THz quantum-cascade lasers based on intra-well optical transitions

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Overview

• Single quantum well: population inversion by resonant tunneling

• Excited states in single quantum well:
  – Multi color lasing (with & without B….)
  – …Vs Bound to continuum :localization in B field (probably no time….)

Single quantum well THz laser


\[ E_{65} = 15.3 \text{ meV} \]
\[ z_{65} = 6.6 \text{ nm} \]
\[ f_{65} = 18 \]
\[ F = 2.9 \text{ kV/cm} \]
\[ L_p = 107.9 \text{ nm} \]
\[ N_p = 140 \]
\[ n_s = 3.8 \times 10^{10} \text{ cm}^{-2} \]

Single QW @ 80 µm: single plasmon WG
Double metal: pulsed operation 49 K

Optical rollover
≠
Injection resonance (NDR)

L=1.5 mm
W = 110 µm
CW operation: low threshold current

Double metal ridge waveguide

$T = 10 \text{ K}$

$L = 0.5 \text{ mm}$

$W = 60 \mu \text{m}$
Performance summary

• Threshold current density: 25 A/cm² @ 10 K
• $T_{\text{max}}$: 49 K pulsed, 40 K CW
• Low power consumption: 100-200 mW in CW at 10 K for an optical power of 10-50 µW (double metal) or 2-3 W dissipated for 1-2 mW output power (single plasmon)
• Nice model system: population inversion by sequential resonant tunneling
The model

- Density matrix at the injection and extraction doublets plus EM field (C. Sirtori et al. JQE 1998, H. Callebaut et al., JAP 2005)
- Tight-binding basis
- Recycle time

\[ |2\rangle \quad \Omega_i \quad \tau_2 \quad \Omega_e \quad |1\rangle \]
Bandstructure (tight-binding)

\[ \text{F} = 3 \text{ kV/cm} \]

Injection resonance

injector region

active well

injector region

resonant tunneling

intersubband transition

\[ g, \tau_4 \]

\[ 107.9 \text{ nm} \]

\[ 0 \text{ [eV]} \]

\[ 0.135 \]

\[ 0.128 \]

\[ 0.05 \]

\[ 0 \]
Model results

\[ \tau_2 - \tau_4 \approx 3.3 \text{ ps} \]

\[ \tau_2 + \tau_4 \approx 22 \text{ ps} \]

\[ \tau_2 \approx 12.65 \text{ ps} \]

\[ \tau_4 \approx 9.35 \text{ ps} \]

\[ \tau_i^\parallel \approx 2.4 \text{ ps} \]

\[ \tau_e^\parallel \approx 1.3 \text{ ps} \]

\[ \alpha_{\text{tot}} = 13 \text{ cm}^{-1}, \ 2\gamma_{21} = 1 \text{ meV}, \]
SQW conclusions

• Clear signature of population inversion by resonant tunneling: optical rollover depends on extraction resonance, far away from injection resonance

• Transport time and population of the lower state are crucial for the good agreement of the model
Intra-well transition: excited states

Gain in oscillator strength
multi-frequency operation

C. Sirtori et al., Opt. Lett. 23, 463
Two color THz laser

F=1.89 kV/cm

1.39 THz structure at higher bias:
alignment for 4->3 transition

$E_{43} = 8.7 \text{ meV}$

$z_{43} = 11.1 \text{ nm}$

$f_{43} = 29$

$L_p = 173.0 \text{ nm}$

$N_p = 95$

$n_s = 5.08 \times 10^{10} \text{ cm}^{-2}$

G. Scalari et al., *Appl. Phys. Lett.*, 88, 141102-
Two color in magnetic field

Current density [A/cm²]

Magnetic field [T]
Two color in magnetic field: 4 T section

\[
\begin{align*}
J_{th}^{130\mu m} &= 43 \text{ A/cm}^2 \\
V_{th}^{130\mu m} &= 9.5 \text{ V}
\end{align*}
\]
Two color in magnetic field: 11.5 T section

\[ J_{th}^{215 \mu m} = 5 \text{ A/cm}^2 \]

\[ V_{th}^{215 \mu m} = 2.5 \text{ V} \]

\[ J_{th}^{130 \mu m} = 29 \text{ A/cm}^2 \]

\[ V_{th}^{130 \mu m} = 12 \text{ V} \text{ (magnetoresistance)} \]
Double metal waveguide
Lasing at 2.3 THz w/out B field

\[
T_{\text{max}} = 67 \text{ K}
\]
\[
J_{\text{thresh}} = 50 \text{ A/cm}^2 @ 10 \text{ K}
\]

Peak power: \(~1-2\text{ mW}\)
Conclusions

• SQW: Very low $J_{\text{thresh}} = 25 \text{ A/cm}^2 @ 10 \text{ K}$, nice model system, low power consumption device

• Two color lasing at two well separate frequencies 2.3 and 1.35 THz

• Waveguide and design optimization: lasing without B field on both colors?