Photonic Bandgap Analysis and Photonic Crystal Manipulation of Butterfly Wings

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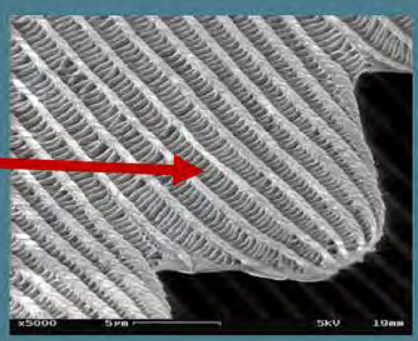
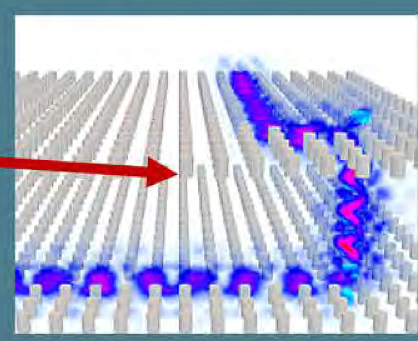
Introduction

Photonic crystals: nanostructures, typically made of materials of different dielectric constants, arranged in a periodic lattice. They can be synthesized to respond to certain wavelengths of light by either absorbing or reflecting. The designs of photonic crystals base on solutions of Maxwell's Equations. [1]

Found in Nature:
- butterflies
- chameleons
- peacock [2]
- sea mouse
- elytra beetles



Manmade Photonic Crystals:
- memory devices
- photonic-crystal fibers
- computer chips [3]
- optical computers
- solar cells

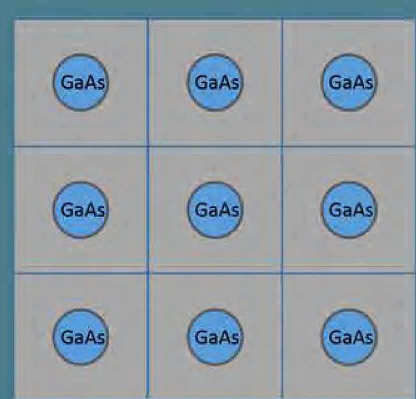


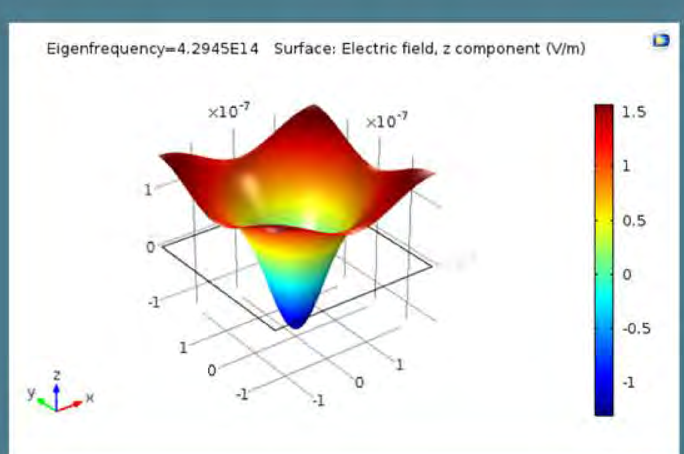
Goal of the Study: To theoretically study photonic crystals using COMSOL software and manipulate the biological photonic structure of a butterfly by comparing a butterfly wing's original reflection spectrum to spectrums collected after being tested with alcohol. Additionally, control of colloidal CdSe quantum dot emission rate by a butterfly wing will be demonstrated.

Theoretical Study

Photonic Bandgap: range of frequencies that prohibit light from propagating within the photonic crystal structure.
If configured in a certain way, photonic crystals can completely reflect light which will superimpose with light traveling into the structure, causing perfect constructive interference (Bragg Reflection).

Using COMSOL and a preloaded program entitled "Bandgap Analysis of a Photonic Crystal", a structure of periodic square cells of 375nm length with GaAs pillars of 70nm radii in the cells' centers was analyzed for photonic bandgap and electric field.

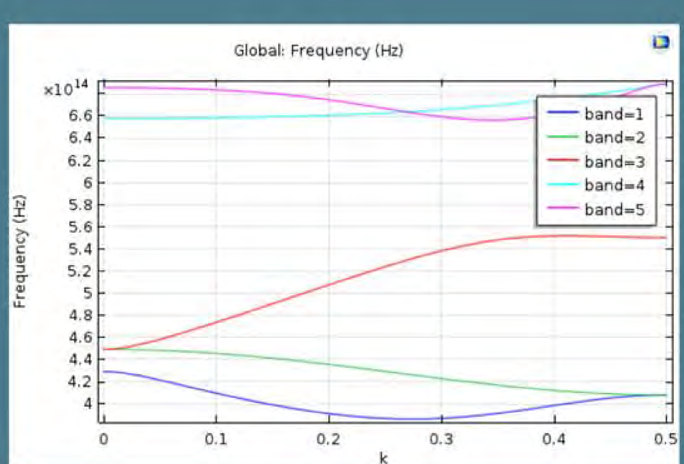




The COMSOL program is able to calculate and graph the electric field using the following photonic crystal equation:

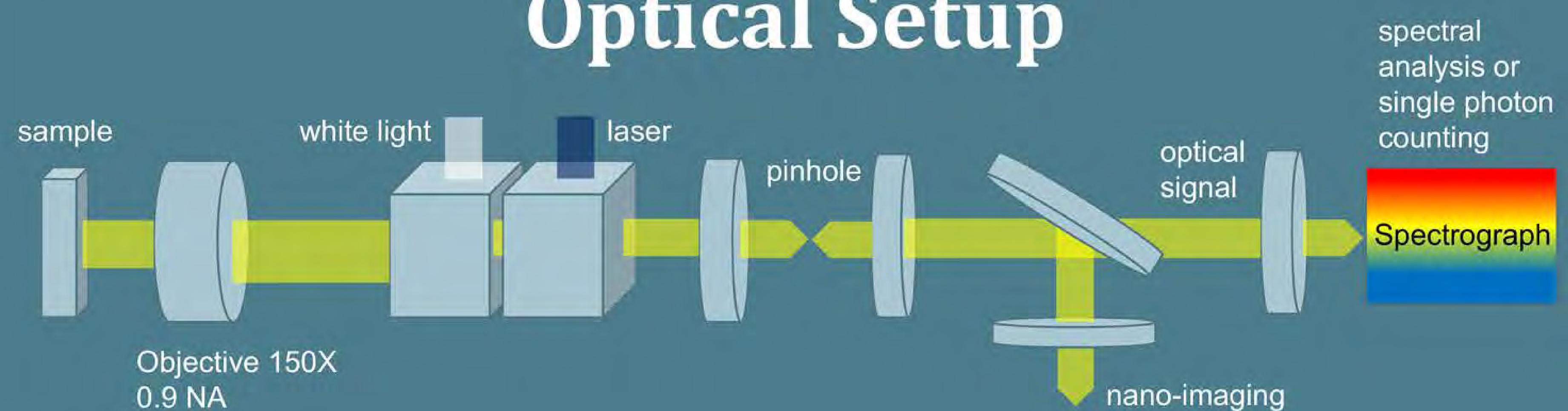
$$\nabla \times \nabla \times E = \left(\frac{\omega}{c}\right)^2 \mathcal{E} E$$

where ω is a selected frequency and $\mathcal{E}$ is the dielectric function. The curls indicate E is a transcendental function.



This graph shows frequency vs. wave vector. The photonic bandgap of this GaAs photonic crystal has a center of 6×10^{14} Hz. Around this frequency, light cannot travel through the crystal; it is completely reflected back.

Optical Setup



Spectrum Collection

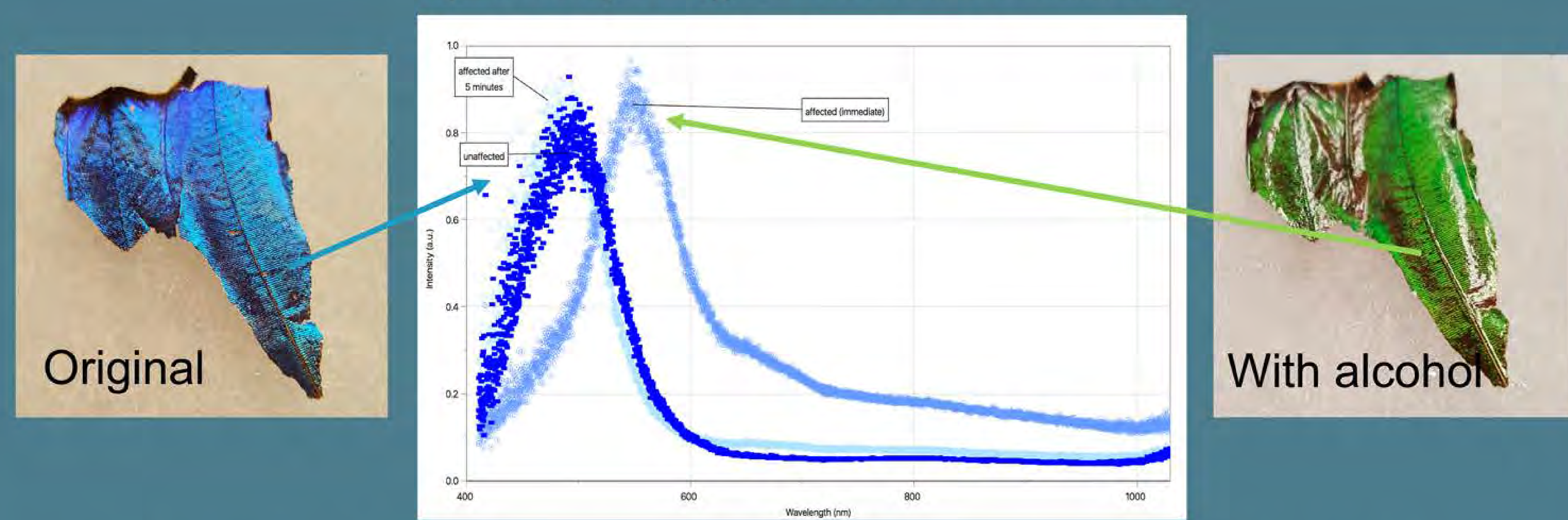
Intensity vs. wavelength spectra were collected for 12 butterfly wings, but wings 2 and 11 were used for photonic crystal manipulation. The following formula was used in calculating the final spectra:

$$R = \frac{I_{wing} - I_{ccd\_dark}}{I_{bkgrd} - I_{ccd\_dark}}$$

I_{ccd_dark} collected by closing camera shutter and collecting spectrum. This is to eliminate any excess dark charges due to the camera, essentially addressing experimental error.
I_{bkgrd} collected by opening shutter and collecting spectrum of pure white light. A neutral density filter was used to prevent camera overexposure.
I_{wing} was collected by placing wing in the slide holder and acquiring spectrum.

Butterfly wing 2 underwent an alcohol test: 15 µL of Isopropyl Alcohol was dropped onto butterfly wing 2 using a pipette.

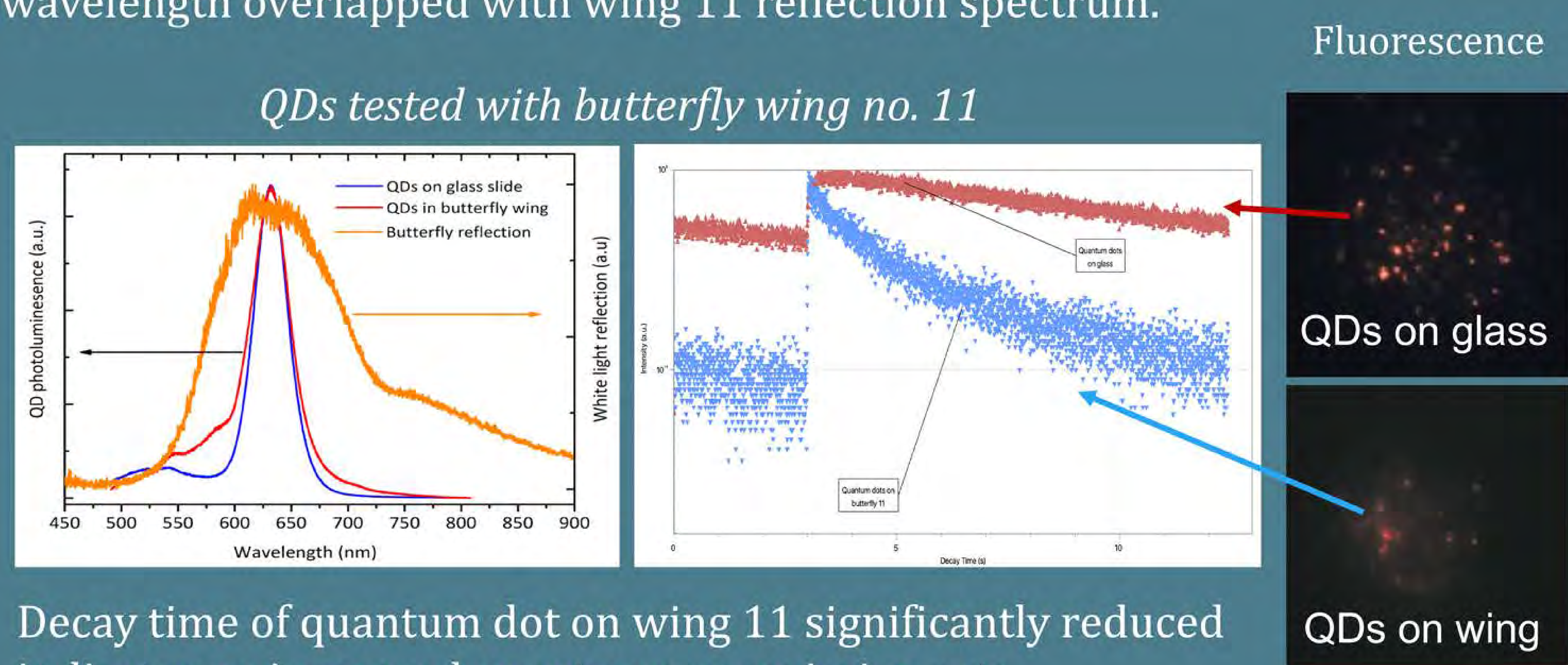
Spectra of Wing 2 Tested with Alcohol



A significant red shift of ~ 50 nm in the reflection spectrum of wing indicates that alcohol has filled into the tiny holes of the wing and altered its effective refractive index.

Next, 15 µL of a colloidal quantum dot solution was dropped onto wing 11. We checked that the quantum dot emission wavelength did not change when compared with similar quantum dots dispersed on a glass slide. This emission wavelength overlapped with wing 11 reflection spectrum.

QDs tested with butterfly wing no. 11



Decay time of quantum dot on wing 11 significantly reduced indicates an increased spontaneous emission rate.

Conclusion/Future Work

The alcohol made considerable changes to wing 2 while quantum dots on 11 indicated significant increase in the spontaneous emission rate. Wing 2 was able to have a red shift of ~50nm. Additionally, decay rate of the dots on the wing is greater than the decay rate of the dots themselves, signifying that the butterfly wing provides an optical mode for the quantum dots to emit light as they have the same frequency of light emitted for wing 11. Future work may lie in applying the two solutions for man-made photonic crystals as they could provide a way to manipulate the structure to change the wavelength or intensity of emitted light.

Acknowledgments

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References

[1] "Photonic Crystal Research." *Photonic Crystal Research*. N.p., n.d. Web. 07 July 2017. <http://ab-initio.mit.edu/photons/>. [2] *Image of a Peacock Wing Slant View*. Digital image. *Strange Stuff and Funky Things*. N.p., 7 Apr. 2014. Web. 10 July 2017. <http://ssaft.com/Blog/dotclear/?post/2014/04/07/Strange-and-Funky-Animal-Photographer-Linden-Gledhill>. [3] Chutinan, A., and Sanjeev John. Waveguides in Photonic Crystal Optical Chip. Digital image. N.p., 28 Oct. 2005. Web. 10 July 2017. <https://www.physics.utoronto.ca/~john/john/PhysRevB72-161316.pdf>.