Form 1

2017 Report Form for Collaboration with Research Center for Biomedical Engineering

Year/month/date	2018/03/14
Number	2042

To Chairman, Board of Directors, Research Center for Biomedical Engineering

Applicant
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Report Form for Collaboration Research

Research Theme	Development of infrared sensor based on 3D photonic crystal
Research Area	1. Biomaterials 2. Bioengineering 3. Functional molecules ④. Chemistry/Electrical Engineering/Mechanical Engineering/Materials Science
Research Period	From: 1/6/2017 To: 31/3/2018

Applicant Organization

Name	Department	Title	Role
Junko Morikawa	Tokyo Institute of Technology, School of Materials and Chemical Technology, Department of Materials Science and Engineering	Professor	Leader
Saulius Juodkazis	Centre of Microphotonics, Swinburne University of Technology, Melbourne, Australia	Professor	Participant
Kestutis Staliunas	Universitat Politecnica de Catalunya (UPC), Fisica i Enginyeria Nuclear, Barcelona, Spain	Professor	Participant
Mangirdas Malinauskas	Laser Research Center, Vilnius University, Lithuania	Researcher	Participant
Kamen Kanev	Research Institute of Electronics, Shizuoka University	Professor	Participant
Arturas Vailionis	Stanford Nano Shared Facilities (SNSF), Geballe Laboratory for Advanced Materials	Staff scientist	Participant

	(GLAM)		
Vygantas Mizeikis	Research Institute of Electronics, Shizuoka University	Professor	Participant, coordinator

Collaboration Partners in the Research Center	

Research Results (Including Purpose, Results, Figures, etc.)

The purpose of this project is development of micro-scale thermal sensors capable of uncooled operation at room temperature offers considerable advantages in cost and operational convenience, higher reliability, reduced power consumption, smaller size and weight, as well as multispectral response capability. Traditional IR detectors exploit either *electronic response* of narrow-gap semiconductors, or *bolometric response* of IR absorbing materials. However, fabrication of semiconductor-based IR detectors often requires advanced semiconductor growth and micro-/nano-fabrication techniques, while their high -sensitivity operation requires external cooling. Traditional bolometric detectors have large size and considerable thermal mass, which limits their response speed. Rapid development of micro-total analysis systems (μTAS), Micro-Opto-Electro-Mechanical Systems (MOEMS) and microfluidic systems demands super-compact, high-sensitivity uncooled IR detectors that can be easily integrated into these systems. In addition to high performance, very low cost and expendability is required for IR detectors. This project pursues practical realization of a novel IR detector concept based on the optical response of 3D nanostructured dielectrics (Nature Photonics 6, 195 (2012)). In particular, structural color of natural photonic crystal (PhC) structures existing in blue scales of *Morpho* butterfly wing, visible as bright blue coloration and the reflection peak centered near the wavelength $\lambda \approx 450$nm, can be modified in the presence of IR radiation. The reflectivity modification mechanism is associated with thermal expansion of the periodic lattice or refractive index modification upon heating due to absorption of IR radiation by the PhC (Nature Photonics 6, 195 (2012)). The proposed research is aimed at realization of micro-scale infra-red (IR) sensing devices based on the above principle. Replication of this behavior in artificially fabricated 3D PhCs is the main goal of this research. It is a major challenge, because it requires fabrication of 3D periodic structures with lattice periods much shorter than 1μm. This challenge is being tackled by using an advanced 3D laser micro-/nano-fabrication technique called Direct Laser Writing (DLW) for the fabrication of artificial photonic crystal structures exhibiting structural color effect. At the present stage of studies, the structural color was mainly pursued, while modification of the structural color by IR radiation, and clarification of its mechanism (presumably, thermal dilation of the photonic crystal lattice, will be addressed during the subsequent stages of research.

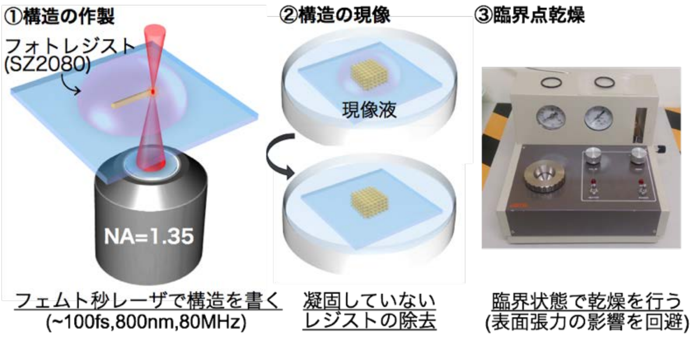

Fig. 1 Experimental procedure for fabrication of 3D PhC structures exhibiting structural color.

The main results achieved during this joint-research effort as well as some experimental details are summarized below. Figure 1 outlines the experimental procedure for the fabrication of photonic crystal structures in photoresist ZS2080, which involves (left to right) exposure of photoresist by spatial scan of a tightly focused femtosecond laser beam which draws a 3D woodpile structure with high spatial resolution, development of the exposed 3D pattern in a liquid development, and drying the sample in a super-critical CO_2 chamber. Figure 2 shows detailed schematic image of the 3D woodpile architecture realized in this work. To tune the structural color region into a visible spectral range, lattice period a_{xy} was decreased to less than 1μm, while diameter of individual photoresist rods composing the structure was close to 200nm.

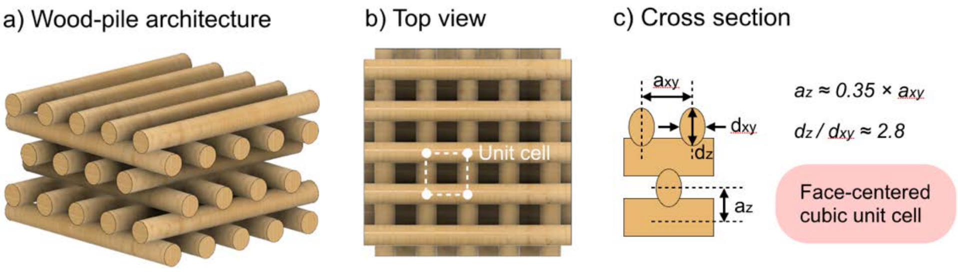

Fig. 2 Schematic explanation of a 3Dwoodpile PhC architecture, (a) perspective view, (b,c) top and side views, and explanation of parameters.

In order to obtain pure and spatially uniform structural color it was necessary to avoid non-uniform deformation of the PhC structures which mainly develop in samples rigidly attached to a glass substrate, since top part of the samples is allowed to shrink, whereas bottom remains fixed at the original size. Shrinkage in photoresist can not be eliminated, however, by fabricating encage structures floating above the substrate it was possible to achieve uniform shrinkage as explained schematically and by Scanning Electron Microscopy (SEM) pictures in Fig. 3.

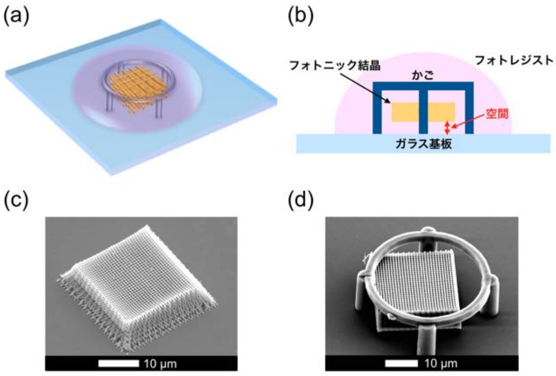

Fig. 3 The advantage of encaged PhC structures, (a,b) schematic explanation, (c) SEM image illustrating non-uniform shrinkage of a PhC sample directly attached to the glass substrate, (d) uniform shrinkage of an encaged PhC sample which is not attached to the substrate .

Figure 4 shows optical microscopy image of a single substrate containing multiple encaged PhC structures with different structural parameters (lattice period a_{xy} was set directly during the sample design, while diameter of individual photoresist rods was controlled indirectly by changing average writing laser power during the DLW). As can be seen from the Figure, most structures exhibit structural color. Moreover, systematic variation of the PhC lattice parameters leads to color change in the entire visible spectral range from blue to deep-red.

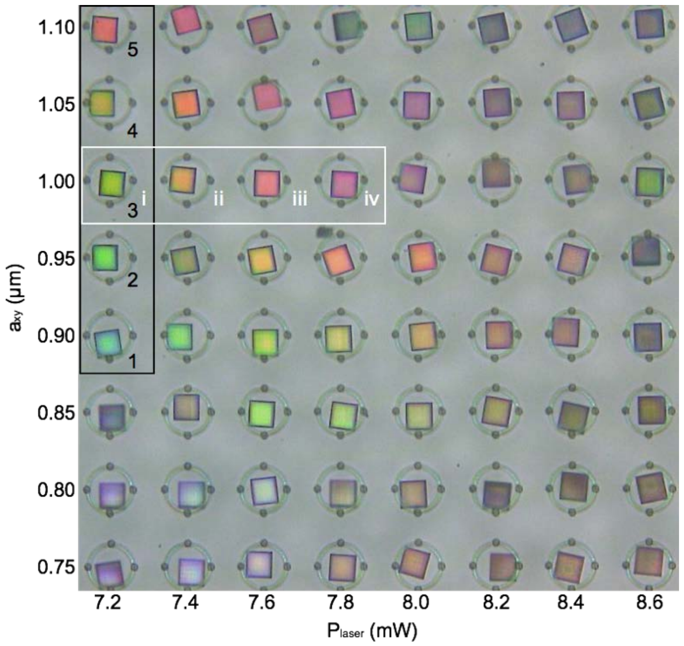

Fig. 4 Optical microscopy images of the fabricated PhC samples exhibiting structural color, and control of the color via PhC lattice parameters.

The apparent color correlates well with experimental reflectance spectra of the structures. This is illustrated by the spectra of structures 1 to 5 (Fig. 4) shown in Fig. 5. Increase in the lattice period leads to red-shift of the main reflectance peak in a broad spectral range from 500 to 600 nm. Such red shift is consistent with so-called Maxwell's scaling behavior characteristic to dielectric photonic crystals. Similar shift can be also observed when the writing laser power increases, leading to ticker dielectric rods composing the woodpile, and larger dielectric filling fraction, as is seen in samples i to iv in Fig. 4.

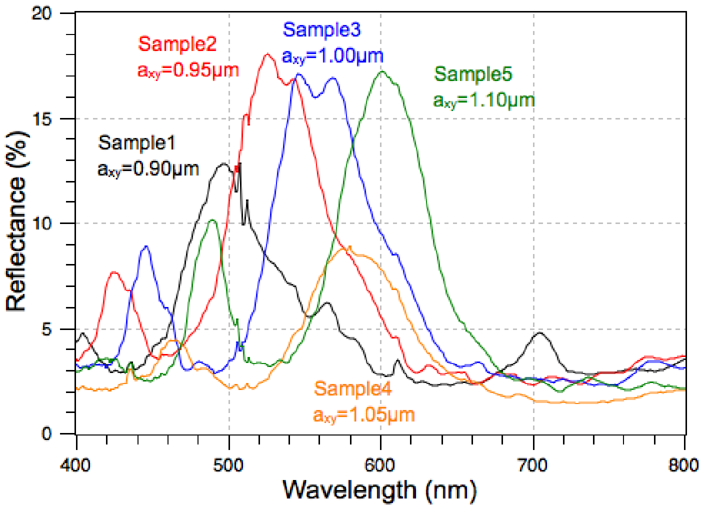

Fig. 5 Experimental reflectivity spectra of several fabricated PhC samples from Fig. 4.

Altogether this data illustrates that 3D PhC structures exhibiting structural color were successfully realized, and color of the samples is controllable via PhC lattice parameters. Hence, the fabricated samples can be used as artificial equivalents of *Morpho* butterfly wing scales, and their sensitivity to the presence of IR irradiation as well as other environmental factors can be investigated. This will be done during continuation of these studies.

List of Publications Related to the Collaboration Research

[1]. Faniayeu, S.Khakhomov, I.Semchenko, V. Mizeikis, Highly transparent twist polarizer metasurface, Appl. Phys. Lett. 111, 111108 (2017).

[2]. Faniayeu, V. Mizeikis, Vertical split-ring resonator perfect absorber metamaterial for IR frequencies realized via femtosecond direct laser writing, Appl. Phys. Expr. 10 (2017).

List of Presentations (Conference, Meeting, etc)

[1]. V. Mizeikis, Direct laser writing of electromagnetic metasurfaces for infra-red frequency range (Invited), SPIE Photonics West 2018, San Francisco CA, Jan. 27-Feb. 1 (2018)

[2]. V. Mizeikis, Z. Hayran, H. Kurt, D. gailevicius, M. Malinauskas, S. Juodkazias, K. Staliunas, Fabrication of optical field concentrators based on 3D chirped photonic crystals by direct laser writing technique, Meta 2017, Incheon, Korea, July 25-28 (2017).

List of Awards

None

Research plan for the next year (from April 1, 2018 to March 31, 2019), if the collaboration research is continued. Prior consent from the collaboration partner in the Research Center is necessary.

The main goals of research proposed for the next year are outlined below:

I. Obtaining experimental evidence that structural color of the fabricated photonic crystals is indeed sensitive to IR radiation. This will be done using experimental setup shown in Fig. 6 (see discussion below). To ensure successful outcome of these studies, several preparatory steps will be needed:

1) Thermal response of natural *Morpho* butterfly wings will be investigated theoretically and experimentally in order to obtain benchmarks for the performance of our samples;
2) 3D woodpile PhCs will be designed theoretically using Finite-Difference Time-Domain (FDTD) simulation aiming for the brightest and most pure structural color (as required for monitoring).
3) Suitability of SZ2080 photoresist as well as similar other photoresist will be re-examoned, taking into account the need for strong absorption at IR wavelengths, low absorption at visible wavelengths, and significant values of coefficient of thermal expansion (CTE).

After these steps, encaged woodpile PhC samples will be fabricated for experimental tests in the presence of IR radiation. Samples with relatively large footprint size ≈ (50x50)μm^2 and bright structural color will be prepared and investigated as shown schematically in Fig. 6. For this purpose experimental setup shown in the Fig 6. which allows monitoring of the structural color (intensity and spectrum) in the presence or absence of IR radiation derived from a broadband (globar) source will be assembled. If necessary, numerical modeling, fabrication, and experimental characterization will be iterated several times in order to obtain artificial PhC structures exhibiting IR sensitivity levels similar to those exhibited by the natural *Morpho* butterfly wing scales.

All participants will be involved in the planning and realization of the proposed experiments as well as interpretation of the obtained data. To promote collaboration between the teams participating in these activities, joint research seminar(s) will be held.

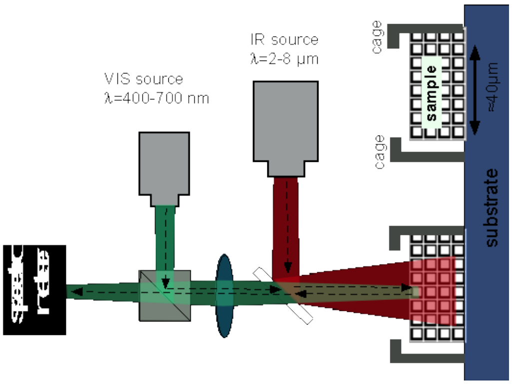

Fig. 6 Experimental characterization of thermal sensitivity of PhC structures, and isolation of the PhC structure from substrate.

II. Finding other possible application areas for 3D PhC structures fabricated using the DLW approach. In this respect, applications of artificial structural color materials realized by other techniques will be analyzed aiming to determine which of them are viable using DLW based approach. The requirements for wide range of applications are summarized in Fig. 7.

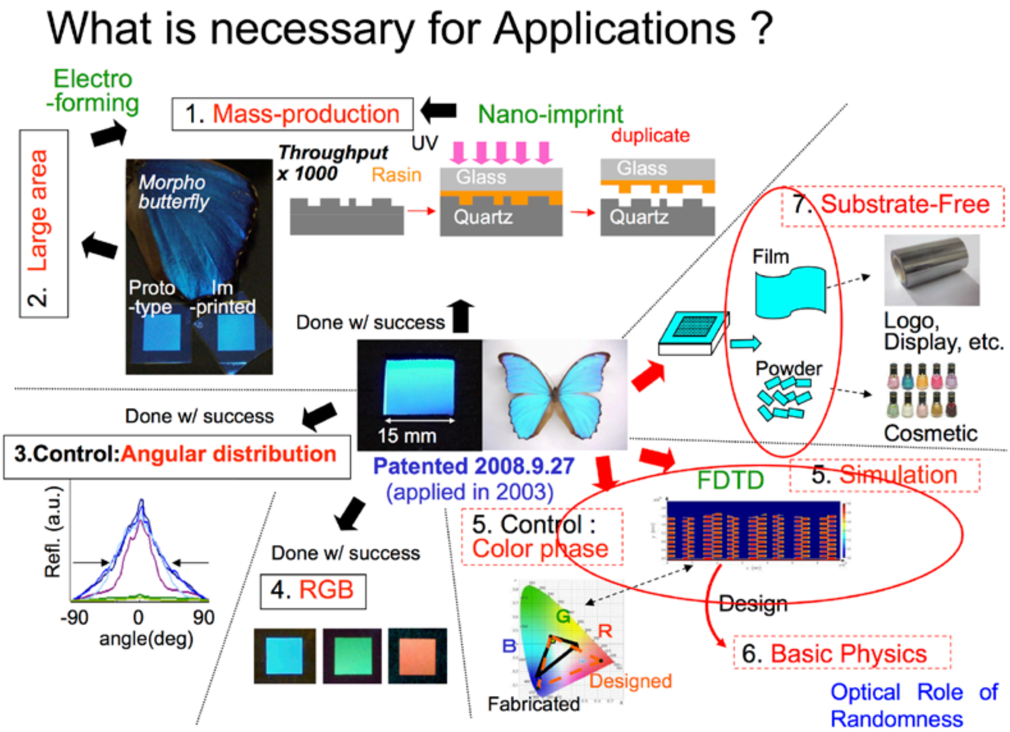

Fig. 7 Summary of requirements and application areas for structural color materials.