# Final Report

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| **Funding Programme:** | **Helmholtz Joint Research Groups** |
| **Project ID No.:** | HCJRG-201 |
| **Project Title:** | Advanced laser technologies for ultrafast spectroscopy of quantum materials |
| **Principal Investigator:** | Franz Kärtner |

## *1)* Work and Results Report

*Please describe the main results and the progress achieved through the Joint Research Group in comparison to the state of the art at the time of writing the application and give an outlook on possible future work and applications.*

### a) Description of the results (max. 4 DIN A4 pages)

*Please describe the scientific and/or technical success of the group as well as secondary results achieved and essential experience gained*

In the past decade, the most prominent quantum materials in condensed matter physics are graphene, topological insulator, iron-based superconductor, *etc*. They continue to form the frontier of current condensed matter physics. One of the most powerful techniques to investigate the electronic and optical properties of these quantum materials is ultrafast laser spectroscopy. Since the intrinsic dynamics of a condensed matter (with the atomic distance at the order of 1 angstrom) is characteristically at the scale of femtosecond/picosecond, ultrafast spectroscopy is the only practical way to time-resolve this evolution process. There are various quantum phases along this dynamical process since photons can interact with condensed matters in all four known degrees of freedom: charge, lattice, spin, and orbital. Different orders within a quantum material interact among themselves, which can be detected by optical spectroscopy as well. Indeed, ultrafast spectroscopy relies on available ultrafast laser sources. As the German side of the Helmholtz-CAS joint research groups, we have developed various wavelength-tunable femtosecond sources aiming for ultrafast spectroscopy applications. Tunable femtosecond sources normally consist of a source laser producing femtosecond pulses at a certain wavelength and a nonlinear optical device converting them to wavelength tunable femtosecond pulses. An exemplary combination is a mode-locked laser plus a synchronously pumped solid-state optical parametric oscillator (OPO). Different from solid-state OPOs that rely on the second-order nonlinearity in optical crystals, the third-order nonlinearity associated with optical fibers offers an alternative means of generating widely tunable femtosecond pulses. Supported by the HCJRG 201 grant, we have developed tunable ultrafast sources based on two different nonlinear fiber-optic mechanisms: soliton self-frequency shift (SSFS) and self-phase modulation (SPM). Most important the derived ultrafast source is tightly synchronized with the source laser, and thus difference-frequency generation (DFG) between these two ultrafast sources may result in a mid-IR laser source featuring tunable wavelength (5-15 μm), <100-fs pulse duration, nJ pulse energy, and 10s mW average power. Such a mid-IR source is of particular importance for the investigation of quantum materials such as topological insulators with the bandgap below 100 meV.

**Wavelength tunable femtosecond source based on SSFS:** Caused by stimulated Raman scattering in an optical fiber with negative group-velocity dispersion, SSFS continuously red-shifts a soliton pulse's center wavelength under increasing the input power, thus enabling a red-shifted, continuously tunable Raman soliton source. Among many quantities that characterize a femtosecond source, timing jitter and relative intensity noise (RIN) are of particular importance and determine whether the femtosecond source is "quiet" enough for our DFG-based mid-IR source. Since the amount of SSFS depends on the excitation pulse's energy, the RIN of the excitation pulse causes the Raman soliton's center-wavelength fluctuations, which is then converted to timing jitter by fiber dispersion. Minimizing the relative timing jitter (RTJ) of a Raman soliton with respect to its excitation pulse is of particular importance for realizing a low-noise mid-IR DFG source. We carried out a detailed study on a Raman soliton's timing jitter, and find that the RTJ between a Raman soliton and the excitation pulse dominates at high frequency the Raman soliton's absolute timing jitter. We demonstrate that a Raman soliton's RTJ can be substantially reduced using fibers with less dispersion and shorter length.

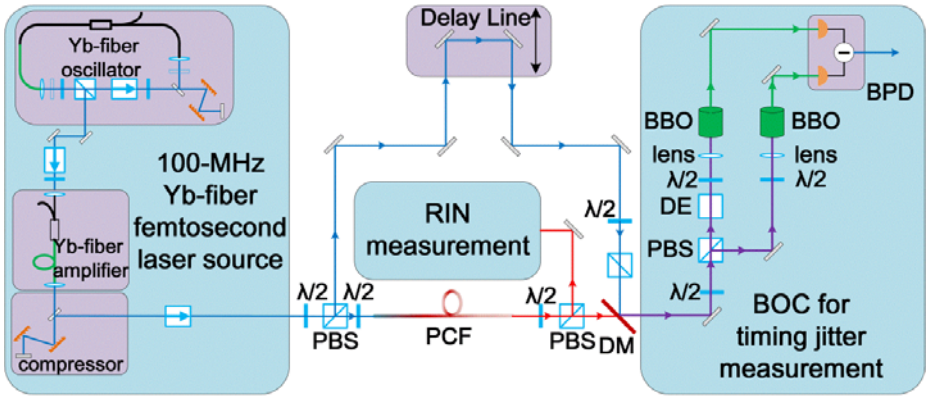


Fig. 1. Schematic setup to characterize RIN and RTJ of Raman soliton source. PBS: polarization beam splitter, PCF: photonic crystal fiber, HWP: Half-wave plate, DM: dichroic mirror, D.E: delay element, BPD: balanced photodetector, OSC: oscilloscope, SSA: signal source analyzer.

Figure 1 illustrates the experimental setup. The Raman soliton source is derived from a home-built Yb-fiber laser system including a 100-MHz Yb-fiber oscillator centered at 1035 nm, an Yb-fiber amplifier, and a pulse compressor. The Yb-fiber oscillator operates in the stretched-pulse mode-locking regime enabled by nonlinear polarization evolution. We optimize both the mode-locking state and net cavity-dispersion to minimize the oscillator's RIN; the integrated RIN from 10 Hz to 10 MHz is 0.018%.

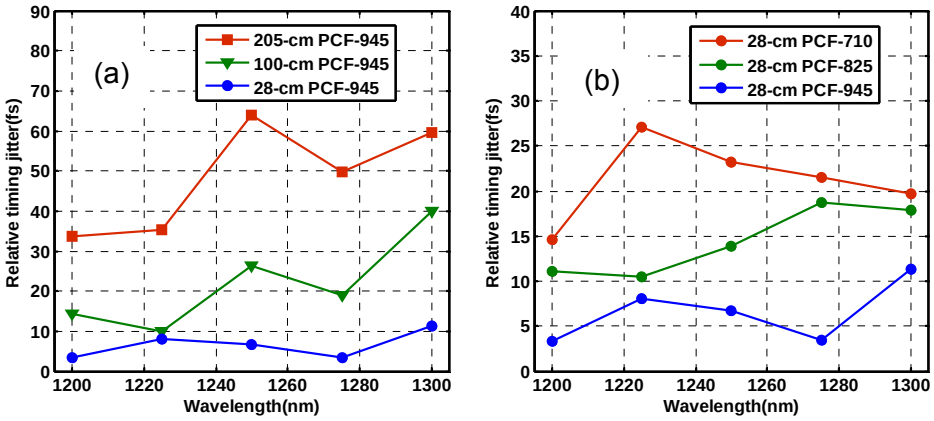


Fig. 2. Integrated RTJ of Raman solitons generated by (a) PCF-945 with different fiber lengths: 28 cm (blue circles), 100-cm PCF-945 (blue triangles), 205-cm PCF-945 (blue squares) and by (b) 28-cm of PCF-945 (blue circles), PCF-825 (green circles), and PCF-710 (red circles).

In our experiments, we compared the Raman soltion generated by three different photonic crystal fibers (PCFs): PCF-945, PCF-825, and PCF-710. To investigate the RTJ dependence on fiber length and dispersion, we measure the RTJ of Raman solitons centered at 1200 nm, 1225 nm, 1275 nm, and 1300 nm as well. Figure 2(a) summarizes the integrated RTJ of these Raman solitons generated by PCF-945 at different fiber length, demonstrating that shorter fiber length leads to less RTJ at all Raman soliton wavelengths. Figure 2(b) presents the integrated RTJs corresponding to different PCFs all at the same fiber length of 28 cm, showing that fiber with less dispersion results in less RTJ for Raman solitons centered at the same wavelength. Our experimental results suggest that RTJ can be significantly reduced by minimizing the accumulated fiber dispersion experienced by the Raman soliton using fibers with less dispersion and shorter length. Further optimization of our laser system (e.g., shorten the excitation pulse duration) may achieve a Raman soliton with attosecond-level RTJ, which is crucial for implementing a low-noise mid-IR ultrafast source via DFG between the Raman soliton and the excitation pulse.

**Wavelength tunable femtosecond source based on SPM:** Recently, we demonstrated a new method of producing widely wavelength tunable femtosecond pulses. The method employs Kerr fiber-optic nonlinearities (dominated by SPM) to broaden an input optical spectrum, followed by optical bandpass

filters to select the leftmost or rightmost spectral lobes. Without external compression, the filtered spectral lobes correspond to ~100-fs (nearly transform-limited) pulses with >1 nJ pulse energy.

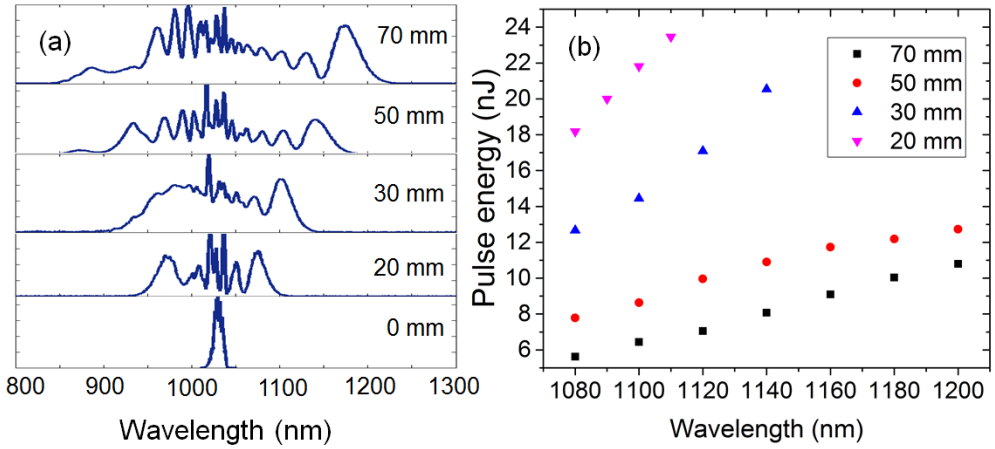


Fig. 3. (a) SPM-enabled spectral broadening in fiber LMA 8 of different length: 20 mm, 30 mm, 50 mm, and 70 mm. The coupled average power is 3 W for all fibers. (b) Pulse energy of the filtered rightmost spectral lobes at different central wavelength for different fiber length

To achieve more pulse energy, we employ large-mode-area (LMA) fiber (LMA-8) for spectral broadening. We coupled 3-W, 190-fs pulses (55-MHz repetition rate) into fiber LMA-8 of four different lengths: 20 mm, 30 mm, 50 mm, and 70 mm. As Fig. 3(a) shows, the rightmost spectral lobe red-shifts with the increased fiber length and peaks at 1080 nm (1170 nm) for 20-mm (70-mm) LMA-8. We then use suitable optical bandpass filters to select these rightmost spectral lobes, resulting nearly transform-limited pulses with ~100-fs duration. We varied the coupled power into these fibers to generate the filtered spectra at different wavelengths. Figure 3(b) summarizes the pulse energies corresponding to the filtered spectra peaking at different wavelengths for the different fiber lengths. As expected, the filtered spectra from shorter fibers exhibit higher pulse energies for the same wavelength shift. For example, the filtered spectrum at 1100 nm has pulse energy of 6.5 nJ, 8.5 nJ, 14.5 nJ, and 22 nJ for fiber length of 70 mm, 50 mm, 30 mm, and 20 mm, respectively. This SPM-enabled source can provide wavelength tunable (in 1.15-1.22 μm) femtosecond pulses with 100 times more pulse energy compared with Raman soliton based tunable source. Numerical simulation shows that for 11-W average power (200-nJ pulse energy) coupled into 20-mm LMA-8, the rightmost spectral lobe is shifted to 1200 nm and the filtered spectrum exhibits >40 nJ pulse energy with >2.2-W average output power.

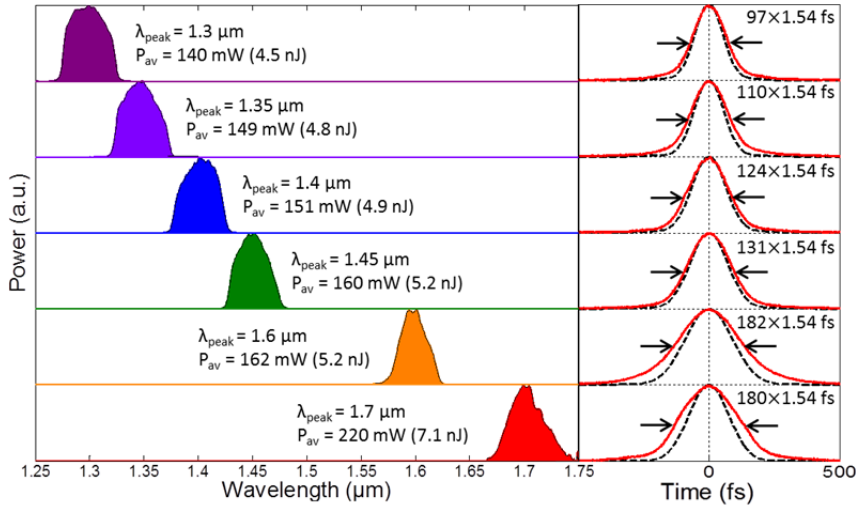


Fig. 4. (Left column) Filtered optical spectra from 2-cm highly nonlinear fiber; their peak wavelength, average power, and pulse energy are labeled in the figure. (Right column) Measured autocorrelation traces (red solid curves) and autocorrelation traces calculated from the transform-limited pulses allowed by the filtered spectra (black dotted curves).

We further applied our method to Er-fiber laser technology and achieved wavelength-tunable

femtosecond sources in 1300-1700 nm (Fig. 4). By applying this SPM-enabled spectral broadening method to both an Yb-fiber laser system and an Er-fiber laser system, we can generate ~100-fs pulses tunable in 825-1700 nm, exceeding one octave wavelength coverage. We are using this powerful source to study the dependence of tissue absorption and scattering on the excitation wavelength. We believe that achieving 1-mm penetration depth in skin is possible. Since all the free-space components in our source can be replaced by fiber or fiber-pigtailed devices, sub-100-nJ-level femtosecond sources can be constructed in an all-fiber format. We believe that such SPM-enabled femtosecond fiber-laser sources provide an energetic, compact, and robust solution for many applications.

**Wavelength tunable femtosecond source in the mid-IR wavelength range:** The 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 and spectroscopy.

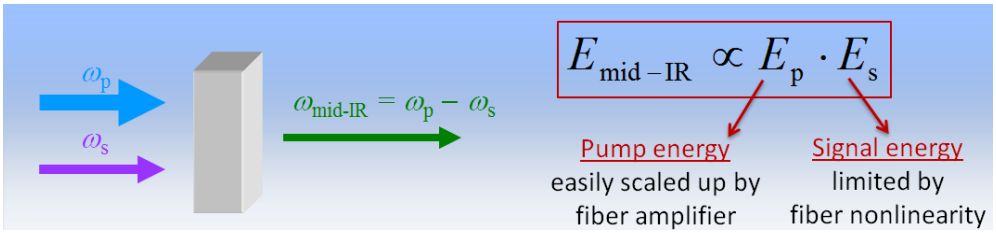


Fig. 5. Mid-IR generation based on difference frequency generation between a pump beam and a signal beam. The mid-IR pulse energy is proportional to the pulse energy product between the pump and signal.

Figure 5 illustrates the DFG process inside an optical crystal, which involves a pump beam (i.e., 1.03 μm pulse produced by our Yb-fiber laser system), a signal beam (i.e., the wavelength tunable pulse in 1.15-1.22 μm), and the generated mid-IR beam. In the conventional design, the pump pulse and the signal pulse differs in energy (or power) by orders of magnitude. For example, the pump pulse in our experiment is derived from the Yb-fiber laser system with a pulse energy of >400 nJ while the signal pulse has an energy of ~100 pJ limited by Raman soliton pulse energy. Our numerical simulation indicates that the mid-IR pulse energy is proportional to the energy product between the pump pulse and the signal pulse, implying energy doubling either the pump pulse or the signal pulse will result in the same mid-IR pulse energy. The simulation shows that DFG between 90-nJ pump pulse and 22-nJ 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. This immediately suggests that energy scaling a DFG-based mid-IR source by increasing the signal pulse energy rather than increasing the pump pulse energy constitutes a more efficient avenue. In fact, the pump pulse energy has to be kept below a certain value to prevent crystal damage. Therefore increasing the signal pulse energy becomes a powerful and practical solution to achieve high-power mid-IR pulses.

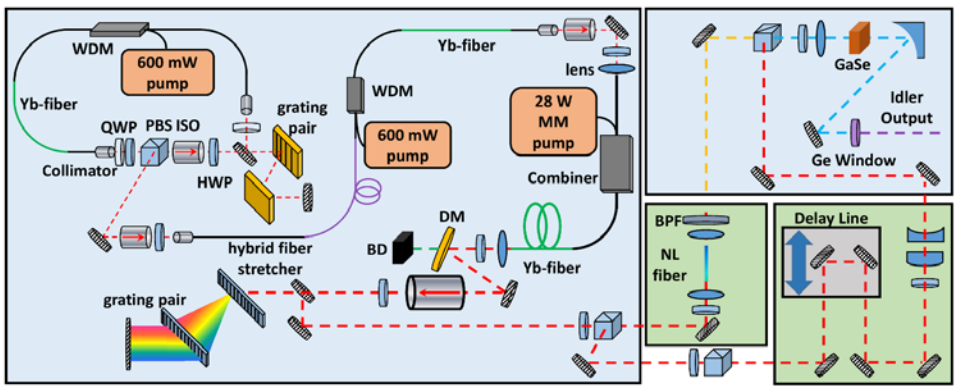


Fig. 5. Schematic setup of high power mid-IR laser source based on DFG. PBS: polarization beam splitter, QWP: quarter-wave plate, HWP: half-wave plate, DM: dichroic mirror, BD: beam dumper, BPF: bandpass filter, ISO: isolator, NL fiber: nonlinear fiber.

We proposed a new method of generating high-power mid-IR femtosecond pulses by using our SPM-enabled source as the signal that features large pulse energy and extremely low timing jitter. Figure 5 illustrates the schematic of the high power mid-IR laser source based on DFG between two synchronized pulse trains that are derived from a high-power Yb-fiber laser system. The home-built high-power fiber laser includes a 30-MHz mode-locked Yb-fiber oscillator centered at 1.03 μm, a hybrid fiber stretcher, a single-mode pre-amplifier, a 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. The optical beam is split into two arms using a half-wave plate (HWP) together with a polarization beam splitter (PBS). By rotating the HWP, we can continuously vary the optical power coupled into the nonlinear fiber to generate SPM-enabled tunable pulses in 1.15-1.22 μm. These pulses are then combined with the pump pulses at 1035 nm by another PBS. The combined pulses are focused into a 1-mm thick GaSe crystal to produce mid-IR pulses via DFG. Current experimental results indicate that we can generate ~nJ level mid-IR pulses with ~200-fs pulse duration tunable in the wavelength range of 6-20 um. Such a powerful mid-IR source constitutes a powerful tool for ultrafast spectroscopy of quantum materials.

## b) Outlook on future work, sustainability (max. 2 DIN A4 pages)

*How far did the JRG intensify the scientific cooperation between Helmholtz and international partners? Did it set new impulses in existing and upcoming research programmes of the Helmholtz Association? Does it form the core of a future, larger scale bilateral or otherwise funded project? Please describe planned activities/ cooperations to further develop the work, if applicable also with additional partners.*

The advanced laser technologies pursued by the Helmholtz-CAS joint research group have set new impulses for the collaboration research between the Helmholtz groups (Prof. Franz Kärtner and Dr. Guoqing Chang) and their University partner group led by Professor Christian Betzel. We are applying our SPM-enabled tunable ultrafast sources to drive a laser-scanning microscope to identify and score protein nano-crystals, which allows controlled production of nano-crystals and therefore enables the study of previously inaccessible protein structures using X-ray radiation. For example, interest in the structure and function of integral membrane proteins is driven largely by their role in human disease. High-resolution protein structures can provide information on ligand binding locations and protein function. The most common strategy for obtaining such structures is currently X-ray diffraction, often performed at synchrotron sources. Complications commonly plaguing soluble protein crystal detection in high-throughput systems are exacerbated in studies of membrane proteins for several reasons. Consequently, crystallizing membrane proteins is notoriously difficult, and often requires screening a large number of trials. Second harmonic generation (SHG) microscopy is a promising candidate for the preliminary observation of chiral crystals. Via the SHG imaging contrast, the presence of protein crystals can be visualized with good sensitivity and background suppression: coherent SHG signals only arise from non-centrosymmetric structures, and they can be enhanced with certain classes of ordered systems. To develop such harmonic-generation microscopy method for protein nanocrystal imaging and sorting, we submitted a joint proposal with Prof. Betzel's group (University partner of this JRG) to Federal Ministry of Education and Research, Germany in 2016 and received 75,000 Euros to develop a fiber-laser driven harmonic-generation microscope. Such a microscope will be installed at European XFEL in the near future.

The tunable ultrafast sources—especially the high-power mid-IR femtosecond source—play an important role in ultrafast spectroscopy of condensed matters. In the investigation of topological insulators, the known bandgap is below 100meV, which falls within the mid-IR (5-10 μm) range. However current available optical parametric oscillators at this wavelength range have very limited output power. Our DFG-based mid-IR source holds the promise to produce widely tunable femtosecond pulses with the average power at least one order of magnitude higher than current mid-IR laser technology. Such a powerful mid-IR source forms the core for future continued bilateral collaboration between the Helmholtz groups (Prof. Franz Kärtner and Dr. Guoqing Chang) and the CAS groups (Prof. Jimin Zhao and Prof. Lu Yu). With a powerful mid-IR laser source, the CAS team will investigate the resonant ultrafast dynamics of the topological insulators (e.g. the most typical 3D topological insulator $Bi_2Se_3$). In the previous ultrafast optical investigation, excitation was achieved with 800 nm photons, and the electrons will pass a long way in the momentum space (through electron-phonon interaction) to reach the Dirac cone right above the bandgap. Thus the direct relaxation and carrier lifetime is unclear.

Herein we use the developed mid-IR laser pulses to directly excite and probe electrons that have been promoted to the Dirac cone conduction band. Only in such a way does the carrier relaxation lifetime directly reflect the topological order such that we can detect the $Z_2$ property of the surface state. If conditions permit we will apply magnetic field to test its inversion symmetry as well. Furthermore we will develop magnetic ion doped $Bi_2Se_3$ sample to verify the anomalous effects that break the time-reversal symmetry; such an optical investigation is absent due to the unavailability of a high-power ultrafast mid-IR laser source. This study may be extended to topological insulators considering interaction between electrons in different materials, *i.e.* in the non-Fermi-gas picture. Current investigations of topological insulators, for example transport measurements, focus on states near the Fermi surface. Mid-IR laser spectroscopy allows us to study topological properties at excited state—a field rarely explored.

The Joint Research Groups have submitted a proposal to CAS to further advance the mid-IR laser technology aiming for understanding the fundamental mechanism of light-matter interaction and time-resolved quantum phase transition in mid-IR wavelength regime. We plan to submit a joint DFG-NSFC proposal in 2018 to further support our next-level collaboration.

## c) Potential for application/exploitation (max. 2 DIN A4 pages)

*How do you yourself assess the potential for application or exploitation of the results? Where do you see future possibilities? Please describe realized or planned measures for applying the results. Please also include information on patents, licences, co-operations with industry, etc.*

The wavelength tunable ultrafast sources developed in this JRG program promise many important potential applications. We plan to apply them driving multi-photon microscope (MPM) to perform biomedical imaging. The success of MPM is largely driven by the rapid advance of femtosecond laser sources in the near infrared wavelength range. To date, no single laser can provide >1 nJ femtosecond pulses tunable in the entire 800-1300 nm wavelength range. Conventional solution relies on multiple laser systems each covering a portion of 800-1300 nm and the stitched spectrum spans the whole wavelength range. A typical combination is a Ti:sapphire laser tunable from 700 to 1040 nm plus a solid-state optical parametric oscillator (OPO) that covers the wavelength tuning range of 1040-1300 nm. However, high complexity (e.g., water cooling required), high cost, and large size of such a solid-state laser solution limits the use of MPM to specialized laboratories. All these drawbacks associated with solid-state lasers can be eliminated in our SPM-enabled ultrafast sources that employ fiber-optic technologies. Figure 6 compares the solid-state laser solution and our fiber laser solution. Together with our collaborators, we are pursuing two applications: (1) biomedical imaging of cancer cells with submicron optical resolution and (2) imaging and sorting protein nanocrystals.

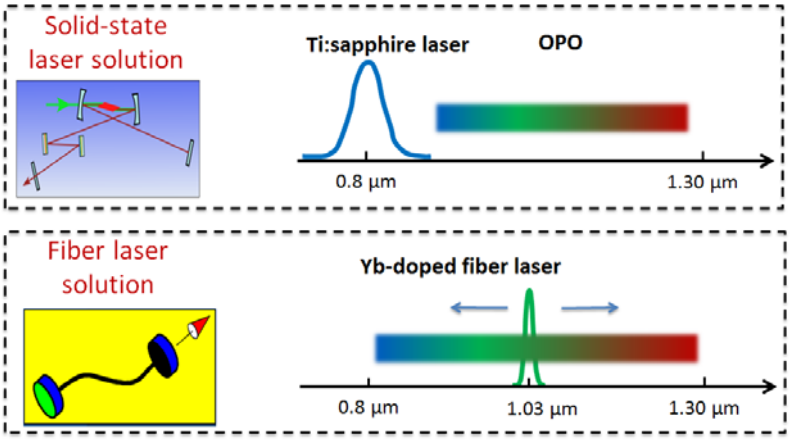


Fig. 6. Ultrafast laser driving source for MPM: solid-state laser solution versus fiber laser solution.

**Biomedical imaging of cancer cells with submicron optical resolution**: To show that such a widely tunable source is suitable for driving MPM imaging using different contrast modalities, we first tune the source to output <100-fs pulses at ~920 nm to match the two-photon excitation wavelength of enhanced green fluorescence protein (EGFP)—the most commonly used labeling protein. Using this source to drive our MPM and collecting the fluorescence signal, we obtained the two-photon excitation fluorescence image of breast cancer cells labeled by EGFP; see Fig. 7(a).

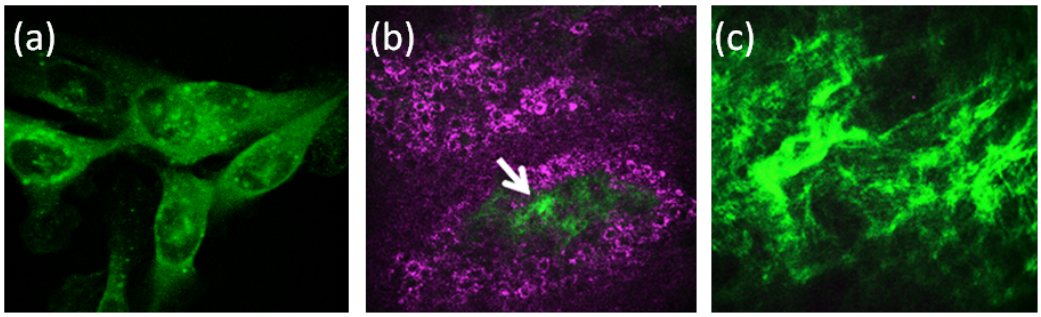


Fig. 7. (a) two-photon excitation fluorescence imaging of breast cancer cells labeled by EGFP. (b,c) Horizontal-sectioned epi-SHG/THG images of ex vivo human skin driven by the filtered source at 1100 nm. Imaging depth: 65 μm for (b) and 110 μm for (c). Cell morphology from the *stratum corneum* to the *stratum basale* in epidermis from THG contrast. Combined with the epi-SHG modality, the collagen fibers in the dermal papilla [arrowhead in (b)] are revealed. Magenta: THG, Green: SHG.

Collaborating with Dr. Rüdiner Greinert's group at Skin cancer center Buxtehude, we applied our SPM-enabled source to harmonic generation tomography of human skin. Unlike fluorescence microscopy, optical harmonics provide naturally endogenous contrasts; their coherent nature offers additional insights to visualize the tissue morphology as bio-photonic crystals. Figure 7(b,c) show the combined SHG/third-harmonic generation (THG) images (SHG in green and THG in magenta) of ex vivo human skin from *stratum corneum* to the reticular dermis. Our SPM-enabled source is tuned to 1100 nm to drive the SHG/THG microscope. The cell morphology in epidermis (Figure 7(b)) and the collagen distribution in dermis (Figure 7(c)) can be clearly distinguished in the 10-frame-averaged video-rate (30Hz) images. >220 μm of imaging penetration depth from the top of the stratum corneum can be obtained. To our best knowledge, this work represents the first demonstration that a femtosecond wavelength-tunable fiber-source can enable THG imaging in the penetration window around 1030 nm – 1215 nm. Ongoing work is to further optimize the tunable ultrafast source and carry out a systematic study aiming to push the penetration depth beyond 1 mm that is necessary for skin cancer investigation. We are also collaborating with Prof. Hartmut Schlueter (from the University Medical Center Hamburg-Eppendorf) and Prof. Dwayne Miller (from Max Planck Institute for the Structure and Dynamics of Matter) to apply our MPM imaging technique to assist laser surgery.

**Imaging and sorting protein nanocrystals:** The relationship between structure and function of biological macromolecules is essential to many areas in the life sciences, pharmacy, medicine and biotechnology, because it provides an understanding about life processes, or their faults at the atomic level. To date, diffraction data for the structural analysis of biomolecules can be measured only at relatively large and regular crystals using synchrotron sources. Using high energy X-ray pulses from a free-electron laser (FEL), however, Prof. Henry Chapman's group at DESY were the first to determine the structure of protein nanocrystals. The capability of controlling production of protein nanocrystals becomes critical for subsequent analysis of these nanocrystals using FELs.

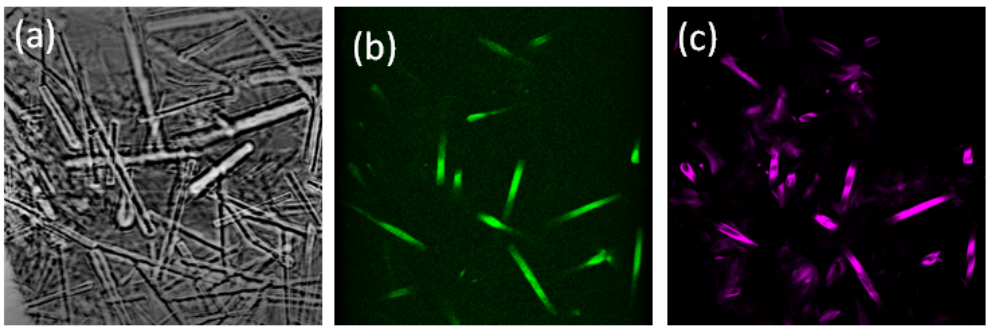


Fig. 8. Imaging protein nano-crystals using 1300-nm femtosecond pulses at different imaging contrast: (a) forward scattering, (b) second-harmonic generation, and (c) third-harmonic generation

To distinguish nanocrystals from amorphous particles, we are developing a harmonic generation microscope to image protein nanocrystals; the microscopy is driven by our SPM-enabled, Er-fiber laser based femtosecond source at 1300 nm. Figure 8 presents experimental results of imaging protein nano-crystals based on different imaging contrasts, i.e., forward scattering (Fig. 8(a)), SHG (Fig. 8(b)), and THG (Fig. 8(c)).

The development of such harmonic-generation microscopy method for protein nano-crystal imaging and sorting has enabled us to submit a joint proposal with Prof. Betzel's group (University partner of this JRG) to Federal Ministry of Education and Research, Germany in 2016, and we received 75,000 Euros to develop a fiber-laser driven harmonic-generation microscope. We also continuously received funding from the Hamburg Centre for Ultrafast Imaging (CUI) with the German excellence initiative to further improve the technology. In the future we will integrate the microscope with the method of depolarized dynamic light scattering (which measures the size of nanocrystals) developed by Prof. Christian Betzel's group. The whole system permits a high quality and fast characterization of nanocrystals for the structural analysis with FELs. Professor Chapman is a further project partner involved to carry out the final measurements to verify the quality of the protein nano-crystals produced at FELs.

We believe that our tunable ultrafast laser source represents a cost-effective substitute of the 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 (fiber laser plus fiber-optic spectral broadening), this energy scalable source paves an avenue to operate MPM in rugged environments outside research labs. Several renowned laser companies (Such as Topica and Coherent) have expressed their interest in our laser technology, showing that our laser sources hold a great promise to be commercialized.

## 2) Qualification of Junior Researchers (max. 2 DIN A4 pages)

*Please describe the main achievements regarding personal qualifications (Diploma, bachelors or masters degrees, conferring of doctorates, "habilitations", appointments/junior professorships, etc.). How far have new career perspectives for young scientists inside the foreign country been developed?*

The education of research personnel and students is an essential and deep-rooted component of this JRG program, which provides an excellent teaching vehicle for graduate students, postdoctoral associates, and visiting scientists. Participants learned aspects of photonics, quantum electronics, nonlinear dynamics, ultrashort pulse lasers, noise, and precision optical measurement techniques. In addition, the investigators teach courses in Nonlinear Optics and Ultrafast Optics.

Two PhD students (Wei Liu and Shih-Hsuan Chia) who involved in the JRG program finished their thesis and obtained the Doctoral degree. Wei demonstrated the SPM-enabled method of producing wavelength widely tunable femtosecond pulses. 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. Wei obtained his Doctoral degree in December 2016, and currently he is working as a postdoctoral research fellow in our group to continue the research in this field. Starting in May of 2017, he will move to USA and work at SLAC National Accelerator Laboratory as a postdoctoral research associate.

Shih-Hsuan applied our SPM-enabled ultrafast source to drive multi-photon microscope to image protein nano-crystals and skin samples. Shih-Hsuan obtained his Doctoral degree in August 2016 with the highest honor of summa cum laude. After graduation, Shih-Hsuan stayed in our group to continue his research on multi-photon microscopy. Recently Shih-Hsuan was offered Assistant Professorship position by National Yangming University, Taiwan and he will resume this position at the beginning of next year.

We also hosted two visiting students in this JRG program: Chen Li (PhD student from Beijing University, China) and Xiang Gao (Master student from Karlsruhe Institute of Technology, Germany). Chen worked with us for one year (01.09.2014-31.08.2015) and co-authored with us one journal paper and four conference papers.

**3) Public relations**
*By which means did you gain publicity (e.g. reporting in media, own website)?*

We mainly gain publicity by presenting our research results at renowned international conferences, such as Advanced Solid State Lasers Congress (ASSL), Conference on Lasers and Electro-Optics (CLEO), the international Ultrafast Optics conference (UFO), Focus on Microscopy (FOM), Europhoton etc. The research results achieved in this JRG program were presented 19 times to the attendees of these conferences, including a forthcoming invited CLEO (May 16, 2017) talk given by Dr. Guoqing Chang (Co-PI of this JRG program). These conference presentations have drawn attention of many other research groups and also several companies.

**4) Networking**
*What co-operation and communication structures have been developed during the course of the funding? What is the contribution of the group to the networking of international partners and the Helmholtz Centre(s)?*

The Helmholtz-CAS joint research group worked closely to pursue the proposed project, based on regular communication by Skype. PIs met personally many times during last 3 years (2014-2016) to share ideas and discuss research progress. For example, Prof. Franz Kärtner (PI from Germany side) visited the Institute of Physics (IOP) at Beijing and met with Prof. Jimin Zhao (PI from China side) and Prof. Lu Yu (Co-PI from China side) to discuss the joint research projects and future collaborations. Dr. Guoqing Chang (Co-PI from Germany side) regularly (May 2014, December 2014, August 2015, March 2016, and October 2016) visited Prof. Jimin Zhao at IOP and communicated the project progress. PIs also met to review the project progress and plan for future experiments when they attended international conferences, such as SPIE Optics&Photonics Conference at San Diego (August 2014) and Conference on Lasers and Electro-Optics at San Jose (May 2015 and June 2016).

The joint research group has helped the networking between DESY and IOP. Prof. Jimin Zhao was in charge of the IOP monthly seminar series, and he invited Prof. Franz Kärtner to visit IOP and deliver a seminar talk. In his talk, Prof. Franz Kärtner introduced DESY and the Center for Free-Electron Laser (CFEL) scicene to the IOP audience.

**5) List of Publications**
*Articles in scientific journals, written contributions to scientific meetings, contributions to books, other publications.*

**Journal papers:**

[1] 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 (under review)

[2] 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 25, 6822 (2017)

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[2] 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)

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