Thin Films

Nano-Link

Center for Nanotechnology Education

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Thin Films

Abstract

In this module, students will learn about the optical properties of thin films. Students will perform an experiment where they will apply a thin film to a piece of card stock paper. The students can then observe the optical properties of the thin film.

Outcomes

Throughout this module, students will learn about:

- Snell's law
- Reflection
- Refraction
- Applications of thin films interference

Prerequisites

Students should have some exposure to the following physical science concepts typically encountered in eighth grade science:

- The wave nature of light
- An introduction to reflection and refraction.

Science Concepts

- Wave nature of light
- Reflection and refraction
- Snell's law
- The relationship between light wavelength and color
- Constructive and destructive interference

Nanoscience Concepts

- Optical properties of films at the nanoscale

Background Information

There are several overlapping concepts that contribute to the phenomenon of thin film interference. These concepts are being applied at the micro- and nanoscale to create more secure computer screens, biological sensors, anti-reflective (AR) coatings, measurement devices, and beautiful gift ribbons.

Figure 1 Refraction of light by water makes the pencil appear to bend at the air - water interface

When light strikes the surface of a transparent material like glass or water, a portion of the incoming light will be reflected. The remaining portion will pass through the material, but because the speed of light in the material will differ slightly from that outside it, the light will

slightly change direction at the interface between the two materials. This bending of the light ray is called refraction, and is familiar to anyone who has placed an object in a glass of water, like the pencil shown in Figure 1.

The amount of refraction, or light bending, by the material depends on its refractive index (or equivalently, its index of refraction). The refractive index is designated "n" and is defined as the ratio of the speed of light in a vacuum (written as c to the speed of light in the material, written as v: $\eta = c/v$

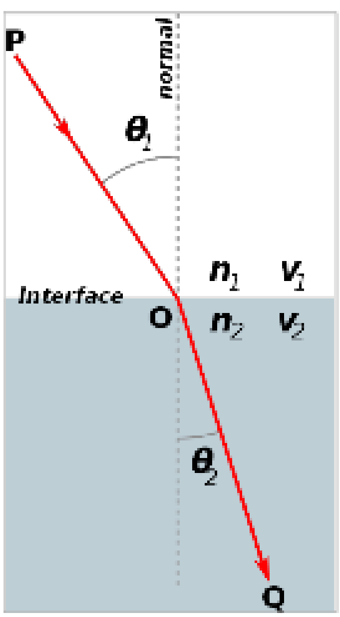


Figure 2 – diagram of light ray

The refraction angle can be predicted using Snell's Law, which relates the angle of the incoming light, the angle of the refracted light, and the refractive indices of the materials on each side of the interface. Refer to Figure 2, which diagrams a light ray coming from a medium with refractive index n_1. The ray makes

an angle of θ_1 with a line perpendicular to the surface, called the "normal". When the light passes into the second medium with a refractive index n_2, the angle to the normal changes to θ_2 due to refraction Snell's Law relates all these quantities:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

where n_1 and n_2 represent the refractive indices of the two media, and θ_1 and θ_2 represent the angles of light with respect to the normal, which is perpendicular to the interface between the media. Snell's Law uses the sine of the angles, rather than the angles themselves, to make the equality.

Wave Interference

In many respects, light behaves like an oscillating wave, similar to a wave traveling on a string or ripples on the surface of a pond. All waves obey the principle of superposition. This means that when two waves interact, they may add or subtract, depending on how they overlap. If the peak of one wave overlaps with the same-sized peak of a second wave, the result will be a peak twice as high. This is known as constructive interference, and is shown in Figure 3. On the other hand, if the peak of one wave overlaps with the trough (low point) of the second wave, the two waves will cancel each other out, a result known as destructive interference. The position of the peak or trough is referred to as the phase of the wave; destructive interference occurs when the two waves are "out of phase".

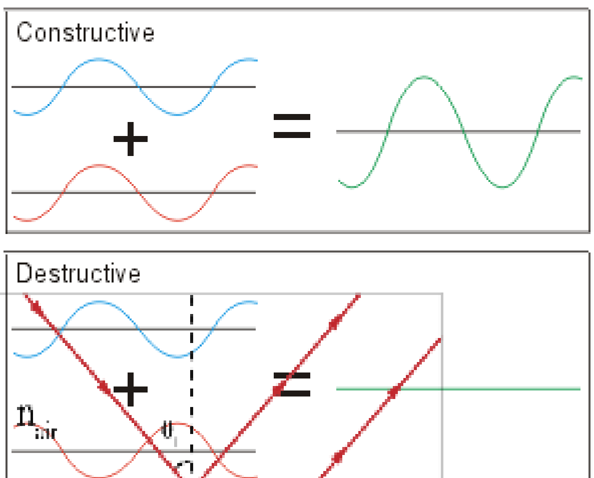
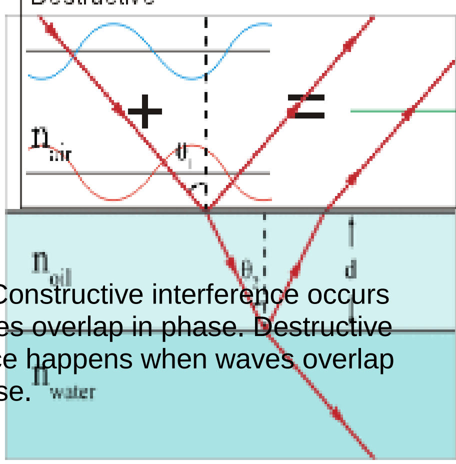


Figure 3. Constructive interference occurs when waves overlap in phase. Destructive interference happens when waves overlap out of phase.



Now consider what will occur when light strikes a thin film of a transparent material resting on another transparent material. An example of this is a thin film of oil on water. The light rays will travel in lines like those shown in Figure 4.

As shown in Figure 4, the incident light hits the thin film, and some of it is reflected, some passes through the thin film and is reflected off the lower boundary, and some continues on into the water below. The light that passes through the thin film and reflects back out of the film will combine with the light reflected from the top of the film. As the light that reflects off of the lower boundary must travel a longer distance than that from the upper boundary, the two light rays may no longer be in phase. (In addition, there is a phase change at the reflection surface in certain cases, the details of which are beyond d the scope of this activity.) The net result is the waves will combine and interfere, and this interference may be constructive, destructive, or some combination, depending on the phases of the two waves.

Recall that white light is made up of a spectrum of different wavelengths of light, which form the colors that we can see. Each individual wavelength will interact with the thin film on its own. For some wavelengths, the extra distance traveled through the thin film will cause the light reflected from the top layer to be completely out of phase with the light reflected from the lower layer. This results in destructive interference—the color corresponding to this wavelength will be removed from the spectrum, and as a result an observer will no longer see multi-wavelength white light, but a new color based on the remaining wavelengths. Similarly, for some other wavelengths, the extra distance traveled through the thin film will cause the light reflected from the top layer to be perfectly in phase with the light reflected from the lower layer. This results in constructive interference, and the color corresponding to this wavelength is now twice as strong. This further alters the color we will see reflected from the thin film.

Figure 4: A thin film of oil (refractive index n_{oil}) on water (refractive index n_{water}

The colors we observe are a sensitive function of film thickness. If the thickness of the thin film is such that the distance a wave must travel through the film matches exactly the wavelength of the incoming wave, when the wave that exits the thin film after reflection will be in phase with

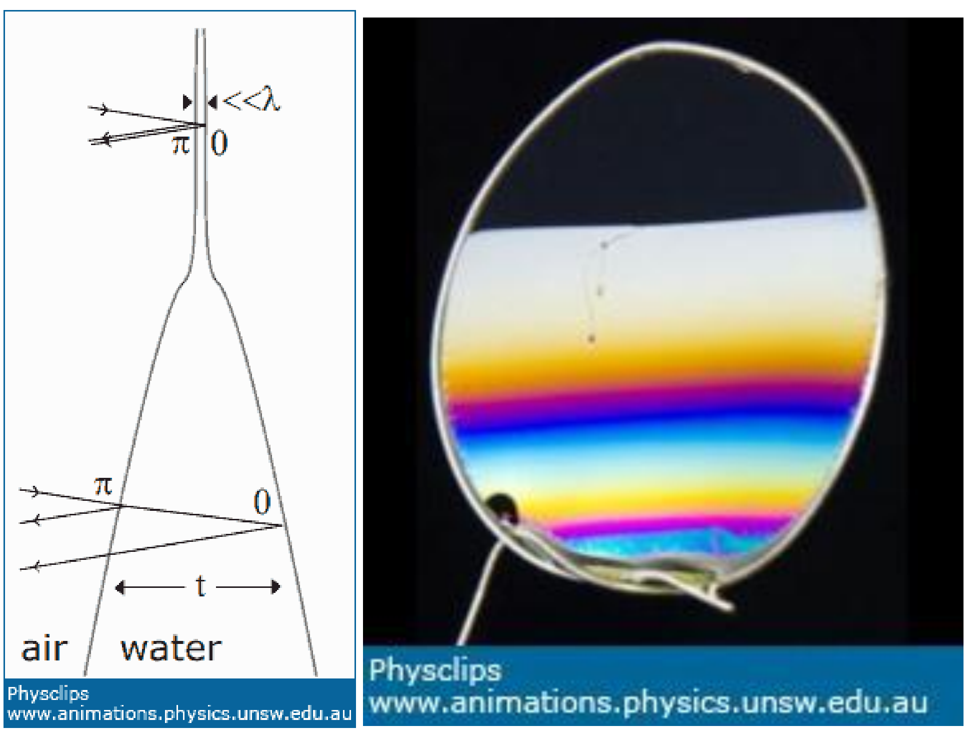


Figure 5. These images show how the phase of reflected light is important in thin films. In the left image, a soap film is created in a wire loop. Gravity causes most of the water to sink towards the bottom of the loop, leaving a very thin region along the top (the black portion in the loop). The image on the right is a cross-sectional view of the soap film seen on the left. The top of the soap film is so

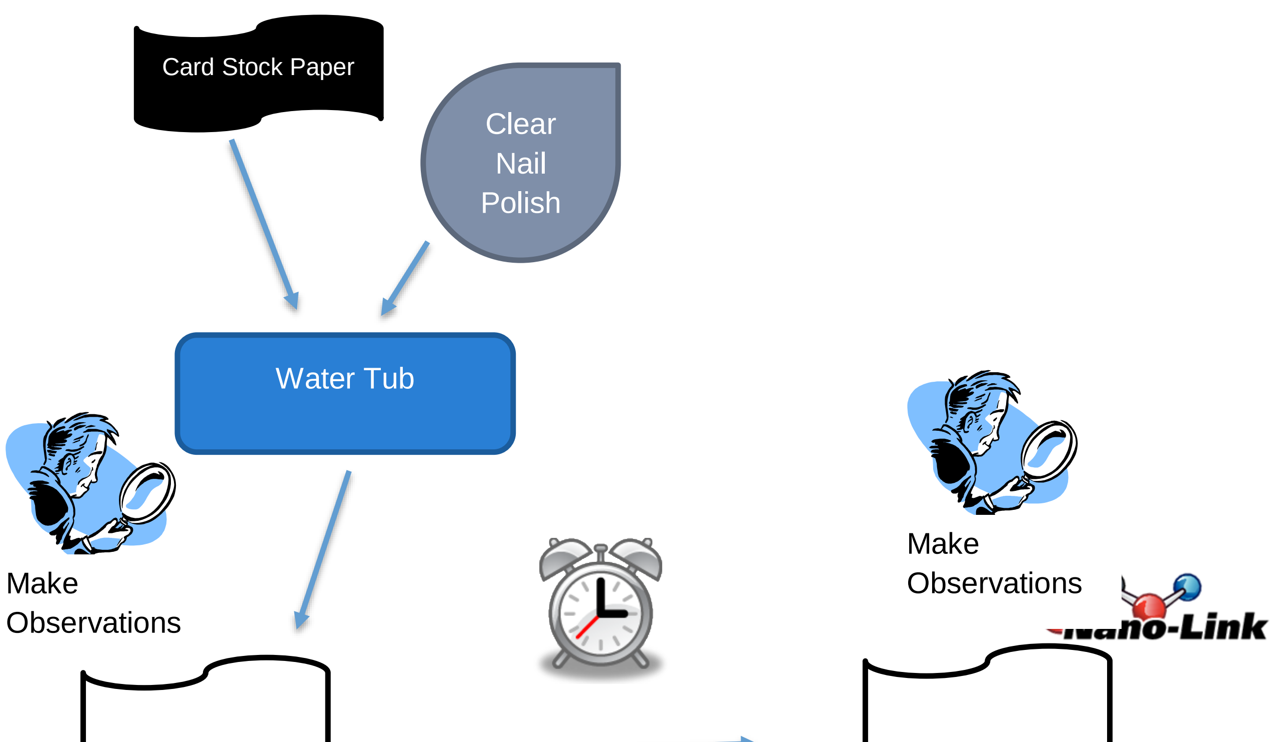
thin that the all of the reflected light rays will overlap approximately and be completely out of phase. The overlapping rays will cancel each other out at all visible wavelengths, and appear as a black, unreflective region. Near the bottom of the soap film, the light rays will interfere with each other differently depending on the wavelength and thickness, creating a repeating rainbow of colors.

the reflection off of the upper boundary. Such constructive interference acts to amplify the intensity of a wave, making it seem brighter to a photo detector such as the human eye. The other wavelengths that are part of the incident light will each be out of phase to some degree with the waves that reflect off of the upper boundary, and will destructively interfere. This results in either reducing the intensity or canceling the wavelength entirely. Thus, as the thickness of the thin film varies so will the color of the reflected light. Figure 5 shows a demonstration of this thickness dependence using a soap bubble film.

In this activity, we use a hydrophobic film, clear nail varnish, which spreads out thinly when a drop of it is added to water. The nail varnish is formulated to dry quickly, so it forms a durable film that can be captured on a paper card and taken out of the water bath for closer examination.

Learning Activity: Aerogels

Activity Flow Charts



Thin Films

Materials and Equipment

- Shallow tub (approx. 8” by 4” by 1”)
- Card stock paper, cut into strips (approx. 10” by 1”-2”, preferably black)
- Clear nail polish • Water

Safety

Aerogel is very drying to the skin and should not be handled without gloves. The aerogel blanket should be kept in a sealed plastic bag and not opened at any time during the experiment. The vials with aerogel should not be opened.

Procedure

1. Fill the tub to between 1⁄2” and 1 inch deep with water.
2. Slide the strip of paper into the water.
3. Using the applicator brush, apply one drop of clear nail polish over the center of the paper strip. Try to get a drop of polish to fall to the surface but do not let the brush touch the water.
4. Wait for the drop to spread out like an oil slick on the surface of the water.
5. Slowly pull the paper strip out of the water, making sure it travels through the film and allowing the film to adhere to the paper.
6. Set the paper and film aside to dry.
7. Once the paper is dry, observe the film and explain what you see.

Questions:

1. Why did the nail polish spread out to a thin film so quickly?
2. Why is black paper preferable?
3. How thin is the film on the surface of the water, and how could we tell?

Discussion questions

1. How might it be useful to know the colors reflected from a thin film?
2. Where are thin films used?

3. Can you think of any thin films in nature?

Current and Future Applications

Thin film interference is important to a number of current and future technological applications:

- Anti-reflective (AR) coatings: Used in eye glasses and auto glass to reduce glare. Du-Pont has developed an AR coating that increases transmittance through glass or plastic in light fixtures (source: http://www2.dupont.com/Diffuse_Light_Reflectors/en_US/assets/downloads/NOW801_AR_Sell_Sheet_me05-21.pdf).
- Semiconductor manufacturers use a technique known as spectroscopic reflectometry to measure the thickness of spin-coatings on wafers. The Toho Technology NanoSpec 6500 is one example: http://www.tohotechnology.com/nanospec-6500.php

Contributors

- This activity was originally developed by NISEnet for the Nano Days curriculum.
- Adapted by Deb Newberry, Dakota County Technical College.
- Additional development by Christopher Kumm, Dakota County Technical College, Rosemount MN and Dr. James Marti, University of Minnesota, Minneapolis, MN.

Sources:

- Tippens, Paul E. Physics. 7th ed. Dubuque, IA: McGraw-Hill, 2007. Print.
- “Interference: Thin film interference and reflections” from Physclips: http://www.animations.physics.unsw.edu.au/jw/light/thin-film-interference-and-reflections.html
- Education.com: http://www.education.com/science-fair/article/thin-film-interference-light-waves/
- Edmund Optics: Anti-Reflection (AR) Coatings http://www.edmundoptics.com/technical-resources-center/optics/anti-reflection-coatings/?ref=right-column
- “My glasses have an anti-reflective coating. How does that work?” from howstuffworks.com: http://science.howstuffworks.com/innovation/science-questions/question615.htm

Image credits:

- Figure 1: http://en.wikipedia.org/wiki/Snell's_law#mediaviewer/File:Snells_law2.svg
- Figure 2: http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/interf.html
- Figure 3: http://method-behind-the-music.com/mechanics/physics
- Figure 4: http://en.wikipedia.org/wiki/Thin-film_interference

- Figure 5: http://www.animations.physics.unsw.edu.au/

Multimedia Resources

Videos

- An excellent video explaining thin film interference, as well as some of the math behind it from ilectureonline.com: https://www.youtube.com/watch?v=7zWqU4QSJg4
- An animated video showing a computer simulation of thin film interference: https://www.youtube.com/watch?v=xjMjWtntm9k

Simulation: "Soap Film Interference" from Hyperphysics

This website contains an interactive window where students can change multiple parameters and observe the impact:

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/soapfilm.html

Alignment of Thin Film Interference Module to the Next Generation Science Standards

The Next Generation Science Standards (NGSS) were published in April 2013. They consist of statements that convey the performance expectations for students. Each performance expectation is a single statement that is built from three parts: science and engineering practices (Practices), disciplinary core ideas (DCI) and crosscutting concepts.

Since the Thin Film Module was created prior to the release of these standards one would expect that it aligns most readily to the individual statements that articulate the practices, DCIs, and crosscutting concepts. The background material, reading, and the slides from the module address the aspects of the NGSS shown in Table 1.

TABLE 1. ALIGNED PRACTICES, DISCIPLINARY CORE IDEAS, AND CROSSCUTTING CONCEPTS		
PRACTICE *No alignments*	***DCI*** *MS. PS4.A:* When light shines on an object, it is reflected, absorbed, or transmitted through the object, depending on the object's material and the frequency (color) of the light. *Strong in teacher and student materials*	***CROSSCUTTING CONCEPT*** *No alignments*
PRACTICE *No alignments*	***DCI*** *MS. PS4.A:* The path that light travels can be traced as straight lines, except at surfaces between different transparent materials (e.g., air and water, air and glass) where the light path bends. *Strong in teacher and student materials*	***CROSSCUTTING CONCEPT*** *No alignments*
PRACTICE *No alignments*	***DCI*** *MS. PS4.A:* A wave model of light is useful for explaining brightness, color, and the frequency-dependent bending of light at a surface between media. *Strong in teacher and student materials*	***CROSSCUTTING CONCEPT*** *No alignments*
PRACTICE *No alignments*	***DCI*** *HS.PS4.A:* Waves can add or cancel one another as they cross, depending on their relative phase (i.e., relative position of peaks and troughs of the waves), but they emerge unaffected by each other. *Strong in teacher and student materials*	***CROSSCUTTING CONCEPT*** *No alignments*

Alignment of Thin Films Module to the Common Core State Standards in English Language Arts/Literacy and Mathematics

The Common Core State Standards (CCSS) were published in June 2010. They articulate student skills for English language arts/literacy and mathematics. The content of the module addresses the concepts and skills shown in Tables 3 and 4.

For English language arts/literacy, the CCSS is organized around College and Career Anchor Standards (CCR) that articulate the over-arching skills that students need to be prepared for college and career. There are grade level versions of each Anchor Standard, as well as versions for science and social studies classrooms (literacy standards). Alignments in Table 3 were made to the Anchor Standards, unless a more specific version of the standard was a closer fit to the skills in the module. Additional alignments may be warranted, depending on the use of associated videos that are provided as links in the module and whether students engage in discussions.

TABLE 3. ALIGNED COMMON CORE STANDARDS FOR ENGLISH LANGUAGE ARTS & LITERACY
CCR.L.6: Acquire and use accurately a range of general academic and domain-specific words and phrases sufficient for reading, writing, speaking, and listening at the college and career readiness level; demonstrate independence in gathering vocabulary knowledge when encountering an unknown term important to comprehension or expression. *Partial in teacher and student materials*

For mathematics, Table 4 shows alignments to standards found in the 8th through 12th grade levels.

TABLE 4. ALIGNED COMMON CORE MATHEMATICS STANDARDS
No alignments