New directions in QCL applications: from optofluidic lasers to plasmonic laser antennas

MIKHAIL BELKIN
Capasso’ group
Division of Engineering and Applied Sciences
Harvard University

mbelkin@deas.harvard.edu
Optofluidic QCL research

**Goal:** QCL fluid tuning and sensing for lab-on-a-chip

- **Electrically-pumped QCL**
  - MOCVD quantum cascade lasers with record performance

- **Various laser structures**
  - (photonic crystal, DFB, etc)
  - Novel designs for large tuning, sensing, spectroscopy, etc

- **Optofluidic QCL-based lab-on-a-chip, optofluidic tuning**

- **Microfluidics delivery**
  - Encapsulation of quantum cascade lasers with PDMS

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*Optofluidics Center for Optofluidic Integration*
Tuning QCL with liquids

D. Hofstetter et al, IEEE PTL, 12, 1610 (2000)

\[ \lambda_{\text{laser}} = 2 \cdot \lambda_{\text{grating}} \cdot n_{\text{eff}} \]

Submitted to Optics Express
Sensing liquids with QCL

\[ J_{th} \approx \alpha_{\text{waveguide}} + \alpha_{\text{mirror}} \]

\[ \alpha_{\text{waveguide}} \approx \alpha_{\text{no liquid}} + \Gamma_{\text{out}} \cdot \alpha_{\text{liquid}} \]

Absorption spectra of water and isopropanol

L-I of \( \lambda = 7.1 \ \mu m \), 6\( \mu \)m ridge device
More sensitivity and tuning?

“Holey” QCL structures

Problem: Ga implantation from FIB leads to QCL shorting
Plasmonic laser antennas

Generates subwavelength intense optical spot

APPLICATIONS

- High-spatial-resolution imaging and spectroscopy
- Nano-optical tweezers
- Nano-optical lithography
- High-density optical data storage
We demonstrated similar results for 800nm laser diode, see E. Cubukcu et al., Appl. Phys Lett. (2006)
Requirements for good THz DFG device

- High-power dual wavelength QCL
- High nonlinearity for DFG
- THz waveguide with low-loss and high confinement
- Phase matching
- Efficient out-coupling of THz radiation
Surface emission in double-metal THz QCL

Material:

Bound-to-Continuum design, 3THz [Barbieri et al., APL 85, 1674 (2004)]. Material is grown in the group of Edmund Linfield, University of Leeds.

Processing:

150µ-wide double-metal waveguides; gratings with different periodicities. Reference devices have no grating.
SE in THz QCL: spectra and power

Without grating (150µ-wide, 2.8mm-long ridge)

With grating (150µ-wide ridge, 1.5mm-long grating with absorbing edges)

Note: spectra are scaled to appear at similar intensity.
Far field profile along the laser ridge for 30.4µ grating

Optical microscope image of the processed devices
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Results for 800nm laser diode

Antenna design

Intensity Enhancement

Antenna Length (nm)

$\lambda = 830 \text{ nm}$

Normalized Intensity Enhancement

Normalized Intensity Enhancement

Antenna Length (nm)

$L_1 = 150 \text{ nm}$

$L_2 = 550 \text{ nm}$

$\lambda_{\text{eff}}$

$\frac{\lambda_{\text{eff}}}{2}$

$3\lambda_{\text{eff}}$

$2$

$20 \text{ nm}$
Sensing liquids with QCL

Preliminary results for narrow-ridge QCL sensing

Laser emission spectra, I=1250mA

Absorption spectra of water and isopropanol

QCL emission wavelength

λ = 7.1 µm
6µm ridge

DI water
Isopropanol

Absorbance, ln(I)

Intensity, a.u.

Voltage, V

Current, A
SEM images of narrow ridge QCLs (T-shape design)
IV and LI for different gratings

LI and IV for surface emitting structures with 29.8, 30.4, and 31.0µ gratings

- 29.8µ grating periodicity
- 30.4µ grating periodicity
- 31.2µ grating periodicity

Power, µW
Current density, A/cm²

29.8µ grating periodicity: 30 to 31 µm periodicity
30.4µ grating periodicity: 30 to 31 µm periodicity
31.2µ grating periodicity: 31 to 32 µm periodicity
Absorbing edges

Calculated transverse mode profile
Waveguide intensity losses = 24 cm⁻¹

Calculated transverse mode profile
Waveguide intensity losses = 3700 cm⁻¹

GaAs substrate

T=5K

Peak power, W

Voltage, V

Current density, A/cm²

Density, a.u.

Wavenumbers, cm⁻¹

no absorbing edges
one absorbing edge
Antenna fabrication

1. Original diode laser facet
2. SiO$_2$ deposition for electrical isolation and surface passivation
3. Evaporation of gold layer
4. Optical Antenna is defined with FIB

100 nm