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

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ABSTRACT

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°.

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 microscopy (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 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 *Charidotella 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

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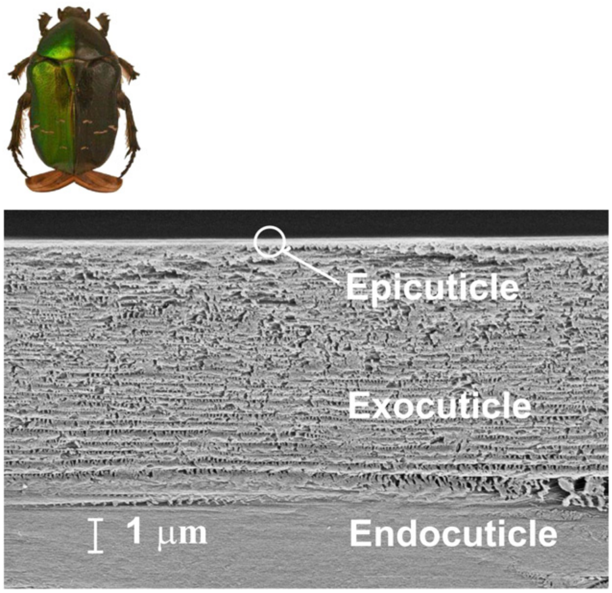

Fig. 1. The scarab beetle *C. aurata* observed through a left-handed (left half) and right-handed (right half) polarizing filters. Two separate photos are combined into one (Photo: Jens Birch). Below a scanning electron microscopy image of a cuticle from *C. aurata* is shown (Image: Torun Berlind).

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 θ 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 μm.

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 μm. Under the exocuticle, the soft endocuticle is found. More detailed descriptions of an insect integument can be found e.g. in Ref. [18].

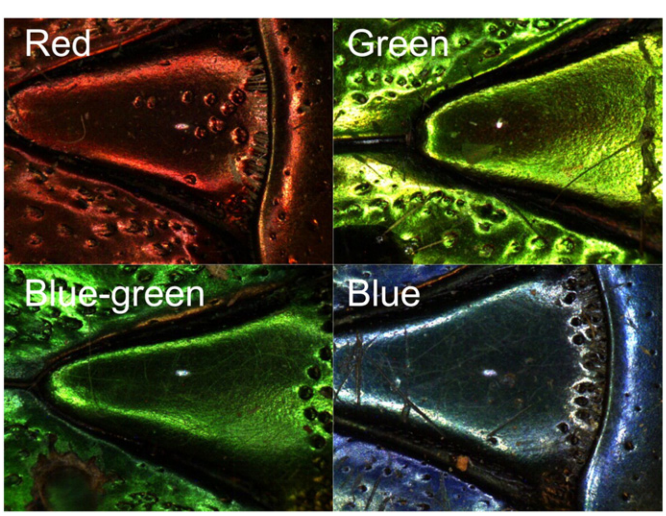

Fig. 2. Photos taken in scattered room light on the scutellum on four *C. aurata* specimens of different color. The measurement areas are seen as small bright spots due to scattered light from the ellipsometer beam.

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 Λ of the helicoidal structure, a rectangular pitch distribution ΔΛ is included which implies that forward calculations are performed and averaged for eight values of Λ in the range Λ − ΔΛ to Λ + ΔΛ. In practice the exocuticle is divided in a sufficiently large number (360 in this case)

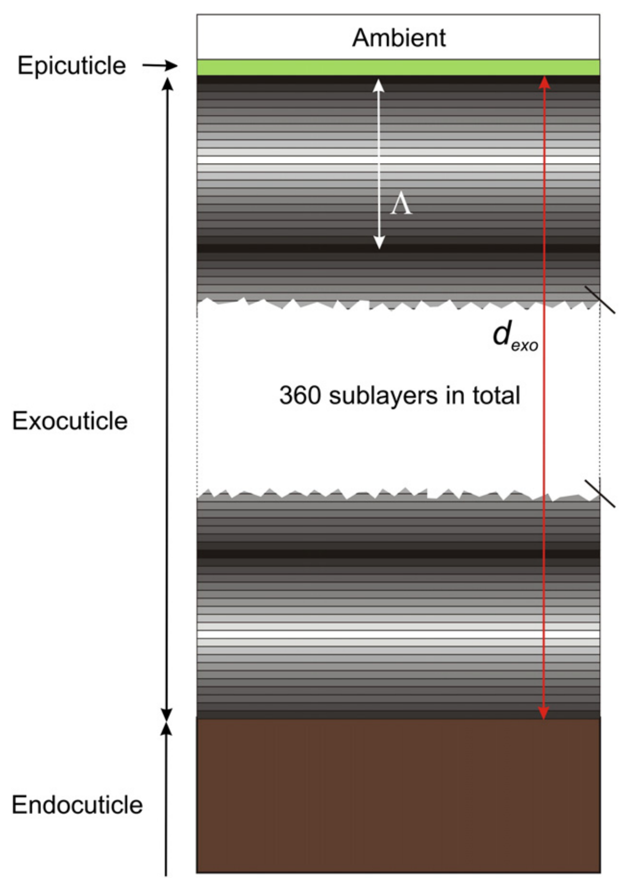

Fig. 3. The structural model used in the analysis. The different parts in the model are from bottom to top: the endocuticle; the exocuticle which mathematically is divided in 360 sublayers; the epicuticle; and the ambient. The direction of the optic axis of each sublayer in the exocuticle is indicated with the gray scale and the pitch Λ is defined as the distance when the optic axis had rotated one full turn.

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