Iridescence and thermal properties of Urosaurus ornatus lizard skin described by a model of coupled photonic structures

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Abstract
This research shows that the morphological characteristics of the external microstructure of the beautiful skin of the Urosaurus ornatus lizard contribute to the explanation of the origin of their iridescent and thermal properties. High-resolution scanning electron microscopy studies revealed that the skin surface of the U. ornatus lizard is constituted by a semi-ordered array of hexagonal photonic crystals with sub-micrometric structural parameters. The iridescence properties of the ventral patch and dorsal surface of the U. ornatus lizard were numerically simulated modeling both surfaces by a set of coupled photonic crystals with structural parameters proposed from statistical measurements of the lattice parameter and holes diameter of its skin surface. The dorsal surface showed the ability to reflect visible light and at least in a significant range the ultraviolet and near infrared radiation. A complete photonic band gap for the transverse magnetic polarization mode of the incident light in both dorsal and ventral surfaces was predicted by calculations. The spectral reflectance and the structure of photonic bands obtained explain the reflection of the infrared radiation by the dorsal surface which might help to the thermoregulation of the lizard body. The results obtained suggest that the selective reflection of incident light performed by the photonic structural array defined on the skin surface of the U. ornatus has a significant contribution to its apparent color.

1. Introduction
In general terms, the change in color involves a modification of absorptive and/or reflective optical properties of an object or living organism. In animals or living organisms, this color change involves the activation of chromatophores; cells responsible for color production and which can be either pigmented or structural. In the pigmentary-type chromatophores, the mechanism of skin color change is based on the migration of pigments or nanostructures within the chromatophores [1, 2]. As a consequence of this phenomenon, after some chemical reactions, a specific color in the animal skin is revealed due to a selective absorption and specular or diffuse reflection of specific wavelengths of the incident light [2, 3]. Pigmentary chromatophores can be melanophores, which are responsible for the production or change of black or brown colors, xanthophores that produce yellow, and erythrophores that produce red color [2, 4]. Structural chromatophores on the other hand, present in only a handful of species, produce color by reflection and scattering specific light wavelengths by ordered cellular arrangements. Structural chromatophores include iridophores, which are colorless, and leucophores, whose function is to reflect white light [4]. It is known that the transparent guanine nanocrystal-containing iridophores produce a diversity of bright colors in reptiles, fish, and amphibians [5, 6]. In biological systems, it has been reported that color is produced in iridophores by thin layer interference [7]. It also has been found that the light
wavelengths reflected by these cells, describing a structured periodical array, can change in response to temperature and osmolarity [6, 7]. Moreover, both color acquisition and change via structural chromatophores can be achieved in the short or long term by the selective reflection of light through structured periodical arrays described on the surface of an object or under the skin of an organism. In general, this selective reflection of light has its origin in the phenomena of interference and diffraction of light waves that take place in these periodical arrays describing photonic structures. A photonic structure defines a refractive index grating with periodical variation in one, two or three dimensions induced by a sequence of alternated materials with different dielectric properties or by the introduction of structural defects in a homogeneous material, which can be holes or regions where usually there is no material present [8, 9]. The specific parameters such as the lattice type, lattice constant, filling factor (percentage of material corresponding to air respect to the matrix or material composing the object of interest) and the aspect ratio (diameter of periodical defects to lattice constant ratio) of a photonic structure defined on the surface of an object determine the reflected light wavelength range which is associated to its apparent color [10]. In Nature the occurrence of photonic structures recognized in the skin, shell, external surface delimiting their body or plumage of some organisms, allows them to develop essential functions to interact with other organisms or protect themselves from predators surrounding the environment where they live [11].

Usually, the nipple arrays or structural defects defining a photonic structure have average dimensions ranging from a few hundred nanometers to around one micron in order to work in the ultraviolet, visible and near infrared regions (UV–vis-NIR) of the electromagnetic spectrum [9, 10]. Furthermore, in the case of photonic structures described by structural defects, which in general are air-filled holes, provide high contrast in the periodic refractive index pattern which is correlated to significant changes in the optical properties of the skin surface of an animal or in general on the surface of an object. Nevertheless, the skin color of an animal can also be the result of a combination of interactions among pigimentary and structural elements [6, 12].

In previous works it has been stablished that colors of belly patches of the U. ornatus lizard are produced structurally by iridophores by means of thin-layer interference in platelets located under its skin surface [7]. So that changes in spacing between these reflecting platelets induced in osmolarity experiments cause corresponding changes in color. It was also found that color is strongly dependent of the incidence angle of light used to illuminate the specimen and the position of the observer [7]. According to Morrison et al the thin layer interference can explains the specular and iridescent nature of color in the U. ornatus [7]. The apparent change in color by varying the viewing angle, which show some objects or animals, called iridescence has a structural origin [10]. In this way, the color coming from the pigimentary origin cannot give rise to iridescence. Certainly, variations in the thickness of a dielectric or semiconductor thin film such as ZnO can also show iridescence due to interference effects. Based on these arguments the aim of the present research is to show that changes in the reflective optical properties of an object are also linked to the microscopic structural characteristics that describe its surface. Indeed, the alternating layers with high and low refractive index producing interference under the skin in the case of some animals of course have a contribution to the origin of the color [7]. However, the iridescence or apparent color dependent on the viewing angle of an object or a living organism has also a contribution coming from the effects of the selective reflection of certain wavelengths concerning the incident illumination on its surface [13–15], which is precisely what we want to show in this work.

In the present research it has been evaluated the optical reflection of light from the beautiful skin of the Urosaurus ornatus lizard emphasizing on the contribution of the morphological characteristics of its external microstructure. The primary goals of this research were to describe in detail the iridescent properties of the ventral patch and dorsal surface of the U. ornatus lizard, based on the study of the morphology of the sub-micrometric array described on its external skin, which defines a photonic structure. These objectives were reached using both high-resolution scanning electron microscopy (SEM) and numerical simulations, using the finite–difference time–domain method to estimate the reflective optical properties of the skin surface of the specimen under study proposing a model of its skin surface constituted by a coupled photonics structures.

From the morphology characterization of the microscopic structure of the skin external surface of the specimen under study, it was found that the surface of the U. ornatus lizard skin certainly describes a photonic structure. Specifically, a semi-ordered hexagonal periodical structure with characteristic sub-micrometric parameters, which give rise to the appearance of partial photonic band gaps that determine the light reflection at specific wavelength ranges in the electromagnetic spectrum. These results allow assuming the skin iridescence of the U. ornatus is originated in the selective reflection of incident light performed by the microscopic structural array described on its skin surface.
2. Materials and methods

2.1. Specimen under study

Urosaurus ornatus caeruleus is a small tree lizard, which inhabits in the southwestern United States, and northern Mexico [16, 17]. These lizards have a small head and typical sizes with snout to vent length (SVL) ranging from 38–68 mm; they have a slim body and a long tail that can be around 60 mm. At adult age, the male exhibits a beautiful bright metallic blue to blue-green patch on its ventral surface, while on its throat or dewlap it exhibits patches of green, blue-green or yellow color. The female specimen instead has a white color underbelly, and orange, white or yellow patches on its throat, but no blue is present [18]. On their dorsal surface, these lizards have patterned spots with a variety of colorations including black, dark brown, blue, grey and tan, which can help them to camouflage in their local habitat. These patterned spots extend up to their tail although the base of their tails usually has a rusty brown color.

2.1.1. Capture specimen methods

An expedition was organized at 31.5 km southeast of Chihuahua City in Chihuahua México during July 2018, in order to capture some lizard specimen of interest. At the search site (28.45324 N, 105.81427 W, elevation 1,555 m), a 5 km road to a village on the outskirts called Horcasitas, an adult male U. ornatus was caught near the location where the specimen lives according to reports in the literature [17]. After collecting the specimen of U. ornatus it was transported to our laboratory in order to prepare it and perform the characterization of its skin surface. We realized that the stress level of the specimen and the temperature of the room where were carried out the experiments affected the color of its skin. In order to diminish this effect and ensure full expression of its blue ventral patch, the room was warmed reaching a temperature of 29 °C using air-conditioned equipment installed in the laboratory. Nevertheless, throughout the day, the mean body temperature of the lizard, measured with a Fluke 51–11 digital thermometer employing a thermocouple, only reached 31 ± 0.1 °C. This temperature is lightly under the range 34 °C–36 °C at which full expression of the blue ventral patch of U. ornatus lizard is ensured [7, 18].

2.2. Morphological and structural characterization of the lizard skin surface

A first macroscopic characterization process of the skin surface of the U. ornatus specimen, using high-resolution digital images captured with a Canon EOS 70D photographic camera was performed. Figure 1 shows a full-color digital photograph of 5472 × 3648 pixels (20.2 MP) of (A) the ventral patch and (B) the dorsal surface of the specimen under study acquired on a reference white plane surface to obtain high contrast. The pictures were taken at room temperature of 29 °C in the presence of cool-white fluorescent ceiling lamps and using the camera flashlight. The interest region covering a significant part of the ventral surface in the image 1(A) was divided into four sections, each with a length of 8.5 mm in the horizontal direction: a, b, c and d, in order to facilitate the analysis of their distinctive features. At first sight in figure 1(A), it is noticeable that the average size of the scales on the skin specimen varies in the different sections. On the dorsal surface, in turn, there are also variations on the scales size as shown in the auscultated area of figure 1(B).
In this research, we made every effort to keep alive the specimen under study, in order to perform a deep characterization of the optical properties of its skin. Unfortunately, the specimen died in captivity. Subsequently, in order to take advantage of this fact, the skin of the dead specimen was cut to obtain some samples from ventral and dorsal surfaces of its skin to characterize its microscopic morphology. The microscopic characterization of the lizard skin surface was performed by high resolution scanning electron microscopy techniques using an electron microscope model JEOL JSM-7401F.

2.3. Numerical calculations of optical reflectance and photonic band structure
In addition, numerical simulations of the optical properties of a model of the skin surface of the specimen studied, constituted by several coupled two-dimensional photonic crystals, were conducted using the finite-difference time-domain method, as described with detail in the supplementary material is available online at stacks.iop.org/JPCO/4/015006/mmedia. From these calculations, the optical reflectance of the lizard skin surface as a function of the observation angle and the photonic band structure associated with its microscopic structure were obtained.

3. Results

3.1. Microscopic morphology characterization
The microscopic characterization of the skin surface of the U. ornatus lizard was made by high-resolution scanning electron microscopy. Three tissue samples from the ventral patch and three samples from the dorsal surface of the lizard skin were obtained, each with an approximate area of 1 cm². These samples were prepared for observation by carrying out a fixing process to stabilize and prevent decomposition of the skin specimen, using glutaraldehyde (C₅H₈O₂) with a 2.5% concentration in a sodium cacodylate solution with a pH equal to 7 at 0.1 mol. The solution was left to sit for 12 h and then was added to an alcohol suspension to remove the water in the tissue, again for 12 h. Then, the samples were stored in a silica desiccator and placed in a special sample holder for their observation. Nevertheless, before observing the samples in the scanning electron microscope, a gold thin film was deposited on the surface of each. Figure 2 shows representative SEM micrographs of a scale from both the ventral and dorsal sections of the lizard skin at different magnifications. Unfortunately, in some of the micrographs, bacteria formed during the time the lizard was stored dead in a freezer before their preparation to be observed in the scanning electron microscope. Figures 2(a)–(e) show representative SEM micrographs of one of the typical scales (located in section c of figure 1(A)) constituting the ventral patch surface morphology of the lizard skin at 500X, 1000X, 3,000X, 5,000X, and 20,000X magnifications, respectively. As shown in figures 2(b) and (c) the whole surface of the scale constituting the ventral patch of lizard skin describes hexagons and other polygons in its structural lattice. In fact particularly, inside each of the hexagonal cells there is a structural arrangement of small holes with diameters ranging from 189 to 583 nm. These holes are separated from one another by an average distance between centers close to 500 nm, as shown in figures 2(d) and (e). Figure 2(f) shows an SEM micrograph of a representative region in the middle dorsal surface of the lizard skin at 5,000 magnifications.

Figure 2. SEM micrographs of one of the representative scales in section c of figure 1(A) corresponding to the ventral patch surface of the U. ornatus skin at (a) 500X, (b) 1000X, (c) 3000X, (d) 5000X, and (e) 20000X magnifications, respectively. (f) SEM micrograph taken at 3000X magnifications of a representative region denoted with a square in the middle dorsal surface of the lizard skin shown in figure 1(B).
In order to characterize in detail the typical dimensions of the microscopic structure of the lizard skin, a statistical study of the diameter of the holes and the distance between its centers (lattice parameter) was performed for both the ventral patch and dorsal surface. The holes diameter and the distance between the centers of adjacent holes in the ventral patch (figure 2(d)) and dorsal surface (figure 2(f)), were measured using ‘Pro-Image Analysis’ software in a selected area of 80 \( \mu m^2 \) in each of the interest regions. As it can be observed in figure 2(d), the arrangement of holes describes a set of clusters with a hexagonal symmetry including one hole at its center. This arrangement of holes has a specific regular order with characteristic dimensions similar to a photonic structure as shown in figures 2(d) and 2(e).

The diameters of these sets of holes filled with air in the ventral patch and dorsal surface describe a Gaussian distribution as shown in histograms represented in figures 3(a) and 3(c), respectively. The average holes diameter in the ventral patch and dorsal surface measured was 0.385 \( \pm \) 0.002 \( \mu m \) and 0.230 \( \pm \) 0.002 \( \mu m \), respectively. The lattice parameter that describes the distance between centers of holes in the ordered structures corresponding to the ventral patch and dorsal surface also has a Gaussian distribution as shown in histograms displayed in figures 3(b) and 3(d). The average lattice parameter in the ventral patch and dorsal surface measured was 0.504 \( \pm \) 0.002 \( \mu m \) and 0.489 \( \pm \) 0.002 \( \mu m \), respectively. It is interesting to remark that both the holes diameter and the lattice parameter of the holes arrangement in the ventral patch are bigger than those structural parameters corresponding to the dorsal surface of the lizard skin.

### 3.2. Numerical calculations of optical reflectance and photonic band structure

Taking into account all the results of the statistical study about the holes diameter and the distance between its centers performed for the ventral patch and dorsal surface of the *U. ornatus* lizard, the optical reflectance and the photonic band structure associated to its skin surface were numerically calculated using the finite-difference time-domain method \cite{19, 20}. Nevertheless, from the observations of the morphology of lizard skin surface performed by SEM, it was determined that there is no regular ordered structure similar to that of a perfect photonic crystal. For this reason, the calculations of the photonic band structure for the ventral patch and dorsal surfaces were developed assuming a set of coupled two-dimensional photonic crystals describing an area of \((70 \times 70) \mu m^2\) with a side length \(L = 70 \mu m\), that included seven different ordered structures. In the case of ventral patch these ordered structures are \(A_V, B_V, C_V, D_V, E_V, F_V\) and \(G_V\) as shown in figure 4, while for the dorsal surface were denoted by \(A_D, B_D, C_D, D_D, E_D, F_D\) and \(G_D\), respectively. As shown in table 1, these ordered structures defining together a set coupled photonic crystals modeling the ventral patch or the dorsal surfaces contribute with a different area to the whole structure and each has a different holes diameter and a specific
lattice parameter. Certainly, each of these ordered structures has a different holes surface density determined by the structural parameters that define it. The contribution of each ordered structure to the completely photonic crystal was determined from the statistical results shown in figure 3 (a)–(d). An effective refractive index of the skin surface of *U. ornatus* lizard was assumed equal to 1.62, which was derived from the refractive index of guanine crystals dispersed in the cytoplasm [5–7, 21]. In summary, since both holes diameter and lattice parameter in the ventral patch and dorsal surface of *U. ornatus*, have a Gaussian distribution, the whole photonic structure used for the numerical calculations was built describing a Gaussian spatial distribution of seven small photonic structures defined by specific structural parameters. The results obtained from the numerical calculations are described below.

Figure 5 shows the reflectance spectrum of the ventral patch obtained from numerical calculations considering different observations angles 0°, 15°, 30°, 45°, 60° and 75° measured from the perpendicular direction to the plane describing the skin surface of *U. ornatus* modeled by a set of coupled photonic crystals shown in figure 4. Calculations of reflectance of belly patch of *U. ornatus* were obtained sending at normal incidence (0° from the perpendicular direction to the plane describing the skin surface) a Gaussian light pulse with a bandwidth ranging from 300 nm to 900 nm over the skin surface modeled. The reflectance spectra were smoothed using the Savitzky–Golay method with the purpose of show its average behavior based on the obtained raw data. Figure 5(d) shows both raw data and filtered signal in order to show the appearance of the obtained original data. Figure 6 shows the corresponding reflectance spectra numerically calculated for the dorsal surface of *U. ornatus* for different viewing angles measured from the perpendicular direction to the plane describing the skin surface. The reflectance spectra shown in figure 6 were obtained using exactly the same conditions used to

| Section | Length (µm) | Lattice parameter (nm) | Hole diameter (nm) |
|---------|-------------|------------------------|-------------------|
| A_V     | 1.95        | 316.5                  | 216.8             |
| B_V     | 6.85        | 378.4                  | 273.1             |
| C_V     | 21.04       | 440.4                  | 329.4             |
| D_V     | 24.47       | 502.4                  | 385.7             |
| E_V     | 11.75       | 564.3                  | 442.0             |
| F_V     | 2.44        | 626.3                  | 498.3             |
| G_V     | 1.46        | 688.2                  | 554.6             |

**Table 1.** Parameters of the two-dimensional photonic structure representing the ventral patch and dorsal surface used in calculations of photonic band structure.
Figure 5. Spectral reflectance of the ventral patch obtained from numerical calculations for different observations angles 0°, 15°, 30°, 45°, 60° and 75° measured from the perpendicular direction to the plane describing the skin surface of the *U. ornatus* modeled by a set of coupled photonic crystals shown in figure 4. Calculations were obtained sending a Gaussian light pulse depicted in (a) with a slashed line at normal incidence (0° from the perpendicular direction to the plane describing the skin surface) with a bandwidth ranging from 300 nm to 900 nm over the skin surface. The reflectance spectrums were smoothed using the Savitzky-Golay method, (d) shows both raw data and filtered signal to show the appearance of the obtained original data.

Figure 6. Spectral reflectance of the dorsal surface of the *U. ornatus*, numerically calculated for different observations angles 0°, 15°, 30°, 45°, 60° and 75° obtained illuminating at normal incidence with a Gaussian light pulse. Calculations were developed under similar conditions to those performed for the spectral reflectance of the ventral patch, modelling the surface by a set of coupled photonic crystals with similar appearance to the ordered structures used to model the ventral patch but with their corresponding structural parameters shown in table 1.
obtain the reflectance spectra shown in figure 5, except this time was used the model of coupled photonic crystal proposed for the dorsal surface described by the ordered structures A_D, B_D, C_D, D_D, E_D, F_D and G_D with structural parameters shown in table 1.

On the other hand, with the aim of evaluate the dependence of reflective properties of the U. ornatus skin surface on the incidence angle of the illumination source, the reflectance spectra of ventral patch and dorsal surface of U. ornatus were also numerically simulated assuming incidence angle different to 0°. Figures 7 and 8 show the reflectance spectra for different.

Viewing angles 0°, 15°, 30°, 45°, 60° and 75° of ventral patch and dorsal surface, respectively, for an incident Gaussian light pulse over the skin surface at a 45° angle respect to the perpendicular direction to the plane describing the skin surface.

Numerical calculations developed also allowed to obtain the photonic band structure associated to the coupled photonic crystals modeling both the ventral patch and dorsal surface of U. ornatus lizard skin under research. Figure 9 shows the photonic band structure for the photonic arrangement modelling the lizard skin surface obtained for TE (transverse electric) and TM (transverse magnetic) polarizations modes. Figures 9(a) and (b) correspond to TE and TM polarizations modes, respectively, for the ventral patch, whereas figures 9(c) and (d) correspond to TE and TM polarization modes, respectively, for the dorsal surface. Figures 9(e) and (f) show the photonic band structure corresponding to TE and TM modes, respectively, for the ventral patch, considering both the lattice parameters and holes diameters in the modeled skin surface reduced in fifty percent respect to the parameters used in calculations of photonic band structure shown in figure 9(a).

4. Discussion

4.1. Numerical calculations of optical reflectance
As it can be observed from reflectance spectra shown in figures 5 to 8, the color of U. ornatus skin is strongly dependent on both the position of the observer and the incidence angle of the illumination source. From the reflectance spectra of the ventral patch shown in figure 5, it can clearly be appreciated notorious variations in the type of light reflected by the lizard skin surface for each viewing angles considered. A Gaussian light pulse depicted in figure 5(a) incident at 0° from the perpendicular direction to the plane describing the skin surface, was used as illumination source. As can be seen in figure 5, the significant value of the reflectance amplitude is essentially distributed in the wavelength range from 400 nm to 800 nm for all viewing angles. For example, the
reflectance spectrum in figure 5(a) for an observation angle of 0° shows two peaks centered at 495 nm and 617 nm, associated to blue and orange colors, respectively. Figure 5(b) shows only a peak value of the reflectance, centered at 516 nm and associated with a green color. Figure 5(c) in turn shows two peak values of the reflectance amplitude, centered at 466 nm and 541 nm describing blue and green colors, respectively. Figure 5(d) corresponding to a viewing angle of 45° including both raw data, and filtered signal, reveals two peak values of the reflectance amplitude which are centered at 472 nm and 553 nm corresponding to blue and yellow colors, respectively. However, the bulk of the reflectance distribution in figure 5(d) is shifted to blue color. Figures 5(e) and (f) corresponding to high viewing angles of 60° and 70°, respectively, have a very similar behavior showing three peaks in their corresponding reflectance spectrum. Nevertheless, the reflectance spectrum shown in figure 5(e) presents a shift to blue color respect to the reflectance spectrum shown in figure 5(f). Clearly, the amplitude of the reflectance spectrum shown in figure 5 decreases when the viewing angle increases because the illumination light pulse was sent at 0° from the perpendicular direction to the plane describing the lizard skin surface.

Regarding the dorsal surface, it also showed a high variation in the type of light reflected for each viewing angles considered, as shown in figure 6. Nevertheless, this time the reflectance spectra obtained for the dorsal surface show different distinctive characteristics respect to the behavior of the reflectance spectra for the ventral patch obtained at the same observation angles and under the same illumination conditions. First, as can be seen in figure 6, the significant value of the reflectance amplitude is essentially distributed in the wavelength range from 350 nm to 900 nm for an observation angle of 0° while for larger observation angles is distributed from 400 nm to 700 nm. In addition, the reflectance spectra of the lizard dorsal surface for viewing angles less than or equal to 45° show higher amplitude values than the reflectance amplitude values obtained for the ventral patch. In other words, the dorsal surface reflects more efficiently the light pulse than the ventral patch for viewing angles less than 45°. It is interesting to remark that at a viewing angle of 0° there is a high reflection by the dorsal surface in all the wavelength range covered by the illumination light pulse. In fact, the peak of reflectance of the dorsal surface located at 553 nm has a value around 65% while for the ventral patch its peak is located at 617 nm and reaches only 47%. Moreover, the dorsal surface reflects around a 10% of UV radiation of the electromagnetic spectrum as shown in figure 6(a), while the ventral patch does not have the ability to reflect this type of radiation as shown in figure 5(a). Furthermore, as shown in figure 6(a) the dorsal surface is a good reflector of the radiation in the wavelength range from 780 nm to 900 nm comprised in the NIR range of the electromagnetic spectrum, exceeding the levels of reflectance of the ventral patch shown in figure 5(a). The
spectral reflectance of dorsal surface in the interval from 780 nm to 900 nm comprised in the NIR range has a value between a 20% and 30% while for the ventral patch is between a 5% and 10%. Thus, the dorsal surface of the *U. ornatus* lizard modeled by a set of coupled photonic crystals with structural parameters based on statistical measurements of the lattice parameter and holes diameter of its skin surface, reflects a part of the radiation in the UV and NIR ranges. This result can help to explain how the *U. ornatus* lizard maintain and control its body temperature.

In order to evaluate the dependence of the reflective properties of the lizard skin surface on the incidence angle of the illumination source also was numerically simulated the reflectance as a function of wavelength considering now an illumination source with different incidence angles. Figures 7 and 8 show an illustrative example of the dependence of the spectral reflectance of the lizard skin surface on the position of the observer for an incidence angle of the illumination source equal to 45° measured from the perpendicular direction to the plane describing the skin surface. Figure 7 shows the reflectance spectra of the ventral patch for viewing angles of 0°, 15°, 30°, 45°, 60° and 75°. As can be observed now in figure 7, the reflectance shows a behavior different to that shown for the reflectance spectrum in figure 5 corresponding also to the ventral patch but with an incident illumination at an angle of 0°. The reflectance spectra shown in figure 7, have now three well-marked picks for viewing angles less or equal to 45° and in addition, for all the observation angles there are a shift of its amplitude toward higher wavelengths respect to the behavior obtained for an incidence angle of 0° shown in figure 5. This shift of the reflectance amplitude toward high wavelengths means that the lizard skin surface tends to reflect...
radiation associated with orange and red colors for observation angles higher or equal to 45° as shown in figures 7(c)–(f).

In the case of reflectance spectra of the dorsal surface shown in figure 8 that includes results for the viewing angles of 0°, 15°, 30°, 45°, 60° and 75° there was also significant changes respect to the reflectance spectra shown in figure 6 for the dorsal surface corresponding to an incident illumination at an angle of 0°. As it can be seen in figure 8, for all the viewing angles there was a notorious shift of the reflectance amplitude toward high wavelengths respect to the reflectance behavior shown in figure 6 obtained for an incidence angle equal to 0°. The bulk of the distribution of the reflected radiation as shown in figure 8, is now concentrated in the wavelength range from 600 nm to 850 nm for all the viewing angles. It is important to note that the amplitude of reflectance did not decrease for large viewing angles as shown in figure 8, but instead had a significate increasing respect to the reflectance obtained for the dorsal surface at similar viewing angles but for an illumination with an incidence angle of 0°. Evidently, numerical calculations for the spectral reflectance predicts a shift toward red color of the radiation reflected by the lizard dorsal surface when the incidence angle of the illumination is 45° measured from the perpendicular direction to the plane describing the skin surface.

A significant fact that must be taken into account between the spectral reflectance of the dorsal surface of the lizard for an incident illumination at 0° and the spectral reflectance for an incident illumination at 45° is as follows. The reflectance obtained for an incident illumination at 0° corresponding to a 0° observation angle has an amplitude between 20% and 30%, in the range between 800 nm and 900 nm, which is not very high or very low. This should be so, because at noon when the rays of sun fall perpendicularly to the Earth surface, the lizard *U. ornatus* must take advantage of this type of radiation to heating its body by exposing its dorsal surface to the Sun without overheating. However, in the late afternoon the rays of sun fall with an inclination with respect to the vertical direction and the lizard should no longer reflect as much radiation in the near infrared range (800 nm–900 nm) to avoid a sudden cooling, as can be seen in the spectral reflectance shown in figure 8 for all the observation angles. For these reasons it is acceptable that the model based on the set of coupled photonic crystals that we have proposed, describes the appropriate behavior of the reflective properties of the *U. ornatus* lizard skin surfaces. This conclusion is reached because it was possible explaining how the *U. ornatus* body can be heated and how it can prevent its cooling when the ambient temperature falls during the afternoon of an ordinary day. On the other hand, the spectral reflectance of the ventral patch explains the change in skin color around green, blue and orange, depending on both the observation angle and the illumination incidence angle.

### 4.2. Calculations of photonic band structure

In relation with the photonic band structure calculations, it is interesting to note how for TE polarization mode shown in figures 9(a), (c), and (e) there is only partial photonic band gaps in both skin surfaces considered. The existence of this partial photonic band gaps means that radiation of the specific wavelengths cannot propagate inside the photonic structure under some specific angles, as indeed occurs due to the iridescence phenomenon present in the *U. ornatus* skin. Nevertheless, for TM polarization mode as shown in figures 9(b), (d) and (f), in both skin surface regions modeled appeared a complete photonic band gap. Indeed, in the case of the ventral patch in figure 9(b), the photonic band gap appears located around a normalized frequency of 0.51 (λ = 940 nm) while for the dorsal surface in figure 9(f) it occurs around 0.32 (λ = 1500 nm). This fact determines that the radiation in these frequency ranges does not propagate for all incidence directions, reflecting the photons of light corresponding to these frequencies. As shown in the right vertical axis of figures 9(b) and (f), these frequency ranges correspond to wavelengths in the NIR range of the electromagnetic spectrum. Nevertheless, it is interesting to note how for TM polarization mode in the case of dorsal surface skin, the photonic band gap is located at a lower frequency than in the case of the ventral patch. Thus, the dorsal surface reflects more electromagnetic radiation in the NIR range at higher wavelengths than that reflected by the ventral patch, as was commented before, which might help to the thermoregulation of *U. ornatus*.

On the other hand, it is possible to assume that the structural parameters of the skin of the processed dead sample observed in the scanning electron microscope may not be precisely those corresponding to the skin of the living specimen. For this reason, as a theoretical exercise, variations of the physical parameters of the coupled photonic structure representing the ventral patch were conducted in the numerical calculations in order to obtain a complete photonic band gap in the visible range of the electromagnetic spectrum. The results of that theoretical exercise are shown in figures 9(e) and (f), which show the photonic band structures for TE and TM modes corresponding to the ventral patch. In these calculations, lattice parameters and holes diameters were both reduced by fifty percent respect of the original structural parameters used in calculations of the photonic bands structure shown in figures 9(a) and (b). As it can be seen in figure 9(f), a complete photonic band gap appeared for TM polarization mode, centered at a normalized frequency of 0.5 corresponding to a wavelength $\lambda = 480$ nm. The photonic band gap now occurs in the visible range of the electromagnetic spectrum and determines that photons with frequencies associated with the blue color are fully reflected from the skin of the *U.*
ornatus lizard. Then according to our model to describe the photonic structure that represents the ventral patch of the U. ornatus, the structural parameters that determine its typical blue color in a living specimen should be around to a half of the original structural parameters measured from the SEM studies.

5. Conclusions

The microscopic structure of the skin surface of the specimen under study investigated via high-resolution scanning electron microscopy revealed that the skin surface of the U. ornatus lizard is constituted by a semi-ordered hexagonal photonic crystals array with sub-micrometric structural parameters. Numerical calculations of the spectral reflectance obtained in this research showed that the color of U. ornatus skin surface, modeled by a set of coupled photonic crystals, was strongly dependent on both the position of the observer and the incidence angle of the illumination source. The model assumed for the ventral patch of the U ornatus lizard describes directly its iridescence properties, which allows explaining their green and blue colors dependent of the viewing angle. Calculations of the spectral reflectance for the dorsal surface showed that it has the ability to reflect a part of the UV radiation of the electromagnetic spectrum, while the ventral patch did not show this ability. Furthermore, the dorsal surface demonstrated to be a good reflector of the radiation in the NIR range of the electromagnetic spectrum, exceeding the levels of the spectral reflectance of this type of radiation obtained for the ventral patch. Thus, the dorsal surface of the U. ornatus lizard modeled by a set of coupled photonic crystals with structural parameters based on the statistical measurements of the lattice parameter and holes diameter of its skin surface, reflects efficiently the radiation in the UV and NIR ranges. This is a relevant result since it allows explaining how the U. ornatus lizard has the ability to control its body temperature.

Numerical calculations developed also allowed to obtain the photonic band structure associated to the coupled photonic crystals modeling both the ventral patch and dorsal surface of the U. ornatus lizard skin. The more relevant results above this subject showed a complete photonic band gap for TM polarization mode of the incident light. Although, partial photonic band gaps were also obtained for TE polarization mode. The existence of complete photonic band gaps for TM polarization mode can explain the high capacity of the dorsal surface to reflect the incident radiation in the NIR range of the electromagnetic spectrum, thus helping in the thermoregulation of U. ornatus. Therefore, from the results obtained in this research, it is plausible to assume that the structural parameters of the photonic structure described on the skin surface of the U. ornatus have a significant contribution in the explanation of the origin of the blue-green color of its ventral patch and their thermoregulation properties.

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