Position Description

1. General Information

Name of the position	**Generation and application of high brightness light sources in the mid-infrared**
Foreseen date of enrolment	1 October 2024
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 (Unilim) & Alex Fuerbach (MQ)
Group of discipline	Photonics, optical fibers, fiber lasers, nonlinear fiber optics

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

Project 1: High brightness light sources for mid-infrared spectroscopy

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 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-

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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).

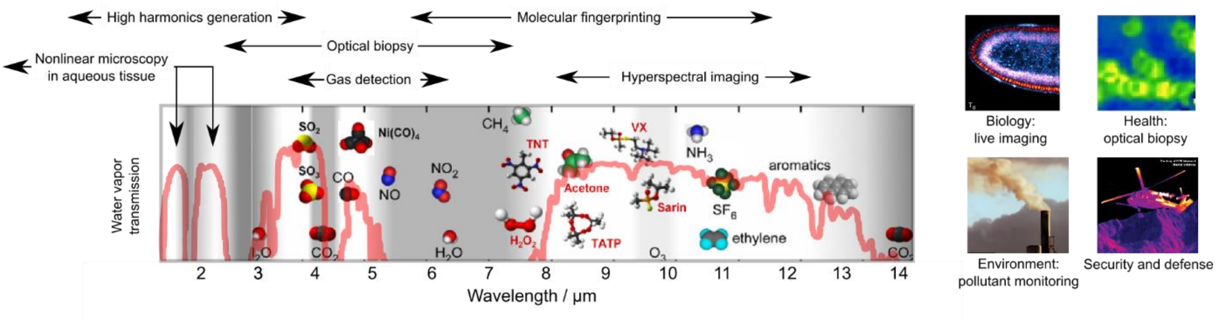

Figure: Applications of high-brightness mid-IR sources

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

The goal will be to design, manufacture, characterize and implement a high repetition rate source of picosecond pulses in the mid-IR. This kind of laser source is necessary to exacerbate parametric mixing in nonlinear media since the detrimental effect of pulse walk-off is avoided with long picosecond pump pulses. The seed laser source will be a commercial laser source emitting 1.5 ps low energy pulses at 1.97 µm. The wavelength will be first converted towards the mid-infrared in a cascade of nonlinear fluoride optical fibers. Then, the pulse energy will be amplified in nonlinear fiber amplifier. Great attention will be paid to tailor the pulse temporal profile in the amplifier to reach long picosecond pulses. Then, the mid-IR source will be used to exacerbate nonlinearities in e.g. chalcogenide or semi-conductor waveguides. Finally, spectroscopic studies with the broadband laser source will be carried out (e.g. trace gas spectroscopy).

References

F. Borondics, M. Jossent, C. Sandt, L. Lavoute, D. Gaponov, A. Hideur, P. Dumas, and S. Février, "Supercontinuum-based Fourier transform infrared spectromicroscopy," Optica **5**, 378-381 (2018)

P. Dumas, M. C. Martin, G. L. Carr, "IR spectroscopy and spectromicroscopy with synchrotron radiation, in synchrotron light sources and free-electron lasers," ed. Springer, Cham, January 2020, 55 pages

G. Granger, M. Bailly, H. Delahaye, C. Jimenez, I. Tiliouine, Y. Leventoux, J.-C. Orlianges, V. Couderc, B. Gerard, R. Becheker, S. Idlahcen, T. Godin, A. Hideur, A. Grisard, E. Lallier, S. Fevrier, Mid-IR Supercontinuum in Gallium Arsenide Waveguide, Photonics West LASE, San Francisco, USA, paper 12405-10 (28 January – 2 February 2023)

D. D. Hudson, S. Antipov, L. Li, I. Alamgir, T. Hu, M. El Amraoui, Y. Messaddeq, M. Rochette, S. D. Jackson, and A. Fuerbach, "Toward all-fiber supercontinuum spanning the mid-infrared," Optica **4**, 1163-1166 (2017)

I. Tiliouine, G. Granger, Y. Leventoux, C. Jimenez, M. Jedidi, V. Couderc, and S. Février, "Two-octave mid-infrared supercontinuum pumped by a 4.5 µm femtosecond fiber source". In 2022 Conference on Lasers and Electro-Optics (CLEO)

Supervisors: Sébastien Février (Unilim), Alex Fuerbach (MQ), Solenn Cozic (Le Verre Fluoré)

Research Fields: Applied physics, photonics, nonlinear optics

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Project 2: *Design and fabrication of fiber laser oscillators and amplifiers for mid-infrared spectroscopy*

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 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).

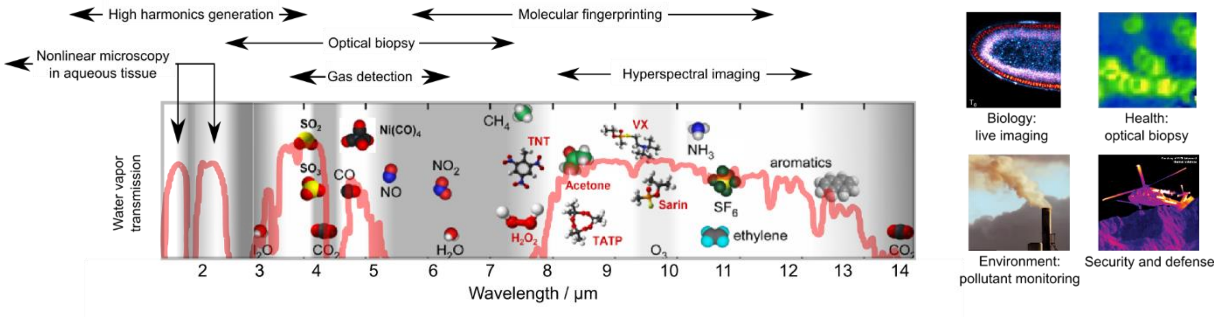

Figure: Applications of high-brightness mid-IR sources

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

Very recently, we have demonstrated the fabrication of thermally stable high numerical aperture integrated waveguides and couplers for the mid-infrared spectral region [Fernandez2022]. Based on these devices, the goal will be to develop the first fully integrated figure-8 laser operating in the 2.7-3.5 µm range, delivering transform-limited femtosecond or picosecond pulses that will subsequently be amplified in an all-fiber amplifier stage. The generated optical pulses will subsequently be spectrally broadened in a

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suitable highly nonlinear medium, for example chalcogenide nanowires or GaAs waveguides. Finally, spectroscopic studies with the broadband laser source will be carried out (e.g. trace gas spectroscopy).

References

F. Borondics, M. Jossent, C. Sandt, L. Lavoute, D. Gaponov, A. Hideur, P. Dumas, and S. Février, "Supercontinuum-based Fourier transform infrared spectromicroscopy," Optica **5**, 378-381 (2018)

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I. Tiliouine, G. Granger, Y. Leventoux, C. Jimenez, M. Jedidi, V. Couderc, and S. Février, "Two-octave mid-infrared supercontinuum pumped by a 4.5 µm femtosecond fiber source". In 2022 Conference on Lasers and Electro-Optics (CLEO)

T. T. Fernandez, B. Johnston, H. Mahmodi, K. Privat, I. Kabakova, S. Gross, M. Withford, A. Fuerbach, "Thermally stable high numerical aperture integrated waveguides and couplers for the 3 µm wavelength range," APL Photonics **7**, 126106 (2022)

Supervisors: Sébastien Février (Unilim), Alex Fuerbach (MQ), Solenn Cozic (Le Verre Fluoré)

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

Project 3: *Few-cycle fiber-based light sources in the mid-infrared*

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 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.

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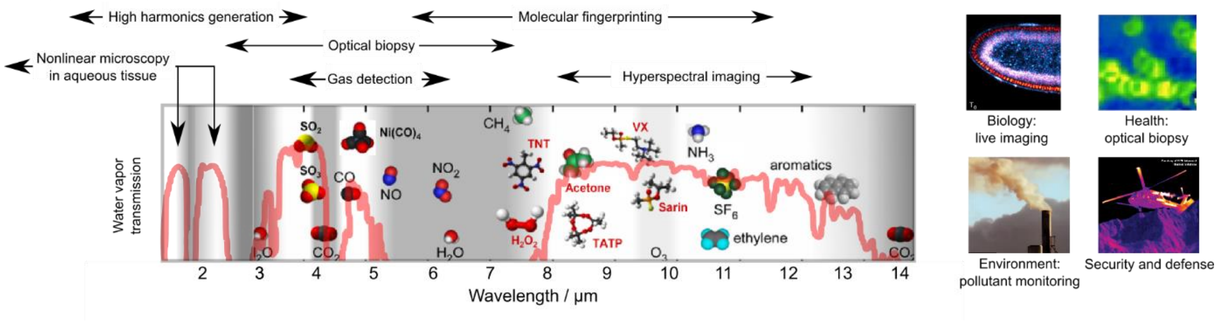

Figure: Applications of high-brightness mid-IR sources

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Research methodology

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Objectives

We plan to propose few cycles laser sources in the mid-infrared from 3 to 4 µm with enough energy per pulse to trigger high-harmonic generation in semi-conductors. The seed laser source will be a commercial laser source emitting 1.5 ps low energy pulses at 1.97 µm. The wavelength will be first converted towards the mid-infrared in a cascade of nonlinear fluoride optical fibers. Then, the pulse energy will be amplified in nonlinear fiber amplifiers made 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 nonlinearly compress the pulse inside the amplifier. Pulse durations of about 30-40 fs (3 to 4 cycles of the electric field) are expected with this technique with potential to decrease to sub-two cycle durations by further self-compression in passive nonlinear devices. Such ultrashort pulses with high energy (tens of nanojoules) are well suited to high-harmonics generation in solid materials such as semi-conductors [Franz2019]. Application to quantum microscopy are foreseen.

References

F. Borondics, M. Jossent, C. Sandt, L. Lavoute, D. Gaponov, A. Hideur, P. Dumas, and S. Février, "Supercontinuum-based Fourier transform infrared spectromicroscopy," Optica **5**, 378-381 (2018)

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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)

Supervisors: Sébastien Février (Unilim), Alex Fuerbach (MQ), 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.

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Benefits include

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

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

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- 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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