Form 1

2019 Report Form for Collaboration with Research Center for Biomedical Engineering

Year/month/date	
Number	**2074**

date: 16/03/2020

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

Applicant

Affiliation: Stanford Nano Shared Facilities,
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Report Form for Collaboration Research

Research Theme	Imaging of laser-induced microexplosions in dielectrics using time-resolved X-ray diffraction technique
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
Arturas Vailionis	Stanford Nano Shared Facilities (SNSF), Geballe Laboratory for Advanced Materials (GLAM)	Staff scientist	Participant
Akira Saito	Division of Precision Sci. & Technology and Applied Physics Graduate School of Engineering, OSAKA University	Associate Professor	Participant
Saulius Juodkazis	Centre of Microphotonics, Swinburne University of Technology, Melbourne, Australia	Professor	Participant

Toshiaki Kondo	Department of Mechanical systems Engineering, Aichi University of Technology	Associate Professor	Participant
Atsushi Ono	Research Institute of Electronics, Shizuoka University,	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 is to use time-resolved monitoring of formation of high-pressure high-temperature (HPHT) phases of materials during their excitation by powerful ultrashort laser pulses. Temporal dynamics of HPHT transformation of the matter provide valuable knowledge about HPHT physical processes taking place inside massive planets and stars, and laser-induced microexplosions technique allows to study this dynamics using simple desktop experiments in a safe laboratory environment. In addition, laser-induced microexplosions technique can be used for synthesis of new phases of materials with unusual physical properties not found at room temperature and ambient pressure. In order to realize laser-induced microexplosions that can efficiently induce phase transitions in maximally large volume of the initial material, and which can be monitored using time-synchronized X-ray and optical pulses, it is most convenient to tailor the spatial properties of optical pu;ses and beams. Here, the main emphasis is on the development of laser-induced microexplosions using Bessel beams. Non-diffracting Bessel beams can propagate without spatial spreading over larger distances, compared to the conventional Gauss beams, and at an appropriately chosen intensity levels are expected to induce microexplosions in larger volume, thus increasing amount of the new-phase material and making easier to perform transient detection of its formation.

The main results achieved during this research effort are summarized below.

1) Opto-mechanical setup for time-resolved XRD experiments was developed. Main features of this setup are illustrated in Fig. 1. The main feature of this setup is capability to overlap spatially a femtosecond laser pulse and an X-ray pulse in the sample under investigation, with temporal delay between the two pulses controlled by an optical delay line within the range from zero to a few nanoseconds. Another important point achieved with this setup is its portability, i.e., it can be easily moved to and installed temporarily at facilities providing temporally-synchronized fs laser and X-ray pulses (for example, Stanford University SLAC Linac Coherent Light Source).

2) Scientific and technical proposal for X-ray beamline time at SLAC was prepared and will be submitted on the To get the proposal approved, it is necessary to demonstrate a good level of preparedness (i.e., design of opto-mechanical setup that enables focusing of the fs laser beam into the sample as discussed above. In the remaining time before submission the proposal will be modified in order to better describe motivation for the proposed experiments better both from the fundamental and applications point of view.

3) Simultaneous alignment of X-ray and optical beams on the sample was found to present a significant technical challenge. According to the currently developed understanding, a geometry where both beams are parallel is the most attractive, whereas non-parallel alignment may be more difficult to achieve. Comparison between the conventional (non-parallel) and the newly developed (parallel) geometries is shown in Fig. 2. As can be seen, the latter geometry requires spherical or axicon lens with central hole in order to allow passage of X-ray beam through the optical elements. This circumstance will demand for customized focusing optics in the future, and

will be studied in more detail during research proposed for the next year (see Research Plan (3) below).

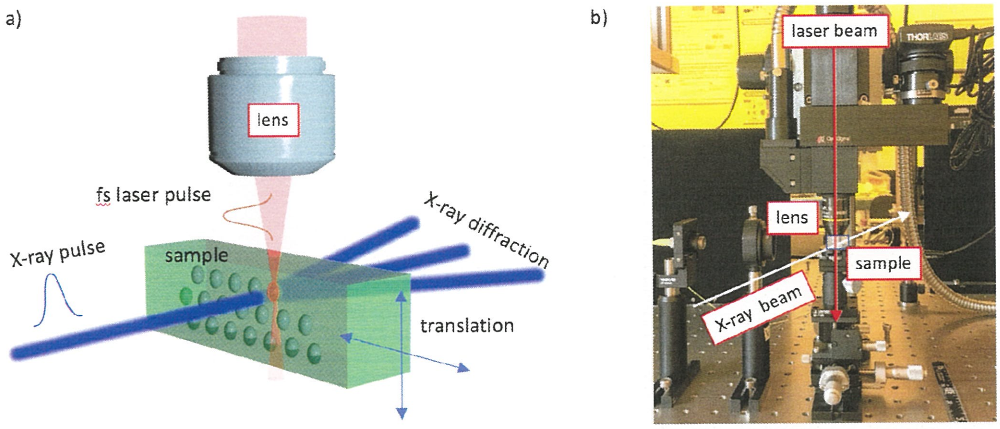

Fig. 1. Opto-mechanical setup for time-resolved X-ray and optical irradiation of the sample, (a) schematic view, (b) assembled prototype portable setup.

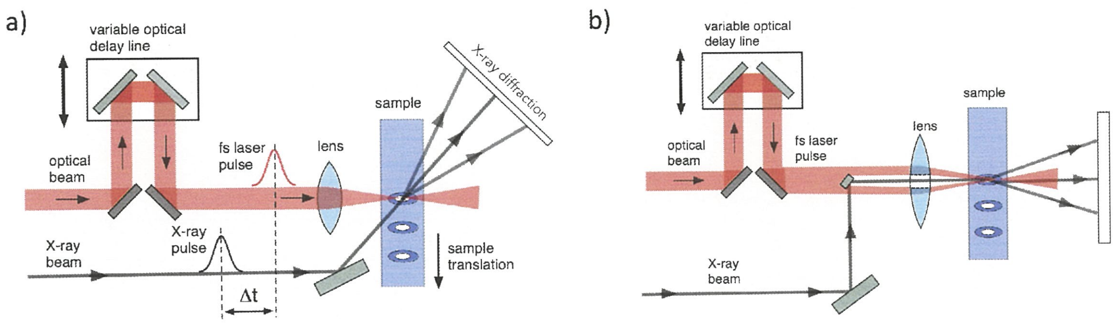

Fig. 2 Comparison between non-parallel (a) and parallel (b) geometries of time-resolved monitoring of new phase formation during laser-induced microexplosions.

4) Experimental protocol for time-resolved experiments in sapphire (Al_2O_3) was developed:

i) X-ray beam has a penetration depth of 100s of micrometers, which is larger than thickness of the intended samples. Therefore, X-ray absorbance will not play major role if sufficiently thin samples are used. The sapphire samples are single-crystals having dimensions of 25mm (length) and 80 micrometers (thickness), with three sides polished. Laser beam can be focused into the sample radiation from the edge.
ii) The size of the X-ray beam determines the distance between the laser shots and thus the rate of continuous movement for the target. With 1-µm x-ray probe a reasonable distance between the shots is ~2 µm, so the speed of transferring the target will be 2 µm x probe repetition rate.
iii) X-ray diffraction pattern from the laser-induced new phase and the background scattering from pristine crystal will be investigated. The total size of the new modified crystals can be estimated as 100 nm^3 per shot. The X-rays diffracted from the crystal will be compared with background scattering from a similar-sized region in pristine crystal not affected by microexplosions.

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) We will continue our efforts in developing and submitting an application for a suitable X-ray beamline at Stanford University. Other possible facilities worldwide will be also examined;
2) Research group at Shizuoka University will continue the development and testing the optical microscope to be used as an X-ray beamline facility;
3) We will continue efforts to expand the spatial domain affected by microexplosions bu using non-diffracting Bessel beams. Ordinary Gaussian beams, which can generate a very small focal region with high optical intensity, are limited in terms of the maximum energy density and amount of laser-affected material. The main limitation is imposed by diffraction: the radius of the diffraction-limited focal spot is $r = 0.61\lambda\ /NA$. For the laser wavelength λ=800 nm and numerical aperture of the focusing lens NA = 1.4, one gets radius of the focal region $r_{foc} \approx 0.35$ μm and focal area of 0.38 μm^2. The absorption length in dense plasma equals to ~30 nm giving the energy deposition volume ~10^{-14} cm^{-3}. With absorbed energy around 100 nJ the absorbed energy density amounts to 10^7 J/cm^3 = 10 TPa. The number of laser-affected atoms constitutes around 10^{11} atoms (a few picograms) making structural studies complicated. In contrast to Gaussian beam, BG beams allow to increase the laser-affected volume by at least two orders of magnitude. It was demonstrated previously that Bessel beam delivering pulses of 150 fs duration and 2 μJ energy, focused inside sapphire can produce cylindrical void of 30 μm length and 300 nm diameter. The resulting void volume is about 2.12×10^{-12} cm^{-3}. During the next year use of Bessel beams for steady-state and time-resolved XRD experiments will be actively investigated. Techniques to generate BB using portable microscope setup in collinear geometry (Fig. 2(b) will be studied theoretically and experimentally.
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.