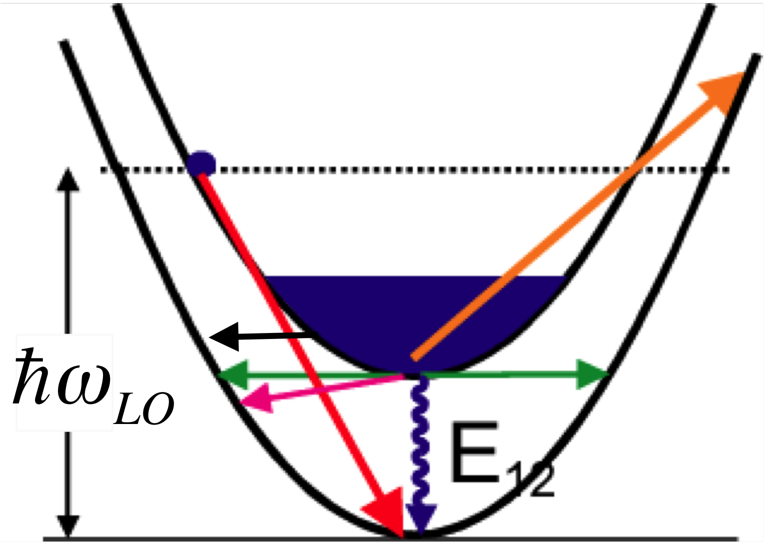
THz Quantum cascade lasers: High performance and last developments

G. Scalari
J. Faist

Gain medium design: in the THz is challenging

Photon energy smaller than the phonon in the host material

$$h\nu < \hbar\omega_{LO}$$



- Emission of optical phonon by thermal electrons (~0.5 ps)
- Absorption of optical phonons (2-5 ps)
- electron-electron scattering (~5-40 ps)
- impurity scattering, interface roughness (~10-30 ps)
- acoustic phonons (~300 ps)
- photons (~10 µs)

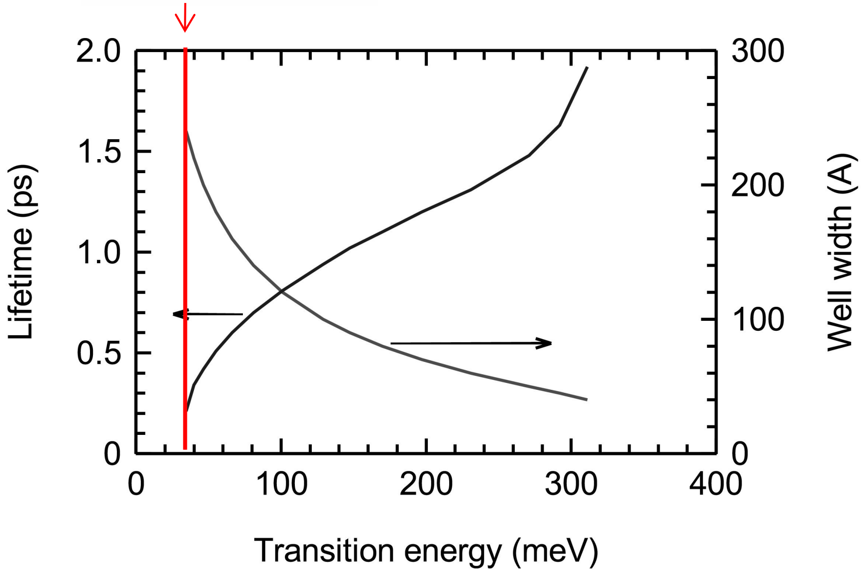
Elastic processes: they thermalize but they do not cool down electron distribution

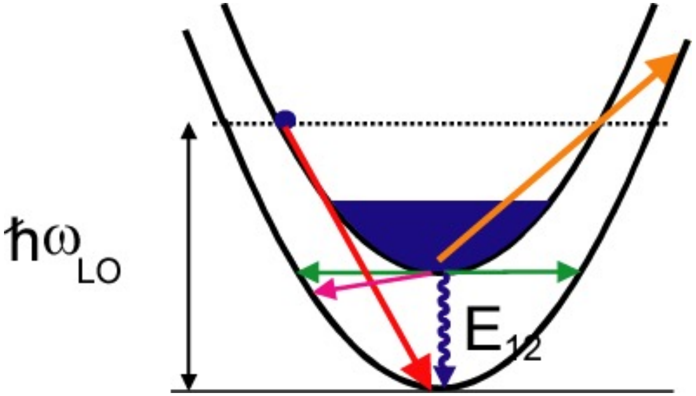
From mid-IR to THz: lifetimes

Mid-IR:
- Optical phonon dominated
- Weak temperature dependence

THz:
- Optical phonon dominated at high T
- Strong temperature dependence

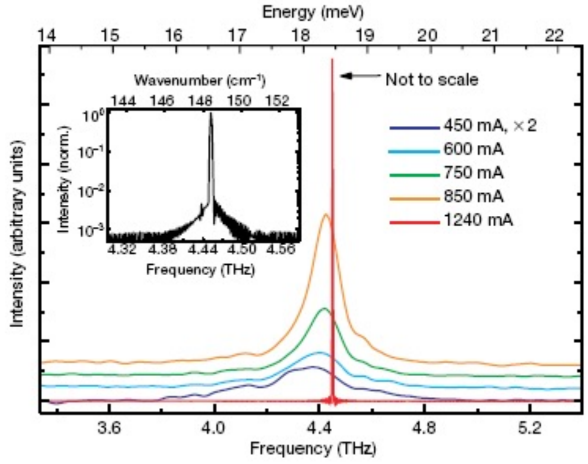
$$E_{21} = \hbar\omega_{LO}$$

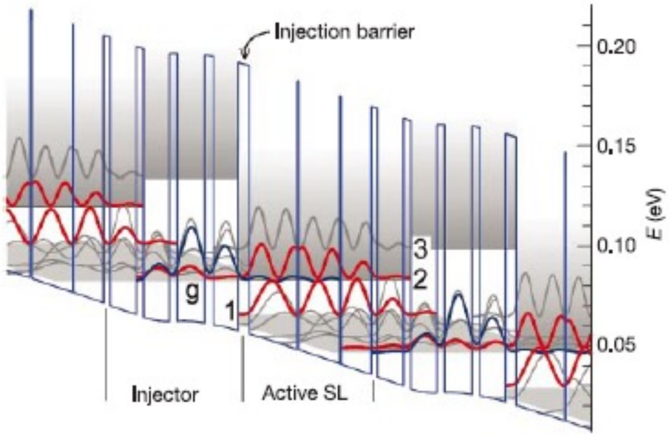




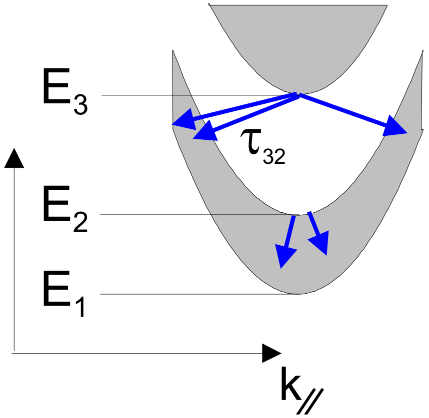
Terahertz semiconductor-heterostructure laser

Rüdeger Köhler*, Alessandro Tredicucci*, Fabio Beltram*, Harvey E. Beere†, Edmund H. Linfield†, A. Giles Davies†, David A. Ritchie†, Rita C. Iotti‡ & Fausto Rossi‡





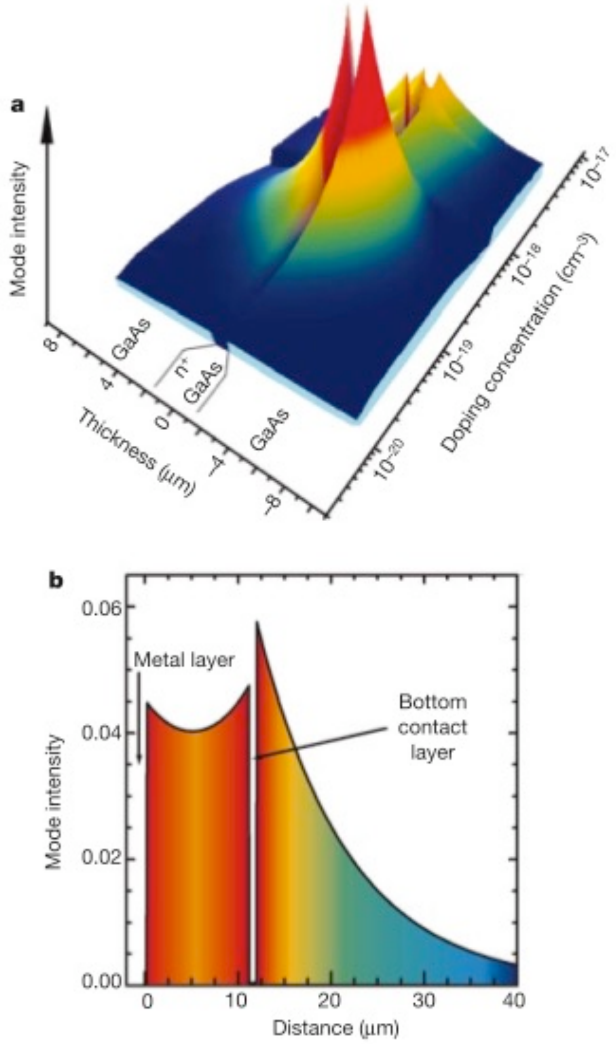
Population inversion by phase space engineering



Tmax ~ 65K

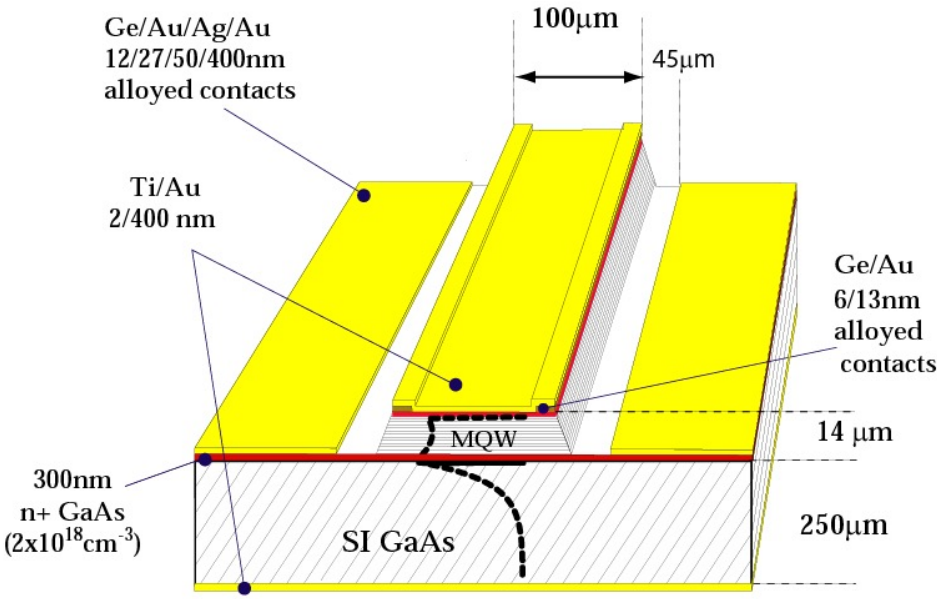
Köhler, Tredicucci et al., NATURE | VOL 417 | 9 MAY 2002 |

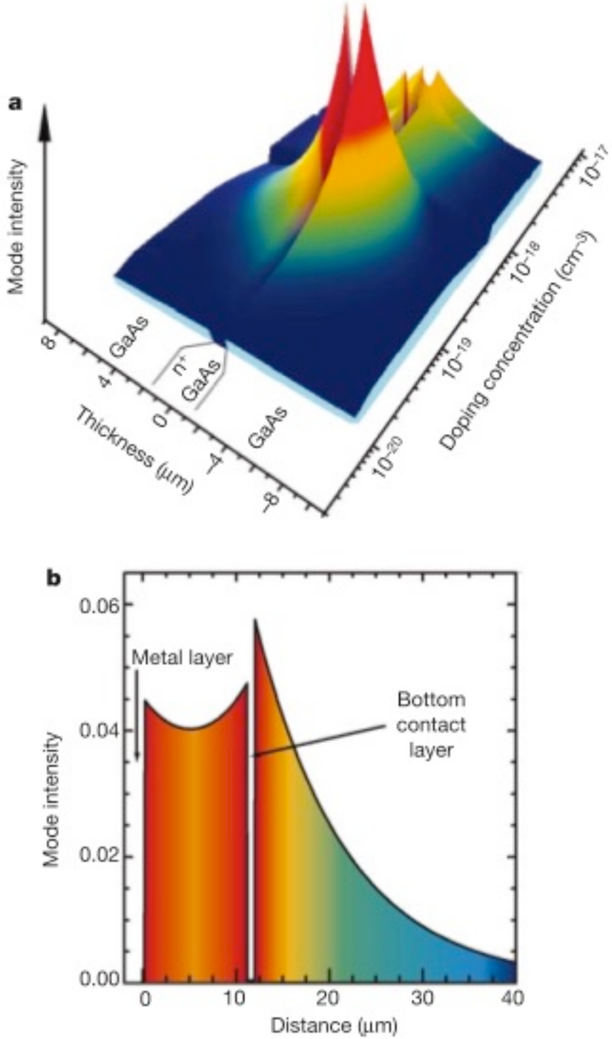
The key is the low loss waveguide.....



$$\alpha_w = 16\,cm^{-1}\,\Gamma = 0.42$$

Surface-plasmon waveguide in the THz





The overlap with the undoped substrate is virtually lossless

Figure of merit Γ/α still good at these frequencies

R. Köhler et al., NATURE | VOL 417 | 9 MAY 2002 | www.nature.com

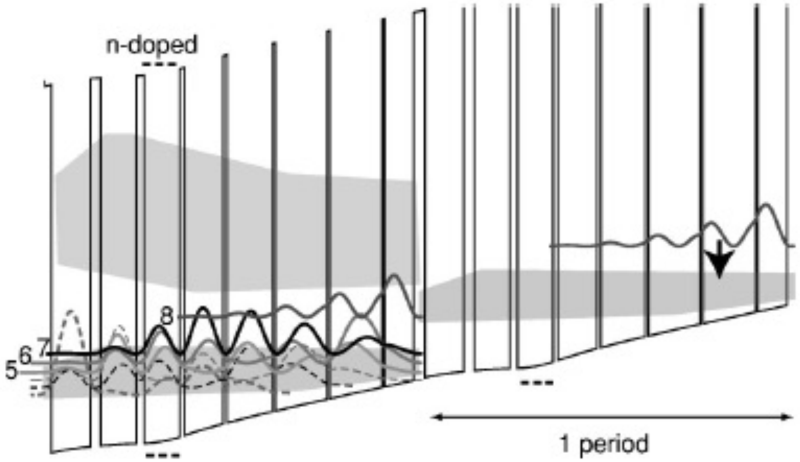
Bound-to-continuum: play on the diagonal transition

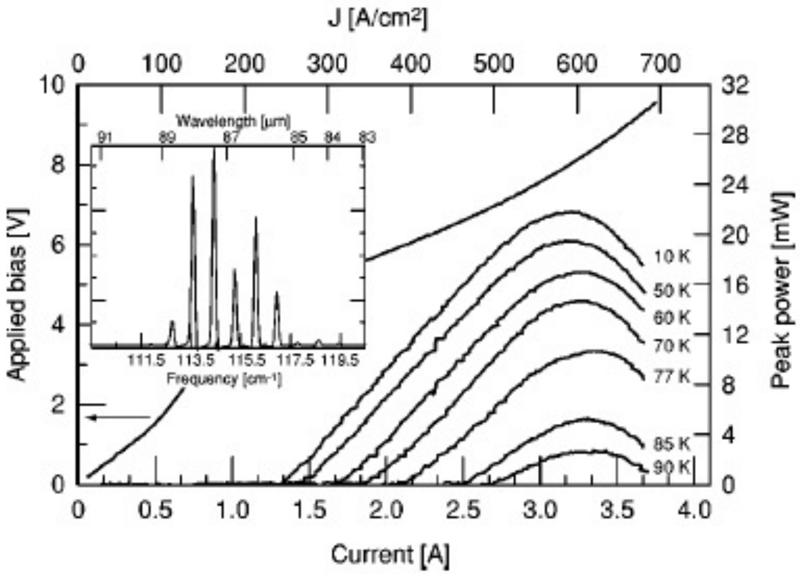
Far-infrared ($\lambda \simeq 87\ \mu m$) bound-to-continuum quantum-cascade lasers operating up to 90 K

Giacomo Scalari,[a] Lassaad Ajili, and Jérôme Faist[b]
Institute of Physics, University of Neuchâtel, CH-2000 Neuchâtel, Switzerland

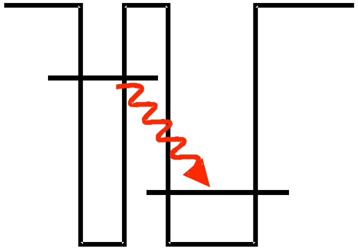
Harvey Beere, Edmund Linfield, and David Ritchie
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom

Giles Davies
School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom



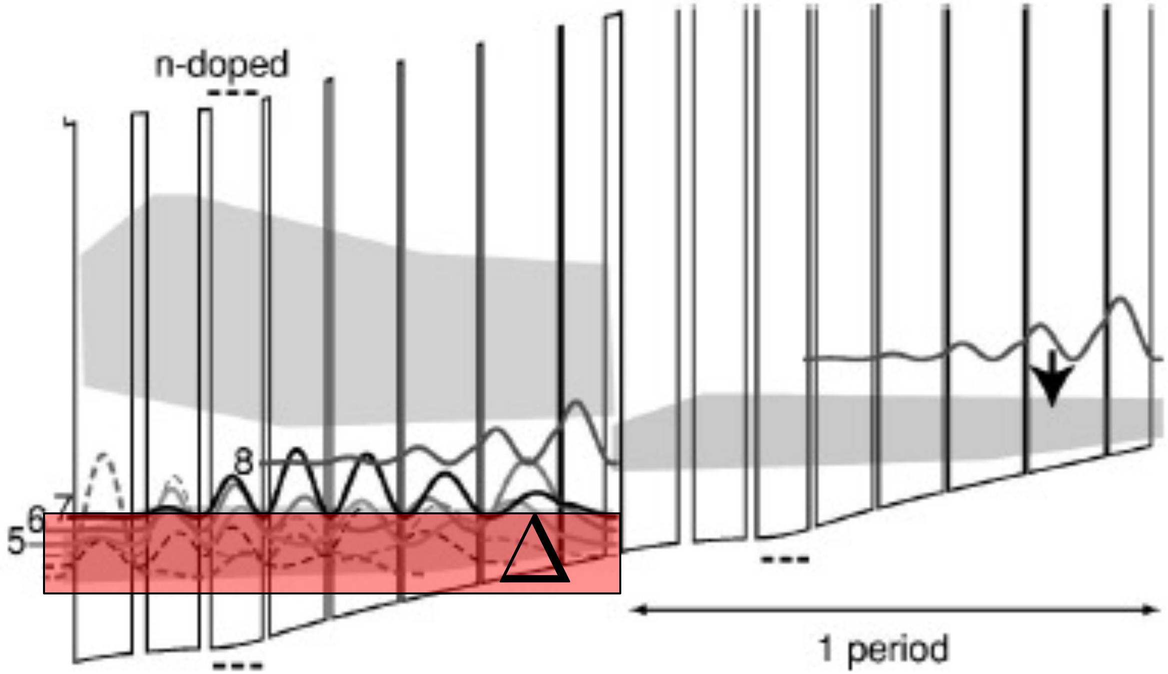


Population inversion:
Phase space + diagonal transition



Appl. Phys. Lett., Vol. 82, No. 19, 12 May 2003

Limit of pure bound-to-continuum structures



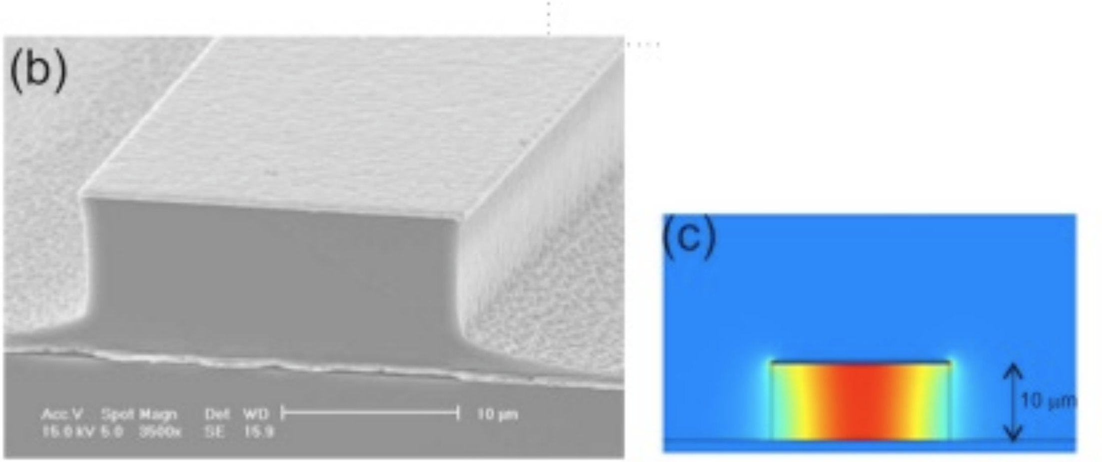
$$\Delta \leq h\nu$$

$$\Delta >> \Gamma \qquad \Delta > kT$$

But the photon energy is 15 meV and so T is limited around 100 K

Γ Broadening of the levels

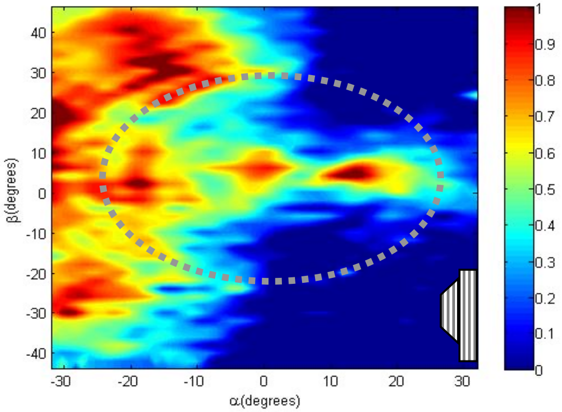
The advent of the double metal waveguide

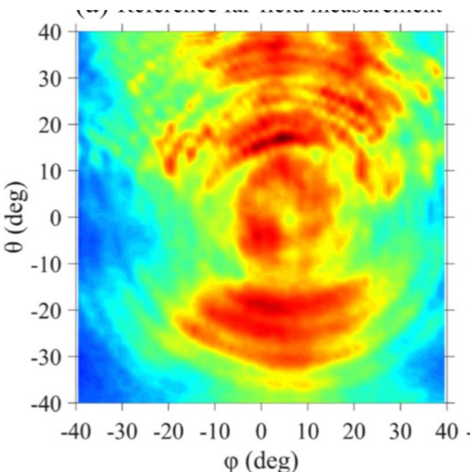


B. Williams Nat. Phot, 2007

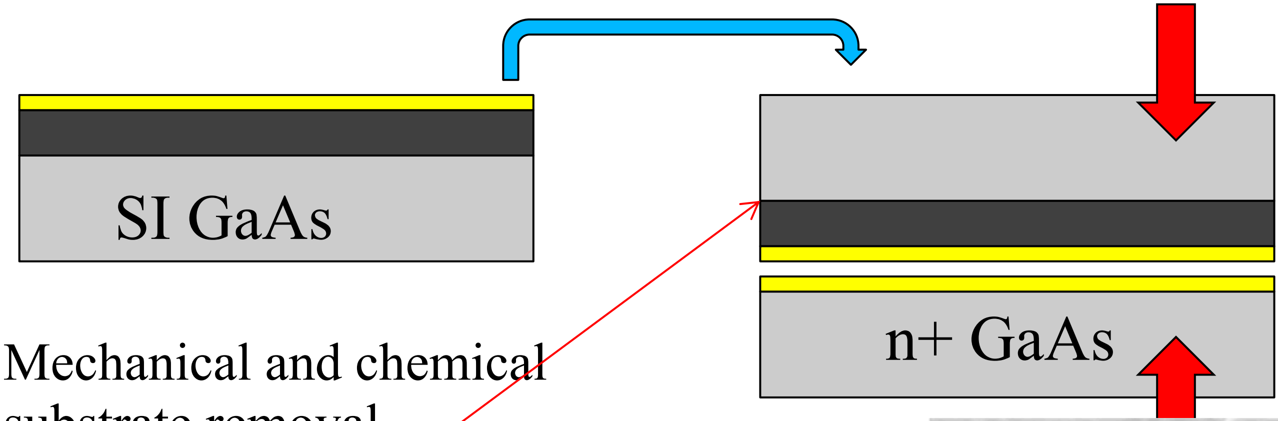
High confinement factor, intrinsical high reflectivity due to impedance mismatch

Highly patterned far field: subwavelength aperture as a laser facet



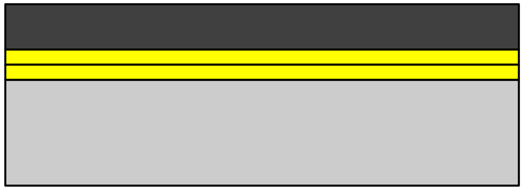


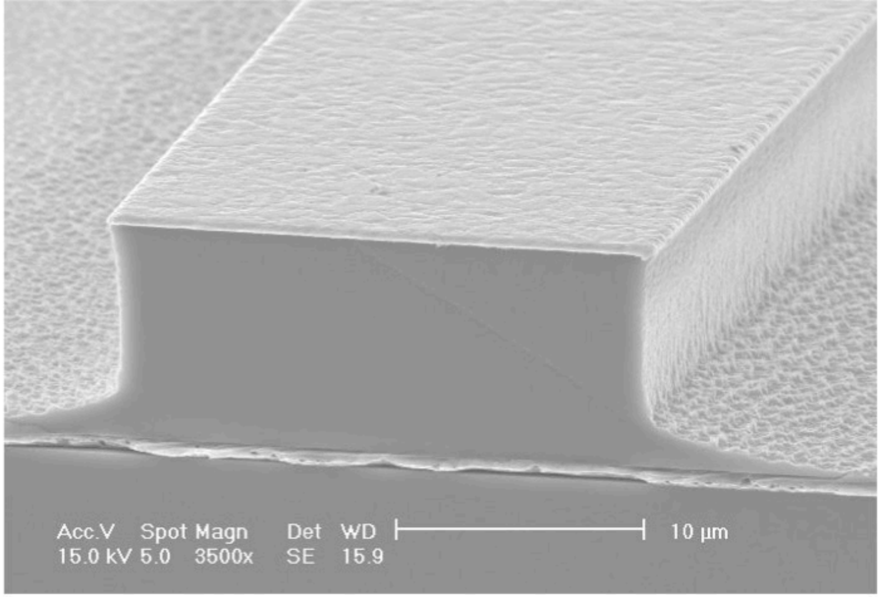
Double-metal waveguide: fabrication technology



Thermocompression
Au/Au bonding

Mechanical and chemical
substrate removal.
Etch stop layer





After substrate removal, standard processing (ridges, grating, contacts...)

Unterrainer (2002), then Williams (2003)

THz waveguides comparison

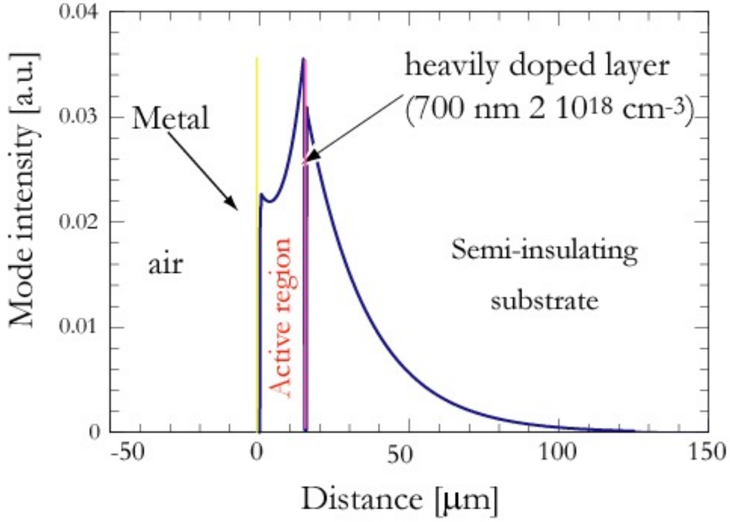
Single plasmon waveguide

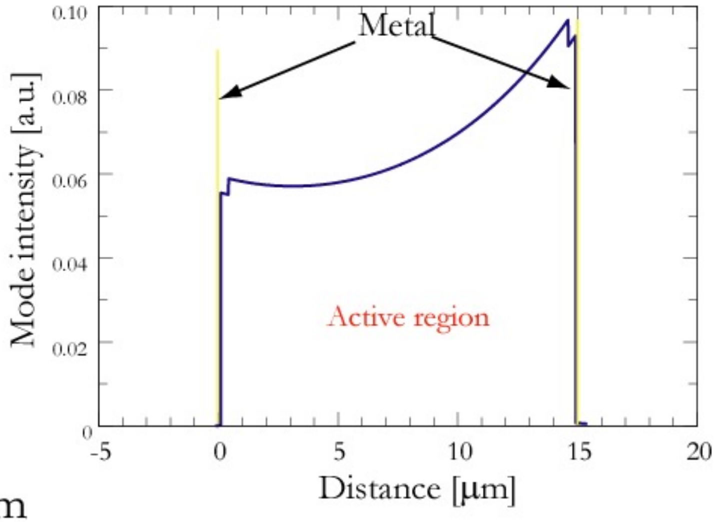
One interface plasmon + one bounding doped layer

Double metal waveguide

Active region sandwiched between two metals

Free carrier absorption α λ^2





$\lambda = 81\ \mu m$

$\Gamma = 0.35$ $\alpha_w = 9.4\ cm^{-1}$

$\Gamma/\alpha_w = 3.7\ 10^{-2}$ cm

$\Gamma = 0.957$ $\alpha_w = 28.7\ cm^{-1}$

$\Gamma/\alpha_w = 3.3\ 10^{-2}$ cm

Growth axis

Threshold condition: $g = \alpha_w/\Gamma + \alpha_m/\Gamma$

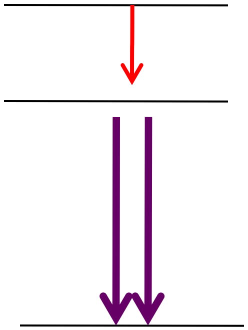
J. Ulrich et al., Physica B, **272**, 216, (1999).

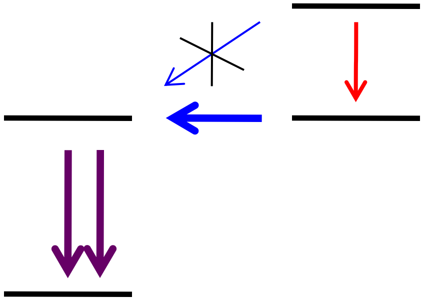
R. Kohler et al., Nature **417**, 156 (2002)

K. Unterrainer et al., Appl. Phys. Lett. **80**, 3060 (2002)
B.S. Williams et al., Appl. Phys. Lett. **83**, 2124 (2003)

“High temperature design”

Potential drop per period > optical phonon energy



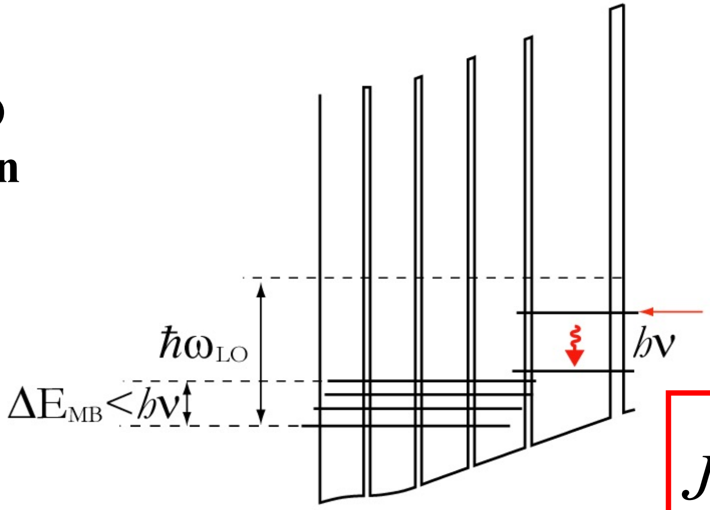


Unfavorable ratio
of lifetimes

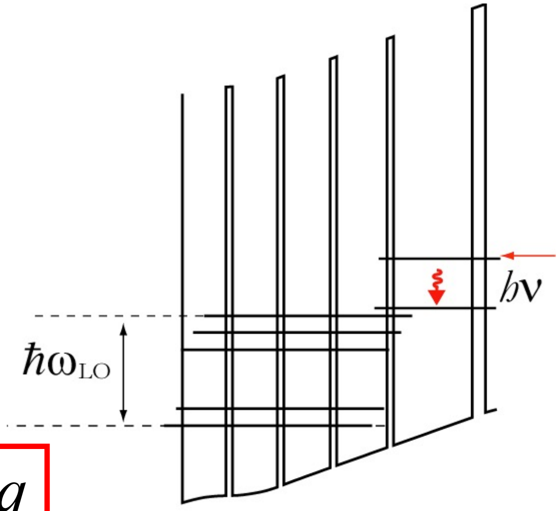
Use selective depopulation of lower
State by resonant tunneling

Principal design strategies

No LO phonon



$$\boxed{J = \frac{n_s q}{\tau}}$$



LO phonon

- **Lower current densities (no LO phonon),**
- **Lower applied bias**
- **longer lower state lifetime (elastic scattering and tunneling, Tmax 100 K)**
- **So far, lowest frequency demonstrated**

R. Kohler et al., Nature **417**, 156 (2002)
G. Scalari et al., Appl. Phys. Lett. **82**, 3165 (2003)
Walther et al., Appl. Phys. Lett., 91, 131122 (2007)

- **Higher current densities**
- **Higher applied bias**
- **shorter lower state lifetime**
- **So far, highest Tmax demonstrated**

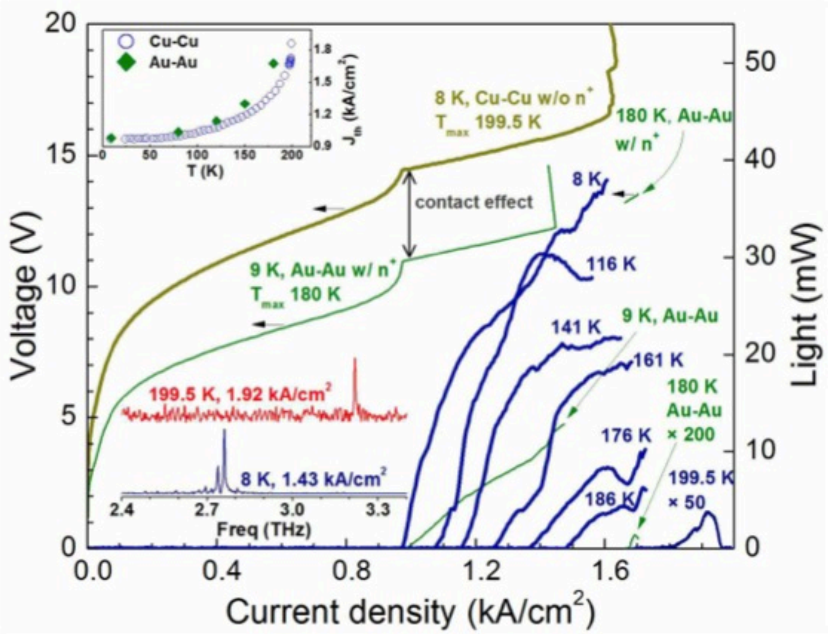
H. Luo et al, Appl. Phys. Lett. 90, 041112 (2007)
M.A. Belkin et al., Opt. Express 16, 3242 (2008)
S. Kumar et al., Appl. Phys. Lett. **94**, 131105 (2009)

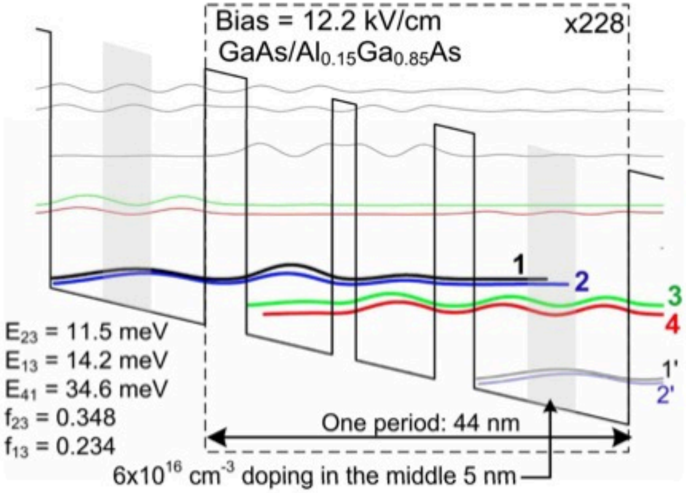
High T_{max} with diagonal 3 W

Terahertz quantum cascade lasers operating up to ~ 200 K with optimized oscillator strength and improved injection tunneling

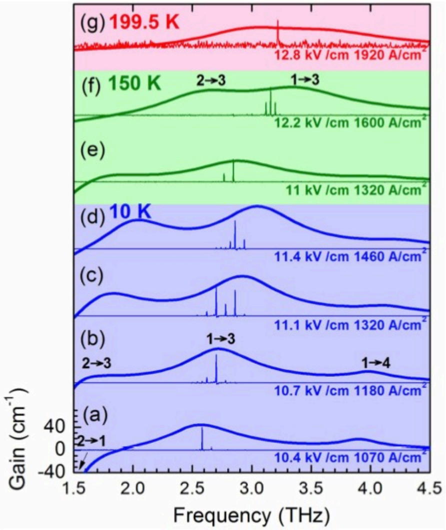
S. Fathololoumi,[1,3,*] E. Dupont,[1] C.W.I. Chan,[2] Z.R. Wasilewski,[1] S.R. Laframboise,[1] D. Ban,[3] A. Mátyás,[4] C. Jirauschek,[4] Q. Hu,[2] and H. C. Liu[1,5]

Received 21 Nov 2011; revised 17 Jan 2012; accepted 18 Jan 2012; published 1 Feb 2012
13 February 2012 / Vol. 20, No. 4 / OPTICS EXPRESS 3866

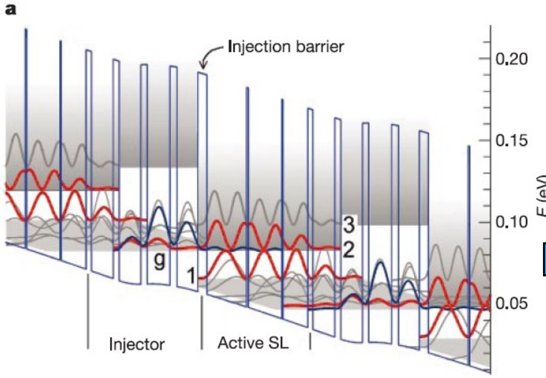




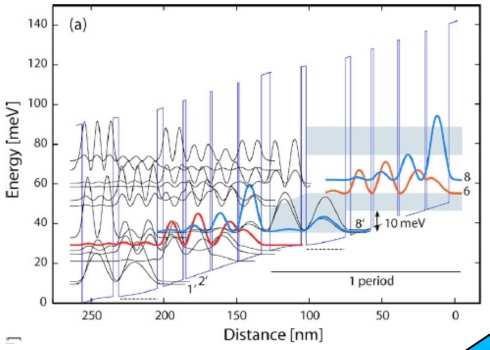
Cu-Cu waveguide instead of Au-Au



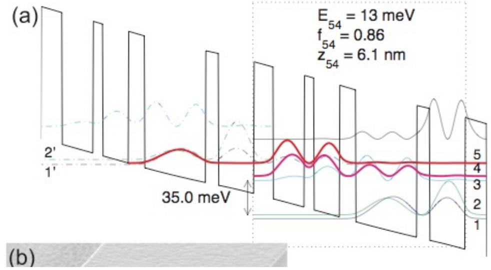
Design evolution: progressively reduce the number of wells



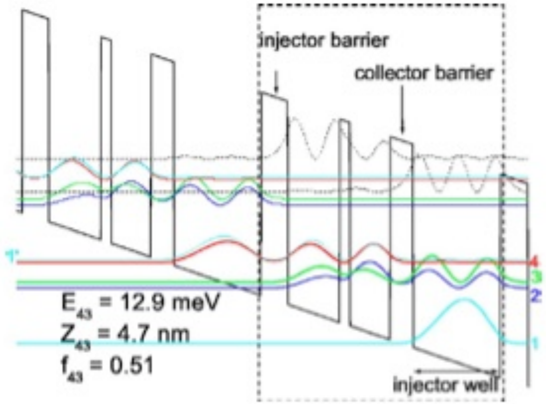
7 QW Kohler et al.



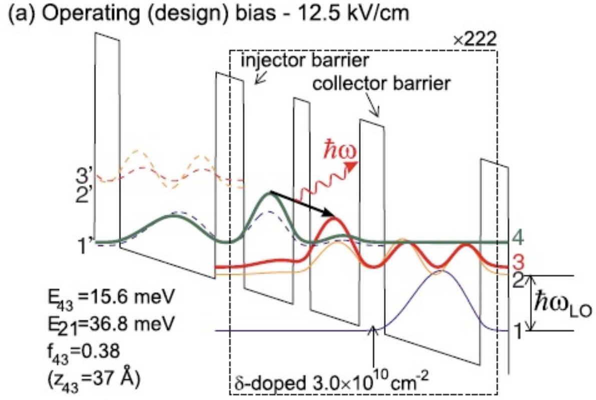
6 QW Walther et al.



4 QW Williams et al.



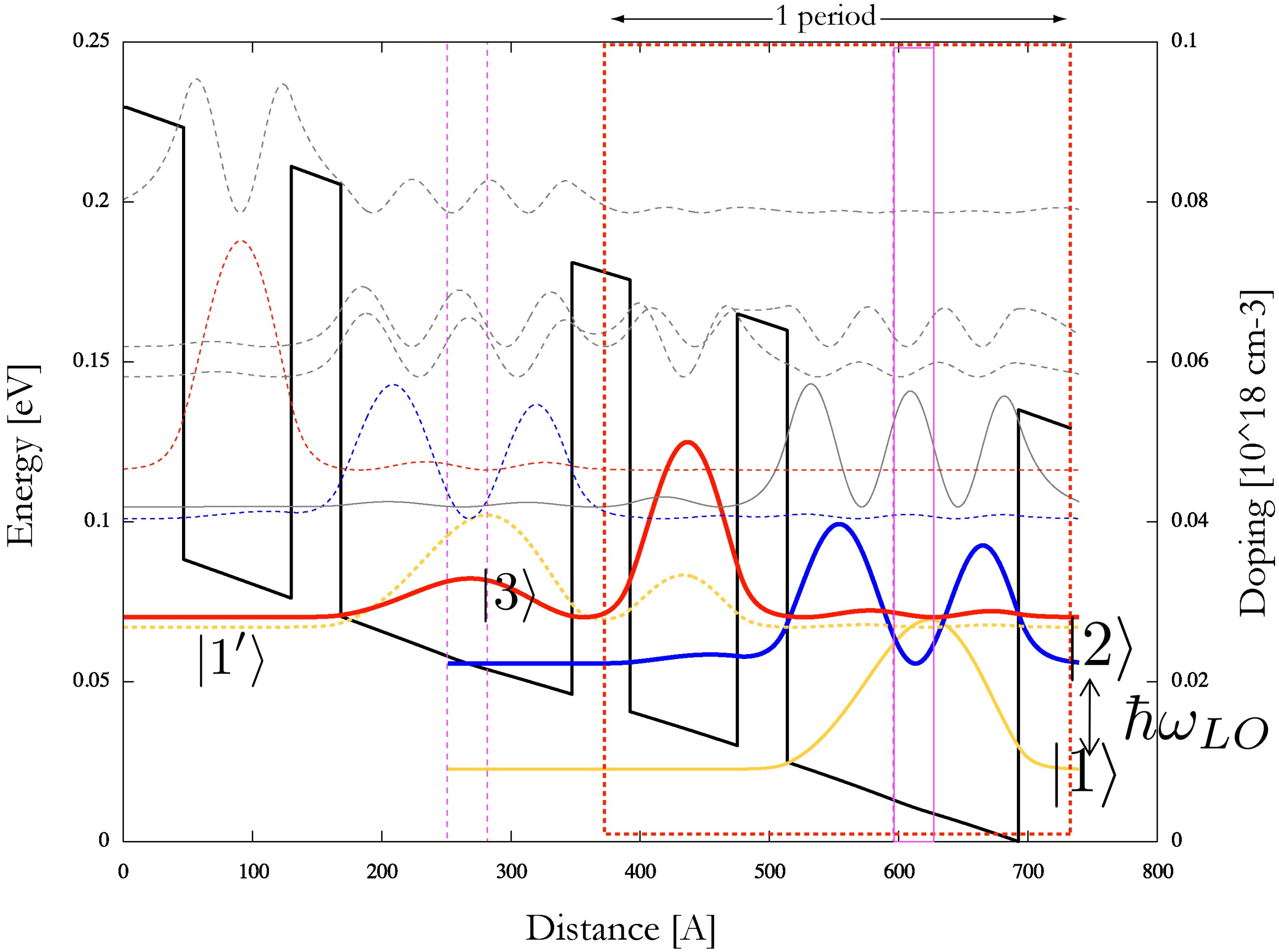
3 QW Luo et al.



3 QW Kumar et al.

….

Two quantum well laser: direct phonon depopulation



GaAs/**$Al_{0.15}$ $Ga_{0.85}$As**

220 periods
Lp=34.5 nm

$$n_s \simeq 3 \times 10^{10}\, cm^{-2}$$

$$z_{32} = 28\,\mathring{A}$$

$$E_{32} = 11.4\, meV$$

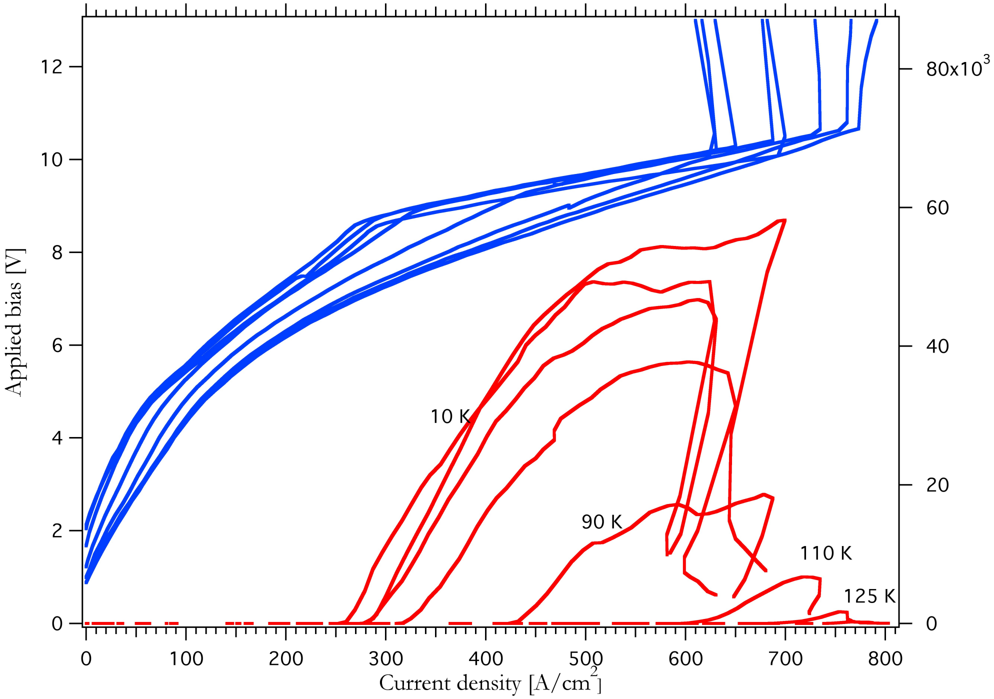
- Strongly diagonal, enhance upper state lifetime
- No more resonant tunneling for the carrier extraction

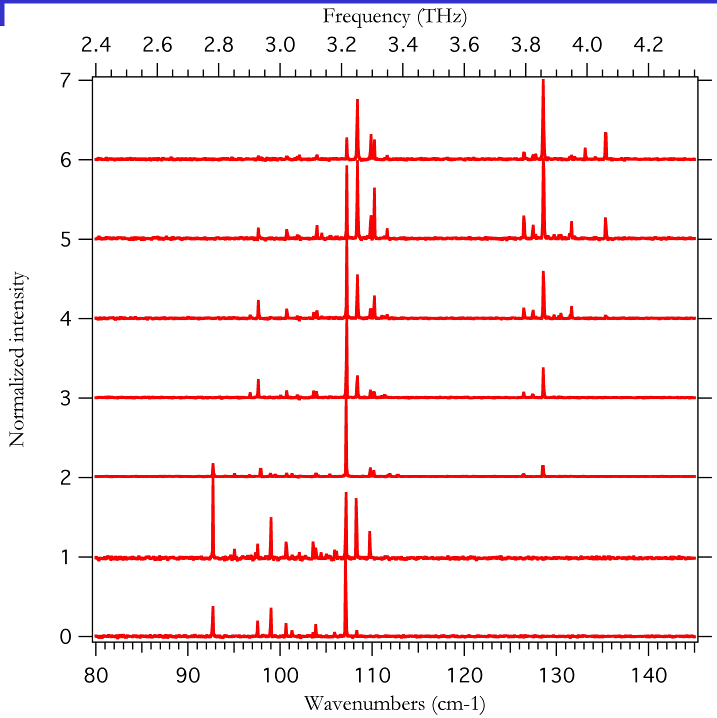
F=14 kV/cm

G. Scalari et al. Op. Express 18, 8043 (2010)

Two well: results in pulsed operation

Standard double metal waveguide





Wide dynamic range: 60 % at low T

Tmax = 125 K

J_{thresh}^{10K}=250 A/cm^2

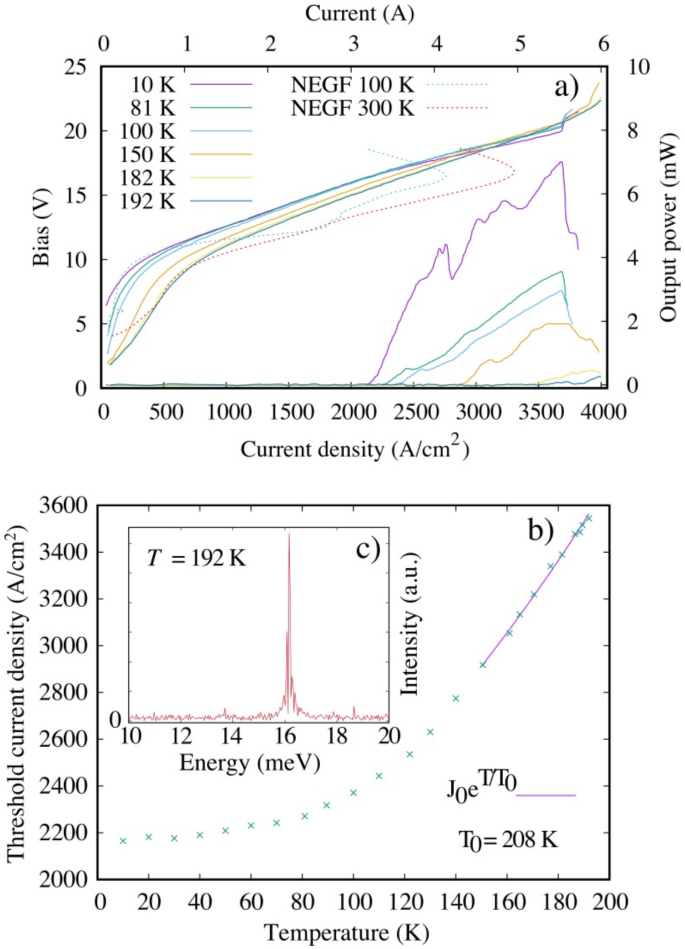
..but…T_0= 64 K

Two-well optimized with NEGF method

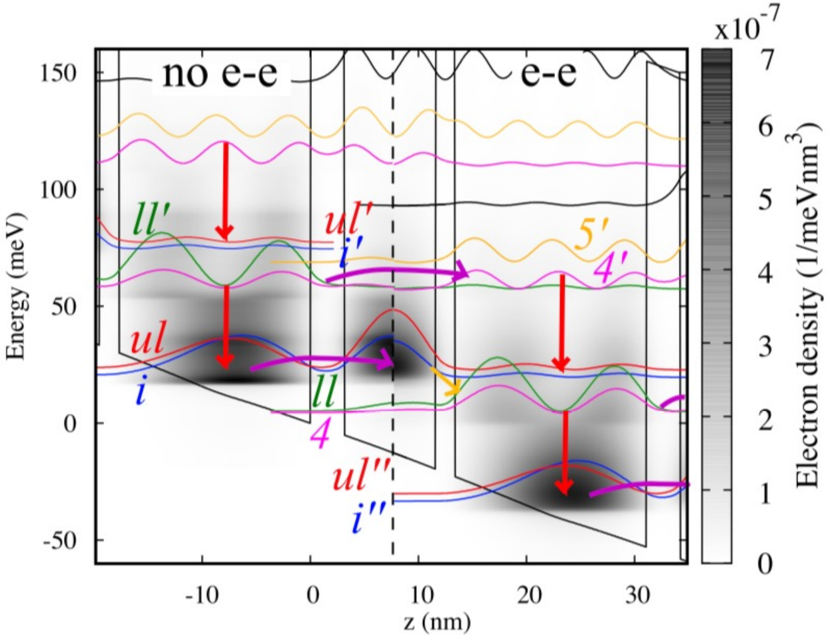
APPLIED PHYSICS LETTERS **112**, 021104 (2018)

Two-well quantum cascade laser optimization by non-equilibrium Green's function modelling

M. Franckié,[1,a)] L. Bosco,[1] M. Beck,[1] C. Bonzon,[1] E. Mavrona,[1] G. Scalari,[1] A. Wacker,[2] and J. Faist[1]



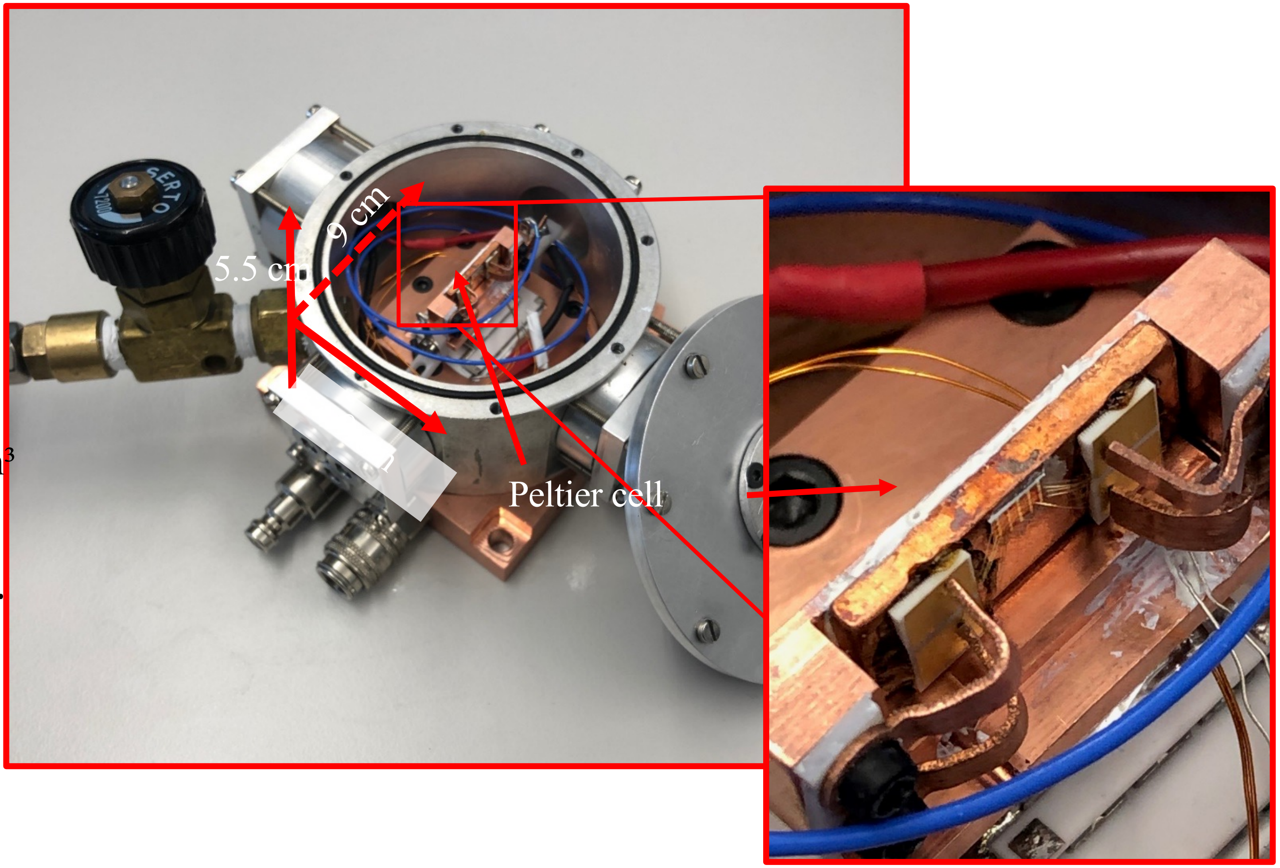
higher Al (25%) content in the barriers



Thermoelectrically Cooled Laser Box

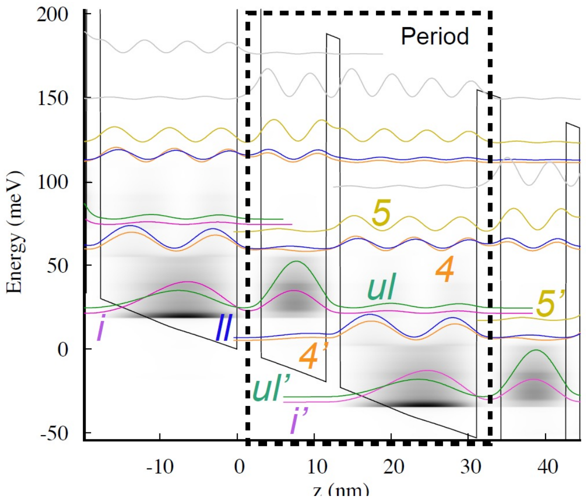
Laser box size
W×L×H = 9×9×5.5 cm^3

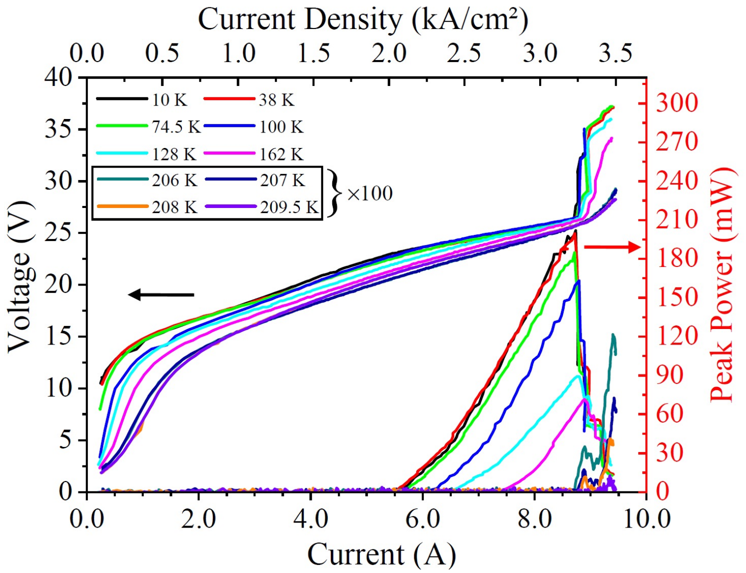
4-stage thermoelectric cooler
ΔT=130 °C



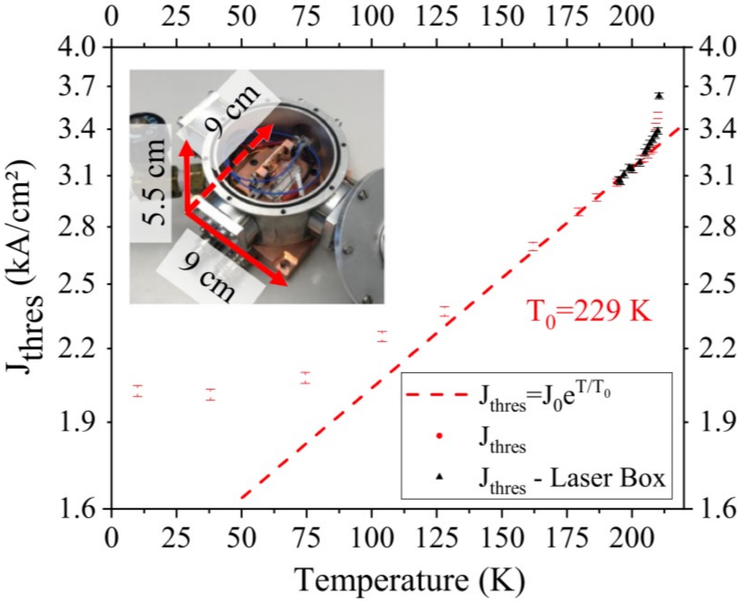
ETH zürich

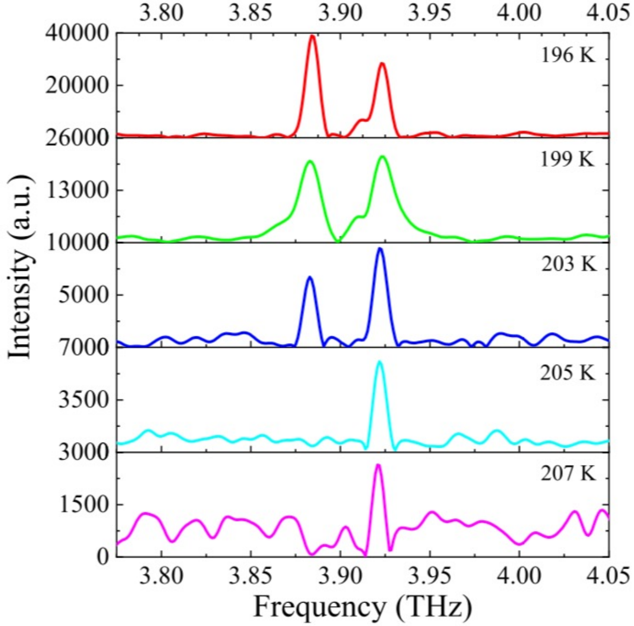
Cu-Cu waveguides: thermoelectrically cooled THz QCL up to 210 K





Full cryo-free operation and detection at 207 K





L. Bosco et al., Appl. Phys. Lett. **115**, 010601 (2019)

Recent results: up to 250 K!!!! (actually 261 K still unpub..)

nature photonics

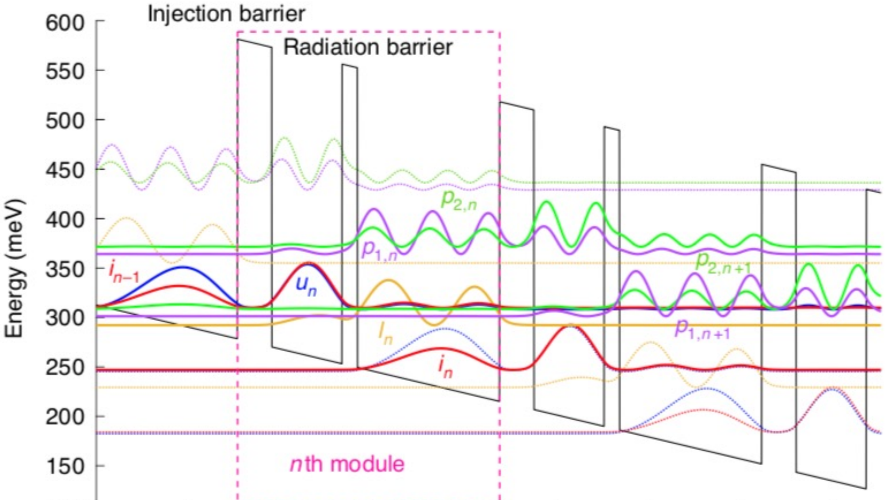
ARTICLES

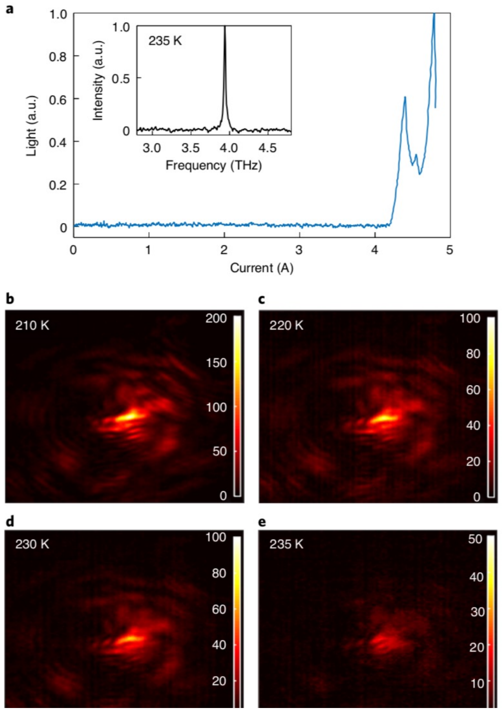
https://doi.org/10.1038/s41566-020-00707-5

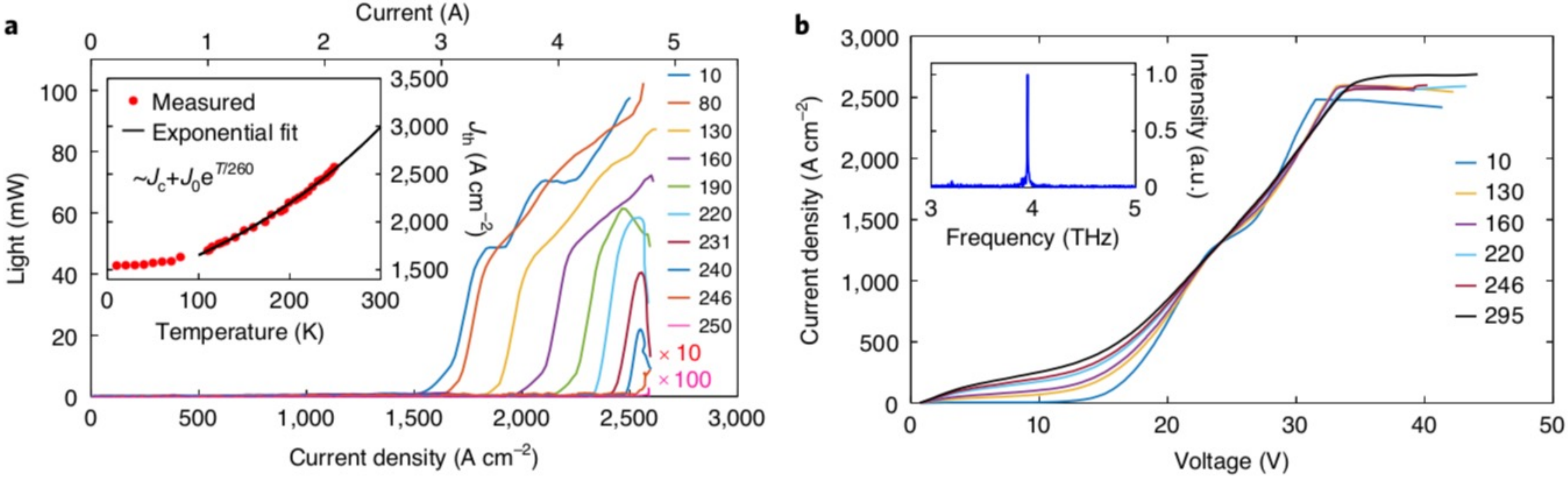
Check for updates

High-power portable terahertz laser systems

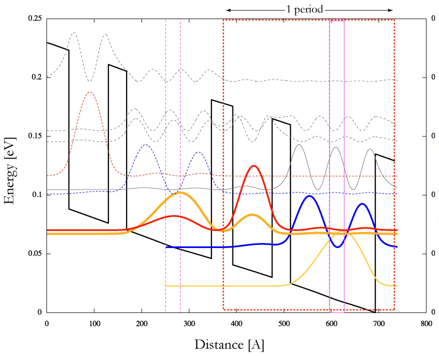
Ali Khalatpour[1], Andrew K. Paulsen[1], Chris Deimert[2], Zbig R. Wasilewski[2,3,4,5] and Qing Hu[1]✉

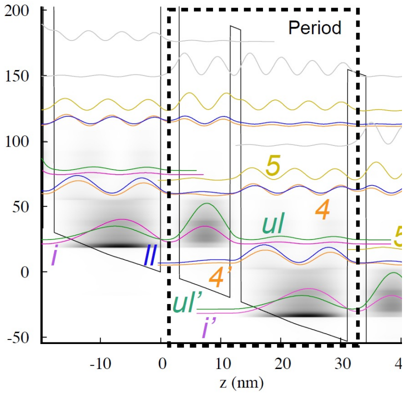


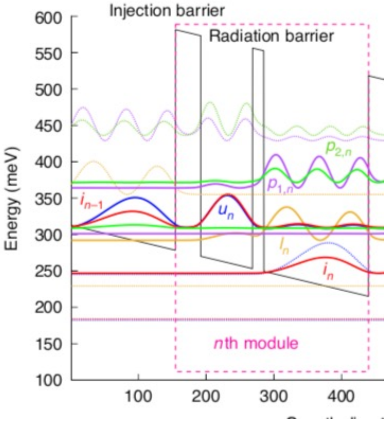




Two wells over 10 years evolution…..





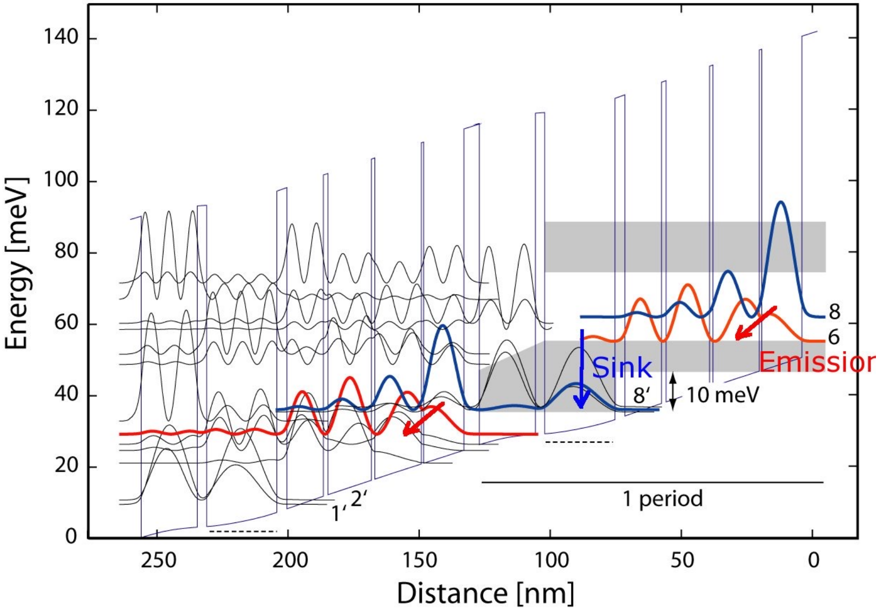


Year	2010	2019	2020
Material composition	GaAs/$Al_{0.15}Ga_{0.85}As$	GaAs/$Al_{0.25}Ga_{0.75}As$	GaAs/$Al_{0.30}Ga_{0.70}As$
Tmax pulsed	125 K	210 K	250 K (260)
Waveguide	Au/Au wet etch	Cu/Cu dry etch	Cu/Cu dry etch
E_{ex}	32 meV	41 meV	55 meV

Low frequency THz QCLs

Difficult to use direct phonon depopulation: selective injection is
The challenge

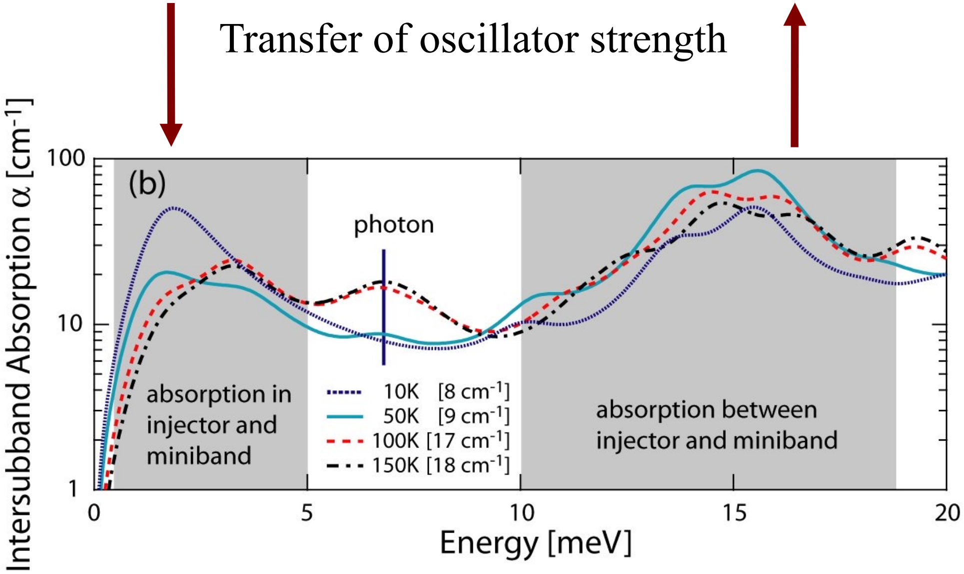
Bandstructure



- Diagonal transition
- Scale extraction energy

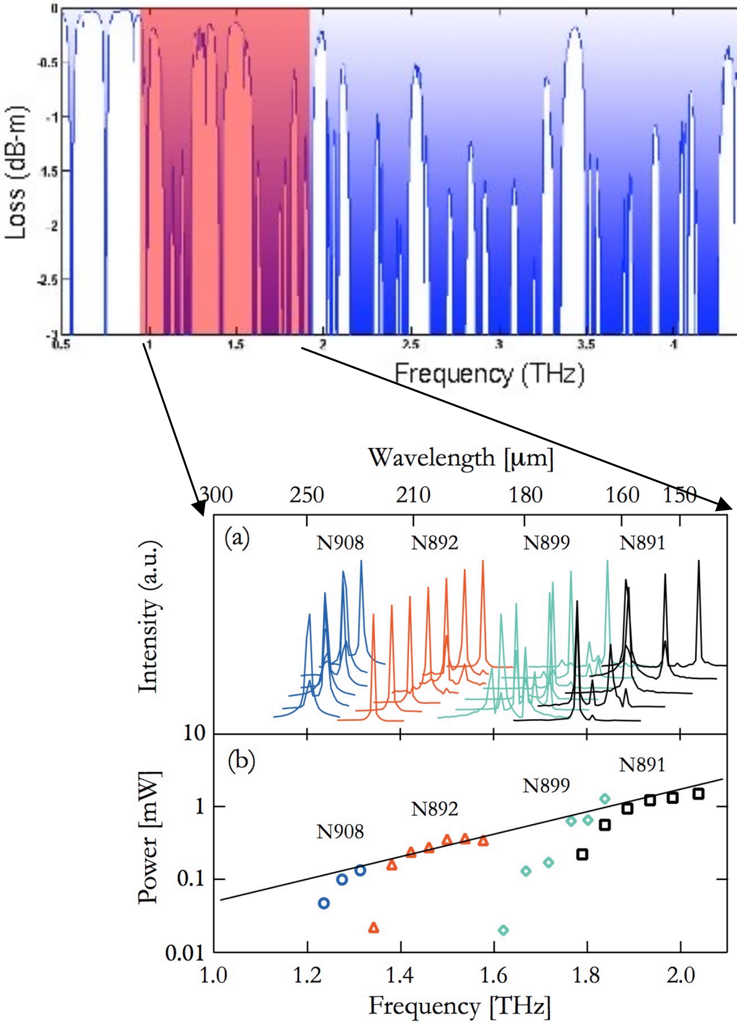
Computed absorption

Transfer of oscillator strength

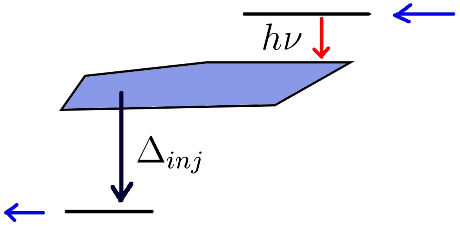


APPLIED PHYSICS LETTERS 89, 231121 (2006)

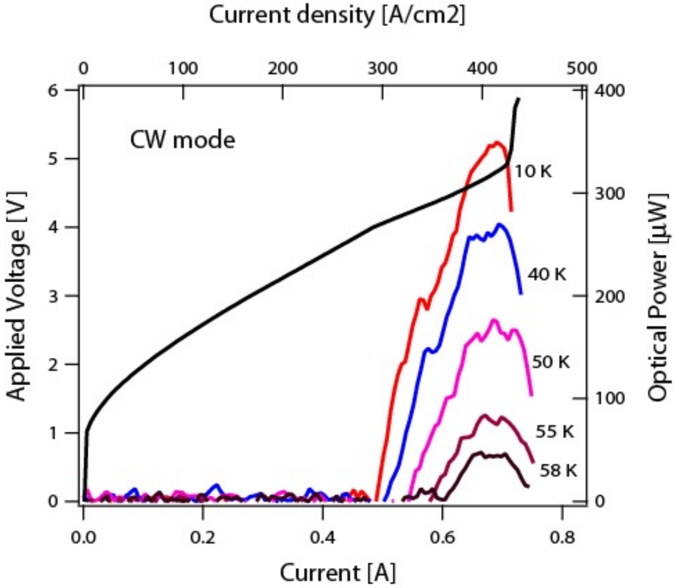
Scalable design (1.2-2THz)



Separate extraction stage

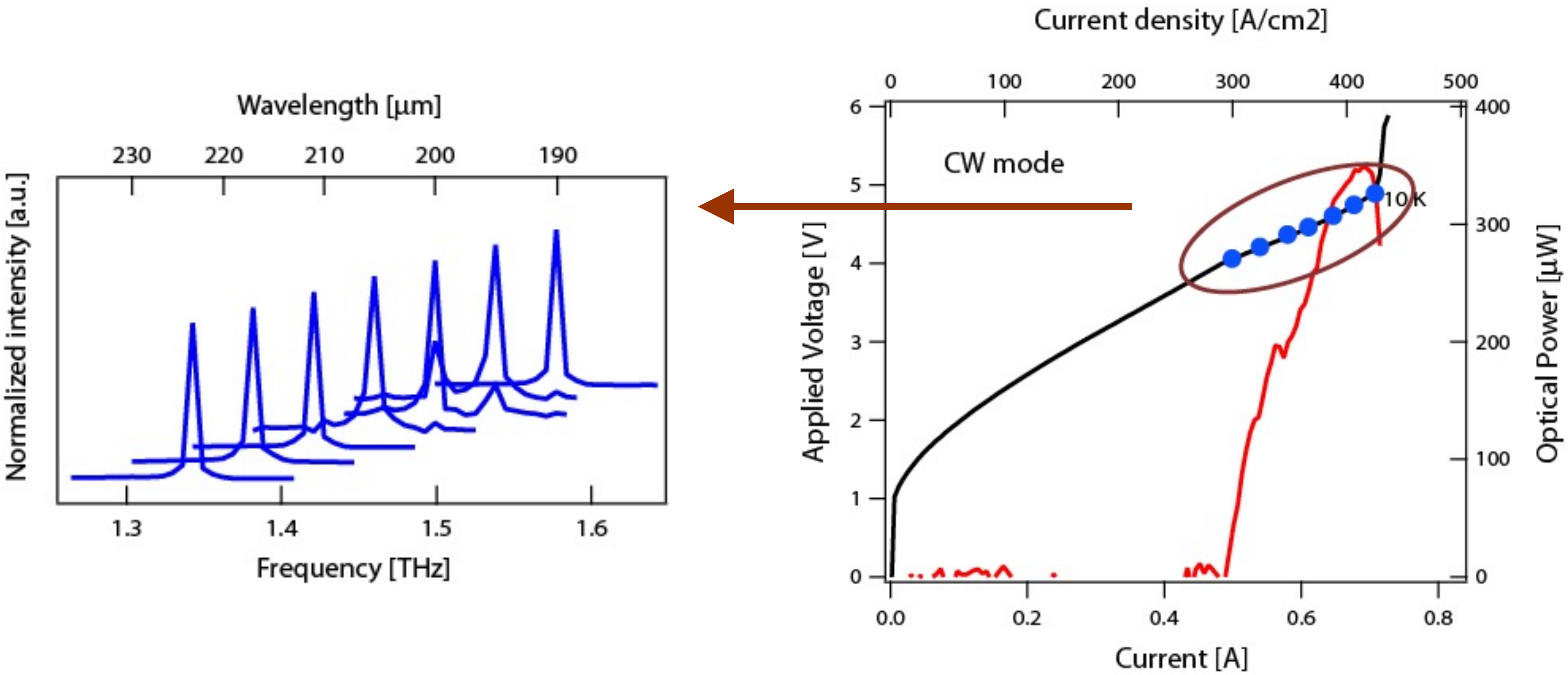


- Extraction and transport separated
- Design is wavelength scalable



G. Scalari et al, Laser & Photonics reviews, (2009)

Marginal population inversion: wide Stark tuning of the gain curve



- Strong Stark shift of gain curve, 16% of center frequency
- Lasing on Fabry-Pérot modes of the cavity (1mm x 165µm)

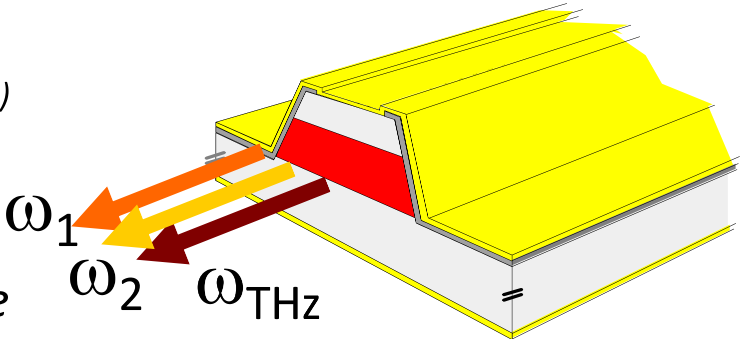
C. Walther *et al*., Appl. Phys. Lett., **91**, 131122, (2007)

Difference Frequency Generation (DFG)

Use intra-cavity DFG in 3-15 µm QCLs to create room-temperature sources in 60-300 µm (1-5 THz) range

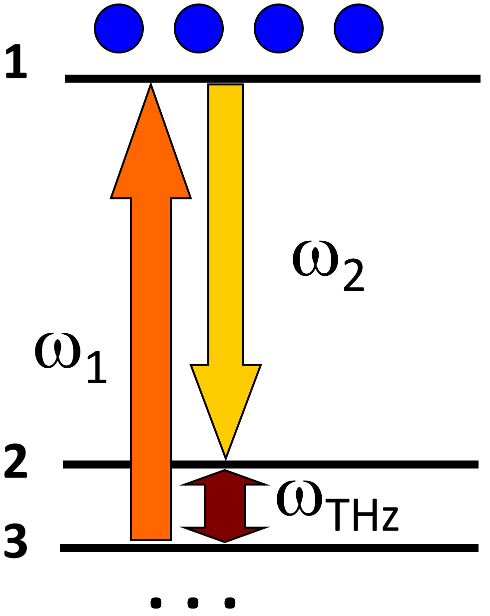
THz QCL source based on intra-cavity DFG

- *Dual-frequency mid-infrared QCLs with giant $\chi^{(2)}$*
- *Coherent THz output at room temperature*
- *THz output tunable over the entire 1-5 THz range*



Belkin lab, UTA

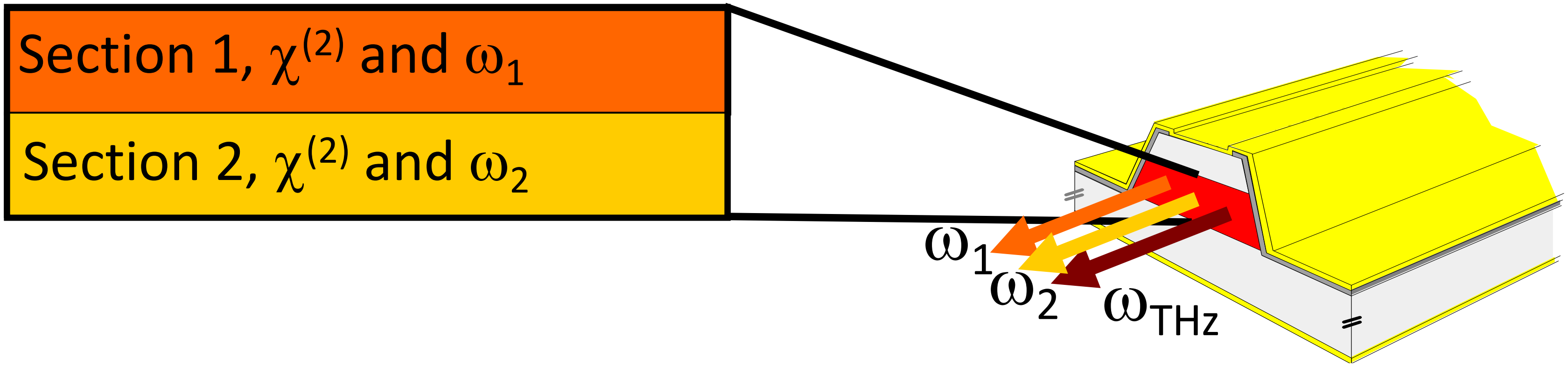
$\chi^{(2)}$ with population inversion



$$\chi^{(2)} = N_e \frac{e^3}{\hbar^2 \varepsilon_0} \times \frac{z_{12} z_{23} z_{31}}{(\omega_{THz} - \omega_{23} + i\Gamma)} \left(\frac{1}{(\omega_1 - \omega_{13} + i\Gamma)} + \frac{1}{(\omega_{12} - \omega_2 + i\Gamma)} \right)$$

Laser action instead of absorption!

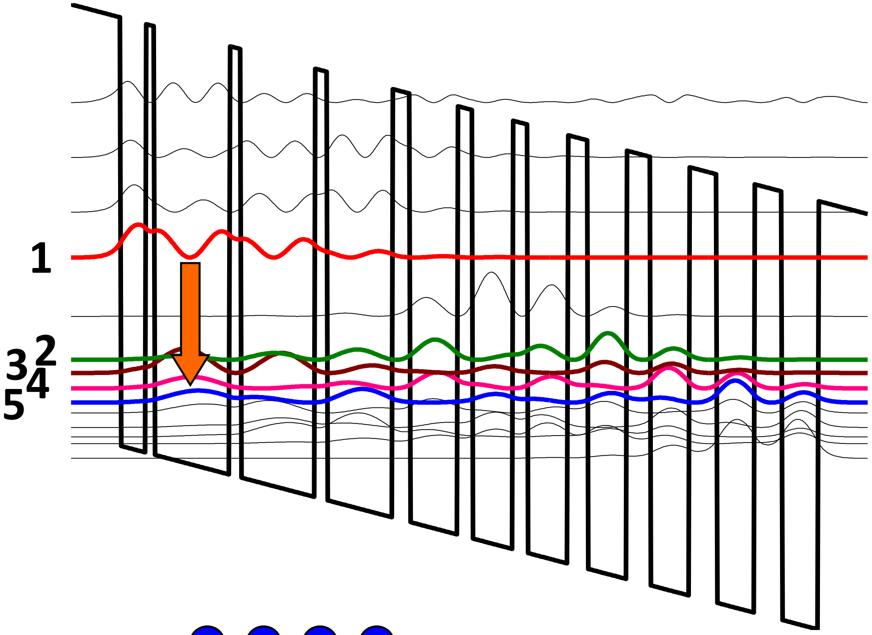
Active region design

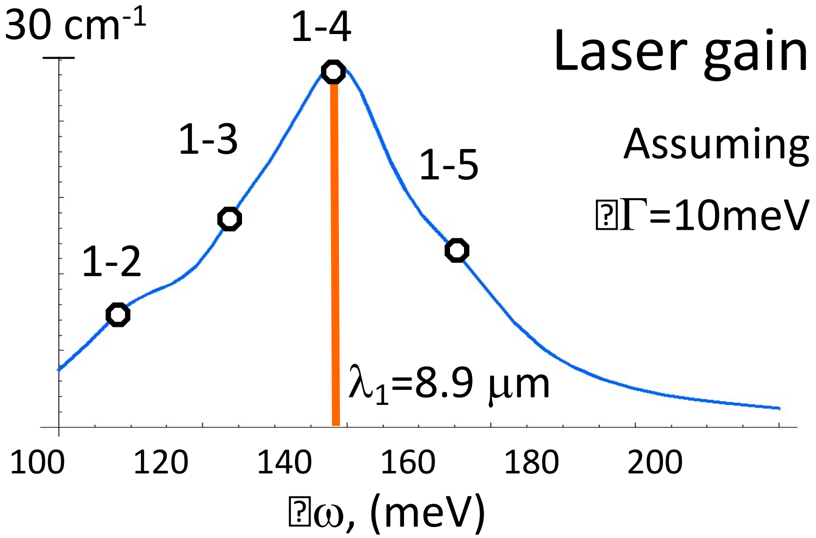


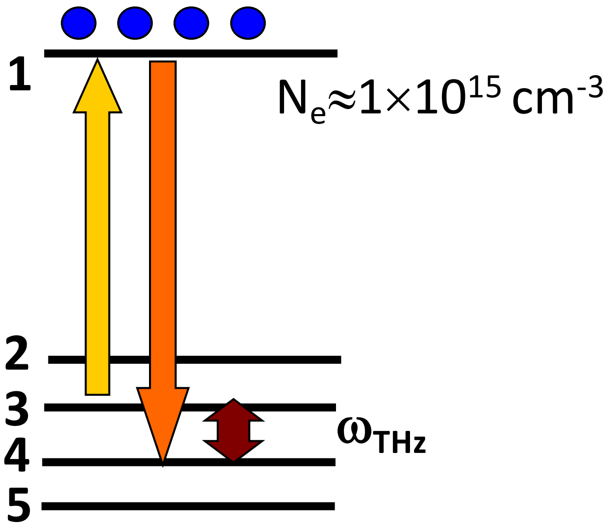
Section 1, $\chi^{(2)}$ and ω_1

Section 2, $\chi^{(2)}$ and ω_2

χ(2)-section design







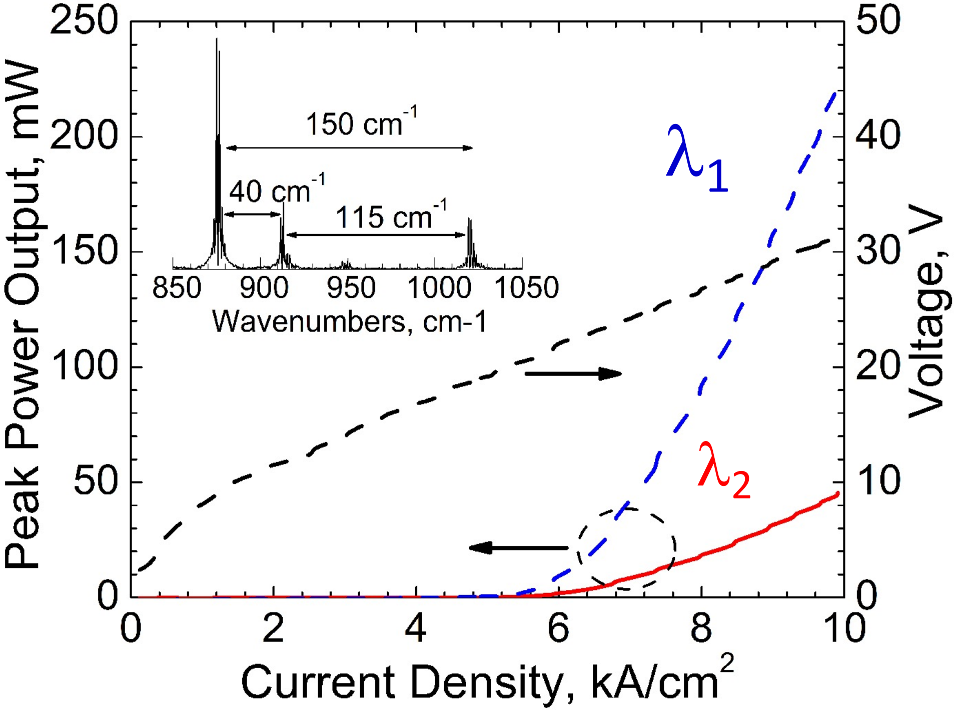
λ_1=8.9 μm

λ_2=10.5μm

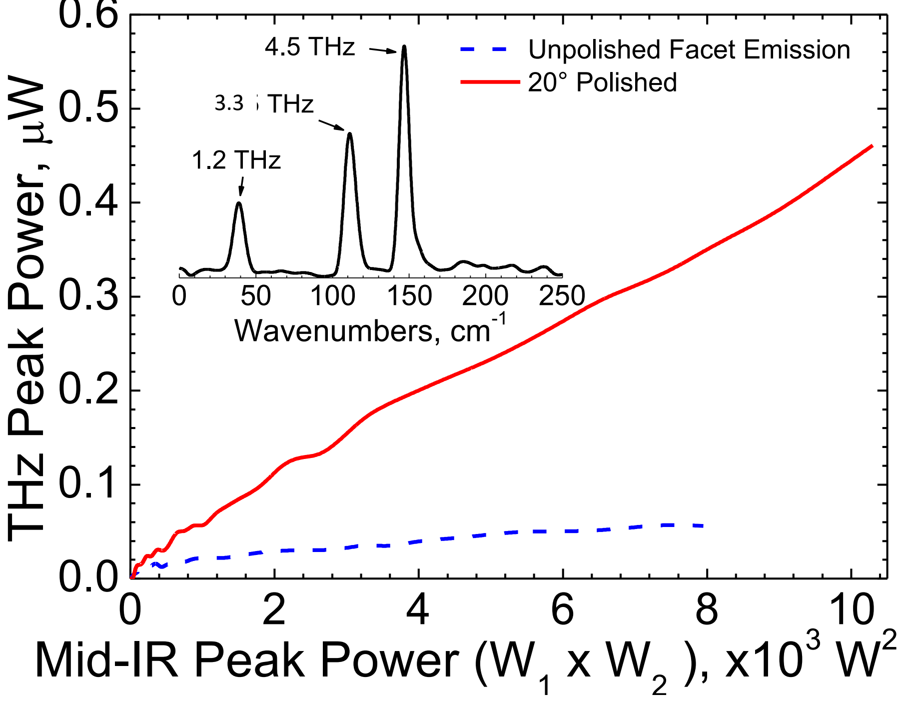
→ λ_{THz}=60 μm

$$\boxed{\chi^{(2)} \approx 1.5\times10^{4}\ \text{pm/V}}$$

Performance (1mm-long, 35µm-wide device)



MIR pump characterization



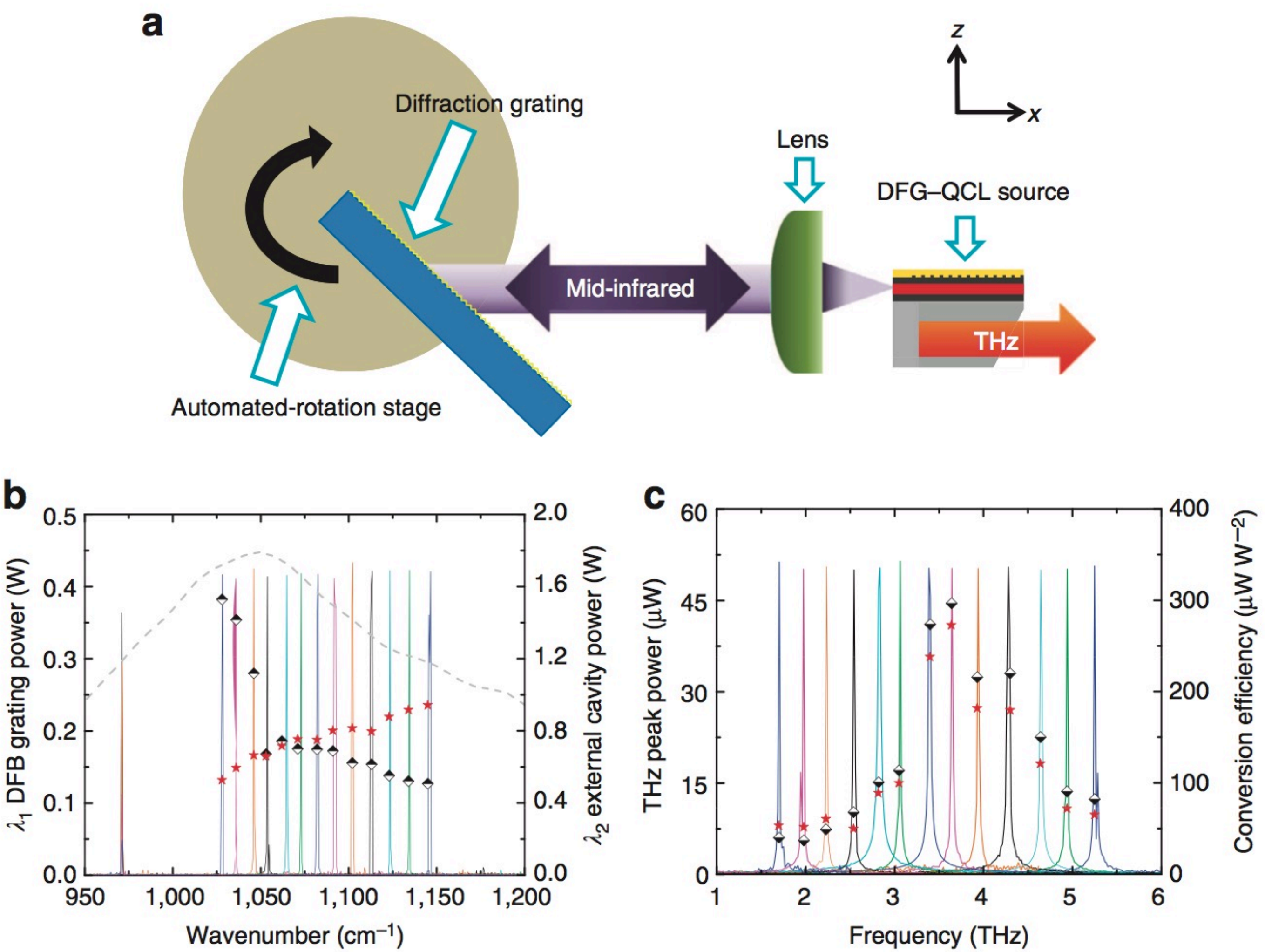
THz output

$$\boxed{\begin{aligned} W_{THz} &= 0.45\ \mu W \\ W_{midIR} &= 270\ mW \end{aligned}}$$

$$\boxed{\begin{aligned} \eta_{ex}(1.2\ THz) &= 8.4\ \mu W/W^2 \\ \eta_{ex}(3.3\ THz) &= 71.1\ \mu W/W^2 \\ \eta_{ex}(4.5\ THz) &= 40.0\ \mu W/W^2 \end{aligned}}$$

Vijayraghavan *et al., Appl. Phys. Lett.* **100,** 251104 (2012), higher power from Northwestern University, Lu et al., *Appl. Phys. Lett.* **101,** 251121 (2012)

External cavity: tunable source



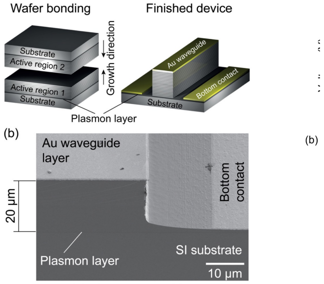
NATURE COMMUNICATIONS | DOI: 10.1038/ncomms3021

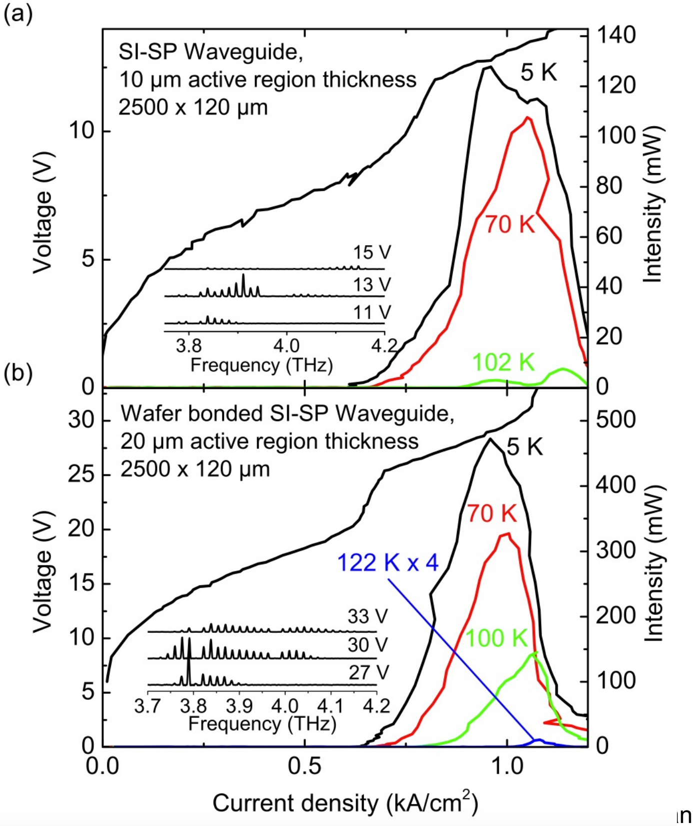
High power THZ QCLs

APPLIED PHYSICS LETTERS **103**, 171113 (2013)

High power terahertz quantum cascade lasers with symmetric wafer bonded active regions

Martin Brandstetter,[1,a)] Christoph Deutsch,[1] Michael Krall,[1] Hermann Detz,[2]
Donald C. MacFarland,[2] Tobias Zederbauer,[2] Aaron M. Andrews,[2] Werner Schrenk,[2]
Gottfried Strasser,[2] and Karl Unterrainer[1]



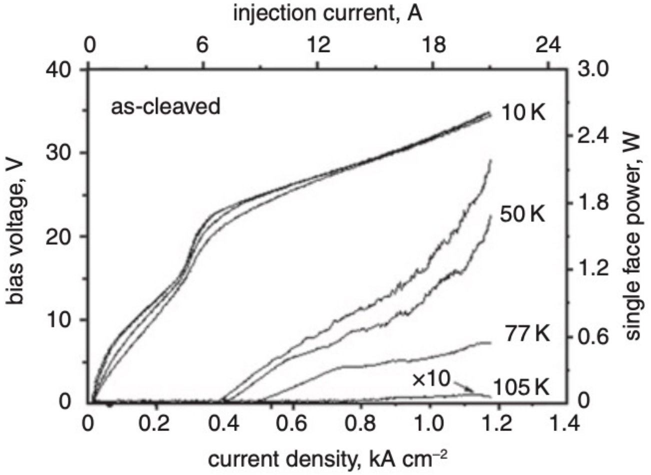


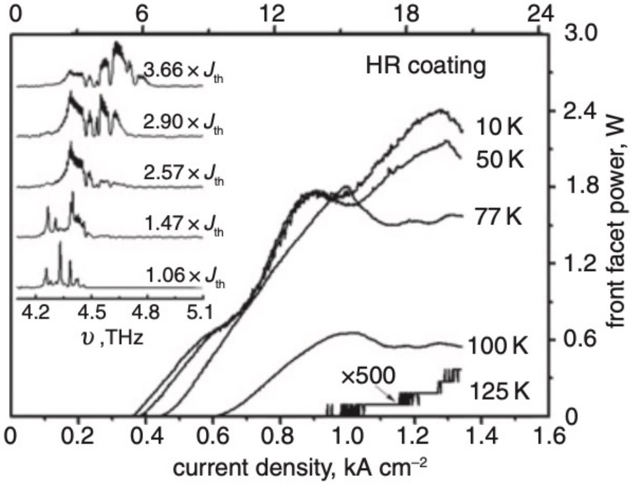
Multi-Watt high-power THz frequency quantum cascade lasers

L.H. Li✉, L. Chen, J.R. Freeman, M. Salih, P. Dean,
A.G. Davies and E.H. Linfield

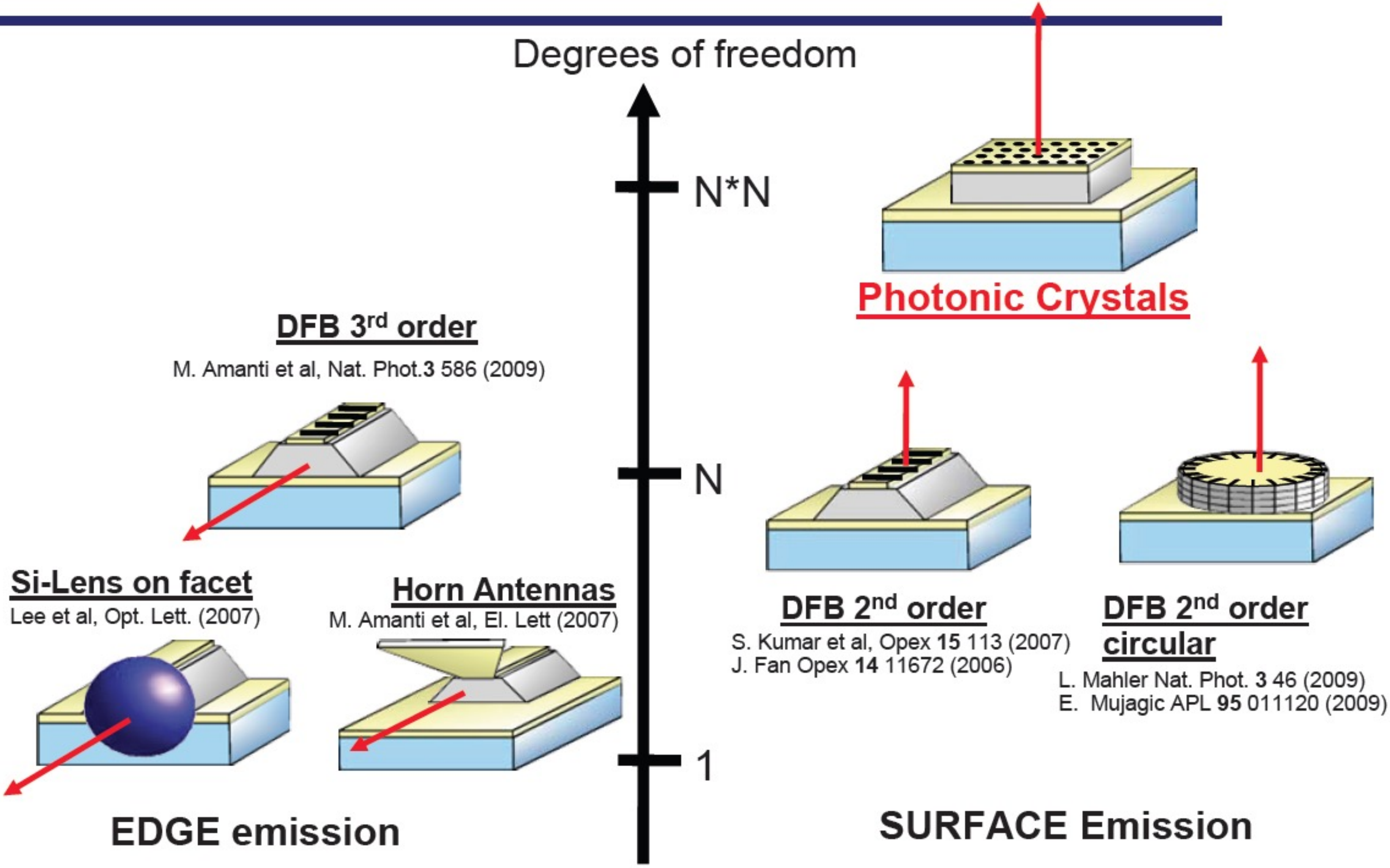
Multi-Watt high-power terahertz (THz) frequency quantum cascade lasers are demonstrated, based on a single, epitaxially grown, 24-µm-thick active region embedded into a surface-plasmon waveguide. The devices emit in pulsed mode at a frequency of ~4.4 THz and have a maximum operating temperature of 132 K. The maximum measurable emitted powers from a single facet are ~2.4 W at 10 K and ~1.8 W at 77 K, with no correction being made for the optical collection efficiency of the apparatus, or absorption by the cryostat polyethylene window.

ELECTRONICS LETTERS 8th June 2017 Vol. 53 No. 12 pp. 799–800





Towards more directional emission



Photonic Crystals

DFB 3rd order

M. Amanti et al, Nat. Phot.**3** 586 (2009)

DFB 2nd order

S. Kumar et al, Opex **15** 113 (2007)
J. Fan Opex **14** 11672 (2006)

DFB 2nd order circular

L. Mahler Nat. Phot. **3** 46 (2009)
E. Mujagic APL **95** 011120 (2009)

Si-Lens on facet

Lee et al, Opt. Lett. (2007)

Horn Antennas

M. Amanti et al, El. Lett (2007)

EDGE emission

SURFACE Emission

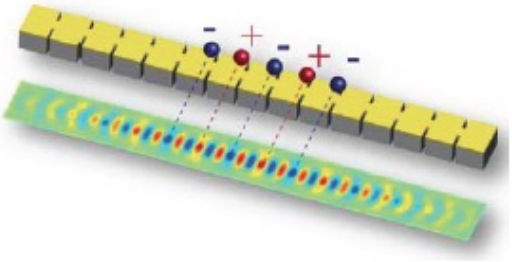
Courtesy R. Colombelli

Applications like integrated solutions

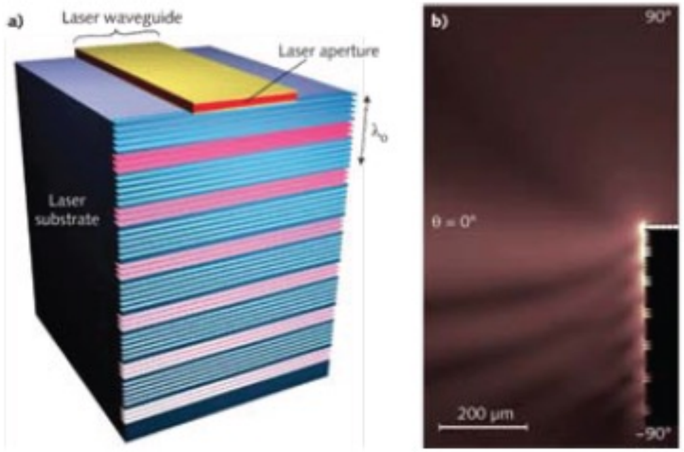
Edge emission

DFB 3rd order

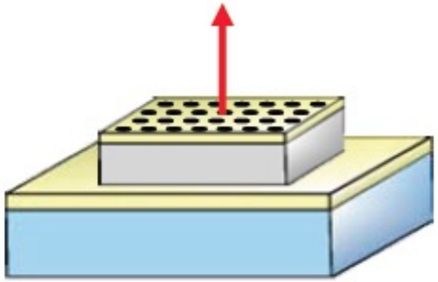
M. Amanti *Nat. Phot.* (2009)



Plasmonic collimator N. Yu, Nat. Mater. (2010)

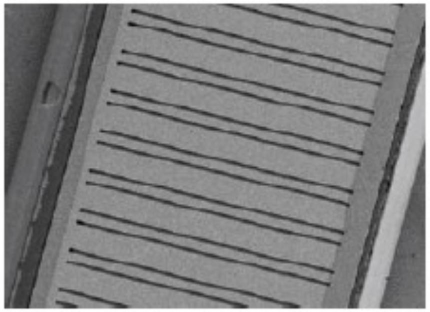


Surface emission



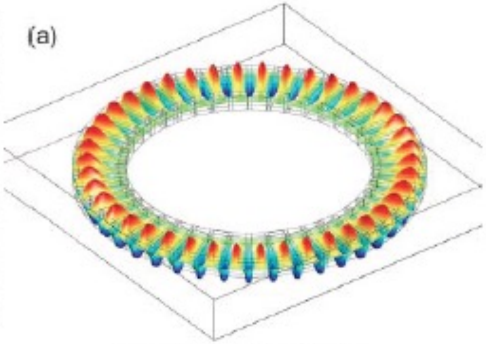
Chassagneux, *Nature* (2009)
Sevin *APL* (2010)

Photonic Crystals



DFB 2nd order

L.Mahler, *APL* (2010)
S.Kumar, OPEX 2007
J.Fan, OPEX 2006



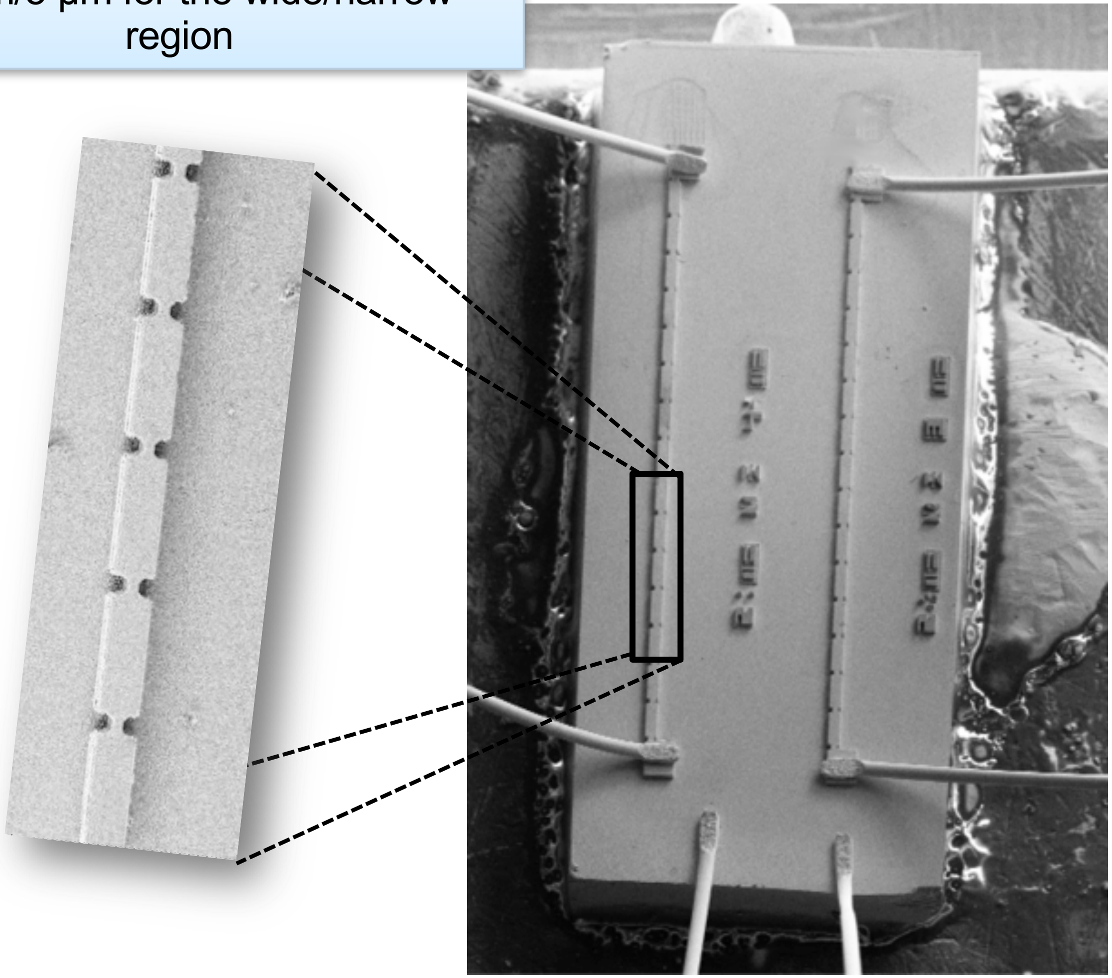
Circular DFB

E. Mujagic *APL* (2009)

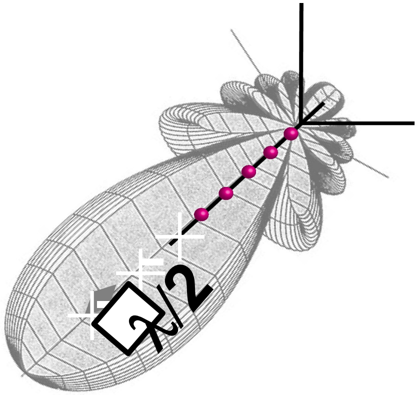
Courtesy R. Colombelli

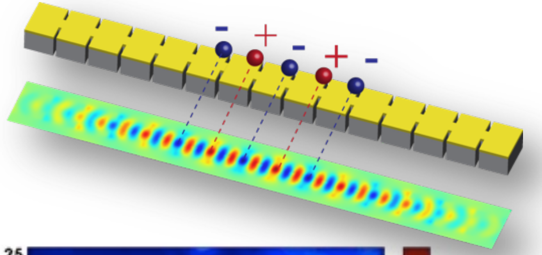
THz photonic wire laser

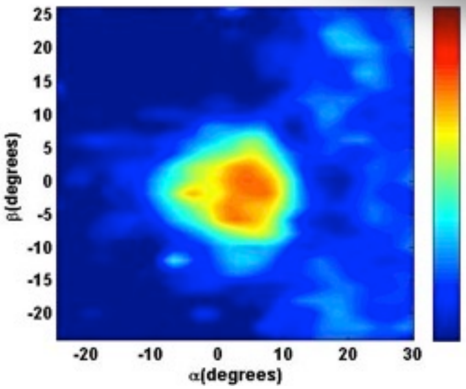
Waveguide width:
15 µm/5 µm for the wide/narrow region



Wavelength in the material
λ/n ~30 µm





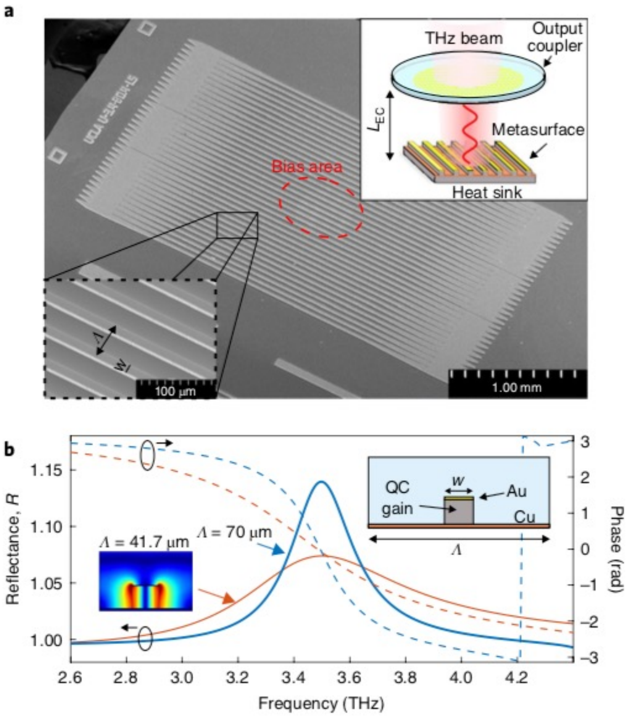


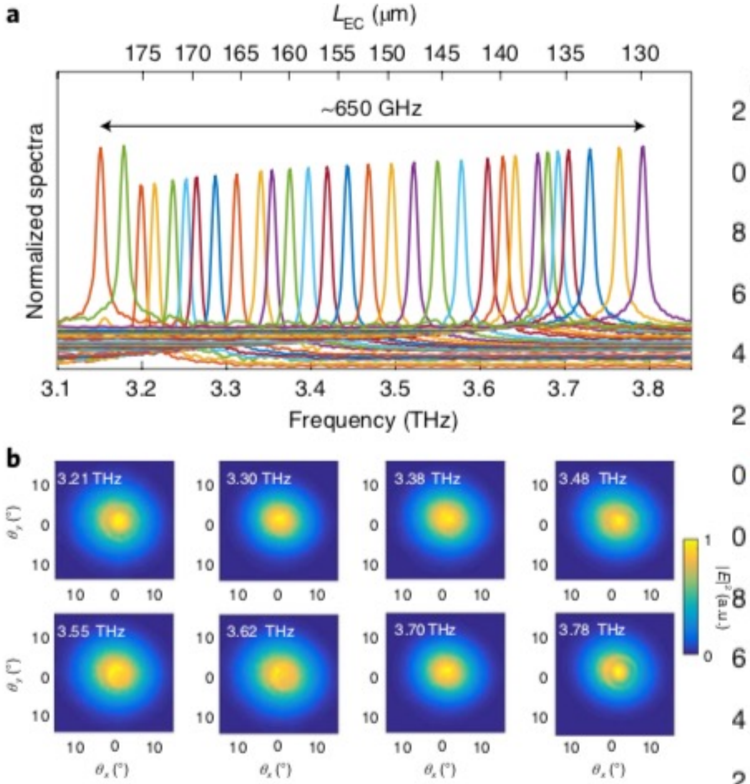
FWHM

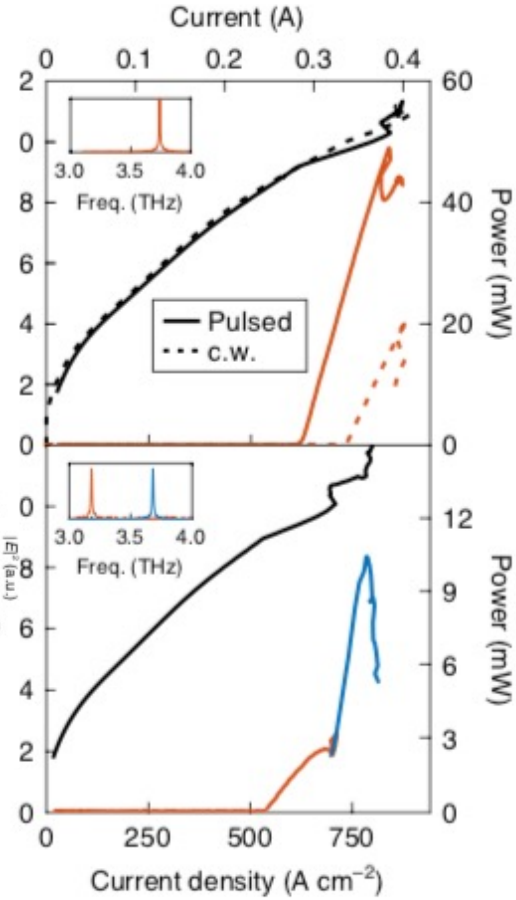
12° X14°

Amanti et al. Optics Express, **18**, 6390 (2010)

THz VECSEL Metasurface laser







nature photonics

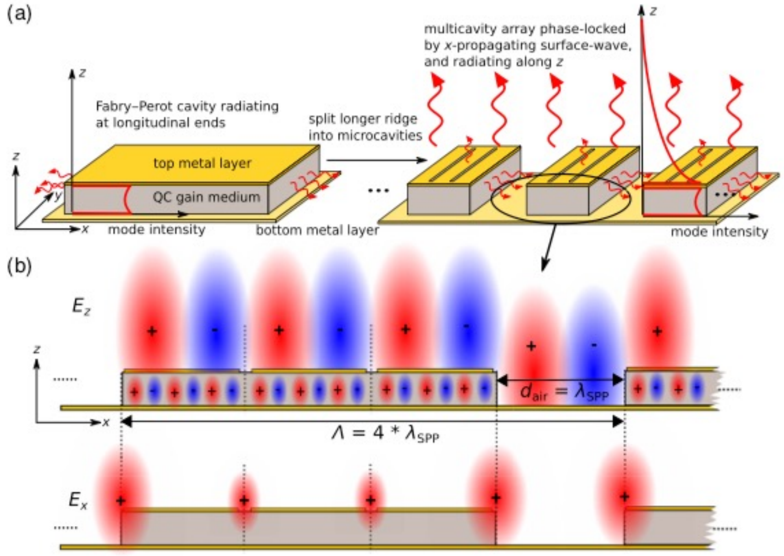
LETTERS

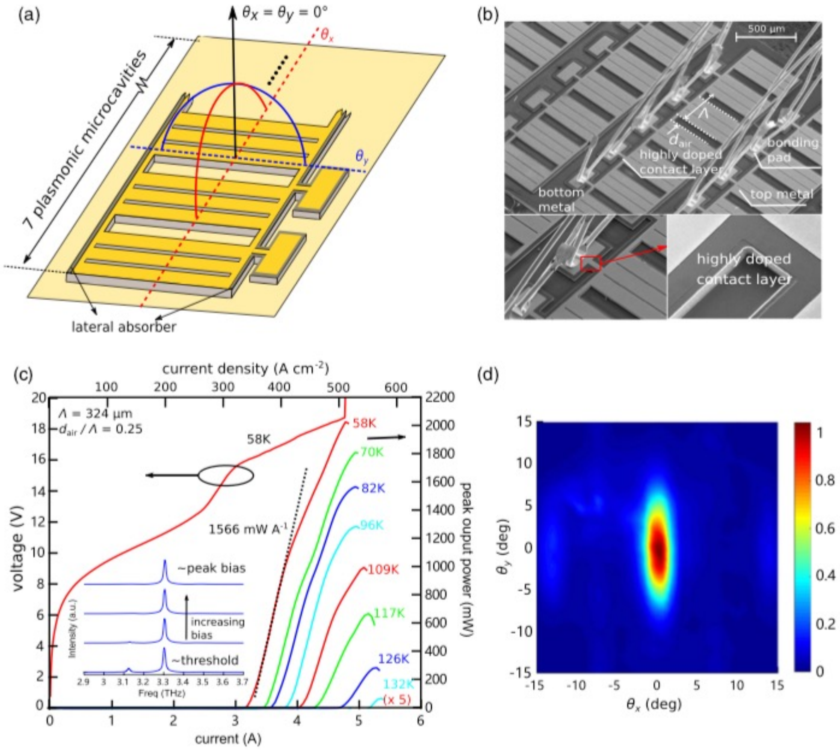
https://doi.org/10.1038/s41566-019-0518-z

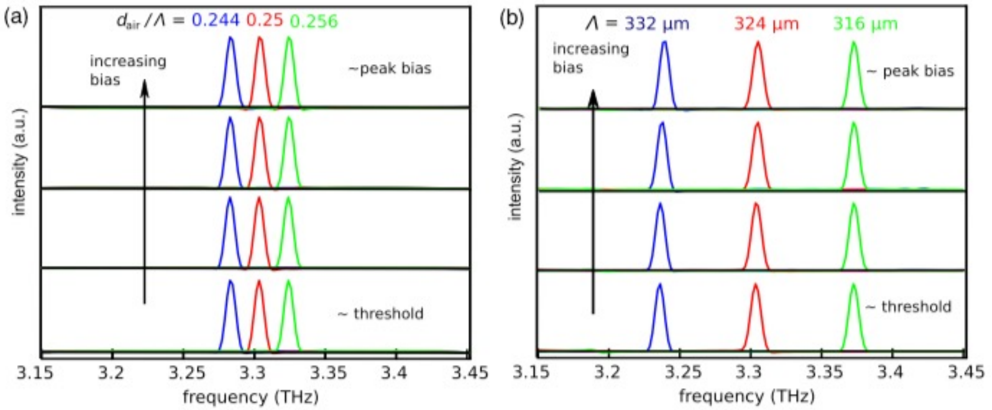
Broadband continuous single-mode tuning of a short-cavity quantum-cascade VECSEL

Christopher A. Curwen[1], John L. Reno[2] and Benjamin S. Williams[1*]

High power (2W!!) single frequency phase locked array







708 Vol. 7, No. 6 / June 2020 / Optica **Research Article**

optica

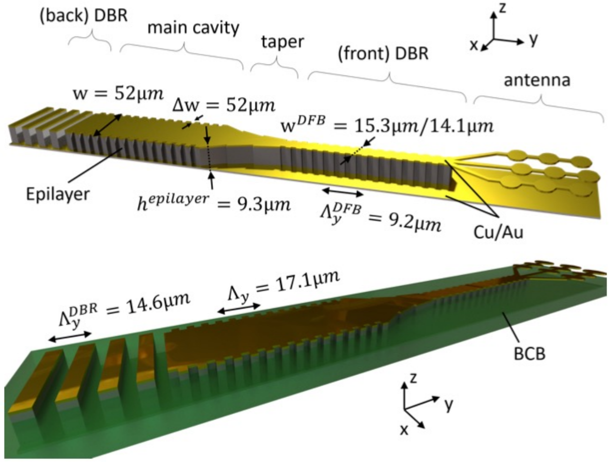
Phase-locked terahertz plasmonic laser array with 2 W output power in a single spectral mode

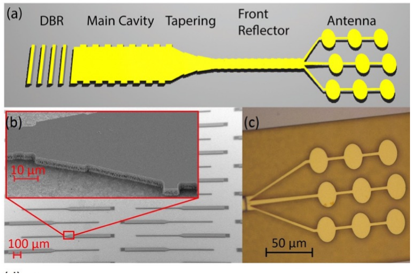
Yuan Jin,[1,3] John L. Reno,[2] and Sushil Kumar[1,*]

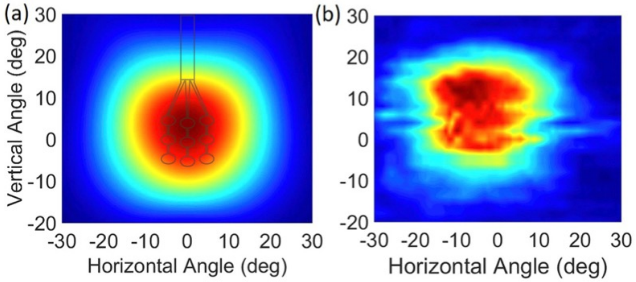
Planarization allows antenna integration

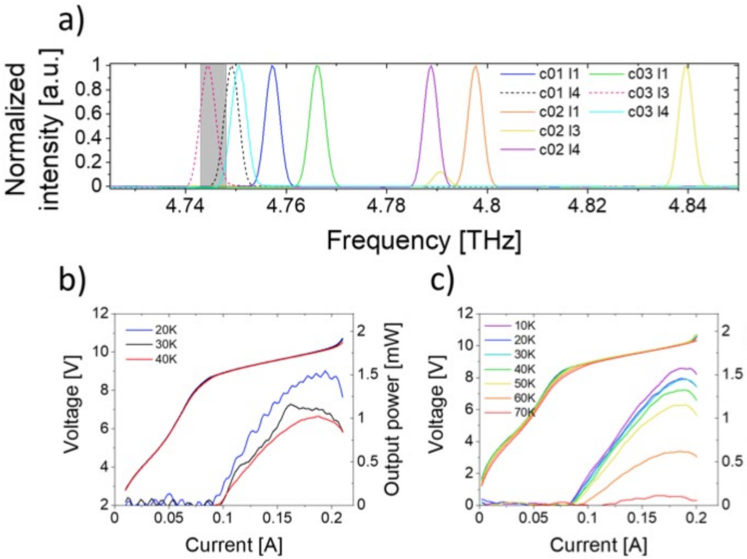
A patch-array antenna single-mode low electrical dissipation continuous wave terahertz quantum cascade laser

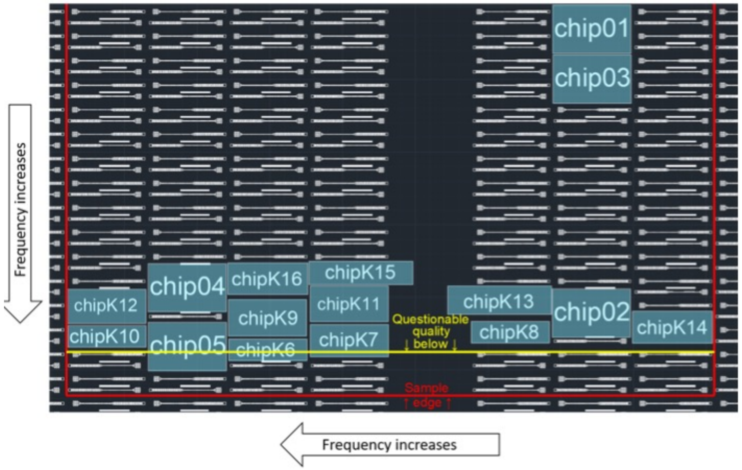
L. Bosco,[1,a)] C. Bonzon,[1] K. Ohtani,[1] M. Justen,[2] M. Beck,[1] and J. Faist[1]
[1]*Institute for Quantum Electronics, ETH Zurich, Auguste-Piccard-Hof 1, 8093 Zurich, Switzerland*
[2]*I. Institute of Physics, University of Cologne, Zulpicher Strasse 77, 50937 Cologne, Germany*







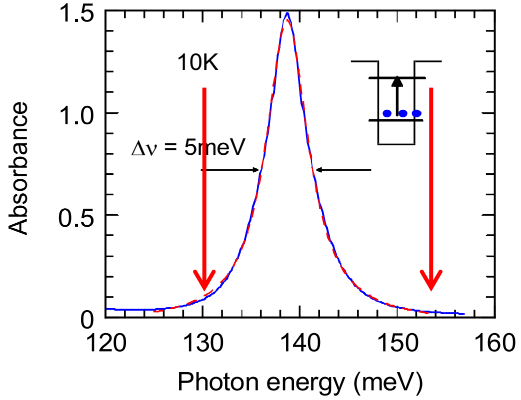


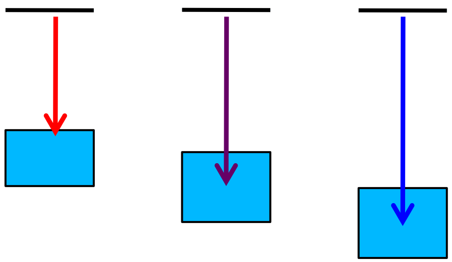


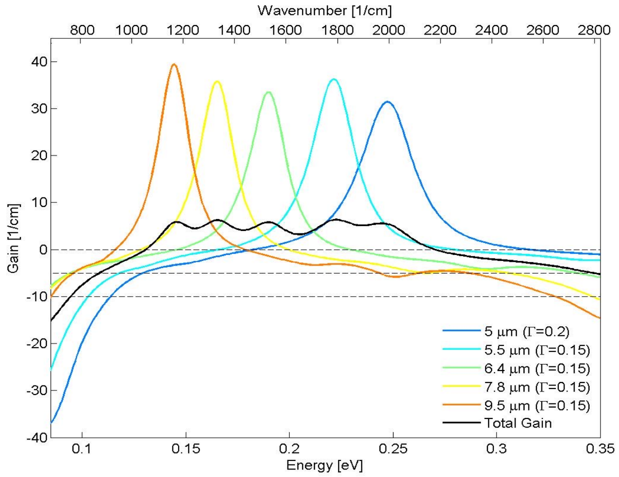
T. Olariu et al., to be submitted

Why are intersubband QCL so good for broadband

- Atomic-like joined density of state
  - Transparent on **both** sides of the transition
  - Possibility to combine active regions at different colors
  - Low dispersion of the gain
- Flexibility in design broadband active region
  - Bound-to-continuum have very broad gain inherently



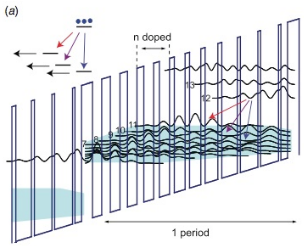




A. Hugi, et al., , *Semicond Sci Tech*, vol. 25, no. 8, p. 083001, (2010).

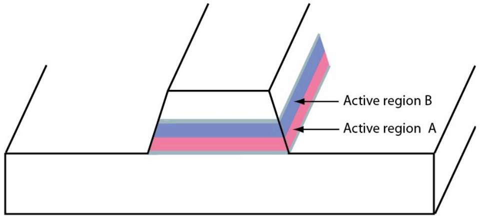
Broadband gain medium: engineering the intersubband gain

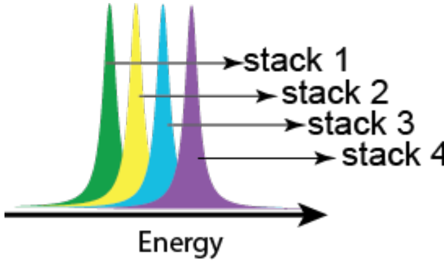
Bound-to-continuum



Intra-period inhomogeneous broadening (Faist et al., APL, 2001)

Heterogeneous cascades

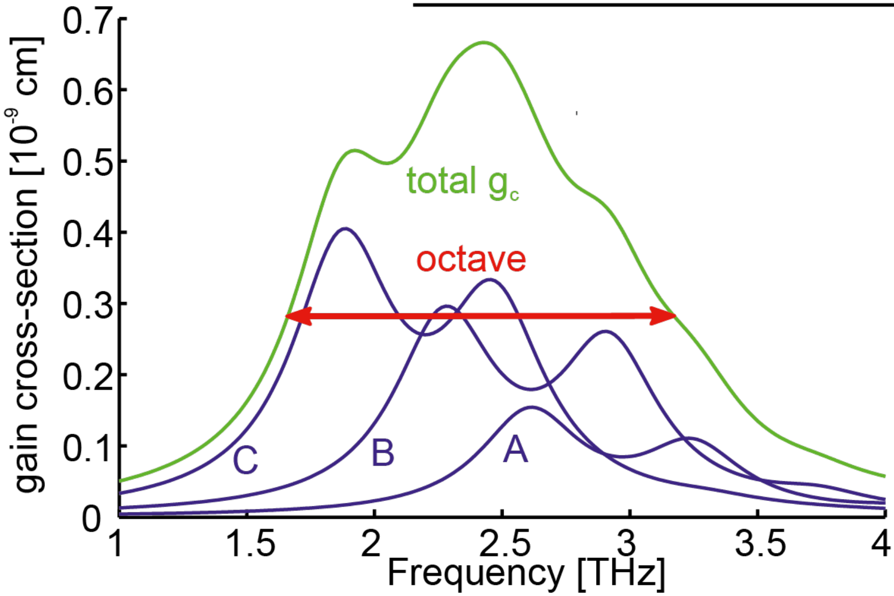




Different active region designs in the same device (Gmachl et al., Nature, 2002)

Modelling of the structure: three different substacks

	Design emission	z_{54}/ z_{53} (Å)	f_{54}/ f_{53}	f'_{54}/ f'_{53}	E_{NDR} (kV/cm)
A	12.1 meV / 3 THz	40.9 /30.3	4.78/3.24	0.32 /0.22	7.25
B	10.7 meV / 2.6 THz	43.1 /35.6	4.59 /4.02	0.31 /0.27	6.95
C	8.9 meV / 2.2 THz	54.2 /44	5.89 /5.16	0.39 /0.35	6.6



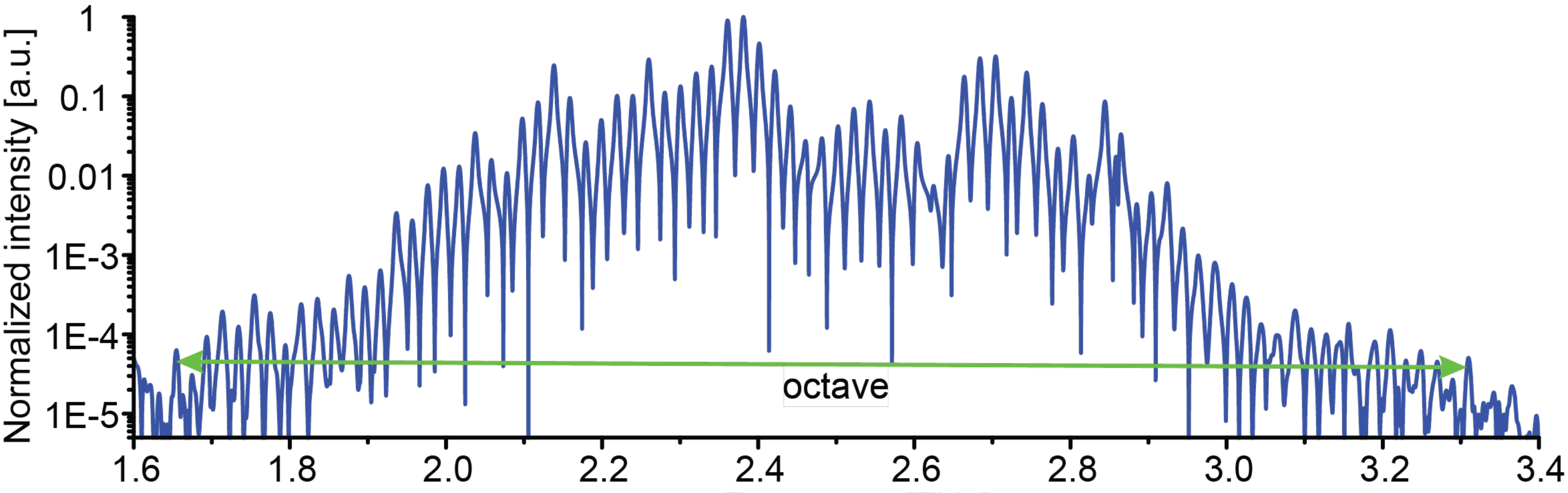
$$g_c^{tot} = \sum_{i=1}^{N} N_{p,i} \cdot g_{c,i}$$

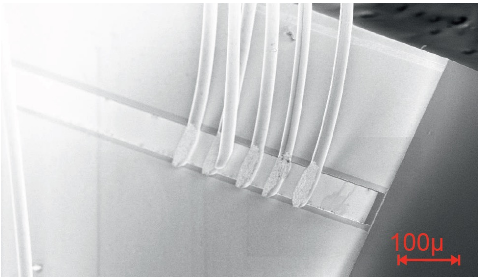
Simple model, no rate eq., only gc

FWHM: 1.6 THz

D.Turčinková, G. Scalari et al., Appl. Phys. Letter **99** 191104 (2011)

Octave spanning laser



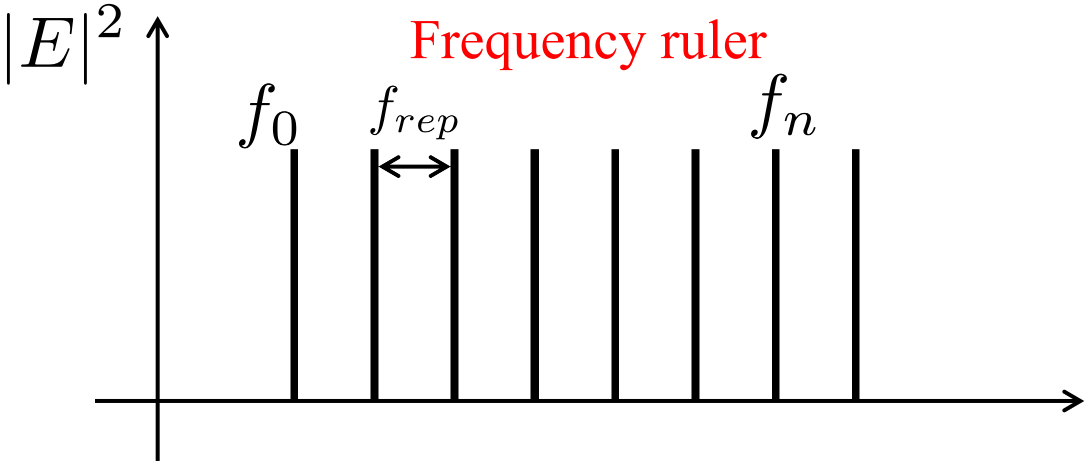


First electrically injected octave spanning laser

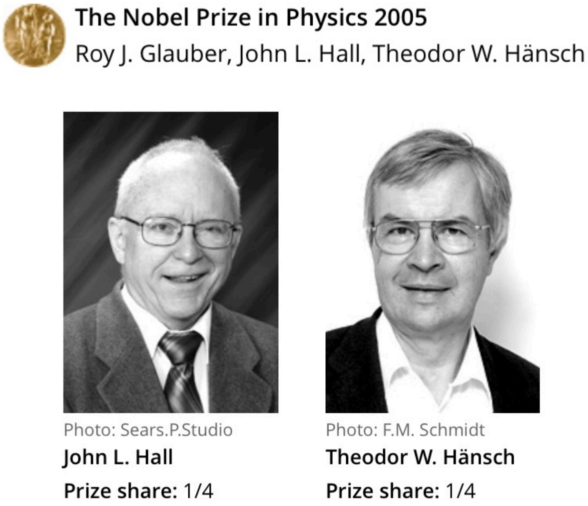
M. Roesch, G. Scalari et al., Nature Photonics 9, 42 (2015)

What is a comb?

Source of electromagnetic radiation with equidistant modes in the frequency domain
The modes are phase coherent



$$f(n) = f_0 + n \times f_{rep}$$



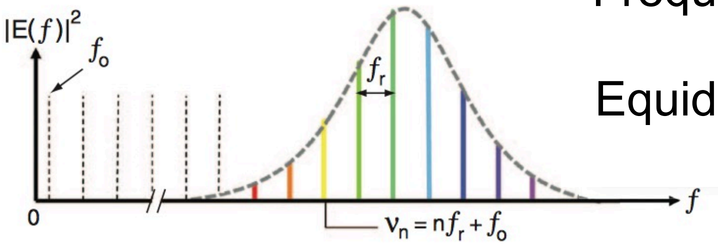
The Nobel Prize in Physics 2005
Roy J. Glauber, John L. Hall, Theodor W. Hänsch

Photo: Sears.P.Studio
John L. Hall
Prize share: 1/4

Photo: F.M. Schmidt
Theodor W. Hänsch
Prize share: 1/4

S.Diddams, JOSA B, Vol. **27**, Issue 11, pp. B51-B62 (2010)
T.Hänsch, Rev. Mod. Phys., Vol **78** (2006)
T.Udem et al., Nature **416**, 233 (2003)

Different comb “families”

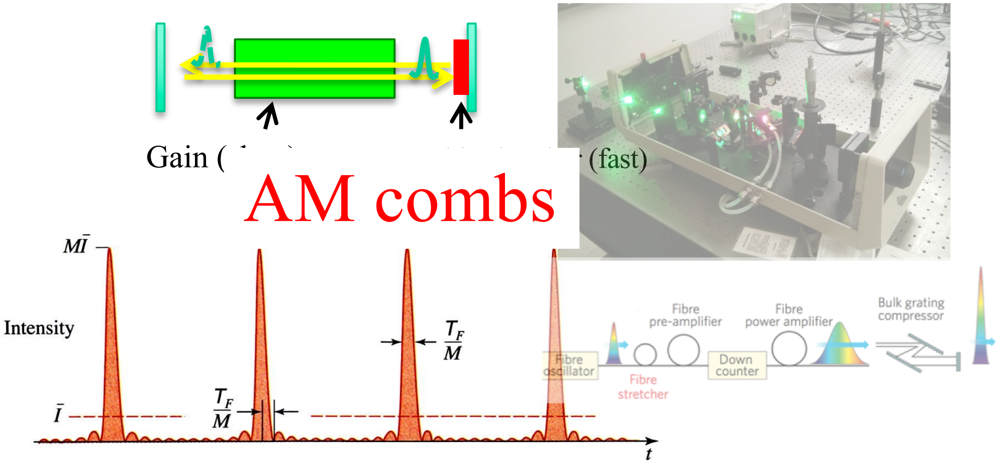


Frequency domain looks the same

Equidistant modes locked in phase

$$f(n) = f_0 + n \times f_{rep}$$

Mode locked lasers: same phases, pulses in the time domain



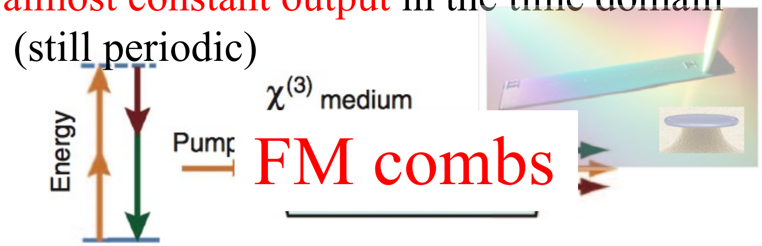
AM combs

Figures from Kippenberg et al., Science (2011)

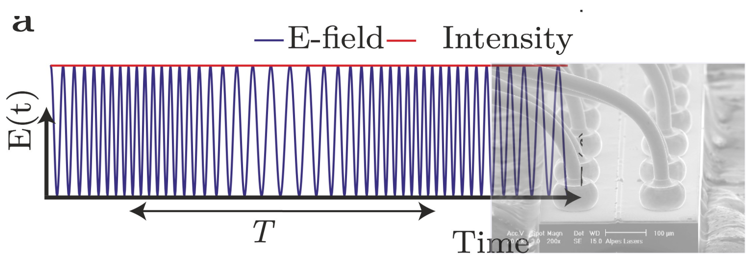
Kerr combs/QCL combs: non-trivial phases

almost constant output in the time domain

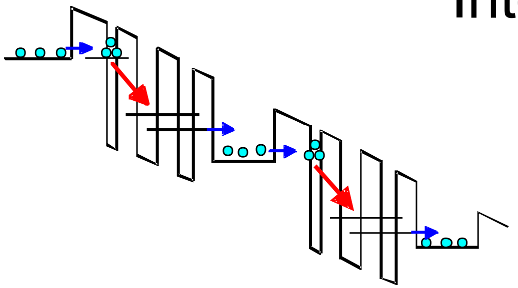
(still periodic)



FM combs



Quantum cascade laser: direct mid-IR and THz comb generation

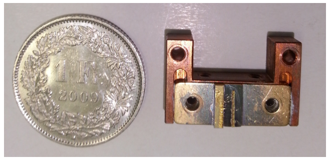


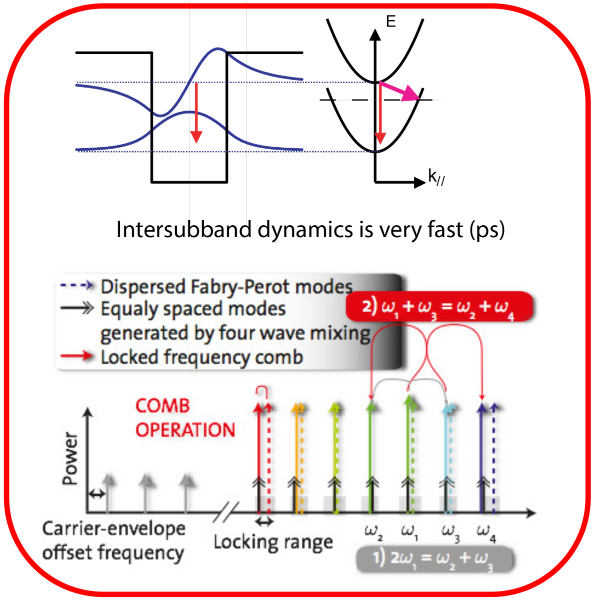
Intersubband transitions

Mid-infrared operation

Broad gain

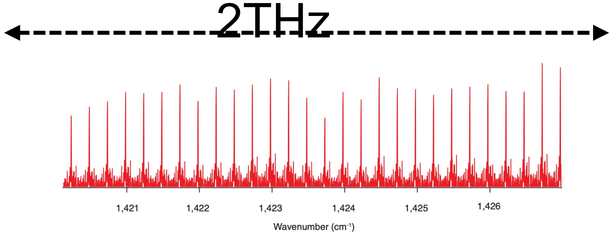
High power



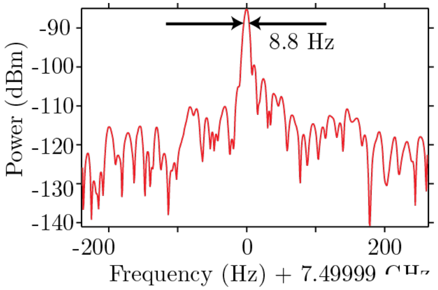


Intersubband dynamics is very fast (ps)

Spectrum



RF Beatnote



$$\chi^{(3)}_{\text{eff}}(\delta\omega,\varDelta)=\frac{2\delta N|\mu_{ab}|^4\left(\delta\omega-\varDelta-i\frac{1}{T_2}\right)\left(-\delta\omega+i\frac{2}{T_2}\right)\left(\varDelta+\frac{i}{T_2}\right)^{-1}}{3\varepsilon_0\hbar^3\left(\varDelta-\delta\omega+i\frac{1}{T_2}\right)D^*(\delta\omega)}$$

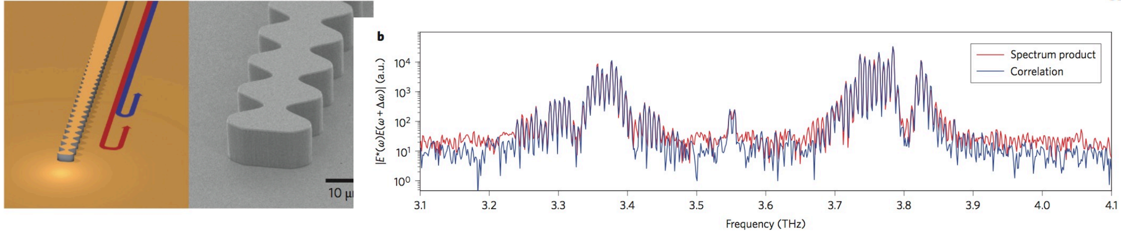
A. Hugi, J. Faist et al., *Nature*, vol. 492, 229–233 (2012)

THz QCL combs

nature photonics ARTICLES
PUBLISHED ONLINE: 11 MAY 2014 | DOI: 10.1038/NPHOTON.2014.85

Terahertz laser frequency combs

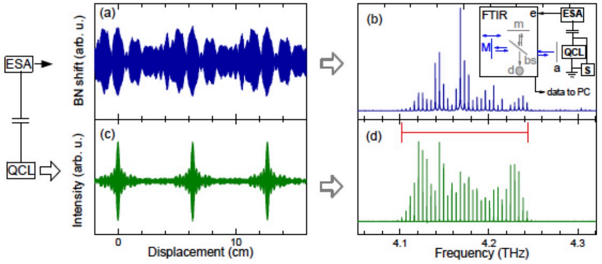
David Burghoff[1]*, Tsung-Yu Kao[1], Ningren Han[1], Chun Wang Ivan Chan[1], Xiaowei Cai[1], Yang Yang[1],
Darren J. Hayton[2], Jian-Rong Gao[2,3], John L. Reno[4] and Qing Hu[1]



Evidence for frequency comb emission from a Fabry-Pérot terahertz quantum-cascade laser

M. Wienold,* B. Röben, L. Schrottke, and H. T. Grahn

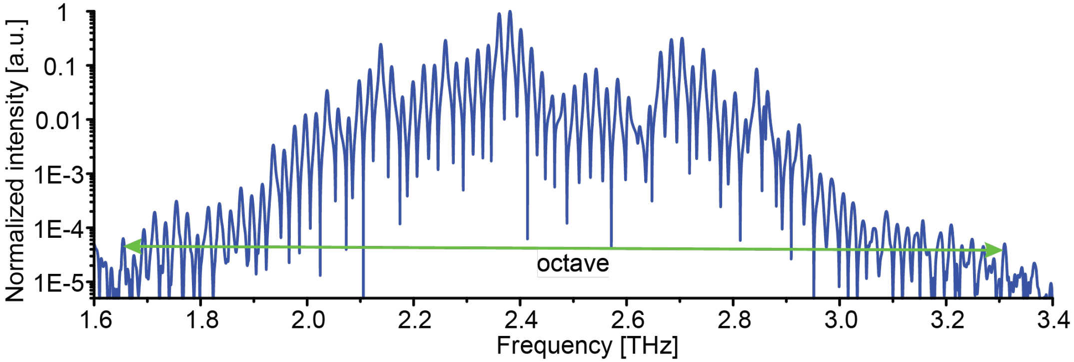
15 December 2014 | Vol. 22, No. 25 | DOI:10.1364/OE.22.030410 | OPTICS EXPRESS 30411



ARTICLES
PUBLISHED ONLINE: 24 NOVEMBER 2014 | DOI: 10.1038/NPHOTON.2014.279
nature photonics

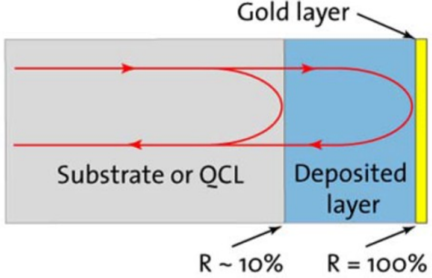
Octave-spanning semiconductor laser

Markus Rösch*, Giacomo Scalari*, Mattias Beck and Jérôme Faist



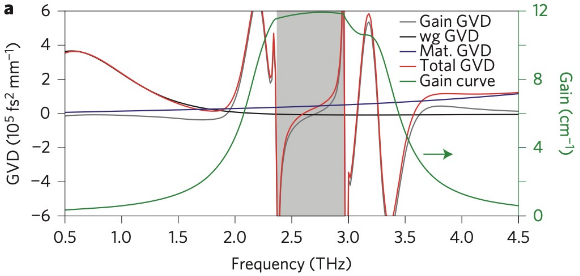
Monolithic dispersion compensation strategies

Gires Tournois interferometer (Mid-IR/ THz)



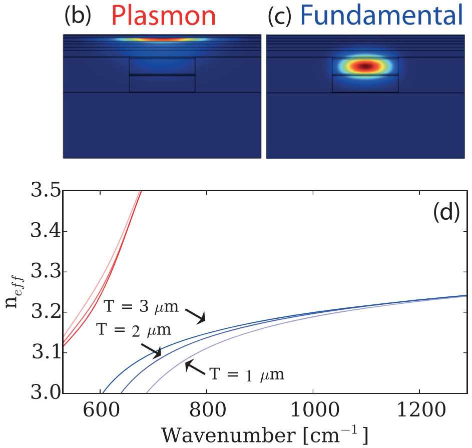
G. Villares, JF, et al, Optica **3**, 252 (2016).

Gain engineering (Mid-IR/ THz)



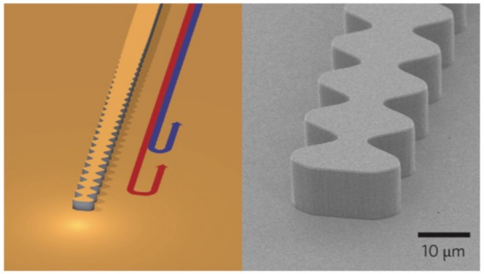
M. Roesch, G.S. et al., Nature Photonics 9, 42 (2015)

Plasmon enhanced waveguide coupled waveguides (Mid-IR)



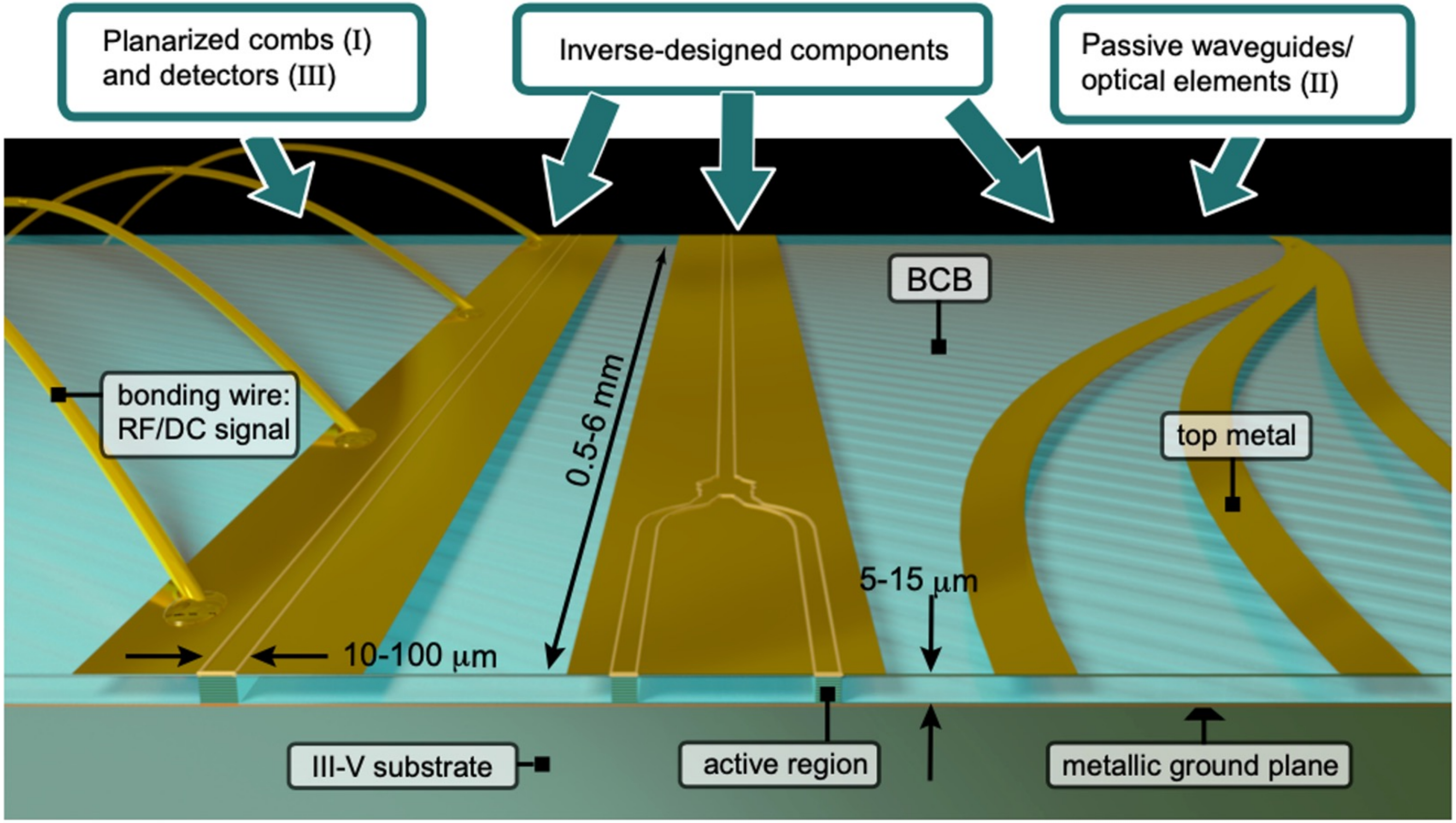
Y. Bidaux, JF, et al. *Opt Lett*, vol. 42, 1604, (2017).

Doubly Chirped mirrors (THz)



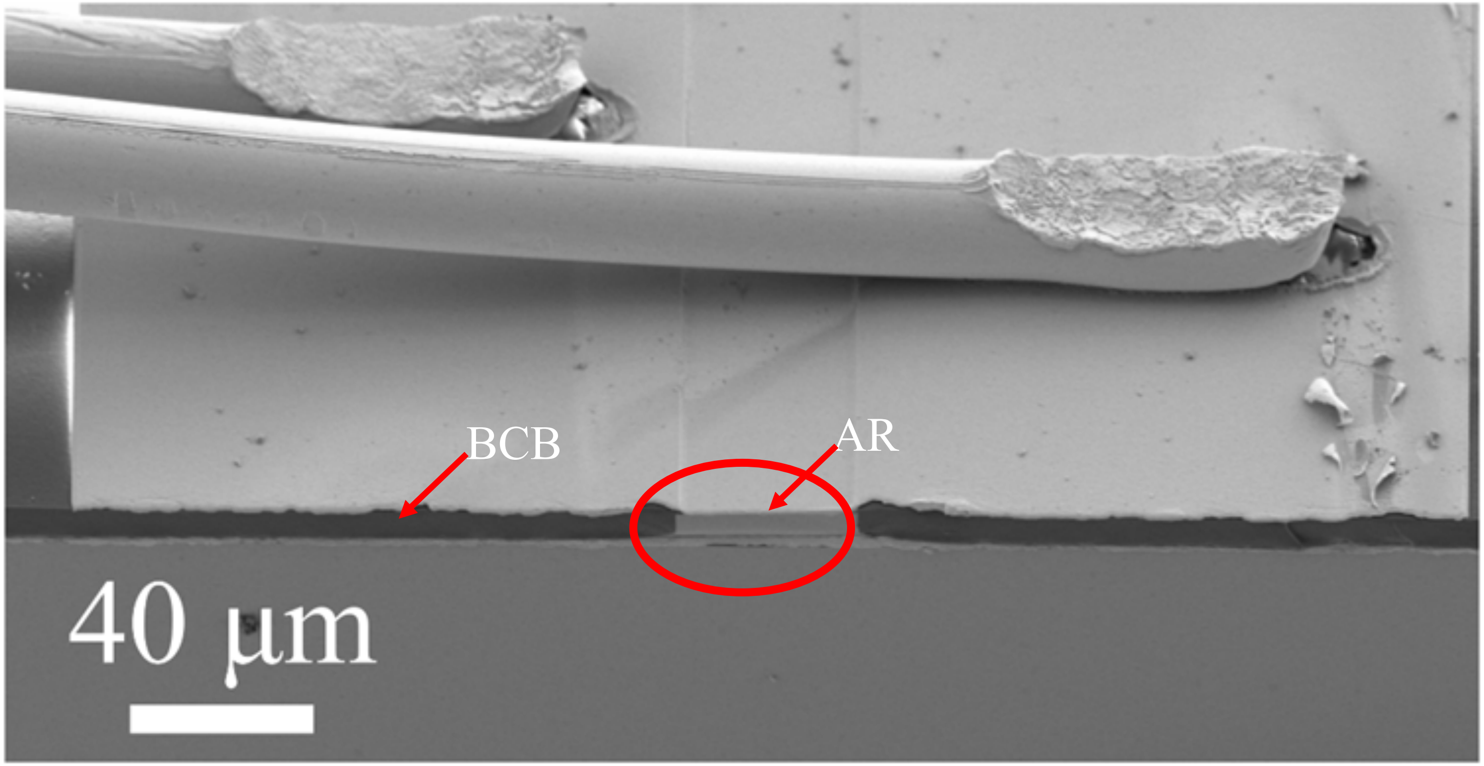
Burghoff et al. Nat. Phot. (2014)

Planarized platform for THz coherent photonics

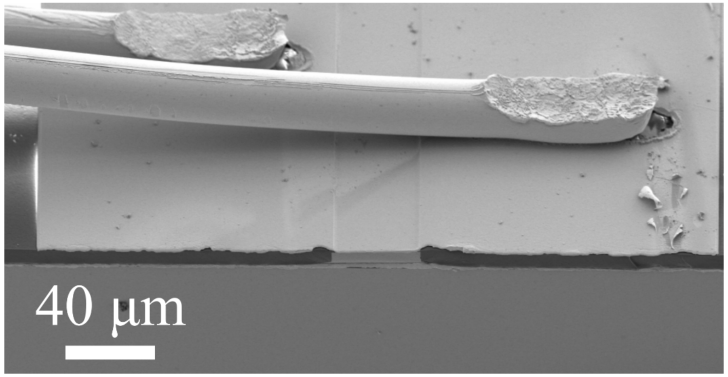


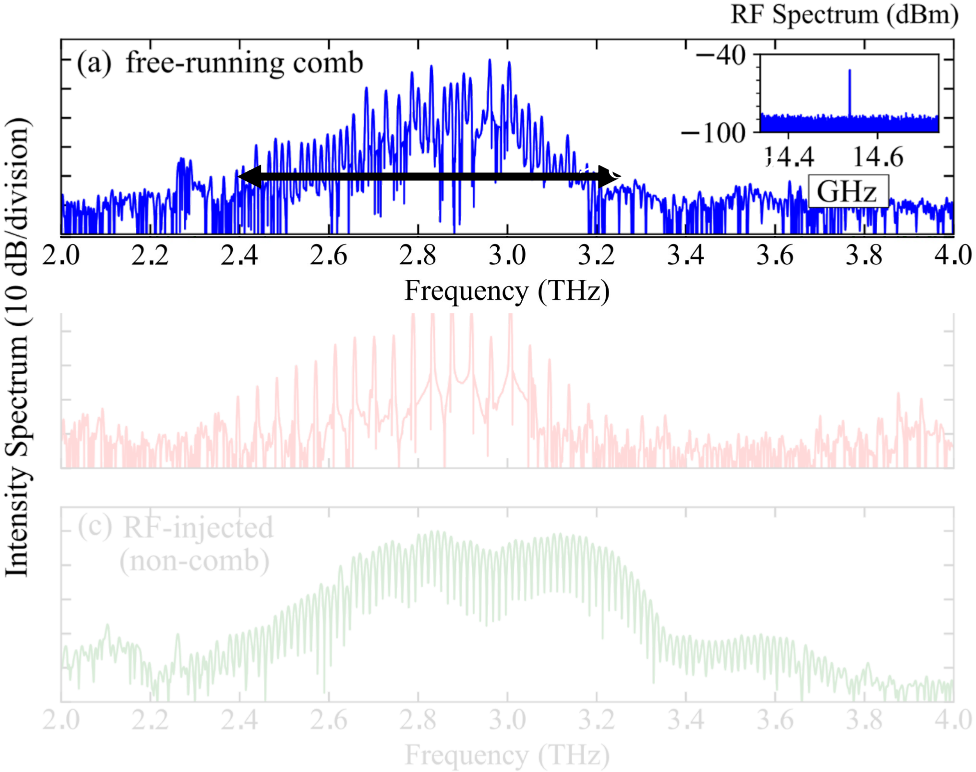
U. Senica,...G.S., accepted in *Light: Science & Applications (2022)*

New waveguide geometries



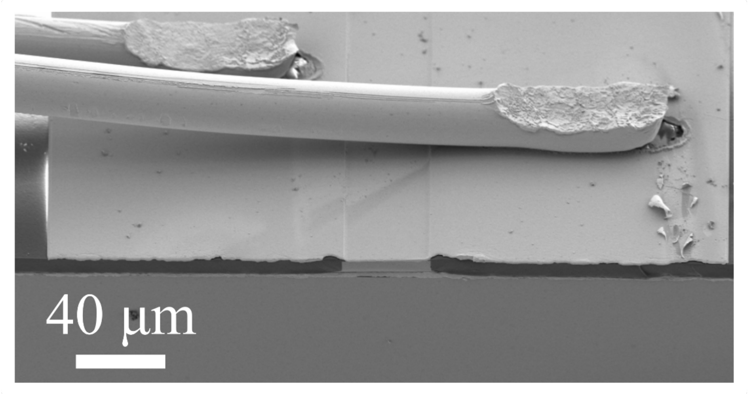
Narrow planarized ridge (40 µm)

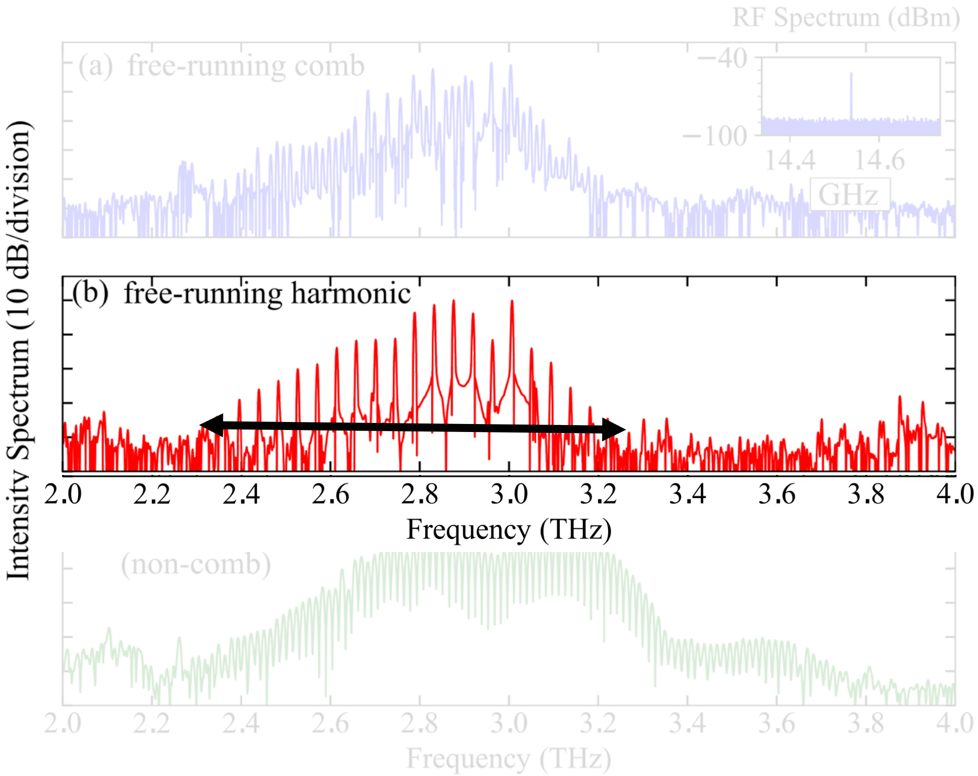




- **Free-running comb: >800 GHz, >-55 dBm RF**

Narrow planarized ridge (40 µm)

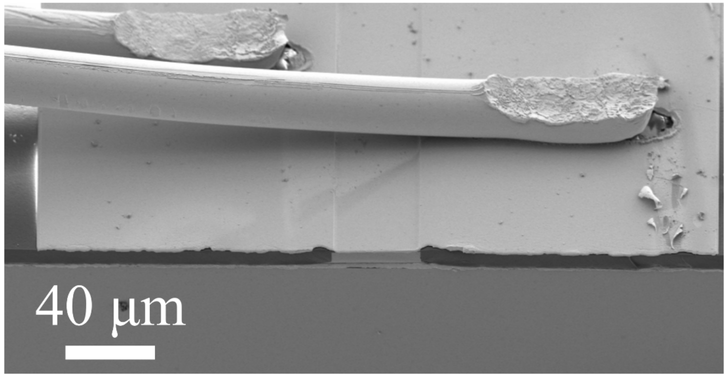


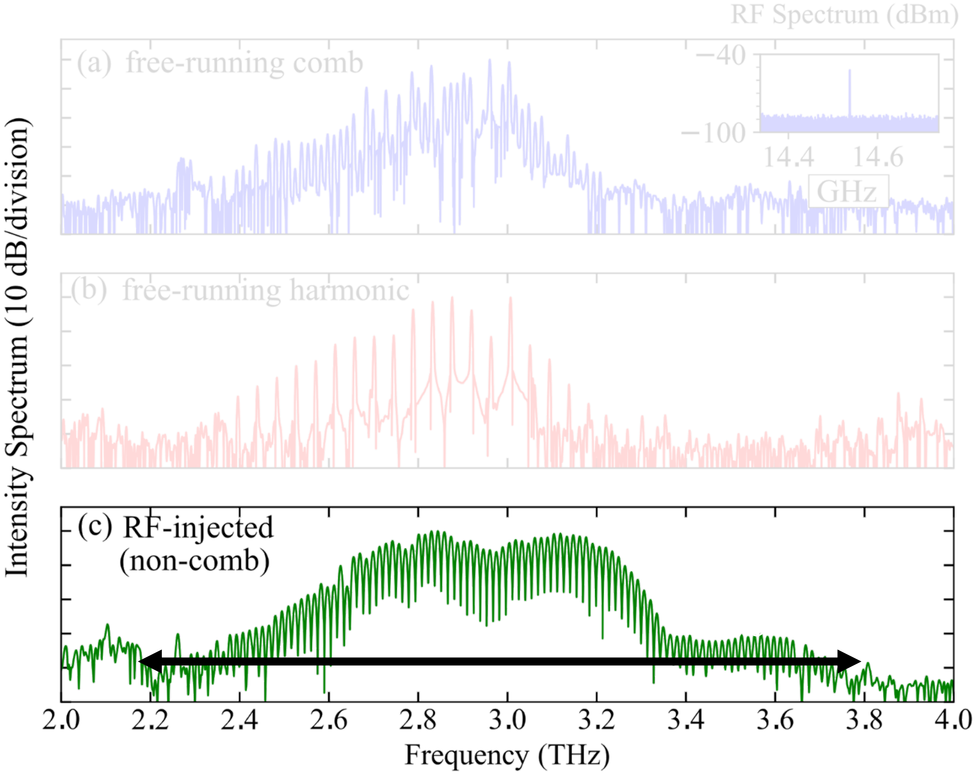


Free-running comb: >800 GHz,
>-55 dBm RF

Free-running harmonic : 1 THz span

Narrow planarized ridge (40 µm)



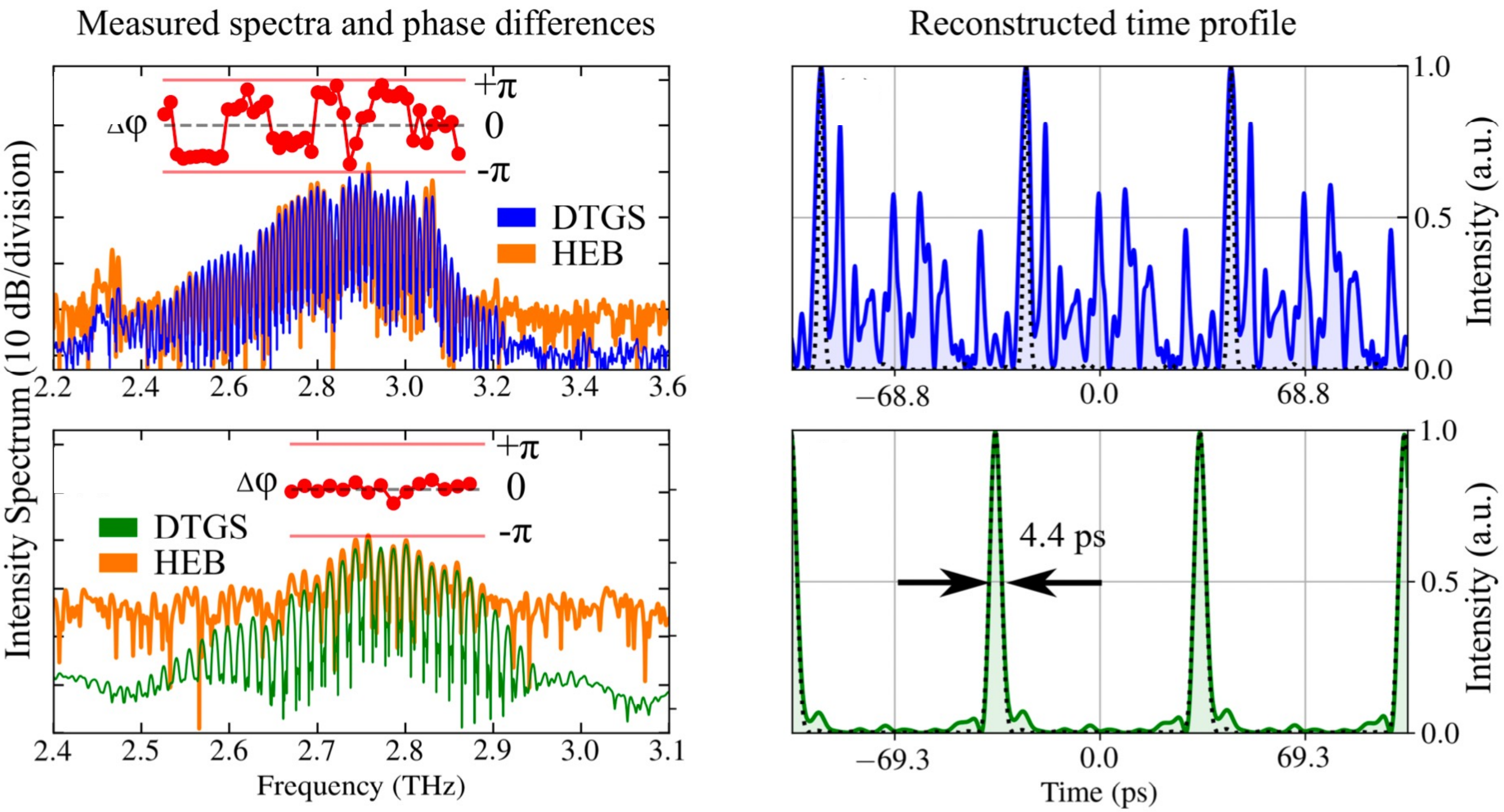


Free-running comb: >800 GHz,
>-55 dBm RF

Free-running harmonic : 1 THz span

RF-injected: 1.6 THz span

Pulses with active mode locking



Measured spectra and phase differences

Reconstructed time profile

RF: -2 dBm

RF: +35 dBm

U. Senica,…., G.S., Light: Science & Appl., (2022)