Annual Report

Funding Programme:	Helmholtz Young Investigators Groups
Project ID No.:	VH-NG-804
Project Title:	Towards Laboratory-Based Ultrafast Bright EUV and X-ray Sources: High-Power Fiber Laser Frequency combs and Cavity Enhanced Ultrafast Optics
Group Leader:	Guoqing Chang
Helmholtz Centre:	DESY
Participating University:	University of Hamburg
Report Period (=Calendar Year):	01/2015-12/2015

1) Group Structure

Please report briefly on the structure and personnel development of your group.

Current group includes the group leader and 6 PhD students. One visiting PhD student from Beijing University visited us for 1 year and worked on low-noise microwave extraction from 1-GHz Yb-fiber lasers.

2) Network

Please describe how you / your research group are integrated within the Helmholtz Centre and the partner university (e.g. as member of committees).

My group closely collaborates with Professor Franz Kärtner’s group at DESY and HI-Jena on developing high-power fiber laser sources and low-noise frequency combs.

Collaborating with Professor Henry Chapman at DESY and Professor Christian Betzel from University of Hamburg, our group is developing a harmonic-generation microscope method to analyze protein nanocrystals. This project is funded by the Hamburg Centre for Ultrafast Imaging (CUI) within the German excellence initiative.

Collaborating with Dr. Markus Perbandt and Dr. Alke Meents both at DESY, we launched a new project – on-chip room-temperature time-resolved protein micro-crystallography based on UV-induced structural changes.

I teach or co-teach a couple of courses to the graduate students registered at University of Hamburg.

3) Satisfaction

How satisfied are you with the general working conditions provided by the Helmholtz Centre / partner university? Is there anything that meets your criticism?

The working conditions are excellent. I have initiated several new research projects and established good collaborations with Skin Cancer Center Buxtehude, DESY, UHH, CUI, HI-Jena, several Universities in China, and with CAS through the Helmholtz-CAS joint research program.

4) Scientific Progress / Milestones

How has your work plan progressed? Which important milestones could be achieved during the report period? Is the progress of your work in accordance with original planning or has the work plan been changed?

For the research projects, we have achieved following milestones in 2015:

1. We demonstrate the first high power fiber-based system specifically designed to optimally seed a high energy Yb:YLF amplifier chain. The fiber-based master-oscillator-power-amplifier (MOPA) seed system operates at a repetition rate of 17.88 MHz, producing 87-W, 4.9-µJ pulses centered at 1018 nm with 1-ns stretched duration and 2-nm bandwidth, ideally matching the emission spectrum of cryogenic Yb:YLF crystals.

2. We experimentally demonstrate a 1-GHz passively offset-free laser source by difference-frequency generation between two spectral components of a spectrally broadened Yb-fiber laser. The source laser is a 1-GHz Yb-fiber oscillator mode-locked by nonlinear polarization evolution, which outputs 400-mW average power, corresponding to 0.4 nJ pulse energy. The oscillator output is amplified to 4.2 W in average power before coupled into a piece of photonic crystal fiber for spectral broadening. Difference frequency generation between the dispersive wave pulse and the Raman soliton pulse leads to offset-free signal at 1030 nm with 10-nm bandwidth. This source will be further improved for extracting low-noise microwaves.

3. We propose and demonstrate a new method of producing wavelength widely tunable femtosecond pulses for driving multi-photon microcopy (MPM). The method employs fiber-optic nonlinearities to broaden an input optical spectrum, followed by optical bandpass filters to select the leftmost or rightmost spectral lobes. Both simulation and experimental results show that the filtered spectral lobes correspond to nearly transform-limited pulses with ~100 fs pulse duration. Fiber dispersion causes optical wave breaking, which slows down the shift of the leftmost/rightmost spectral lobes and ultimately limits the wavelength tuning range of the filtered spectra. A detailed numerical simulation verified by subsequent experimental results reveal that such a dispersion-induced limitation can be overcome by shortening the fiber length while increasing the input pulse energy. The benefits are twofold: (1) optical wave breaking is alleviated leading to larger spectral shift and (2) the filtered spectral lobes have higher power, indicating a practical approach of power scaling. We use 20-mm commercially photonic crystal fiber to achieve spectral broadening and several optical bandpass filters to select the leftmost/rightmost spectral lobes. The experimental results show that we can implement a femtosecond (70-120 fs) source with wavelength tunable from 825 nm to 1210 nm with >1 nJ pulse energy). We believe that our proposed source represents a potential cost-effective substitute of conventional MPM driving source, i.e., a combination of Ti:sapphire laser plus a solid-state OPO. With the possibility of implementing our ultrafast source in an all-fiber format (Yb-fiber laser plus fiber-optic spectral broadening), this energy scalable approach paves an avenue to operate MPM in rugged environments outside research labs.

4. In collaboration with Dr. Ruediger Greinert's group at Skin Cancer Center Buxtehude, we developed a multi-modal nonlinear microscope aiming to study skin cancer. Various imaging contrast agents exist in different sections of skin when irradiated by femtosecond optical pulses: endogenous chromophores such as melanin and NADH emit autofluorescence, non-centrosymmetric structure (e.g., collagen) allow second harmonic generation (SHG), and cell surface and refractive-index inhomogeneity permit third harmonic generation (THG). These imaging modalities constitute the least invasive way of visualizing skin at the sub-cellular level. A wavelength-tunable femtosecond source is thus demanded to cover the wavelength range of 700-900 nm for two-photon fluorescence excitation and 1200-1300 nm for efficient SHG and THG detection. Our microscope is driven by a novel fiber-based ultrafast source we recently developed that covers the above-mentioned wavelength range. The required pulse energy is also optimized for imaging skin. A proof-of-principle study of a human skin sample using multiple imaging modalities enabled by the ultrafast source demonstrates the potential for virtual skin biopsy.

Besides the work at DESY, I have visited Massachusetts Institute of Technology (MIT) on a regular basis as a visiting scientist and supervised the development of high repetition rate Yb-fiber laser frequency combs and participated in a project on chip-scale frequency combs. The expertise acquired from working on these MIT projects is crucial for the ongoing projects we are pursuing at DESY.

In collaboration with Prof. Franz Kärtner, we have successfully constructed a high power Yb-fiber laser system, which delivers 60-fs pulses with 100-W average power. However the pulse energy is limited to 1.5 micro-joule, too low to drive high-harmonic generation for achieve extreme ultra-violet (EUV) pulses. Ongoing work is to further energy scale up this ultrafast source and eventually implement a table-top high-power EUV source, which is the first part of the originally proposed project.

5) Financial Plan / Time Schedule
Can you comply with the financial plan and time schedule or do you see a need for adjustment?

At this stage, everything works out in terms of the financial plan and time schedule.

6) Status
Do you hold a joint Junior Professorship or a W2/W3 Professorship? Do you aim for such a position? What is the status of your negotiations in this respect?

No, I do not hold a joint Junior Professorship or a W2/W3 Professorship.
Yes, I aim pursuing such a position, i.e. an academic career path in general. The negotiations will start this summer.

7) Teaching Activities of the Group Leader

Co-teach (together with Dr. Markus Perbandt) a 11-lecture main course—When Laser Physics Meets Life Science—for graduate students from the Hamburg Center for Ultrafast Imaging

Design and teach a 5-lecture main course—*Introduction to Nonlinear Optics*—for graduate students from International Max-Plank Research School.

Co-teach *Ultrafast Optical Physics* in SoSe 2015 jointly with Prof. Kärtner at University of Hamburg

8) Publications of the Group

<u>5 Journal papers published (or to be published) since 2015</u>

[5] W. Liu, C. Li, Z. Zhang, F. X. Kaertner, and **G. Q. Chang**, "Self-phase modulation enabled, wavelength-tunable fiber laser sources: an energy scalable approach," Opt. Express (to submit).

[4] F. X. Kaertner, F. Ahr, A. _L. Calendron, H. Cankaya, S. Carbajo, **G. Q. Chang**, G. Cirmi, K. Doerner, U. Dorda, A. Fallahi, T. Hartin, M. Hemmer, R. Hobbs, Y. Hua, R. Huang, R. Letrun, N. Matlis, V. Mazalova, O. Muecke, E. Nanni, W. Putnam, K. Ravi, R. Reichert, I. Sarrou, X. Wu, H. Ye, L. Zapata, D. Zhang, C. Zhou, R. J. D. Miller, K. Berggren, H. Graafasma, A. Meents, R. W. Assmann, H. N. Chapman, and P. M. –L. Fromme "AXSIS: exploring the frontiers in attosecond X-ray science, imaging and spectroscopy," Nuclear Instruments and Methods in Physics Research A (to appear)

[3] Gengji Zhou, Ming Xin, F. X. Kaertner, and **G. Q. Chang**, "Timing jitter of Raman solitons," Opt. Lett. 40, 5105 (2015)

[2] A. G. Glenday, C. –H. Li, N. Langellier, **G. Q. Chang**, L.-J. Chen, G. Furesz, A. Zibrov, F. X. Kärtner, D. F. Phillips, D. Sasselov, A. Szentgyorgyi, and R. L. Walsworth, "Operation of a broadband visible-wavelength astro-comb with a high-resolution astrophysical spectrograph" Optica 2, 250 (2015)

[1] W. Liu, D. N. Schimpf, T. Eidam, J. Limpert, A. Tuennermann, F. X. Kärtner, **G. Q. Chang**, "Pre-chirp managed nonlinear amplification in fibers delivering 100 W, 60 fs pulse" Opt. Lett. 40, 151 (2015)

<u>12 conference papers published since 2015</u>

[12] Q. Cao, C. Li, Y. Z. Liu, X. Gao, Z. G. Zhang, F. X. Kaertner, and **G. Q. Chang**, "Passively offset-free Yb:fiber laser source at 1 GHz repetition rate," Paper JTh2A.141, CLEO/QELS, San Jose (2016)

[11] Y. Hua, W. Liu, L. E. Zapata, M. Hemmer, G. J. Zhou, N. Schimpf, T. Eidam, J. Limpert, A. Tuennermann, F. X. Kaertner, and **G. Q. Chang**, "87-W, 1018-nm Yb-fiber ultrafast seeding source for cryogenic Yb:YLF amplifier," Paper SM4Q.5, CLEO/QELS, San Jose (2016)

[10] W. Liu, C. Li, H.-Y. Chung, S.-H. Chia, Z. G. Zhang, F. X. Kaertner, and **G. Q. Chang**, "Widely tunable ultrafast sources for multi-photon microscopy," Paper SM2I.7, CLEO/QELS, San Jose (2016)

[9] H. –Y. Chung, W. Liu, S. –H. Chia, F. X. Kaertner, and **G. Q. Chang**, "Fiber-nonlinearity enabled femtosecond laser sources for nonlinear light miccroscopy," Paper P1-C/32, Focus on Microscopy (2016)

[8] S. –H. Chia, H. –Y. Chung, W. Liu, F. X. Kaertner, and **G. Q. Chang**, "Virtual skin biopsy based on ultrafast fiber lasers," Paper WE-MO1-PAR-D, Focus on Microscopy (2016)

[7] Q. Cao, F. X. Kaertner, and **G. Q. Chang**, "Timing jitter optimization of Raman soliton and dispersive wave," Paper UFO0092, Ultrafast Optics X (2015)

[6] W. Liu, C. Li, Z. G. Zhang, F. X. Kaertner, and **G. Q. Chang**, "Yb-fiber laser based ultrafast source emitting 50-fs pulses at 920 nm," Paper UFO0123, Ultrafast Optics X (2015)

[5] G. J. Zhou, M. Xin, F. X. Kaertner, and **G. Q. Chang**, "Timing jitter optimization of Raman solitons," Paper UFO0055, Ultrafast Optics X (2015)

[4] J. K. Lim, H. –W. Chen, S. H. Xu, Z. M. Yang, F. X. Kaertner, and **G. Q. Chang**, "3 GHz frequency comb via difference frequency generation," Ultrafast Optics X (2015)

[3] D. Schimpf, W. Liu, T. Eidam, J. Limpert, A. Tuennermann, F. X. Kaertner, and **G. Q. Chang**, "CPA-free ultrafast fiber laser source based on pre-chirp managed nonlinear amplification," paper STu1O.4, CLEO/QELS, San Jose (2015)

[2] G. J. Zhou, M. Xin, F. X. Kaertner, and **G. Q. Chang**, "Relative timing jitter and its effect on nonlinear wavelength conversion," paper SF2D.4, CLEO/QELS, San Jose (2015)

[1] **G. Q. Chang** and F. X. Kaertner, "Ultrafast fiber laser technologies for multiphoton microscopy," paper TU-AF2-PAR-E-1, Focus on Microscopy, Gottingen, Germany (2015)

9) External Funding

As co-PI, I submitted a joint proposal with Prof. Christian Betzel (PI) and Prof. Henry Chapman (co-PI) to BMBF to validate a method to characterization and differentiation of amorphous and crystalline biomolecular micro- and nanoparticles. We are awarded 70k Euros to develop a second-harmonic generation microscope.

10) Patent Applications

No. of pending/granted patents

None.

11) Awards received by Group Members / Professorship Appointments offered to Group Leader

None.