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):	01/2016-12/2016

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. Wei Liu—the first PhD student joining the group—defended his thesis and graduated in December 2016. Now he stays in the group as a postdoctoral research fellow.

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 DESYand 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. Ruediger Greinert at the Skin Cancer Center Buxtehude, we are applying multi-photon microscopy imaging to study skin cancers.

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 2016:

1. The mid-infrared (mid-IR) wavelength range between 6 and 20 μm, in particular, has been known as the fingerprint region. Spectroscopic information of these vibrational bands reveals the molecular structure and, in turn, identifies the ingredients of the sample under test. In this scenario, a high power, low noise, tunable mid-IR femtosecond source is highly desired from the viewpoint of rapid high-resolution sensing. We proposed a new method of generating high-power mid-IR femtosecond pulses by using self-phase modulation (SPM) enabled pulses as the signal. SPM-enabled pulses feature large pulse energy and extremely low timing jitter. Our simulation indicates that difference-frequency generation (DFG) between 90-nJ pump pulse and 22-nJ SPM-enabled signal pulse can generate 1-nJ mid-IR pulse at 10 μm, representing >10 times energy increase compared with current demonstrated DFG-based mid-IR source.

2. To experimentally verify the new method of generating high-power mid-IR pulses, we constructed a high-power fiber laser system including a 30-MHz mode-locked Yb-fiber oscillator centered at 1035 nm, a hybrid fiber stretcher, a single-mode pre-amplifier, a large mode-area (LMA) Yb-fiber amplifier, and a pulse compressor. Based on chirped-pulse amplification, this Yb-fiber laser system produces 180-fs pulses with 15-W average power and 500-nJ pulse energy. We employed this laser source to investigate the energy scalability of SPM-enabled ultrafast sources. Using LMA fibers, we show that SPM-enabled spectral broadening followed by spectral filtering can generate ultrashort pulses with 16.5-nJ pulse energy at the wavelength of 1225 nm. We believe that >20 nJ femtosecond pulses with wavelength tunable over the entire 1200-1300 nm band can be achieved. We are now generating high-power mid-IR femtosecond pulses based on DFG between such an energetic SPM-enabled pulse and the laser pulse at 1035 nm.

3. We demonstrate an energy scalable approach to implement ultrafast fiber laser sources suitable for deep tissue multi-photon microscopy imaging. Enabled by fiber-optic nonlinearities (dominated by SPM), these unique ultrafast sources produce nearly transform-limited pulses of 50-90 fs in duration with the center wavelength tunable in the wavelength range of 1030-1215 nm, capable of driving second-harmonic generation (SHG) or third-harmonic generation (THG) imaging of human skin. In collaboration with Dr. Ruediger Greinert’s group at Skin Cancer Center Buxtehude, we applied such a high-energy source to a proof-of-principle study of *ex vivo* human skin THG/SHG images. The horizontal histology section from *stratum corneum* to the reticular dermis can be obtained with >220 μm penetration depth.

4. We performed a detailed numerical and experimental study of SPM-dominated spectral broadening of narrowband spectra generated by an Er-fiber laser system. Using proper optical filters to select the leftmost or rightmost spectral lobes results in ultrafast sources widely tunable from 1.3 to 1.7 μm with the pulse energy up to >10-nJ and the pulse duration

as short as ~50 fs. Compared with conventional Raman soliton enabled ultrafast source, our approach features broader wavelength coverage and superior energy scalability. Currently we are applying such an ultrafast tunable source to three-photon excitation microscopy imaging.

5. Recently we demonstrated a different amplification technique—pre-chirp managed amplification (PCMA), in which seeding pulses are nonlinearly amplified such that the amplified spectrum was substantially broadened. Using an Yb-doped rod-type large-pitch fiber (LPF) as the power amplifier, PCMA enabled us in year 2015 to generate 75 MHz, ~60 fs, linearly-polarized 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. In year 2016, we investigated energy scaling of PCMA using circularly polarized seeding pulses. Because the nonlinear refraction coefficient for the circularly polarized light is 2/3 of that for linearly polarized light, using circularly polarized seed can scale up the pulse energy (and average power) by 1.5 times without changing the spectral bandwidth of the amplified pulse. Using this method, we obtain 100-W, 26-fs pulses at 23.7-MHz repetition rate, corresponding to 4.2-μJ pulse energy. 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?

Granted tenure by DESY. 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

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 2016 jointly with Prof. Kärtner at University of Hamburg

8) Publications of the Group

<u>5 Journal papers published (or to be published) since 2016</u>

[5] Y. Z. Liu, W. Liu, D. N. Schimpf, T. Eidam, J. Limpert, A. Tuennermann, F. X. Kaertner,

and **G. Q. Chang**, "100-W ultrafast Yb-fiber laser system based on Pre-chirp managed nonlinear amplification employing circular polarization," Opt. Lett. (To submit)

[4] H. –Y. Chung, W. Liu, F. X. Kaertner, and **G. Q. Chang**, "Er-fiber laser based, energy scalable ultrafast sources tunable in 1300-1700 nm," Opt. Express (Submitted)

[3] W. Liu, S. –H. Chia, H. –Y. Chung, F. X. Kaertner, and **G. Q. Chang**, "Energetic ultrafast fiber laser sources tunable in 1030-1215 nm for deep tissue multiphoton microscopy," Opt. Express 25m 6822 (2017)

[2] 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 24, 15319 (2016)

[1] 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 S0168900216002564 (2016)

<u>18 conference papers published since 2016</u>

[18] **G. Q. Chang**, "Advanced ultrafast laser sources harnessing fiber nonlinearities," CLEO/QELS, San Jose (2017) (<u>Invited</u>)

[17] Q. Cao, F. X. Kaertner, and **G. Q. Chang**, "Towards high power and low noise mid-infrared DFG ultrafast source," JTu3L.5, CLEO/QELS, San Jose (2017)

[16] H. –Y. Chung, W. Liu, and **G. Q. Chang**, "Er-fiber laser enabled femtosecond source tunable from 1.3-1.7 um for nonlinear optical microscopy," Paper SM3L.2, CLEO/QELS, San Jose (2017)

[15] H. –Y. Chung, W. Liu, F. X. Kaertner, and **G. Q. Chang**, "Femtosecond source widely tunable from 1.3-1.7 um for three-photon microscopy," Paper P1-A/4, Focus on Microscopy (2017)

[14] S. –H. Chia, H. –Y. Chung, W. Liu, F. X. Kaertner, and **G. Q. Chang**, "Multiphoton microscopy based on 1 GHz – 1MHz energetic ultrafast tunable fiber sources," Paper SU-AF-PAR-D, Focus on Microscopy (2017)

[13] G. J. Zhou, M. Xin, Y. Z. Liu, F. X. Kaertner, and **G. Q. Chang**, "SPM-enabled fiber laser source beyond 1.2 µm," Advanced Solid-State Lasers, Boston (2016)

[12] W. Liu, S. –H. Chia, H. –Y. Chung, F. X. Kaertner, and **G. Q. Chang**, "Energy scalable ultrafast fiber laser sources tunable in 1030-1200 nm for multiphoton microscopy," Advanced Solid-State Lasers, Boston (2016)

[11] Y. Z. Liu, W. Liu, D. Schimpf, T. Eidam, J. Limpert, A. Tuennermann, F. X. Kaertner, and **G. Q. Chang**, "100-W few-cycle Yb-fiber laser source based on pre-chirp managed amplification employing circular polarization," Advanced Solid-State Lasers, Boston (2016)

[10] W. Liu, Y. Z. Liu, D. Schimpf, T. Eidam, J. Limpert, A. Tuennermann, F. X. Kaertner, and **G. Q. Chang**, "Pre-chirp managed nonlinear amplification for >100 W ultrafast sources," paper PA115-22, SPIE Photonics Asia, Beijing (2016) (invited)

[9] W. Liu, Y. Z. Liu, D. Schimpf, T. Eidam, J. Limpert, A. Tuennermann, F. X. Kaertner, and **G. Q. Chang**, "Pre-chirp managed nonlinear amplification for >100 W ultrafast sources," paper 2586791, the 8th International Symposium on Ultrafast Phenomena and Terahertz Waves, Chongqing, China (2016) (invited)

[8] W. Liu, C. Li, H. –Y. Chung, S. –H. Chia, Z. G. Zhang, F. X. Kaertner, and **G. Q. Chang**, "Ultrafast fiber laser source tunable in 825-1210 nm for multi-photon microscopy," paper FWG-3, Europhoton, Vienna (2016)

[7] Y. Z. Liu, W. Liu, D. Schimpf, T. Eidam, J. Limpert, A. Tuennermann, F. X. Kaertner, and **G. Q. Chang**, "Energy scaling of pre-chirp managed nonlinear amplification using circular polarization," paper 18.2, Europhoton, Vienna (2016)

[6] J. Ruppe, S. Y. Chen, T. Zhou, M. Sheikhsofla, Z. G. Zhang, **G. Q. Chang**, F. X. Kaertner, J. Nees, and A. Galvanauskas, "Coherent pulse stacking extension of CPA to 9 ns effectively-long stretched pulse duration," paper SM4I.2, CLEO/QELS, San Jose (2016)

[5] 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)

[4] 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)

[3] 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)

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

[1] 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)

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.