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參展科別 物理與天文學

作品名稱 Beautiful Butterfly: The Physics Behind
The Colors

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1 Introduction

Our everyday life is characterized by colors. We are especially drawn to the extraordinary variety of iridescent butterflies, whose colors change according of the angle of view.

The scientific name for butterfly, *Lepidoptera*, comes from the Greek, meaning scaled wings. The varied color palette of a butterfly's wing not only serves to identify its species but also achieves a number of important functions, such as mating, camouflage, and a warning of danger. As a result of the great variety of colors and patterns that can be observed, a great deal of scientific research has been carried out, focused on identifying the origin of these colors [3].

In recent decades, there have been tremendous technological advances in image processing and high resolution microscopy. A recent example is the Nobel Prize for Chemistry 2017 for the development of cryo-electron microscopy. This opened up new opportunities to explore structures at the nanometer scale, and the analysis of these nanostructures in a scientific way. Past research relied mainly on the measured values available and a degree of guesswork. In my research, I have had the opportunity to work with these gauges and compare different butterflies.

The color on the butterfly wings results either from the pigmentation (chemical color) or from the structure (physical color) of the wing scales. Colors such as yellow, black, red and brown are mainly created by pigments. The interaction of light and structures in and on the surface of butterfly wings, often the size of the wavelength of the light, results in physical colors [13] [7]. These colors are usually bright and dependent on the viewing angle (unlike chemical pigments that spread light diffusely) [18] [16]. The colors produced here are usually golden, green, purple and blue [17].

But, where do these colors come from and why do certain species dazzle more than others? To get to the heart of the matter, I have identified the following key questions:

1. How are the different colors of the butterfly wings related to the nanostructures of scales and to the pigments?
2. Using the nanostructure, is it possible to identity the wavelength of the reflected light?

In this paper, I focus on the structural colors of butterflies and study the physics behind them. This includes parachuting in areas such as diffraction gratings, scattering of light, interference in thin films, and multilayer interference.

In order to experience the greatest possible diversity, I have selected butterflies from different species for the measurements. Using the spectrometer, I was able to measure the light reflected from butterflies. The high-resolution microscopes such as the laser microscope and the scanning electron microscope gave me the opportunity to study the detailed nanostructures of the wing. In addition, I was able to analyze and evaluate my results using existing physical models and MATLAB simulations (Maxwell equations).

2 Theory

2.1 Light and colors

Without light, we couldn't see anything. For our eyes to perceive colors, light must strike matter and be reflected, scattered or absorbed by it, or flex or bend around the object.

Light is an electromagnetic wave. Thus, the electromagnetic wave visible to the human eye is typically named as light. This lies in a wavelength range of 380 to 780 nanometers. Physics and chemistry describe light through the wave-particle dualism, according to which, depending on the experiment, the properties of a wave or a particle called a photon are attributed to the light. The photon is a particle that moves in a vacuum at the speed of light of $c = 2.998 \times 10^8 \frac{m}{s}$.

In the context of light, the following phenomena occur:

1. **Reflection:** Reflection is a phenomenon in which the light wave changes direction when hitting a boundary between two media and thus does not leave the first medium. Thus, the change of direction takes place at the interface of two media.
2. **Refraction:** When refracted, the light wave changes its direction as it moves from one medium to another. Therefore, it does not spread straight, but is broken.
3. **Diffraction:** If light strikes a sharp edge or a narrow gap, it does not spread out in a straight line, as in the ray model, but is diffracted at the edge or gap, so that it can be perceived in regions where it is unlikely to arrive. But, we can explain this with the wave model.
4. **Interference:** A wave has wave crests and wave troughs. The amplitude of the wave is called its maximum deflection. If several waves with a frequency f and wavelength λ meet, then the interference emerges.

The Interference is the superposition of several waves, where the amplitudes of the waves are being added together. This can lead to a strengthening or weakening of the wave [10].

Should wave crest and trough meet, they erase one another (destructive interference). If two wave crests or two wave troughs meet each other, a larger wave crest or trough occurs (constructive interference).

- **Thin Film Interference:** The shimmering colors of an oil film on water or on soap bubbles are the result of the wave character of light. This form of interference is commonly referred to as thin-film interference and is the result of constructive or destructive interference. For this phenomenon to occur, the thickness of the film must be on the order of the wavelength of the light.

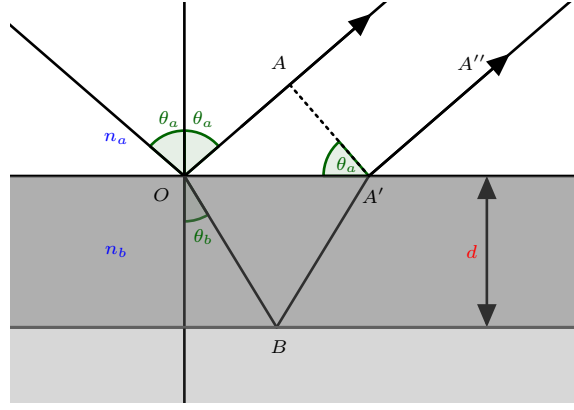


Abbildung 2.1: Ray path in the thin-film interference.

For constructive interference, the following condition applies:

$$2n_b d \cos \theta_b = m \lambda \quad (2.1)$$

n_b is the refractive index, d the thickness of the thin film, θ_b is the angle of refraction, m is an integer, which determines the order of interference, and λ is the wavelength of light.

It is important to note that when light from a material with a smaller refractive index falls on that with a higher one, the phase of the wave changes by π , whereas in the opposite case it does not.

- **Multi Film Interference:** Multi film interference is similar to the thin-film interference, but with several films [5].

For constructive interference for two films, the following condition applies:

$$2(n_a d_a \cos \theta_a + n_b d_b \cos \theta_b) = m \lambda \quad (2.2)$$

The refraction angles in the films A and B are θ_a and θ_b . The thickness of the films A and B are d_a and d_b .

5. **Scattering:** The scattering of light is the deflection of a light beam from a straight path due to irregularities in the medium, particles or in the interface between two media. The Rayleigh-Scattering is the most famous (for example, the blue of the sky).
6. **Iridescence:** One may speak of an iridescent or shimmering color, if this changes depending on the perspective of the observer and the angle of incidence of the light.

2.1.1 Structural Colors

Structural colors are also called physical colors. They arise from the micro and nano structures due to the thin-film and multi film interferences of light waves. In contrast to the formation of the pigment colors, is the reflection and interference of importance instead of the absorption. These structures can be simple, solid, pierced or porous multi-films. In addition, conical, embedded or gyroid micro structures come into question [1].

Our eye perceives this superposition light wave as a color. These structural colors will not fade over time because they are only related to the internal structure of the material. In addition, the colors can change with viewing angle. The most common structural-based colors are blue, purple and green.

In nature, we encounter innumerable living beings whose color intensity is based among other things on structural colors. These organisms have evolved over millions of years, and have found a way to optimize the geometry of the micro and nano structures.

2.1.2 Pigment Colors

Pigment colors are also called chemical colors. These are particulate organic or inorganic solids which are generally insoluble. These are embedded in a carrier and are not affected by it.

Pigments and dyes produce colors by selective absorption and reflection of specific wavelengths of the light spectrum. The green color in the leaves due to chlorophyll is an example of this.

2.2 The Maxwell Equations

The research that suggests that light is an electromagnetic wave goes back to the 19th century. This work was mainly done by two scientists. The first was James Maxwell, a Scottish physicist and mathematician who predicted the existence of electromagnetic waves. His work is summarized by the well-known Maxwell equations. The other was Heinrich Rudolf Hertz, a German physicist who worked on the origin of these waves. He hypothesized that the electron oscillation generates electromagnetic waves [4] [5].

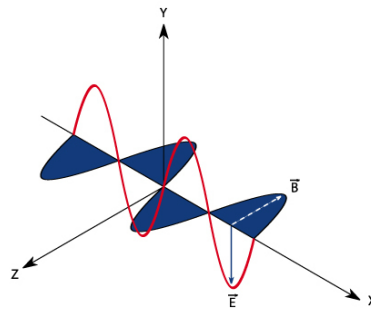


Abbildung 2.2: Electromagnetic waves are composed of electric and magnetic fields. This figure shows an electromagnetic wave which is polarized linearly in the y direction and propagates in the positive x direction. The electric field is polarized along the y-axis, and the magnetic field along the z-axis in the vertical plane. The both fields form a right angle to each other [12].

Different subsets of the spectrum of this electromagnetic radiation have been defined separately because some of their physical properties are very different. The visible light has wavelengths from 400 to 700 nm. Infrared light refers to the subset of the spectrum that has longer wavelengths than the visible light. The ultraviolet light refers to the subset of the spectrum that has wavelengths shorter than the visible light.

The Maxwell equations for electric and magnetic fields in the medium are generally summarized as follows:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \quad (2.3)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2.4)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.5)$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \quad (2.6)$$

$\mathbf{E}$, $\mathbf{B}$ and $\mathbf{J}$ are electric fields, magnetic flux density, or free current density. ρ , ϵ , ϵ_0 , μ and μ_0 are charge density, permittivity of the medium, permittivity of the vacuum, magnetic permeability of the medium, and magnetic permeability of the vacuum.

In the case of light, $\mathbf{J}$ and ρ are zero, i.e. there are no sources or also: Light waves propagate in the vacuum. Thus, the above equations are further reduced to:

$$\nabla \cdot \mathbf{E} = 0 \quad (2.7)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2.8)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.9)$$

$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \quad (2.10)$$

The above equations can be combined into two equations. To reduce them, we $\nabla \times$ from the left part of Eq. 2.9 and then set Eq. 2.10 into:

$$\nabla \times (\nabla \times \mathbf{E}) = -\frac{\partial}{\partial t} \nabla \times \mathbf{B} \quad (2.11)$$

$$= -\mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} \quad (2.12)$$

Using the following vector relationship (i.e., red from red):

$$\nabla \times (\nabla \times \mathbf{E}) = \nabla (\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} \quad (2.13)$$

and the Eq. 2.7, we get a partial differential equation:

$$\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} \quad (2.14)$$

In a similar way, using $\nabla \times$ from the left part of the Eq. 2.10 and Insertion from the Eq. 2.9, we gain the following relation:

$$\nabla \times (\nabla \times \mathbf{B}) = -\mu_0 \epsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2} \quad (2.15)$$

With the application of the same vector relation and Eq. 2.8 we get the complete equivalent equation corresponding to the magnetic flux density:

$$\nabla^2 \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2} \quad (2.16)$$

Eq. 2.14 and Eq. 2.16 are partial differential equations (PDGs). Partial differential equations generally do not have trivial solutions and in most cases are only solved numerically. We will briefly discuss the numerical technique to solve the Maxwell equations.

2.3 Finite Difference Method

In this paper, I model Maxwell equations described by Partial Differential Equations, which cannot be analytically solved except for some special cases. Therefore, I use numerical algorithms that provide a standard approach that includes many steps from a correct mathematical formulation of the initial question to the final numerical simulation. The crucial step is the discretization of the original mathematical model.

In the context of numerical modeling, the discretization describes a process of transferring a continuous model into a discrete counterpart (i.e. formulating the problem on a finite number of points with the smallest possible error). Mathematically, it reduces the differential equation to a system of algebraic equations that can then be solved on a computer. Theoretically, the obtained numerical results cannot be distinguished from the exact solution (in the case of a large system of equations, the exact solution can be arbitrarily approximated). In practice, only a limited (i.e., rather small) number of cells are used. Discretization can be performed in space and / or time. The most important and most frequently used discretization methods are finite difference methods (FDM), finite volume methods (FVM) and finite element methods (FEM) [5].

The FDM is, relatively, the simplest discretization, and the most popular [15]. It is derived from the Taylor series and is a simple application of the definition of the derivative. The FDM constructs numerically solvable differential equations from differential equations by approximating approximations by ratios between finite differences [6]. Therefore, the method can be applied to both Maxwell's equations of time and frequency domains.

For a differential equation $u(x) : \mathbf{R} \rightarrow \mathbf{R}$ is the derivative at point x defined by:

$$u_x \equiv \left(\frac{\partial u}{\partial x} \right) = \lim_{\Delta x \rightarrow 0} \frac{u(x + \Delta x) - u(x)}{\Delta x} \quad (2.17)$$

If Δx is small but finite, the expression on the right is an approximation to the exact value of u_x . If we replace the continuous differentiable operator with the discrete difference operator, we get:

$$\left[\frac{du}{dx} \right]_r^i = \frac{u(x_{i+1}) - u(x_i)}{\Delta x} \quad (2.18)$$

where $x_{i+1} = x_i + \Delta x$ is the right neighboring lattice point of x_i . The difference operator mentioned above is often referred to as a *forward* difference. In a similar way we can define other difference operators. For example, the operator for the *backward* difference is specified:

$$\left[\frac{du}{dx} \right]_l^i = \frac{u(x_i) - u(x_{i-1})}{\Delta x} \quad (2.19)$$

The *central* differential operator is then as follows:

$$\left[\frac{du}{dx} \right]_c^i = \frac{u(x_{i+1}) - u(x_{i-1}))}{2\Delta x} \quad (2.20)$$

Building on the above theory, we use the Finite Difference Time Domain (FDTD) to discretize the Maxwell equations in the Cartesian coordinate system. The Maxwell's equations (i.e. Eq. 2.9 and Eq. 2.10) are written as:

$$\partial_y E_z - \partial_z E_y = -\partial_t B_x \quad (2.21)$$

$$\partial_z E_x - \partial_x E_z = -\partial_t B_y \quad (2.22)$$

$$\partial_x E_y - \partial_y E_x = -\partial_t B_z \quad (2.23)$$

and

$$\partial_y B_z - \partial_z B_y = \mu_0 \epsilon_0 \partial_t E_x \quad (2.24)$$

$$\partial_z B_x - \partial_x B_z = \mu_0 \epsilon_0 \partial_t E_y \quad (2.25)$$

$$\partial_x B_y - \partial_y B_x = \mu_0 \epsilon_0 \partial_t E_z \quad (2.26)$$

And the Eqs. 2.21 – 2.26 according to the finite difference method numerically, we approximate each partial derivative through a relation between differences as [15]:

$$\frac{E_z^{i,j+1,k} - E_z^{i,j,k}}{\Delta_y^j} - \frac{E_y^{i,j,k+1} - E_y^{i,j,k}}{\Delta_z^k} = -\frac{B_x^{n+1} - B_x^n}{\Delta_t} \quad (2.27)$$

$$\frac{E_x^{i,j,k+1} - E_x^{i,j,k}}{\Delta_z^k} - \frac{E_z^{i+1,j,k} - E_z^{i,j,k}}{\Delta_x^i} = -\frac{B_y^{n+1} - B_y^n}{\Delta_t} \quad (2.28)$$

$$\frac{E_y^{i+1,j,k} - E_y^{i,j,k}}{\Delta_x^i} - \frac{E_x^{i,j+1,k} - E_x^{i,j,k}}{\Delta_y^j} = -\frac{B_z^{n+1} - B_z^n}{\Delta_t} \quad (2.29)$$

and

$$\frac{B_z^{i,j,k} - B_z^{i,j-1,k}}{\Delta_y^j} - \frac{B_y^{i,j,k} - B_y^{i,j,k-1}}{\Delta_z^k} = \mu_0 \epsilon_0 \left(\frac{E_x^{n+1} - E_x^n}{\Delta_t} \right) \quad (2.30)$$

$$\frac{B_x^{i,j,k} - B_x^{i,j,k-1}}{\Delta_z^k} - \frac{B_z^{i,j,k} - B_z^{i-1,j,k}}{\Delta_x^i} = \mu_0 \epsilon_0 \left(\frac{E_y^{n+1} - E_y^n}{\Delta_t} \right) \quad (2.31)$$

$$\frac{B_y^{i,j,k} - B_y^{i-1,j,k}}{\Delta_x^i} - \frac{B_x^{i,j,k} - B_x^{i,j-1,k}}{\Delta_y^j} = \mu_0 \epsilon_0 \left(\frac{E_z^{n+1} - E_z^n}{\Delta_t} \right) \quad (2.32)$$

To solve the PDE, we need to apply appropriate initial and boundary conditions. For the initial conditions we assume that the simulation can be started with a point light source or a plane wave light source. In addition, there are two main types of constraints in the literature: (i) Periodic (Periodic boundary condition, PBC) and (ii) Absorbent (Perfectly matched layer PML). However, the detailed description of these boundary conditions is not part of this paper [14] [2] [19].

3 Materials and Method

The reason why I selected butterflies for my research is that they offer an amazing variety and choice of colors. The physics behind it, such as the change of color with the viewing angle (interference), is fascinating to explore. Another reason is that with butterflies the colors remain intact even as a dead specimen, which makes my investigation possible.

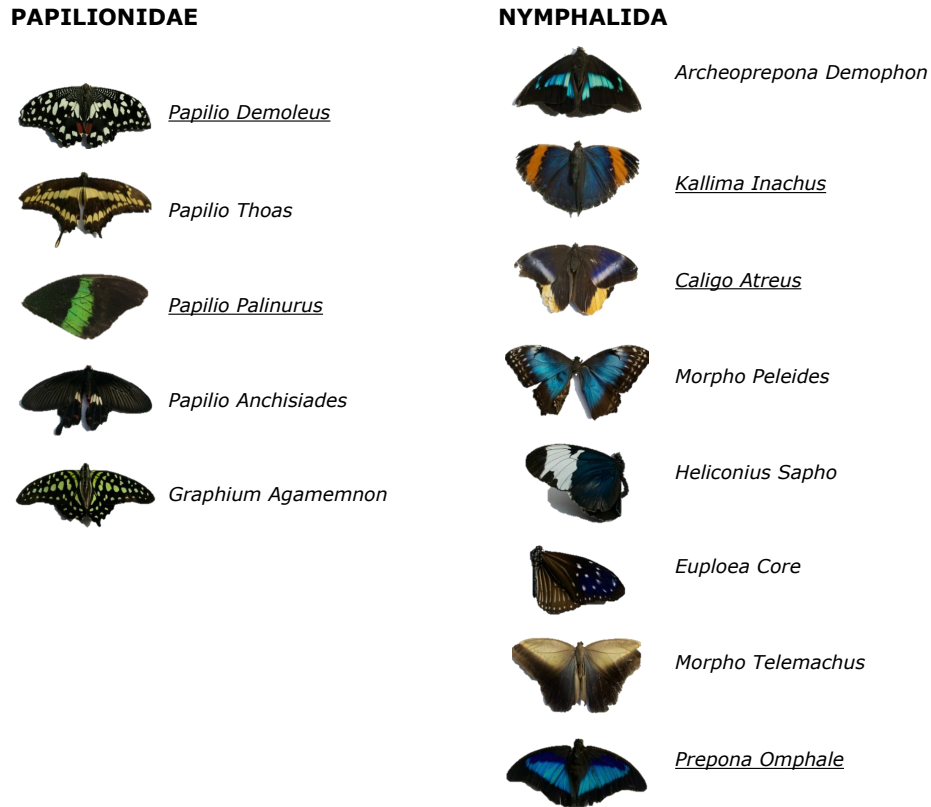


Abbildung 3.1: The butterfly families *Papilionidae* and *Nymphalida*.

First, I analyzed and researched the 13 butterflies, generously donated to me by Papiliorama [9]. After a list of criteria, I selected five interesting specimens (underlined names in the Fig. 3.1).

The criteria are:

1. On the wings you can see clear color transitions.
2. The course of these colors is clearly defined in *Kallima inachus*.
3. The butterflies have a great variety of colors.
4. While photographing, I noticed that the colors of some selected butterflies depending on the angle appear different (angle dependent).
5. Selection of many different species.

Reasons:

With a great variety of colors, it is possible that it has different scales for each color.

The clear transitions and the definite course of the colors contribute to the fact that the wings look very visually appealing.

In order to be able to analyze the butterflies' nanostructures ($1\text{ nm} = 10^{-9}\text{ m}$) and thus answer the question about the colors, I have used the following measuring instruments:

1. Spectrometer
2. Laser Microscope
3. Scanning Electron Microscope

3.1 Spectrometer

With a spectrometer, it is possible to measure the intensity of light as a function of the wavelength. In my case, I could measure the light reflected from the butterfly wings. It is also possible to measure e.g. ultraviolet light (ca. 100 nm) or infrared light (ca. $1\text{ }\mu\text{m} - 1\text{ cm}$). However, these values were not relevant to my experiment, which is why I limited myself to the visible light.

In a first step, I calibrated the instrument with white or black paper. Then I attached the wings to a sliding plate. By being able to move the plate in x and y direction with set screws, it was possible to specifically measure a fixed grid. On this plate, I attached the butterfly to a black background, otherwise the light reflected from the background would have corrupted the measurements.

I tried this procedure in advance on a color matrix. I evaluated the resulting files with the program MATLAB.

For my first measurements I measured various butterfly wings. I simply moved the spectrometer by hand over the respective wing and looked at the many wavelengths of the individual colors. Because this method was very inaccurate, I was trying for a long time to find another way.

Finally, I came up with the idea to fix the wing on a moveable plate. By being able to move the plate in x and y direction with set screws, it was possible to specifically measure a fixed grid. On this plate, I attached the butterfly to a black background, otherwise the light reflected from the background would have corrupted the measurements.

I first tried this procedure on a color matrix (see Fig. 3.2) to see if this method works. I also wanted to check how exactly the spectrometer can measure the different colors. The color matrix was printed with a CMYK printer, i.e. red, green, blue were mixed colors.

Then I examined the butterfly wings with the spectrometer. For this I put a grid with mesh size 18 by 18 over the wing. Each square mesh has an edge length of $1,5\text{ mm}$ (see Fig. 3.3). Then I measured each of the meshes with the spectrometer to see if there are differences in the reflected light within each color.

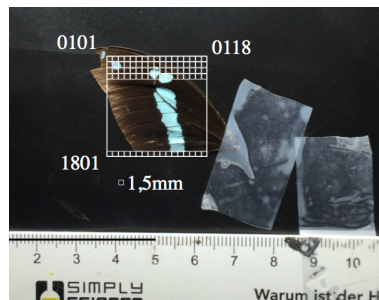


Abbildung 3.3: Measuring plan for the measurement of a wing with the spectrometer.

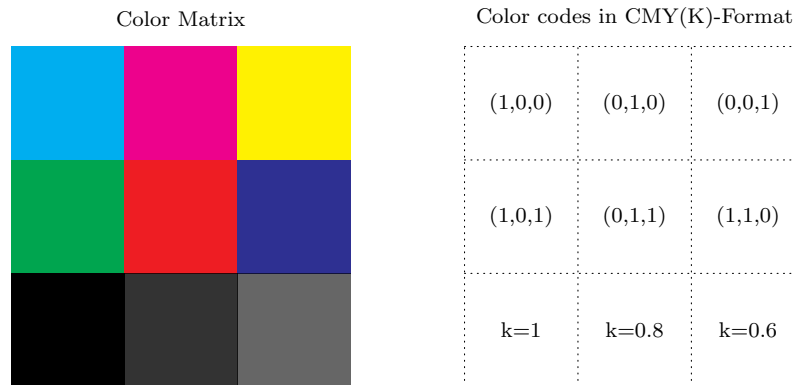


Abbildung 3.2: Color matrix for checking the spectrometer.

Before I made any further measurements, I wanted to first look at the structure. For this I used the laser microscope.

3.2 Laser Microscope

In a laser microscope, the preparation is scanned with a focused laser beam. Scanning a focused laser beam allows you to capture very high resolution digital images.

The laser moves from the highest point of the object to the deepest and makes a picture of each layer. These pictures are then put together. The result is a picture of the object showing the different structures and their height profile. It also makes optical pictures. It uses a two-way light source that consists of a laser light source and a white light source. The two light sources together provide the colors, laser intensity, and height information necessary to produce deep field color images, laser intensity images, or height images.

On my next visit to the university, I took measurements under the laser microscope with the five selected butterflies. During the measurements I photographed the butterflies and showed their measuring position.

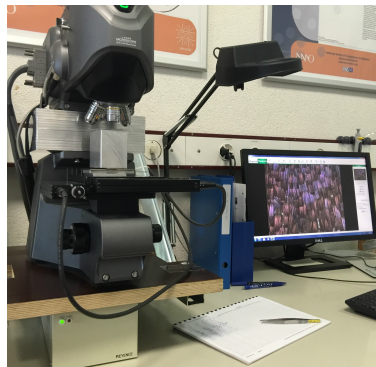


Abbildung 3.4: Laser microscope in the lab.

First, I created an overview image of the butterfly. Afterwards, I have selected good spots (for example, places where the butterfly had no injuries or not too many scales had fallen off) and

deepened in these places.

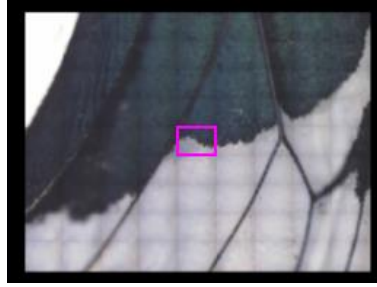


Abbildung 3.5: Overview picture taken with the laser microscope.

It was important to get an initial overview of the structure in the different areas. This was a prerequisite for the SEM measurements, because in order to perform SEM measurements, you need a $1\text{ cm} \times 1\text{ cm}$ sample that had to be sputtered first with a gold layer. So I needed to know exactly which body I wanted to investigate.

3.3 Scanning Electron Microscope

In the scanning electron microscope (abbreviated to REM), an electron beam is scanned over the object to be magnified. The way in which the electrons are reflected is translated on the computer, producing an image of the surface structure of the sample ?? c.

With the SEM it is not possible to examine samples larger than 1 cm^2 . Therefore, one must first cut out a corresponding sample from the object to be examined ?? a.

So that the sample does not charge and thereby change, it is first sputtered with gold. This means that it is coated in a special device with a layer of gold or platinum. This layer is only a few nanometers thick ?? b.

3.4 Alcohol Experiment

To differentiate between structural colors and pigment colors, I sprayed different butterflies with ethanol. I've used ethanol ($n_e = 1,4$) because it has a similar index of refraction to chitin ($n_c = 1,53$), is translucent, and evaporates quickly, so the butterflies eventually return to their original colors. The idea behind it was that the ethanol fills the interstices of the nanostructures and thus only the pigment colors emerge. By filling in the structures no reflections and no interference can take place.

3.5 MATLAB Simulation

I have used numerical simulations to calculate the solution to *Maxwell's* equations. A numerical simulation is a scientific technique that describes a physical system with a regulatory mathematical model and solves it on a computer. The mathematical equations can not be solved analytically and will be solved numerically (on a computer). Numerical simulations are now referred to as the third pillar of science and contribute to both theory and experimentation. Numerical simulations supplement experiments, thereby reducing the time, cost, and risk of experimentation.

Maxwell FDTD is a MATLAB-based FDTD toolbox with Maxwell equations. It solves the equations through the FDTD method (Finite -Difference-Time-Domain) and requires MATLAB R2011a [11].

4 Results and Discussion

4.1 Spektrometer

The results obtained in my measurements (in terms of reflection) were visually displayed using MATLAB. The figures 4.2, 4.3 and 4.4 show that the turquoise parts of the butterfly reflect blue, green and brown light. By contrast, the black part reflects little to no light, which is why I did not introduce any graphics here. The degree of reflection (in percent) was calculated using the equation 4.1.

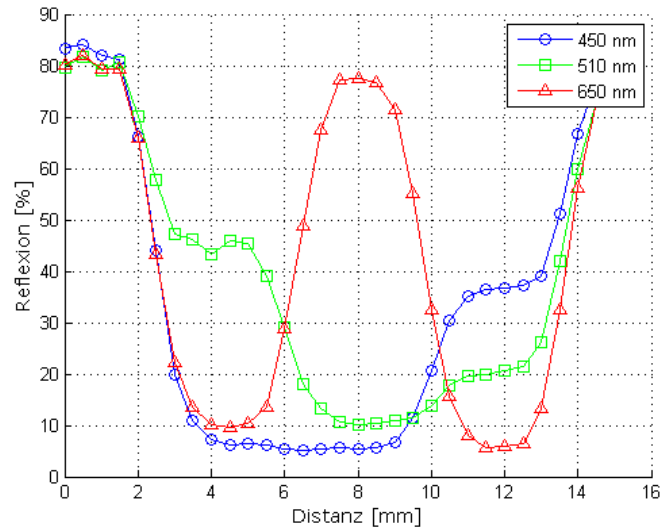


Abbildung 4.1: The different wavelengths of light emitted by the different positions of the color matrix (Fig. 3.2).

The spectrometer is moved from left to right according to the following order: white (border) - green (square) - red (square) - blue (square) - white (border). The curve (reflection, distance) is qualitatively correct. The ends of the diagram show that all primary colors are reflected. This means that the graph reflects there more or less the same intensities of green, red and blue light and these combine to white light. The peaks of green, red and blue are located on the left, middle and right position of the graph. This corresponds to the color matrix, in which green, red and blue squares are in this order.

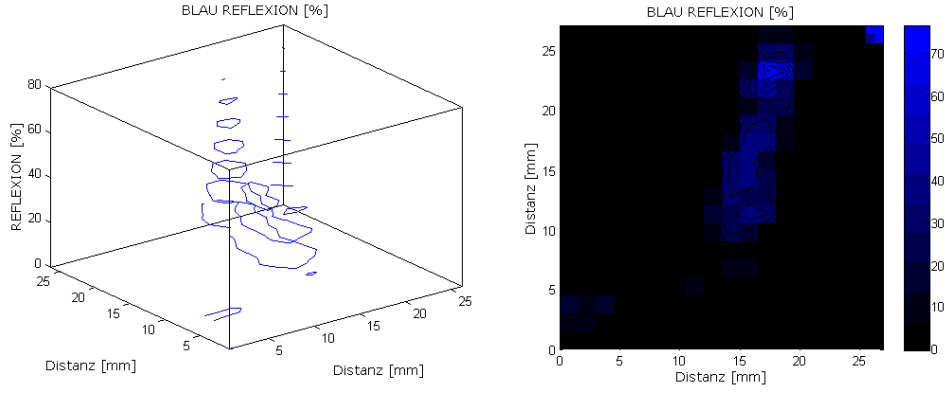


Abbildung 4.2: Reflected light of the turquoise-blue surface of the butterfly *Archeoprepona Demophon* (Blue content).

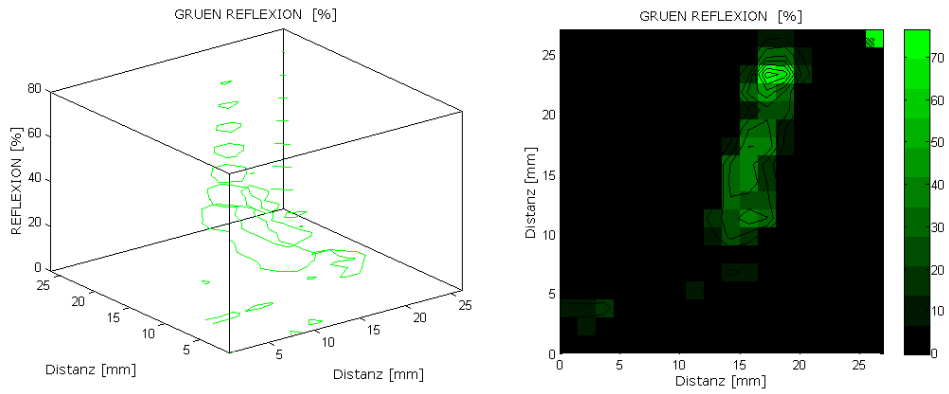


Abbildung 4.3: Reflected light of the turquoise-blue surface of the butterfly *Archeoprepona Demophon* (Green content).

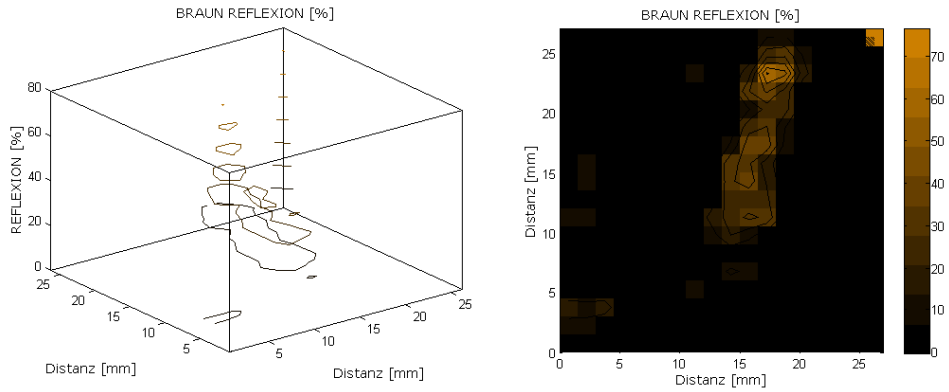


Abbildung 4.4: Reflected light of the turquoise-blue surface of the butterfly *Archeoprepona Demophon* (Braun content).

$$R = \frac{m(sample) - m(dark)}{m(ref) - m(dark)} \quad (4.1)$$

R is the reflected light as a percentage. $m(sample)$ is the intensity of the reflected wave of the sample for a given place. $m(dark)$ is the intensity of the reflected wave of the black background. $m(ref)$ is the intensity of the reflected wave of the white background. This formula is applied for

all calculations.

As can be seen in figures 4.2, 4.3 und 4.4 different colors are responsible for the coloring of the butterfly flukes of *Archeoprepona Demophon*. Finally, they create the mixed color that our eyes see. The colors green and blue are about the same intensity, with brown also occurs.

4.2 Laser Microscope

I carried out my laser microscope measurements at the University Basel. There I set everything on the **VK software**. Then I searched for the essential parts and the transitions between two colors so that I could compare them. I had already seen the structural difference in the spectral measurements, where the color was either absorbed or reflected in different spectral tones. The figures 4.5 - 4.7 show the general data set that I get from the laser microscope:

With the laser microscope I was able to correlate structure and height with the color.

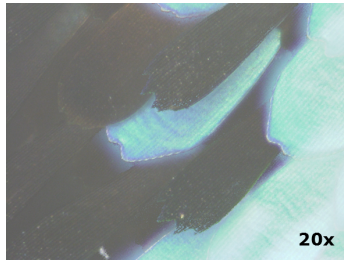


Abbildung 4.5: Wings (*Archeoprepona demophone*) optically recorded with the laser microscope.

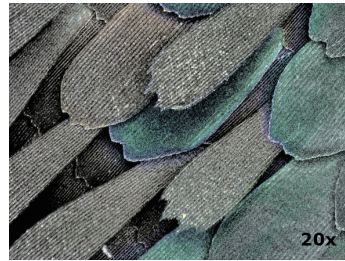


Abbildung 4.6: Wings (*Archeoprepona demophone*) optically recorded with the laser microscope. Superposition of the laser and the optical images.

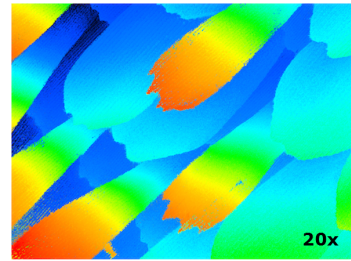


Abbildung 4.7: Height image of the wing (*Archeoprepona demophon*) taken with the laser microscope.

The different colored scales show many differences. The blue scales have a notch at the tip, while the black ones have more of these notches, which are much more pronounced. The black scales are almost jagged. Also the blue scales lie flat on the wing and see all very similar, but, at the black scales there are two different types. Every second scale is slightly wider and lies flat, the others are narrower and stand up slightly (see Fig. 4.5, 4.6 and 4.7). The distance between the grooves of the blue scales is significantly smaller than that of the grooves of the black scales.

4.3 Scanning Electron Microscope

The transparent and blue scales of the butterfly *Caligo Atreus* look very similar, on the nano structures too ???. The only difference is that the blue scales have some filled cavities. I suspect these include pigments because the nanostructures of the two colors are almost identical. These pigments are stored in the chitin of the scale [5] [16].

The presence of the black scales of the butterfly *Papilio Demoleus* testifies that all wavelengths of visible light are absorbed ???. The perforated nanostructure of the black scales can thus be regarded as a light absorber. Here, the size of the hole, the thickness of the hole wall and the depth of the hole play an important role [5].



PREPONA OMPHALE

HELLBLAU, DUNKELBLAU UND BRAUN

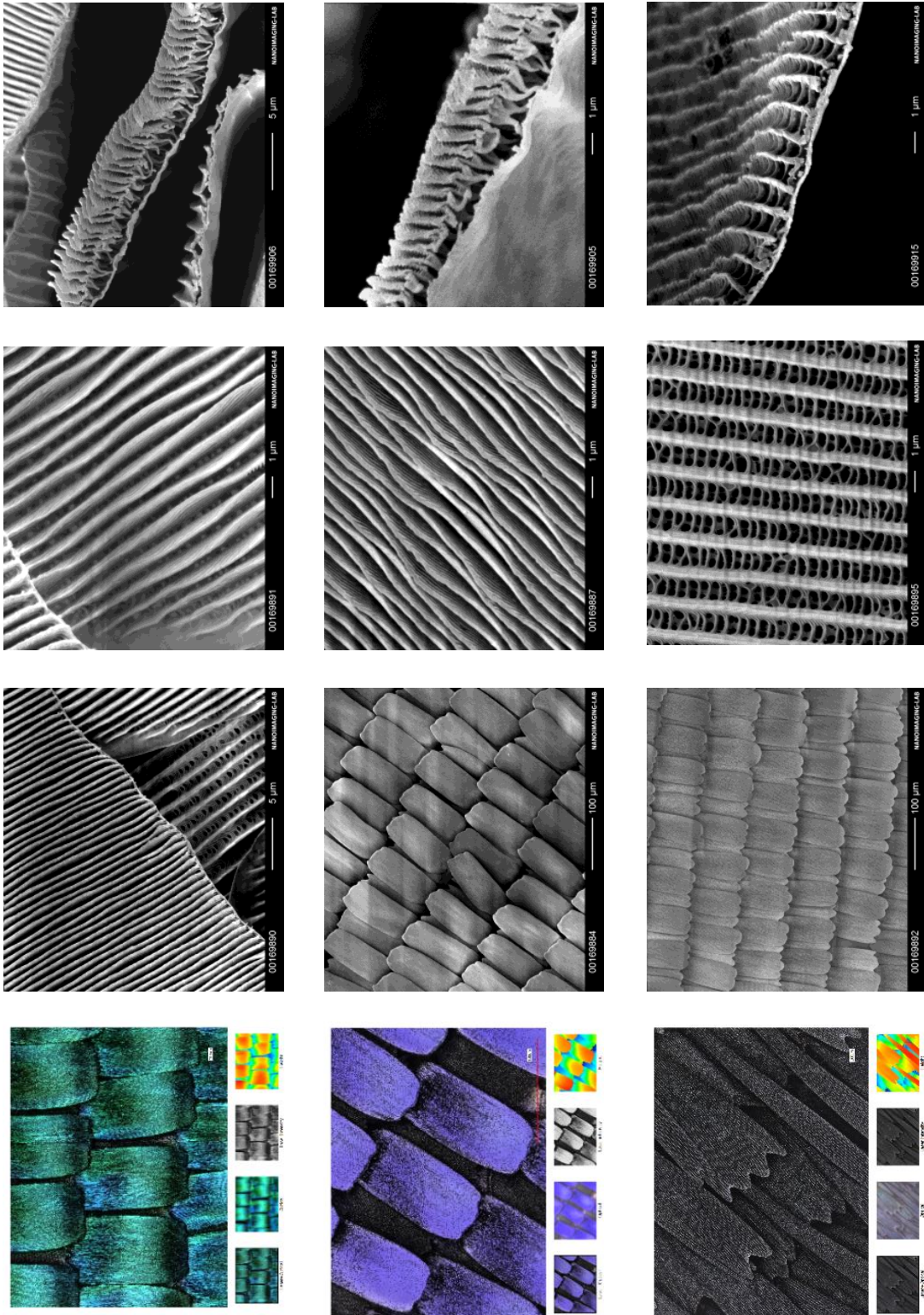
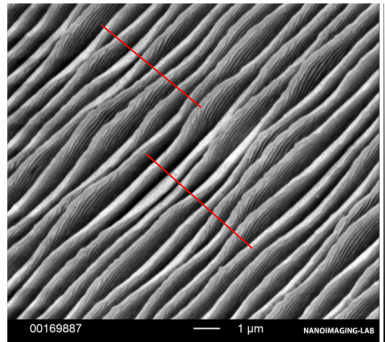
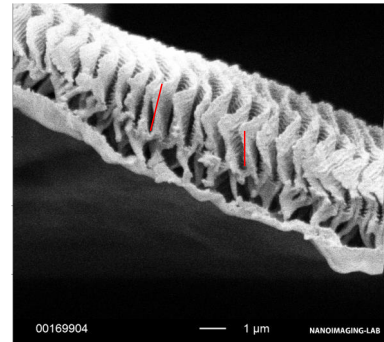


Abbildung 4.8: Laser microscope and SEM pictures for the butterfly *Prepona Omphale*.

PREPONA OMPHALE (DUNKELBLAU)

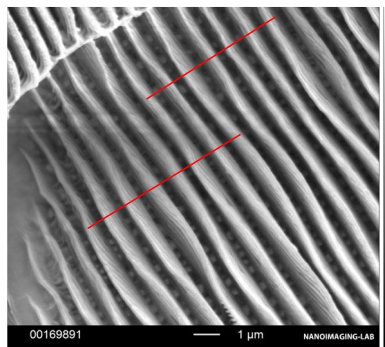


Abstand Rillen

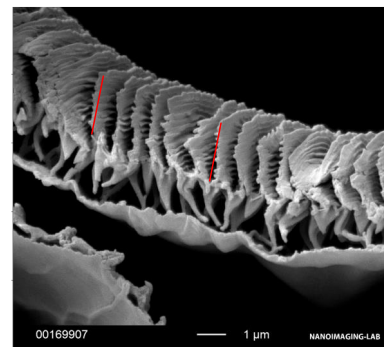


Höhe

PREPONA OMPHALE (HELLBLAU)

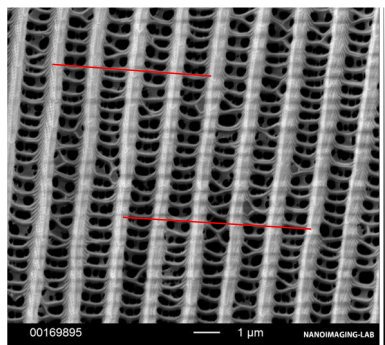


Abstand Rillen

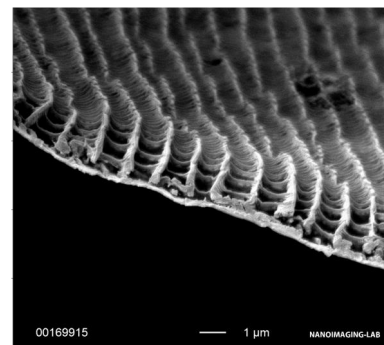


Höhe

PREPONA OMPHALE (SCHWARZ)



Abstand Rillen



Höhe

Abbildung 4.9: Measurement (red lines) of the average distance between two grooves and the average height of the ribs for the butterfly *Prepona Omphale*.

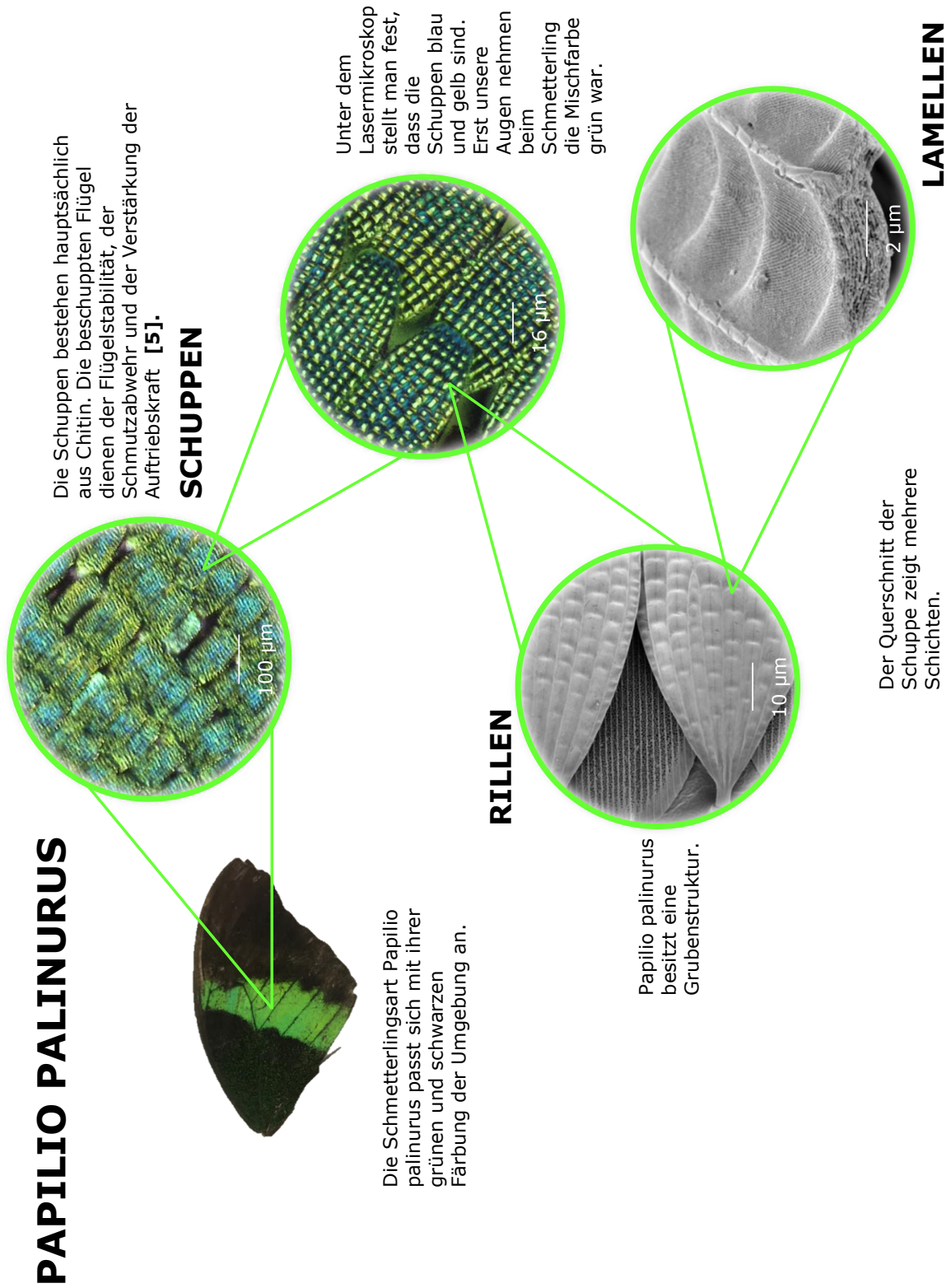
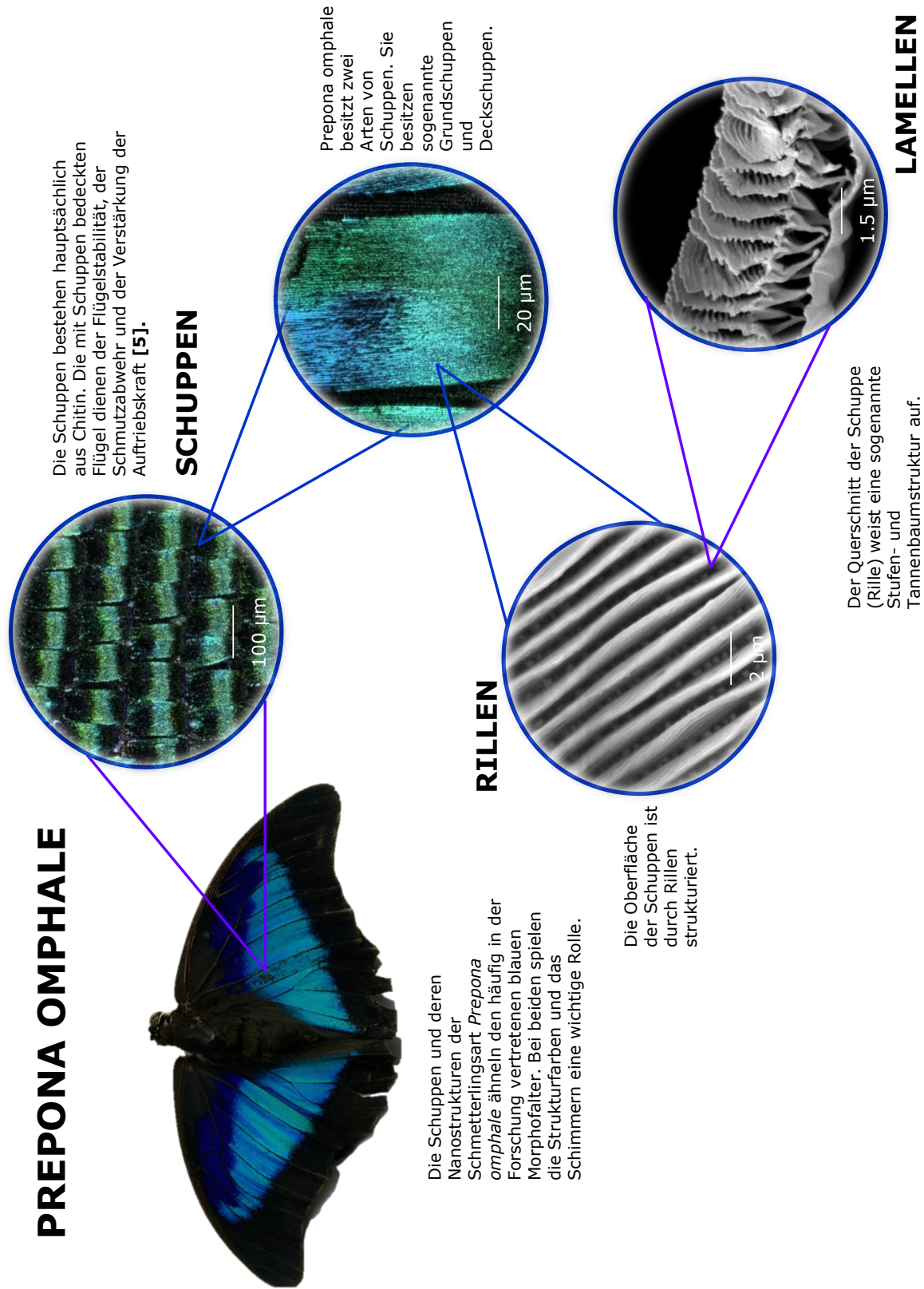


Abbildung 4.10: Analysis of the butterfly wing *Papilio Palinurus*.

Abbildung 4.11: Analysis of the butterfly wing *Prepona Omphale*.

Name	Abstand Rillen (μm)	Breite (nm)	gefüllte Zwischenräume	Wellenlänge (nm) (Lamellen)
Caligo Atreus (Blau)	1.10	92	70%	558
Caligo Atreus (Durchsichtig)	1.77	57	-	347
Kallima Inachus (Orange)	1.64	-	-	
Kallima Inachus (Blau)	1.31	-	15%	
Papilio Demoleus (Rot)	1.61	-	90%	
Papilio Demoleus (Blau)	1.70	-	100%	
Papilio Demoleus (Schwarz)	1.37	-	10%	
Papilio Palinurus (Grün)	0.13	-	10%	
Prepona Omphale (Hellblau)	0.60	78	-	478
Prepona Omphale (Dunkelblau)	0.76	89	-	547
Prepona Omphale (Braun)	1.18	110	-	673

Tabelle 4.1: The different measurements of the butterflies, which I have done with Gwyddion [8]. I calculated the wavelengths using equation 2.1.

In the calculations I assume a vertical incidence of light. Important here is the lamella thickness d and the refractive index n , which in this case is a measure of the density of chitin and is 1,53.

4.3.1 Tannenbaum Structure: Interference

Most scales of butterflies (*Lepidoptera*) have longitudinal grooves, which are usually 2 to 3 μm . The distance between them is very small (approximately between 0.5 - 1.8 μm , see Table 4.1). The grooves have several stacked layers called lamellae. In consideration of the cross-sectional view (SEM) of the grooves of the butterfly *Prepona omphale* is the tannenbaum-like structure visible (Fig. 4.12 b).

At the interfaces of the lamellae, the light is either reflected, refracted or absorbed. On the one hand, the thickness of the individual lamellae determines which wavelengths are reflected and, on the other hand, which interferes at a certain viewing angle. This phenomenon is called thin-film interference in multiple layers (Fig. 4.12 c).

The overall structure (grooves and lamellae) captures the incident light. The light bounces off the slats until it is reflected again at the angle of incidence (Fig. 4.12 a). This type of structure can reflect up to 80% of the light.

What's fascinating in this kind of butterflies is that it can also shine, and changes color based on the angle.

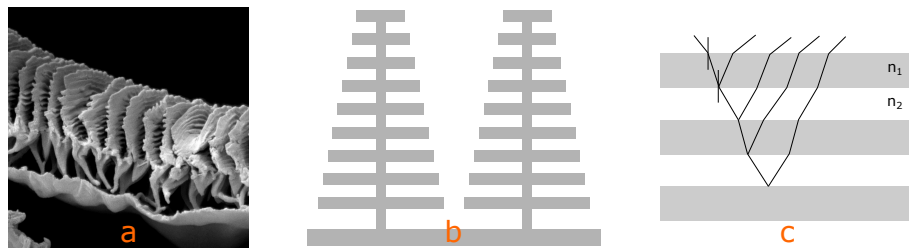


Abbildung 4.12: Tannenbaum structure interference (grooves and lamellae).

To understand how the vertical and horizontal periodicity of the Tannenbaum structure affects the colors of the butterfly *Prepona omphale*, two constructed simple fir tree structures in blue and red were used.

The figure illustrates the reflection, refraction and transmission of the incident light rays in each layer of the Christmas tree structure. For simplicity, only two layers are shown in the figure.

Using the same approach as in Chapter 3.1 one can prove that the optical path difference is given by $2(n_a d_a \cos(\theta_a) + n_b d_b \cos(\theta_b))$ for the first two layers. For several lamellae, the equation is derived from Huxley's method. But, beyond the scope of this paper.

4.3.2 Pit Structure: Phenomenon

The color of the butterfly species *Papilio palinurus* changes depending on the viewing angle from green to turquoise blue.

Their scales have many concave pits with a diameter of $4 - 6 \mu m$ haben (Fig. 4.13 a-b). Below these pits are several crimped layers. The flat area (center of the pit) contributes to the yellow color and the inclined area (sides) contributes to the blue color. As soon as white light falls on said structure, the yellow light is selectively reflected from the lower end of the curve. The blue light strikes the sides of the curve, is reflected and hits again on the opposite side of the curve wall, where it is reflected in the opposite direction. The remaining light is likely to be absorbed.

As described above, only yellow and blue colors are selectively reflected. Only their combination results in our eyes the color green. The change of the angle leads to another combination of blue and yellow (Fig. 4.13 c). That's how we see turquoise blue.

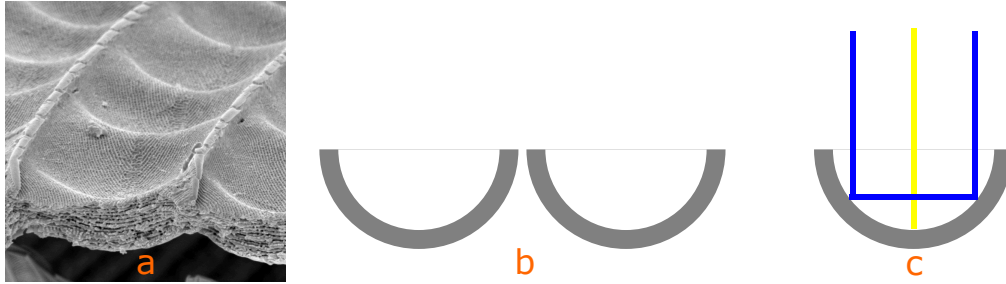


Abbildung 4.13: Grubenstruktur Phänomen (Grube).

4.4 Alcohol Experiment

When I filled the butterfly wing with alcohol, it was possible for me to recognize only the pigment colors. The reason for this is that the alcohol fills the nanostructures and thus no reflections and no interference can take place (Fig. 4.14 [1,4,5]).

In the case of butterflies, in which the color cannot be seen anyway because of the texture colors (but through pigments in the chitin), they remained almost unchanged (Fig. 4.14 [2,3]).



Abbildung 4.14: The comparison of butterfly with and without alcohol on their wings.

4.5 MATLAB Simulation

To confirm the result of the optical response theoretically, I performed the mathematical modeling of the Maxwell equations (Eq. 2.7 – 2.10) for *Einzelbaum* (T1) and *Zwei Bäume* (T2) Models (Fig. 4.15) [2]. Both T1 and T2 models are simplified 2D representations of tannenbaum-like multi-film structures present on the *Prepona Ompahle* butterfly (as observed under the scanning electron microscope). The scales of the butterflies are mostly made of chitin, whose refractive index is 1.53. For my models, SiO_2 is used because the refractive index is 1.55.

I performed simulations with two different wavelengths of light, 400 nm, and 700 nm. For 400 nm is dominated the blue color, and for 700 nm the red color. For the simulation, a planar wave with a wavelength of 400 nm and 700 nm falls from the top of the model. The model is 1000 nm to +1000 nm in the x -direction and it has in the y -direction a height of 2500 nm. The PML-boundary condition (perfectly matched layer) is used on all four sides of the Cartesian Coordinate. The simulation can reach a stationary solution.

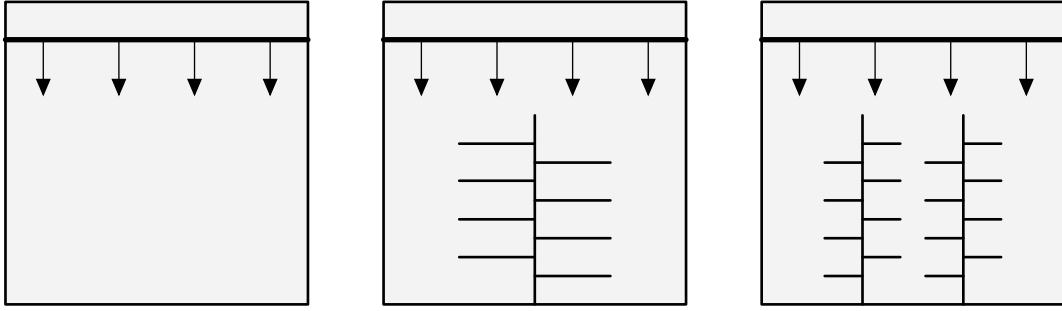
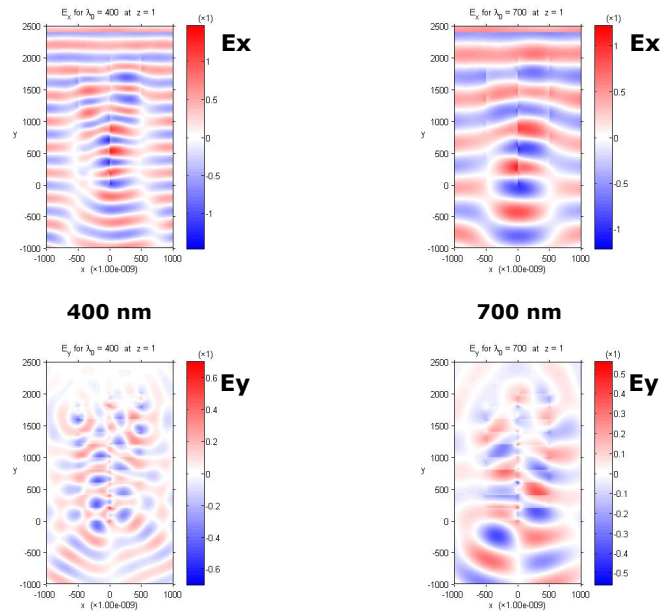


Abbildung 4.15: The 2D tannenbaum T1 (center) and T2 (right) structures.

The results for the T1 structure are given in figure 4.16, where the upper figure shows the electric field in the x -direction and the lower figure shows the electric field in the y -direction. Figure 4.17 shows the magnetic field strength for the T1 structure. In a similar way, the results for the T2 structure are shown in figure 4.18 angegeben.


 Abbildung 4.16: E_x und E_y for the T1-Structure with 400 nm and 700 nm wavelengths.

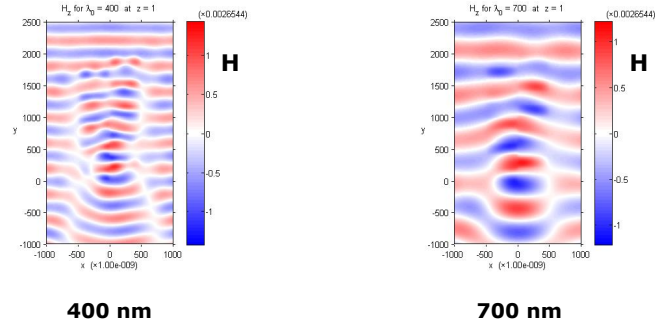


Abbildung 4.17: H for the T1-Structure with 400 nm and 700 nm wavelengths.

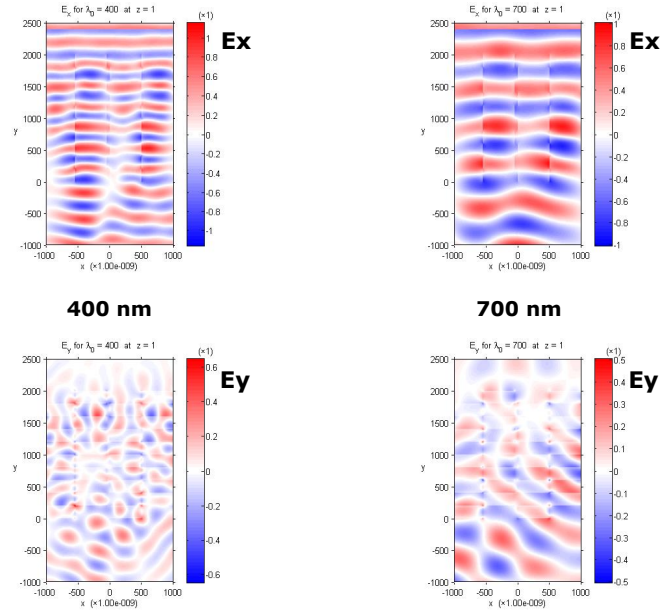


Abbildung 4.18: E_x und E_y for the T2-Structures with 400 nm and 700 nm wavelengths.

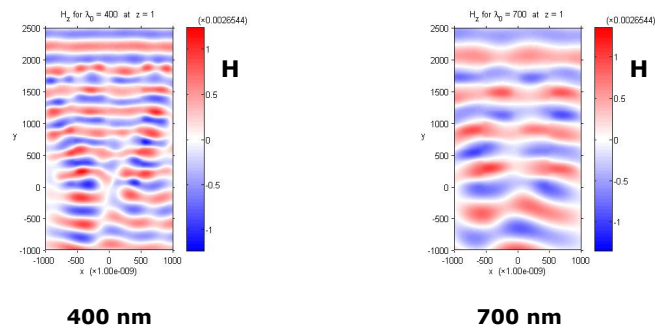


Abbildung 4.19: H for the T2-Structure with 400 nm and 700 nm wavelengths.

When we observe the electric field in the y-direction of the T1 structure (lower diagrams in Fig. 4.16), the blue color dominates exactly where the structure is. This helps to make the electric field at and around the structure the strongest. I have highlighted these with green ellipses in figure 4.20.

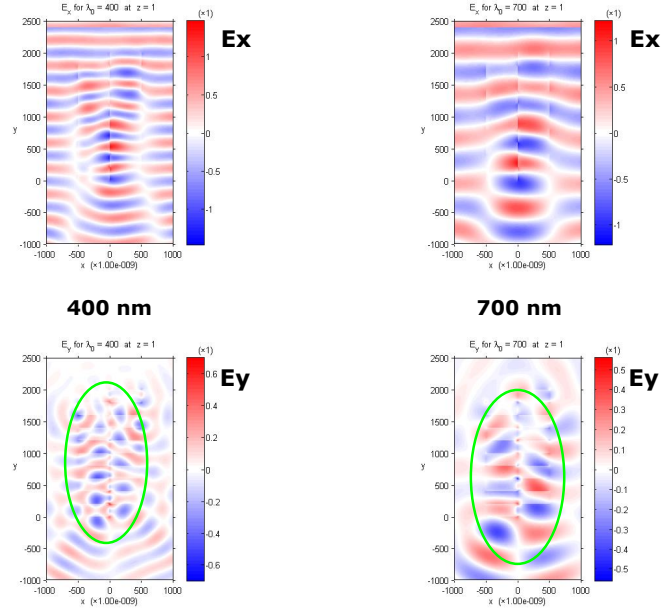


Abbildung 4.20: Comparison of E_y for the T1-Structure with 400 nm and 700 nm wavelengths.

From this calculation, I hypothesize that the structures create variations in electric and magnetic fields that may possibly lead to interference. A similar behavior is observed for the T2 structures. See the electric field in the y-direction of the structure T2 (lower diagrams in Fig. 4.18) and the highlighted figures with a strong electric field 4.21).

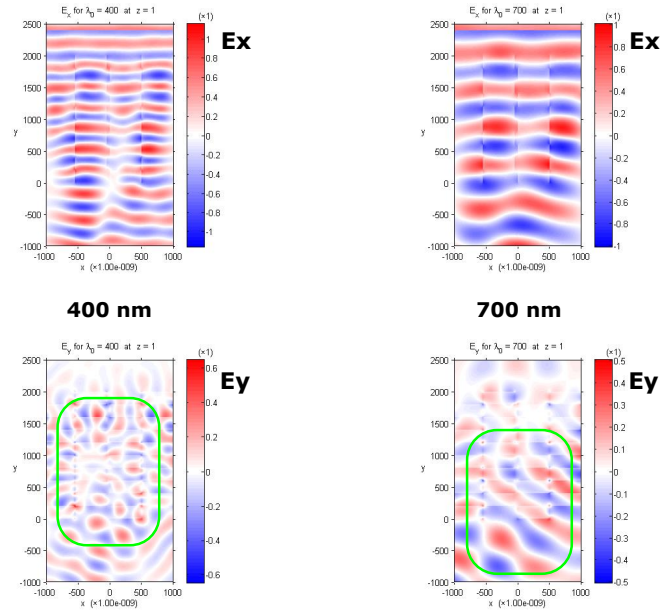


Abbildung 4.21: Comparison of E_y for the T2-Structure with 400 nm and 700 nm wavelengths.

The reflectivity of the two different tree structures (T1 and T2) is numerically calculated by measuring the ratio of the reflected power to the incident power.

Simulation of wavelengths ranging from 400 nm to 800 nm was performed. 18 simulations were performed from 400 nm in 25 nm steps for the next run.

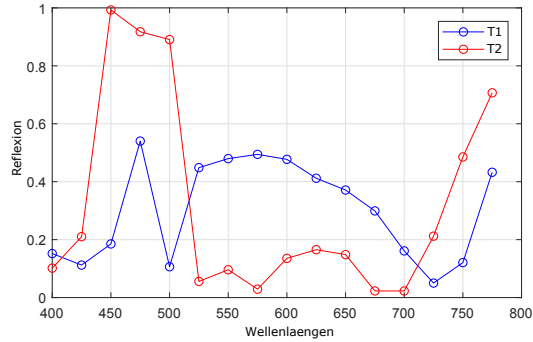


Abbildung 4.22: Reflectivity of T1 (blue) and T2 (red) structures.

It can be seen (see Fig. 4.22) such that the maximum reflectivity for T1 and T2 structures in the range of 450 nm to 475 nm. The T2 structure shows a higher reflectivity as the T1-structure. The results of the simulations show that a growing number of tannenbaum increase the reflectivity of the color blue. Blue is thus amplified by constructive interference on several tannenbaums.

5 Conclusion and Outlook

In this paper I examined the scientific reasons for the coloring of the butterfly wings, with my focus on the structural colors.

In a first step, I analyzed the light reflected from the butterfly wings with a spectrometer. I realized that further research was needed to understand the origin of the differently colored butterfly wings. To find out the relationship between the color and the structure, I decided to examine the different wings with a laser microscope and a scanning electron microscope. These studies allowed me to gain insight into the rigid structures of the wings and, in addition, a closer look at the scanning electron microscope images showed that the two butterfly species *Papilio Palinurus* and *Prepona Omphale* have two different types of nanostructures.

While *Papilio Palinurus* butterfly-like structures are present in the butterfly species, in the second butterfly *Prepona Omphale* tannenbaum structures are represented. I realized that these nanostructures consist of grooves with lamellae. Lamellae produce thin-film and multi-film interference that causes the wings to stain. However, I was only able to confirm this phenomenon for butterflies with lamellae. Therefore, a detailed physical model is needed to get to the bottom of the structural colors.

This was the inspiration to understand the behavior of light in the nanostructures using mathematical modeling. Based on scanning electron micrographs, I created two simple models with the tannenbaum structure.

In a second step, I used the Maxwell equations to determine the electric and magnetic fields around the model structures. These equations were solved for the discretization of the original partial differential equations with the Finite Difference Method. From this calculation, I hypothesize that the structures create variations in electric and magnetic fields that may possibly lead to interference.

If I get the opportunity to re-examine and deepen this topic, my work would include studying more sophisticated models of scale structures, as well as more advanced techniques for solving the Maxwell equations. I also investigated why the above hypothesis is stronger in the y – direction of the electric field than in the x – direction. Furthermore, 3D modeling should be considered in next step instead of 2D modeling.

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A Nomenclature

Zustandsgrößen

f	Frequenz
λ	Wellenlänge
t	Koordinatenzeit
x	x-Koordinate
y	y-Koordinate
z	z-Koordinate
E	Elektrisches Feld
B	Magnetische Flussdichte
H	Magnetische Feldstärke
J	Dichteströmung

Parameters

h	Plancksches Wirkungsquantum
ρ	Elektrische Ladungsdichte
ϵ	Permittivität (Material)
ϵ_0	Permittivität (Vakuums)
μ	Magnetische Permeabilität (Material)
μ_0	Magnetische Permeabilität (Vakuums)
c	Lichtgeschwindigkeit (Vakuums)

Mathematischer Operator

∇	Gradienten
$\nabla \cdot$	Divergenz
$\nabla \times$	Rotation

【評語】 160028

1. This project beautifully reproduces the microstructure of butterfly wings.
2. The explanation of the colors seen physically makes sense.
3. Distinguish between multi-colors and a-few-color butterfly wings are clearly simulated and explained.