

QuantERA Call 2021

Final Report

General information about project

Registration code QuantERA2021-QATACOMB

Project title Quantum correlAtions in TerAhertz qcl COMBs

Project acronym QATACOMB

Project start date 01/06/2022

Project end date (Indicate date considering project extension) 31/05/2026

Project duration (project duration considering project extension) 48

Number of institutions in project (including coordinator) 3

Project proposal
[QATACOMB.pdf \(1193.77 kb\)](#)

Project website <https://qatacomb.ino.cnr.it/>

Publishable summary of the project (publishable abstract)

The main goal of the QATACOMB project is to develop the technology necessary to detect non-classical effects in THz radiation. The chosen playground for this challenging task are 1) harmonic quantum cascade lasers (HQCL) as laser sources, 2) graphene field effect transistors and cavity based photoconductive switches as receivers, engaged in 3) a twin-beam quantum correlation detection setup. All these aspects of the project need to be carefully devised, realized and characterized, as the technological leap needed to bring them up to the task is huge.

The main results achieved up to now can be summarized as follows:

- i) TUM developed two simulation tools for the modeling of HFC combs, based on the rotating wave approximation (RWA) and the full-wave approach, respectively. In both cases, carrier transport and dynamical density matrix simulations were combined to achieve self-consistency. To this end, existing code was adapted by adding noise, the possibility of active microwave modulation (for the RWA tool), and other effects. In close collaboration with experiment, the tools were used for the design and improvement of below described HFC comb devices.
- ii) CNR-NANO devised a strategy to obtain broadband HFC emission of a pre-defined order in QCL, by design. By patterning n regularly spaced defects on the top-surface of a double-metal Fabry-Perot QCL, CNR-NANO demonstrate harmonic comb emission with modes spaced by $(n+1)$ free spectral range and with a record optical power/mode of ~ 270 mW.
- iii) CNRS has been concentrating on developing coherent detection techniques that are sensitive at high THz frequencies (~ 3 THz), compared to typical detection methods that are more sensitive around 1 THz frequencies, to be compatible with where THz QCLs operate. This has been based on photoconductive sources, where cavities, both optical and THz, can be designed and realized through standard fabrication methods. These have been validated separately in THz generation schemes showing enhanced emission and controllable THz spectral response.
- iv) Regarding the twin-beam quantum correlation detection setup, a new vacuum cell comprising the whole optical bench has been designed. The cell features all the electrical connections for a stand off alignment of the optical elements inside, the cold finger connections for liquid helium cooling of sources and detectors, an optical grating optimized for THz radiation, that has been ad hoc devised and 3D printing realized.

The first half of QATACOMB has permitted a range of objectives to be attained, which will contribute to the impact of the project: i) Academic: Immediate impacts have included new results that have led to publication of articles in well regarded scientific journals and invitation of the partners to leading conferences. ii) Socio-economic: the already demonstrated ability to control HFC generation by design in THz QCLs paves the way for a number novel applications, which can be of industrial interest. Wider impact is expected also with the development of the novel quantum detectors, while a patent request has already been issued. iii) People: One postdoctoral researcher and one PhD student have been recruited on QATACOMB funding. These researchers have already experienced a range of interdisciplinary skills underpinning the project, and have strongly contributed to the project development.

Consortium composition

1. Project Coordinator (P1)

Institution details

EC Participant Identification Code (PIC) 999979500

Institution country

Italy

Institution name

CONSIGLIO NAZIONALE DELLE RICERCHE

Type of institution

Public research organisation

Department

Istituto Nazionale di Ottica

Institution city

ROMA

Institution address

PIAZZALE ALDO MORO 7

Principal Investigator (PI - Project Leader)

Title

Dr

First name

Luigi

Last name

Consolino

Gender

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Academic age

Senior Researcher

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luigi.consolino@ino.cnr.it

2. Partner 2 (P2)

Institution details

EC Participant Identification Code (PIC) 999997930

Institution country

France

Institution name

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

Type of institution

Public research organisation

Department

Institution city

PARIS

Institution address

RUE MICHEL ANGE 3

Principal Investigator (PI - P2)

Title

Dr

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Academic age

Senior Researcher

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3. Partner 3 (P3)

Institution details

Principal Investigator (PI - P3)

EC Participant Identification Code (PIC) 999977463	Title Dr
Institution country Germany	First name Christian
Institution name TECHNISCHE UNIVERSITAET MUENCHEN	Last name Jirauschek
Type of institution Public research organisation	Gender Man
Department School of Computation, Information and Technology	Academic age Senior Researcher
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Project Team

No.	Title, First name, Last name	Academic age	Institution name, Department, Type of institution	Gender
1	Dr Luigi Consolino Principal Investigator (PI - Project Leader)	Senior Researcher	Project Coordinator (P1) CONSIGLIO NAZIONALE DELLE RICERCHE Istituto Nazionale di Ottica Public research organisation	Man
2	Dr Sukhdeep Dhillon Principal Investigator (PI - P2)	Senior Researcher	Partner 2 (P2) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS Public research organisation	Man
3	Dr Christian Jirauschek Principal Investigator (PI - P3)	Senior Researcher	Partner 3 (P3) TECHNISCHE UNIVERSITAET MUENCHEN School of Computation, Information and Technology Public research organisation	Man
4	Dr Miriam Vitiello	Senior Researcher	Project Coordinator (P1) CONSIGLIO NAZIONALE DELLE RICERCHE Istituto Nazionale di Ottica Public research organisation	Woman
5	Dr Lucia Sorba	Senior Researcher	Project Coordinator (P1) CONSIGLIO NAZIONALE DELLE RICERCHE Istituto Nazionale di Ottica Public research organisation	Woman
6	Dr Paolo De Natale	Senior Researcher	Project Coordinator (P1) CONSIGLIO NAZIONALE DELLE RICERCHE Istituto Nazionale di Ottica Public research organisation	Man

7	Dr Juliette Mangeney	Senior Researcher	Partner 2 (P2) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS - Public research organisation	Woman
8	Dr Pascal Morfin	Senior Researcher	Partner 2 (P2) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS - Public research organisation	Man
9	Dr José Palomo	Senior Researcher	Partner 2 (P2) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS - Public research organisation	Man
10	Dr Roberto Eramo	Senior Researcher	Project Coordinator (P1) CONSIGLIO NAZIONALE DELLE RICERCHE Istituto Nazionale di Ottica Public research organisation	Man
11	Dr Iacopo Galli	Senior Researcher	Project Coordinator (P1) CONSIGLIO NAZIONALE DELLE RICERCHE Istituto Nazionale di Ottica Public research organisation	Man

Number of jobs created within the framework of the current project

No.	Institution name, Department, Type of institution	Title, First name, Last name	Type (Fellowship/ Contract)	New/ Continuation	Gender	Duration (months)
1	Project Coordinator (P1) CONSIGLIO NAZIONALE DELLE RICERCHE Istituto Nazionale di Ottica Public research organisation	Dr Sagar Sutradhar	Contract	New	Man	12
2	Partner 3 (P3) TECHNISCHE UNIVERSITAET MUENCHEN School of Computation, Information and Technology Public research organisation	DR Lukas Seitner	Contract	New	Man	36

Consortium details

1. Has there been any change in the consortium composition since the mid-term report was delivered?

No

2. Have you had any relevant problems with the implementation of the work plan?

Yes

Please select the reason(s) that may explain the problems:

- ☐ Difficulties in recruiting personnel
- ☐ Poor communication between project partners
- ☐ Change of one project partner
- ☐ One or more partners underperforming
- ☒ Experimental/technical difficulties
- ☐ Other

Comments:

The project goals were very challenging, the final goal of performing final quantum limit measurements of non-classical radiation in the THz window could not be achieved. A lot of work has been done to build the path towards this goal.

3. Have new collaborations been made with groups outside the consortium, since the QuantERA project started, due to the results of this project?

Yes

Please indicate how many: 1

With other partner of QuantERA consortium? No

Please provide information:

University of Leeds, Prof. Edmund Linfield.

4. Do you have a platform/website for data sharing?

Yes

Is this data available (or will be) to the scientific community?

- ☐ Available only to the consortium
- ☐ Available to the scientific community
- ☒ Available to the public

5. Have any of the partners used other partners' infrastructures within the scope of the project?

No

6. Has the consortium or any consortium partners applied to other Calls due to this QuantERA project?

Yes

How many submitted in Transnational calls:
How many were granted in Transnational calls:
How many submitted in National calls: 1
How many were granted in National calls: 1

7. Is the collaboration between consortium partners expected to continue after the funding period?

Yes

Please describe how:

The partners will continue informally in joint publication, measurement sessions and future applications to transnational calls.

8. Are there early career researchers scientists in the consortium research groups?

Yes

Please indicate the % of young scientists in relation to all the scientists on the research groups: 30

Project Progress

Topic/topics addressed

Quantum technology (QT) platforms, capable of exploiting non-classical states of atoms, light and solid-state systems, have been recently realized in a variety of strategic fields, such as communication, computation, information, sensing and metrology. Successful achievements in the visible and near-infrared parts of the electromagnetic spectrum have led to astonishing results, opening the quest for the migration to less conventional spectral regions. In this regard, QT migration to the terahertz (THz) frequency range is technologically challenging, although of huge technological potential, aiming at exploiting the peculiar features of this long wavelength radiation, e.g. transmissivity through otherwise opaque materials, or robustness with respect to Rayleigh scattering, can potentially allow a plethora of frontier applications, such as quantum-secured fast digital data transfer in opaque or harsh environments (dust, smog, particulate) or quantum-enhanced sensitivity in spectroscopic and metrological THz setups. The possibility of developing a miniaturized solid-state platform for generation, detection and complete characterization of non-classical states of THz frequency light is therefore a very challenging and futuristic task, also given the large technological gap dividing the unconventional THz spectral region and the friendly visible or near-infrared ones. QATACOMB has pushed THz technology beyond the previous limits, paving the way towards QT application in this very unconventional spectral region.

Concerning quantum optical modeling, TUM has developed a symbolic-numeric Python library. We have taken into account a third-order Kerr-like nonlinearity to model the interactions between different HFC comb modes. Since the governing equations yield an infinite hierarchy problem for quantum mechanical moment recursion, different truncation rules have been implemented. It turned out that in the large-photon-number limit these recursion computations become numerically unstable. Hence, we have started investigating the error scaling with truncation order depending on the photon number.

CNR implemented an experimental methodology that alleviates the influence of device fabrication and operation uncertainties on the emission state of THz QCL frequency combs (FCs) allowing the specific order of a harmonic frequency comb (HFC) to be determined in advance. We engineer, by design, broadband HFCs with a tailored number of harmonic modes of a pre-defined order in standard FP cavity THz QCLs. By employing a heterogeneous gain medium and a cavity architecture that integrates a fixed number of scattering points (defects) placed at designed points along the top surface of the double-metal QCL cavity, we demonstrate harmonic comb emission over the entire operational range of the QCL, with harmonic modes spaced by (n) FSR. Our approach adopts a standard linear cavity, rather than a ring cavity, and does not require external modulation which would necessitate complex external circuitry. $N=8$ th-order harmonic combs have been engineered implementing both homogeneous (optical bandwidth ~ 0.5 THz) and heterogeneous (optical gain bandwidth ≥ 1 THz) QCL active regions, with a central frequency at ~ 3 THz. For both QCLs, CNR fabricated FCs and HFCs (with mode spacing in the 115-120 GHz range) with localized top surface (N-1) graphene scatters, equally distributed Fourier transform infrared emission spectra and beat note intensity maps have been measured experimentally. All devices show stable comb behaviour at a driving current corresponding to the peak optical power.

The primary role of the CNRS partner was to enhance coherent detection of THz signals, with a specific focus on improving performance at frequencies around 3 THz and applying these advancements to the detection of harmonic quantum cascade laser combs. Currently, Electro-Optic Sampling (EOS) is the standard method for THz detection. This technique relies on a crystal, where the thickness plays a critical role: thinner crystals offer broader bandwidth but at the cost of lower signal amplitude, necessitating a compromise between these two factors. The CNRS partner also investigated the dynamics of harmonic comb operation in ring QCLs, aiming to advance their use in pulse and harmonic generation and using the detector advances of WP2.

CNR demonstrated state-of-the-art THz photo-thermoelectric detectors based on hBN-encapsulated graphene, integrated with an antenna-coupled Salisbury screen photonic cavity. The hBN-graphene heterostructure reduces disorder and residual carrier density, thus improving the thermoelectric properties of graphene, while the Salisbury screen architecture improves THz field-enhancement at the graphene junction and enhances electromagnetic absorption.

Related to WP3, the core of the twin-beam detection setup devised for WP3 is a reflection optical grating, employed for spatially separating the components of the THz HFC QCL. This component is not commercially available for THz radiation, therefore CNR devised, realized and characterized a new one. The experimental setup has been devised to operate under strict vacuum conditions, in order to avoid absorption by molecules present in laboratory air, as mentioned in the initial work plan. The detection setup was prepared for the twin beam detection and was tested with the HFC QCL.

Activities implemented

WP1: The role of TUM was modeling of QCL operation on the levels of carrier transport, device dynamics and quantum optics. Regarding semiclassical simulations, we have further developed our multiphysics simulation approach. Here, the quantum active region is self-consistently modeled by combining carrier transport with dynamical density matrix simulations. For more realistic modeling, we have implemented linewidth enhancement due to nonparabolicity effects and Bloch gain based on a microscopic description. Furthermore, the optical field evolution is captured by Maxwell's equations (or related propagation equations). Since cavity engineering is increasingly used as an additional method (besides active region design) to control the QCL dynamics, we have extended our approach by including, e.g., slits, defects, distributed saturable losses, and tapering. This has enabled the simulation of various experimental designs fabricated by CNR, in particular actively mode-locked QCLs using graphene stripes for saturable absorption along the waveguide, and defect-engineered harmonic frequency comb (HFC) devices. Furthermore, based on a transmission line model, electrical microwave modulation and propagation has been implemented, as is often used for enforcing mode-locked operation and HFC generation, and for frequency comb stabilization. Also our full-wave simulation tool which does not invoke the commonly applied rotating-wave approximation (open-source tool mbsolve) has been further developed, and used for the investigation of free-running HFCs as well as of THz comb devices by CNRS based on intracavity down-conversion of a mid-infrared comb. For both tools, fluctuations (e.g., due to spontaneous emission) have been added for a realistic simulation of the optical field buildup and noise characteristics.

WP2:

CNR fabricated and tested THz QCL FCs and HFCs, exploiting different cavity architectures: i) Fabry-Perot, ii) longitudinal wire lasers with distributed top surface graphene scatters, iii) micro-rings with localized defects. $N=8$ th-order harmonic combs have been engineered implementing both homogeneous (optical bandwidth ~ 0.5 THz) and heterogeneous (optical gain bandwidth ≥ 1 THz) QCL active regions, with a central frequency at ~ 3 THz. For both QCLs, CNR-NANO fabricated FCs and HFCs (with mode spacing in the 115-120 GHz range) with localized top surface (N-1) graphene scatters, equally distributed Fourier transform infrared emission spectra and beat note intensity maps have been

measured experimentally. All devices show stable comb behaviour at a driving current corresponding to the peak optical power. CNR also conceived an architecture for the generation of HFC at the second harmonic by design, throughout the entire QCL dynamic range, engineering micro-ring THz QCL. Experimental results, in excellent agreement with simulations, have shown that four equidistant defects (pads) distributed at each $\pi/2$ interval, results in stable second harmonic generation across the entire dynamic range of the device. We employed a heterogeneous active medium composed of multiple active regions, which expanded the emission bandwidth, aiming to a spectral coverage of more than 1 THz, unreached so far.

To address the limitations related to EOS technique, CNRS explored the development of a cavity-based photoconductive antenna (PCA). This approach incorporates a nano-structured grating for optical beam confinement to enhance optical absorption and a $\lambda/4$ cavity to enhance THz confinement at the QCL frequencies of 3 THz. The materials used optimised LT-GaAs, which, due to its defects, enables faster free-carrier relaxation, making it more suitable for detection. The new fabrication process involves bonding a LT-GaAs wafer to a metal-polymer substrate to realise the thick $\lambda/4$ cavity, and realising the electrode structure on the surface using clean-room fabrication methods. The challenge here was to be able to realise cavity thickness of a few to ten microns whilst conserving the targeted performances.

Related to hBN-encapsulated graphene detectors, coupled with an antenna-coupled Salisbury screen photonic cavity, it is worth mentioning that this combined materials and photonic strategy enables efficient zero-bias photo-thermoelectric detection at room temperature, achieving noise-equivalent powers $< 10 \text{ pWHz}^{1/2}$, minimum detectable powers of $\sim 150 \text{ pW}$, a dynamic range spanning six orders of magnitude and response times of 3 ns at $\sim 3 \text{ THz}$. Remarkably, this unique combination of specs represents the state-of-the-art among available high frequency THz detectors and places these devices among the most competitive room-temperature THz receivers. Frequency-resolved measurements show that the detector response is governed by antenna-cavity field enhancement. These results establish hBN-encapsulated graphene integrated with engineered THz cavities as a powerful route towards next-generation detectors for spectroscopy, communications and emerging quantum technologies.

WP3: Regarding the novel THz reflection grating, the simulation performed by CNR returned an optimal configuration with an echelle configuration and step dimensions of $100 \times 50 \text{ }\mu\text{m}$. In this configuration the obtained separation for beams 90 GHz apart is 3.26 degrees. Finally, the devised optical grating has been 3D printed and gold deposition has been performed, covering the device with a 200nm thick Cr/Au layer by thermal evaporation. The realized optical grating has been inserted in the devised twin-beam detection setup, actively separating the modes of the HFC QCL.

The CNRS partner also investigated the dynamics of harmonic comb operation in ring QCLs, aiming to advance their use in pulse and harmonic generation and using the detector advances of WP2. QCLs that were designed for harmonic comb operation, successfully realized by the partner CNR, were characterized to understand their build-up dynamics that can influence their frequency comb noise characteristics.

Significant results

WP1:

1. Design of HFCs: Based on the developed simulation tools, defect-engineered harmonic frequency comb (HFC) devices with heterogeneous active region by CNRs were simulated. For comparison, free-running comb devices were also theoretically investigated, which required full-wave simulations beyond the rotating-wave approximation since there the inversion grating due to spatial hole burning is fully included (and not only in form of a truncated spatial Fourier representation). The simulations clearly demonstrate, in agreement with experimental observations, that the sensitivity of free-running HFCs to external conditions and exact design details (e.g., fabrication tolerances) can be avoided by control mechanisms. In particular, our simulations confirm that defect-engineered waveguides allow stabilization and adjustment of the harmonic order of the HFC without external current modulation, which would require expensive high-frequency circuitry.
2. Modeling of nonclassical light: The most basic quantum optical HFC model, featuring a classical pump mode and two sidebands, predicts that for squeezing/entanglement the parametric gain rate, i.e., intensity times nonlinear susceptibility, should be large compared to the gain and loss. For THz as compared to mid-infrared QCLs, the nonlinear susceptibility is much bigger while gain/loss are comparable, thus favoring nonclassical light generation in THz QCLs.

WP2:

1. CNR demonstrates stable 2nd - 6th order, HFC emission in terahertz frequency QCLs by respectively patterning an individual or a couple of equally spaced distributed multilayer graphene absorbers on the top metallic waveguides demonstrating record optical power/mode $> 400 \text{ }\mu\text{W}$. CNR-NANO also developed HFC microring THz QCL patterning scattering on the micro-ring top contact to strategically induce losses in the cavity for the stabilization of the HFC emission. The experimental results, in strong agreement with numerical simulations, demonstrate that introducing four equally spaced defects at angular intervals of $\pi/2$ effectively suppresses some of the WG modes, resulting in stable second-harmonic comb operation in continuous wave
2. CNRS optical devices were systematically successfully realized and characterization efforts were focused on the influence of the contact geometry and cavities, both of which contributed to improving high-frequency performance and detection capabilities. The performance agreed with electromagnetic simulations showing enhanced response at the targeted higher frequencies, with an optimal THz cavity size of around $7 \text{ }\mu\text{m}$. The results of the interdigitated cavity-based PCAs show significant promise, achieving enhanced detection by a factor of 100 at 3 THz, as well as extending the detection range up to 12 THz. Although the targeted performances were reached, future work can further improve the devices such as optimizing cavity size, improving coupling with nano-gratings, and combining plasmonic confinement with THz cavities.
3. CNR demonstrated that hBN-encapsulated, high-quality graphene is key to advancing THz photodetector performance. By suppressing disorder-induced charge puddles and preserving graphene's intrinsic electronic transport properties, we demonstrate a novel heterostructure engineering that yields Seebeck coefficients that are 100% larger than those of CVD-based devices, leading to markedly enhanced photo-thermoelectric conversion. When combined with the strong electromagnetic absorption enabled by the AgSS architecture, this improved thermoelectric efficiency translates directly into high responsivities ($\sim 1 \text{ kV/W}$) and low noise-equivalent powers. The resulting receivers exhibit NEPs below $10 \text{ pW Hz}^{-1/2}$, minimum detectable powers of $\sim 150 \text{ pW}$, a dynamic range spanning six orders of magnitude, and response times of 3 ns at $\sim 3 \text{ THz}$ at room temperature.

WP3:

1. For the THz optical grating characterization, given the geometrical constraints of the setup employed and the devised grating pitch ($D=180 \text{ }\mu\text{m}$), we could simulate the diffraction angles expected for the HFC QCL emitted frequencies, together with the expected efficiency curve. Regarding the diffraction angles, experimental data are close to the simulation, and a fit on the experimental data, returns an average grating groove pitch of $D=180.1 \pm 0.9 \text{ }\mu\text{m}$, which is in perfect agreement with the devised one. At the same time, the measured relative efficiencies for

modes at 2.72 THz, 2.895 THz and 3.156 THz are very close to the values theoretically expected. Indeed, the prototype of the optical device has shown extremely good performance. Overall, the optical grating, 3D-printed by CNR, results in a fully usable device, capable of selecting and isolating single modes emitted by a QCL HFC.

2. Regarding harmonic comb operation in ring QCLs, CNRS demonstrated the important role of phase offsets in the build-up dynamics when comparing Fabry-Perot and ring lasers for harmonic comb generation. Indeed, owing to the perfect shape of the ring laser, resulting in zero phase offset, harmonic comb behaviour is observed instantaneously from the build-up over hundreds of picoseconds to stable operation at nanosecond timescales. This is in strong contrast to the Fabry-Perot lasers with phase offsets that result in instabilities in harmonic behaviour. This was corroborated with simulations from the partner TUM. The ring laser geometries also showed a rich frequency comb behaviour when coupled to other type of waveguides where the bias conditions of the ring alter the emission and propagation characteristics of the coupled system. Our time-resolved measurements reveal distinct and highly controllable switchable operation between multi-mode emission with pulse generation and stable single-mode operation. This work is important as it shows the role of defects or phase offset in low noise frequency comb operation and will impact THz photonic circuits, as well as THz Quantum Optics.

Deviations

The Consortium has been working extensively on the project tasks, developing the technology needed for the final goal with progress in several areas, both experimental and theoretical. The project has advanced with results that go beyond the state-of-the-art, e.g. the ability to control harmonic frequency comb (HFC) generation by design in THz QCLs, the development of advanced simulation tools for the modelling of HFC combs, and the realization of new types of coherent sources and detectors based on cavities for sensitive detection of quantum states. As an example, related to the THz detectors developed in WP2, the achieved combination of sensitivity, speed, dynamic range and operating frequency represents the state-of-the-art performance for detection at high THz frequencies (~ 3 THz). These results establish the integration of high-quality layered material heterostructures with engineered photonic absorption as a powerful route towards scalable, high-performance THz technologies. In some cases, devices that were initially not included in the project were investigated, i.e. in-depth investigation of the dynamics of harmonic comb operation was investigated in both Fabry-Perot and ring based QCLs. These were characterised to understand their build-up dynamics that can influence their frequency comb noise characteristics. Indeed, in the ring lasers, we were able to demonstrate that harmonic comb behaviour is observed instantaneously from the build-up over hundreds of picoseconds to stable operation at nanosecond timescales, whereas Fabry-Perot lasers showed instabilities in the harmonic behaviour. This is vital behaviour as it shows that lower noise characteristics are therefore expected from the ring laser and that these geometries, which were not initially planned in the project, are better adapted for the investigation of quantum optics.

6 Milestones were initially set for the QATACOMB project, and 4 were successfully achieved, leading to real advancement in THz science, proved by a plethora of papers published in high-impact factor scientific journals. The 2 remaining milestones, related to the detection of non-classical states of light, were very ambitious, considering that this kind of measurements have only been performed in the visible and near infrared spectral regions. The same measurements have not been demonstrated in the mid-infrared region, despite more advanced and performing detectors, and despite the possibility to realize coherent source with an astonishing grade of quantum coherence, i.e. optical parametric oscillators (OPOs).

Finally, it is worth mentioning that the twin-beam experimental setup has devised and realized, operating under strict vacuum conditions, in order to avoid absorption by molecules present in laboratory air, as mentioned in the initial work plan. The setup was finally prepared for the twin beam detection and was tested with a THz HFC QCL.

How does the project perform compared to the initial work plan in terms of budget, timing and outcomes?

Behind schedule

Has the duration of the project been extended?

Yes

Please indicate the extension time (in months): 12 and the reason:

An extension of 12 months has been requested.

Deliverables and milestones

No.	Deliverables / Milestones	Type	Partners involved	Comments
1	M1: First THz HFC design based on coupled carrier transport and dynamic simulations of THz HFCs	Report	TECHNISCHE UNIVERSITAET MUENCHEN (P3)	Was provided to CNR in time. In particular, simulations confirmed that using a defect-engineered waveguide structure provides stabilization and robustness against parameter variations, and enables harmonic order adjustment.
2	M2: Realization and characterization of THz QCL harmonic frequency combs with intermode spacing > 80 GHz, output power per comb mode > 1 mW	Report	CONSIGLIO NAZIONALE DELLE RICERCHE (P1)	CNR successfully developed HFC THz QCL with intermode spacing of 120 GHz (8th order) and output power/mode of 1mW in this latter configuration.
3	M3: Realization of twin nanoscale THz quantum sensors with operating temperature >10 K, NEP ~0.2 pW/Hz ^{1/2} , external quantum efficiency > 1%, bandwidth > 200 MHz	Report	CONSIGLIO NAZIONALE DELLE RICERCHE (P1)	CNR successfully developed zero-bias photo-thermoelectric detectors operating at room temperature, with noise-equivalent powers < 10 pW/Hz ^{1/2} , minimum detectable powers of ~150 pW, a dynamic range spanning six orders of magnitude and response times of 3 ns at ~3 THz. CNR also successfully developed antenna-coupled tunnel field-effect transistors, based on multilayer graphene/hBN/bilayer graphene/hBN that detect multiwavelength beams at frequencies ~3 THz with record performances. We reach noise-equivalent powers of ~10-12 W/Hz ^{1/2} , a power dynamic range exceeding 5 orders of magnitude, limited by the maximum output power (0.8 mW) of the employed source, and a minimum detectable power at the nW-level, in a frequency-scalable device architecture.
4	M4: Realisation of twin nano-photoconductive switches with sensitivities to mV/cm fields at QCL frequency	Report	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)	Enhanced photodetectors based on cavities and nano-structures were developed that showed an increase by a factor of 100 compared to electro-optic crystals at the targeted QCL frequencies. This was achieved using a set of different cavity thicknesses. This corresponds to be able to detect fields on the order of mV/cm. Although twin photodetectors were not realised within the project, performances of multiple detectors showed the reliability and fabrication yield of the detectors, highlighting that they can be applied in a twin photodetector geometry.

5 M5: Detection of non-classical states between side QCL comb modes

Report

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

The twin-beam experimental setup has devised and realized, operating under strict vacuum conditions, in order to avoid absorption by molecules present in laboratory air, as mentioned in the initial work plan. The setup was prepared for the twin beam detection and was tested with a THz HFC QCL.

However, the detection of non-classical states of light could not be achieved. It has to be considered that this is a very ambitious goal, considering that this kind of measurements have only been performed in the visible and near infrared spectral regions. The same measurements have not been demonstrated in the mid-infrared region, despite more advanced and performing detectors, and despite the possibility to realize coherent source with an astonishing grade of quantum coherence, i.e. optical parametric oscillators (OPOs).

6 M6: Electric field correlations between side QCL comb modes

Report

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

Owing to delays in the optimisation of the coherent photodetectors for ultrafast detection and a breakdown in the laser system, the electric field correlation experiments was not achievable in the timeframe of the project. However, in-depth investigation of the dynamics of harmonic comb operation was investigated in both Fabry-Perot and ring based QCLs. Lower noise characteristics are expected from the ring laser and these geometries, which were not initially planned in the project, are better adapted for the investigation of quantum optics.

Collaboration

Transnational collaboration

The partners were active in collaborating with each other and sharing information on the project's progress. This included the organization of several project meetings, and beyond these formal meetings, regular meetings, discussion and exchange of samples have taken place between all partners throughout the duration of the project. Collaboration on project management was usually organized through email messaging, with the help of tools for collective decision (e.g. doodle.com). All partners have participated in the project meetings and the general advancement goals of the project.

Interactions within the Quantum Flagship

Part of the present Consortium is has been involved in the Quantum Flagship H2020-FETFLAG-2018-2020 QOMBS (Quantum simulation and entanglement engineering in quantum cascade laser frequency combs) project, focusing on mid-IR QCLs. The modeling and device optimization techniques developed there have in part provided a useful basis for the tasks envisioned in the QATACOMB project.

Part of the present Consortium is also involved in the H2020-FETOPEN-2018-2020 project EXTREME-IR (Extreme Optical Nonlinearities in 2D materials for Far-Infrared Photonics). The project aims to break the technological barrier existing in the realization of coherent sources in the 5-12 THz spectral window. This will be attempted by pioneering a radically new platform exploiting nonlinear optics in 2D materials to realize functionalized, compact and coherent far-infrared sources. Despite the two projects being related to such different subjects, the project EXTREME-IR opens new perspectives towards a new set of materials and a new class of devices that could be interesting in the long term for far infrared generation and detection.

Consortium Meetings

N°	Date	Location	Attending partners	Purpose/ main issues/ main decisions?
1	14/06/2022	Sesto Fiorentino (FI) Italy	CONSIGLIO NAZIONALE DELLE RICERCHE (P1) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2) TECHNISCHE UNIVERSITAET MUENCHEN (P3)	Kick off meeting.
2	10/02/2023	Online meeting	CONSIGLIO NAZIONALE DELLE RICERCHE (P1) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2) TECHNISCHE UNIVERSITAET MUENCHEN (P3)	6 months meeting. Project management, discussion on general advancement goals of the project.
3	18/07/2023	Paris, France	CONSIGLIO NAZIONALE DELLE RICERCHE (P1) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2) TECHNISCHE UNIVERSITAET MUENCHEN (P3)	1 year meeting. Project management, discussion on general advancement goals of the project, sample exchange.
4	04/11/2024	Munich, Germany	CONSIGLIO NAZIONALE DELLE RICERCHE (P1) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2) TECHNISCHE UNIVERSITAET MUENCHEN (P3)	2 year meeting. Project management, discussion on general advancement goals of the project, sample exchange.
5	09/09/2025	Online meeting	CONSIGLIO NAZIONALE DELLE RICERCHE (P1) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2) TECHNISCHE UNIVERSITAET MUENCHEN (P3)	3 year meeting. Project management, discussion on general advancement goals of the project, sample exchange.
6	19/06/2026	Online meeting	CONSIGLIO NAZIONALE DELLE RICERCHE (P1) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2) TECHNISCHE UNIVERSITAET MUENCHEN (P3)	Closing meeting, Project management, discussion on goals of the project, ideas for next steps and project continuation.

Mobility of human resources

List of publications, presentations and posters

N°: 1

Year: 2023

Title: Self-consistent simulations of intracavity terahertz comb difference frequency generation by mid-infrared quantum cascade lasers

Journal: Journal of Applied Physics

DOI number: 10.1063/5.0151036

Status: In press

Output type: International Peer-reviewed journals

Link:

<https://pubs.aip.org/aip/jap/article/133/23/233103/2896994/Self-consistent-simulations-of-intracavity-comb-difference-frequency-generation-by-mid-infrared-quantum-cascade-lasers>

All co-authors & Gender

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Jirauschek, Christian (gender: Man)

De Natale, Paolo (gender: Man)

Seitner, Lukas (gender: Man)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

2023 - J appl phys Popp.pdf
(23/10/2023, 2244.11 kb)

N°: 2

Year: 2023

Title: Theory of Hybrid Microwave–Photonic Quantum Devices

Journal: Laser & Photonics Review

DOI number: 10.1002/lpor.202300461

Status: In press

Output type: International Peer-reviewed journals

Link:

<https://onlinelibrary.wiley.com/doi/full/10.1002/lpor.202300461>

All co-authors & Gender

Jirauschek, Christian (gender: Man)

Partner institutions

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

Laser Photonics [...]ntum Devices.pdf
(23/10/2023, 1211.06 kb)

N°: 3

Year: 2023

Title: Influence of eigenstate basis sets on self-starting harmonic comb simulations in THz QCLs

Journal: Numerical Simulation of Optoelectronic Devices

DOI number: 10.1109/NUSOD59562.2023.10273518

Status: Accepted

Output type: International Communications (presentations, posters)

Link: <https://ieeexplore.ieee.org/document/10273518>

All co-authors & Gender

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Seitner, Lukas (gender: Man)

Partner institutions

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

Talk.pdf
(30/10/2023, 3515.21 kb)

N°: 4

Year: 2023

Title: Short pulse generation from a graphene-coupled passively mode-locked terahertz laser

Journal: Nature Photonics

DOI number: 10.1038/s41566-023-01195-z

Status: In press

Output type: International Peer-reviewed journals

Link: <https://www.nature.com/articles/s41566-023-01195-z>

All co-authors & Gender

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Mangeney, Juliette (gender: Woman)

Dhillon, Sukhdeep (gender: Man)

Vitiello, Miriam (gender: Woman)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS

(P2)
TECHNISCHE UNIVERSITAET MUENCHEN (P3)

s41566-023-01195-z-3.pdf
(23/10/2023, 2148.18 kb)

N°: 5
Year: 2023
Title: Anti-correlation phenomena in quantum cascade laser frequency combs
Journal: APL Photonics
DOI number: 10.1063/5.0160103
Status: Accepted
Output type: International Peer-reviewed journals
Link:
<https://pubs.aip.org/aip/app/article/8/10/106106/2917006/Anti-correlation-phenomena-in-quantum-cascade>

All co-authors & Gender
Consolino, Luigi (gender: Man)
De Natale, Paolo (gender: Man)

Partner institutions
CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

APL photonics Chomet.pdf
(23/10/2023, 8021.14 kb)

N°: 6
Year: 2023
Title: Time/frequency-domain characterization of a mid-IR DFG frequency comb via two-photon and heterodyne detection
Journal: Optics Express
DOI number: 10.1364/OE.493321
Status: Accepted
Output type: International Peer-reviewed journals
Link:
<https://opg.optica.org/oe/fulltext.cfm?uri=oe-31-21-35330>

All co-authors & Gender
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Partner institutions
CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

2023 - Opt Exp Gabbrielli.pdf
(30/10/2023, 5370.78 kb)

N°: 7
Year: 2025
Title: Dynamic modeling of mode-locked pulses and frequency combs in strongly microwave-modulated semiconductor lasers
Journal: APL Photonics
DOI number: 10.1063/5.0270594
Status: Accepted
Output type: International Peer-reviewed journals
Link:
<https://pubs.aip.org/aip/app/article/10/11/116107/3373306/Dynamic-modeling-of-mode-locked-pulses-and>

All co-authors & Gender
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Partner institutions
TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 8
Year: 2025
Title: Aspects of cavity engineering in THz quantum cascade laser frequency combs
Journal: Nanophotonics
DOI number: 10.1515/nanoph-2025-0145
Status: Accepted
Output type: International Peer-reviewed journals

All co-authors & Gender
Jirauschek, Christian (gender: Man)
Seitner, Lukas (gender: Man)

Partner institutions
TECHNISCHE UNIVERSITAET MUENCHEN (P3)

Link:

<https://onlinelibrary.wiley.com/doi/pdf/10.1515/nanoph-2025-0145>

N°: 9

Year: 2025

Title: Effective discrete-level density matrix model for unipolar quantum optoelectronic devices

Journal: Nanophotonics

DOI number: 10.1515/nanoph-2024-0766

Status: Accepted

Output type: International Peer-reviewed journals

Link:

<https://onlinelibrary.wiley.com/doi/10.1515/nanoph-2024-0766>

All co-authors & Gender

Jirauschek, Christian (gender: Man)

Partner institutions

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 10

Year: 2024

Title: Multi-domain modeling of free-running harmonic frequency comb formation in terahertz quantum cascade lasers

Journal: IEEE Photonics J.

DOI number: 10.1109/JPHOT.2024.3370189

Status: Accepted

Output type: International Peer-reviewed journals

Link: <https://ieeexplore.ieee.org/document/10449362>

All co-authors & Gender

Jirauschek, Christian (gender: Man)

Seitner, Lukas (gender: Man)

Partner institutions

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 11

Year: 2024

Title: Theoretical model of passive mode-locking in terahertz quantum cascade lasers with distributed saturable absorbers

Journal: Nanophotonics

DOI number: 10.1515/nanoph-2023-0657

Status: Accepted

Output type: International Peer-reviewed journals

Link:

<https://onlinelibrary.wiley.com/doi/10.1515/nanoph-2023-0657>

All co-authors & Gender

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Vitiello, Miriam (gender: Woman)

Partner institutions

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 12

Year: 2024

Title: Modeling of fluctuations in dynamical optoelectronic device simulations within a Maxwell-density matrix Langevin approach

Journal: APL Quantum

DOI number: 10.1063/5.0183828

Status: Accepted

Output type: International Peer-reviewed journals

Link:

<https://pubs.aip.org/aip/apq/article/1/1/016109/3270823/Modeling-of-fluctuations-in-dynamical>

All co-authors & Gender

Jirauschek, Christian (gender: Man)

Seitner, Lukas (gender: Man)

Partner institutions

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 13
Year: 2024
Title: Sculpting harmonic comb states in terahertz quantum cascade lasers by controlled engineering
Journal: OPTICA
DOI number: 10.1364/OPTICA.509929
Status: Accepted
Output type: International Peer-reviewed journals
Link: <https://doi.org/10.1364/OPTICA.509929>

All co-authors & Gender
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 Vitiello, Miriam (gender: Woman)

Partner institutions
 TECHNISCHE UNIVERSITAET MUENCHEN (P3)
 CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 14
Year: 2026
Title: Quantum cascade laser roadmap
Journal: arXiv
DOI number: 10.48550/arXiv.2602.17042
Status: In preparation
Output type: International Peer-reviewed journals
Link: <https://arxiv.org/abs/2602.17042>

All co-authors & Gender
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Partner institutions
 CONSIGLIO NAZIONALE DELLE RICERCHE (P1)
 CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)
 TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 15
Year: 2026
Title: Time domain modeling of actively modulated semiconductor lasers
Journal: Photonics Europe 2026
DOI number: 10.1117/12.3100009
Status: Accepted
Output type: International Communications (presentations, posters)
Link: <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/14090/140900L/Time-domain-modeling-of-actively-modulated-semiconductor-lasers/10.1117/12.3100009.full>

All co-authors & Gender
 Jirauschek, Christian (gender: Man)
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Partner institutions
 TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 16
Year: 2025
Title: A symbolic-numeric computation framework for bosonic operators: modeling quantum features in QCL frequency combs
Journal: Photonics West 2025
DOI number: 10.1117/12.3043228
Status: Accepted
Output type: International Communications (presentations, posters)
Link: <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/13376/1337600/A-symbolic-numeric-computation-framework-for-bosonic-operators--modeling/10.1117/12.3043228.full>

All co-authors & Gender
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Partner institutions
 TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 17

All co-authors & Gender



Year: 2025

Title: Dynamic modeling of quantum cascade lasers based on Maxwell-density matrix approaches

Journal: Photonics West 2025, invited talk

DOI number: 10.1117/12.3042759

Status: Accepted

Output type: International Communications (presentations, posters)

Link:

<https://www.spiedigitallibrary.org/conference-proceedings-of-spie/13385/133850F/Dynamic-modeling-of-quantum-cascade-lasers-based-on-Maxwell-density/10.1117/12.3042759.full>

Jirauschek, Christian (gender: Man)

Partner institutions

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 18

Year: 2025

Title: Cavity engineering of THz QCLs: a Maxwell-Bloch-based model to tailor the emission spectra

Journal: Photonics West 2025

DOI number: 10.1117/12.3042740

Status: Accepted

Output type: International Communications (presentations, posters)

Link:

<https://www.spiedigitallibrary.org/conference-proceedings-of-spie/13376/133760P/Cavity-engineering-of-THz-QCLs--a-Maxwell-Bloch-based/10.1117/12.3042740.short>

All co-authors & Gender

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Vitiello, Miriam (gender: Woman)

Seitner, Lukas (gender: Man)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 19

Year: 2024

Title: Modeling of short pulse generation in THz quantum cascade lasers with embedded graphene saturable absorber

Journal: Photonics West 2024

DOI number: 10.1117/12.3002788

Status: Accepted

Output type: International Communications (presentations, posters)

Link:

<https://www.spiedigitallibrary.org/conference-proceedings-of-spie/12895/3002788/Modeling-of-short-pulse-generation-in-THz-quantum-cascade-lasers/10.1117/12.3002788.full>

All co-authors & Gender

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Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 20

Year: 2024

Title: Theoretical investigation of harmonic frequency comb formation dynamics in defect-engineered THz quantum cascade lasers

Journal: SPIE Photonics Europe 2024

DOI number: 10.1117/12.3017516

Status: Accepted

Output type: International Communications (presentations, posters)

Link:

<https://www.spiedigitallibrary.org/conference-proceedings-of-spie/12994/1299406/Theoretical-investigation-of-harmonic-frequency-comb-formation-dynamics-in-defect/10.1117/12.3017516.short>

All co-authors & Gender

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Partner institutions

TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 21

Year: 2025

Title: Extended spectral response of cavity-based terahertz photoconductive antennas and coherent detection of quantum cascade lasers

Journal: Nanophotonics

DOI number: 10.1515/nanoph-2025-0088

Status: Accepted

Output type: International Peer-reviewed journals

Link:

<https://onlinelibrary.wiley.com/doi/full/10.1515/nanoph-2025-0088>

All co-authors & Gender

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Palomo, José (gender: Man)

Mangeney, Juliette (gender: Woman)

Partner institutions

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 22

Year: 2024

Title: Terahertz digitated photoconductive antennas based on a single high resistivity metal and nanoplasmonic electrode

Journal: Photonics and Nanostructures - Fundamentals and Applications

DOI number: 10.1016/j.photonics.2024.101248

Status: Accepted

Output type: International Peer-reviewed journals

Link: <https://doi.org/10.1016/j.photonics.2024.101248>

All co-authors & Gender

Dhillon, Sukhdeep (gender: Man)

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Palomo, José (gender: Man)

Partner institutions

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 23

Year: 2026

Title: Narrowband THz pulses centered at 1 THz with high average power emission (> 0.6 mW) using thick quarter-wavelength cavity-based photoconductive antennas

Journal: to be decided

DOI number: no doi

Status: In preparation

Output type: International Peer-reviewed journals

Link: no link

All co-authors & Gender

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Partner institutions

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 24

Year: 2026

Title: Phase offsets in the build-up dynamics of harmonic frequency combs in Fabry-Perot and Ring THz quantum cascade lasers

Journal: to be decided

DOI number: no doi

Status: In preparation

Output type: International Peer-reviewed journals

Link: no link

All co-authors & Gender

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Partner institutions

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 25

Year: 2022

Title: Field-resolved high-order nonlinearities and ultrafast dynamics in a terahertz quantum cascade laser

Journal: International Quantum Cascade Lasers School & Workshop (IQCLW) 2022

All co-authors & Gender

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Jirauschek, Christian (gender: Man)

Partner institutions

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS



DOI number: no doi
Status: Accepted
Output type: International Communications (presentations, posters)
Link: no link

(P2)
TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 26
Year: 2023
Title: Enhanced large area Terahertz Emitter using optical plasmonic nano-antenna
Journal: GDR NanoTeraMIR, Dunkerque, France 24 - 26 May 2023
DOI number: no doi
Status: Accepted
Output type: International Communications (presentations, posters)
Link: no link

All co-authors & Gender
Dhillon, Sukhdeep (gender: Man)
Mangeney, Juliette (gender: Woman)

Partner institutions
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 27
Year: 2024
Title: Cavity based photoconductive antennas for coherent detection of THz QCLs
Journal: International Quantum Cascade Lasers School & Workshop (IQCLSW) 2024
DOI number: no doi
Status: Accepted
Output type: International Communications (presentations, posters)
Link: no link

All co-authors & Gender
Dhillon, Sukhdeep (gender: Man)
Mangeney, Juliette (gender: Woman)

Partner institutions
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 28
Year: 2025
Title: Cavity based photoconductive antennas for coherent detection of THz QCLs
Journal: International Conference on Infrared and Millimeter Waves/THz Electronics (IRMMW-THz), 2025
DOI number: no doi
Status: Accepted
Output type: International Communications (presentations, posters)
Link: no link

All co-authors & Gender
Dhillon, Sukhdeep (gender: Man)
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Partner institutions
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 29
Year: 2026
Title: Narrowband THz pulses centered at 1 THz with high average power emission (> 0.6 mW) using thick quarter-wavelength cavity-based photoconductive antennas
Journal: International Workshop on Terahertz Technology and Applications 2026, Kaiserslautern / Fraunhofer ITWM Germany
DOI number: no doi
Status: Accepted
Output type: International Communications (presentations, posters)
Link: no link

All co-authors & Gender
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Mangeney, Juliette (gender: Woman)

Partner institutions
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 30
Year: 2026
Title: Enhanced terahertz spectral response of cavity-based photoconductive antennas and application to QCL coherent detection
Journal: SPIE Photonics Europe 2026, Invited
DOI number: 10.1117/12.3107712
Status: Accepted
Output type: International Communications (presentations, posters)
Link:
<https://www.spiedigitallibrary.org/conference-proceedings-of-spie/PC14079/3107712/Cavity-based-photoconductive-antennas-for-enhanced-THz-detection-and-application/10.1117/12.3107712.full>

All co-authors & Gender
 Dhillon, Sukhdeep (gender: Man)
 Mangeney, Juliette (gender: Woman)

Partner institutions
 CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)

N°: 31
Year: 2026
Title: Time-resolved emission dynamics in ring-shaped THz QCLs driven by a bus laser
Journal: International Quantum Cascade Lasers School & Workshop (IQCLSW) 2026
DOI number: no doi
Status: Accepted
Output type: International Communications (presentations, posters)
Link: no link

All co-authors & Gender
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 Jirauschek, Christian (gender: Man)
 Vitiello, Miriam (gender: Woman)
 Mangeney, Juliette (gender: Woman)

Partner institutions
 CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)
 CONSIGLIO NAZIONALE DELLE RICERCHE (P1)
 TECHNISCHE UNIVERSITAET MUENCHEN (P3)

N°: 32
Year: 2026
Title: Frequency and intensity noise of a grating-tuned external-cavity quantum cascade laser
Journal: Optics Express
DOI number: 10.1364/OE.586860
Status: Accepted
Output type: International Peer-reviewed journals
Link:
<https://opg.optica.org/oe/fulltext.cfm?uri=oe-34-10-18375>

All co-authors & Gender
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 De Natale, Paolo (gender: Man)

Partner institutions
 CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 33
Year: 2026
Title: Electron-to-photon noise transfer in midinfrared semiconductor lasers
Journal: Physical Review Applied
DOI number: 10.1103/3t25-1gnk
Status: Accepted
Output type: International Peer-reviewed journals
Link:
<https://journals.aps.org/prapplied/abstract/10.1103/3t25-1gnk>

All co-authors & Gender
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Partner institutions
 CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 34

All co-authors & Gender



Year: 2025

Title: Characterization of optically rectified THz frequency comb in lithium niobate waveguides

Journal: SPIE LASE, 2025

DOI number: 10.1117/12.3041150

Status: Accepted

Output type: International Communications (presentations, posters)

Link:

<https://www.spiedigitallibrary.org/conference-proceedings-of-spie/13347/133470M/Characterization-of-optically-rectified-THz-frequency-comb-in-lithium-niobate/10.1117/12.3041150.short>

Consolino, Luigi (gender: Man)

De Natale, Paolo (gender: Man)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 35

Year: 2024

Title: QCL-Based Cryogen-Free THz Optical Wireless Communication Link

Journal: Laser & Photonics Review

DOI number: 10.1002/lpor.202301082

Status: Accepted

Output type: International Peer-reviewed journals

Link:

<https://onlinelibrary.wiley.com/doi/full/10.1002/lpor.202301082>

All co-authors & Gender

Consolino, Luigi (gender: Man)

Vitiello, Miriam (gender: Woman)

De Natale, Paolo (gender: Man)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 36

Year: 2024

Title: Metrology of frequency comb sources: assessing the coherence, from multimode to mode-locked operation

Journal: Nanophotonics

DOI number: 10.1515/nanoph-2023-0805

Status: Accepted

Output type: International Peer-reviewed journals

Link:

<https://www.degruyterbrill.com/document/doi/10.1515/nanoph-2023-0805/html>

All co-authors & Gender

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Eramo, Roberto (gender: Man)

De Natale, Paolo (gender: Man)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 37

Year: 2026

Title: Dispersing THz harmonic frequency comb modes by a 3D printed diffraction grating

Journal: to be decided

DOI number: no doi

Status: In preparation

Output type: International Peer-reviewed journals

Link: no link

All co-authors & Gender

Consolino, Luigi (gender: Man)

Vitiello, Miriam (gender: Woman)

De Natale, Paolo (gender: Man)

Eramo, Roberto (gender: Man)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 38

Year: 2025

Title: Experimental analysis of the thermal management and internal quantum efficiency of terahertz quantum cascade laser harmonic frequency combs

Journal: Nanophotonics

DOI number: 10.1515/nanoph-2025-0207

Status: Accepted

All co-authors & Gender

Vitiello, Miriam (gender: Woman)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)



Output type: International Peer-reviewed journals

Link:

<https://www.degruyterbrill.com/document/doi/10.1515/nanoph-2025-0207/html>

N°: 39

Year: 2025

Title: Engineering THz-frequency light generation, detection, and manipulation through graphene

Journal: Applied Physics Review

DOI number: 10.1063/5.0199461

Status: Accepted

Output type: International Peer-reviewed journals

Link:

<https://pubs.aip.org/aip/apr/article/12/1/011321/3337059/Engineering-THz-frequency-light-generation>

All co-authors & Gender

Vitiello, Miriam (gender: Woman)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 40

Year: 2024

Title: Harmonic quantum cascade laser terahertz frequency combs enabled by multilayer graphene top-cavity scatters

Journal: Nanophotonics

DOI number: 10.1515/nanoph-2023-0912Digital Object Identifier (DOI)

Status: Accepted

Output type: International Peer-reviewed journals

Link:

<https://onlinelibrary.wiley.com/doi/10.1515/nanoph-2023-0912>

All co-authors & Gender

Vitiello, Miriam (gender: Woman)

Sorba, Lucia (gender: Woman)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

N°: 41

Year: 2023

Title: Graphene-coupled passive mode-locked terahertz laser

Journal: SPIE OPTO, 2023, San Francisco, California, United States

DOI number: 10.1117/12.2650017

Status: Accepted

Output type: International Communications (presentations, posters)

Link:

<https://www.spiedigitallibrary.org/conference-proceedings-of-spie/PC12440/2650017/Graphene-coupled-passive-mode-locked-terahertz-laser/10.1117/12.2650017.full>

All co-authors & Gender

Vitiello, Miriam (gender: Woman)

Partner institutions

CONSIGLIO NAZIONALE DELLE RICERCHE (P1)

Valorisation

N°: 1
Output type: International patents pending
Year: 2024
Lead partner: CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (P2)
Title/ Name/ Link: Photoconductive antenna for terahertz waves, method for producing such photoconductive antenna and terahertz time domain spectroscopy system

Societal Impact:
The patent is expected to have good impact on the THz optoelectronic market.

Comments:
No comments.

Management outputs

Please list all other project outputs e.g. PhD thesis defended, MA thesis defended, grants received as a result of the QuantERA project, other – please specify.

Bachelor-Theses:

- Über den Einfluss hochfrequenter Modulation auf Gain-Parameter von Quantenkaskadenlasern - 17.11.2025
- Untersuchung der Verstärkungsparameter freilaufender THz-Quantenkaskadenlaser-Frequenzkämme auf Basis der Maxwell-Bloch-Gleichungen - 05.11.2025
- Comparative Analysis of the Maxwell-Bloch Equations in Full-Wave and with Rotating Wave Approximation for Quantum Cascade Lasers using mbsolve - 18.06.2025
- Modeling the Gain Dynamics of Semiconductor Optical Amplifiers - 19.10.2024
- Towards the Development of a Maxwell-Bloch Solver in the Rotating-wave Approximation - 02.04.2024
- Carrier Transport Simulations of Quantum Cascade Laser - 29.03.2023

Master theses:

- Optimizing the Object Model of a Quantum Cascade Laser Simulation Framework - 24.12.2024
- Numerical Analysis and Optimization of Cavity Geometry in Ring-Type Terahertz Quantum Cascade Lasers - 29.10.2024
- Implementing Diffusion in a Maxwell-Bloch Equation Solver to Better Model Quantum Cascade Lasers - 31.10.2023

PhD Thesis:

- Photonic Engineering and Ultrafast Dynamics of THz device : from THz cavity-based detectors to hybrid 2D material-Quantum Cascade Lasers - 12.12.2025

Project impact

On the basis of sentences below (from the Call Announcement), please, describe the impacts resulting from your work: "Funded projects are expected to significantly advance the state-of-art of quantum sciences and technologies by achieving one or more of the following targets:

- A) develop a deeper fundamental and practical understanding of systems and protocols for manipulating and exploiting quantum information;
 - B) enhance the robustness and scalability of quantum information technologies in the presence of environmental decoherence, hence facilitating their real-world deployment;
 - C) develop reliable technologies for the different components of quantum architectures;
 - D) identify new opportunities and applications fostered through quantum technologies, and the possible ways to transfer these technologies from laboratories to industries;
 - E) enhance interdisciplinary in crossing traditional boundaries between disciplines in order to enlarge the community involved in tackling these new challenges."
 - F) Spread excellence throughout Europe by involving partners from the widening countries
 - G) Build leading innovation capacity across Europe by involvement of key actors that can make a difference in the future, for example excellent young researchers, ambitious high-tech SMEs or first-time participants
- (You may choose one or more of the above):

The Consortium has made significant progress across both experimental and theoretical fronts, successfully advancing key technologies toward the project's ultimate goals. Several outcomes have surpassed the current state-of-the-art, including:

- Design-driven control of harmonic frequency comb (HFC) generation in terahertz quantum cascade lasers (THz QCLs).
- Advanced numerical simulation tools for modeling HFC operation.
- Novel cavity-based coherent sources and detectors designed for sensitive quantum state measurements.
- Realization of novel THz optical tools.

Specifically, a novel experimental methodology was developed, that alleviates the influence of device fabrication and operation uncertainties on the emission state of THz QCL frequency combs (FC) allowing the specific order of the harmonic frequency comb (HFC) to be determined in advance; the high-frequency (~3 THz) detectors developed under Work Package 2 (WP2) achieved benchmark performance across sensitivity, speed, dynamic range, and operating frequency. These results demonstrate that combining high-quality layered material heterostructures with engineered photonic absorption is a powerful, scalable pathway for advanced THz applications.

To better understand noise dynamics, the team also investigated non-planned device configurations, analyzing the operation of both Fabry-Perot and ring-based QCLs. Characterization revealed that ring lasers exhibit instantaneous harmonic comb behavior—transitioning smoothly from picosecond-scale build-up to nanosecond-scale stability—whereas Fabry-Perot lasers display operational instabilities. Consequently, ring geometry offers lower noise characteristics, making it significantly better suited for quantum optics research.

Regarding the realized THz grating, the 3D-printed device results in a fully usable device, capable of selecting and isolating single modes emitted by a QCL HFC. The realization process, based on polymeric materials proves to be a valid approach for the fabrication of a cost-effective diffraction gratings, relying on simple manufacturing techniques that do not require specialized facilities. We believe that this manufacturing method, combined with the Bottema design model, can pave the way to manipulation of THz radiation emitted by state-of-the-art harmonic combs, also in view of future quantum detection systems in this spectral range. Finally, in line with the initial work plan, a dedicated twin-beam experimental setup operating under strict vacuum conditions was designed and constructed to eliminate atmospheric molecular absorption. The system was fully prepared for twin-beam detection and successfully tested using a THz HFC QCL.

Overall, the technology developed throughout the project will surely have a deep impact on future THz science, opening the possibility to develop quantum based applications in this spectral region.

Please, describe any other (unexpected?) impact the project has made:

No other project outputs.

RESPONSIBLE RESEARCH AND INNOVATION ASPECTS

Education and public engagement

Please indicate all activities related to education and public engagement starting with the most important ones (in terms of outcome, impact, opportunities for transnational collaborations and synergy with other European and international initiatives). The table can be expanded if applicable.

N°: 1

Title of activity:

SPIE Photonics West 2023

Type of activity: Conferences

Lead partner: Project Coordinator (P1)

Date/period: 28/01/2023 – 02/02/2023

Place:

San Francisco, USA

Type of audience: Scientific Community (higher education, Research)

Size of audience: 100

N°: 2

Title of activity:

European Optical Society Annual Meeting (EOSAM) 2023

Type of activity: Conferences

Lead partner: Project Coordinator (P1)

Date/period: 11/09/2023 – 15/09/2023

Place:

Dijon, France

Type of audience: Scientific Community (higher education, Research)

Size of audience: 80

N°: 3

Title of activity:

Terahertz-Related Devices and Technologies - TeraTech 2023

Type of activity: Conferences

Lead partner: Project Coordinator (P1)

Date/period: 04/09/2023 – 08/09/2023

Place:

Aizu-Wakamatsu City, Fukushima-ken, Japan

Type of audience: Scientific Community (higher education, Research)

Size of audience: 40

N°: 4

Title of activity:

IRMMW-THz 2022, 47th International Conference on Infrared, Millimeter, and Terahertz Waves

Type of activity: Conferences

Lead partner: Project Coordinator (P1)

Date/period: 28/08/2022 – 02/09/2022

Place:

Delft, The Netherlands

Type of audience: Scientific Community (higher education, Research)

Size of audience: 50

N°: 5

Title of activity:

18th IEEE Nanotechnology Materials and Devices Conference (IEEE-NMDC 2023)

Type of activity: Conferences

Lead partner: Partner 3 (P3)

Date/period: 22/10/2023 – 25/10/2023

Place:

Paestum, Italy

Type of audience: Scientific Community (higher education, Research)

Size of audience: 30

N°: 6

Title of activity:

International Conference on Electromagnetics in Advanced Applications (ICEAA 2023)

Type of activity: Conferences

Lead partner: Partner 3 (P3)

Date/period: 09/10/2023 – 13/10/2023

Place:

Venice, Italy

Type of audience: Scientific Community (higher education, Research)

Size of audience: 20

N°: 7

Title of activity:

Numerical Simulation of Optoelectronic Devices (NUSOD 2023)

Type of activity: Conferences

Lead partner: Partner 3 (P3)

Date/period: 18/09/2023 – 21/09/2023

Place:

Torino, Italy

Type of audience: Scientific Community (higher education, Research)

Size of audience: 50

N°: 8

Title of activity:

Photonics and Electromagnetics Research Symposium (PIERS 2023)

Type of activity: Conferences

Lead partner: Partner 3 (P3)

Date/period: 03/07/2023 – 06/07/2023

Place:

Prague, Czech Republic

Type of audience: Scientific Community (higher education, Research)

Size of audience: 30

N°: 9

Title of activity:

Infrared Terahertz Quantum Workshop (ITQW 2023)

Type of activity: Workshops

Lead partner: Partner 3 (P3)

Date/period: 25/06/2023 – 30/06/2023

Place:

Erice, Italy

Type of audience: Scientific Community (higher education, Research)

Size of audience: 75

N°: 10

Title of activity:

Numerical Simulation of Optoelectronic Devices (NUSOD) 2022

Type of activity: Conferences

Lead partner: Partner 3 (P3)

Date/period: 12/09/2022 – 16/09/2022

Place:

Online

Type of audience: Scientific Community (higher education, Research)

Size of audience: 40

N°: 11

Title of activity:

International Quantum Cascade Lasers School & Workshop (IQCLSW 2022)

Date/period: 23/08/2022 – 28/08/2022

Place:

ETH Zürich and Monte Verità, Switzerland

Type of activity: Workshops

Lead partner: Partner 3 (P3)

Type of audience: Scientific Community (higher education, Research)

Size of audience: 50

N°: 12

Title of activity:
International Quantum Cascade Lasers School & Workshop 2024

Type of activity: Conferences

Lead partner: Project Coordinator (P1)

Date/period: 25/08/2024 – 30/08/2024

Place:
Ischia (Italy).

Type of audience: Scientific Community (higher education, Research)

Size of audience: 200

N°: 13

Title of activity:
International Workshop “Quantum THz Nanomaterials and Devices: Science, Technology and Applications”

Type of activity: Conferences

Lead partner: Project Coordinator (P1)

Date/period: 05/07/2026 – 11/07/2026

Place:
Erice Italy

Type of audience: Scientific Community (higher education, Research)

Size of audience: 100

N°: 14

Title of activity:
International workshop “Quantum Materials and Structured Light” (QMSL) 2024

Type of activity: Conferences

Lead partner: Project Coordinator (P1)

Date/period: 06/07/2024 – 12/07/2024

Place:
Erice, Italy

Type of audience: Scientific Community (higher education, Research)

Size of audience: 80

Actions on Gender equality

N°: 1

Type of activity:

Participation to "Octopus-lab" meetings.

Description / Objectives:

Octopus-lab is a project designed to spread awareness about the causes and effects of gender inequality in the academic and research world. The first activity of the workshop consists of the series of meetings "Octopus: The tentacles of gender inequality in eight episodes".

Level (internal/project level vs. External activity):

External activity

Target audience:

All students of the University of Florence and to the staff of UniFI and CNR, INFN and INAF research institutions, upon registration.

N°: 2

Type of activity:

Organization of a true gender equality conference

Description / Objectives:

The "International "Infrared and Terahertz quantum workshop" (ITQW) has been organized by CNR unit with the declared objective of a 50% women participation to the workshop.

Level (internal/project level vs. External activity):

External activity

Target audience:

Broad scientific audience

Open Science

Please indicate actions undertaken and to address Open Science in this project.

In order to address Open Science in the QATACOMB project, all the related scientific publications have been submitted to peer-reviewed open access journals, or have been uploaded in open access repositories, e.g. ArXiv.org. Moreover, the official website of the QATACOMB project (<https://qatacomb.ino.cnr.it/>) with a designed logo, intended for the publication of news, partner information, scientific publications and more, as well as for internal communications has been constantly updated, with all the information and links to ensure maximum diffusion through open access channels.

Ethics

Please describe any ethical issues which have appeared in the reporting period as well as actions taken in order to address these issues.

There are no ethical issues to report.

COOPERATION WITH INDUSTRY

To identify a project with a commercial, industrial application, please describe your work focusing on:

- stating what are key commercially relevant applications of your work,
- identifying existing/potential industrial partners or end users you already working with and any product requirements and specifications,
- requirements you have for industrial collaboration (e.g. access to equipment, testing facilities, and product requirements),
- what you can offer industry (e.g. research laboratories, highly specialised equipment and research expertise, highly qualified researchers).

(Indicative length: 1-2 pages)

No cooperation with industry to be reported so far.

Other

Additional comments, opinions, requests and suggestions for improvement to QuantERA

[No additional comments.](#)

Coordinator signature

Date



Luigi
Consolino
26.08.2026
13:03:25
GMT+02:00