ACADEMIE UNIVERSITAIRE 'LOUVAIN'

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BIOSTRUCT

OPTICAL PROPERTIES OF NATURAL AND ARTIFICAL STRUCTURES (PROPRIÉTÉS OPTIQUES DES STRUCTURES NATURELLES ET ARTIFICIELLES.)

Report concerning the period of :
1st January 2014 to 31st December 2014

Report of Scientific Activities /Rapport d'Activités Scientifiques

No. 4

1st January 2014 to 31 December 2014

Project Start-date: 1st October 2010 | Duration: 60 months

Project Coordinator: Olivier Deparis

Previous Coordinator: Jean Pol Vigneron

Institutions:

Université de Namur

(formerly Facultés Universitaires Notre-Dame de la Paix, Namur)

and

Université Catholique de Louvain, Louvain-la-Neuve.

Period covered by this report:

Work on the BioSTRUCT project (Optical Properties of Natural and Artificial Structures / « Propriétés Optiques des Structures Naturelles et Artificielles ») officially commenced on the 1st October 2010. In accordance with the instructions, the first three interim reports related work performed between 1 October 2010 and 31 December 2013. This report covers the period from 1 January to 31 December 2014. The eligible expenses that were incurred during this period have been included in the project accounts.

Participants :

FUNDP-LPS : Laboratoire de Physique du Solide, Université de Namur [Photonics of Life Research Group/ « Groupe de Recherche en Photonique du Vivant »]

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1. On sick-leave: February to October 2014, left project on 31st Dec 2014.
2. Joined project part-time from 1st October 2014.

SST/IMCN/NAPS : Institute of Condensed Matter and Nanosciences, Nanoscopic Physics [UCL- PAMO : Unité de Physique Atomique, Moléculaire et d'Optique]

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Summary of the project and its evolution, in context:

To recap, this project involved concerted actions between UCL and the University of Namur (formerly FUNDP) examining the propagation of light waves in interfacial materials including an integrated approach, basic research (observational and theoretical studies) and more applied developments (such as the synthesis of complex structures and analysis of possible inclusion of findings in the luminous flux management systems). Part of the inspiration for the design of artificial structures comes from the observation of living beings such as ants, beetles, butterflies and birds, for which the project team has developed a particular expertise.

The overall aim of this concerted action project is to highlight new visual effects on artificial surfaces, however, as noted in previous years, realizing this goal requires labour-division between the laboratories concerned, with each individually taking a portion according to their expertise and greatest strengths. Specifically, the tasks of the project can be subdivided into three areas-

1. The search for new natural photonic structures ,
2. characterization and understanding of their operation and
3. the development and operation of synthesis methods to attain greater facility at structuring bio-inspired optical devices in one, two and three dimensions.

The portion of research undertaken by the University of Namur is that which looks for new natural photonic structures. This part of the research includes an exploration of biological systems with interesting optical properties (colouring, texturing, visual effects, chromatic response to external influences ...). To date, the search for appropriate agencies has involved reviews of the collections of several museums and contacts have been made with the Royal Institute of Natural Sciences Museum of Belgium and the Royal Museum for Central Africa in Tervuren.

In 2014, this work has additionally involved one field trip of particular note- a voyage to Panama by physics doctoral student Louis Dellieu, accompanied by entomological expert Dr Jacques Pasteels of

Université Libre de Bruxelles. The samples collected from this trip are expected to yield data for the doctoral studies of M. Dellieu later in this BIOSTRUCT project and thereafter. These samples are expected to be scientifically useful for publications both within this project and after its completion. Potentially, therefore, samples collected from this trip may well have a utility beyond the end of this project- giving the project additional longevity beyond the end of its funding.

The death of Prof. Jean-Pol Vigneron in 2013, and the long-term illness of Priscilla Simonis in 2014 have slightly altered the details of the research at U. Namur, with regard to the specific animals studied and the precise research now yielding the most results for the U. Namur/ LPS team. However, before leaving the BIOSTRUCT project at the end of 2014, Priscilla Simonis and her collaborators, continued studies of the ant *Cataglyphis bombycina*, such that they are now ready for publication; additionally, the study of "Radiative contribution to thermal conductance in animal furs and other woolly insulators" has now been completed and was published in 2014. From January 2015, U. Namur will appoint Dr. Branko Kolaric as a post-doctoral researcher, in place of Priscilla Simonis. His work over the coming year will centre on the design and fabrication of surfaces with combined wetting and optical function properties and will allow the LPS (University of Namur) team to complete its share of the research.

This year also saw the Jean-Pol Vigneron Memorial Conference (Living Light), which was not funded by BIOSTRUCT, specifically, but was held at U. Namur in April 2014. This conference was notable and relevant because it gave a forum for the presentation of work undertaken in this project to numerous world-leading figures within the subject from other institutions. The conference expanded opportunities for scientifically productive future collaborations and enabled scientific networking relevant to this project. Finally, the conference resulted in the production of a special issue of *Materials Today,* in which a selection of notable research papers presented at the conference were published
(see http://www.sciencedirect.com/science/journal/22147853/1/supp/S).
These publications constitute another lasting output from this project (publications resulting from this project and its staff in 2014 are listed below- this includes the conference publications mentioned). A copy of the conference abstract booklet is available online at http://www.living-light-2014.be/all_abstract - this includes presentations made by BIOSTRUCT researchers that were not ultimately included in the *Materials Today* supplement.

For their part, the project staff at SST/IMCN/NAPS : Institute of Condensed Matter and Nanosciences, Nanoscopic Physics [UCL- PAMO : Unité de Physique Atomique, Moléculaire et d'Optique] continue to study the optical properties of cylindrical natural or bio-inspired multilayer systems. An experimental set-up was designed and constructed for the observation of light scattering by objects of cylindrical symmetry. The set-up is ready and it was used in 2014 to study thin quartz wires, with and without multilayer cover. The Mie scattering formalism is applied to analyse the results as they are produced.

. The research in the BIOSTRUCT project continues to yield results in line with the project's initial objectives, however, as the project enters its final year, we are also mindful that it is now laying foundations for work and ongoing studies that will exceed the remit of the initial project. Specifically in terms of training doctoral students in the field and allowing them to conduct and publish research that lays foundations for their future careers within this subject and, hence, the long-term continuation and expansion of the project's goals. In this context, the one major output from UCL SST/IMCN/NAPS : Institute of Condensed Matter and Nanosciences, Nanoscopic Physics [UCL- PAMO : Unité de Physique Atomique, Moléculaire et d'Optique] during 2014 consisted of the publication “Optical properties of micro and nanostructured bioinspired materials” and the doctoral thesis of Abdessitir Deraoui. The latter was presented on 5th December 2014 – announcement of thesis defence and the thesis can be found online at: http://tinyurl.com/ou5sup8 . A second doctoral student, Toto Mabiala, is currently producing a thesis in conjunction with the BIOSTRUCT project at the University of Kinshasa. The thesis title is “Etude des propriétés optiques de systèmes multicouches cylindriques naturels ou bio-inspirés” ; originally, it was expected that M. Mabiala would finish this project in November 2014. However, due to circumstances beyond his control, there has been a slight postponement and the work on this thesis is still being finalized. We look forward to presenting further details of M. Mabiala’s project and the finished work from it in our final report.

During 2014, work at UCL (SST/ICTM/ELEN : Institute of Information and Communication Technologies, Electronics and Applied Mathematics, Pôle en ingénierie électrique [DICE-EMIC]) reproduced photonic structures found in *Papilio blumei* and *Suneve coronata*, to study their properties and compare them.

The attention was focused here on their optical properties, namely the polarization of light by reflection. The results were presented at the "Living Light 2014" conference in Namur and the conference of the International Joint Unit in Grenoble in the form of a poster. Our research was also presented at the "Scientific WINFAB Day" conference in Louvain-la-Neuve. Finally, the results have been accepted for publication in the journal "Bioinspiration & Biomimetics" from IOPscience (currently *in press*). Images of the poster and slides / article are presented in the following pages. The group then became interested in making "morpho" type-structures, in order to study their various properties (reflectance, colour change depending on the environment, polarization properties, etc .....) This work is ongoing, however research already completed is showing good results (illustrated below) regarding the manufacture of structures.

Description of work done during the past year (2014) and its results:

This information is provided in either French or English, depending upon the availability of descriptive text.

List

1. “Circular polarization in nature: Factual, theoretical and experimental summary”
   Serge Berthier, Priscilla Simonis and Magali Thomé
2. “Efficient screening of solar radiation by total internal reflection on the Saharan desert ant *Cataglyphis bombycina* (Formicidae)”
   Priscilla Simonis, Serge Aron, El Mostafa Oualim, Younes Bahou, Mohammed Harmouchi and Jean Pol Vigneron

3. “Radiative contribution to thermal conductance in animal furs and other woolly insulators “Priscilla Simonis, Mourad Rattal, El Mostafa Oualim, Azeddine Mouhse and Jean Pol Vigneron
4. “Bioinspired multilayer polarizer for anti-counterfeiting”, - Poster presentation at the international conference- "Living Light- Olivier Poncelet, Priscilla Simonis and Laurent Francis
5. “Bioinspired multilayer polarizer for anti-counterfeiting”, - Short Poster presentation at “UMI France - Canada Nanotechnologies & Nanosystèmes” - Olivier Poncelet, Priscilla Simonis and Laurent Francis
6. “Overview of Natural Photonic crystals and their technological applications”
Olivier Poncelet, Guillaume Tallier and Laurent Francis
7. “Synthesis of bio-inspired multilayer polarizers and their application to anti-counterfeiting, bioinspiration & biomimetics”- Olivier Poncelet, Guillaume Tallier, Priscilla Simonis, Alain Cornet and Laurent Francis.
8. “Optical Properties of Micro and Nanostructured Bioinspired Materials”, Abdessitir Deraoui, Kamel Mallat, Alain Cornet and Pierre Defrance,
9. « Elaboration et Caractérisation Optique de Microstructures à Multicouches d’Inspiration Biologique » , Abdessitir Deraoui,
10. “ Synthesis of "morpho"-type-structures and characterization of their various properties: preliminary notes”, Olivier Poncelet and Laurent Francis

1. Circular polarization in nature: Factual, theoretical and experimental summary

Serge Berthier, Priscilla Simonis and Magali Thomé

The circular polarization of light created by living organisms has recently been the subject of renewed interest since the discovery, in a marine arthropod, of a visual device sensitive to this state and able to distinguish the left circular polarization from the right one. Numerous other organisms that circularly polarize light by reflection, mainly beetles of the Scarabaeidae family, have been identified. We now want to establish their sensitivity to this polarization state. Along with this, the experimental techniques used to characterize the polarization states of light, as well as the structures that generate them, have significantly changed. In this project, we studied the different sources of circular polarization found in nature, animal origin or not, as well as the theoretical bases for their study. We also evaluated different experimental techniques.

Under the conditions and with the materials found in nature, we found that only living organisms are capable of generating a circular polarization of light of high quality. The total reflection on an interface air/water does not induce sufficient phase shift in a single pass to achieve the optimum value of $\pi/2$. Circular or nearly circular polarization remains the prerogative of living beings and, for the vast majority, of insects. On the other hand, the sensitivity of some of these organisms to this state of polarization has been demonstrated, even if the evolutionary interest is not yet clearly understood. In beetles, the appearance of the elytra is the result of not always independent optical phenomena. The helical organization of chitin layers of exocuticle generates both interference phenomena, responsible for the color of the insect, and polarization effects – often? almost circular. These effects are interrelated, and the direction of rotation of the polarization depends on the frequency. For most of them, these insects are green and left –handed polarized at these frequencies. New analytical techniques, the generalized ellipsometry and polarimetric imaging allow an accurate determination of the spectral variations of each element of the Mueller matrix for different angles of incidence, to visualize the structural elements responsible for the effects observed and to determine the spatial distribution of the reflected waves. These analyzes confirm the reversal of circular polarization for few species, as predicted by the theory. This complex phenomenon is mainly due to the reversal of the sign of the phase factor of the structure. This factor is deduced from the values of the ordinary and extraordinary indices of the material. These indices are poorly known and should strictly be determined for each species in future studies.

2. "EFFICIENT SCREENING OF SOLAR RADIATION BY TOTAL INTERNAL REFLECTION ON THE SAHARAN DESERT ANT CATAGLYPHIS BOMBYCINA (FORMICIDAE)"

Priscilla Simonis, Serge Aron, El Mostafa Oualim, Younes Bahou, Mohammed Harmouchi and Jean Pol Vigneron

The desert ant *Cataglyphis bombycina* (Formicidae) is one of the terrestrial living organisms best prepared to withstand high temperatures. One of the most obvious features is its white metallic colour. We show that the high optical reflection is obtained on a dense covering of the body by bristles, which assume a triangular prismatic shape. The tiny prisms are oriented with a flat basal plane parallel to the cuticle surface and it is demonstrated that total reflection conditions are satisfied on this face for light entering and exiting through the other faces. The entry and exit faces are configured to maximize light transmission by a diffractionless corrugation. Overall, these results reveal that the bristle shape affords protection to the desert ants against the intense solar radiation

Note: This project was mentioned in the previous year's report- the studies on this topic are now complete and the draft paper describing them was completed in 2014– this is available in a secure vault online at- http://tinyurl.com/obtqjkl .

3. RADIATIVE CONTRIBUTION TO THERMAL CONDUCTANCE IN ANIMAL FURS AND OTHER WOOLLY INSULATORS

Priscilla Simonis, Mourad Rattal, El Mostafa Oualim, Azeddine Mouhse and Jean Pol Vigneron

The mechanism by which a stack of absorbers limits radiative heat transfer was examined in detail both for black-body shields and grey-body shields. This demonstrated that radiation energy transfer rates should, theoretically, be much faster than conduction rates. Moreover, for opaque screens, increased reflectivity will dramatically reduce the rate of heat transfer, improving thermal insulation. This simple model is thought to contribute to the understanding of how animal furs, human clothes, rock-wool insulators, thermo-protective containers, and many other passive energy-saving devices operate.

Because of their efficient scattering power, crisscrossed fibrous materials are effective localizers of thermal radiation. Starting from specific one-dimensional models, new tracks for functional optimization can certainly be found. Our results indicate that a stack of thin metal layers, separated by thin homogeneous or fibrous spacing layers might provide an insulating system that can be as efficient or even outperform actual systems, while keeping the thickness to a much more manageable minimum [1]. Reports have been published showing that insulating layers with such a structure can be 3 to 5 times thinner than standard woolly layers, with similar performances [2].

Natural selection means that organisms change when exposed to extreme conditions. Polar bear fur contains several different sizes of hair, with a large density of interfaces. This produces the scattering needed to retrodiffuse heat. A polar bear (*Ursus maritimus*) does not produce a strong thermal image against snow. The same structure also gives it its white colour because the illuminating daylight is effectively scattered over the fur. The slight greenish coloration of these bears is actually related to the presence of marine algae that develop in the fur and absorb blue light as most plant forms.

The dromedary camel (*Camelus dromedarius*) has to deal with a different challenge: keeping heat out of its body. Here again, a double layer of hair, with a strong melanin concentration reduction, provides the necessary multiple scattering of solar radiation, from the outside, to help in blocking heat absorption. It should be observed that the scattered radiation corresponds to the solar spectrum, which only contains visible, some UV and near infrared rays. The thermal insulation here is then directly related to the visual appearance of the animal and the elimination of thermal absorption is directly visible in the luminosity and the desaturation of the colour of the dromedary camel fur.

This work, suggests that radiative thermal transfer provides a better view of thermal insulation than the more frequent approach, which is based on the low thermal conductance of air. Structures like furs and arrays of feathers do slow down air convection, but radiation seems to be much faster than conductance to provide thermal leaks. So, the control of thermal radiation could be a leading factor for biological adaptation in organisms like mammals and birds living in very high or cold environments and which need to control heat exchange efficiently.

[1] U. Sivert and A. Heidi, ”Thermal insulation performance of reflective material layers in well insulated timber frame structures,” Proc. 8th Symp. Building Physics in the Nordic Countries 1, 1-8 (2008).

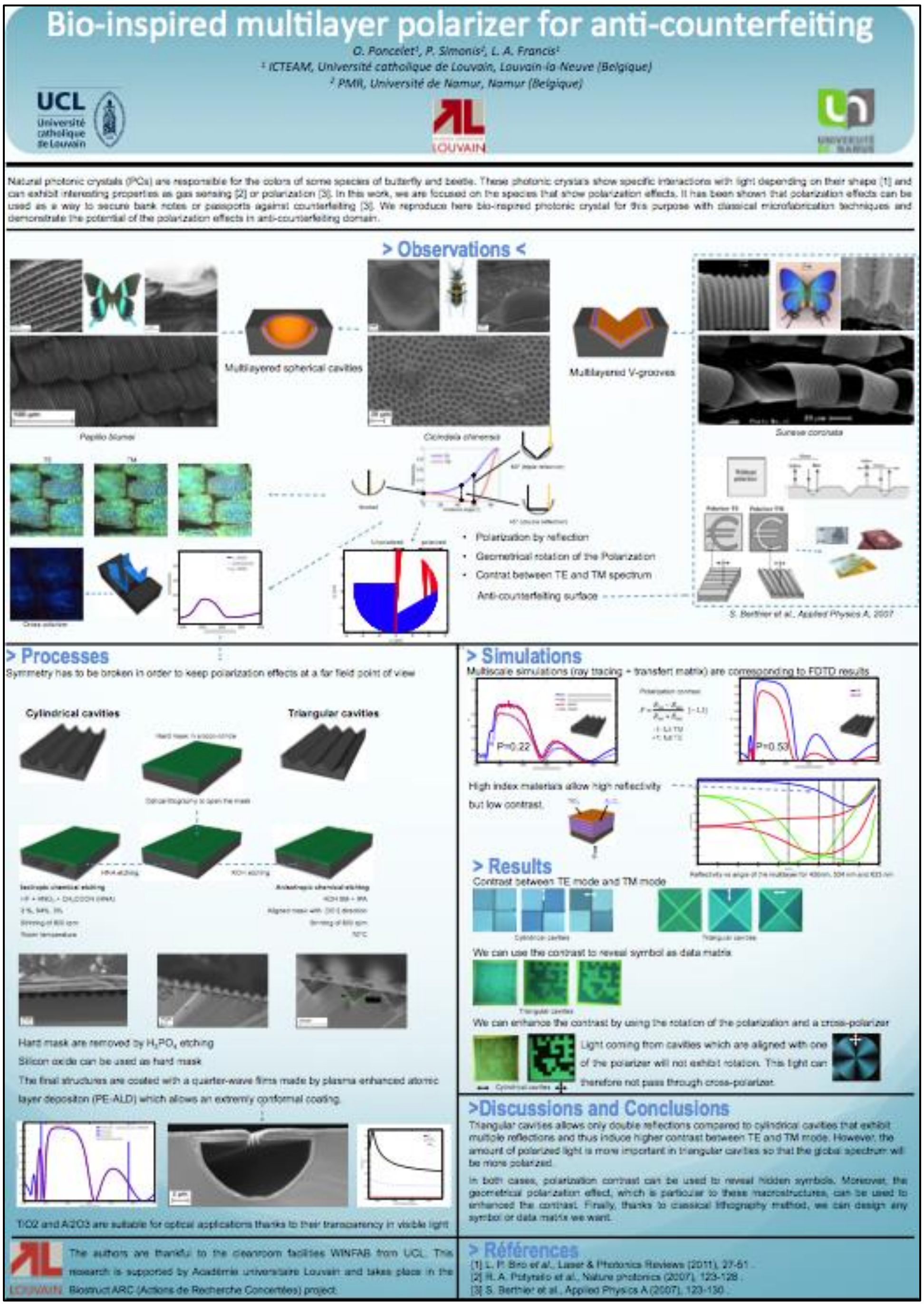
[2] T. I. Ward and S. M. Doran, ”The thermal performance of multi-foil insulation”, U. K. Government building regulation report, (2005)

Note: This project was mentioned in the previous year’s report- the studies on this topic are now complete and the paper describing them was published in 2014 – see publications list below.

4. “BIO-INSPIRED MUTLILAYER POLARIZER FOR ANTI-COUNTERFEITING”: POSTER PRESENTATION AT THE INTERNATIONAL CONFERENCE- "LIVING LIGHT: UNITING BIOLOGY AND PHOTONICS - A MEMORIAL MEETING IN HONOUR OF PROF JEAN-POL VIGNERON",

Olivier Poncelet, Priscilla Simonis and Laurent Francis

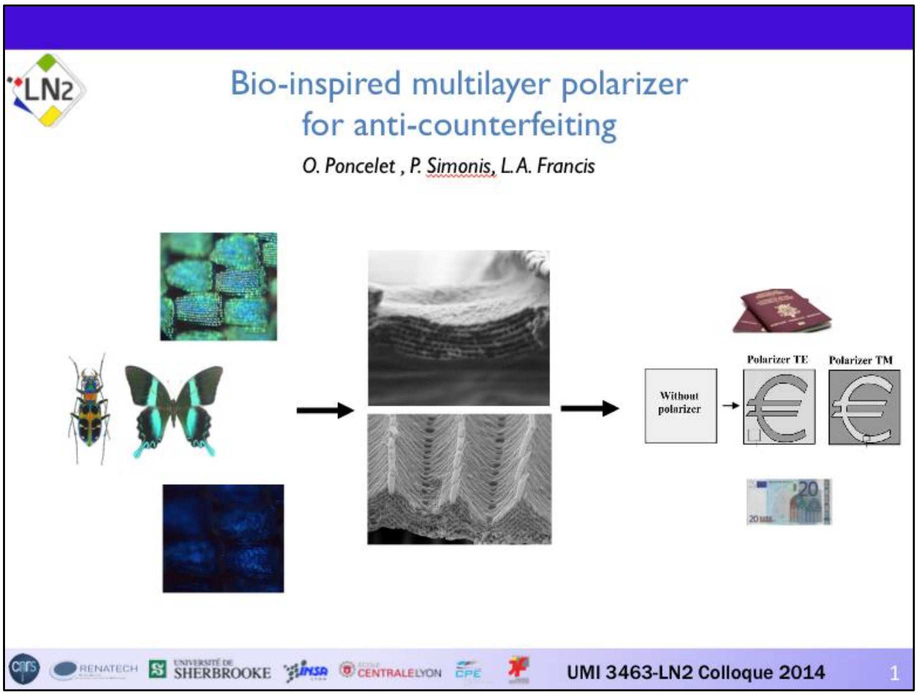
10-12 April 2014 University of Namur



5. "BIO-INSPIRED MUTLILAYER POLARIZER FOR ANTI-COUNTERFEITING": SHORT PRESENTATION AND POSTER AT "UMI FRANCE - CANADA NANOTECHNOLOGIES & NANOSYSTÈMES"

Olivier Poncelet, Priscilla Simonis and Laurent Francis

at Allevard les Bains 9-10 July 2014

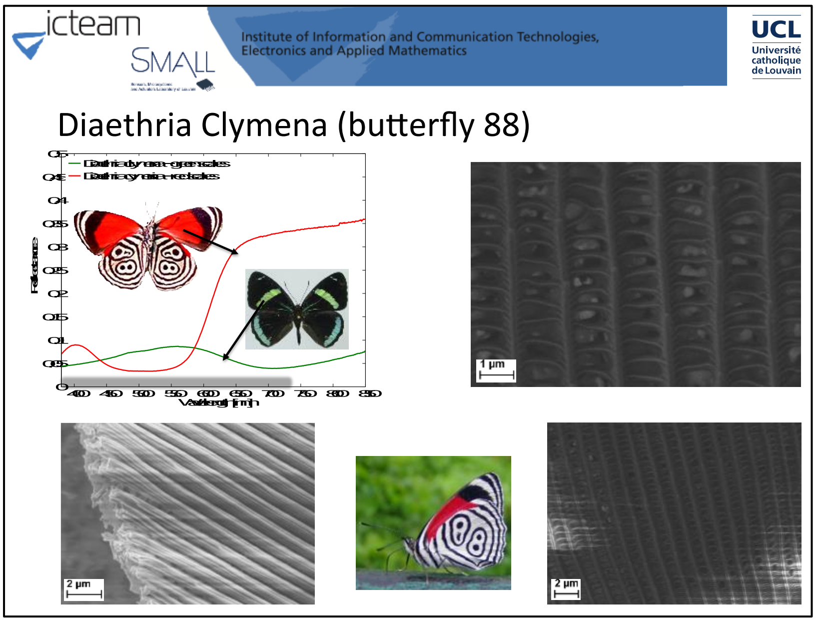


6. “OVERVIEW OF NATURAL PHOTONIC CRYSTALS AND THEIR TECHNOLOGICAL APPLICATIONS”

Olivier Poncelet, Guillaume Tallier and Laurent Francis

Research Presentation: Given at Winfab Scientific Day, Louvain-la-neuve, 17th October 2014.

This presentation involved consideration of photonic crystals in various insects- notably, the butterflies *Diathria clymena* (also known as “Cramer’s Eighty-eight” , or “The 88 butterfly”), *Morpho godarti*, *Papilio blumei* and the moth *Urania leilus*. One slide from the presentation is shown below as an example-



7. SYNTHESIS OF BIO-INSPIRED MULTILAYER POLARIZERS AND THEIR APPLICATION TO ANTI-COUNTERFEITING, BIOINSPIRATION & BIOMIMETICS

Olivier Poncelet, Guillaume Tallier, Priscilla Simonis, Alain Cornet and Laurent Francis.

Some insects, such as *Papilio blumei* or *Suneve coronata*, are known for exhibiting polarization effects on light, like colour, contrast or geometrical polarization rotation by reflection on their wing scales. The photonic structures found in these species and showing these properties are multilayered spherical cavities or triangular grooves, which polarize the light, due to multiple inner reflections. In addition to the intrinsic colour mixing properties of these photonic structures, these polarization effects, are interesting to the field of anti-counterfeiting, due to their invisibility to the naked eye.

In this work, we used micro-fabrication techniques to produce bio-inspired cylindrical (C-grooves) and triangular grooves (V-grooves) that demonstrate the same properties. Theoretical analyses were conducted, using multi-scale simulation (MS) and finite-difference time-domain (FDTD) techniques, in order to compare the polarization capabilities of both structures. The V-grooves showed greater polarization contrast than the C-grooves, but the spectrum was specular. The C-grooves exhibited lower polarization effects but had a dispersive spectrum. In both cases, the structures showed additional optical properties, such as diffraction, macroscopic colour contrast under a polarizer and contrast inversion, due to geometries which contributed to their uniqueness.

Because reflection of light on the V-groove structure was highly directional, the process has to be precisely controlled to get exactly a 45° side slope. Further, as the process is crystalline direction dependent, V-grooves cannot be produced in all directions on a silicon wafer. In any case, C-grooves and V-grooves demonstrate the following properties, which are necessary for anticounterfeiting: polarization contrast, polarization rotation, colour mixing, and contrast inversion. Such properties provide unique optical identification. Moreover, micro-fabrication silicon technology such as wet etching and photolithography enable easy production of these structures on large surfaces and with any desired symbol. For a large-scale implementation, silicon can be used as a stamp to imprint its shape in other materials like polymethyl methacrylate (PMMA). This technique can be used to produce V-grooves and C-grooves in soft and flexible materials, which are more convenient for banknotes, for example. The biggest challenge for the manufacture of final samples remains the coating with a conformal multilayer. In this work, we have used atomic layer deposition, which provides a highly conformal coating with very good thickness control.

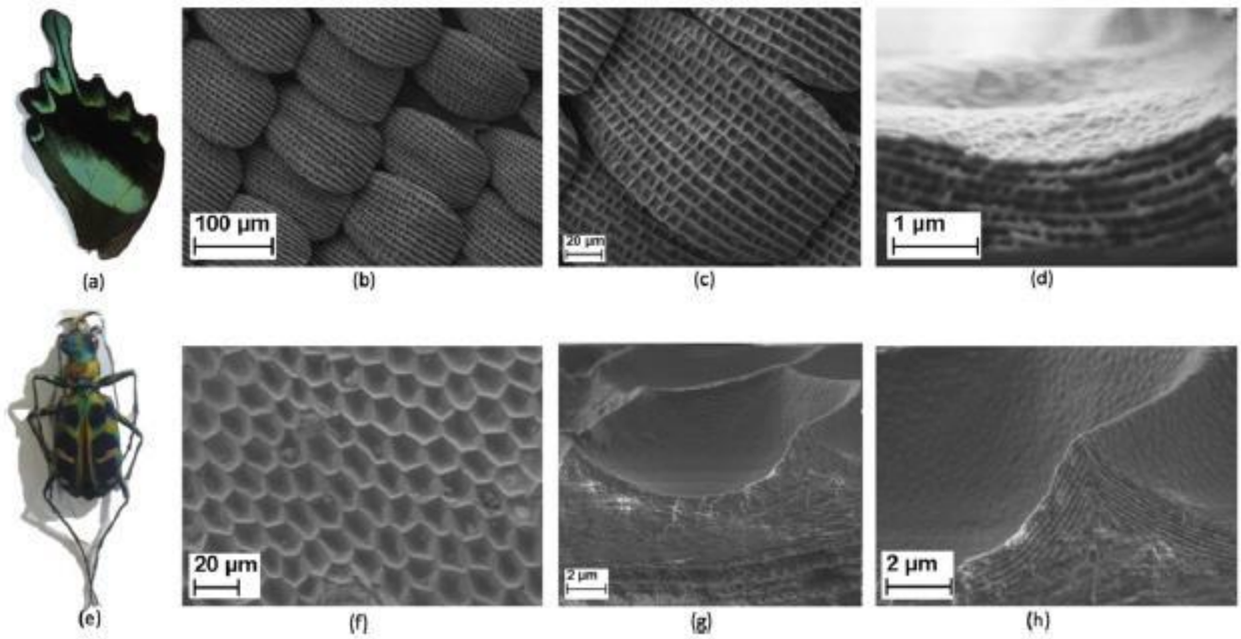


Figure 1. (a) A wing of *P. blumei*. (b), (c) SEM view of the wing's green scales. (d) SEM cross-section of a single scale showing the inner PC. (e) *C. chinensis*. (f) SEM view of the cuticle. (g), (h) SEM cross-section of the cuticle. Multilayers describe a quarter-wave stack (Bragg mirror). The cavity width for *P. blumei* is around 5–10 μm and 15–20 μm for *C. chinensis*.

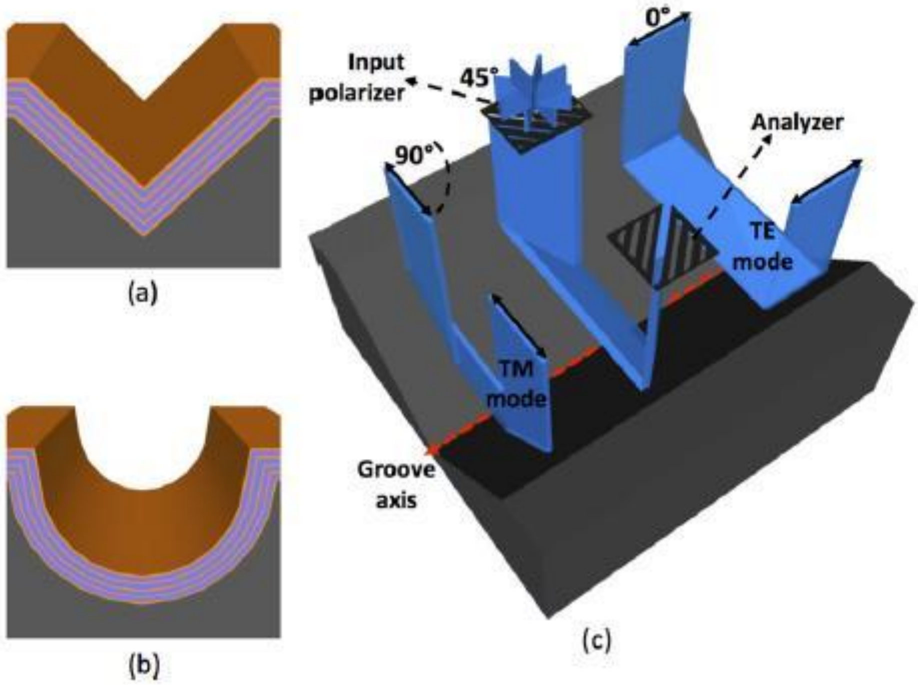


Figure 2. Schematic representation of (a) V-groove and (b) C-groove. (c) Representation of reflection depending on polarization. TE (TM) mode is defined when incident polarization is parallel (perpendicular) to the groove axis. The middle ray shows a geometric rotation of the polarization. The reflected light is not blocked by a cross-polarizer configuration. The red arrow defines the groove axis.

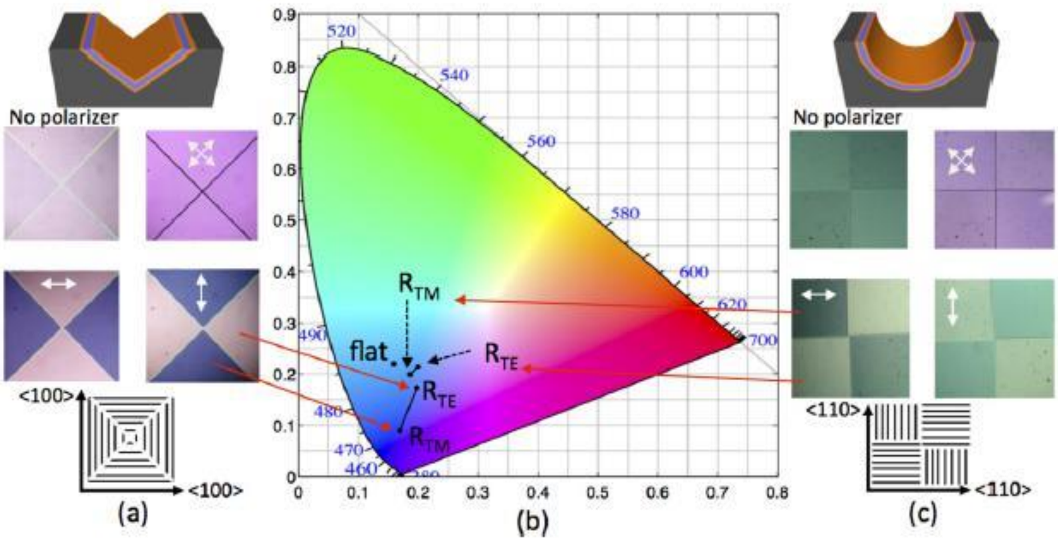


Figure 3: Optical microscope view of multilayered V-grooves and C-grooves observed through a polarizer compared with simulation. The white arrows show the polarizer orientation. The red arrows show the theoretical colour of the sample on the CIE diagram. (a) Results for V-grooves under microscope with and without polarizers. The bottom picture shows the orientation of the grooves and the corresponding orientation. (b) CIE 1931 chromaticity diagram. Simulated RTE and RTM CIE coordinates for V-grooves and C-grooves are plotted on the diagram. The flat point is the coordinate for the reference multilayer. (c) Results for C-grooves under microscope, with and without polarizers.

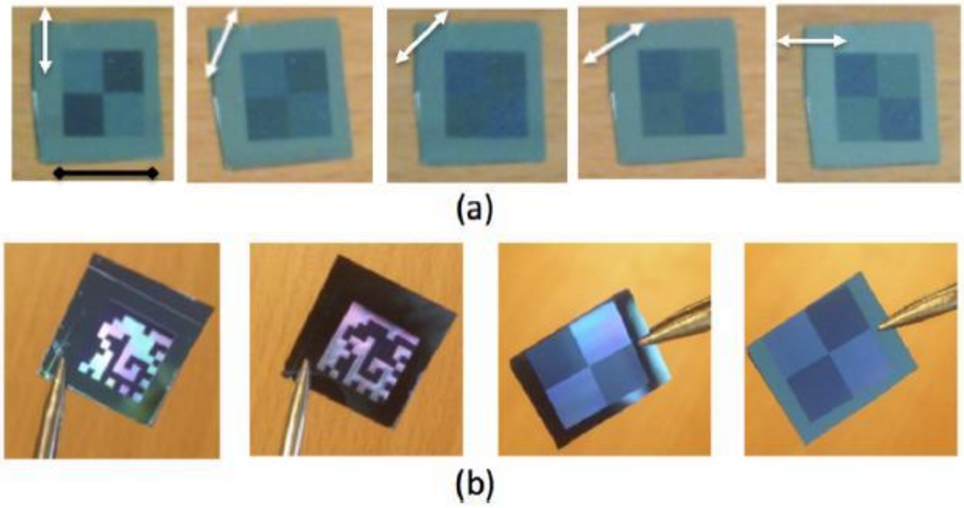


Figure 4: Macroscopic view of the samples. (a) C-grooves exhibit contrast inversion with a polarizer. The white arrows show polarizer direction. The black line is a 1-cm scale bar. (b) The rainbow effect on a sample (left) and an example of contrast inversion by simply flipping a sample (right).

8. OPTICAL PROPERTIES OF MICRO AND NANOSTRUCTURED BIOINSPIRED MATERIALS

Abdessitir Deraoui, Kamel Mallat, Alain Cornet and Pierre Defrance

In nature, there are a great many situations in which optics plays a crucial role; this is particularly the case for birds and insects whose colour is usually associated with their behaviour and is a factor in (interspecific and intraspecific) recognition. The phenomenon of iridescence, in which variation in coloration depends on the illumination and the direction of observation is well known in the living world. The material forming the elytra of beetles, for example, is chitin and its refractive index is close to that of ordinary glass. SEM observation shows that in many iridescent beetle species, the material is in the form of a multilayer, separated by layers of air. These layers disturb the refractive index of chitin and cause multiple reflections, which interfere and explain the phenomenon of iridescence. Models have been produced for some species that clearly confirm this interpretation [1], but they also show that it is possible to produce structured surfaces in the laboratory with properties similar to natural structures. By using design ideas from nature we are able to work towards the development of applications in a range of different technologies. This study was aimed at developing methods for producing samples based on natural structures, where optical properties can be interesting. We also reviewed typical bio-inspired photonic structures and considered biomimetic fabrications. The resulting samples were characterized by various methods in order to understand their properties; the role of surface roughness in the structure's optics was evaluated.

It is now well known that submicron structures are responsible for the structural colour through light interference in layered or lattice structures and through Tyndall scattering [2]. The physical structure and surface chemistry of these insects provides surprising properties that could offer a variety of applications ranging from photonic security tags to self cleaning surfaces and protective clothing and to industrial sensors. In this work, we created structures by etching periodic pyramid on surfaces of a flat sample of silicon and coated it with an alternating multilayer of the materials. The optical properties of the bio-inspired structures are also investigated. The combination of the nanofabrication technique, useful design methodologies inspired by biological systems would surely have profound impacts on our society.

Subsequently, a theoretical model was proposed to explain the observed extraordinary reflective properties successfully.

Essentially, we wanted to fabricate a sample as shown in Fig.1 below. A pyramid with a base opening of D=100 µm and h=50µm of thickness (see Fig.1). For this, we used Photolithography (figure 2) and Anisotropic Wet Etching. Aspects of the fabricated structure are shown in Figures 3 and 4.

Figure 1. Design of the pyramid system

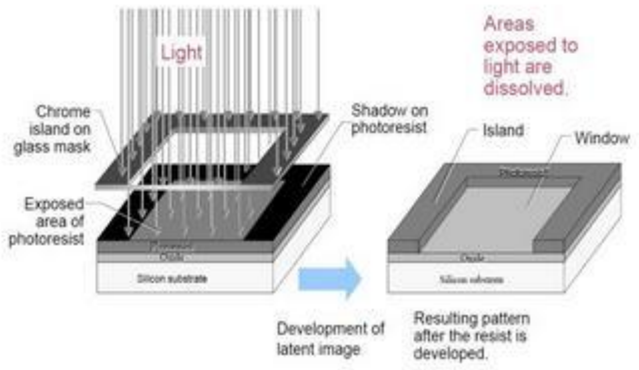


Figure 2- Schematic of the photolithographic process sequence used to structure a thin-film layer
In this case, a mask with the desired pattern was created with Cadence Virtuoso Layout Editor IC 5.0.0.

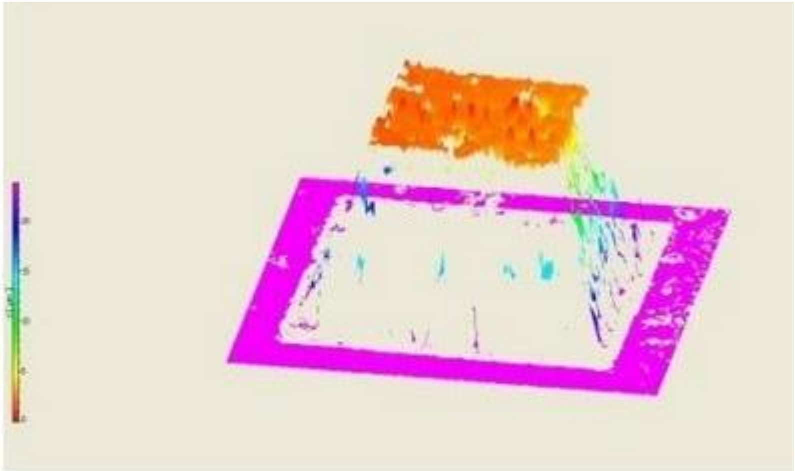


Figure 3- 3D topography of the final design of sample measured by coherence scanning interferometry Polytec MSA-500

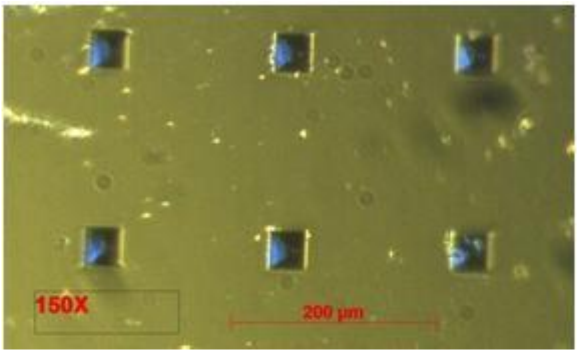


Figure 4- Imaging microscopy of the structured surface of the bioinspired sample.

The knowledge acquired in performing this study was used to develop an artificial structured surface which reproduces the visual effect found with the *Chrysochroa vittata* beetle. Although the physics of structural colours is well understood, it remains a challenge to create artificial replicas of natural photonic structures. O. Deparis *et al*. [3] and J.P. Vigneron *et al*. [1] used to develop also an artificial bio-inspired multilayer system which reproduces the visual effects provided by the insects cuticle. But our main goal in this work, was to analyze the role of roughness. We determined the optical properties changing of these structured surfaces based on the characteristics of surface roughness. We used a combination of pholithographic process, anisotropic wet etching, to fabricate pyramid structures on silicon substrate. Then we exploited the robustness of this thin-layer design in order to copy the changing colours of *Chrysochora vittata* into a bio-inspired artificial reflector, with thin metal layers acting as periodic perturbation of a dielectric. Morphology characterization was conducted with coherence scanning interferometry and stereomicroscopy and we measured the optical properties using scatterometry techniques. The measurements, when compared with theoretical modelling and numerical simulations confirmed the natural-artificial similarities.

Thus, in summary, we operated the strength of the surface roughness made by micro and nanofabrication to create the multiple reflections due to the internal surfaces of the pyramid to mimic or to produce samples based on natural structures, in which optical properties can be interesting. We anticipate that object designers will find many uses for these iridescent bio-inspired materials. The results from this work were published in The *International Journal of Optics and Applications* in 2014, as detailed in the publications section below.

[1] J.-P. Vigneron, M. Rassart, C. Vandenbem, V. Lousse, O. Deparis, L.P. Biro, D. Dedouaire, A. Cornet, P. Defrance, “Spectral filtring of visible light by the cuticle of metallic woodboring beetles and microfabrication of a matching bioinspired material” Phys. Rev. E, (2005).

[2] Huxley, J. The coloration of Papilio zalmoxis and P. antimachus and the discovery of Tyndall blue in butterflies, Proc. R. Soc. Lond. B 193 pp441-453 (1976)

[3] Deparis, O. , Vandenbem, C. , Welch, V. , Rassart, M. , Lousse, V. , Vigneron, J-P. , De Vriendt, V. & Lucas, S., 1 Jan 2007, Conference on Lasers and Electro-Optics Europe – Technical Digest

Note: This research subject was mentioned in earlier report(s), however, the paper describing this particular study was completed and published in 2014 – see publications list below.

9. « ELABORATION ET CARACTERISATION OPTIQUE DE MICROSTRUCTURES A MULTICOUCHES D'INSPIRATION BIOLOGIQUE »

Abdessitir Deraoui,

Thèse présentée pour obtenir le diplôme de docteur en Science- physique

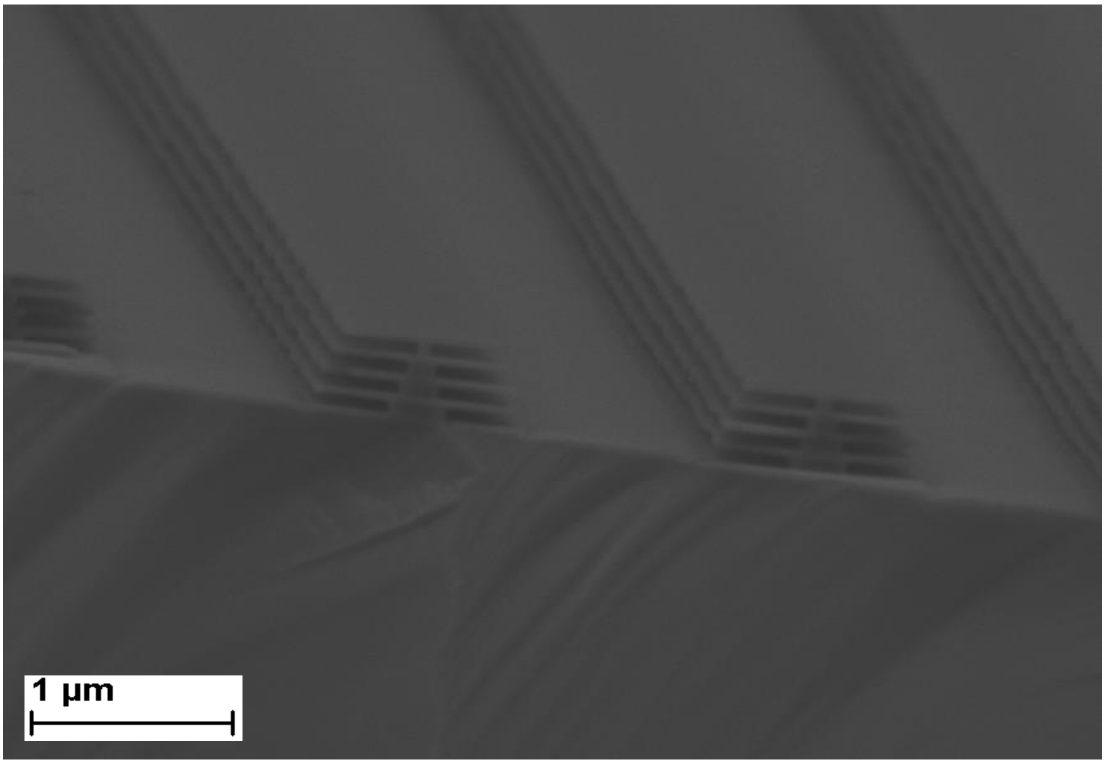
More details below, thesis defence information plus full Doctoral Thesis online in secure vault at: http://tinyurl.com/o9afto7 and http://tinyurl.com/ou5sup8 , respectively.

10. " SYNTHESIS OF "MORPHO"-TYPE-STRUCTURES AND CHARACTERIZATION OF THEIR VARIOUS PROPERTIES: PRELIMINARY NOTES ON RESEARCH AT AN EARLY STAGE",

Olivier Poncelet and Laurent Francis

Further to our earlier work reproducing the photonic structures found in *Papilio blumei* and *Suneve coronate* (results of which, we presented at the ALD 2013 conference), we became interested in making "morpho" type-structures, in order to study their various properties (reflectance, color change depending on the environment, polarization properties, etc .....).

This work is ongoing, however the preliminary research already completed is showing good results regarding the manufacture of structures (see below).



Micro-structure de type *morpho* réalisée en Al2O3 et TiO2 à l'aide de gravure anisotrope et isotrope

Synthetic presentation of work for each PhD student who is party-to the ARC agreement :

(Une présentation synthétique des travaux de thèse effectués par chaque doctorant à charge de la convention ARC) :

« Elaboration et Caractérisation Optique de Microstructures à Multicouches d'Inspiration Biologique »

Thèse présentée pour obtenir le diplôme de docteur en Science- physique

Par Abdessitir Deraoui,

Sommaire :

La dissertation se compose de quatre chapitres-

Dans le premier chapitre, les bases de la théorie électromagnétique de la lumière et plus particulièrement les phénomènes d'optique ondulatoire qui peuvent donner lieu aux couleurs dites structurales seront détaillées. Ces concepts seront nécessaires à la compréhension des chapitres ultérieurs. Il est consacré aussi à l'état de l'art des principaux équipements de caractérisation optique que nous avons utilisé. Nous donnerons une description générale (théorique et principes de mesures) pour chacun d'eux. Notre étude est orientée spécialement vers la détermination des qualités morphologiques et propriétés optiques des matériaux.

Le deuxième chapitre est dédié à la reproduction artificielle bioinspirée des quatre échantillons irisés que nous avons décrits plus haut. Nous présenterons la procédure d'élaboration et de fabrication pour chacun des échantillons ainsi que leur analyse morphologique.

Dans le chapitre trois, nous détaillerons les résultats de la simulation et les mesures expérimentales pour chaque structure élaborée. La modélisation est basée sur les matrices de transfert pour les trois premières structures. En ce qui concerne les surfaces cylindriques, le formalisme de Lorenz-Mie a été utilisé pour simuler l'interaction entre les ondes électromagnétiques et les surfaces à symétrie cylindrique. Les analyses spectrales effectuées par différentes techniques adéquates à chaque structure sont comparées avec les résultats théoriques. Cette comparaison permettra de se rendre compte de l'adéquation du formalisme utilisé et par ailleurs la compréhension des propriétés optiques de ces structures.

Et dans le même objectif de recherche de ce travail de thèse, à savoir la reproduction artificielle des phénomènes naturels, s'inscrit le quatrième chapitre qui a été inspiré de l'étude de l'effet coloré observé chez le papillon *Troïdes magellanus*. L'analyse morphologique prouve que l'origine de sa coloration est différente des autres spécimens déjà étudiés car elle est due à la présence de fluorophore. Le rayonnement de fluorescence interagit avec la structure. Dans ce chapitre, nous présenterons une réplique de ce phénomène avec une structure Fabry-Pérot et un fluorophore pour voir dans quelle mesure nous pouvons contrôler la fluorescence dans des multicouches.

Pdf noting date the thesis defence was completed, plus Abdessitir Deraoui's full doctoral thesis are online in a secure vault at http://tinyurl.com/o9afto7 and http://tinyurl.com/ou5sup8 , respectively.

List of Publications and Reports Carried out during the period covered by this report:
Liste des publications et rapports effectués durant cette période :

"***Synthesis of bio-inspired multilayer polarizers and their application to anti-counterfeiting, bioinspiration & biomimetics***", Olivier Poncelet, Guillaume Tallier, Priscilla Simonis, Alain Cornet & Laurent Francis, Bioinspiration & Biomimetics, ***In press*** (Accepté et validé. En cours de publication pour 2015),

"***Optical Properties of Micro and Nanostructured Bioinspired Materials***", Abdessitir Deraoui, Kamel Mallat, Alain Cornet and Pierre Defrance, International Journal of Optics and Applications, (2014), **4 (2)**, pp 31-39, DOI: 10.5923/j.optics.20140402.02

" ***Elaboration et Caractérisation Optique de Microstructures à Multicouches d'Inspiration Biologique***", Abdessitir Deraoui, Thèse présentée pour obtenir le diplôme de docteur en Science- physique (Doctoral thesis), completed by Dec 2014.

"Radiative contribution to thermal conductance in animal furs and other woolly insulators", Priscilla Simonis, Mourad Rattal, El Mostafa Oualim, Azeddine Mouhse, and Jean-Pol Vigneron, Optics Express, (2014), **22 (2)**, pp 1940-1951.

"A two-in-one superhydrophobic and anti-reflective nanodevice in the grey cicada Cicada orni (Hemiptera)", L Dellieu, M Sarrazin, P Simonis, O Deparis and J.-P. Vigneron (2014), Journal of Applied Physics, **116 (2)** , 024701,

"Theoretical condition for transparency in mesoporous layered optical media: Application to switching of hygrochromic coatings)", O Deparis, MN Ghazzal, P Simonis S. Mouchet, H. Kebaili, J. de Coninck, E. M. Gaigneaux and J. P. Vigneron, (2014), Applied Physics Letters, **104**, 023704, http://dx.doi.org/10.1063/1.4862658

"Circular polarization in nature: factual, theoretical and experimental summary", S Berthier, M Thomé, P Simonis, (2014), Materials Today: Proceedings, **Vol. 1, Supplement**, pp145–154, "Living Light: Uniting biology and photonics - A memorial meeting in honour of Prof Jean-Pol Vigneron"

*"**Living Light 2014 Editorial: Photonics from Living Materials**",*
Michaël Sarrazin, Serge Berthier, Philippe Lambin, Materials Today: Proceedings **Volume 1, Supplement,** (2014), Living Light: Uniting biology and photonics -- A memorial meeting in honour of Prof Jean-Pol Vigneron, pp 107–108

"Nanostructured Surfaces: Bioinspiration For Transparency, Coloration And Wettability", Olivier

Deparis, S. Mouchet, L. Dellieu, J.-F. Colomer, M. Sarrazin,
Materials Today: Proceedings **Volume 1, Supplement**, (2014), Living Light: Uniting biology and photonics -- A memorial meeting in honour of Prof Jean-Pol Vigneron, *Pages 122-129*

" Multiscales And Multifunctional Natural Structures Replicas"
Magali Thomé, Serge Berthier, Lionel Nicole, Materials Today: Proceedings **Volume 1, Supplement**, (2014), Living Light: Uniting biology and photonics -- A memorial meeting in honour of Prof Jean-Pol Vigneron, *Pages 221-224,*

Principle Visits, Work-trips and Expeditions:
(Visites principales et missions effectuées:)

L. Dellieu & J. Pasteels **Insect Collecting Mission to Panama City** **4^{th}-23^{rd} February 2014 (L. Dellieu)** **14^{th} February – 1^{st} March 2014 (J. Pasteels)**	**L. Dellieu:** "Expedition to collect cicadas and springtails for doctoral thesis of L. Dellieu, in order to investigate the structures covering the insects' wings/elytra. Material still being analysed at time of this report." **J. Pasteels:** « Le travail réalisé au STRI (Panama) est le prolongement des travaux antérieurs réalisés par JP Vigneron et son équipe sur les changements de couleurs structurales des cassides (Coléoptères). Une étude préliminaire en TEM (coll Prof J. Billen, KUL) avait mis en évidence une multicouche non détectée en SEM, qui pouvait être le « réflecteur doré » des cassides. Le but premier était de récolter et de fixer pour observations en TEM des espèces manifestant différents patterns dorés sur les élytres, patterns fixes tant qu'en vie, ou pouvant s'éteindre de manière réversible. Ceci impliquait l'observation in situ d'individus vivants. Les élytres de quatorze espèces ont été fixées, dont trois pouvaient éteindre et rallumer leur réflecteur. Pour deux espèces, les élytres d'adultes immatures, chez lesquels le réflecteur doré n'était pas encore fonctionnel, ont également été fixées. Des mesures spectrophotométriques sur 8 de ces espèces et des observations en SEM pour 4 d'entr'elles ont été réalisées par Jonathan Pimpurniaux, étudiant UN en stage au STRI. Des observations en TEM ont déjà été réalisées pour 6 espèces et se poursuivent. Les observations confortent l'hypothèse selon laquelle la multicouche située entre l'épiderme et l'endocuticule serait le réflecteur doré pour toutes les espèces capables ou non de l'éteindre. Ceci doit encore être confirmé par l'étude de physiciens de ses propriétés optiques. Accessoirement des cigales ont été récoltées pour Louis Delieu et des morceaux de feuilles bleues et vertes de Selaginella ont été fixées pour étude en TEM (projet de l'UN). »

Settat (Morocco), Université Hassan 1er, Faculté des Sciences et Techniques Pierre Defrance June 8-14, 2014	Vacuum Physics and techniques, addressed to the Master's degree students (about 25 in number), Additional discussions of multilayer deposition applications related to this project with scientists and students. The course contains both theory and practical, with a strong emphasis on producing and maintaining high and ultrahigh vacuum in both scientific and industrial applications.
Kinshasa (République Démocratique du Congo), Université de Kinshasa **Pierre Defrance** **May 25 - June 1, 2014**	Tasks: (1) Course: Dielectric materials , addressed to the Master's degree students (about 20) (2) Analysis and discussion of the results of the thesis of Toto Mabiala: study of optical properties of cylindrical natural or bio-inspired multilayer systems. The course is based on the book "Solid State Physics" (Kittel) and every participant received lectures notes.

Exceptional Materials/ Equipment Received during the year :

(Matériel exceptionnel » réceptionné durant l'année écoulée:)

None

Predicted Activities for the Following Year:
(Prévisions d'activités pour l'année suivante:)

Biomimetic solutions will be sought for the following issues:
Transparency and self-cleaning properties
Passive thermal control, high performance Lighting,
non-polluting textile colouring

Active hygrochromically controlled reflectance
Radiative heat insulation
Protection from Solar UV
Control light polarization

For each of these issues above, details of contacts & external support obtained are given below:

(Les indications qui suivent donnent, pour chaque question, les contacts et supports extérieurs obtenus:)

Groupe de Recherche en Photonique du Vivant

Thème des recherches : Innovations bio-inspirées

FUNDP NAMUR

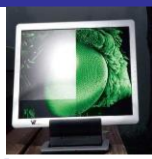
Physics of Matter and Radiation

Transparence et propriétés d'auto-nettoyage

Ailes transparentes et super-hydrophobes de *Cocytia d'Urvillei*

Cleanoptic – Greenomat

UCL – ULg – FUNDP – Certech
ESE-Solar – AGC – Solvay



Affichage – Vitrages – Panneaux solaires thermiques ou photovoltaïques

Contrôle thermique passif

Ailes noires super-absorbantes de *Troides magellanus*

PIC-CUD et CUD-IC

FUNDP – Univ. Ouagadougou – CNRST Burkina Faso – U. Hassan Ier Settat Maroc

Panneaux solaires thermiques
Serres inverses pour la conservation des aliments (refroidissement passif)

Eclairage à haute performance

Emission de lumière à haut rendement lucioles *Photinus sp.*

ARC – Académie Louvain
ESRF (synchrotron Européen)

FUNDP – UCL

Diodes luminescentes
Extraction de lumière des sources solides

Coloration textile non polluante

Coloration bleue de la tarentule *Pamphobeteus antinous*

ARC – Académie Louvain

FUNDP – UCL – Hong Kong Institution of Textile and Apparel - TRAITEX

Coloration des textiles par interférence de lumière

FUNDP NAMUR

Groupe de Recherche en Photonique du Vivant

Thème des recherches : Innovations bio-inspirées

Physics of Matter and Radiation

Contrôle hygrométrique actif de la réflectance

HGCM – Winnomat

FUNDP – UCL – UMons
AGC – Nanoxid

La Casside neotropicale *Charidotella egregia* Passe activement de doré à rouge

Contrôle actif de la transparence des vitrages

Isolation thermique radiative

ARC – Académie Louvain

FUNDP – PARIS 6 - U. Hassan Ier, Settat Maroc

Isolation thermique des fourrures d'animaux

Optimisation de l'isolation thermique

Protection solaire UV

FUNDP – L'Oréal Paris

La structure des filaments d'edelweiss la protège des UV

Utilisation des structures photoniques pour la protection solaire UV

Contrôle de la polarisation de la lumière

FUNDP - PARIS 6

Les Rutelidae filtrent la lumière pour produire une polarisation circulaire

La polarisation circulaire est utilisée pour le rendu 3D