Numerical models for multi-wavelength mid-IR Quantum Cascade Lasers
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Research context and motivation

• Quantum Cascade Lasers (QCLs). Quantum Cascade Lasers are a particular class of semiconductor lasers, where the electronic transitions occur between confined states in the conduction band, which are named subbands. Therefore these transitions do not involve holes: QCLs are unipolar devices and transition energies are fully controlled by quantum confinement.
• Optical frequency combs (OFC). An Optical Frequency Comb is a set of equally spaced optical lines having constant phase difference and amplitude [1]. It has been recently demonstrated that QCLs can operate as frequency combs in both mid-IR and THz region [2].
• Applications. A particularly appealing application of OFCs is the so called dual comb spectroscopy. This technique is characterized by high resolution, high sensitivity and no moving parts and its use is especially interesting in the mid-infrared region, where most fundamental roto-vibrational absorption bands of light molecules can be found. Another interesting field of application for OFCs is the optical communication area where they may be used for the generation of sub-THz signal for wireless networks.

Addressed research questions/problems

• Development of a semiconductor-like model. The available models for the description of the multi-mode behavior of QCLs are based on the theory of two or three layers laser and then incomplete. Our new approach exploits instead a more realistic phenomenological expression of the optical susceptibility which well reproduces the optical properties of the semiconductor active medium and leads to a set of Effective Semiconductor Maxwell-Bloch Equations (ESMBEs).
• Accounting for a realistic Fabry-Perot configuration. The cavity configuration which corresponds to real devices is the Fabry-Perot. The inclusion of this configuration into our model allows us to account for the formation of a carrier grating inside the laser cavity, due to the Spatial-Hole Burning, which influences the laser dynamics and provide for a more realistic description of the system, compared with the ring cavity configuration considered so far.
• Reduction of the simulation time. Since the complete description of the laser behavior is based on a complex set of nonlinear partial differential equations (ESMBEs), the numerical simulations are computationally heavy. An effort to obtain a more simple mathematical approach is planned, in order to reduce the total simulation time.
• Reproducing of the experimental results. A tuning of the model parameters will possibly allow to reproduce the experimental results performed both in the mid-IR and THz region that show a peculiar behavior of the system, characterized by an alternation between locked and unlocked regimes, and the presence of a continuous wave emission just above the laser threshold.

Submitted and published works


Adopted methodologies

Optical Susceptibility

• alpha-factor #0
• Gain and refractive index dependence from carrier density
• Asymmetric profile of gain and refractive index as functions of the frequency.

Effective Semiconductor Maxwell-Bloch Equations (ESMBEs)

\[
\begin{align*}
\frac{d\sigma}{d\omega} &= \frac{2\pi}{\hbar} \sigma \rho \\
\frac{d\rho}{d\omega} &= \frac{2\pi}{\hbar} \left( \rho - \sigma \right) \\
\frac{d\sigma}{d\tau} &= \frac{2\pi}{\hbar} \left( \sigma - \rho \right)
\end{align*}
\]

OFC indicators based on multimode dynamics

\[
\begin{align*}
\frac{d\sigma}{d\omega} &= \frac{2\pi}{\hbar} \sigma \rho \\
\frac{d\rho}{d\omega} &= \frac{2\pi}{\hbar} \left( \rho - \sigma \right) \\
\frac{d\sigma}{d\tau} &= \frac{2\pi}{\hbar} \left( \sigma - \rho \right)
\end{align*}
\]

Novel contributions

Simulation results

Results of numerical simulations of the multi-mode dynamics of a typical Quantum Cascade Laser emitting in the mid-IR region are shown.

Future work

• Reduction of the ESMBEs to two master equations for the forward and backward fields, which will unify the QCL lasers to the family of physical systems described by modified CGLE systems. This will allow to make the role of critical parameters in influencing the self-locking mechanism and to reduce the simulation time.
• Reproduce recent experimental results on direct modulation of QCL achieving an increase of the extension of the comb regime and bandwidth, in collaboration with the Laboratoire Matériaux et Phénomènes Quantiques (MPQ), Université Denis Diderot- Paris VII.

List of attended classes

• 01/08/01 – CAD of semiconductor devices and processes (10/2/2019, 8 CFU)
• 03/09/10 – Communication (9/3/2019, 1 CFU)
• 01/09/20 – Materials by design – How structure meets function (3/7/2019, 3 CFU).
• 01/09/19 – Photonics: a key enabling technology for engineering applications (24/7/2019, 5 CFU).
• 01/09/18 – Time management (21/2/2018, 1 CFU)
• 01/09/18 – Photonics Devices (October 2018-January 2019, exam to be taken)