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Development of Infrared sensor based on 3D photonic crystal

[1] Organization

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[2] Research progress

This joint research project pursues development of infrared (IR) sensor capable of high-sensitivity uncooled operation, all-optical remote readout, and integration into micro-scale systems. The sensing mechanism is based on 3D photonic crystal structure, whose resonant reflectance band is tuned to visible spectral range, and can be modified by infrared irradiation absorbed by the photonic crystal lattice thus allowing to perform infrared sensing by monitoring visible reflectivity of the sensor. Such sensitivity was discovered first in some naturally existing PhC structures, such as blue scales covering wings of *Morpho* butterflies, whose resonant reflectance band at visible wavelengths ($\lambda \approx$ 450nm) becomes modified in the presence of IR radiation. The principle of IR sensitivity is illustrated schematically in Fig. 1.
However, since naturally existing biological systems can not be easily integrated into practical devices, artificial structures exhibiting similar IR sensitivity must be prepared. However, fabrication of 3D PhC structures is still a challenging task, and in this project we aim at realizing artificial 3D photonic crystal structures capable of such "wavelength conversion" mechanism using a rapid prototyping technique called Direct Laser Write (DLW). The principle of DLW fabrication in photoresist is explained in Fig. 2.
The main research focus during this year was realization of the structural color phenomenon in the fabricated photonic crystals, because structural color is the main prerequisite to realization of the IR sensing mechanism described above. In this report we describe our efforts in theoretical and experimental studies of the structural color phenomenon.

[3] Results

(3-1) Research results

Practical realization of devices based on the above principles requires coordinated studies in several areas of research, such as nanophotonics, micro-/nano-fabrication, thermal imaging, and polymer science, represented by the participants of this project and their respective resereach groups. To promote collaboration, a mini workshop

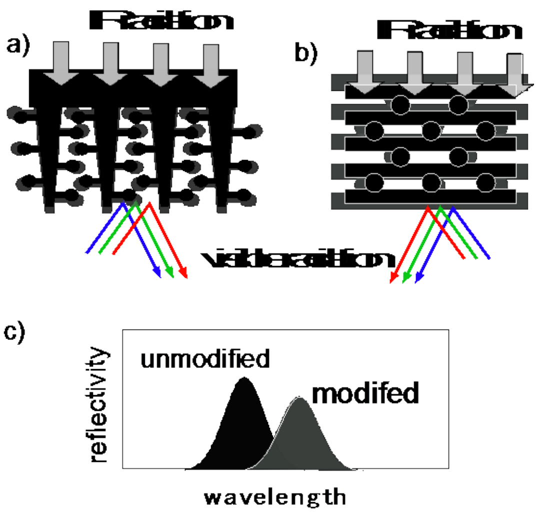

Fig. 1. IR sensitivity mechanism in natural and artificial in PhCs: (a) in natural *Morpho* butterfly wing, (b) in artificial 3D PhC structure, (c) modification of visible optical reflectivity of the PhC due to IR irradiation.

entitled "Applications of Infrared, Visible, and X-ray Beams for Fabrication and Imaging " was organized on February 1, 2016 at the Research Institute of Electronics, Shizuoka University. The workshop was attended by participating researchers, as well as interested guests and students.
Presentations and discussions during the workshop were centered on the following topics:

A. Fundamental studies of structural color phenomenon

The biomimetic new materials based on the Morpho butterfly, which produce highly reflective blue coloration. The brilliant blue color of the Morpho butterfly has been a physical mystery, which has a single color in too wide angular range (> ± 40° from the normal) despite the interference effect. The key to solve the Morpho-blue's mystery having both interference and a single color in wide angular range is a peculiar optical nanostructure on their scales. This principle is based on a skillful combination of two opposed characters, the ordered and disordered nanostructures.
After proven the principle of the mystery by emulating the specific nanostructures of their scales by extracting the optical essence, we found the reproduced Morpho-color to serve wide applications, because it can produce a conspicuous single color in wide angular range with high reflectance without any chemical pigment, which is also resistant to fading caused by chemical change for long time.
Thus, we have developed various technologies for practical applications of the specific color, such as mass-production processes, large-area fast fabrication, production of RGB colors, control (both in the reflective angles and in spectra) and simulation of their optical properties.
One of the remaining key issues is to produce the substrate-free color materials such as micro-powders, because all processes have long been accompanied with the thick substrate designed with a specific nanostructure, which has fatally limited the variety of applications. We developed a simple process to fabricate the color powders. This process will extend effectively the applications of the Morpho-color, which enables the coloring without any limit of shape.
Another remaining problem is how to complete the large-area fabrication process. The key point is how to

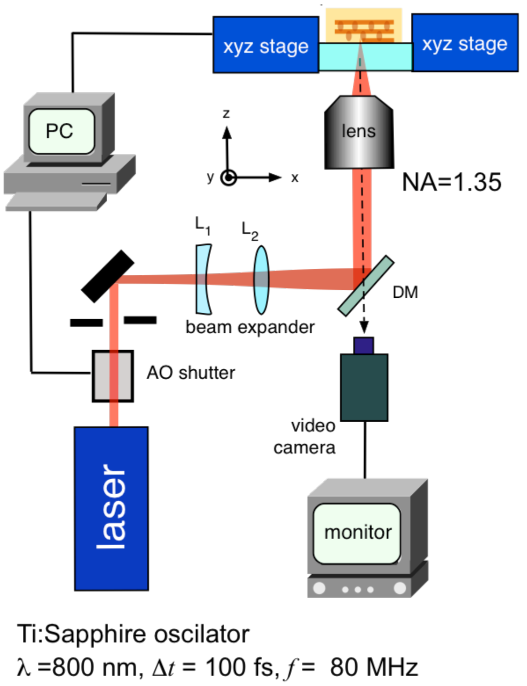

Fig. 2. Optical setup for DLW fabrication of PhC structures in photoresist.

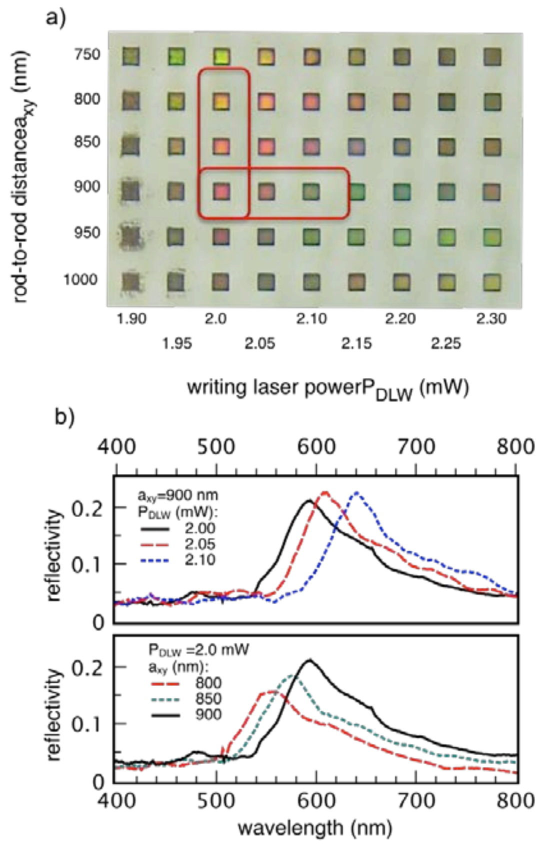

Fig. 3. Control of the structural color in 3D woodpile photonic crystals, (a) optical microscopy images of 3D woodpile PhC structures with different lattice periods fabricated at different exposure levels exhibit different colors in reflectance, (b) visible reflectivity spectra of these structures exhibit the corresponding spectral variations.

produce the nanopatterns in large area, easily and quickly. One of the candidate processes is the laser ablation, whereas some difficulties have been found in reproducibility. We discussed about how to solve this problem using our own possible facilities by limited man-powers and time. Our collaboration will be a potential good solution for this problem.

The last issue is how to realize the FDTD simulations in 3D by use of standard personal comupters (PC). Certainly, we have succeeded in revealing the specific optical role of the nano-disorder in the Morpho-nanopatterns, whereas we need still more realistic 3D simulations, which requires unrealistic long time for our present PCs. We discussed about the potential countermeasures to overcome this difficulties.

In future, a variety of applications are relevant to the structural color: cosmetics, decorations, textures, paints, security (such as hologram), etc. Especially, in case of the Morpho-type color, it realizes both of wide reflective angle and high reflectivity that are usually not compatible with each other. These characters are fit well to the use of posters or displays.

B. Practical realization of PhC structures exhibiting structural color by DLW technique in photoresist.

3D architecture woodpile photonic crystals were fabricated by femtosecond DLW lithography in photoresist, and their optical properties were characterised by micro-reflectance spectroscopy at visible and near-infrared wavelengths. The results are summarized in Fig. 3. The fabricated structures were found to exhibit resonant optical reflectance at wavelengths corresponding to high-frequency photonic bands, where opening of photonic stop gaps is not expected. The visible reflectance leads to structural color that can be controlled experimentally via photonic crystal lattice period and dielectric filling ratio. According to theoretical analysis and numerical simulations of sample reflectance spectra and photonic band diagrams, resonant reflectance and visible coloration of the samples can be associated with coupling losses which occur when plane waves incident from outside become converted to strongly dispersive, low group velocity Bloch modes of the photonic crystal. This phenomenonis useful from the practical viewpoint, since it occurs at high frequency/short wavelength, and allows realisation of stuctural color in samples with relatively large lattice periods $a \approx 1$ μm. Consequently, requirement for high resolution of 3D fabrication becomes somewhat relaxed, and fabrication time becomes shortened. Discrete photonic crystals exhibiting structural color may be useful in photonic crystal-based environmental and imaging sensors.

(3-2) Ripple effects and further developments

Exchange of scientific expertise between the participants was very helpful for coordination of experimental and theoretical work towards the goal of this project. Also, it has contributed to strengthening of domestic and international collaboration at Research Institute of Electronics.

It must be also stressed that joint work of all participants during the mini-workshop and informal discussions have broadened the scope of existing domestic and international research collaborations at RIE, as well as opened new venues for collaboration in the future.

[4] Achievements

Scientific articles:

(1) M. Malinauskas,A. Zukauskas,Y. Hasegawa,V. Hayasaki,V. Mizeikis, R. Buividas, S. Juodkazis, "Ultrafast laser processing of materials: from science to industry", Light: Science & Applications , accepted (2016).

Travelling report

Name:	Prof. Saulius Juodkazis
Affiliation:	Centre of Microphotonics, Swinburne University of Technology, Melbourne, Australia
Period of time:	2016.01.31-02.04
Destination:	Shizuoka University, Japan
Purpose:	To carry out a joint research, plan the future collaboration, participate at the mini-workshop and report previously obtained results.
Name of receiver:	Prof. Vygantas Mizeikis