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2008

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 main research focus during this year was search for the suitable biocompatible photoresist. Previously, hybrid organic-inorganic resist known as SZ2080 was used to demonstrate realization of structural color effect; applicability of this resist for IR sensing is now being tested. At the same time, we have tried to expand the range of initial materials by investigating a silk-based photoresist. This system is entirely organic and perfectly biocompatible. Recent studies have demonstrated possibilities to micro-structure this type of photoresist using two-photon exposure and DLW technique, However, relatively little is known about its optical, and thermal properties of silk-based photoresists. These properties were at the center of discussions that took place during the project workshop which was held on December 8 and 9, 2016 at the Research Institute of Electronics, Shizuoka

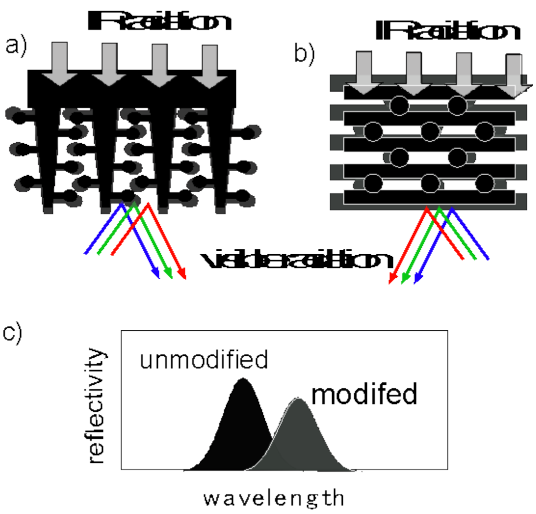

Fig. 1. IR sensitivity mechanism in natural and artificial in PhCs: (a) in natural *Morpho* butterfly wing, (b) in artificial 3D PhC structure, (c) modification of visible optical reflectivity of the PhC due to IR irradiation.

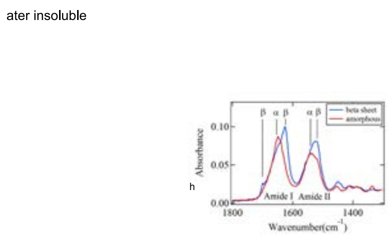

Fig. 2. Summary of physical and chemical properties and processes enabling optical fabrication of silk-based photoresist.

University. The workshop was attended by the participating researchers, as well as interested guests and students.

[3] Results

(3-1) Research results

Presentations and discussions during the workshop were centered on the following topics:

A. Fundamental studies of silk fabrication by DLW.

Practical realization of DLW in silk stems from its high solubility in water after irradiation by femtosecond laser pulses. Summary of main physical and chemical properties of silk, their modification via laser irradiation, and comparison between optical absorption spectra in laser-irradiated and pristine areas is given in Fig. 2. Participants of the workshop focused their attention on these properties and their role for application of silk as photoresist in DLW fabrication. Earlier, application of this material for electron-beam lithography (EBL) has attracted much attention, whereas optical lithography and DLW in silk are relatively new ideas.
Figure 3 illustrates some of the newly obtained results on laser fabrication of silk. Since silk for the experiments is available in the form of 5-10 μm thick fibers, the latter were embedded into an epoxy matrix (EPIKOTE 828) for mechanical support during laser fabrication. DLW mechanical setup allows sample positioning with high spatial accuracy, which makes it easy to locate individual fibers and select positions for laser exposure. Femtosecond laser fabrication was performed using laser pulses of 1064 nm wavelength, about 400 fs duration, and 80-420 nJ

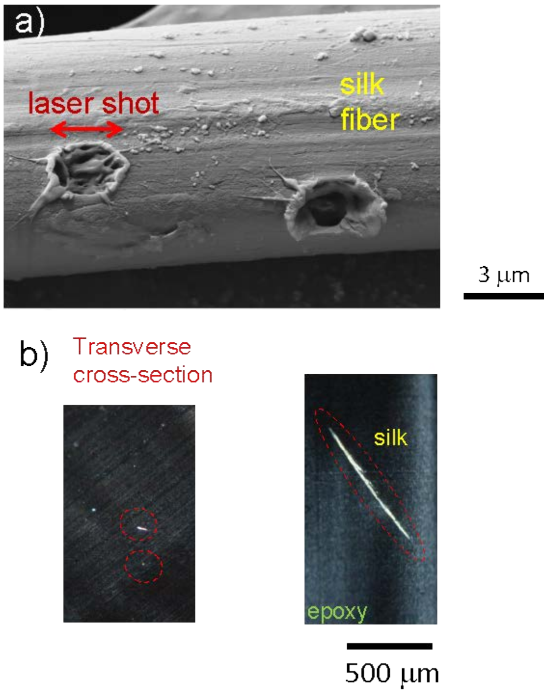

Fig. 3. Femtosecond laser fabrication of silk fibers embedded in a polymer matrix (a), transverse (left) and longitudinal (right) cross-section of the fiber showing the extent of laser fabricated areas.

pulse energy. The pulses were focused to a spot of about 1μm diameter on the surface of the fiber. According to SEM image in Fig.3(a), laser exposure may lead to surface ablation. However, further experiments have demonstrated that in addition to surface, deeper regions of material become photomodified, and become soluble in water. Thus, silk acts as a positive photoresist that can be developed in water. Modification of silk in these deeper regions are illustrated in Fig. 3(b), which shows images of sliced vertical and longitudinal cross-sections of the silk fiber. This simple result illustrates the possibility of 3D patterning in photoresist using DLW method.

B. Thermal properties of silk-based photoresist

Photoresist intended to be applied for fabrication of PhC-based IR sensors must possess substantial optical absorption bands at infra-red frequencies. Till now, relatively little is known about IR absorption spectra of silk-based photoresist. To gain some initial knowlwdge about these properties, IR absorption spectra of laser fabricated and pristine regions were measured using micro Fourier-Transform Infra Red (FTIR) spectroscopy. Some of the obtained data is shown in Fig. 4. As can be seen,

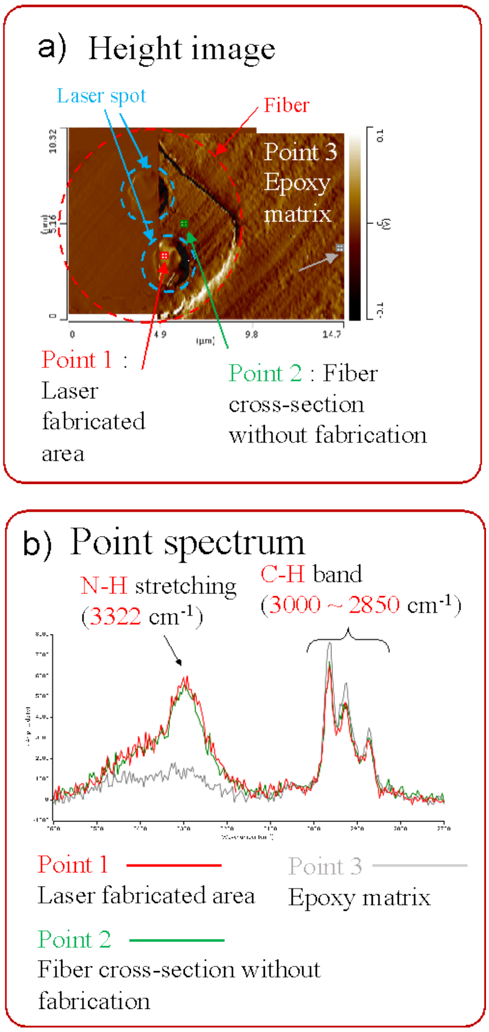

Fig. 4. Selection of laser-irradiated and pristine areas on cross-section of silk fiber (a), infra-red absorption spectra measured in these areas, and a similar spectrum measured in the epoxy matrix (b).

both laser-fabricated and pristine silk exhibit significant infra-red absorption bands (some of these bands are absent in the epoxy matrix into which silk fibers were embedded). Absorption bands in fabricated and pristine areas exhibit small differences that are attributed to effects of laser fabrication; detailed studies of these effects will be reported in the future.

(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. Joint work and discussions between the participants 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) J. Morikawa, M. Ryu, K. Maximova, A. Balčytis, G. Seniutinas, L. Fan, V. Mizeikis, J. Li, X. Wang, M. Zamengo, X. Wang, and S. Juodkazis, " Silk fibroin as a water-soluble bio-resist and its thermal properties", RSC Adv. 6, 11863-11869 (2016).

(2) S. Rekštytė, T. Jonavičius, D. Gailevičius, M. Malinauskas, V. Mizeikis, E. G. Gamaly, S. Juodkazis, "Nanoscale Precision of 3D Polymerization via Polarization Control", Adv. Optical Mater. 4, 1209–1214 (2016).

Travelling report

Name:	Prof. Saulius Juodkazis
Affiliation:	Centre of Microphotonics, Swinburne University of Technology, Melbourne, Australia
Period of time:	2016.12.7-10
Destination:	Shizuoka University, Japan
Purpose:	To carry out a joint research, plan the future collaboration, participate in the project workshop and report previously obtained results.
Name of receiver:	Prof. Vygantas Mizeikis

Name:	Mr. Meguya Ryu
Affiliation:	Dept. of Organic and Polymeric Materials, Tokyo Institute of Technology
Period of time:	2016.12.8-9
Destination:	Shizuoka University, Japan
Purpose:	To carry out a joint research, plan the future collaboration, participate in the project workshop and participate in preliminary experiments.
Name of receiver:	Prof. Vygantas Mizeikis