Comparison and analysis of Mueller-matrix spectra from exoskeletons of blue, green and red Cetonia aurata

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A B S T R A C T

The exoskeleton, also called the cuticle, of specimens of the scarab beetle Cetonia aurata is a narrow-band reflector which exhibits metallic shine. Most specimens of C. aurata have a reflectance maximum in the green part of the spectrum but variations from blue–green to red–green are also found. A few specimens are also more distinct blue or red. Furthermore, the reflected light is highly polarized and at near-normal incidence near-circular left-handed polarization is observed. The polarization and color phenomena are caused by a nanostructure in the cuticle. This nanostructure can be modeled as a multilayered twisted biaxial layer from which reflection properties can be calculated. Specifically we calculate the cuticle Mueller matrix which then is fitted to Mueller matrices determined by dual-rotating compensator ellipsometry in the spectral range 400–800 nm at multiple angles of incidence. This non-linear regression analysis provides structural parameters like pitch of the chiral structure as well as layer refractive index data for the different layers in the cuticle. The objective here is to compare spectra measured on C. aurata with different colors and develop a generic structural model. Generally the degree of polarization is large in the spectral region corresponding to the color of the cuticle which for the blue specimen is 400–600 nm whereas for the red specimen it is 530–730 nm. In these spectral ranges, the Mueller-matrix element $m_{41}$ is non-zero and negative, in particular for small angles of incidence, implicating that the reflected light becomes near-circularly polarized with an ellipticity angle in the range 20°–45°.

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1. Introduction

Several beetles, particularly in some subfamilies of Scarabaeidae, display structural colors and show interesting polarizing properties in the reflected light from their exoskeletons [1]. In particular near-circular polarization phenomena are observed. This was found by Michelson more than 100 years ago [2]. This phenomenon is illustrated in Fig. 1 which shows a specimen of the scarab beetle Cetonia aurata (Linnaeus, 1758) observed through left-handed and right-handed polarizing filters. The optical polarization and color phenomena originate from nanostructures in the outer part of the exoskeleton of a beetle. In C. aurata the nanostructure is multilayered as seen in electron microscropy (Fig. 1). C. aurata, also called the rose chafer, is a scarab beetle known from most of Europe to Siberia. As adult it is active and flies during spring and summer, mostly in warm and sunny weather. It feeds on flowers of several plant species as roses and in southern Europe sometimes it is a pest in orchards, destroying flowers and ovaries. The biological function of the color and the polarization properties is however not known.

The possibilities to use natural photonic structures or replicas made from them in technical applications are intensively explored [3]. Among suggestion of potential applications found in the literature are selective chemical sensors based on nanostructures in scales from the butterfly Morpho sulkowskyi [4], fast infrared detectors also based on butterfly scales [5] and bioinspired polarization cryptation [6]. The beetle Cyphochilus insulanus exhibits structural white coatings [7] and tunable coatings are found in Charidiotella egregia [8].

Mueller-matrix measurements have been employed to explore the fascinating color and polarization properties in beetles [9–14] and simulations based on structural models have also been performed [14]. More recently linear regression approaches have been presented to extract structural parameters from Mueller-matrix data [15]. In this report we apply the recently suggested structural model to differently colored specimens of the scarab beetle C. aurata. The applicability of the model for the differently colored specimens is discussed. In addition we use the Mueller-matrix data to derive ellipticity and degree of polarization of the light reflected from the beetles under illumination with unpolarized light.

2. Experimental details

A dual rotating-compensator ellipsometer (RC2, J.A. Woollam Co., Inc. [16]) was used to determine the normalized Mueller-matrix $M$ of
exoskeletons of specimens of the scarab beetle *C. aurata* with a precision better than ±0.005 in the elements $m_{ij}$ ($i, j = 1, 4$). In a dual rotating-compensator ellipsometer, the two rotating compensators are frequency-coupled e.g. with a 3:5 frequency ratio. As a consequence, the detector signal contains a dc and 24 nonzero harmonic components which are used to determine the 15 normalized Mueller-matrix elements as described by Collins and Koh [17]. Measurements were performed at angles of incidence $\theta$ between 20° and 75° in steps of 5° in the spectral range 245–1700 nm. Only data in the range 400–800 nm are reported here. Focusing lenses were used to reduce the beam size to around 50 $\mu$m.

Four specimens of *C. aurata* of different color were studied. The specimens will be identified as red, green, green–blue and blue. All measurements were performed on the scutellum which is a small triangular-shaped part of the cuticle on the thorax of a beetle. Fig. 2 shows images of the scutella on the four specimens studied. The small bright spot seen on each scutellum is due to scattered light from the focused ellipsometer beam. Three regions as marked in Fig. 1 are normally identified in a cross section of the cuticle of these beetles. On top there is a thin multilayered wax layer which is referred to as the epicuticle with a thickness of less than 400 nm for the beetles studied here. The color- and polarization-generating multilayered region is found under the epicuticle and is called the exocuticle and has a thickness in the range 10 to 20 $\mu$m. Under the exocuticle, the soft endocuticle is found. More detailed descriptions of an insect integument can be found e.g. in Ref. [18].

The Mueller-matrix data were analyzed using a model with twisted biaxial layers with a top uniaxial multilayer as schematically shown in Fig. 3. The twisted layers, which represent the exocuticle with a total thickness $d_{exo}$ mimic a helicoidal structure and accounts for the color and polarization properties. The data exhibit some interference oscillations due to the overall thickness of the cuticle but these effects are not included in the model. The model data are smooth as the helicoidal structure is assigned a small absorption and the exocuticle is considered semi-infinite. The small absorption is included to model bulk scattering from inhomogeneities in the cuticle. The uniaxial top layer with thickness $d_{epi}$ at the cuticle–air interface represents the epicuticle. The refractive indices in the helicoidal structure as well as in the epicuticle are modeled with Cauchy dispersions. To account for variations in pitch $\Lambda$ of the helicoidal structure, a rectangular pitch distribution $\Delta \Lambda$ is included which implies that forward calculations are performed and averaged for eight values of $\Lambda$ in the range $\Lambda - \Delta \Lambda$ to $\Lambda + \Delta \Lambda$. In practice the exocuticle is divided in a sufficiently large number (360 in this case).
of biaxial sublayers. These biaxial sublayers, as well as the uniaxial epicuticle, are each described with a $4 \times 4$ layer matrix containing the sublayer optical properties. An algorithm for arbitrarily anisotropic homogeneous layered systems described by Schubert [19] is used for calculations of the four Jones matrix reflection coefficients $r_{pp}$, $r_{ss}$, $r_{ps}$ and $r_{sp}$, where $p(s)$ indicates polarization parallel (perpendicular) to the plane of incidence. The elements of $M$ are then obtained by a transform from the Jones matrix [20]. These algorithms are implemented in the commercial software used (CompleteEASE, J.A. Woollam Co., Inc.). Further details about modeling are found elsewhere [15].

Non-linear regression analysis was performed with the Levenberg-Marquardt algorithm in CompleteEASE. A best fit was found by minimizing the mean squared error (MSE)

$$
MSE = \frac{1000}{N_\lambda N_\theta N} \sum_{i=1}^{L} \sum_{j=1}^{4} \left[ \left( m^{exp}_{ij} - m^{mod}_{ij}(x) \right)^2 \right]^{1/2}
$$

where $L = N_\lambda N_\theta$ is the product of the number of wavelengths $\lambda$ and angles of incidence, i.e. the total number of Mueller matrices measured. $M$ is the number of fit parameters in the fit parameter vector $x$ and

![Normalized Mueller-matrix data measured on a green C. aurata.](Image)

![Experimental (dotted curves) and model-generated (solid curves) $m_{41}$ spectra for the four beetles.](Image)
Table 1
Structural parameters found in the analysis.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(d_{ep} (\text{nm}))</th>
<th>(\Lambda (\text{nm}))</th>
<th>(\Delta \Lambda (\text{nm}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>387</td>
<td>425</td>
<td>24</td>
</tr>
<tr>
<td>Green</td>
<td>363</td>
<td>367</td>
<td>15</td>
</tr>
<tr>
<td>Green-blue</td>
<td>350</td>
<td>352</td>
<td>13</td>
</tr>
<tr>
<td>Blue</td>
<td>370</td>
<td>328</td>
<td>13</td>
</tr>
</tbody>
</table>

superscripts exp and mod indicate experimental and model-generated data, respectively. The fit parameters in \(x\) are the epicuticle thickness \(d_{ep}\), \(\Lambda\), \(\Delta \Lambda\) and the Cauchy parameters of the refractive indices of the biaxial epicuticle and the layers in the exocuticle [15].

In addition to the structural parameters, the ellipticity angle \(\varepsilon\) and the degree of polarization \(P\) under illumination of unpolarized light are presented. Both \(\varepsilon\) and \(P\) are derived from \(\mathbf{M}\) using \(\mathbf{S}_t = \mathbf{M} \mathbf{S}_i\), where \(\mathbf{S}_t\) and \(\mathbf{S}_i\) are the Stokes vectors for the reflected and incident light, respectively. With incident light described with a normalized Stokes vector \(\mathbf{S}_i = [1, 0, 0, 0]^T\), we find

\[
\varepsilon = \frac{1}{2} \sin^{-1} \left( \frac{m_{41}}{\sqrt{m_{21}^2 + m_{31}^2 + m_{41}^2}} \right) \tag{2}
\]

\[
P = \sqrt{m_{21}^2 + m_{31}^2 + m_{41}^2}. \tag{3}
\]

3. Results and discussion

Fig. 4 shows, as an example, primary experimental Mueller-matrix data measured on the green \(C. aurata\). We observe that at small \(\theta\), the spectral variations are more pronounced whereas at large \(\theta\), \(\mathbf{M}\) is similar to a near-dielectric surface with all \(n_i\) being almost constant with \(\lambda\). A shift towards shorter wavelengths with increasing \(\theta\) is also seen in all elements. The data are also highly symmetric, i.e. \(m_{41} = m_{14}\) and \(m_{31} = -m_{13}\) to give a few examples.

The twisted biaxial layer model described above is employed to extract values on structural parameters from measured \(\mathbf{M}\)-data. Since we are aiming for extracting parameters describing the helicoidal structure we only use data up to \(\theta = 60°\) in the regression. For larger \(\theta\), the spectra exhibit only small spectral variations and model imperfections will lead to increase of systematic errors. The fits are generally very good given the complexity of the model and the type of samples studied. Fig. 5 shows model fits to the \(m_{41}\)-spectra at \(\theta = 20°\) from the four beetles. Recall that Fig. 5 only shows fits to one element in \(\mathbf{M}\) at one angle of incidence. However in the analysis all elements are used at three angles of incidence. The interference oscillations from the cuticle thickness are clearly seen but were not possible to model using the current model. The green-blue specimen has the smallest width of the minimum in \(m_{41}\) around 540 nm indicating a small pitch distribution. The green specimen has a little wider minimum as well as the red specimen. For the blue specimen the spectral variations are more complex with three minima. However, the model reproduces the shallow minimum in \(m_{41}\) indicating that the model is representative also for the blue specimen.

In Table 1, \(\Lambda\) and \(\Delta \Lambda\) from the modeling are presented. The numerical values verify the observations from Fig. 5. In addition to the structural parameters in Table 1, the analysis also provides refractive index data for the biaxial epicuticle and for the biaxial layers in the helicoidal structure in the exocuticle. These refractive indices are typically in the range 1.4 to 1.6 depending on wavelength and vary from specimen to specimen depending on density effects. Examples of wavelength dependent biaxial index of refraction determined on a green \(C. aurata\) are found in [15].

Fig. 6 shows \(P\) for reflection of unpolarized light at \(\theta = 20°\) derived using Eq. (3). Values of \(P\) up to 0.8 are found for the red specimen. Compared with Fig. 5, it is seen that \(P\) is significantly larger in the spectral regions where \(m_{41}\) is non-zero. Outside this range, \(P\) is around 0.15 independent of color of the beetle. Fig. 7 shows the ellipticity angle \(\varepsilon\) for the red and the blue specimens determined using Eq. (2). It is seen that \(\varepsilon\) is close to \(-45°\) at some wavelengths, i.e. at these wavelengths the polarization state of the reflected light is near-circular and left-handed as \(\varepsilon\) is negative. Outside the spectral region where \(m_{41}\) is non-zero, \(\varepsilon\) is small indicating near linearly polarized light. In summary Figs. 6 and 7 show that the degree of polarization is large in the spectral region where \(m_{41}\) is non-zero with almost circularly polarized light originating from the twisted multilayered cuticle structure. Outside this range, the polarized part of the reflected irradiance is linearly polarized due to standard Fresnel reflection effects. Notice that \(P\) and \(\varepsilon\) are obtained by transforming experimental data by using Eqs. (2) and (3).

4. Concluding remarks

Mueller-matrix ellipsometry reveals complex reflection properties of the cuticle of \(C. aurata\) and is very rich in information about the cuticle nanostructure. A model with a chiral dielectric layer provides a good description of the Mueller-matrix elements. The model can be applied to red, green, blue-green and blue specimens of \(C. aurata\). Future work includes development of the model to include oscillations due to the cuticle thickness and comparison with other beetles in the same family.

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References