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Cite as: AIP Advances 9, 075311 (2019); doi: 10.1063/1.5108773
Submitted: 2 May 2019 • Accepted: 5 July 2019 •
Published Online: 17 July 2019

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ABSTRACT
Inspired by alternative hybrid-biophotonic structures and modern computational electromagnetics in plasmonics, herein, we attempted to understand the plasmonic properties of a metal film (gold or palladium) on the surface features of butterfly wing scales, as they might represent the dominant features of structure-enhanced and/or structure-attenuated optical properties. Light-harvesting plasmonic antenna was loaded on these natural substrates. We examined the plasmonic properties of three models representing the scales of three lepidoptera species. Each scale model was assumed to have a 100 nm metal coating. In addition to the electron micrograph of the lepidopterans’ wings, the optical properties of the investigated structures were numerically studied using the finite-difference time-domain technique. We first constructed the biophotonic models of butterfly structures coated with a metal film, and then they were verified by scanning electron microscopy images using Lumerical Software, which provided an accurate solution of Maxwell’s equation for the micro/nanostructures. The metal samples were palladium or gold, while the investigated scales of butterfly species were Catopsilia pomona, Danaus genutia, and Cetboia penthesilea. Electric field and absorption spectra were observed under broadband light irradiations at perpendicular- and parallel-polarized light illuminations. As a result of the formation of variations of metals on the different features of wing scales, we observed changes in the absorption intensities and a redshift in the main peak absorbance. The spectra further showed a close relationship with the electric field distribution. A metal film coated on the butterfly wing scales acted as an optical plasmonic sensitivity to amplify and attenuate the visible light, whereas the existence of wave propagating modes from the well-defined structural variations resulted in a reduction and enhancement of the bandwidth of absorbance. Among the three simulation models, the Cetboia penthesilea scale model coated with a gold film demonstrated the best plasmonic properties to the electric field, in terms of its potential application for further biophotonic structure fabrication.

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I. INTRODUCTION

It is well known that structural colors on butterfly wing scales generally originate from their micro/nanostructures, in terms of their physical color. The physical mechanism exists when a tissue composed of matter with diverse indices of refraction is arranged in periodic structures with spaces in order of the wavelengths of light irradiation. Therefore, such a natural photonic structure serves as an alternative structure in the development of the new hybrid photonic devices, although currently existing artificial photonic devices are still being built and show great stable optical characteristics. These points have motivated many studies to focus on building biodegradable, biocompatible, and implantable photonic devices to be integrated on the substrates. For instance, Garrett et al. have used the gold-coated Graphium weiskei substrate to detect hemozoin as a malaria pigment within lysed blood via surface-enhanced
Raman spectroscopy.\textsuperscript{,2} Elbaz et al. have used *Morpho*, *Papilio*, and *Ornithoptera* substrates to regulate cell orientation.\textsuperscript{,3} Narasimhan et al. have used a polymer-based *Chorinea* template to detect intracellular response in a white rabbit.\textsuperscript{,4} Chen et al. have assembled cardiac tissues on the *Morpho* substrate to detect single-cell-level mechanics.\textsuperscript{,5} Rasson et al. have fabricated a concave porous silicon multilayer to mimic *Papilio blumei*. Optical sensitivity on ethanol vapor was improved compared to the standard one.\textsuperscript{,6} Jiang et al. have used *Morpho didius* butterfly scales to detect nitrogen, methanol and ethanol vapors. The experimental result was in agreement with the principal component analysis (PCA) simulation method. Wang et al. have fabricated ZnO coated on *Pieris canidia* to generate a biophotonic device with low cost.\textsuperscript{,7} Aideo et al. have fabricated ZnO coated on *Graphium agamemnon* to control the optical properties of ZnO inclusion.\textsuperscript{,8} All previous literature has indicated that structural colors from different species of butterfly are sensitive to optical and chemical sensitivity. However, the optical sensitivity of such hybrid photonic devices to the refractive index of ambient environments can also be substituted, using other wing scales of lepidoptera species coated with a metal film. It is possible that state-of-the-art noble metal-coated natural photonic structures are able to absorb more or less visible light via localized surface plasmon resonance under the dense scale environments, compared to the noble metal alone.\textsuperscript{,9}

Meanwhile, the application of computational electromagneticics in plasmonics has recently become an important state-of-the-art advancement in science and technology, since the fast rising capacity of PC and simulation times produce accurate and workable solutions to complicated problems, reducing unnecessary steps in the actual experiment. Plasmonic frequency range differs from the conventional domain, such as the microwave band where the computational device has progressed because there is no extraordinary modeling method involved. Furthermore, most plasmonic topologies are managed well with reputable numerical approaches offered by commercial software packages. The coupling of plasmonic and plasmonic structures under incident light illumination in this frequency regime will be effectively evaluated, using traditional electromagnetic techniques. Maxwell’s laws remain equivalent, even though the considered frequency is orders of magnitude larger in plasmonics with respect to the microwave. Maxwell’s laws are also accurate and stable inasmuch as the quantum effect is not taken into account. Among simulation methods, the finite-difference time-domain approach is versatile, as the interaction between materials and electromagnetic waves are projected into a space lattice by defining a suitable value of permittivity and permeability to individual electric and magnetic fields, respectively, without being time-consuming.\textsuperscript{,10} These methods do not only provide the accurate time-stepping pattern but also determine the solution to the concurrent equation and offer the dissipation-free numerical wave propagation as well.

Inspired by the alternative hybrid-biophotonic structures and modern computational electromagnetics in plasmonics, herein, we attempted to understand the optical properties of a metal film (gold or palladium) on the surface features of butterfly wing scales. Three kinds of butterfly wing scales—*Catopsisia pomona*, *Danaus genutia*, and *Cethosia pentbesilea*—were studied as they might represent the dominant features of the structure-enhanced and/or structure-attenuated optical properties, whereas light-harvesting plasmonic antenna were loaded onto these natural substrates. We analyzed alterations of butterfly wing scale micro/nanostructures coated with a metal film, especially a change in spaces of the ridge set on the base layer, using Lumerical software that is a general design tool for constructing and simulating optical absorption structures based on the solution of electromagnetic waves for micro/nanostructures. The finite-difference time-domain method allowed a fast converging formulation of Maxwell’s equation and a numerical stabilization scheme, as this method was noniterative and fundamentally stable. We finally obtained the tendency of electric field distribution and absorption spectra along with the changing of metals and scale templates under the different polarization modes. This work will potentially offer a new direction for the design and fabrication of high-performance biocontrolled photonic devices for biomedical applications.

II. MATERIALS AND METHODS

Three species of butterfly wings, as shown in Fig. 1, were obtained from the Faculty of Agricultural Technology, King Mongkut’s Institute of Technology Ladkrabang, Thailand. These species consisted of *Catopsisia pomona* (CPom), *Danaus genutia* (DG), and *Cethosia pentbesilea* (CPen). Wings (dorsal-hindwing of male specimens) were cut into small slices with an area of 5 x 5 mm\(^2\) by scalpel. The surface of each specimen was sputtered with a gold layer approximately 10 nm thick to prevent the charging effect during imaging. Then, specimens were loaded onto a sample holder and later put inside a scanning electron microscopic (SEM) vacuum chamber. The scanning electron microscope was operated under a secondary electron direction mode at a range of 1-20 kV of accelerating voltage (Quanta250, USA). Scanning electron microscopy images at a low magnification showed chitin structures. High magnification of scanning electron micrographs remarkably showed the dense-to-moderate discrete ridges of chitins perpendicular to the base layer, whereas a split of the base layer ran parallel to the ground scales.

After examining the electron micrographs of samples as shown in Fig. 2(a), a computational model was introduced to mimic the actual geometry of specific species of butterflies. An example of such model is shown in Fig. 2(b). In this model, the base layer was simplified as a rectangular slab. The upper structure known as the ridge

FIG. 1. Digital photo of three species of butterfly wings: *Catopsisia pomona* (a), *Danaus genutia* (b), and *Cethosia pentbesilea* (c).
The mesh setting was 5 nm. The second step was to define monolayer absorber on the top and bottom of the computational domain. Perfectly matched layers in the z-axis were applied by constructing the perfectly matched layers in the x-y axes. Absorbance of the optical system was finally calculated by absorbance = 1 – transmittance – reflectance, where light transmittance and light reflectance as well as absorption intensity were obtained by the frequency-domain field and power monitors.

III. RESULTS AND DISCUSSION

The simulation results among the three computational models of the scales coated with a metal film obtained by the finite-difference time-domain solution are displayed in Figs. 3 and 4, showing field maps and optical absorption spectra from different metal films coated on the different butterfly wing scale microstructures, respectively. Computational electromagnetics on the field of plasmonic dipole for the scale coated with a metal film is depicted in Fig. 3. Dense microstructures of the scale templates cause a relatively low light absorption in a broad angle, which may possibly further significantly generate the anisotropic shape leading to polarization-dependent structural colors. Therefore, the intense electric field in the field map proves the existence of wave propagating modes in the dense ridges. It is also shown that the electric field amplitude is further enhanced, due to a strong coupling of localized surface plasmon resonance of a metal film on the dense scales. The structure is composed of a specific metal with a space in between. When a distance is closer, it is just responsible for a single rod. When the space becomes larger, it is responsible for a biophotonic device causing an enhancement of the electric field there. Then, excitation of surface plasmon resonance brings about the appearance of hot spots on a sample surface. Illumination of the sample therefore leads to a polarization dependence of sharp tips on the surface of the sample, probably leading to a narrow bandwidth of absorption intensity in the spectra as well. Furthermore, the field map of the scale model coated with a palladium film shows a relatively low light absorption through the ridges compared to that of the gold film, probably leading to a broad bandwidth of absorption intensity in the spectra.

Absorption patterns appear in the redshift and are completely sensitive to the polarization changes according to Fig. 4, partly due to changes of the scale periods. These patterns are similar to the polarization dependence of the electric field distributions in Fig. 3. The most prominent differences in absorption bandwidth appeared in 550-700 nm. Localized surface plasmon resonance peak position was at approximately 670 nm in the scale model coated with a palladium film which coincides with each other. Both polarization directions show an increased absorption intensity, which is approximately 1.5 times higher than the localized surface plasmon resonance peak.

### TABLE I. Geometrical dimensions of butterfly wing scale templates used for optical simulation systems. X, Y, and Z represent the width, height and thickness, respectively (see Fig. 2 for a comparison).

| Sample code | Butterfly species       | X x Y x Z (μm)     | Pillar Periodicity (μm) |
|-------------|-------------------------|--------------------|-------------------------|
| CPom        | *Catopsilia pomona*     | 0.525 x 3.569 x 71.033 | 3.465                  |
| DG          | *Danaus genutia*        | 0.228 x 1.831 x 37.000 | 1.739                  |
| CPen        | *Cetbosia penthesilea*  | 0.162 x 1.148 x 40.033 | 1.199                  |
position at 620 nm in the scale model coated with a gold film. The increased optical absorption intensity is assigned to a change in the scale and metal composition from gold to palladium film. The red shift of the absorption spectra changes by $670 - 620 = 50$ nm for the same scale templates, because of a difference in the dielectric constant between palladium and gold. Moreover, the absorption spectra of the scale model coated with gold film show a clear peak of small bandwidth compared to those of the scale model coated with palladium film because the electric field intensity distribution within the plasmonic structures of gold is higher than that of palladium. This bandwidth becomes stronger when adding gold onto the dense scale template. Furthermore, the surface plasmon resonance ratio of gold, which is defined by an actual part of the dielectric constant divided by an imaginary part of the dielectric constant, is seven-fold higher than palladium. Therefore, it is possible to use it for designing highly selective man-made photonic structures.

Further analysis indicates the interesting relationship between electric field and absorption intensities for a metal film coated on the structural patterns of the butterfly wing scales. It is observed that the physical property of the simulation models of butterfly wing
scales is a dominant factor in distinguishing the different types of metals coated onto the scale templates. Furthermore, even though the absorption intensity of palladium is stronger than that of gold, its broader bandwidth in the spectra is not suitable for the design of highly selective man-made photonic structures. Moreover, light absorption of *Cetbosia pentbesilea* is inferior to that of the other two species. The typical architecture of the sample *Cetbosia pentbesilea* is therefore chosen as a prototype architecture. Finally, for further biophotonic structure fabrication, a gold film coated on *Cetbosia pentbesilea* is strongly recommended as the scale coated with a metal film because it shows not only structural color as a result of the smallest geometry of the microstructures reflected in a restricted wavelength range but also shows plasmonic properties of gold in these dense templates. In terms of plasmonic properties, it is possible that our gold coated *Cetbosia pentbesilea* might absorb more or less visible light via localized surface plasmon resonance compared to a test of gold-coated *Graphium weiskei* from Garrett’s group.

To validate the numerical results, optical characterization of these structures should be carried out in a real measurement. In addition to the physical mechanism, it is possible that the embedded pigments of butterfly wing scales are further responsible for the spectral filters, increasing the light absorption in the limited wavelength of the pigment absorption band. Thus, these natural scale templates probably behave more or less like wavelength independent structural colors. Furthermore, both physical and pigmented mechanisms of natural scale templates coated with noble metal film possibly offer strong optical sensitivity and selectivity in the photonic devices. Further experimental studies are currently in progress and comparative results will be presented in the future.

IV. CONCLUSION

We have applied the Lumerical package to construct a simulation model of the metal-coated butterfly wing scales with a specific thickness of a metal film, using the finite-difference time-domain method. The optical system was constructed and simulated in order to obtain the electric field and absorption profile. For both the palladium and gold coating, the thickness was 100 nm, and the scales of the three butterfly species employed in this study were *Catopsilia pomona*, *Danaus genutia*, and *Cetbosia pentbesilea*. The simulation results showed that the most pronounced absorbance among the scale models coated with a metal film was observed in visible wavelength of the light, offering a difference in absorption intensity and its bandwidth, conforming to the simulated electric field distribution. Upon changing polarization direction of the scale model coated with a metal film, there was a significant difference for absorption spectra, and a significant difference was clearly recognized by the electric field profile. The coupling of the dense scales with the localized surface plasmon resonance of a noble metal showed a significantly higher electric field response than the moderate scales, partly due to the larger reactive sites providing much more efficient surface area sensitivity to incidental light. Among the three simulation models, the *Cetbosia pentbesilea* scale model coated with a gold film demonstrated excellent plasmonic properties to the field map. It is suggested that this hybrid photonic structure may be beneficial by serving as a guideline for engineering a new platform for biophotonic devices in the near future. Future research work would involve experimentally fabricating the gold or palladium film on these butterfly wing scales. The scales would act as the effective biological resonance cavity, while a metal film might act as a high gain emitting medium. The bare metal film acting as the standard for liquid sensing would be compared its optical response to changes in the surrounding environment due to exposure to the ethanol liquid form, and may also be compared to one of the metal films coated on butterfly wing scales.

ACKNOWLEDGMENTS

This work was supported by King Mongkut’s Institute of Technology Ladkrabang, Bangkok 10520, Thailand. The authors also thank Dr. Jarongsak Pumnuan for providing the specimens of butterfly wings.

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