Position Description

1. General Information

Name of the position	**Deep ultraviolet generation from high-energy mid-infrared fiber laser drivers**
Foreseen date of enrolment	1 January 2025
Position is funded by	• COFUND, Marie Skłodowska-Curie Actions (MSCA), Horizon Europe, European Union • University of Limoges (UniLim) • Macquarie University (MQ)
Research Host	University of Limoges XLIM UMR CNRS 7252
PhD awarding institutions:	University of Limoges & Macquarie University
Locations	Primary: Limoges, France Secondary: Sydney, Australia
Supervisors	Sébastien Février XLIM, Alex Fuerbach Macquarie
Group of discipline	Photonics, optical fibers, fiber lasers, nonlinear fiber optics

2. Research topics (only one of these projects will be funded):

Project 1: *Microjoule-class picosecond chirped-pulse amplifier at 3 µm*

Context

In recent years, strong-field laser physics has experienced a shift towards longer wavelengths, i.e. from the near-infrared to the mid-infrared (mid-IR) spectral range (see works by Anne L'Huillier, Pierre Agostini and Ferenc Krausz, Nobel Laureates in Physics 2023 [1,2]). This is because the low linear excitation rate of mid-IR light in wide band gap semiconductor and dielectric materials allows for applying electric fields nearly as strong as the critical electric field strength. This allows for transitioning from conventional non-linear optics to strong-field physics in solids without inflicting optical damage to the sample. This transition is marked by non-perturbative high harmonic generation (HHG) in solids [3,4].

We demonstrated recently high harmonic generation from polycrystalline ZnO thin films synthesized by RF-magnetron sputtering directly on fiber facets. The films were pumped by various in-house built laser sources delivering sub-100 fs pulses at wavelengths ranging from 2 µm to 3 µm [5]. With proper arrangement, harmonic generation down to 212 nm (the limit of our current detection system is 200 nm) was recorded. Thanks to the fiber delivery, this approach holds promises for the *in situ* exploration of electronic responses in materials science. Nevertheless, an optimization of the laser source (in terms of energy, duration and repetition rate) as well as of the non-linear medium itself is necessary to increase the harmonic yield and to explore deeper in the ultraviolet. The goal of the project is to develop few-cycle lasers

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in the mid-infrared (between 3 and 5 µm) with enough energy per pulse to trigger high-harmonic generation in semi-conductors deep into the ultraviolet (down to approx. 50 nm).

Objectives

We propose to develop a laser source delivering sub-100 fs pulses with microjoule level energy at wavelengths ranging from 2 µm to 3 µm based on rare-earth doped fibers (Er^{3+}, Ho^{3+} or Dy^{3+}) in silica or fluoride glasses. The seed laser source will deliver broadband femtosecond pulses originating from soliton dynamics in nonlinear fluoride fibers. It will be developed jointly by the partners based on custom components and fibers. The amplifier will exploit the chirped pulse amplification technique developed in the near-infrared. To this aim, the seed radiation will be stretched, pre-amplified, pulse-picked and finally boosted in rare-earth doped fluoride fibers (e.g. Er^{3+}, Dy^{3+}, Ho^{3+} depending on the wavelength of the seed). Great attention will be paid to amplify properly the pulse so as to reach (sub-)picosecond durations after the grating-based compressor. Then, a strategy based on post-compression in gas-filled hollow-core inhibited-coupling photonic crystal fibers [6,7] will be applied to post-compress the high-energy pulse to sub-100 fs durations. Such ultrashort pulses with high energy (hundreds to thousands of of nanojoules) will be exploited for high-harmonics generation in solid targets down to the deep ultraviolet.

References

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[2] G. Doumy, J. Wheeler, C. Roedig, P. Agostini and L.F. DiMauro, High order harmonics from mid-infrared drivers for attosecond physics," in Atomic Processes in Plasmas, edited by K. B. Fournier (2009)

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[5] I. Tiliouine, H. Delahaye, G. Granger, Y. Leventoux, C. E. Jimenez, V. Couderc, and S. Février, "Fiber-based source of 500 kW mid-infrared solitons," Opt. Lett. 46, 5890-5893 (2021) https://doi.org/10.1364/OL.445235

[6] B. Debord, F. Amrani , L. Vincetti, F. Gérôme and F. Benabid, "Hollow-Core Fiber Technology: The Rising of Gas Photonics", Fibers 7, 16 (2019)

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Supervisors: Sébastien Février (XLIM), Alex Fuerbach (Macquarie university), Solenn Cozic (Le Verre Fluoré)

Research Fields: Applied physics, photonics, nonlinear optics

Project 2: Hollow-core fiber based post-compression in the mid-infrared

Context

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semiconductor and dielectric materials allows for applying electric fields nearly as strong as the critical electric field strength. This allows for transitioning from conventional non-linear optics to strong-field physics in solids without inflicting optical damage to the sample. This transition is marked by non-perturbative high harmonic generation (HHG) in solids [3,4].

We demonstrated recently high harmonic generation from polycrystalline ZnO thin films synthesized by RF-magnetron sputtering directly on fiber facets. The films were pumped by various in-house built laser sources delivering sub-100 fs pulses at wavelengths ranging from 2 µm to 3 µm [5]. With proper arrangement, harmonic generation down to 212 nm (the limit of our current detection system is 200 nm) was recorded. Thanks to the fiber delivery, this approach holds promises for the *in situ* exploration of electronic responses in materials science. Nevertheless, an optimization of the laser source (in terms of energy, duration and repetition rate) as well as of the non-linear medium itself is necessary to increase the harmonic yield and to explore deeper in the ultraviolet. The goal of the project is to develop few-cycle lasers in the mid-infrared (between 3 and 5 µm) with enough energy per pulse to trigger high-harmonic generation in semi-conductors deep into the ultraviolet (down to approx. 50 nm).

Objectives

We propose to develop a laser source delivering sub-100 fs pulses with tens of nanoujoule energy at wavelength longer than 4 µm. The system will be developed jointly by the partners based on custom components and fibers. The pulse characteristic will be manipulated in a cascaded all-solid fiber system to provide 50-70 fs pulses based on soliton dynamics in fluoride fibers, either passive or rare-earth doped (Er^{3+}, Ho^{3+} or Dy^{3+}). These pulses will be exploited for high-harmonics generation in solid targets with the aim to provide a dense comb of harmonics by increasing the seed wavelength. This source will be well suited to vacuum ultraviolet – visible supercontinuum generation for electronic spectroscopy.

References

[1] A. Schiffrin, T. Paasch-Colberg, N. Karpowicz, V. Apalkov, D. Gerster, S. Mühlbrandt, M. Korbman, J. Reichert, M. Schultze, S. Holzner, J. V. Barth, R. Kienberger, R. Ernstorfer, V. S. Yakovlev, M. I. Stockman, and F. Krausz, "Optical-field-induced current in dielectrics," Nature 493, 70–74 (2013)

[2] G. Doumy, J. Wheeler, C. Roedig, P. Agostini and L.F. DiMauro, High order harmonics from mid-infrared drivers for attosecond physics," in Atomic Processes in Plasmas, edited by K. B. Fournier (2009)

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[4] D. Franz, S. Kaassamani, D. Gauthier, R. Nicolas, M. Kholodtsova, L. Douillard, J.-T. Gomes, L. Lavoute, D. Gaponov, N. Ducros, S. Février, J. Biegert, L. Shi, M. Kovacev, W. Boutu, and H. Merdji, All semiconductor enhanced high-harmonic generation from a single nanostructured cone, Nature Scientific Reports 9, 5663 (2019) https://doi.org/10.1038/s41598-019-41642-y

[5] I. Tiliouine, H. Delahaye, G. Granger, Y. Leventoux, C. E. Jimenez, V. Couderc, and S. Février, "Fiber-based source of 500 kW mid-infrared solitons," Opt. Lett. 46, 5890-5893 (2021) https://doi.org/10.1364/OL.445235

Supervisors: Sébastien Février (XLIM), Alex Fuerbach (Macquarie university), Solenn Cozic (Le Verre Fluoré)

Research Fields: Applied physics, photonics, lasers, nonlinear optics

Project 3: Mid-infrared spectroscopy in gas-filled inhibited coupling hollow core fibers

The middle-wave infrared (mid-IR) spectral region is also known as the molecular fingerprint region since most molecules produce characteristic vibrational signatures between 3 and 12 µm. Combined with the fact that the Earth's atmosphere exhibits two windows of relatively high transparency from 3 to 5 µm and from 8 to 12 µm, the mid-IR spectral region

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attracts a great deal of attention for high-resolution molecular spectroscopy and remote monitoring of atmospheric pollutants [Dumas2020]. Highly sensitive biological and chemical sensors for homeland security and industrial and environmental monitoring as well as advanced astronomy applications such as planet hunting are examples of emerging applications of high brightness light sources covering the mid-IR.

In this context, we developed a Watt-level mid-IR fiber supercontinuum source pumped by an ultrafast thulium-doped fiber oscillator emitting at 2 µm and demonstrated its suitability for high-resolution spectromicroscopy [Borondics2018]. This new type of bench-top, optical fiber-based laser source can be used for high spatial resolution infrared micro-spectroscopy and chemical imaging rivaling, and in some regard even surpassing, the performances achieved at large-scale synchrotron facilities [https://optics.org/news/9/3/43]. However, the spectral coverage was limited to 4.3 µm due to the nonlinear medium used. Growing efforts from various research communities are deployed to reach deeper into the mid-IR by means of (i) truly mid-IR transparent nonlinear media and (ii) longer wavelength pump sources. Along this line, continuous efforts have been made in the photonics groups at the universities of Limoges and Macquarie to develop several pulsed pump sources optimized to a variety of nonlinear mid-IR waveguides. For example, we have developed an ultrafast 3 µm source to exacerbate supercontinuum generation in engineered chalcogenide microwires up to 12 µm [Hudson2017]. We have also developed a mid-IR supercontinuum source by pumping off-the-shelf chalcogenide fibers by means of an in-house built 4.5 µm ultrafast fiber laser [Tiliouine2022]. Very recently, we demonstrated for the first time to our knowledge efficient mid-IR supercontinuum generation via exacerbation of second-order nonlinearities in Gallium arsenide (GaAs) waveguides by means of a picosecond laser at 2.7 µm [Granger2023]. In this research project, we plan to improve the performance of the experimental configurations studied recently in order to demonstrate the potential of the sources for spectroscopic studies further in the mid-IR (5-12 µm).

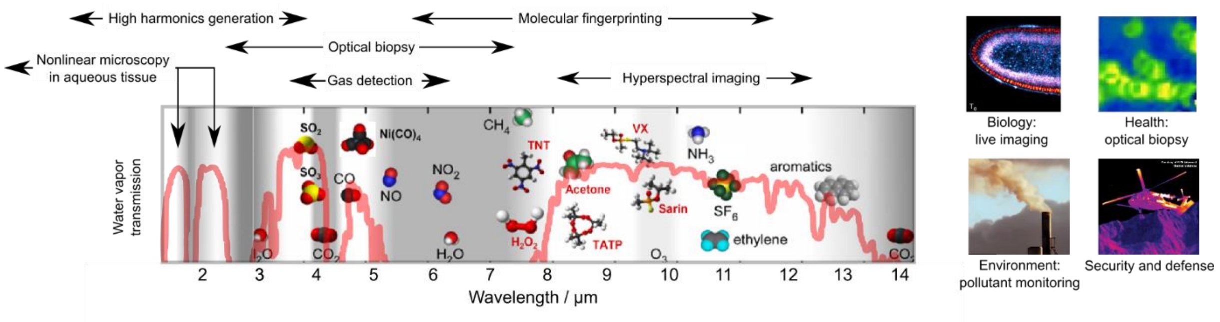

Figure: Applications of high-brightness mid-IR sources

Research methodology

Our research methodology is a mix between numerical and experimental studies. We develop numerical models to predict the propagation of light pulses in various realistic nonlinear media under various input conditions. From the numerical study, we deduce the parameters for the seed laser and nonlinear medium most appropriate to a specific application. Then we fabricate and characterize the seed laser and test the nonlinear media. These nonlinear media are either commercially available or designed and manufactured with the help of collaborators. Companies like *Le Verre Fluoré*, *SelenOptics* and *Coractive* provide mid-IR transparent fibers. *Thales Research and Technology* provide us with GaAs waveguides. In a feedback loop, we refine the characteristics of the laser seeders in terms of wavelength, pulse duration, energy, and repetition rate to the nonlinear media available. We can also laser post-process the nonlinear media to modify their characteristics and ensure a better match with the characteristics of the source. Finally, we refine the numerical models with the new experimental knowledge generated. This research methodology will be deployed in the three topics below.

Objectives

We demonstrated in 2023 the first spectroscopic studies of low-concentration methane in gas-filled hollow-core fibers on the fundamental absorption line of the gas at 7.65 µm [Bizot2023]. The system was able to measure low concentration of 22 ppm. Limitations were identified in relation to the noise of the supercontinuum and the nature of the hollow core fiber. Based on these findings, the goal will be to increase the sensitivity of the system by more than one order of magnitude in order to be able to detect low concentrations of methane in the atmospheric air (usual concentration is below 2 ppm). First, the stability of the laser supercontinuum will be improved by developing coherent supercontinuum

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in the all-normal dispersion regime. Second, we will use hollow core fibers based on the inhibited coupling guidance mechanism as gas cells [Debord2019] in order to increase the stability of the measurement by removing artefacts related to the multimode nature of the usual silver-coated hollow core fibers.

References

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Supervisors: Sébastien Février (XLIM), Alex Fuerbach (Macquarie university), Solenn Cozic (Le Verre Fluoré)

Research Fields: Applied physics, photonics, lasers, nonlinear optics

3. Employment Benefits and Conditions

University of Limoges offers a 36-months full-time work contract (with the option to extend up to a maximum of 42 months), with 2 months' probation period and 35 working hours per week.

The remuneration, in line with the European Commission rules for Marie Skłodowska-Curie grant holders, will consist of a gross annual salary of 28,668 EUR. Of this amount, the estimated net salary to be perceived by the Researcher is 1,920 EUR per month. However, the definite amount to be received by the Researcher is subject to national tax legislation.

Benefits include

- Becoming a Marie Skłodowska-Curie fellow and be entitled to join the Marie Curie Alumni Association

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- Access to all the necessary facilities and laboratories of the photonics group at University of Limoges and Macquarie University.
- Tuition fees exemption at both PhD awarding institutions.
- Yearly travel allowance to cover flights and accommodation for participating in AUFRANDE events.
- 10,000 EUR allowance to cover flights and living expenses for 12 months in Australia.
- 47 days paid holiday leave.
- Sick leave.
- Parental leave.

4. PhD enrolment

Successful candidates for this position will be enrolled by the following institutions and must comply with their specific entry requirements, in addition to AUFRANDE's conditions.

Applicants must hold a Master's degree with a major research component and a grade of at least a Distinction level (75% or greater in second year).

Applicants must provide evidence of the required level of English language proficiency.

More information on University of Limoges' requirements

Important: as XLIM Laboratory (University of Limoges) is subjected to ZRR (Zone à Régime Restrictif) regulation, hiring choices must be approved by the Haut Fonctionnaire Securité Défense (HFSD).

Visit the website: https://www.unilim.fr/research/phd-doctoral-studies/preparing-a-phd-thesis/admission-criteria-for-the-doctorate/?lang=en

More information on Macquarie University's requirements

All short-listed applicants will need to demonstrate their suitability for entry to the program by submitting an application to the PhD program and the Cotutelle scholarship via Macquarie University's online application system. The application must include:

- A detailed research proposal; and
- An evidence of the required level of English language proficiency.

Furthermore, applicants must qualify for a Cotutelle scholarship. Macquarie University assesses applicants for the scholarship based primarily on academic merit and research experience, emphasising previous thesis outcomes. Additional information such as peer-reviewed publications, conference and poster presentations and relevant work or professional experience may also be taken into account. Applicants are rated according to the principle and process outlined in the Graduate Research Scholarship Rating Sheet.

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Successful applicants (if non-Australian citizen) will be required to:

- Meet Australian visa requirements; and
- Obtain Overseas Student Health Cover (OSHC) for the entire duration of their study in Australia.

Visit the website: https://policies.mq.edu.au/document/view.php?id=380

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