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Quantum Cascade Lasers

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The electromagnetic spectrum

Limited by transit time and $RC$, at least two poles and $P \propto 1/\nu^4$.

Limited by energy gap, even for Pb-salt lasers, $\nu > 10$ THz.

Electronics (transistors, etc.)

Photonics (laser diodes, etc.)

Pb-salt lasers

Quantum-cascade lasers

4meV 40meV 0.4 eV
**Interband versus intersubband lasers**

Interband Laser:
- $\hbar\omega$ set by bandgap
- Bipolar: electron-hole recombination
- Opposite band dispersion

Intersubband Laser:
- $\hbar\omega$ chosen by design
- Unipolar: electrons make intraband transitions
- Same subband dispersion
Bandgap engineering: “artificial atoms”

Common material systems:
- InGaAs/InAlAs/InP (mid-infrared QCLs)
- GaAs/AlGaAs (THz QCLs)
Quantum-cascade lasers (QCLs)

Population inversion:
\[ \Delta n \equiv n_3 - n_2 = \frac{J}{e} \tau_3 \left( 1 - \frac{\tau_{21}}{\tau_{32}} \right) \]

must have \( \tau_{32} \gg \tau_{21} \)

\( \hat{\hbar} \omega \)
However, population inversion (amplification) observed at an unstable point of I-V curve, i.e. in the negative differential resistance (NDR) region.
First quantum cascade laser

- $\lambda \sim 4.25 \mu m (0.30 \text{ eV})$
- Pulsed $T_{\text{max}} = 125 \text{ K}$
- $J_{\text{th}} = 14000 \text{ A/cm}^2$

Faist, Capasso et. al., Bell Labs, Science, 1994
Importance of the “injector” region

Injector region prevents current flow until the desired level alignment is reached, population inversion is obtained prior to the occurrence of NDR region in the I-V
Quantum-cascade lasers
(courtesy of Prof. Jerome Faist at Univ. Neuchâtel)

Cascade: N repetition of a period
-> 1 electron may generate N photons
Best performing mid-infrared QCL design today: double phonon depopulation

- $\lambda \sim 9.15 \, \mu m (0.135 \, eV)$
- CW $T_{\text{max}} = 310 \, K$
- $J_{\text{th}} = 4000 \, A/cm^2$

$E_{32} \sim E_{21} \sim E_{\text{LO}} \sim 34 \, \text{meV}$

the LO-phonon energy in the semiconductor, Enables fast depopulation

First room temperature continuous-wave operation

Faist group, Science (2002)
Time line of QCL development

- Continuous-wave room temperature operation in the wavelength range 4-10 µm (photon energy 0.30 eV down to 0.12 eV)
- > 1 Watt cw power at room-temperature

Applications in molecular spectroscopy, chemical and biological sensing, trace gas detection
N$_2$O + methane sensing using pulsed QCL

(Courtesy of J. Faist)

Set-up Schematics  Spectral measurement  Allan Plot

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AERODYNE RESEARCH, Inc

σ = 0.06 ppb in 100s!

D.D. Nelson et al, Spectrochimica acta, 60 (14): 3325-3335 DEC 2004
Light detectors based on intersubband transitions: Quantum Well Infrared Photodetector (QWIP)

GaAs substrate

AlGaAs

Courtesy of H. C. Liu, NRC, Canada
Infrared thermal imaging

Looking at things by their body head and temperature difference.

The most effective wavelength region is 8 – 12 µm for night vision.

Courtesy of H. C. Liu
GaAs Based QWIPs – the only commercial large IR array

- GaAs/AlGaAs based QWIPs cover $\lambda > 6 \, \mu m$
  - Change the quantum well parameters to vary spectral response
- No theoretical upper limit for cut-off wavelength
- Naturally narrow band ($\Delta \lambda / \lambda \sim 10\%$) detection
- 4” & 6” substrate & matured processing technologies
- EXCELLENT Large format Imaging

Courtesy of H. C. Liu
The terahertz gap

Power Performance of Solid-State Sources

Plot adapted from:
(2005 survey of THz sources,
Dr. J. Hesler, Virginia Diode Inc.)

THz Quantum Cascade Lasers:
- $\nu \sim 1.2$–5.0 THz ($\lambda \sim 300$–$60\mu$m)
- CW Power ~ 1–140 mW (10 K)
- Peak operating temperature:
  - 186 K (pulsed), 117 K (cw)
THz Applications – imaging, spectroscopy, sensing

- Astronomy and space science
  - Study of early universe and galaxy formation – cool (30K) interstellar dust
    - ESA Herschel satellite (0.48-1.25 THz, 1.41-1.91 THz), 2008 launch
    - Ozone layer monitoring – NASA EOS-Aura satellite (OH (2.510 THz and 2.514 THz) and OH₂ (2.503 THz), launched 2004, gas laser as local-oscillator ($20M)
  - Security applications – weapon detection, package inspection, drug and explosive detection
  - Terahertz imaging for medical applications – e.g. sub-dermal carcinoma detection based on differences in water content of tumor
  - Chemical gas sensing, agent detection
  - Biological sensing – stretching and twisting modes in DNA. These low-frequency modes are associated with specific species.
  - End-point detection in dry-etching processes
  - Plasma diagnostics in fusion experiments
- ...
Advantages of remote sensing at THz vs. IR

- At infrared frequencies, $\hbar \omega \gg kT$, upper level is empty, can only perform absorption/transmission spectroscopy.

- At THz frequencies, $\Delta E = \hbar \omega \ll kT$, significant upper level population, can perform emission spectroscopy as well. Passive remote sensing much more flexible and versatile (eg. imaging) than transmission spectroscopy.

- The enabling component is a coherent CW source for the local oscillator.
There are many strong resonances in the terahertz for cool (~ 30 K) interstellar dust.

- Probe of early universe and galaxy/star formation processes.
- 98% of photons and 50% of luminosity in universe are in THz.

THz-rays application, MIT Technology Review (June, 2003)

TAMING THE TERAHERTZ
T-rays could be more versatile than x-rays

**IMAGING** Just as x-ray technology came along in the 1890s—allowing doctors to peer beneath flesh to see bones and organs—another promising imaging technology is now emerging from an underused chunk of the electromagnetic spectrum: the terahertz frequencies. These so-called t-rays can, like x-rays, see through most materials. But t-rays are believed to be less harmful than x-rays. And different compounds respond to terahertz radiation differently, meaning a terahertz-based imaging system can discern a hidden object’s chemical composition. Thanks to this power, “terahertz imaging is getting hotter and hotter,” says Xi-Cheng Zhang, a terahertz pioneer at Rensselaer Polytechnic Institute. Potential applications range from detecting tumors to finding plastic explosives. And since t-rays penetrate paper and clothing, a terahertz camera could detect hidden weapons.

Terahertz frequencies are tough to produce and detect. They’re higher than microwaves but lower than infrared light. “You’re never sure whether to use electronics-based or optics-based technology,” says Martyn Chamberlain of the University of Leeds in England, a leading terahertz researcher. The terahertz sources now on the market tend to emit many frequencies at once, limiting their utility. In the past year, however, several research projects have made substantial progress in developing devices that produce t-rays within a narrow frequency band—a requirement for precise chemical sensing and medical imaging.

One such system, made by Brattleboro, VT-based Vermont Photonics, works by sending an electron beam across the microscopically rippled surface of a conductor, such as aluminum; the beam causes electrons in the conductor to move up and down the undulations, a motion that shakes t-rays. Changing the generated, says Vermont Photonics cofounder Michael Mross. The company is targeting its instrument primarily at observing interactions involving biomolecules for applications such as drug discovery. Another approach is something called the “quantum cascade laser,” a neat bit of semiconductor engineering used to produce infrared light. Moving the technology into the terahertz range requires exquisite precise control over the materials. Last year, Qin Hu, an MIT electrical engineer, demonstrated a quantum cascade laser that produces a continuous terahertz beam at a well-defined frequency.

The most near-term application for terahertz technology is in medical imaging. In one ambitious effort, Teraview, a Cambridge, England-based startup, has used terahertz imaging to detect skin cancers that elude other imaging technologies—in particular, tumors that form invisibly beneath the surface of the skin. T-rays could also identify unknown biological materials, since biomolecules naturally vibrate at terahertz frequencies, and each has a distinct terahertz “fingerprint.” In other words, specific proteins absorb certain characteristic t-ray frequencies, which change their molecular arrangement, or conformation; sensors can then monitor this absorption to indicate the identity of the protein. “Life is a terahertz process,” says Chamberlain. One potential application is automated identification of biological warfare agents, such as anthrax. Another is a t-ray chemical sensor, which would take advantage of the fact that other large molecules, such as polymers, also respond to terahertz waves in characteristic ways. A terahertz camera built by Qin et al. of Farnborough, England, takes eerily invasive pictures of people through their clothes.

But the interaction of t-rays with proteins raises the question of how safe human exposure is. The European Union is sponsoring a program, called Terahertz Bridge, to study just that. Preliminary results have been encouraging; researchers have seen no evidence of irreversible, x-ray-like tissue damage from the doses of t-rays that would be used for bodily imaging. “So far, it’s safe,” says Gian Piero Galerano, coordinator of Terahertz Bridge.

While scientists go through contortions to produce t-rays, nature has it much easier. Terahertz radiation continues to propagate throughout space from its origin in the Big Bang. Says Chamberlain, “The universe is full of this stuff.” Before long, humans may begin putting it to practical use. —Herb Brody

Picture taken with short THz pulses and mechanical scan.
THz spectroscopy of explosives

Tribe et al., TeraView Ltd. (UK)

Time-domain spectral imaging for explosive identification

Shen et al., TeraView Ltd. (UK)

RDX - Principal ingredient in plastic explosive

lactose

RDX

Raw THz image

Lactose chemical map

RDX chemical map

Tribe et al., TeraView Ltd. (UK)

Shen et al., TeraView Ltd. (UK)
TNT-116 molecule phonon mode at 3.48 THz ($\lambda \sim 86\mu$m, $h\nu \sim 14$meV)

Courtesy X. C. Zhang at RPI.
Mid-infrared versus Terahertz QCLs: Energy scales

First terahertz quantum-cascade laser

- 1971 – Intersubband laser in superlattice proposed by Kazarinov and Suris.

- 1994 – Quantum cascade laser (QCL) demonstrated by Faist et al. at Bell Labs ($\lambda=4.2 \ \mu m$)

- Oct. 2001 – First terahertz QCL demonstrated by Köhler et al. at Pisa using chirped superlattice ($\lambda=68 \ \mu m$)

\[ \alpha_{fc} \propto \lambda^2 \]
THz QCL active region: a simple 3-level model design

- $f_{32}$ – oscillator strength ($\propto |z_{32}|^2$ (dipole-matrix element))
- $\Delta n$ – population inversion ($=n_3 - n_2$)
- $\Delta \nu$ – linewidth of intersubband transition

Peak Intersubband gain:

- 1 QCL period ($\sim 50$ nm) $\times N$ ($\sim 200$)

GaAs/Al$_{0.15}$Ga$_{0.85}$As
Terahertz intersubband scattering mechanisms

Population inversion:
\[ \Delta N = \frac{J}{e} \tau_3 \left( 1 - \frac{\tau_2}{\tau_{32}} \right) \]
must have \( \tau_{32} > \tau_2 \)

\[ \tau_{21} \approx 0.3 \text{ ps} \quad \text{depopulation (e-LO)} \]
\[ \tau_{32,\text{rad}} \sim 10 \mu\text{s} \quad \text{radiative lifetime} \]
\[ \tau_{e-LA} \sim 100 \text{ ps} \quad \text{acoustic-phonon} \]
\[ \tau_{e-\text{imp}} \sim 7 - 20 \text{ ps} \quad \text{impurity scattering} \]
\[ \tau_{e-\text{int}} \sim 10 \text{ ps} \quad \text{interface roughness} \]
\[ \tau_{e-e} \sim 5 - 50 \text{ ps} \quad \text{electron-electron} \]

thermally activated e-LO
\[ \tau_{e-LO,\text{hot}}^{-1} \approx \tau_{LO}^{-1} \exp\left( \frac{\hbar \omega - E_{LO}}{k_B T_e} \right) \]
Coupled quantum wells - anticrossing

Essential for understanding of coupled well designs

Two isolated identical wells

A coupled double-well structure

The anticrossing gap \( \Delta_0 \) characterizes how strongly the two wells couple.

\( \Delta_0 = 0 \Rightarrow \text{no coupling} \)

\( \Delta_0 \) large \( \Rightarrow \) strong coupling
Coupled quantum wells – part 2

\( \Delta_0 \) decreases exponentially with the thickness of this barrier.

- Out of resonance
- Localized
- Weakly coupled

\( \Delta \sim 1.5 \Delta_0 \)

- Resonance (i.e. anticrossing)
- De-localized (large overlap)
- Strong interaction (radiative/scattering)

\( \Delta = \Delta_0 \)

\( \Delta_0 \) decreases exponentially with the thickness of this barrier.
Electron transport by resonant-tunneling

1’$\leftrightarrow$2 “Rabi” oscillation is faster for a thinner barrier, i.e. a larger anticrossing splitting $\Delta_0$
Coherent vs. Incoherent tunneling through a barrier

Barrier thickness $\uparrow$, $\Delta_0 \downarrow$

Coherent tunneling: Large $\Delta_0$

$J_\text{res}$ is large and independent of barrier thickness, $J_\text{res} \propto 1/\tau$

Incoherent tunneling: Small $\Delta_0$

$J_\text{res}$ is small and is controlled by barrier thickness, $J_\text{res} \propto \Delta_0^2$

$\tau$ – lifetime of levels 2 and 2'

$\Delta_0$ – anticrossing energy gap between 1’ and 2

$J_\text{res}$ – current density at resonance
Lasing transition is vertical between levels 5 and 4, yielding a large oscillator strength of $f_{54} \approx 0.96$.

At the designed bias, level 4 is at resonance with level 3, enabling a very fast ($\tau_4 \approx \tau_3 \sim 0.5$ ps) depopulation scattering, while keeping the upper level’s lifetime relatively long ($\tau_{5\rightarrow2,1} \approx 7$ ps).
**Cu-Cu thermocompression wafer bonding**

400° C – 60 min pressure ~ 5 MPa

- Copper – good thermal conductivity
- Improved bond quality and stability
- Fabrication more difficult and requires very clean interface

Adapted from Prof. Reif’s group at MIT, 2004-2005
Record high operating temperatures (MIT, 2005-2007)

Design: FL178C-M7, 23-μm wide, 1.22-mm long ridge

- $T_{\text{max}} = 117 \text{ K (CW)}$
- Narrow ridge: width/$\lambda \sim 0.22$
- CW power dissipation $\approx 1-2 \text{ W}$ (as compared to $\approx 20-50 \text{ W}$ for our earliest designs)
- Still $>1 \text{ mW}$ power at 78 K

Design: FL178C-M10, 100-μm wide, 2.1-mm long ridge

- $T_{\text{max}} = 169 \text{ K (Pulsed)}$
- $k_B T_{\text{max}} \approx 1.2 \times \hbar \omega$, a value that is unprecedented for any solid-state photonic device
Historically, because of weak intensities and broad linewidths of THz spontaneous emission, design of THz QCLs has been mostly based on vertical structures with a large oscillator strength $f_{ij}$.

In this new design, a diagonal structure was developed with a small $f_{ij}$ ($\approx 0.38$), in order to increase the upper-state lifetime at high temperatures.
The maximum operating temperature is 186 K
Real-time THz imaging using QCLs and focal-plane array cameras

QC Laser mounted in PT Cryorefrigerator

Off-axis Paraboloid

Transmission

Si Lens

Object

Ge Window

Reflection

VOx Bolometer Element

Microbolometer Camera
240x320 pixel

MIT, 2005-2008
Real-time THz video taken with a QCL

Plastic Mechanical Pencil

-4.3 THz (68 um)
-48 mW peak power
-Using f/1 -- 25 mm Si Lens
-320x240 pixel VOx microbolometer camera
-SNR ~ 200
-Images shown in log scale (light color represents high intensity)
Real-time THz video taken with a QCL

Polystyrene block with an embedded metal screw
Real-time THz video taken with a QCL

Pencil hand writing inside a paper envelope
MIT terahertz QCL group

Supervisor: Prof. Qing Hu
Past group members: Benjamin S. Williams (now at UCLA)
Hans Callebaut
Present group members: Sushil Kumar
Alan W. M. Lee
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