Phase resolved stimulated emission from THz QCLs

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Motivation

- Quantum cascade lasers
  - Lack of information regarding internal processes
  - Phase information lost by intensity measurements
- Only phase resolved transmission data includes:
  - Internal dynamics
  - Loss mechanisms
Few-cycle THz generation

short optical pulses of a Ti-Sapphire laser

rectification

few-cycle THz pulses

\[ E(t) = E_{\text{env}}(t) \cos(\omega t) \]

\[ P(t) = \varepsilon_0 (\chi^1 E(t) + \chi^2 E^2(t) + ...) \]

\[ P_{\text{nl}}(t) = \frac{\varepsilon_0 \chi^2}{2} \left\{ E_{\text{env}}(t)^2 \cos[(\omega + \omega)t] + E_{\text{env}}(t)^2 \cos[(\omega - \omega)t] \right\} \]

- nonlinear crystals
- semiconductors

“half-cycle” electric pulse

100-10 fs long @10-100 THz
THz time-domain spectroscopy

Transmission THz-TDS setup with:
- Femtosecond laser (<85 fs, 20 nJ)
- Photoconductive THz emitter
- Electro-optic detection with GaP
- High dynamics & bandwidth
- Electric field + phase measured
- Power detection with Bolometer
THz-QCL Parameters

- MBE grown THz-QCL\(^1\) based on AlGaAs/GaAs bound-to-continuum design
- 90 cascade modules
- Threshold current \(\sim 400\) mA
- Emission at 2.87 THz (95 cm\(^{-1}\))
- Surface plasmon waveguide

Measurement technique

THz time-domain spectroscopy scheme

NIR 80 MHz

THz emitter

QCL

EO sensor

Bolometer

THz Probe signal

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Power detection with Bolometer
Phase resolved spectroscopy of 2-level system

Density matrix

\[
\begin{pmatrix}
\rho_{aa} & \rho_{ab} \\
\rho_{ba} & \rho_{bb}
\end{pmatrix}
\]

\(\rho_{aa}, \rho_{bb} \sim \text{population}\)

\(\rho_{ab}, \rho_{ba} \sim \text{coherence}\)

- Standard spectroscopy \(\rightarrow\) sensitive only to probe intensity changes (\(\int E^2 dt \sim \rho_{aa} - \rho_{bb}\))
- Phase resolved measurement of the electric field \(\rightarrow\) \(\rho_{ab}\)
Coupling THz waves into QCL

Problems to solve:
- THz beam waist to large
- More than one ridge hit
- Optical leakage
- Aperture masks other ridges
- ‘Solid immersion’ lens focuses beam
- Optical leakage suppressed
- High coupling efficiency

Diagram showing coupling of THz waves into QCL with a 'solid immersion' lens, which focuses the beam and suppresses optical leakage, aiming for high coupling efficiency.

Graph showing amplitude (arb. u.) vs. frequency (THz) with a clear signal level, noise level, THz-QCL emission range, and THz beam alignment.

THzLab logo at the bottom right corner.
THz pulse amplification in THz-QCL

- First-time phase resolved measurement of QCL emission
- Stimulated QCL emission phase-locked to the THz seed pulse
- Modulation spectroscopy applied suppresses QCL heating effects
Spectral features

- Signal is combination of absorption, reduced losses & gain
- Separation by spectral filtering
- Oscillation centre frequency at 2.87 THz = Lasing line
Spectral feature

- Measured response does not contain Drude as component
- Additional frequency features: Injector inter-subband absorption?
Gain & Spectral hole burning

- Re-normalization shows real spectral gain shape
- Gain bandwidth 300 GHz (FWHM)
- Single pass gain >17 cm\(^{-1}\)
- Spectral hole burning @ 2.87 THz
- Observed gain region exceeds the region of lasing
- Gradual alignment of cascades and its break-up
Multi-pass signal in QCL

First internal reflection (3 waveguide passes \(\rightarrow\) shaping)
- Centre frequency shifted to region with highest gain
- Modulation gets longer \(\rightarrow\) linewidth narrowing

First round-trip signal

Spectrum of QCL signal
Longitudinal spatial hole burning in THz-QCL

- Visible under lasing conditions
- Current dependency matches with LI
- Lasing electric field forms a pattern
- Frequency selective scattering
  → Longitudinal spatial hole burning
Summary

- Phase resolved probing used for a gain medium
- Real gain bandwidth of a QCL determined
- Spectral & spatial hole burning observed
- Dynamics of starting lasing operation

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