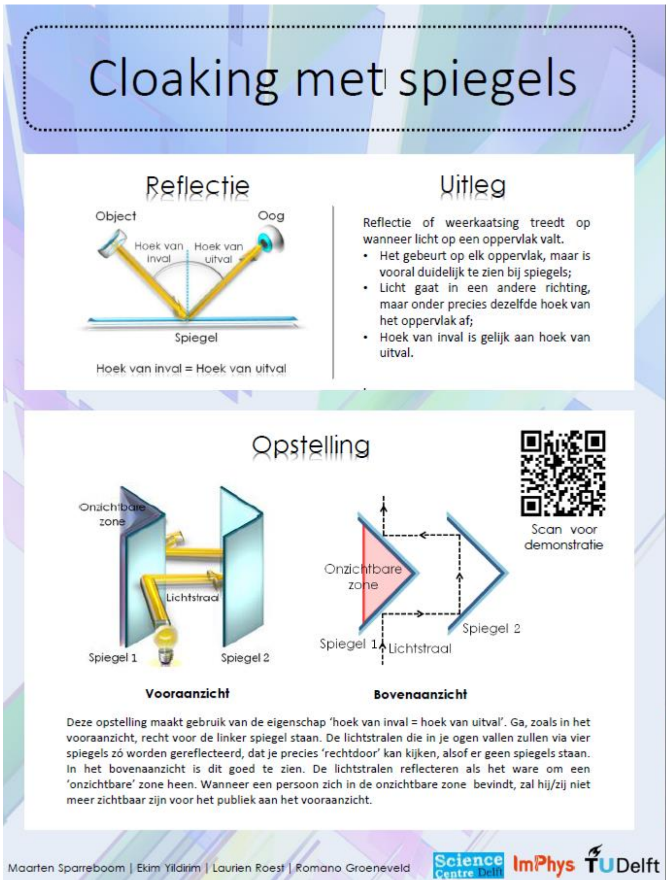
Holografie

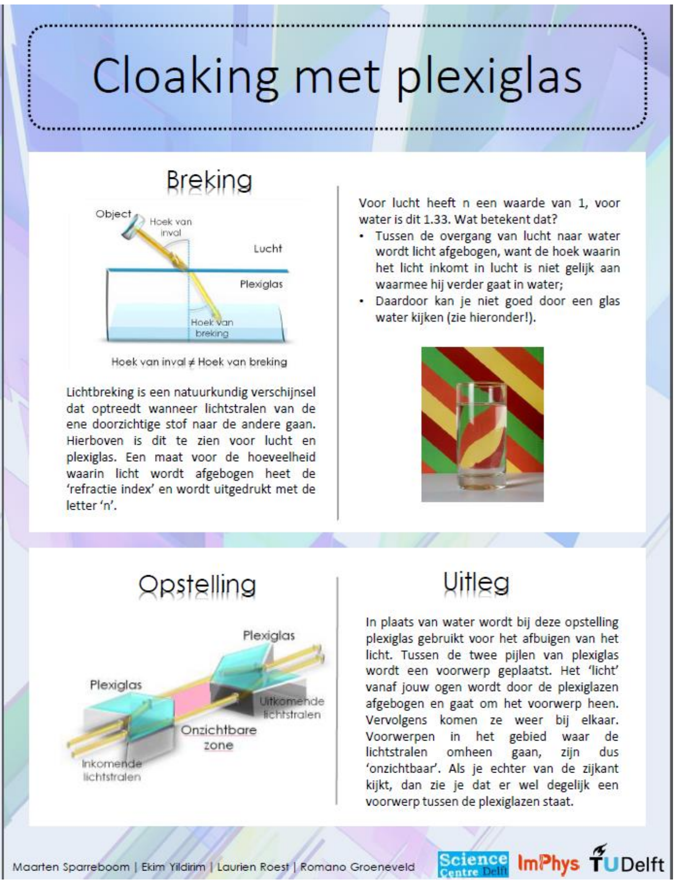
Holografie is het maken van een driedimensionale afbeelding van een voorwerp. Het is de meest precieze techniek om 3D-afbeeldingen te maken. Om een hologram te zien heb je geen bril of andere hulpmiddellen nodig. Alleen moet het licht dat op het hologram valt vaak een bepaalde kleur hebben. Hologrammen worden onder andere gebruikt op creditcards en bankbiljetten.
Op de drie afbeeldingen hiernaast is een hologram te zien die vanuit verschillende hoeken is gefotografeerd. Je ziet dat de afbeelding verandert als de camera de foto vanuit een andere hoek maakt. Het is alsof het echt voor je staat en je eromheen kunt kijken. Dit is anders dan bij een 3D-afbeelding. Hierbij blijft het beeld hetzelfde onder welke hoek je ook kijkt. Het effect van een hologram is duidelijk te zien in de afbeeldingen hiernaast waar goed de verandering van de positie van de schaakstukken gezien kan worden.
Hieronder is een afbeelding van een hologram van een microscoop te zien. Een hologram geeft heel goed de diepte weer. Je kunt zo voor het hologram gaan staan dat je door de microscoop kunt kijken. Je zou dan een vergrote computerchip kunnen zien. Dit laat goed zien hoe het beeld verandert als de kijkhoek verandert.

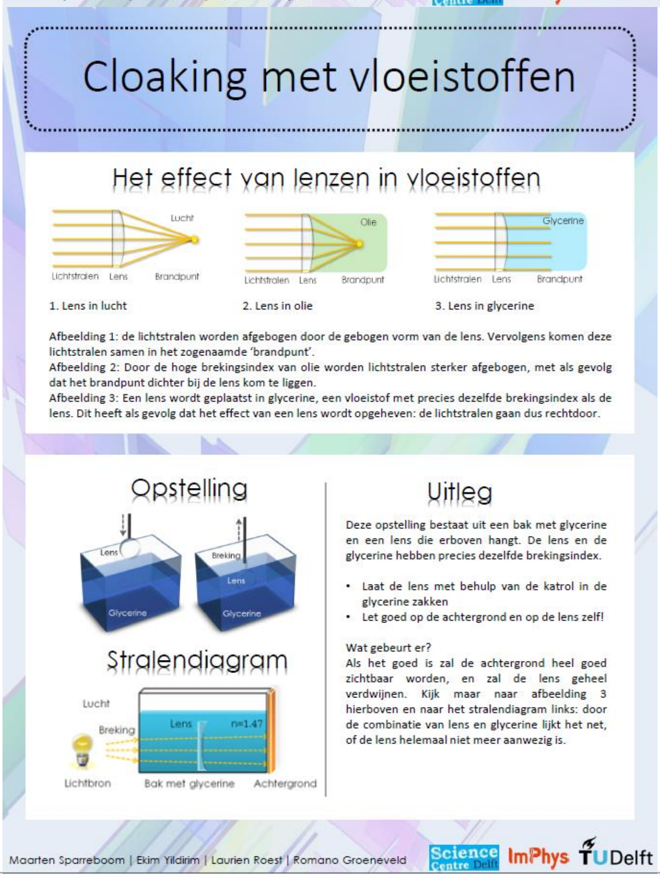




Appendix 9 – Posters cloaking group







Appendix 10 – Poster LED group