Form 1

2019 Report Form for Collaboration with Research Center for Biomedical Engineering

Year/month/date	
Number	2038

date: 16/03/2020

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: 1/6/2019 To: 31/3/2020

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 (GLAM)	Staff scientist	Participant

	(GLAM)		
Toshiaki Kondo	Department of Mechanical systems Engineering, Aichi University of Technology	Associate Professor	Participant
Vygantas Mizeikis	Research Institute of Electronics, Shizuoka University	Professor	Participant, coordinator

Collaboration Partners in the Research Center	Coordinator for the project: Vygantas Mizeikis, Professor Research Institute of Electronics, Shizuoka University, Japan All partners have already been collaborating on various joint research projects and produced joined publications. Contents of this proposal has been discussed among the partners.

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

The purpose of this project is development of micro-scale uncooled thermal sensors offering advantages over conventional detectors in terms of sensitivity, compactness, and reduced power consumption. This goal is pursued by realizing photonic structures whose working principles are radically different from those of traditional IR detectors. Traditional detection schemes exploit *electronic response* of narrow-gap semiconductors, or *bolometric response* of IR absorbers. These approaches rely on advanced semiconductor growth and micro-/nano-fabrication, detectors require cooling for high sensitivity, and their response speed is limited due to their considerable thermal mass. Development of micro-total analysis systems (μTAS), Micro-Opto-Electro-Mechanical Systems (MOEMS) and microfluidic systems require compact, high-sensitivity uncooled IR detectors that can be easily integrated into these systems during fabrication process. One of the new photonic strategies for implementation of improved IR detectors was described recently (Nature Photonics 6, 195 (2012)) and exploits thermal expansion of 3D photonic crystal (PhC) lattice under IR irradiation. Its proof-of-the principle demonstration for all-optical remote IR sensing was demonstrated using natural 3D PhC structure of blue scales of *Morpho* butterfly wings, but more realistic applications require artificial PhC structures composed of organic material similar to the natural protein (chitin) composing the wing scales, and exhibiting the structural color phenomenon. Fabrication and characterization of artificial 3D PhCs exhibiting similar IR sensitivity is the main goal of this research project. Reaching this goal is a big challenge, since it requires 3D structuring biocompatible organic materials with spatial resolution better than 1 μm. At the present time very few nanostructuring techniques can satisfy this requirement. We have used femtosecond laser nanolithography known as Direct Laser Writing (DLW) technique for the fabrication of 3D PhC structures. Previously we have pursued fabrication of 3D PhC structures exhibiting e structural color phenomenon, and control of the structural color via PhC lattice parameters and fabrication conditions. Here, we use post-fabrication thermal treatment (annealing) of the samples in order to further reduce their lattice period and tune their structural color by exploiting the lattice shrinkage.

The main results achieved during this research effort are summarized below. Figure 1 outlines experimental procedure for the fabrication of 3D PhC structures in photoresist ZS2080. Photoresist is exposed by a tightly focused femtosecond laser beam, which is translated to draw a 3D woodpile structure. Chemical development dissolves unexposed photoresist leaving the exposed 3D woodpile PhC structure. Using careful control of the DLW exposure, diameter of woodpile rods of less than 200nm can be achieved. The figure also illustrates how in order to allow the fabricated structures to shrink uniformly without distortions, encaged PhC samples not attached to the supporting glass substrate were fabricated.

Figure 2 describes in detail shrinkage of 3D woodpile architecture PhC due to thermal treatment. Since thermal treatment destroys organic component of photoresist SZ2080, this leads to volume and size reduction of photoresist lines. According to the data in the Figure, thermal treatment at 400°C allows one to achieve lattice shrinkage by up to 60%.

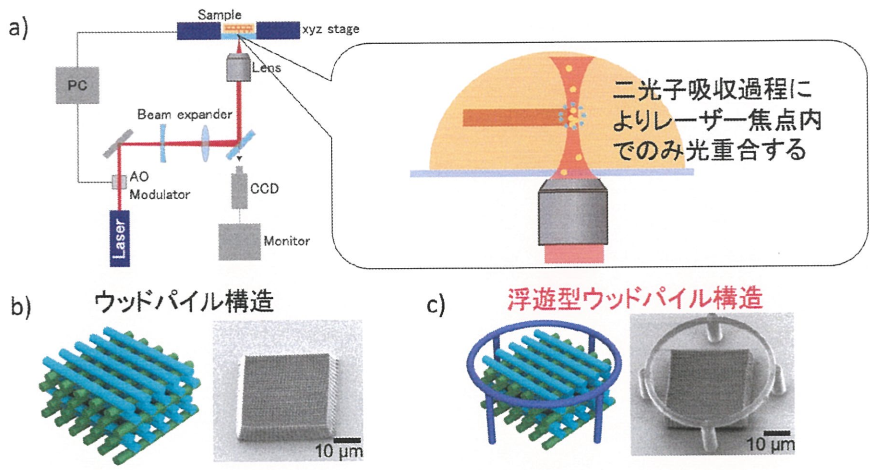
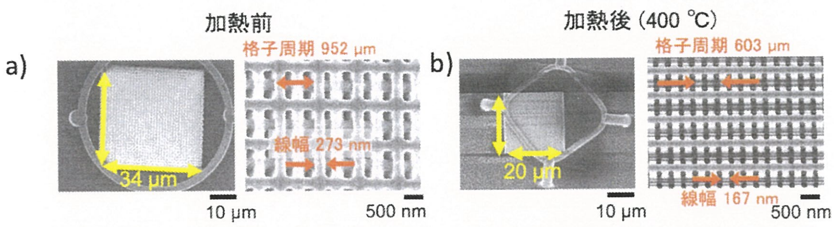


Fig. 1 Schematic explanation of fabrication procedure of 3D PhC structures using DLW technique (a), 3D woodpile photonic crystal sample fabricated attached to the glass substrate (b), encaged 3D woodpile sample that is not attached to the substrate.



c)

	作製時	200 ℃	300 ℃	400 ℃	
線幅 [nm]	273	257	193	167	38.9%減少
格子周期 [nm]	952	900	717	603	36.7%減少
構造高さ [μm]	13.0	11.3	6.2	4.5	65.4%減少

加熱温度の上昇につれて収縮量が増加

Fig. 2 Woodpile PhC sample before (a) and after (b) annealing at 400°C illustrates shrinkage of the structure due to pyrolysis of organic component of the photoresist used, quantitative evaluation of shrinkage is given in the table (c).

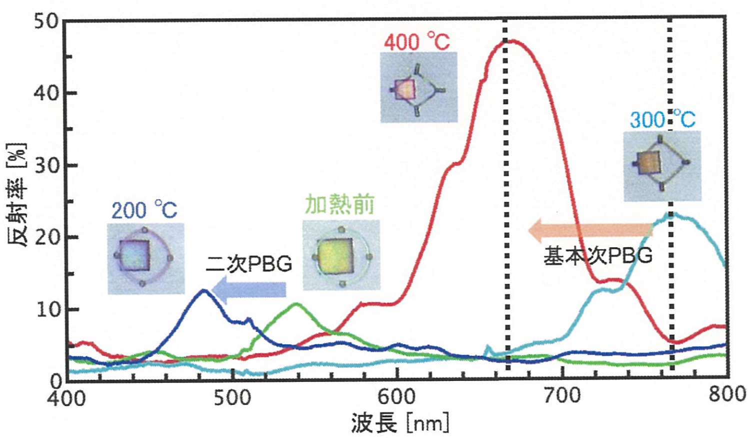


Fig. 3 Reflectivity spectra of several samples before and after thermal treatment, illustrating strong blue-shifts of the photonic stop gap reflectance peaks due to structure shrinkage. Optical images of the samples shown as insets to the plot illustrate size reduction sue to shrinkage and change of the apparent structural color.

Figure 3 summarizes optical properties of a 3D woodpile architecture PhC samples before and after thermal treatment. When the lattice period decreases due to photoresist shrinkage, photonic stop gap (PSG) wavelength is expected to exhibit a blue-shift due to the so-called Maxwell's scaling behavior. This expectation os indeed confirmed by the experimental data in Fig. 3. Interestingly, amplitude of the reflectance peak has increased after the last annealing step (400^0C). This behavior is attributed to increased refractive index of the photoresist., which has been now depleted of the organic component and consists mostly of denser inorganic component possessing a higher refractive index.

The above results illustrate that post-DLW thermal annealing of the PhC samples provides a versatile method to control their optical properties, including structural color. These findings are important from the practical standoint, since they enable realization structural color in PhCs without the need to downscale their lattice period during DLW fabrication of the initial samples. In the future we plan to focus stronger on this method to control structural color and optical as well as thermal properties of microstructured polymers.

List of Publications Related to the Collaboration Research
[1]. A. Butkutė, L. Čekanavičius, G. Rimšelis, D. Gailevičius, V. Mizeikis, A. Melninkaitis, T. Baldacchini, L. Jonušauskas, M. Malinauskas, Optical damage thresholds of microstructures made by laser three-dimensional nanolithography, Opt. Lett. 45, 13-16 (2020).
List of Presentations (Conference, Meeting, etc)
[1]. D. Paipulas, S. Rekšytė, T. Tičkunas, M. Malinauskas, V. Mizeikis, Reversible deformations in laser-written polymeric microstructures: New platform for sensing and micro-actuation applications (Invited), SPIE Photonics West 2020, San Francisco CA, February 1 – 6 (2020). [2]. V. Mizeikis, Z. Hayran, H. Kurt, M. Turduev, D. Gailevicius, M. Malinauskas, S. Juodkazis, K. Staliunas, Direct laser writing of optical field concentrators based on chirped three-dimensional photonic crystals, SPIE Photonics West 2020, San Francisco CA, February 1 – 6 (2020).
List of Awards
None

Registration of research-theme continuation for next year Prior consent from the collaboration partner in the Research Center is necessary	Yes	No
Research plan for the next year (from April 1, 2020 to March 31, 2021), if the collaboration research is continued.		

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

1) Theoretical and experimental studies of structural color modified by thermal treatment and lattice shrinkage. These studies will be conducted using FDTD numerical simulations and optical characterization of real samples fabricated by DLW technique. We will try to determine parameters of the PhC structures for which strongest and most environmentally-sensitive structural color can be obtained, and modified by thermal annealing. We expect realization of 3D woodpile architecture PhC strictures having lattice period less than 500 nm using this approach.
2) Studies of thermal properties of photoresists SZ2080, SU-8 and others will be continued in order to modify and maximize values of coefficient of thermal expansion (CTE) obtainable in these materials, which is an important requirement for PhC-based IR sensors.
3) Experimental studies of thermally properties of the fabricated PhC structures will be continued, with a special focus on the possibility to realize anisotropic flow of thermal energy in these samples.

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.