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Louise Jumpertz

Nonlinear Photonics in Mid-infrared Quantum Cascade Lasers

Doctoral Thesis accepted by
Télécom ParisTech and mirSense, Paris, France

Springer

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Supervisor's Foreword

I am very honored that Springer is publishing Louise Jumpertz's thesis.

Louise's Ph.D. thesis investigated the nonlinear photonics properties of mid-infrared (mid-IR) quantum cascade lasers (QCLs) operating under external perturbations like optical feedback and optical injection. QCLs are a new class of unipolar semiconductor lasers based on intra-conduction-band quantum well transitions and that emit light from the mid-IR to the THz region. The topic of QCLs is very modern and under rapid development. The first QCL was demonstrated in 1994 at Bell Labs, in the mid-IR spectral range, at cryogenic temperatures. Since then, mid-IR-emitting QCLs have matured over the last 15 years hence providing nowadays room-temperature continuous-wave (CW) operation across the entire 3–15 μm range, and watts of CW output power over the 4–11 μm range. A number of companies now offer mid-IR QCLs as commercial products. Mid-IR QCLs are used in both the defense and civilian sectors with numerous applications, such as infrared countermeasures, chemical and environmental gas sensing, atmospheric communications, high-resolution spectroscopy and microscopy, breath analysis, and other biomedical sensing. The spectacular development of QCLs and their increasing use in practical applications also raise multiple urgent questions related to their stability and dynamical properties. Although a few studies have already reported on the QCL nonlinear dynamics, these are very sparse, hence the field remains almost unknown. As a consequence of that, the objective of Louise's thesis is to address the first-ever comprehensive analysis of the QCL nonlinear dynamics.

Overall, I have been extremely impressed by the amount of work done by Louise throughout her thesis and the level of understanding she has achieved. Her thesis is articulated in 7 chapters including one general introduction, one introducing QCLs, and one discussing optical feedback in interband semiconductor lasers. Among the impressive amount of results, I would like hereinafter to emphasize some of them, which can be seen as strong cutting-edge research results.

1. Louise unveils the first-ever observation of a chaotic radiation in the mid-IR window. Louise drove the 5.6-μm wavelength device into a chaotic regime of operation by applying sufficiently strong optical feedback. As the strength of the

optical feedback was increased, the birth of optical instabilities was observed as a dramatic change in the temporal characteristics of the laser's emission: The initial steady signal started to oscillate and then fluctuated strongly. Low frequency fluctuations were observed in the laser's output—a clear signature of the butterfly effect, hence providing the first-ever source of deterministic temporal chaos at mid-IR wavelengths. As the observed chaotic dynamic appears as similar to class A laser dynamics without a signature of relaxation oscillations, Louise also contradicted the 35-year knowledge of laser diode destabilization from optical feedback, by demonstrating a sequence of bifurcations to chaos originating from self-pulsations at the external cavity frequency, a scenario only observed in gas lasers so far. Chaotic light at mid-infrared wavelengths could be useful for various applications, including encoded atmospheric optical communications, unpredictable countermeasure sources, and jam-resistant remote detection.

2. Louise proves that QCLs are sensitive to optical feedback and elucidated the five dynamical regimes originally observed at Bell Labs in 1986 for interband lasers. She showed that, depending on the external cavity length and the feedback ratio, the emission of mid-IR QCL emitting around 5.6 μm evolves from stable and single mode to a beating between two modes then to a single mode on a mode different from the free-running one; to unstable regime and, finally, to stable and single-mode emission. However, these regimes appear at much higher feedback which is a direct consequence of the sub-picosecond carrier dynamics.
3. From a dynamical viewpoint, Louise confirms the very important role of the linewidth enhancement factor. The α-factor is not strictly zero, contrary to what was predicted theoretically. Two techniques based on optical feedback are used, self-mixing interferometry and wavelength evolution at low feedback ratios, resulting in values ranging from 0.8 to 2.9 strongly dependent on the bias current. These effective α-factor values are consistent with other measurements realized above threshold and at room temperature.
4. Lastly, Louise demonstrates the possibility to engineer the emission pattern of broad-area QCLs using off-centered optical feedback with and without spatial filtering. These results pave the way of powerful sources for optical countermeasures, including night vision blinding and missile out steering. The beam profile of the laser can be strongly improved by suppression of spatial nonlinear effects such as beam steering and this results in operation on the fundamental transverse mode.

To summarize, Louise's thesis provides significant advances toward improving the understanding of QCL dynamics. This excellent research work impacts on the community of QCLs where the current topics concern mode-locking, frequency comb generation, and frequency stabilization hence bringing the question of the QCL dynamics. Lastly, it also impacts on the large community of chaos applications where research is therefore pushed here forward to directions with new wavelengths for the realization of unpredictable countermeasures and encoded atmospheric communication systems. I am confident that this Springer Thesis will be of international appeal.

Paris, France
June 2017

Prof. Frédéric Grillot

Abstract

Mid-infrared quantum cascade lasers are unipolar semiconductor lasers, which have become widely used sources for applications such as gas spectroscopy, free-space communications, or optical countermeasures. Applying external perturbations such as optical feedback or optical injection leads to a strong modification of the quantum cascade laser properties. Optical feedback impacts the static properties of mid-infrared Fabry–Perot and distributed feedback quantum cascade lasers, inducing power increase, threshold reduction, modification of the optical spectrum, which can become either single- or multimode, and enhanced beam quality of broad-area transverse multimode lasers. It also leads to a different dynamical behavior, and a quantum cascade laser subject to optical feedback can oscillate periodically or even become chaotic: This work provides the very first analysis of optical instabilities in the mid-infrared range. A numerical study of optical injection furthermore proves that quantum cascade lasers can injection-lock over a few gigahertz, where they should experience enhanced stability and especially improved modulation bandwidth. Furthermore, some promising dynamics appear outside the locking range with periodic oscillations at a tunable frequency or high-intensity events. A quantum cascade laser under external control could therefore be a source with enhanced properties for the usual mid-infrared applications, but could also address new applications such as tunable photonic oscillators, extreme events generators, chaotic LIDAR, chaos-based secured communications, or unpredictable countermeasures.

Preface

Quantum cascade lasers are unipolar semiconductor lasers offering access to wavelengths from the mid-infrared to the terahertz domain and promising impact on various applications such as free-space communications, high-resolution spectroscopy, LIDAR remote sensing, or optical countermeasures. Unlike bipolar semiconductor lasers, stimulated emission in quantum cascade lasers is obtained via electronic transitions between discrete energy states inside the conduction band. Recent technological progress has led to quantum cascade lasers operating in pulsed or continuous-wave mode, at room temperature in single- or multimode operation, with high powers up to a few watts for mid-infrared devices.

Mid-infrared applications require sources with extremely high performances, in terms of output power, modulation bandwidth, single-mode emission, or narrow linewidth. In interband laser diodes, these properties can usually be significantly improved using external control, either optical injection or optical feedback. The former consists in injecting the light emitted by a first master laser into a second slave laser, whereas in the latter configuration, the light from a single laser is reinjected in its own active region. In the case of optical feedback, depending on the external cavity length and the feedback ratio, i.e., the ratio between reinjected and emitted light, the emission characteristics can either be greatly improved or significantly deteriorated. The dynamical behavior of the laser will also be impacted, leading to stable, periodic, or chaotic emission. Furthermore, optical feedback can reduce the complex spatial nonlinearities occurring in broad-area lasers, such as beam steering or filamentation.

The carrier lifetime of quantum cascade lasers is three orders of magnitude faster than that of interband lasers, and the α-factor is expected to be much smaller, the dynamical response of these structures to optical feedback would therefore be different from that of laser diodes. However, this phenomenon has almost never been studied in quantum cascade lasers, and it is worth verifying whether optical feedback can improve the emission properties of such devices. Furthermore, since parasitic optical feedback may arise from the experimental setups, it is also of prime importance to see whether a quantum cascade laser can destabilize and eventually become chaotic when subjected to this effect. Finally, optical injection might be able to improve the laser properties much more than optical feedback.

Therefore, the objective of this thesis is to study the nonlinear dynamics of quantum cascade lasers subject to optical feedback or optical injection. This work is a collaboration between Télécom ParisTech, mirSense, and the Direction Générale de l'Armement (DGA), to make the most of the expertise of each structure.

Paris, France Dr. Louise Jumpertz

List of Publications

Journal Publications

1. **L. Jumpertz**, M. Carras, K. Schires and F. Grillot, “Regimes of external optical feedback in 5.6 µm distributed feedback mid-infrared quantum cascade lasers”. *Appl. Phys. Lett.*, vol. 105, p. 131112, 2014.
2. **L. Jumpertz**, F. Michel, R. Pawlus, W. Elsässer, K. Schires, M. Carras and F. Grillot, “Measurements of the linewidth enhancement factor of mid-infrared quantum cascade lasers by different optical feedback techniques”. *AIP Adv.*, vol. 6, no. 1, p. 015212, 2016.
3. **L. Jumpertz**, K. Schires, M. Carras, M. Sciamanna and F. Grillot, “Chaotic light at mid-infrared wavelength”. *Light Sci. Appl.*, vol. 5, p. e16088, 2016.
4. **L. Jumpertz**, C. Caillaud, C. Gilles, S. Ferré, K. Schires, L. Brilland, J. Troles, M. Carras and F. Grillot, “Estimating optical feedback from a chalcogenide fiber in mid-infrared quantum cascade lasers”. *AIP Adv.*, vol. 6, no. 10, p. 105201, 2016.
5. S. Ferré, **L. Jumpertz**, M. Carras, R. Ferreira and F. Grillot, “Beam shaping in high-power broad-area quantum cascade lasers using optical feedback”. *Sci. Rep.,* vol. 7, p. 44284, 2017.

Invited Conference Presentations

1. **L. Jumpertz**, F. Michel, R. Pawlus, W. Elsässer, M. Carras and F. Grillot, “Linewidth broadening factor and gain compression in quantum cascade lasers”. SPIE Photonics West, 2016.
2. F. Grillot, **L. Jumpertz**, K. Schires, M. Carras and M. Sciamanna, “Deterministic temporal chaos from a mid-infrared external cavity quantum cascade laser”. SPIE Photonics West, 2016.
3. **L. Jumpertz**, K. Schires, M. Carras and F. Grillot, “Première observation de l’effet papillon dans un laser à cascade quantique émettant dans le moyen infra-rouge”. Journée Nationales d’Optique Guidée (JNOG), 2016.

Conference Presentations

1. V. Trinité, S. Ferré, **L. Jumpertz**, G. Maisons, M. Carras, G.-M. De Naurois, T. Mansipur and F. Capasso, “Experimental and theoretical study of the gain saturation in MIR QCL”. International Quantum Cascade Laser School and Workshop (IQCLSW), 2014: poster presentation.

2. **L. Jumpertz**, M. Carras, K. Schires and F. Grillot, “Regimes of feedback effects in mid-infrared distributed feedback quantum cascade lasers”. International Symposium on Physics and Applications of Laser Dynamics (IS-PALD), 2014: oral presentation.
3. **L. Jumpertz**, M. Carras and F. Grillot, “First experimental observation of external optical feedback regimes in mid-infrared quantum cascade lasers”. Mid-Infrared Optoelectronics: Materials and Devices (MIOMD), 2014: oral presentation.
4. V. Trinité, S. Ferré, **L. Jumpertz**, G. Maisons, M. Carras, G.-M. De Naurois, T. Mansipur and F. Capasso, “Experimental and theoretical study of the gain saturation in MIR QCL”. Mid-Infrared Optoelectronics: Materials and Devices (MIOMD), 2014: oral presentation.
5. **L. Jumpertz**, M. Carras, K. Schires and F. Grillot, “Etude expérimentale des régimes d’auto-injection optique dans les lasers à cascade quantique”. Journée Nationales d’Optique Guidée (JNOG), 2014: oral presentation.
6. **L. Jumpertz**, S. Ferré, K. Schires, M. Carras and F. Grillot, “Nonlinear dynamics of quantum cascade lasers with optical feedback”. SPIE Photonics West, 2015: oral presentation.
7. L. Brilland, L. Provino, S. Venck, D. Méchin, C. Caillaud, S. Ferré, C. Gilles, **L. Jumpertz**, M. Carras and J. Troles, “Optical characterization of a single mode mid infrared microstructured optical fiber up to 10 μm: Potential for supercontinuum generation and applications for QCLs based sensors”. Conference on Lasers and Electro-Optics (CLEO) Europe, 2015: oral presentation.
8. **L. Jumpertz**, F. Michel, R. Pawlus, W. Elsässer, M. Carras and F. Grillot, “Etude expérimentale du facteur de couplage phase-amplitude dans un laser à cascade quantique émettant dans le moyen infra-rouge”. Journée Nationales d’Optique Guidée (JNOG), 2015: oral presentation.
9. **L. Jumpertz**, F. Michel, R. Pawlus, W. Elsässer, K. Schires, M. Carras and F. Grillot, “Experimental investigation of the above-threshold linewidth broadening factor of a mid-infrared quantum cascade laser”. IEEE International Photonics Conference (IPC), 2015: oral presentation.
10. **L. Jumpertz**, K. Schires M. Carras, M. Sciamanna and F. Grillot, “Chaotic pulsing in quantum cascade lasers subject to optical feedback”. International Symposium on Physics and Applications of Laser Dynamics (IS-PALD), 2015: oral presentation.
11. J. Troles, C. Caillaud, C. Gilles, L. Provino, L. Brilland, **L. Jumpertz**, S. Ferré, M. Carras, M. Brun and J.-L. Adam, “Elaboration of a chalocogenide microstructured optical fiber presenting high birefringence”. American Ceramic Society Glass and Optical Material Division (GOMD), 2016: oral presentation.

12. M. F. Pereira, D. Winge, A. Wacker, **L. Jumpertz**, W. Elsässer, M. Carras and F. Grillot, “The Linewidth Enhancement Factor of QCLs”. International Quantum Cascade Laser School and Workshop (IQCLSW), 2016: poster presentation.
13. M. F. Pereira, D. O. Winge, A. Wacker, **L. Jumpertz**, F. Michel, R. Pawlus, W. Elsässer, K. Schires, M. Carras and F. Grillot, “Nonequilibrium Green’s functions theory for the alpha factor of quantum cascade lasers”. SPIE Nanoscience + Engineering, 2016: oral presentation.
14. T. Newell, **L. Jumpertz**, F. Grillot, C. Lu and R. Kaspi, “Investigation of a broad-area quantum cascade laser with external cavity feedback”. International Symposium on Physics and Applications of Laser Dynamics (IS-PALD), 2016: oral presentation.
15. S. Ferré, **L. Jumpertz**, M. Carras and F. Grillot, “Mode control and pattern stabilization in broad area quantum cascade laser by optical feedback”. International Symposium on Physics and Applications of Laser Dynamics (IS-PALD), 2016: oral presentation.

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In *Witches abroad*, Terry Pratchett wrote:

> Because the universe was full of ignorance all around and the scientist panned through it like a prospector crouched over a mountain stream, looking for the gold of knowledge among the gravel of unreason, the sand of uncertainty. [...] But the trouble was that ignorance became more interesting, [...] and people stopped patiently building their little houses of rational sticks in the chaos of the universe and started getting interested in the chaos itself - partly because it was a lot easier to be an expert on chaos, but mostly because it made really good patterns that you could put on a t-shirt.

So let's study chaos...

Contents

Acronyms

AM	Amplitude Modulation
BA	Broad-Area
CPR	Chirp-to-Power Ratio
CW	Continuous-Wave
DFB	Distributed Feedback
DT	Double Trench
ESA	Electrical Spectrum Analyzer
FM	Frequency Modulation
FP	Fabry–Perot
FTIR	Fourier Transform Infrared
FWHM	Full-Width at Half-Maximum
HR	High-Reflectivity
HVPE	Hydride Vapor Phase Epitaxy
ICL	Interband Cascade Laser
IR	Infrared
LEF	Linewidth Enhancement Factor
LFF	Low Frequency Fluctuations
LOC	Large Optical Cavity
MBE	Molecular Beam Epitaxy
MCT	Mercury–Cadmium–Telluride
MOCVD	Metal-Organic Chemical Vapor Deposition
OPO	Optical Parametric Oscillator
PPLN	Periodically Poled Lithium Niobate
QCL	Quantum Cascade Laser
RAM	Residual Amplitude Modulation
RIN	Relative Intensity Noise
RF	Radio-Frequency
SEM	Scanning Electron Microscopy
SNR	Signal-to-Noise Ratio
VCSEL	Vertical-Cavity Surface-Emitting Laser