Wave Optics III: Thin Films

Introduction

The colors found in living things are mostly a consequence of the pigments their surfaces contain, i.e., they result from the absorption and reflection of specific wavelengths of light. However, some organisms (especially insects) exhibit *structural color* that results from interference of light waves. We have already encountered a beetle that carries a diffraction grating on its cuticle. Now we will explore another phenomenon that also gives iridescent color in beetles and butterflies: *thin-film interference*.

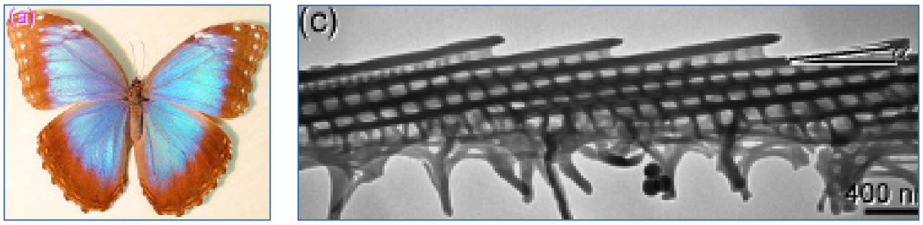
Learning goals

At the end of this module, you should be able to…

- Determine from the indices of refraction whether an incident wave will experience a phase change upon reflection.
- Determine the wavelengths that will experience constructive or destructive interference using the thicknesses and refractive indices of the layers.
- Explain how the wavelengths that experience constructive interference change depending on the angle of incidence.

A. Butterfly wings

The beautiful blue color of the wings of the butterfly *Morpho peleides* (see below) derives from interference between light waves reflected from layers within the scales that cover the wing. As seen in the transmission electron micrograph (TEM) below on the right, the scales consist of layers of chitin separated by air layers. Light waves incident on the scales of the wing are reflected from the top of the chitin layer (the air-chitin interface, wave 1), from the bottom of the chitin layer



Photograph of male *Morpho peleides* (left) and TEM cross-sectional image of a cover scale from the wing (right).[1]

(the chitin-air interface, wave 2), from the top of the next chitin layer (wave 3), and so forth as shown in the diagram below. Constructive interference between the reflected waves only occurs for specific wavelengths of light, and so the wing appears colored even though there is no pigment in the chitin (it is transparent). Except for the light reflected from the top surface (wave 1), each of the reflected waves will be reflected multiple times: ray 2 will be reflected again from the top of the chitin layer, and so forth. We will neglect those multiple reflections, as they do not affect our analysis of what wavelength of light will undergo constructive interference and provide the color of the wing. (The multiple reflections do influence how wide a range of wavelengths is reflected, and the intensity of the reflection.)

From the TEM image above it has been determined that in the scales of the *Morpho* wing the chitin layers have a thickness $d_c = 75$ nm and the air layers between them have a thickness $d_a = 60$ nm. The chitin has an index of refraction $n = 1.56$.

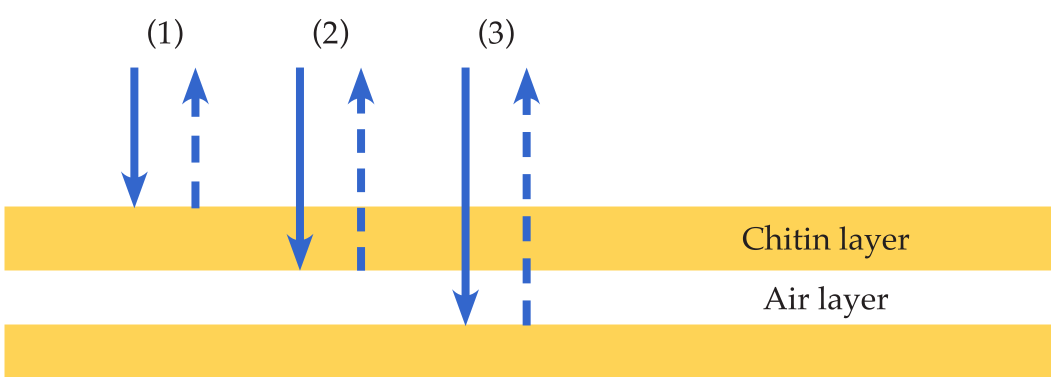


Diagram of portion of cover scale. Solid lines represent incident light; dashed lines represent reflected light.

1. Yong Ding, Sheng Xu and Zhong Lin Wang, "Structural colors from *Morpho peleides* butterfly wing scales," *Journal of Applied Physics* **106**, 074702 (2009).

1. Does a wave reflected from the top surface of the chitin layer (wave 1 or wave 3) undergo a change in phase? Why or why not?
2. Does a wave reflected from the bottom surface of the chitin layer (wave 2) undergo a change in phase? Why or why not?
3. If the wavelength of the incident light in air is λ and the index of refraction of the chitin layer is n, what is the wavelength of the light inside the chitin layer?
4. What is the difference in length between the path traveled by wave 1 and the path traveled by wave 2, in terms of d_c?
5. For what values of the wavelength λ will wave 1 and wave 2 interfere constructively?
6. Answer questions #4 and 5 about constructive interference between waves 1 and 3 (note that you now will also have to consider the thickness d_a of the air layer).
7. Answer questions #4 and 5 about constructive interference between waves 2 and 3.
8. Are the values you calculated for the wavelengths consistent with the perceived color of the *Morpho* wing?
9. If the butterfly wing were immersed in acetone ($n = 1.35$), what color would it appear to be? The acetone would fill all the air spaces.
10. The outer portions of the wing of *M. peleides* are reddish rather than blue, although the cover scales there are made of the same chitin as the scales of the inner part of the wing. What does that tell you about how the structures of the cover scales in the two regions of the wings are likely to differ?

B. Beetles

In a previous studio we looked at beetles that exhibit iridescence due to ridges on the cuticle that act like a diffraction grating. Many species of beetles get their color in a different way, from thin-film interference. The cuticle of these beetles consists of alternating layers of two kinds of chitin with different indices of refraction (rather than alternating layers of chitin and air as in the butterfly wing). The surface portion of the wings of the buprestid beetle *Chrysochroa raja* (found in India, China and Southeast Asia) consists of about 17 layers that alternate between 55 nm in thickness (the dark stripes in the micrograph below) and 78 nm in thickness (the light stripes). These two types of layers have indices of refraction of 1.68 and 1.55 respectively.[2]

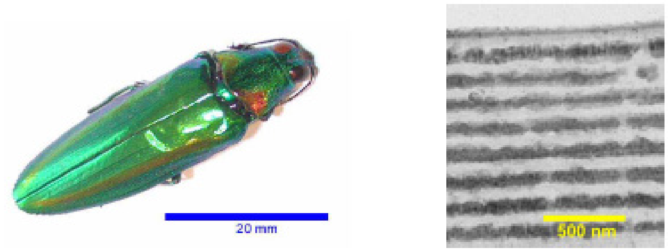
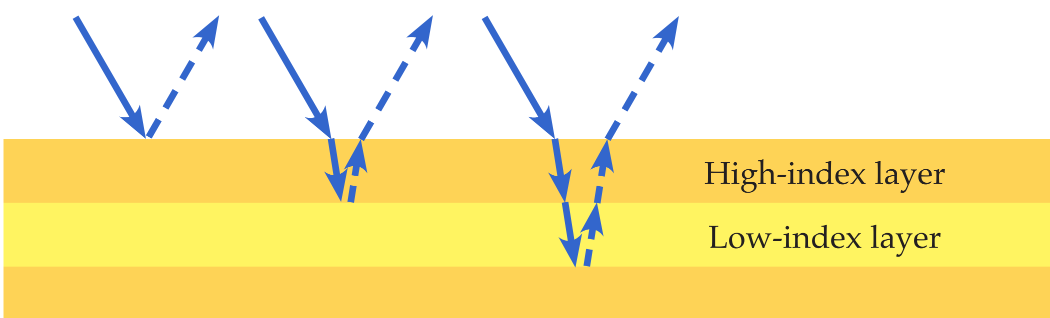


Photo of *C. raja* (left) and transmission electron micrograph of a cross section of its exocuticle (right). (From Noyes et al. 2007)

1. Using your analysis of the butterfly wing as a guide, determine the wavelengths that would experience constructive interference upon striking this beetle. Note that the top layer is made of the type of chitin that has the larger index of refraction (i.e., it is a dark stripe).
2. Does your result agree with the color of the beetle in the photograph?

Like other insects with structural color, the perceived color depends on the angle at which the insect is viewed.

3. Why would this be true?
4. The diagram below shows schematically the situation when light is incident on the beetle at an angle of 30°. Adapt your analysis above to determine the wavelengths that would experience constructive interference at this angle.
5. How would the perceived color of the beetle vary as you changed your viewing angle from 0° to 30°?



2. J.A. Noyes, P. Vukusic and I.R. Hooper, “Experimental method for reliably establishing the refractive index of buprestid beetle exocuticle,” *Optics Express* **15**, 4351-4358 (2007).

C. Anti-reflection coatings

So far you have explored constructive interference from multi-layer thin films. It is also possible for interference to be destructive, a phenomenon exploited in making *anti-reflection coatings* for optical elements such as eyeglasses. In order to allow the lenses to be thinner (and thus lighter weight), eyeglass lenses can be made of a plastic that has a high index of refraction ($n = 1.70$). The high index causes the plastic to reflect light more effectively than does glass, so it is desirable to reduce the reflection to avoid glare and to allow more light to reach the eye. This can be done by applying a thin coating to the plastic to produce destructive interference.

1. Consider a plastic eyeglass lens with a coating of thickness d with index n_c. Light with wavelength λ is incident perpendicular to the lens. Under what circumstances will there be destructive interference between the light reflected from the top of the coating and the light reflected from the coating/lens interface? That is, how must n_c, d, and λ be related in order for this to happen?
2. Determine suitable values for n_c and d that will result in destructive interference for 500 nm light. Note that materials to use for coatings that have $n < 1.3$ or $n > 2.5$ are difficult to find.
3. Does the index of refraction of the eyeglass lens itself matter? Explain.

D. Bringing it all together

To assess your understanding of some of this studio's key ideas, your group must answer the following questions together without help from the instructors or other groups.

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A similar arrangement to the one that produces an anti-reflection coating for an eyeglass lens can be used to produce a surface with very high reflection, i.e., a mirror. The scales of fish such as the sprat *Clupea sprattus* are highly reflective and give the fish its shiny silver color. They are made of alternating layers of guanine crystals ($n_g = 1.83$) and cytoplasm ($n_c = 1.33$). The thickness d_g of the guanine layers is 98 nm.[3]

3. E.J. Denton and M.F. Land, "Mechanism of reflexion in silvery layers of fish and cephalopods," *Proc. Roy. Soc. B* **178**, 43-61 (1971).

1. Under what circumstances will there be constructive interference so that light of wavelength λ is highly reflected? That is, how must n_g, n_c, d_g, the thickness d_c of the cytoplasm layers, and λ be related in order for this to happen?
2. The wavelength of light that is most strongly reflected from the ventral scales of the sprat is 720 nm. What is the thickness of the cytoplasm layers?
3. When the salinity of the water in which the sprat swims is increased, the wavelength of maximum reflection for the fish's scales shifts to shorter wavelengths. The guanine crystals are not affected by the salt, and the change in the index of refraction of the water and of cytoplasm is negligible. What causes the shift (be specific)? This phenomenon means that sprat scales can be used as an osmometer.