Examenarbete

Optical Studies and Micro-Structure Modeling of the Circular-Polarizing Scarab Beetles

*Cetonia aurata*
*Potosia cuprea*
*Liocola marmorata*

Johan Gustafson
Examensarbetet utfört vid Laboratory of Applied Optics, IFM
2010-10-18

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**Author**

Johan Gustafson

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The aim of the work presented in this thesis is to contribute to a fundamental understanding of polarizing phenomena in some scarab beetles. The aim is also to study the beetle structures as inspiration in fabrication of artificially sculptured films. The three investigated species *Cetonia aurata*, *Potosia cuprea* and *Liocola marmorata* are of the family Scarabaeidae and subfamily Cetoniinae (Guldbaggar). They were all collected at Swedish locations and are the only species of Cetoniinae scarabs in Sweden. This work reports on their optical properties represented by Mueller matrix elements, degree of polarization data and trace curves in the Cartesian complex plane representation of polarized light. From these results we verify an earlier structural model for the *Cetonia aurata* and make way for similar models of the other two species.

The ellipsometer used in this work is of dual rotating compensator type from which the complete Mueller-matrix for the medium examined can be obtained. The ellipsometric measurements were conducted on the scutellum for four different angles of incidence, 45°, 55°, 65° and 75° over a wave-length range of 245 1000 nm.

Common for all examined species is that left polarization is observed in the wavelength range of 400 800 nm. For most of these species the polarization state is close to circular at some wavelengths especially at smaller angles of incidence. In general the degree of polarization is high (above 50%) when the polarization is near-circular. The degree of polarization also shows a clear dependence on the angle of incidence. The earlier model for *Cetonia aurata* shows a good agreement with the experimental data of this work. The model is also found as a good basis to work from to create models for the other two species.

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Contents

Abstract iii

Acknowledgments v

Contents iv

Chapter 1 Introduction 1
  1.1 Background ............................................................ 1
  1.2 Aim of this thesis ...................................................... 1

Chapter 2 Theory 2
  2.1 Polarized light .......................................................... 2
  2.2 The Stokes vector and degree of polarization ................. 3
  2.3 The Mueller-matrix .................................................... 4
  2.4 Ellipsometry ............................................................... 5
  2.5 Optical properties ..................................................... 5
  2.6 Cartesian complex-plane representation ..................... 6

Chapter 3 Experimental details 7
  3.1 Instrument ................................................................. 7
  3.2 Samples and measurement .......................................... 11

Chapter 4 Results and discussion 13
  4.1 $M_{41}$-elements, degree of polarization and trace ............ 14

Chapter 5 Summary and future work 23

Bibliography v

Appendix $M_{21}$-, $M_{31}$- and $M_{41}$-elements and depolarization for all samples and directions
Chapter 1
Introduction

1.1 Background

Some scarab beetles have a metallic glossy appearance which fascinates many scientists. Already in the early 1900 [1] studies were made regarding the structural- and optical properties of some scarabs. It was found that the investigated scarabs did not get their color from pigmentation and also that some scarabs reflected circular-polarized light. Already at that time it was assumed that the colors occurred due to interference phenomena and that the polarization may originate from chiral structures in the cuticle. But still today we are partly unfamiliar with the structures.

The Applied Optics group at IFM has made some preliminary studies on the aforementioned phenomenon in scarabs. Work has mainly been done on the green scarab *Cetonia aurata*. For this beetle it has been observed that the cuticle reflects circular polarized light for some wavelengths when illuminated with unpolarized light, a phenomenon only rarely occurring naturally. An optical model of the micro-structures in the cuticle of *Cetonia aurata* was made, for which the optical properties of the investigated samples had a good compliance with the theoretical data.

1.2 Aim of this work

The aim of the work presented in this thesis is to contribute to a fundamental understanding of the polarizing phenomenon in the scarab beetles *Cetonia aurata*, *Potosia cuprea* and *Liocola marmorata*. The aim is also to study the beetles structures as inspiration in fabrication of artificially sculptured films. These results are used to verify an earlier model for the *Cetonia aurata* and make way for similar models of the other two species and/or an universal model for all three.
Chapter 2
Theory

2.1 Polarized light

A complete description of light and its interaction with matter is given by the four vector fields, electric-field strength $E$, electric displacement density $D$, magnetic-field strength $H$ and magnetic-flux density $B$. The polarization of light can be determined by the components of the electric field vector $E$.

The amplitudes and correlation by phase difference of the components of $E$ determine the state of polarization.

A phase-difference of $\pi \cdot n \ (n = 0, 1, 2, 3\ldots)$ gives plane polarized light, $\pi/2$ left-handed circular and $3\pi/2$ right-handed circular. Other amplitude and/or phase-differences gives elliptic polarization which is the most general polarization state. Unpolarized light are defined as light where the components is completely uncorrelated to each other. Partly polarized light is a mix of unpolarized- and polarized light, that is with one non-correlated and one correlated.

It is common to represent the polarization with the ellipticity ($e$) and the azimuth ($\theta$) of the polarization ellipse. Where $e$ is given by

$$e = \tan(\varepsilon) = \frac{b}{a}$$

(2.1)
2.2 The Stokes vector and degree of polarization

The Stokes vector formalism describes polarized as well as partly polarized light and is represented by a vector of four real parameters,

\[
\mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I_X + I_Y \\ I_X - I_Y \\ I_{+45^\circ} - I_{-45^\circ} \\ I_r - I_l \end{bmatrix}
\]  

(2.2)

where \( I_X, I_Y, I_{+45^\circ}, \) and \( I_{-45^\circ} \) are the irradiances for linear polarization in the X, Y, +45° and -45° directions, respectively, and \( I_r \) and \( I_l \) are the irradiances for right-handed and left-handed polarization. The physical meaning of the Stokes parameters is:

- \( S_0 \); irradiance of the complete light-wave.
- \( S_1 \); difference between the irradiances of the x- and y-components.
- \( S_2 \); difference between the irradiances of the light wave in the +45° and -45° directions of linear polarization.
- \( S_3 \); difference between the irradiances of the right- and the left circular state of polarization.

The Stokes vectors are often normalized to \( I_0 = I_X + I_Y \) making \( I_0 = 1 \). In Tab. 2.1 normalized examples of common Stokes vectors are presented.

<table>
<thead>
<tr>
<th>Stokes vector</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1,0,0,0]^T</td>
<td>unpolarized</td>
</tr>
<tr>
<td>[1,1,0,0]^T</td>
<td>linear in the X-direction</td>
</tr>
<tr>
<td>[1,-1,0,0]^T</td>
<td>linear in the Y-direction</td>
</tr>
<tr>
<td>[1,0,1,0]^T</td>
<td>linear in the +45°-direction</td>
</tr>
<tr>
<td>[1,0,-1,0]^T</td>
<td>linear in the -45°-direction</td>
</tr>
<tr>
<td>[1,0,0,1]^T</td>
<td>right circular</td>
</tr>
<tr>
<td>[1,0,0,-1]^T</td>
<td>left circular</td>
</tr>
</tbody>
</table>

*Table 2.1 Examples of normalized polarization states.*

3 H. Arwin
The degree of polarization $P$ is the amount of light being polarized and can be described with the Stoke elements.

$$ P = \frac{I_{\text{pol}}}{I_{\text{tot}}} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \tag{2.3} $$

### 2.3 The Mueller-matrix

The Mueller-matrix is an operator that represent a polarizing optical element, and is commonly denoted $M$. If a sample is depolarizing, this matrix is required to give a full description of the optical response. The matrix operates on a Stokes vector representing the incident light, $S_i$, and its results is the Stokes vector, $S_o$, representing the emerging light.

$$ S_o = M \cdot S_i \tag{2.4} $$

$$ \begin{bmatrix} S_{o0} \\ S_{o1} \\ S_{o2} \\ S_{o3} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} S_{i0} \\ S_{i1} \\ S_{i2} \\ S_{i3} \end{bmatrix} \tag{2.5} $$

The 4x4 matrix that validates the expression above is defined as the Mueller-matrix.

In this work much focus is applied to the $m_{21}$, $m_{31}$ and $m_{41}$ parameters since they are the parameters effecting the emerging Stokes vector, eg. 2.5, with particular attention on $m_{41}$ since this parameter is connected to the circular polarizing properties of a surface irradiated with non-polarized light.

$$ \begin{bmatrix} S_{i0} \\ S_{i1} \\ S_{i2} \\ S_{i3} \end{bmatrix} = \begin{bmatrix} m_{11} \cdot S_{i0} & m_{21} \cdot S_{i0} & m_{31} \cdot S_{i0} & m_{41} \cdot S_{i0} \\ 0 & 0 & 0 \end{bmatrix} = \{ \text{Normalized} \} = \begin{bmatrix} m_{11} \\ m_{21} \\ m_{31} \\ m_{41} \end{bmatrix} \tag{2.6} $$

Also note that $m_{11}$ gives a linear relationship between the total irradiance before and after interaction with the sample, since the irradiance of the complete light-wave after interaction is $m_{11} \cdot S_{i0}$, where $S_{i0}$ is the irradiance before interaction.
2.4 Ellipsometry

The method to analyze the change of state of polarization of light due to interaction with a material is called ellipsometry. Two great advantages with this technique is that it is non-destructive to the sample and also not sensitive to the irradiance of the measurement beam. The data obtained gives both optical and structural (layer thickness, surface roughness, crystal orientation etc.) information.

There are basically three kinds of ellipsometer methods; reflection, transmission and scattering ellipsometry. In this study an ellipsometer working in reflection mode has been used.

In Mueller matrix ellipsometry, an optical surface is probed with a known polarized light wave (Fig. 2.2). The reflected light wave is then detected and represented by a Stokes vector. As shown in section 2.3 the Mueller-matrix can now be calculated.

2.5 Optical properties

The optical properties of a medium can be described as an complex function which is commonly denoted \( N \).

\[
N = n + i \cdot k
\]  (2.7)

The real part \( n \) is the common refractive index, depending on the speed of light in the medium and the imaginary part \( k \) is the extinction coefficient describing the absorption of the medium.
Isotropic and anisotropic media is a concept of uniformity or non-uniformity in the different physicals directions in a sample. For uniaxal media the properties are the same in two directions (a plane) called the ordinary directions but different in the third direction, denoted the extraordinary direction. For biaxial media the properties is different in all directions. An obvious effect is that the optical properties will be different in the different direction of an anisotropic material.

When the real part of the index of refraction $n$, is unknown an empirical mathematical formula, the Cauchy model, can be applied to model it. This model is defined as:

\[ n(\lambda) = A + \frac{B \lambda^2}{\lambda^2 + C \lambda^4} \]  

where $n$ is the index of refraction, $A$, $B$ and $C$ are material specific constants and $\lambda$ is the wavelength of the light.

2.6 Cartesian complex-plane representation

A convenient way to display polarized light is trace curves in the Cartesian complex-plane.

\[ \chi = \frac{E_Y}{E_X} \]  

where $E_Y$ and $E_X$ are the complex components of the $E$ vector. $\chi$ can be divided into two parts, one complex ($\chi_i$) and one real ($\chi_r$). When $\chi_i = 0$ and $\chi_r = |1|$ the light is circular-polarized, left in the negative region and right in the positive. When $\chi_i = 0$ the light is linear-polarized. Some examples of the polarizations characteristics for different points in the Cartesian complex-plane can be seen in fig. 2.3.

Figure 2.4 representation of polarized light in the Cartesian complex-plane. [3 H. Arwin]
Chapter 3
Experimental details

3.1 Instruments

The ellipsometer used in this work RC2 (J.A.Woollam Co.) has dual rotating compensators (there of the name “Rotating Compensator 2”). A compensator change the phase of the light wave, making it possible to generate light with a Stokes parameter \( S_3 \neq 0 \). The advantage of using dual compensators is that the polarized state of both the incident- and emerging light can be determined, and therefore the complete Mueller-matrix can be obtained. By letting the two compensators rotate at different angular speed but with a certain ratio, a minimum of the highest order of terms in the Fourier wave-form can be found, making calculations quicker to obtain the needed atleast 16 independent non-zero Fourier amplitudes [5].

The whole spectral range of 245-1690 nm is probed at the same time. The beam is dispersed by a grating and then each separated wavelength is detected by means of an array of diodes.

The system have several custom hardware components. For the measurements in this study a translator sample stage was used as well as, focusing lenses and a sample camera. The lenses enables a smaller measurement area, about 50\( \mu \)m in diameter depending on the angle of incidence. The translator sample stage allows to move the sample in the plane, allowing to freely chose the point to be investigated, the camera gives an good overview of the sample and which point that is irradiated.

![Figure 3.1 RC2 overview](image)
By analyzing the measured data information about sample structure and optical properties are obtained. A typical analysis scheme is described in Fig. 3.1. The main steps are;

- The full Mueller-matrix of the sample is measured.
- A model of the sample is built up in the analysis software (see below). Information about the sample from literature/fabrication as well as data from other characterization methods such as electron microscopy, serve as input to the model. In general, the model will consist of two or more layers, each describing their optical properties.
- The simulated data can now be calculated from the model and compared with experimental data. Model parameters can be set as fit-parameters and a minimization of the mean square error (see below) can be done. If the fit is bad (high mean square error) the model must be refined. The procedure is repeated until a good fit is obtained.
- When the fit between experimental and model data is sufficiently good the model should give information about the sample structure (layer thicknesses, roughnesses, porosity etc.) as well as optical properties of the constituting layers.

The analysis software CompleteEASE is a management- and analysis program created for use with the RC2 instrument. It is a multipurpose program containing several features relevant for the samples in this work. In particular the program has been used to present Mueller-matrix data (e.g. $n_{41}$ and degree of polarization $P$) and for model data fitting. A screen-shot from the the software is presented in Fig. 3.3.

The main feature of CompleteEASE is the modeling function, which allows the user to build a model of a sample, layer by layer, giving each layer different optical properties. There are many different features for modeling in the software.
optical reference data exist for many materials and data for several materials are included in the software database. Predefined general models functions can also be generated including Cauchy dispersion, B-spline models or Lorentz oscillators. A layer can also be managed as uniaxal or biaxal and given different parameters in the ordinary and extra ordinary direction. Surface or interface roughness as well as porosity can be modeled using effective medium approximations (EMA).

The earlier model for *Cetonia aurata* (seen below) [1] is divided into two layers grown on a substrate (the thickness of the first layer makes the interaction with the substrate approximately none). Where the first layer represent the exocuticle and the second layer represent the epicuticle. The utter part of the cuticle is the epicuticle, with a thickness of about 1-2 μm. The surface is a thin waxlayer on cement, beneath is a chitin structure. The exocuticle is built by several layers of mainly chitin [7]. The hypotheses is that the exocuticle is of chiral structure, with different direction of the refractive index. Practically this has been modeled as a uniaxial layer divided into slices, given a discrete pitch through the layer.
As can be seen in Fig. 3.4, layer #2 (The epicuticle) has the thickness and the optical properties (modeled with Cauchy dispersion) as fit parameters. In the graded layer (the exocuticle) the optical properties (Graded layer) and the number of Turns in Phi are set as fit parameters.

The fitting procedure is an iterative non-linear regression algorithm called the Levenberg-Marquardt method. When the model data is fitted to the Mueller-matrix data the mean square error (M.S.E.) is used as the goal function to minimize. The MSE is defined as:

\[
MSE = \sqrt{\frac{1}{3n-m} \sum_{i=1}^{n} \left[ (N_{E_i} - N_{G_i})^2 + (C_{E_i} - C_{G_i})^2 + (S_{E_i} - S_{G_i})^2 \right]} \cdot 1000 \quad (3.1)
\]

where \( n \) is the number of wavelengths, \( m \) is the the number of fit-parameters.

\( N = \cos(2\Psi) \), \( C = \sin(2\Psi) \times \cos(\Delta) \) and \( S = \sin(2\Psi) \times \sin(\Delta) \). \( E \) indexes the measured data and \( G \) indexes the generated model data.

The MSE can approximately be seen as the mean difference between the measured data and the model simulation, divided wavelength by wavelength. A good model gets a lower MSE. For a simple model a MSE value of 1 can be considered as good whereas for more complex bulk media (as in present work) MSE values over 10 can be acceptable. [6].

In the present study modeling was made for the *Cetonia aurata* specimen, the final model is displayed in Fig. 3.4. The Epicuticle had a thickness of 520.7 nm and the thickness of the exocuticle is as mentioned above a fixed thickness, therefore this could not be determined.
3.2 Samples and measurements

The scarab beetles examined are of the family Scarabaeidae and subfamily Cetoniinae. The three investigated species *Cetonia aurata* (Linnaeus 1761), *Potosia cuprea* (Fabricius 1775) and *Liocola marmorata* (Fabricius 1792) where all collected at swedish locations and are the only species of Cetoniinae scarabs in Sweden.

<table>
<thead>
<tr>
<th>Picture</th>
<th>Date of capture</th>
<th>Place of capture</th>
<th>Species</th>
<th>Color seen by eye</th>
<th>Denotation</th>
</tr>
</thead>
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<td>31.4.1964</td>
<td>Öland Skogsby</td>
<td>Cetonia aurata, Gräsgörn guldbagge (Linnaeus 1761)</td>
<td>Grass green</td>
<td>CA</td>
</tr>
<tr>
<td><img src="image2.png" alt="Picture" /></td>
<td>14.7.1957</td>
<td>Gröttnäsby Holmedalen Värmland</td>
<td>Potosia cuprea, olivgrörn guldbagge (Fabricius 1775)</td>
<td>Olive green</td>
<td>PC1</td>
</tr>
<tr>
<td><img src="image3.png" alt="Picture" /></td>
<td>14.7.1957</td>
<td>Gröttnäsby Holmedalen Värmland</td>
<td>Potosia cuprea, olivgrörn guldbagge (Fabricius 1775)</td>
<td>Matt brown</td>
<td>PC2</td>
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<tr>
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<td>Unknown</td>
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<td>Shiny brown</td>
<td>PC4</td>
</tr>
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<td><img src="image6.png" alt="Picture" /></td>
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<td>Unknown</td>
<td>Liocola marmorata, brun guldbagge (Fabricius 1792)</td>
<td>Brown</td>
<td>LM</td>
</tr>
</tbody>
</table>

*Table 3.1 Samples overview*
Prior to the ellipsometry measurements the investigated scarab specimens were chosen by an ocular investigation using circularly left- and right-polarizing glasses. All samples were examined on the scutellum in four different beam directions (± X and ± Y) as shown in Figure 3.5.

Each sample was mounted on the translator sample stage and aligned. The ellipsometric measurements were then conducted for each of the four directions over four different angles of incidence, 45°, 55°, 65° and 75°. The angles were confined to the interval 45°-75° due to the use of lenses, for higher or lower angles the lenses would collide with the sample stage.

The complete wavelength range of the RC2 was measured, but due to an increased noise level above 1000 nm only the range of 245-1000 nm was considered in this work. Depending on the signal level different acquisition times were set between X and Y to give less noisy results.

The alignment was performed at an angle of incidence of 65°. This angle was chosen from a series of test measurements where alignment at different angles of incidence was conducted. At 65°, the detected signal was strongest providing best conditions for alignment. Aligning the samples are very difficult and the signal has been pendulous. Some samples gave a clear and steady well focused signal, but for others it was very weak and scattered.

Due to the rather thick samples and a needle which is mounted through the scarab, the probing at different angle of incidence occurred at different point on the scutellum. This is due to the lack of compensation for the displacement of the rotating axis.
Chapter 4
Results and discussion

As mentioned above, the $m_{41}$ element is of highest interest and will be the main data displayed in this chapter. A complete presentation of the Mueller-matrix data can be found in the appendix. In addition the degree of polarization $P$ and trace-curves will be presented.

Figure 4.1 shows measurements on the _Cetonia aurata_ specimen (CA) for all angles of incidence ($45^\circ$, $55^\circ$, $65^\circ$ and $75^\circ$) and for both positive and negative X-measurement directions. The graphs imply that the $m_{41}$ element is approximately the same regardless of the sign of the measurement direction.

Figure 4.1  Comparison of the $m_{41}$ element for positive and negative measurement direction.
4.1  $m_{41}$ elements, degree of polarization and trace curves

The Mueller-elements for all samples showed similar relation regardless of measurement directions. Due to this, only $m_{41}$ data and degree of polarization for the positive directions will be shown in this section. Data for all measurement directions are displayed in the appendix.

Also trace-curves in the Cartesian complex-plane representation will be displayed below. Circular areas has been placed around the point for circular polarized light. The outer brighter ring represent the ellipticity $e = 0.5$ and the inner when $e = 0.8$. The point nearest to circular polarization (highest absolute value of $e$) and the corresponding polarization ellipse is marked. In the $m_{41}$-element curves under the trace-curves the same point and corresponding degree of polarization is marked.
Figure 4.2. Sample CA, $m_{41}$-elements, degree of polarization and trace curves.
Figure 4.3. Sample LM, m41-elements, degree of polarization and trace curves.
Figure 4.4. Sample PC1, m_{11}-elements, degree of polarization and trace curves.
Figure 4.5. Sample PC2, m41-element, degree of polarization and trace curves.
Figure 4.6. Sample PC3, m41-element, degree of polarization and trace curves.
Potosia cuprea (PC4) Trace curve X-direction, 45° angle of incidence

Potosia cuprea (PC4) Trace curve Y-direction, 45° angle of incidence

Angle of incidence: 45°, 55°, 65°, 75°

Figure 4.7. Sample PC4, m_{41}-element, degree of polarization and trace curves.
Figure 4.2 shows $m_{44}$ data for specimen CA where a distinct left polarization is observed between 400-600 nm. The X and Y direction is similar for the lower angles of incidence, but for 65° and 75° in the X direction the $m_{44}$ is to the absolute value higher and more distinct. The degree of polarization is approximately the same for both directions. Between 400-600 nm a lower degree of polarization occur.

Figure 4.3 shows $m_{44}$ data for specimen LM where left polarization is observed between 400-800 nm. Results in the X and Y direction are very similar and only small local differences are seen. The degree of polarization is similar up to 650 nm but is lower in the X direction for incident angles of 45° and 55°. Between 400-600 nm a lower degree of polarization occur.

Figure 4.4 shows $m_{44}$ data for specimen PC1 where a weak right polarization occurs for 65° and 75° at around 475 nm. The reflected light is otherwise left polarized in the range 425-650 nm. The results in the X and Y direction are quite similar except regarding the right polarization. The characteristics of the degree of polarization is similar in both directions but with some smaller value differences.

Figure 4.5 shows $m_{44}$ data for specimen PC2 which is mainly left polarized in the range 425-1000 nm, but right polarized at some wavelengths along the whole range. The spectra are very noisy. The peaks is broader in the X direction. The degree of polarization is similar in both directions and it is varying a lot in the range of 600-1000 nm.

Figure 4.6 show $m_{44}$ data for specimen PC3 which is left polarized in the range 400-750 nm. The absolute $m_{44}$ is higher in the X direction for both ranges. The degree of polarization is very similar in both directions but with some localized differences.

Figure 4.7 shows $m_{44}$ data for specimen PC4 where a weak right polarization occurs for 65° and 75° from 550-650 nm. The reflected light is otherwise left polarized in the range 400-750 nm. The left polarization is higher in the X direction, but the
characteristics is the same for both. The degree of polarization is similar in both
directions and lowest in the range of 435-750 nm (but more local around 600 nm for
higher angles of incidence).

The characteristics is very similar between PC1 and PC3, the greener scarabs. Also
the PC4 shows a polarization alike these samples, but without an peak in the range
400-600 nm. Seen by eye this sample has a more brownish appearance. The m₄₁
activity range seems to be in the range of the color seen by eye, which could explain
the non-existing peak in the 400-600 nm range for PC4. The depolarization is
approximately the same for all three samples. The PC2 is very different from the
other PC:s. Both the m₄₁ and the depolarization is active in another range. The only
difference between this sample and the others, seen by eye, is that the surface is
matte.

All scarabs show left polarization in the wavelengths range of 400-800 nm. For most
of the samples the polarization state is close to circular at some wavelengths
especially at smaller angles of incidence. In general the degree of polarization is high
(above 50%) when the polarization is near circular. The different angles of incidence
shows a red-shift (polarization in higher wavelength region) for lower angles, these
also has the highest degree of polarization. Left polarization is dominant, but at some
wavelengths a slight right polarization can be noticed. The depolarization shows a
clear dependence on the angle of incidence. The degree of polarization due to angle
of incidence is (except for some local intervals) observed in descending order, 55°,
65°, 45°, 75°.
5 Summary and future work

It is possible to make quantitative measurements of the polarization properties of the presented scarabs in the wavelength range of 245-1000 nm. The characteristics of the $m_{41}$ as well as other Mueller-matrix elements can be well determined. For wavelengths above this range the signal is more noisy.

Common for all samples is that left polarization is observed in the wavelength range of 400-800 nm. For most of these species the polarization state is close to circular at some wavelengths especially at smaller angles of incidence. In general the degree of polarization is high (above 50%) when the polarization is near circular. A red-shift for lower angles of incidence occurs, also a higher degree of left and right polarization. Left polarization is dominant, but at some wavelengths a slight right polarization can be noticed. The degree of polarization shows a clear dependence on the angle of incidence. The degree of polarization due to angle of incidence is (except for some local intervals), arranged in descending order, 55°, 65°, 45°, 75°.

The earlier model for Cetonia aurata (CA) shows a good agreement with the experimental data of CA. However the model does not agree well with the other species in this study. Since the characteristics of the optical properties is similar, it is likely that the earlier model gives a good base to work from. The Potosia cuprea (PC) has dual peaks for the $m_{41}$ element, where the one of lower wavelength is in the region of the peak for the CA and the one of higher wavelength is in the region of the peak for Liocola marmorata (LM). It is possible that adding another layer of different pitch or allowing for two different chiral structures, where the proportion can be changed, in the same layer may give a model applicable to all of the three species. Presently, efforts are being made to create a more general model.
Bibliography


[2]. [http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html](http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html)


Appendix (m_{21} -, m_{31} - and m_{41} -elements for all samples and also the degree of polarization)

m_{41} -elements and degree of polarization for all samples in all directions

Cetonia aurata (CA)
Liocola marmorata (LM)

Angle of incidence: 45°, 55°, 65°, 75°
Potosia cuprea (PC1)

Angle of incidence: 45°, 55°, 65°, 75°
Potosia cuprea (PC2)

Angle of incidence: 45°, 55°, 65°, 75°
Potosia cuprea (PC3)

Angle of incidence: 45°, 55°, 65°, 75°
Potosia cuprea (PC4)

Angle of incidence: 45°, 55°, 65°, 75°
m21- and m31-elements for all samples in all directions

Cetonia aurata (CA) and Liocola marmorata (LM)

Angle of incidence: 45°, 55°, 65°, 75°

The brighter curves are m21-elements
Potosia cuprea (PC1 and PC2)

Angle of incidence: 45°, 55°, 65°, 75°

The brighter curves are m21-elements
Potosia cuprea (PC3 and PC4)

Angle of incidence: 45°, 55°, 65°, 75°
The brighter curves are m21-elements