Harmonic Frequency Combs of Quantum Cascade Lasers: Origin, Control, and Prospective Applications

Presented by:

OSA Applied Spectroscopy Technical Group

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This Executive Committee is finishing its 3-year service term in June 2018. New leadership team will be announced soon!

Thank you for your support. It has been a pleasure to serve the Applied Spectroscopy group!

Technical Group Activities

APPLIED SPECTROSCOPY TECHNICAL GROUP

- Webinars

  Organized webinars on a variety of topics concerning latest advances in applied spectroscopy.

- Information dissemination

  Monthly collection of papers concerning various topics in applied spectroscopy from OSA suite of journals. Sent out to all group members by email.

- Interested in presenting your research? Have ideas for technical group events? Contact us at OSA.AppliedSpectroscopy.TG@gmail.com.

  After mid-June 2018 we will redirect your questions to the new leadership team.

Welcome to today's webinar!

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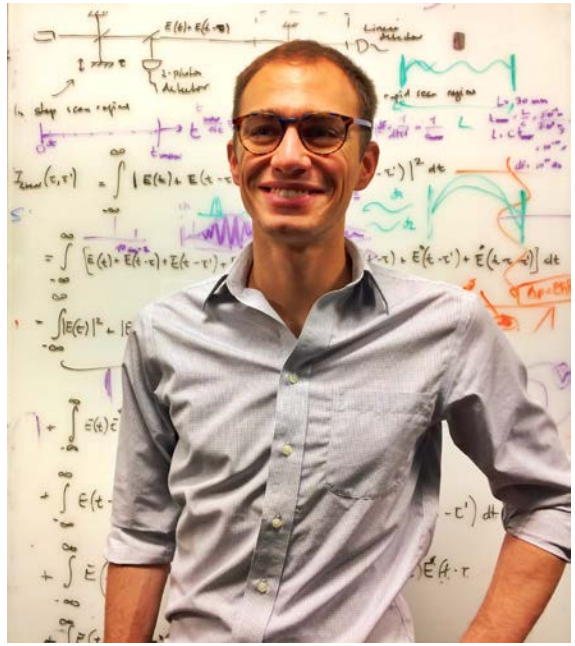
APPLIED SPECTROSCOPY TECHNICAL GROUP

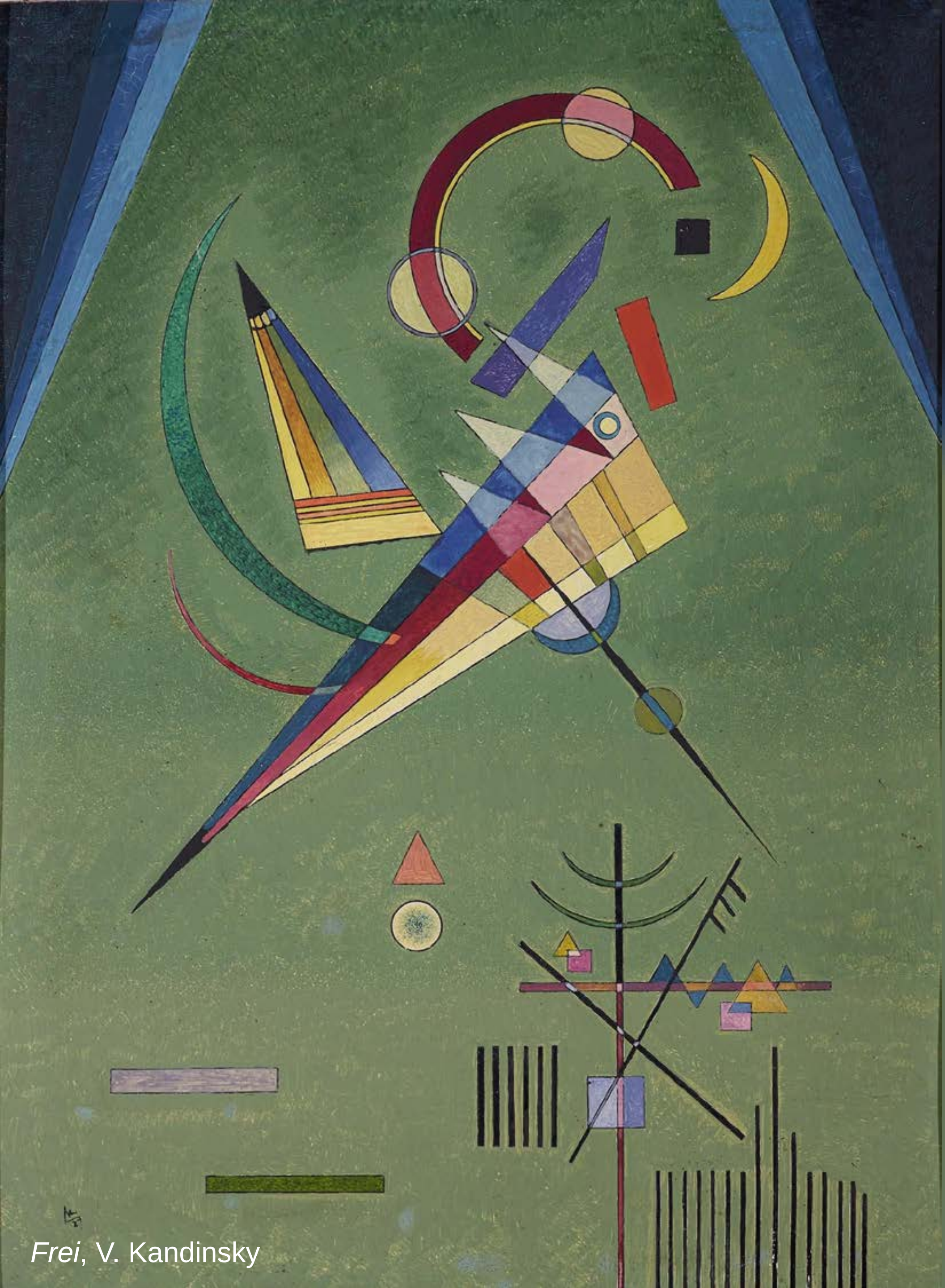


Dr. Marco Piccardo

School of Engineering and Applied Sciences, Harvard University

Harmonic frequency combs of quantum cascade lasers: origin, control, and prospective applications

May 29, 2018

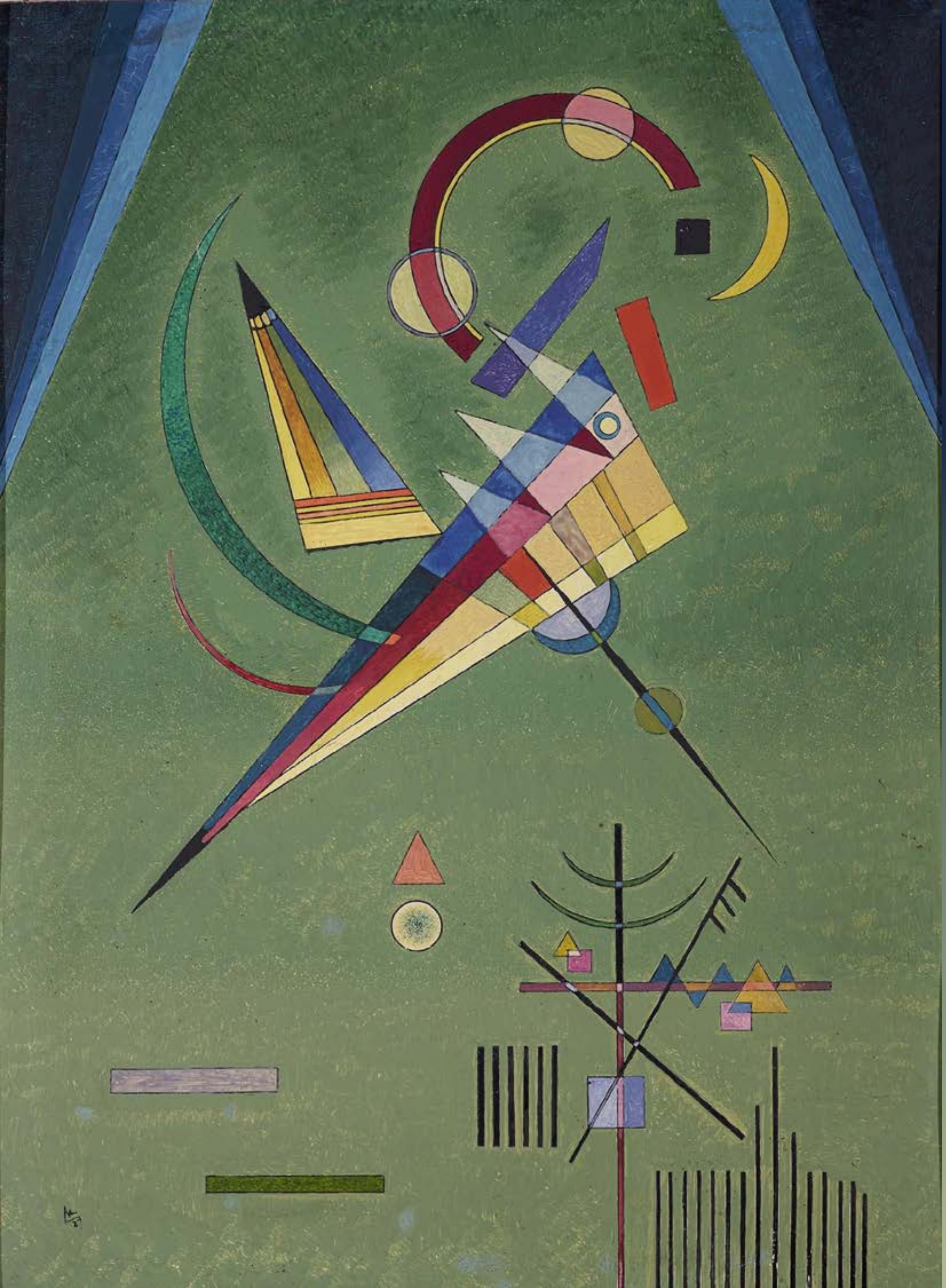


Frei, V. Kandinsky

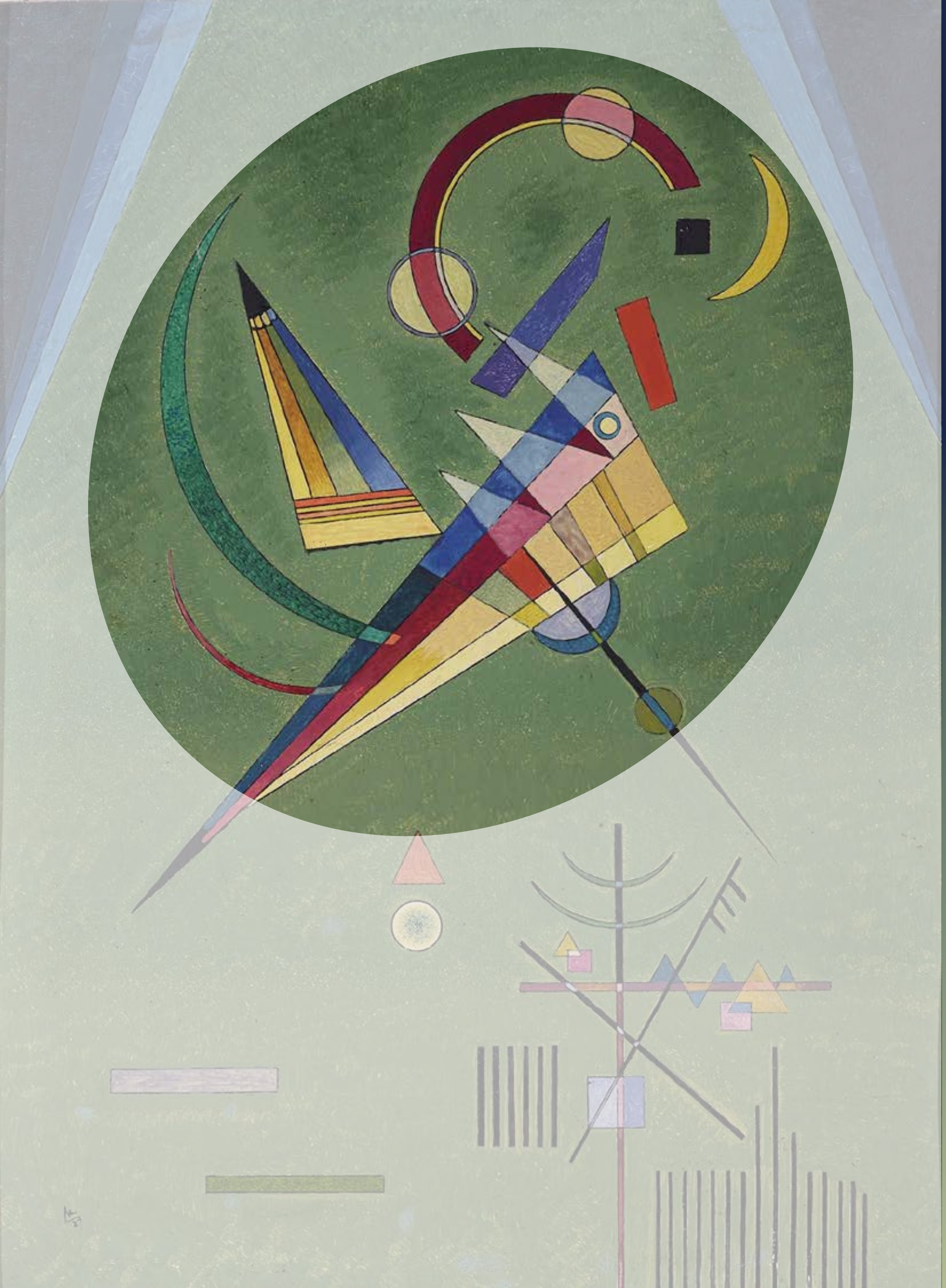
Harmonic Frequency Combs of Quantum Cascade Lasers:
Origin, Control, and Prospective Applications

Marco Piccardo

Capasso Group, SEAS, Harvard University

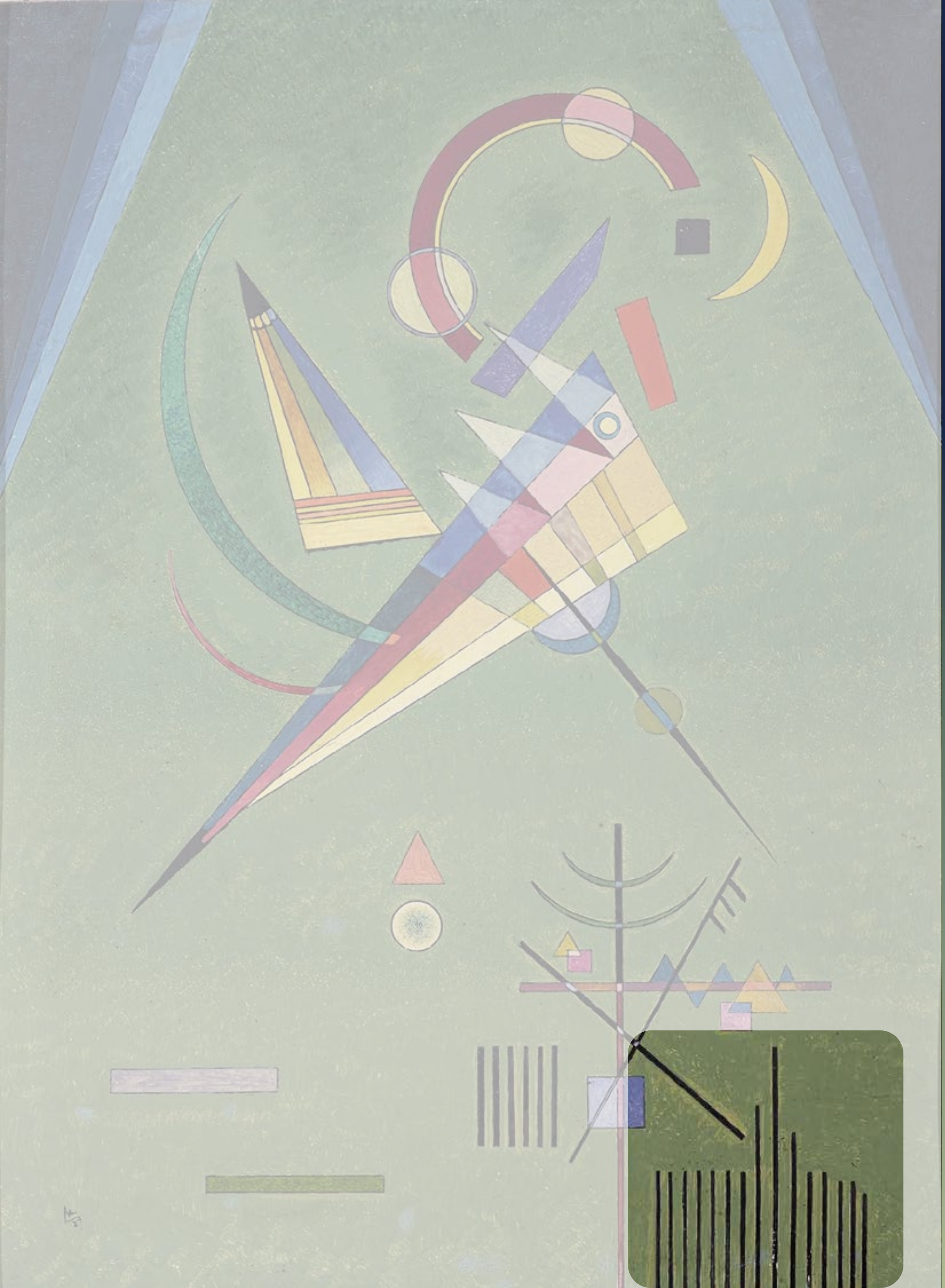


Outline



Outline

Basic elements: quantum cascade lasers and multimode states



Outline

Basic elements: quantum cascade lasers and multimode states

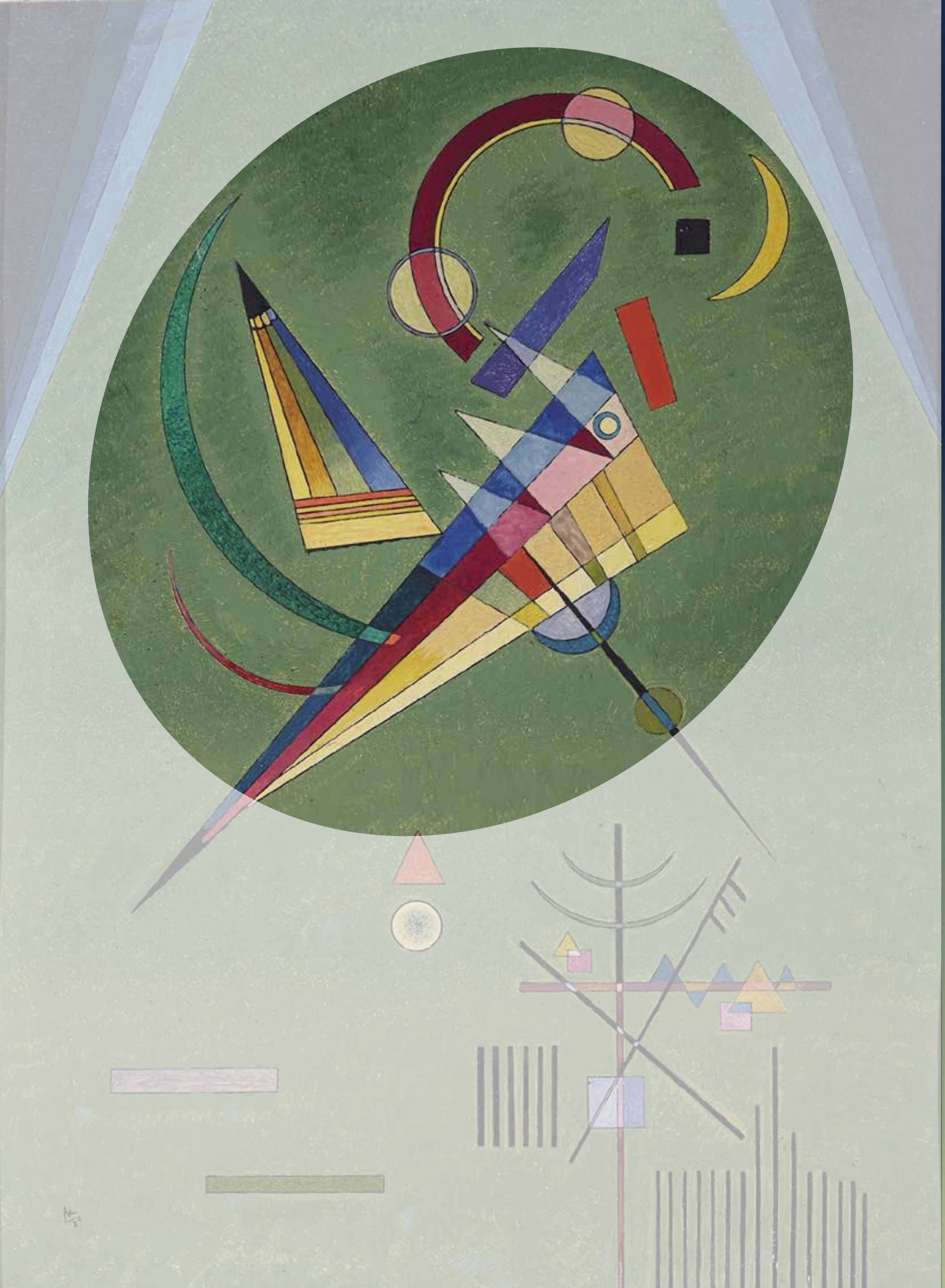
The harmonic state

Outline

Basic elements: quantum cascade lasers and multimode states

Applications

The harmonic state

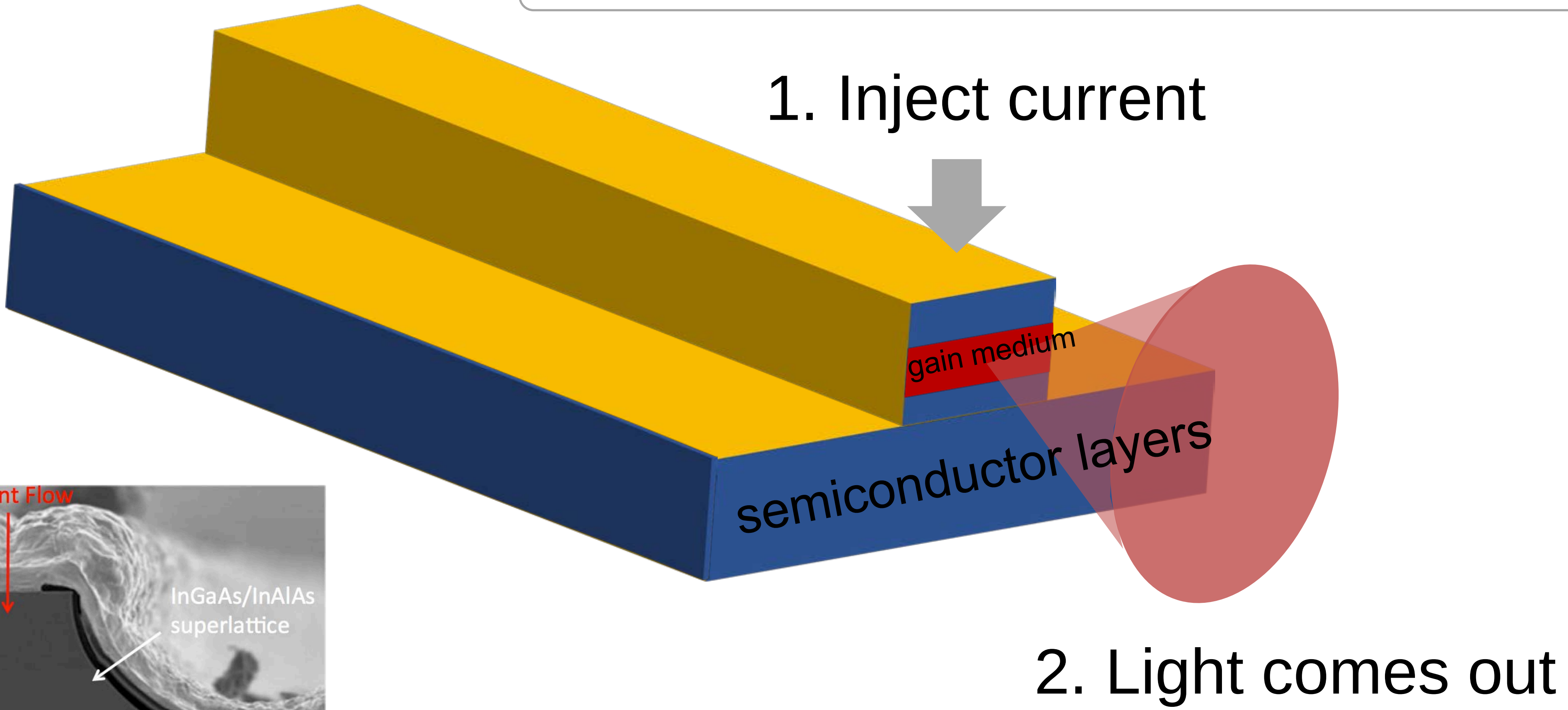


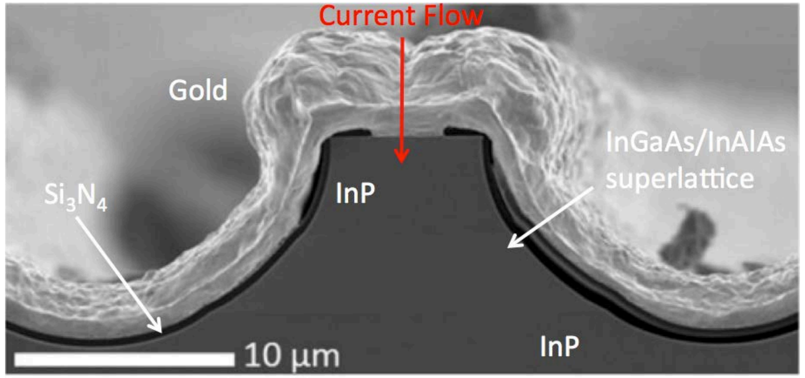
Outline

Basic elements: quantum cascade lasers and multimode states

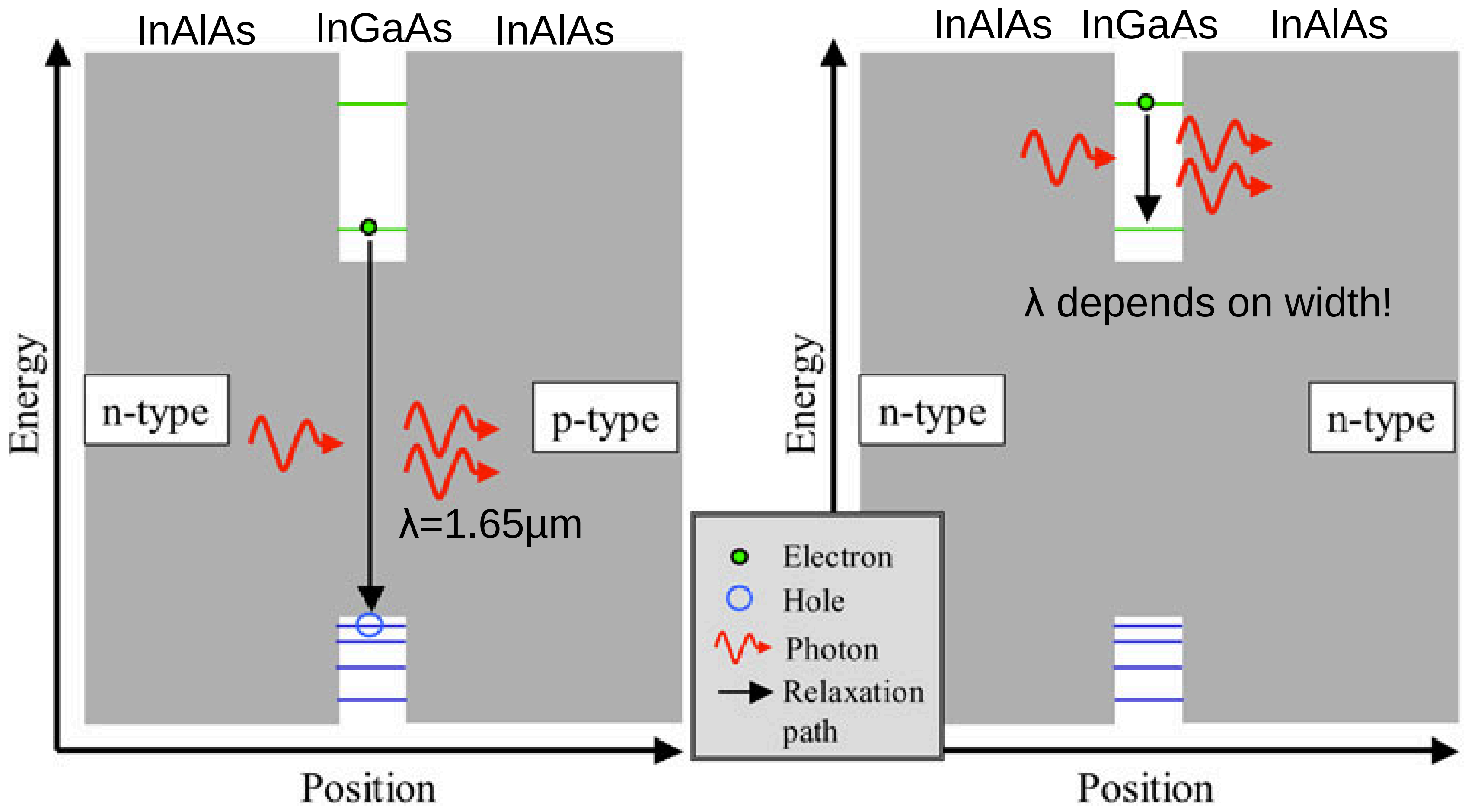
What does a QCL look like?

Laser = Gain Medium + Optical Cavity



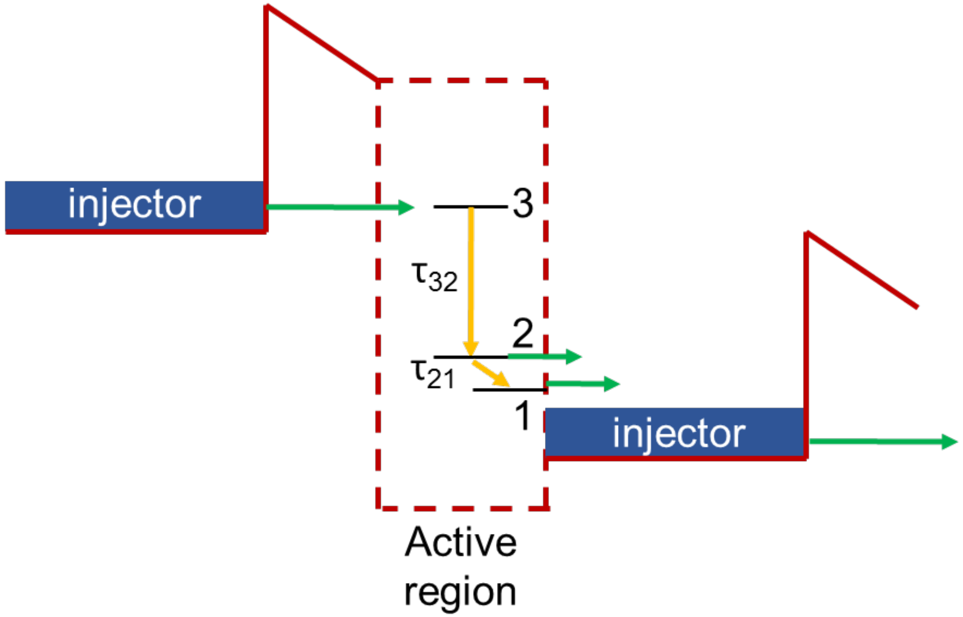


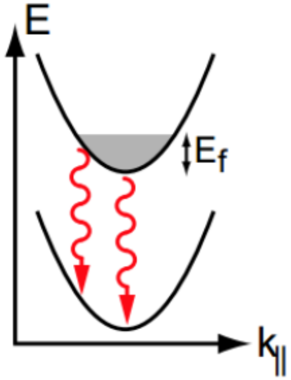
Interband vs. Intersubband

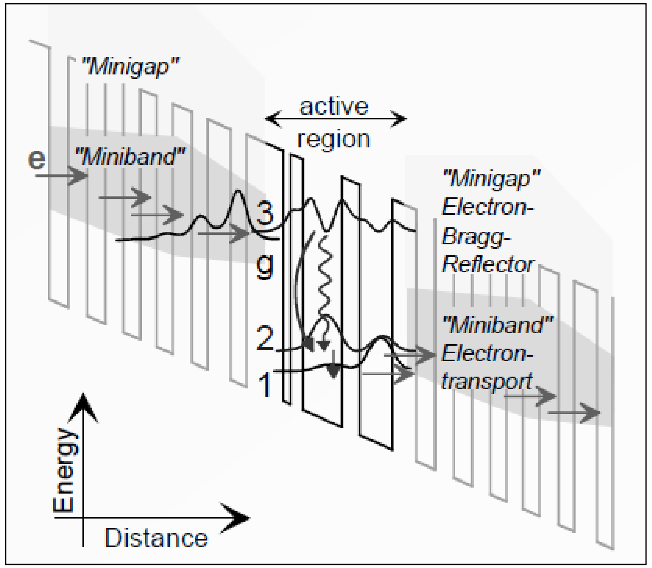


- Intersubband: wavelength determined by layer thickness, not by the bandgap of the material!
- QCLs can be designed to emit from 3 to 300 µm

It’s a little more complicated, but keep it simple.



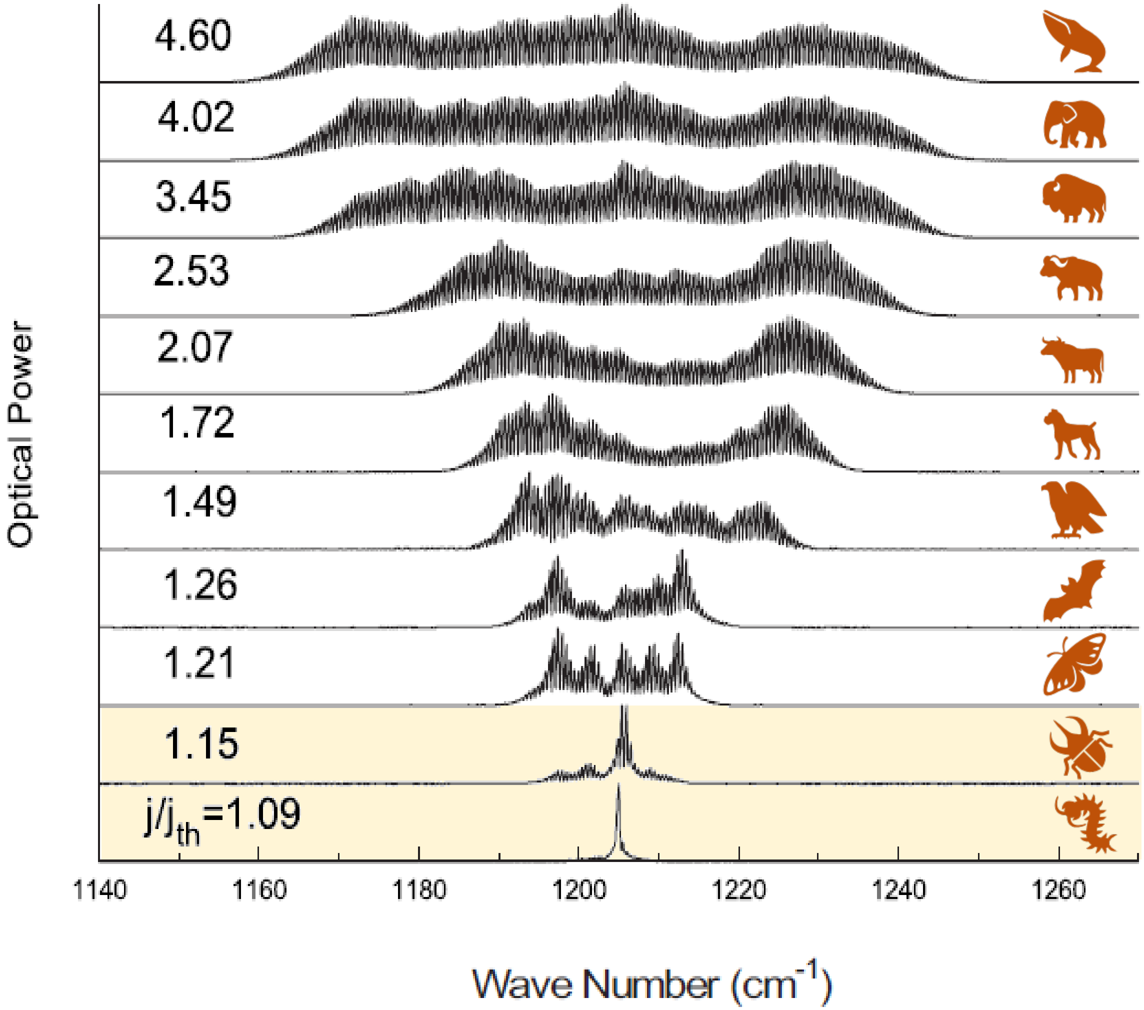




Typically: $\tau_{32} \approx 1$ ps, $\tau_{21} \approx 0.2$ ps

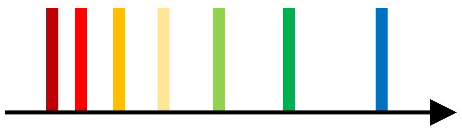
These picosecond time-scales make the QCL very different from other lasers.

A zoology of spectra



2. Nothing forces the modes to be equally spaced, so it’s not a frequency comb.

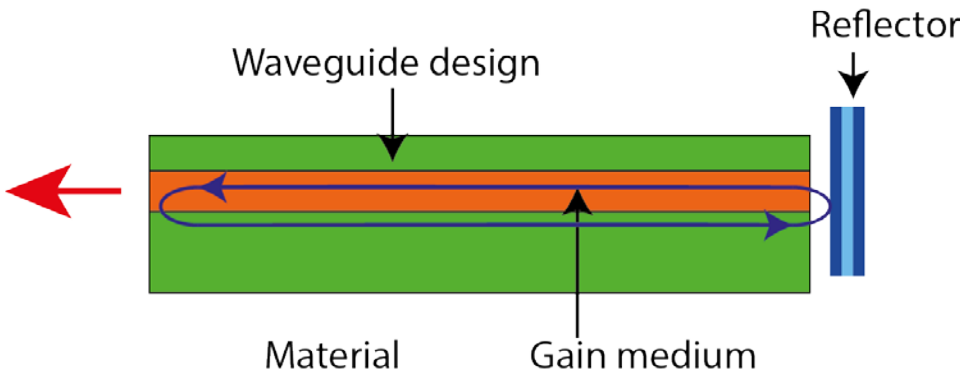
$$\nu_m = \left[\frac{c}{n_g(\nu)2L}\right]m$$



1. QCLs emit many modes due to a lack of carrier diffusion.

State of the understanding of QCL spectra in 2012

Dispersion engineering enables the formation of a frequency comb.



A. Hugi *et al.*, Nature, 492 (2012)
J. Faist *et al.*, Nanophotonics 5, 272 (2016)
G. Villares *et al.*, Optica 3, 252 (2016)
Y. Bidaux *et al.*, Opt. Lett. 42, 1604, (2017)
Y. Bidaux *et al.*, Laser & Photonics Reviews 12, 1700323 (2018)

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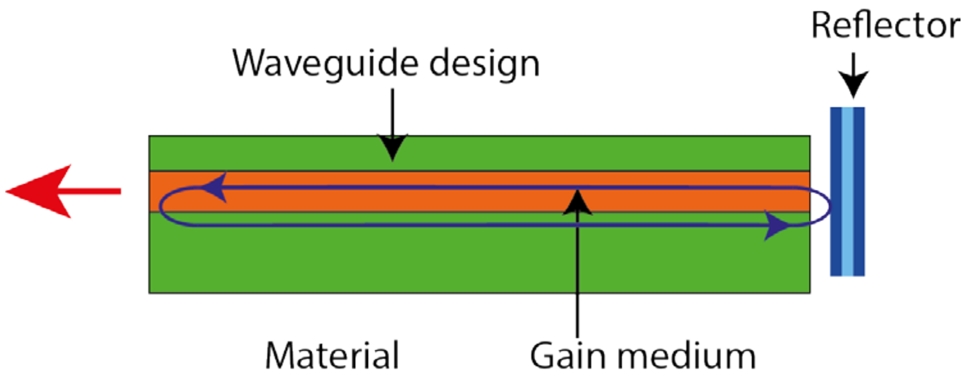
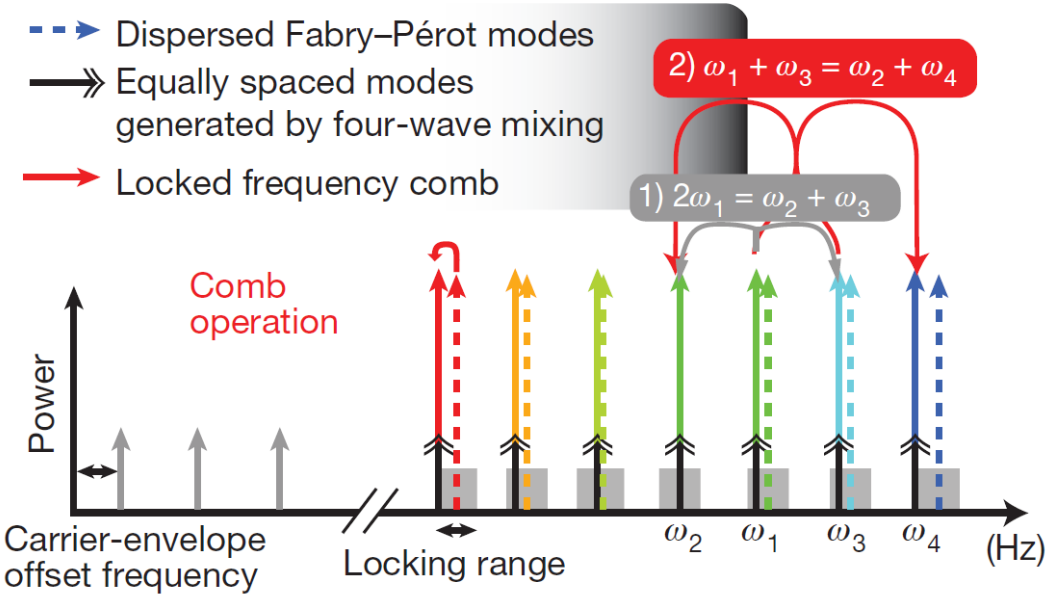
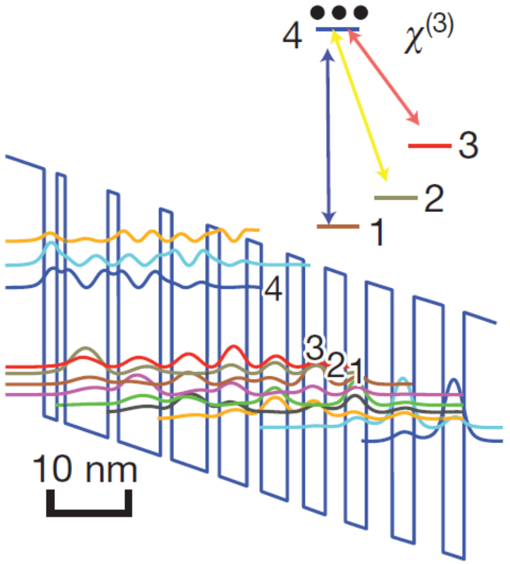


Spatial hole burning + Resonant $\chi^{(3)}$





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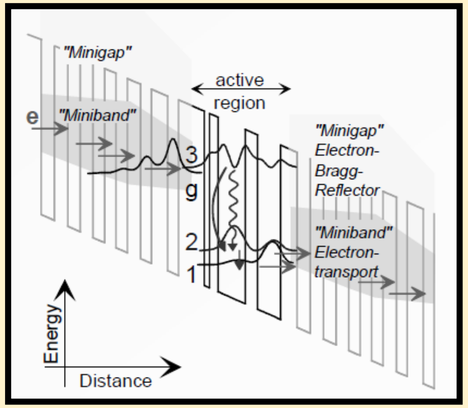
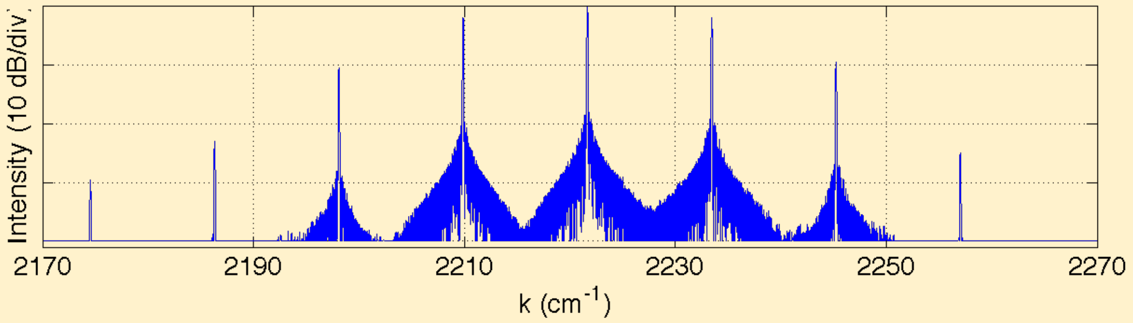
A quantum cascade laser renaissance

New physics that was hidden in plain sight

Quantum Cascade Lasers (1994-present)

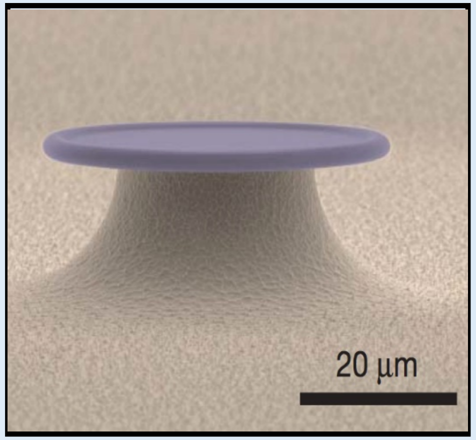


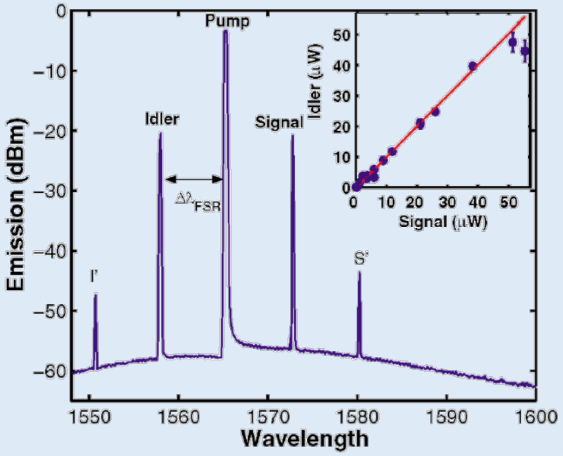


Frequency Combs

Lasers

Microresonators (2004-present)





Nonlinearity

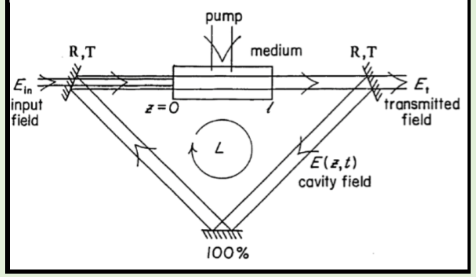
Parametric interactions

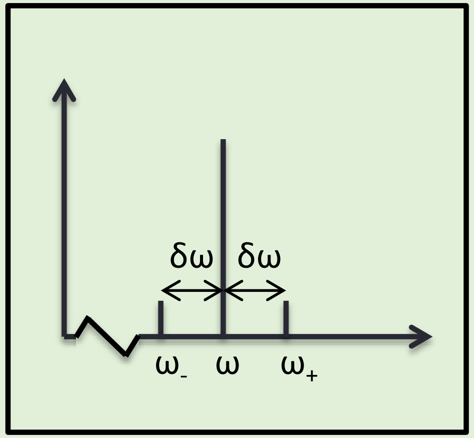
Laser Instabilities (1968-1980s)

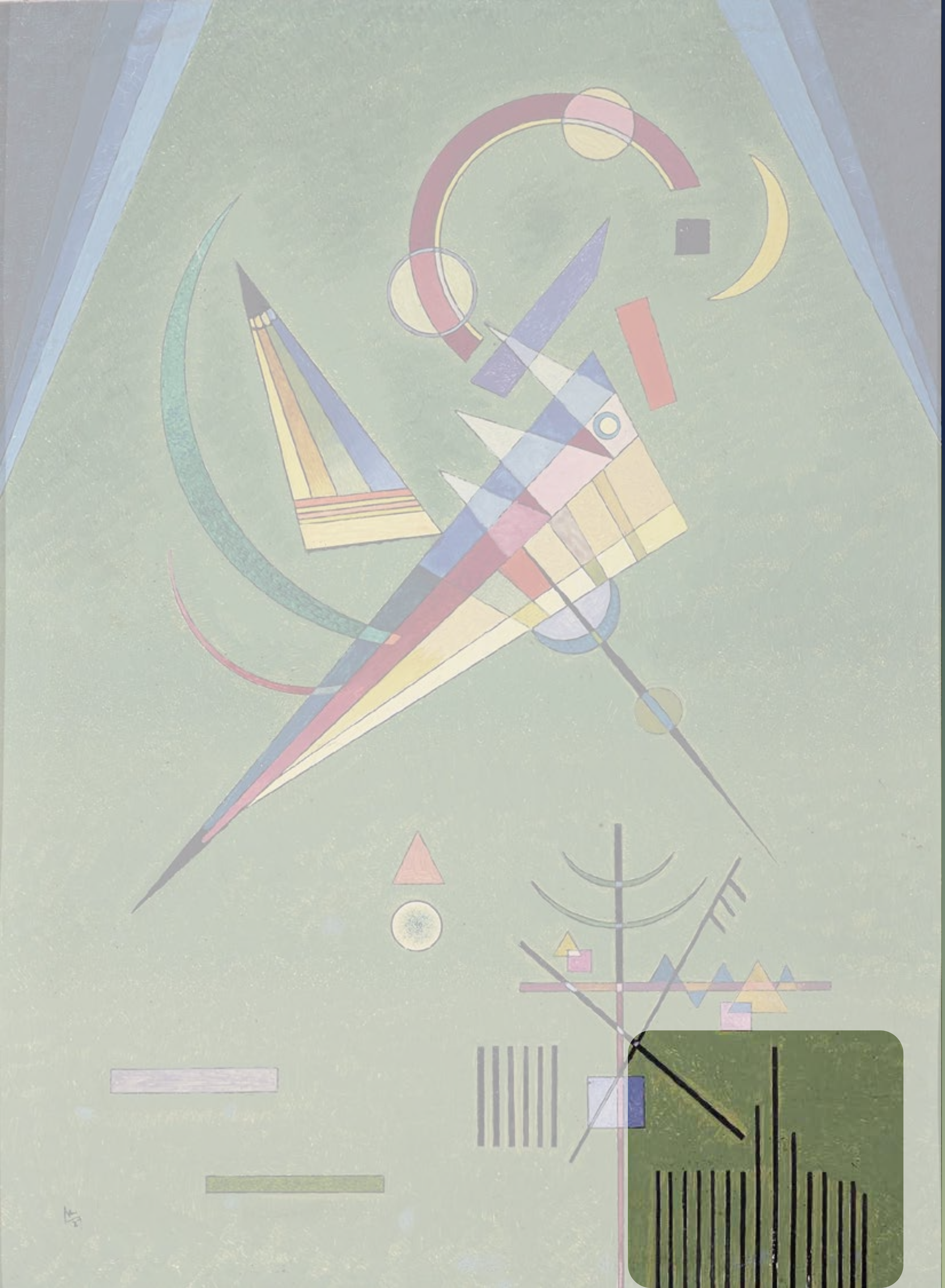
$$\dot{P}+\gamma_\perp P=\gamma_\perp E\sigma$$

$$\dot{\sigma}+\gamma_{||}\sigma=\gamma_{||}[\lambda+1-\tfrac{1}{2}\lambda(E^*P+EP^*)]$$

$$c(\partial E/\partial x)+\dot{E}+\kappa E=\kappa P,$$







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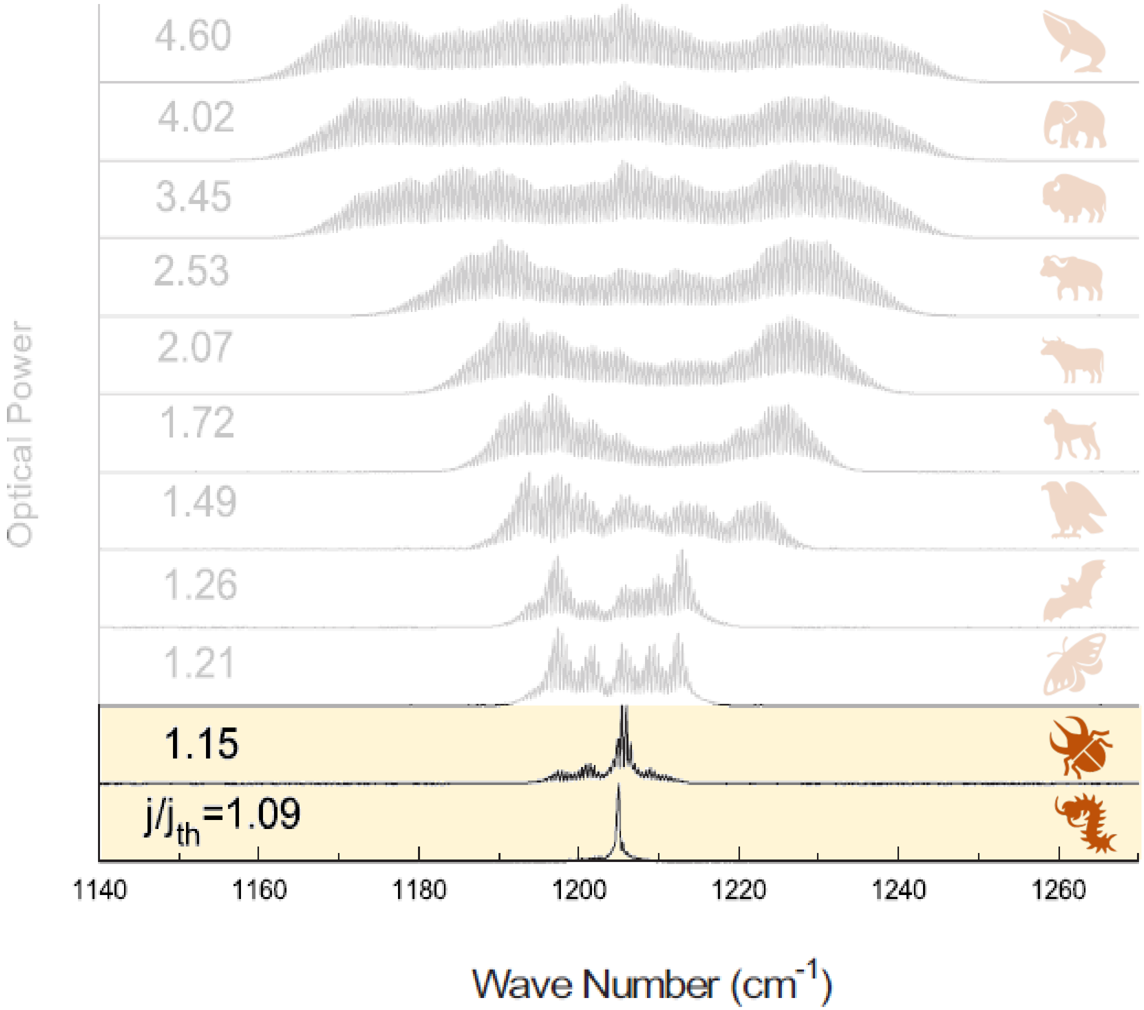
Basic elements: quantum cascade lasers and multimode states

The harmonic state

A zoology of spectra



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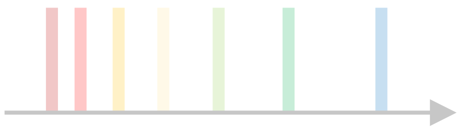


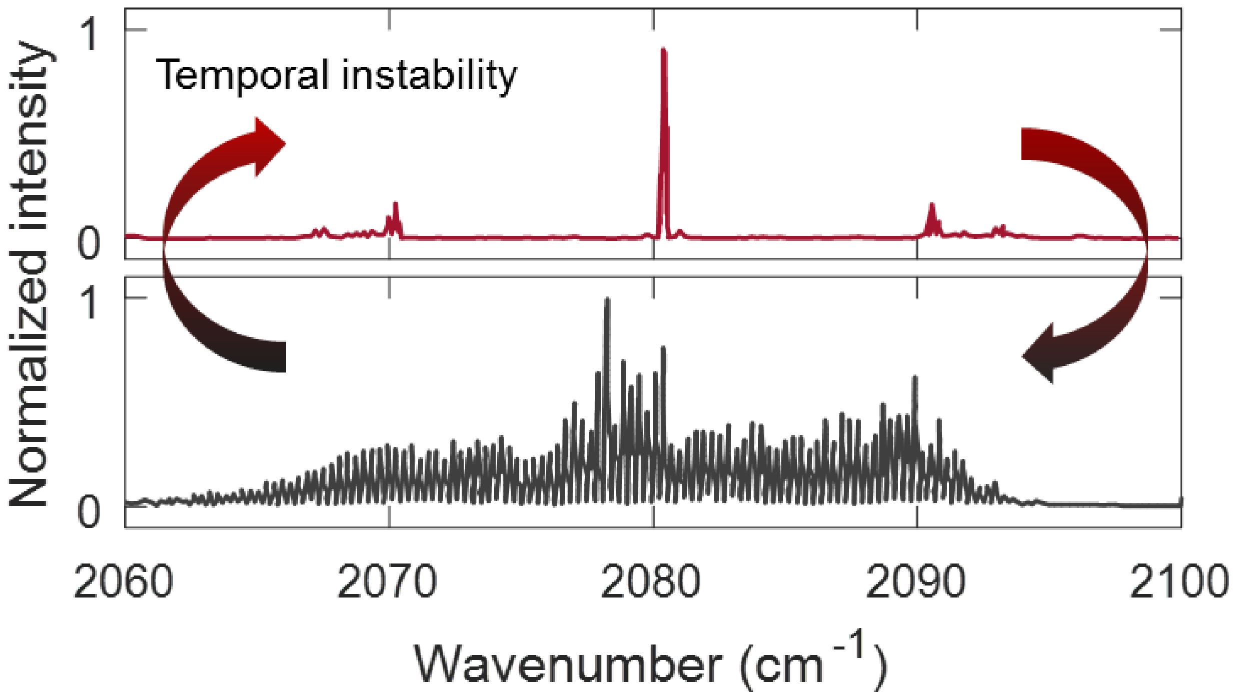
1. QCLs emit many modes due to a lack of carrier diffusion.

State of the understanding of QCL spectra in 2012

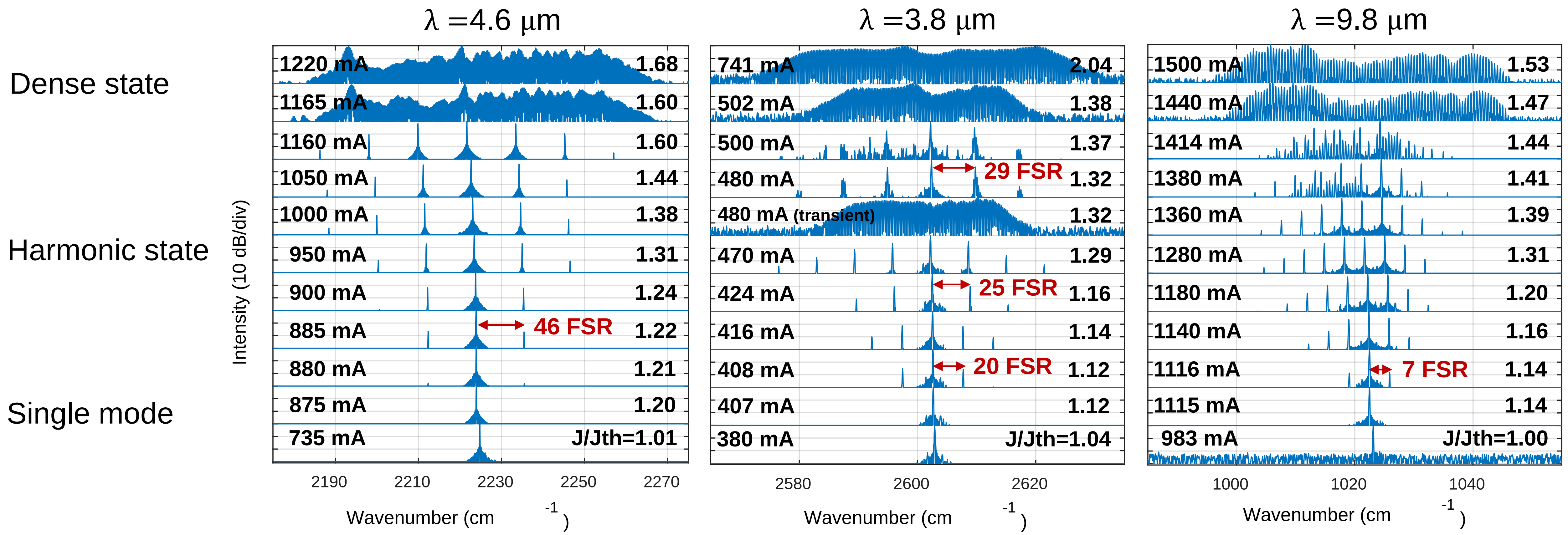
A. Gordon *et al.*, Phys. Rev. A 77, 053804 (2008)

What is the second mode to lase?

Increase slowly the DC current in the laser



The discovery of the harmonic state



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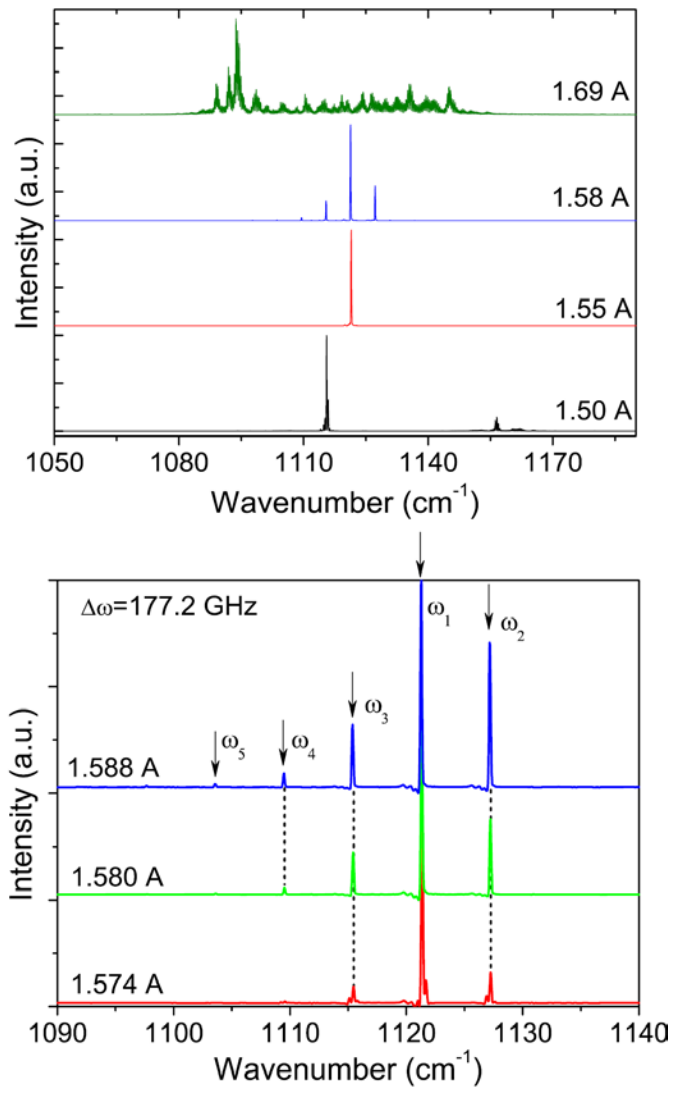
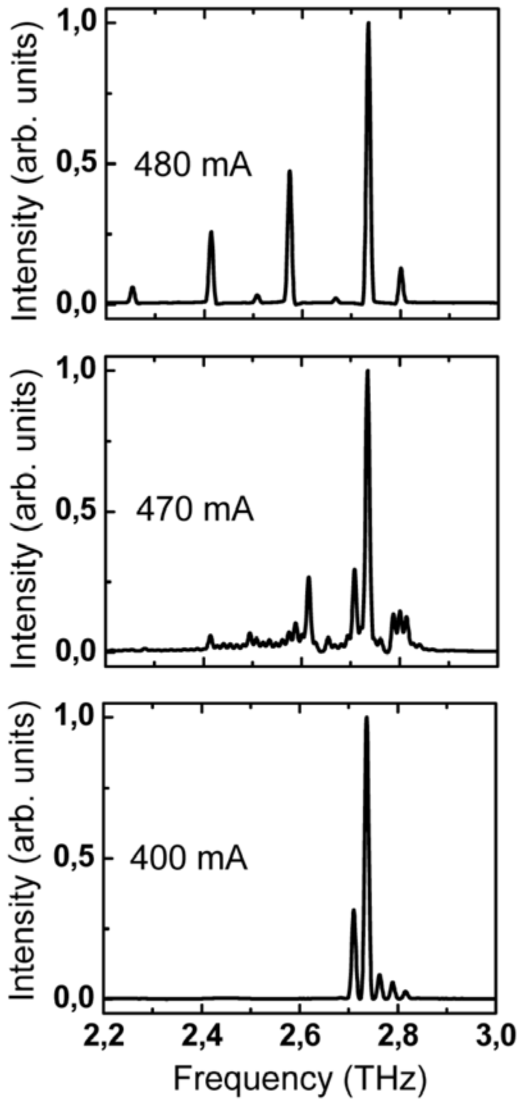
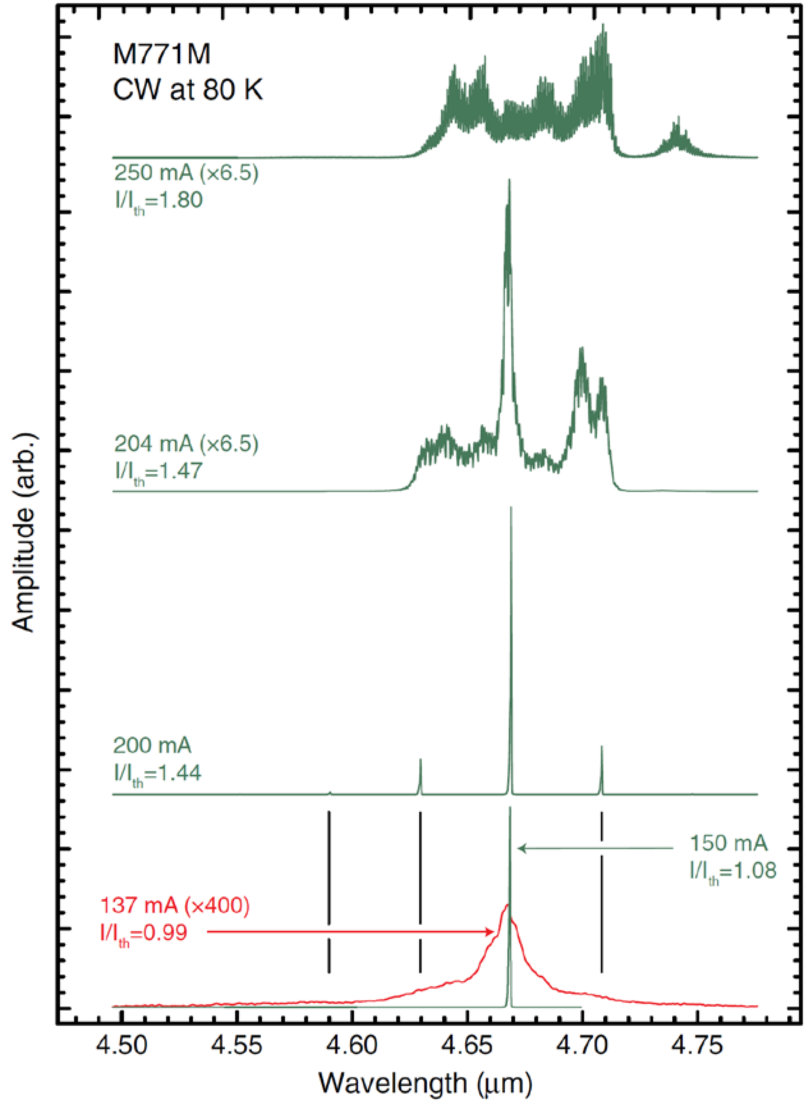
T. S. Mansuripur *et al.*, Phys. Rev. A, 94, 063807 (2016)

M. Piccardo, P. Chevalier *et al.*, Opt. Express 26, 9464 (2018)

Observations in other groups





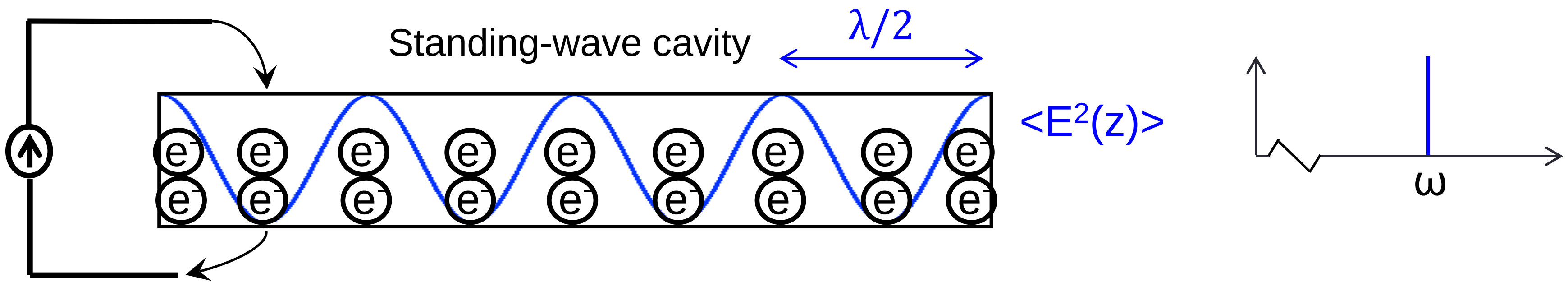


Q.Y. Lu, …, C. Sirtori, Appl. Phys. Lett. 106, 51105 (2015)

H. Li, …, S. Barbieri, Opt. Express 23, 33270 (2015)

R. L. Tober, …, G. Belenky, JOSA B 31, 2399 (2014)

The origin of the harmonic state – **1. Population grating**



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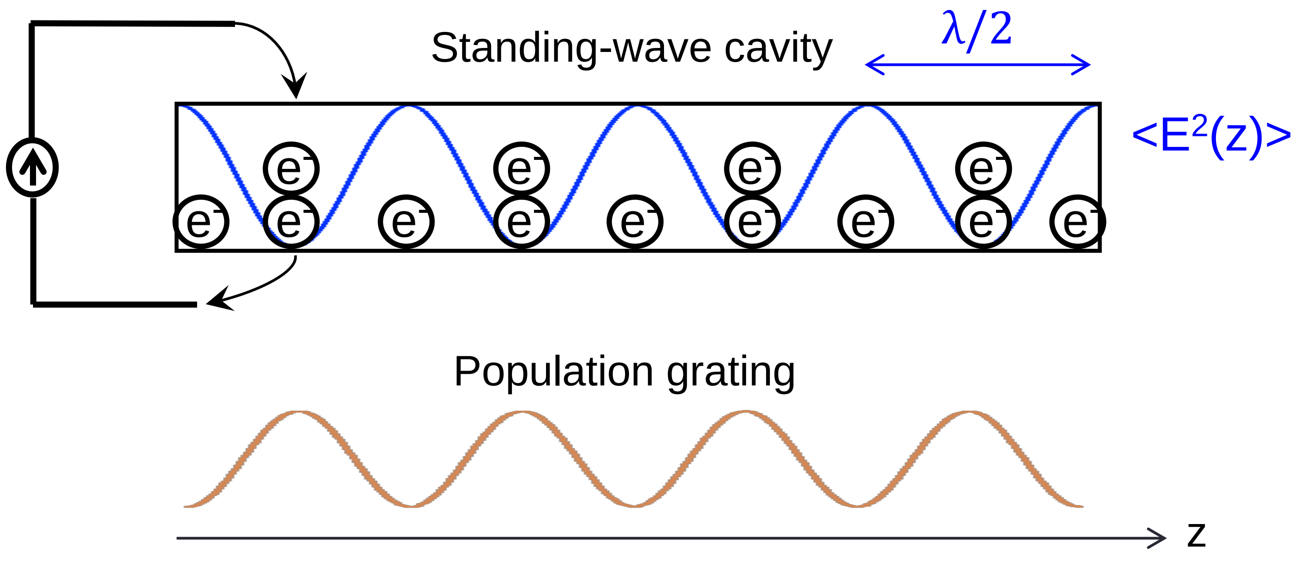

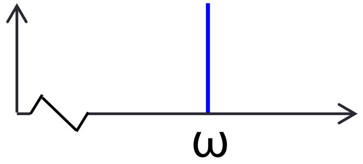

T. S. Mansuripur et al., Phys. Rev. A, 94, 063807 (2016)

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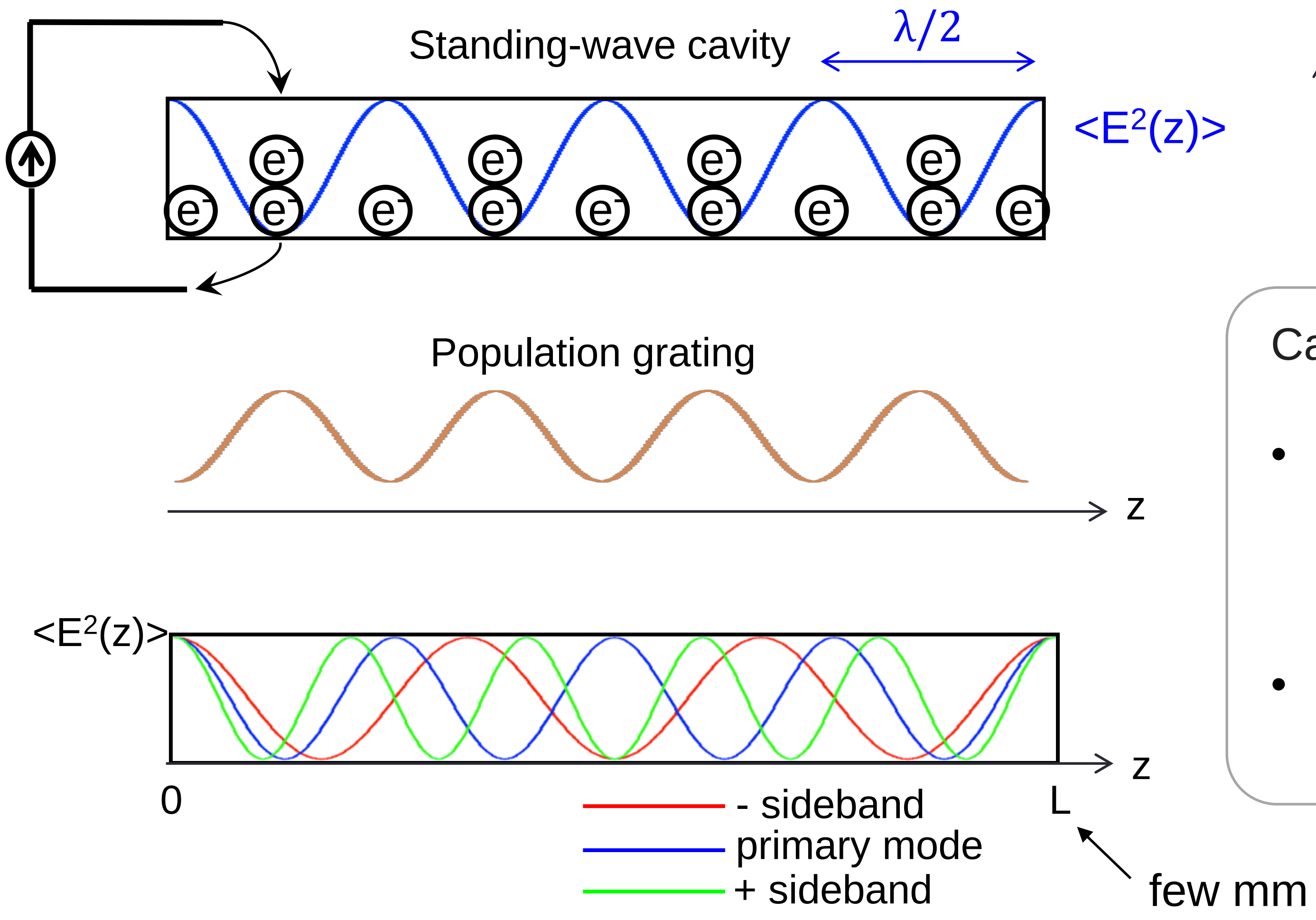
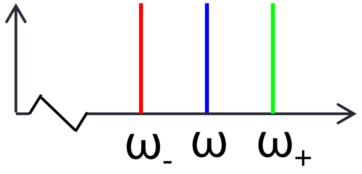


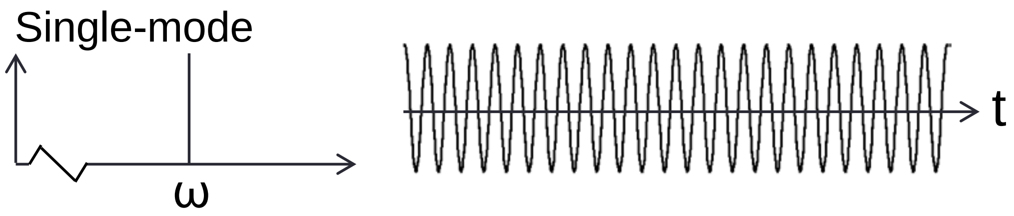


Can electron diffusion wash out the grating?

- In 1 ps, an electron can diffuse $\sqrt{\mu \cdot kT \cdot \tau_{32}/q}$ = 150 nm at 300K in InGaAs
- That's nowhere near enough to traverse a $\lambda/4$ from node to anti-node

T. S. Mansuripur et al., Phys. Rev. A, 94, 063807 (2016)

The origin of the harmonic state – **2. Population Pulsations**



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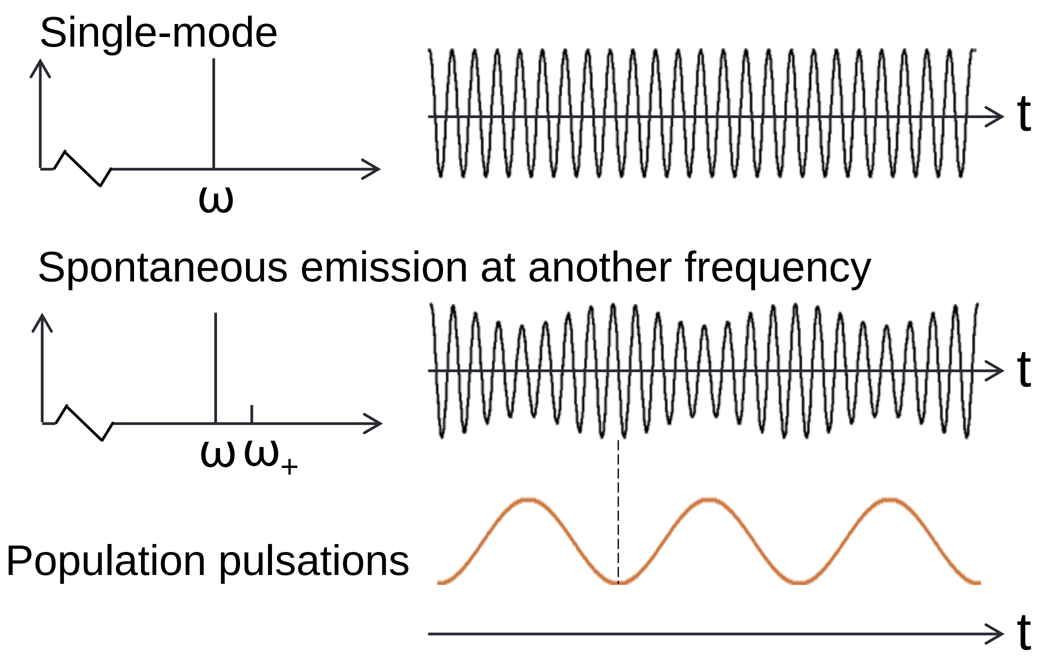
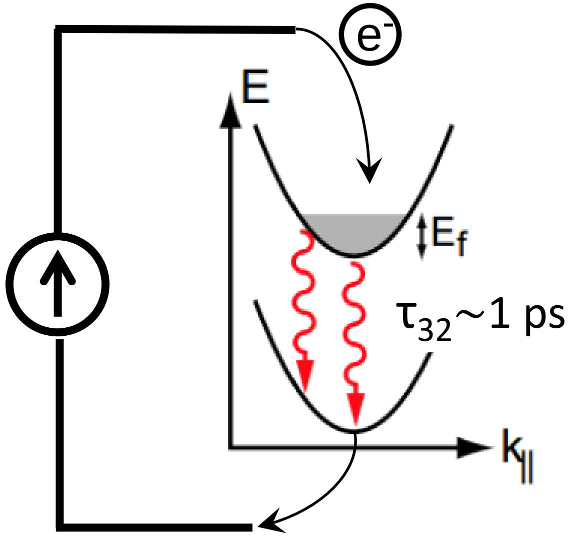


Time varying intensity
→ Time-varying transition rate



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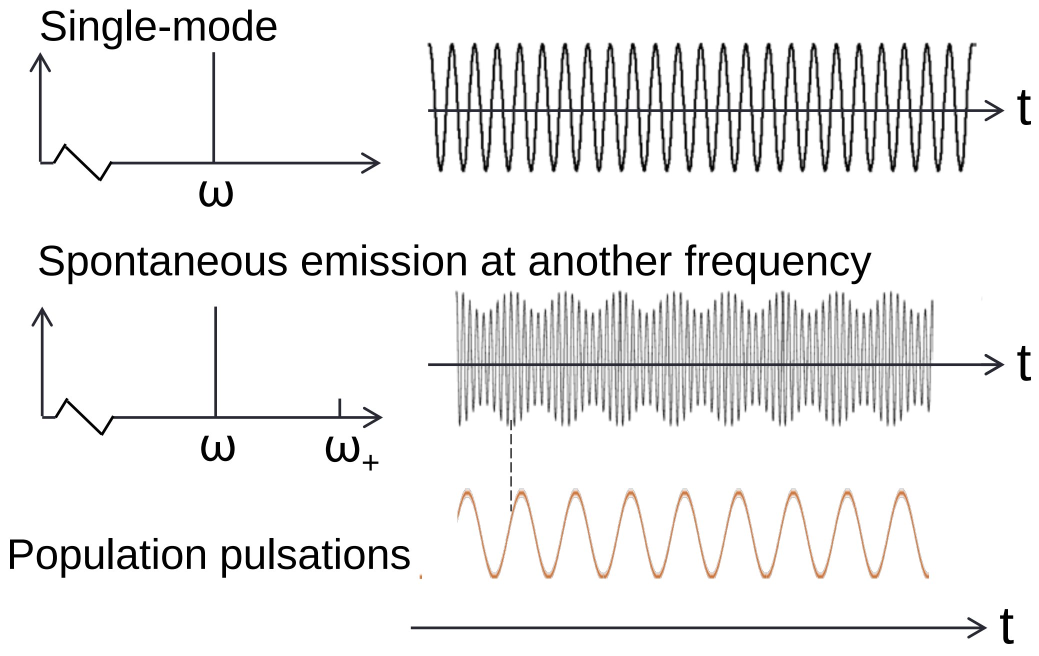

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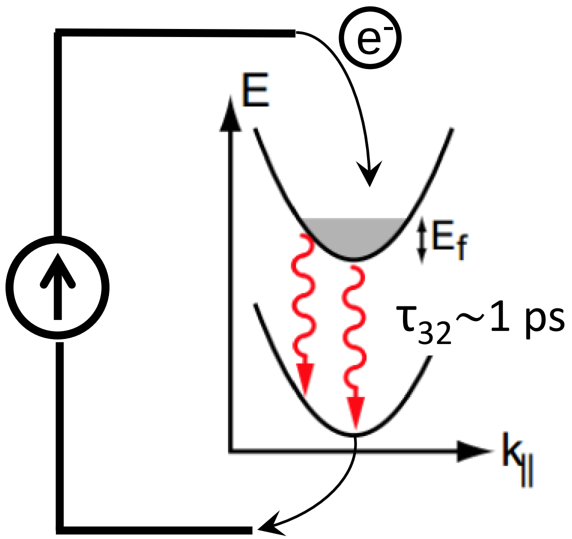
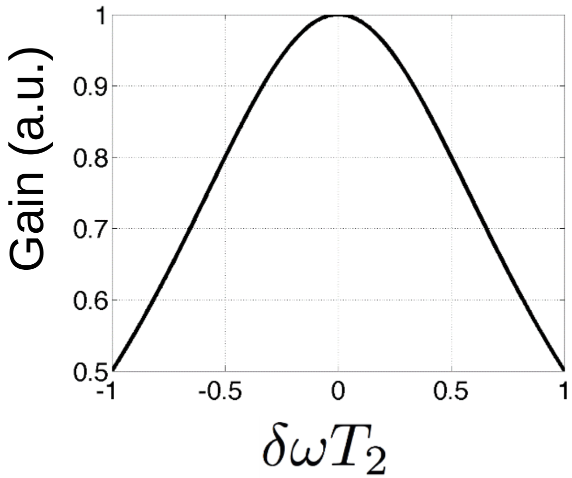


Inversion responds to modulation **up to some limit**

Population pulsations and population grating work *in tandem* to create the harmonic state.

Lorentzian gain



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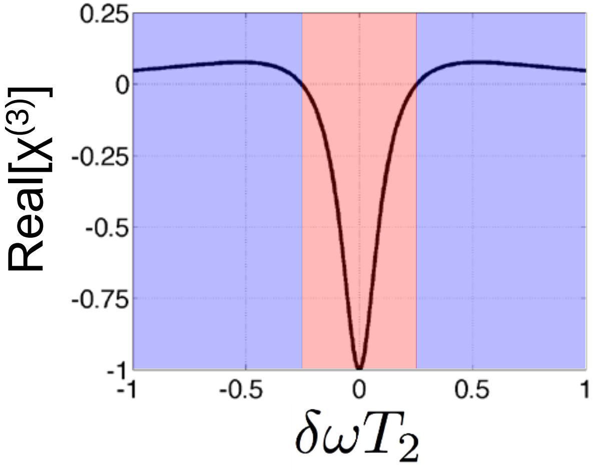
Parametric gain



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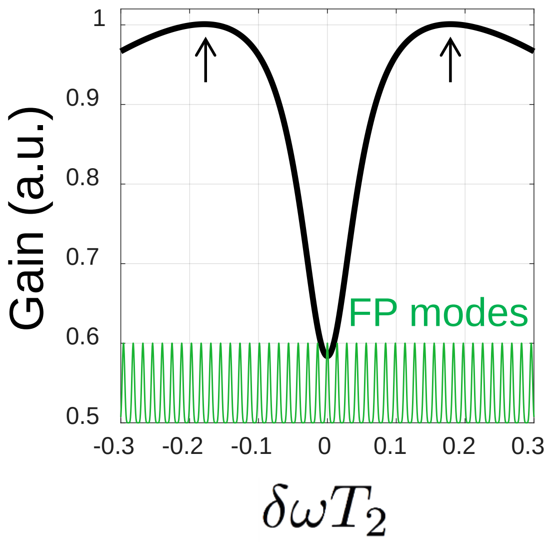
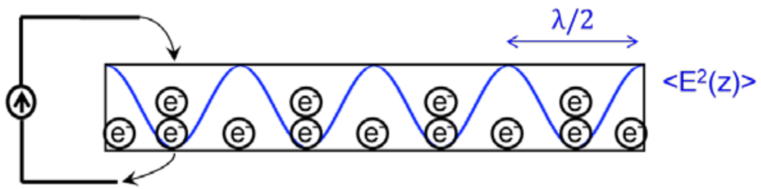
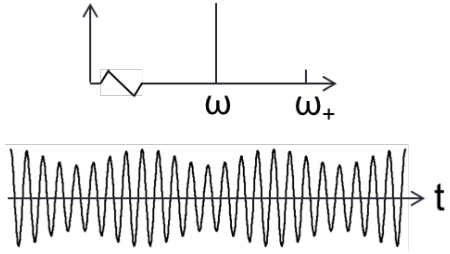
Total gain

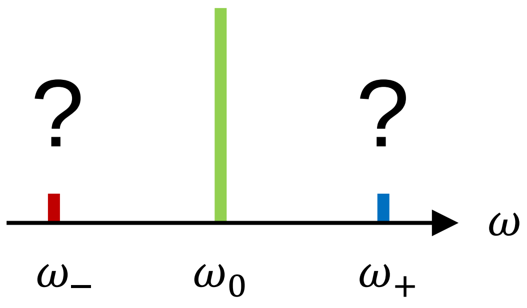






T. S. Mansuripur et al., Phys. Rev. A, 94, 063807 (2016)

Linear analysis of the instability: a perturbative approach



Find the linearized solution for weak sidebands in the presence of a strong central mode.

This gives the gain spectrum for sideband generation.

Maxwell-Bloch equations

$$\partial_t \rho_{ul} = -\left(i\omega_{ul} + \frac{1}{T_2}\right)\rho_{ul} - i\frac{dE}{\hbar}\Delta,$$

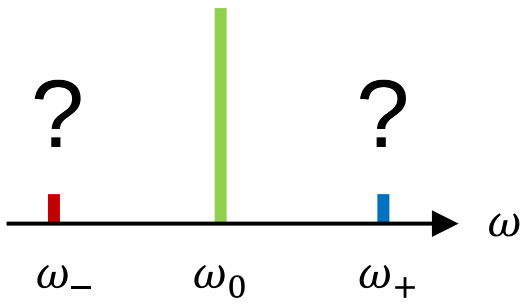
$$\partial_t \Delta = -\frac{\Delta - \Delta_p}{T_1} - 2i\frac{dE}{\hbar}(\rho_{ul} - \rho_{ul}^*) + D\frac{\partial^2 \Delta}{\partial z^2},$$

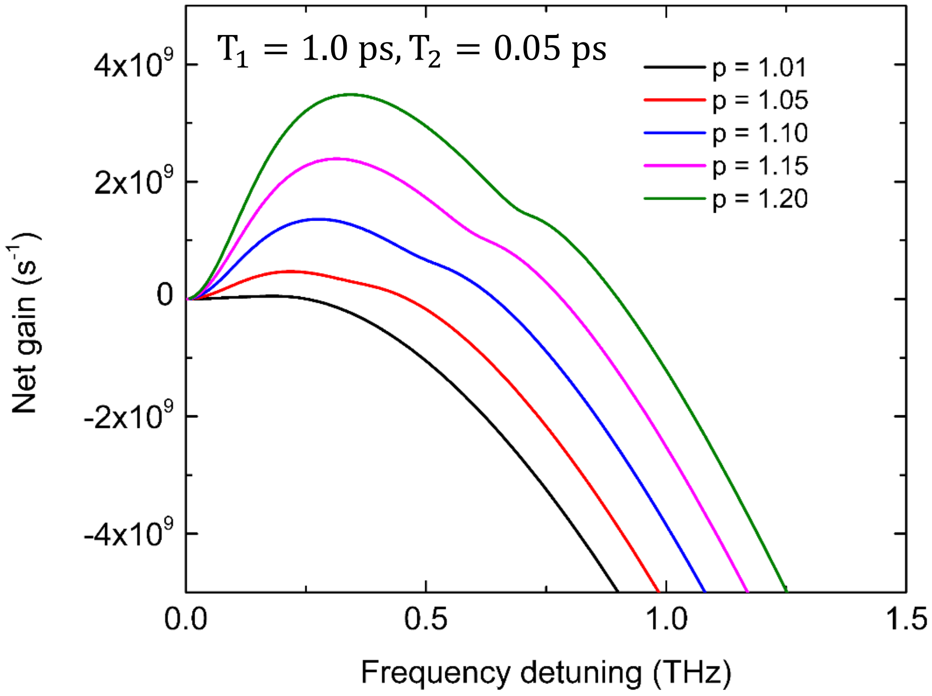
$$\partial_z^2 E - \frac{n^2}{c^2}\partial_t^2 E = \kappa d \partial_t^2(\rho_{ul} + \rho_{ul}^*),$$

$$E = E_0 \cos(k_0 z) e^{-i\omega_0 t} + E_+ \cos(k_+ z) e^{-i\omega_+ t} + E_- \cos(k_- z) e^{-i\omega_- t} + \text{c.c.},$$

T. S. Mansuripur et al., Phys. Rev. A, 94, 063807 (2016)

Linear analysis of the instability: a perturbative approach

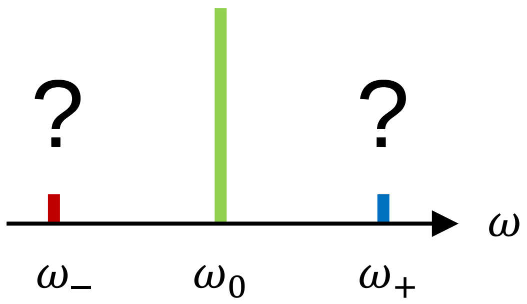


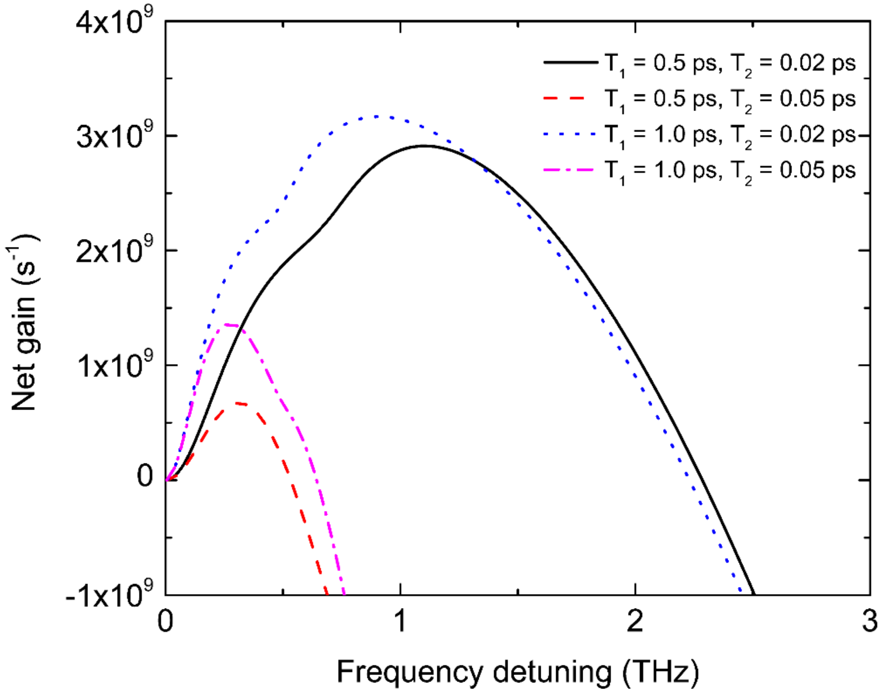


Parametric contribution becomes significant at a pumping level that is only fractionally higher than the lasing threshold

T. S. Mansuripur et al., Phys. Rev. A, 94, 063807 (2016)

Linear analysis of the instability: a perturbative approach





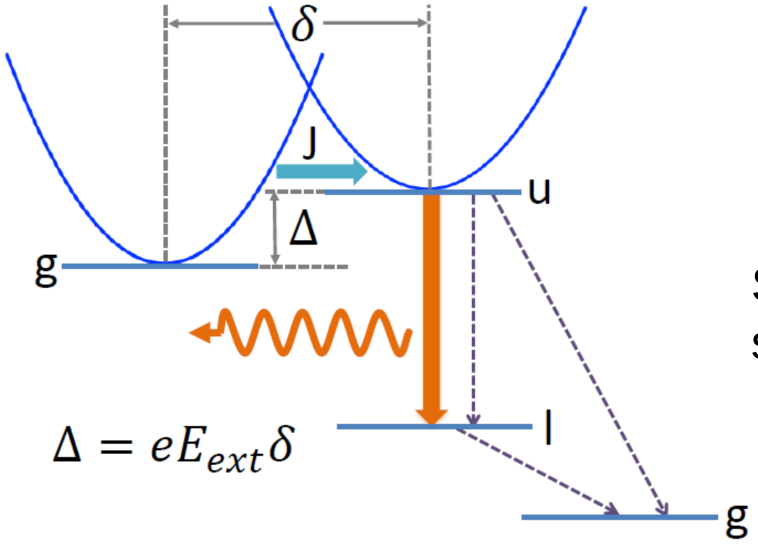
Detuning corresponding to maximum gain:

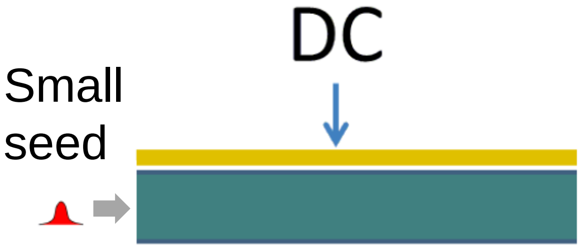
$$\delta\omega^2 = \frac{d|E_0|}{\hbar}\frac{1}{\sqrt{T_2 T_g}} - \frac{1}{T_g^2}$$

Greater sideband gain with wider sideband separation for shorter dephasing time T_2 (broader laser gain spectrum).

T. S. Mansuripur et al., Phys. Rev. A, 94, 063807 (2016)

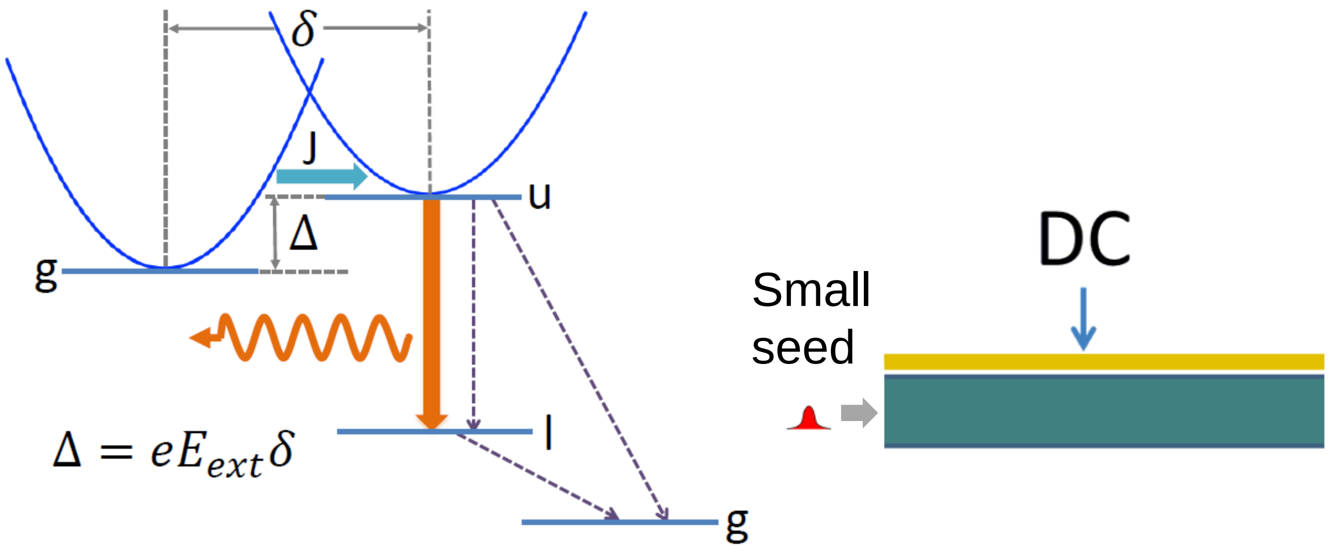
Space- and time-domain QCL simulator

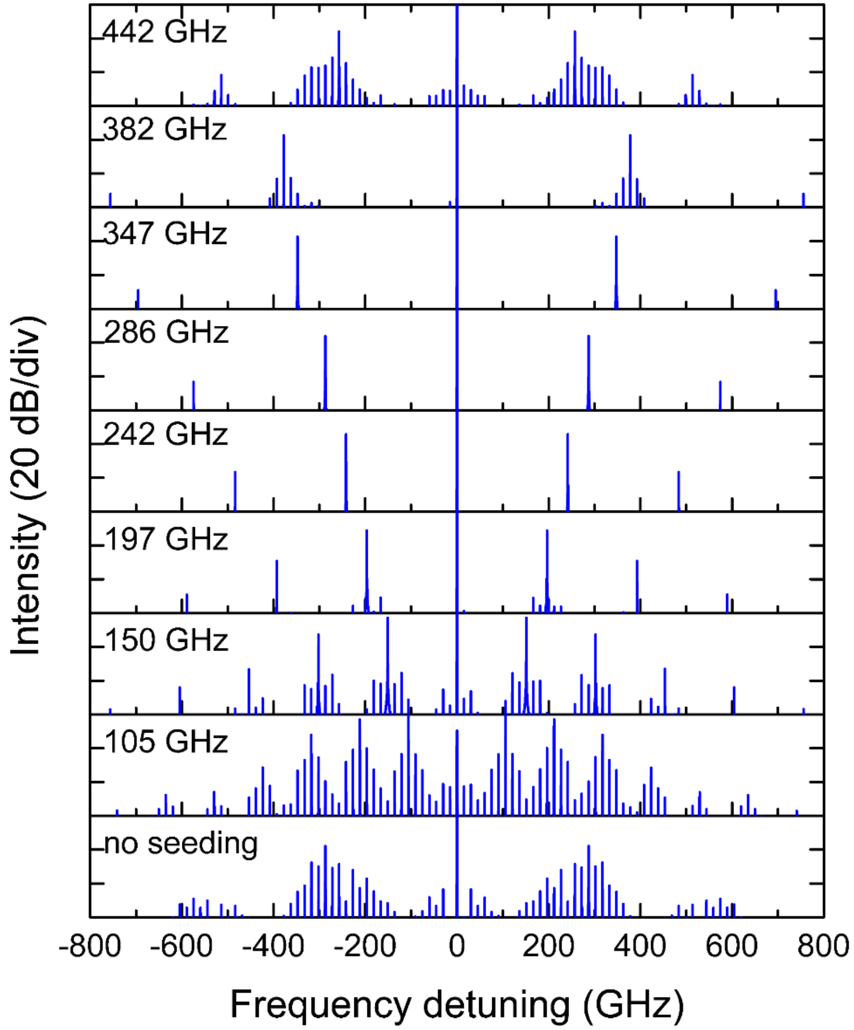




Y. Wang, A. Belyanin, Opt. Exp. 23, 4173 (2015)

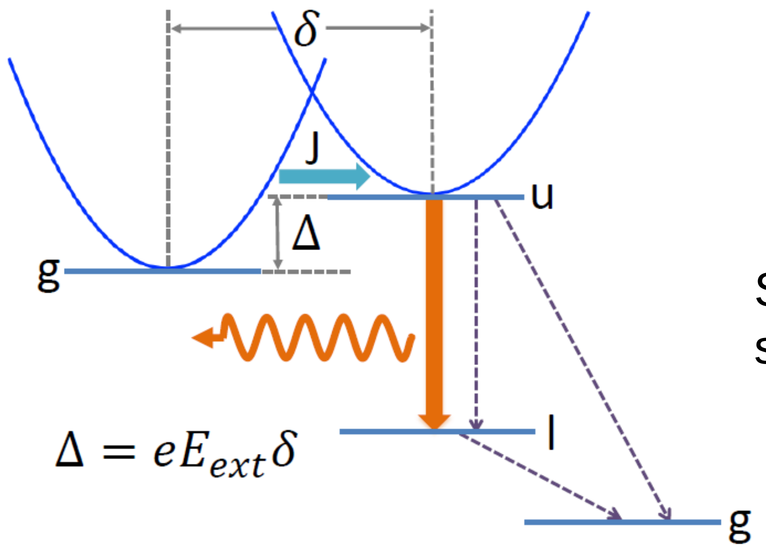
Space- and time-domain QCL simulator

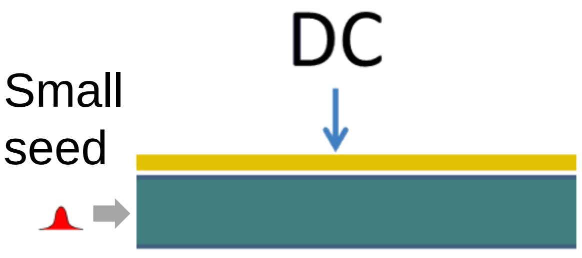


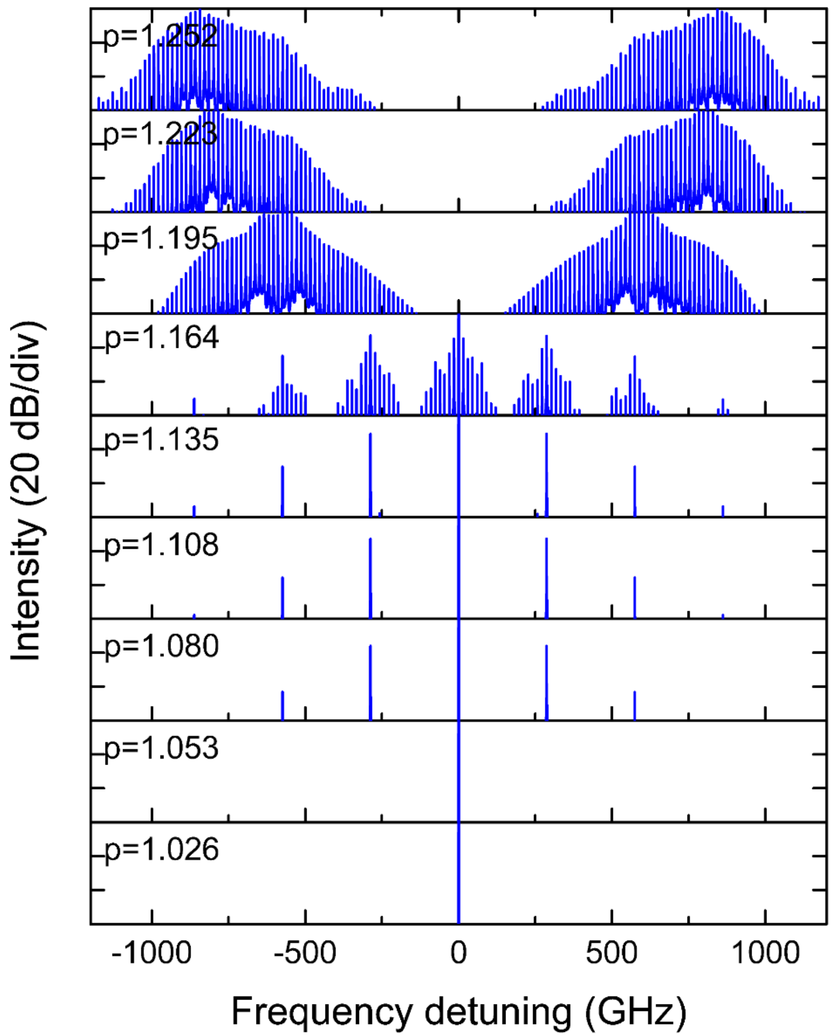


Harmonic state exists in a finite frequency range

Space- and time-domain QCL simulator



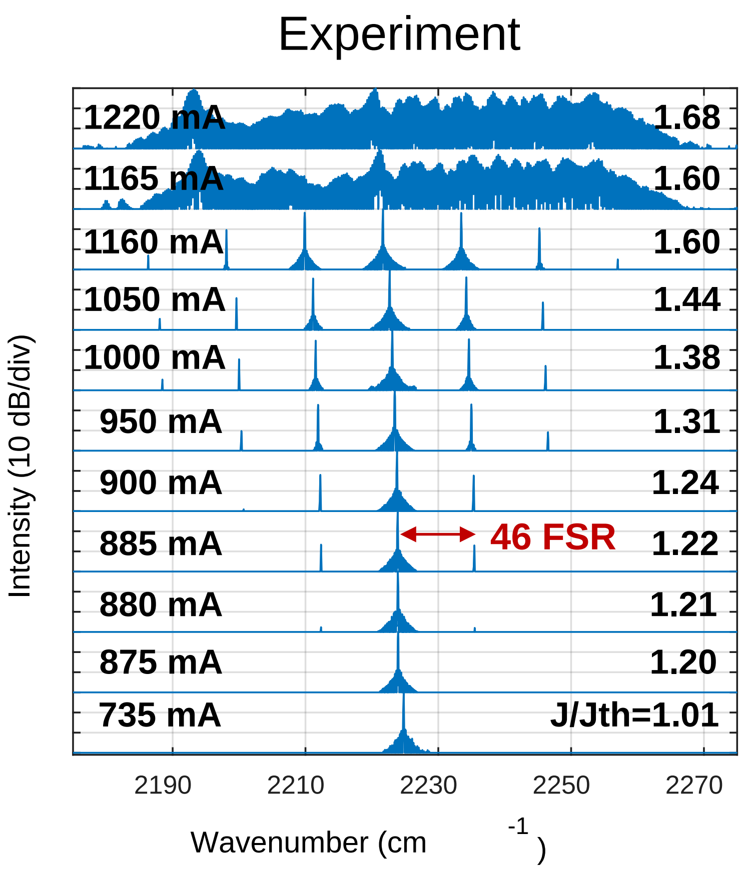




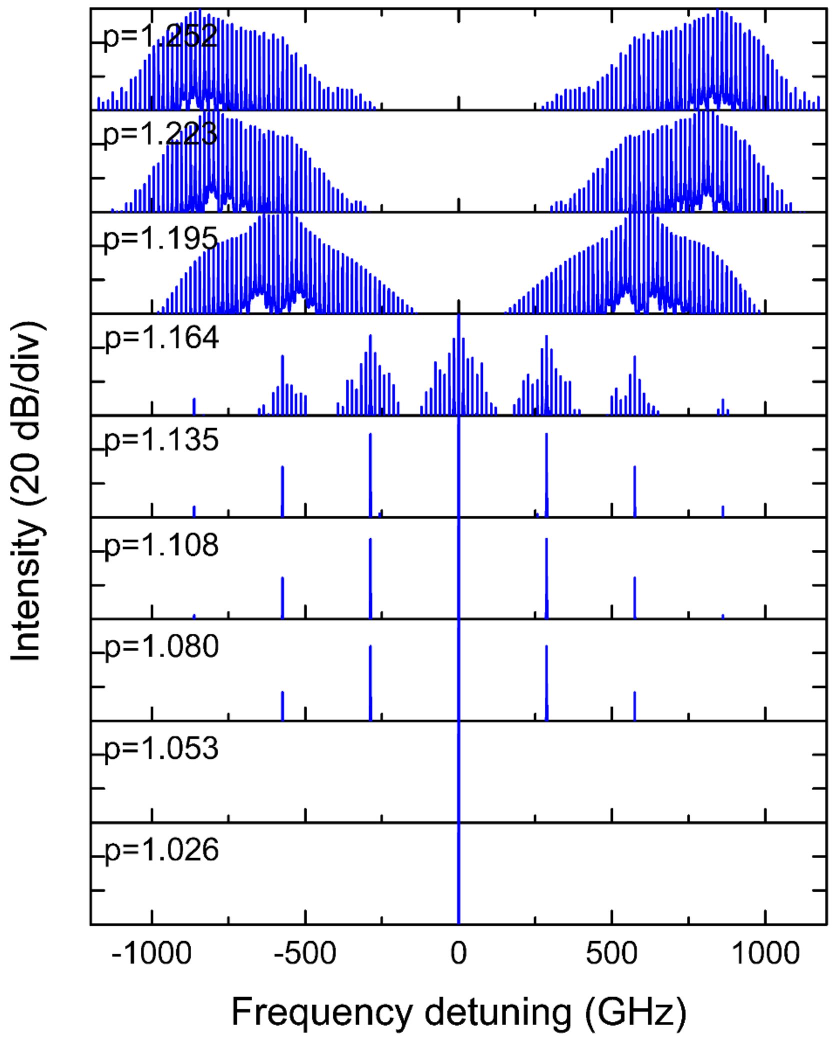
Harmonic state exists in a finite frequency range

…and a finite range of pumping levels.

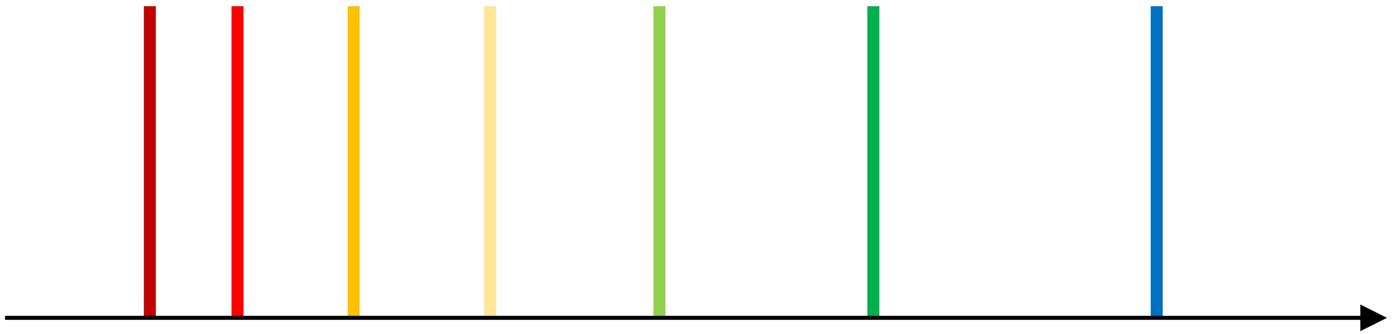
Space- and time-domain QCL simulator



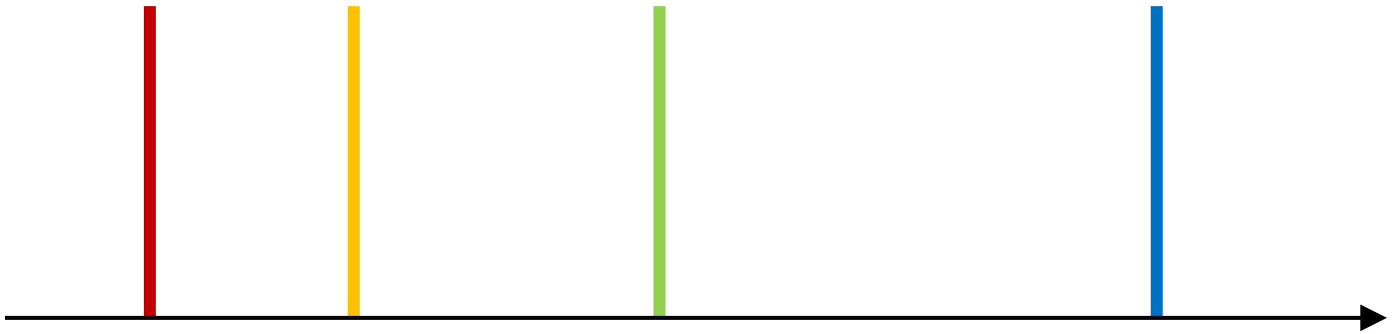
provided by: THORLABS



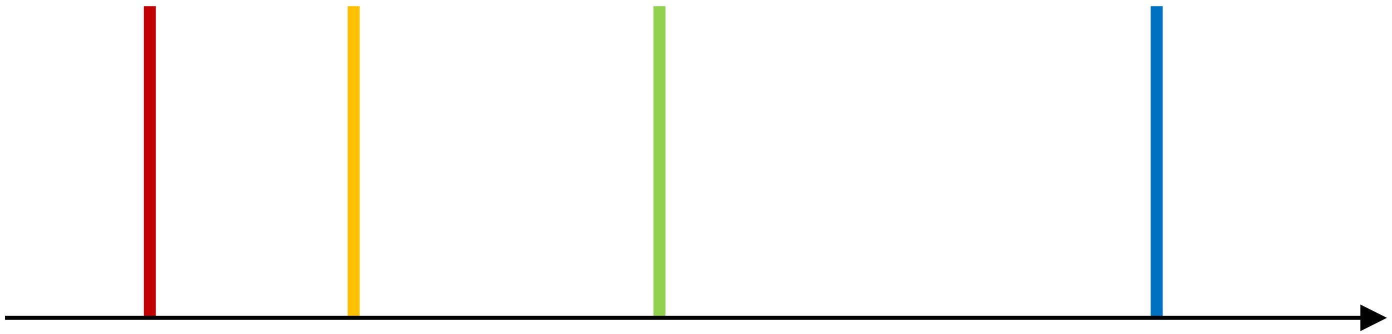
Mode skipping does not imply mode locking.

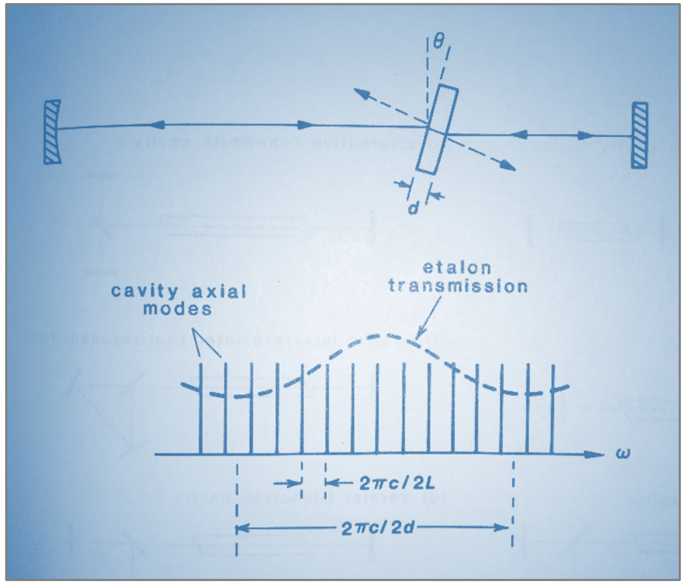


Mode skipping does not imply mode locking.

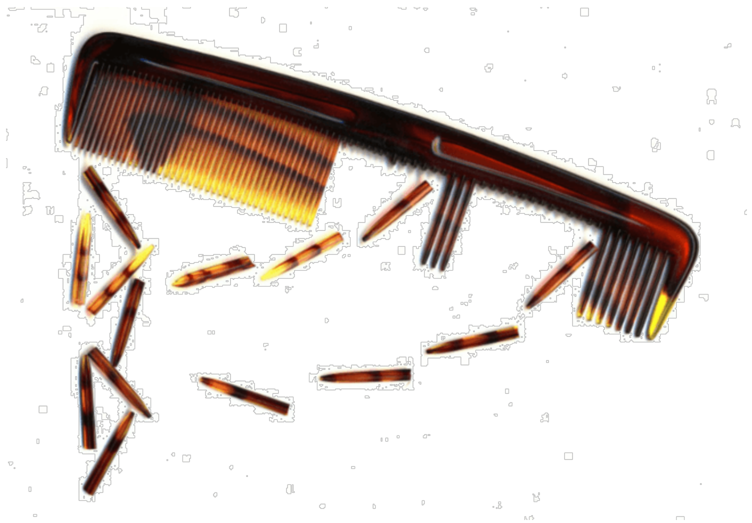


Mode skipping does not imply mode locking.



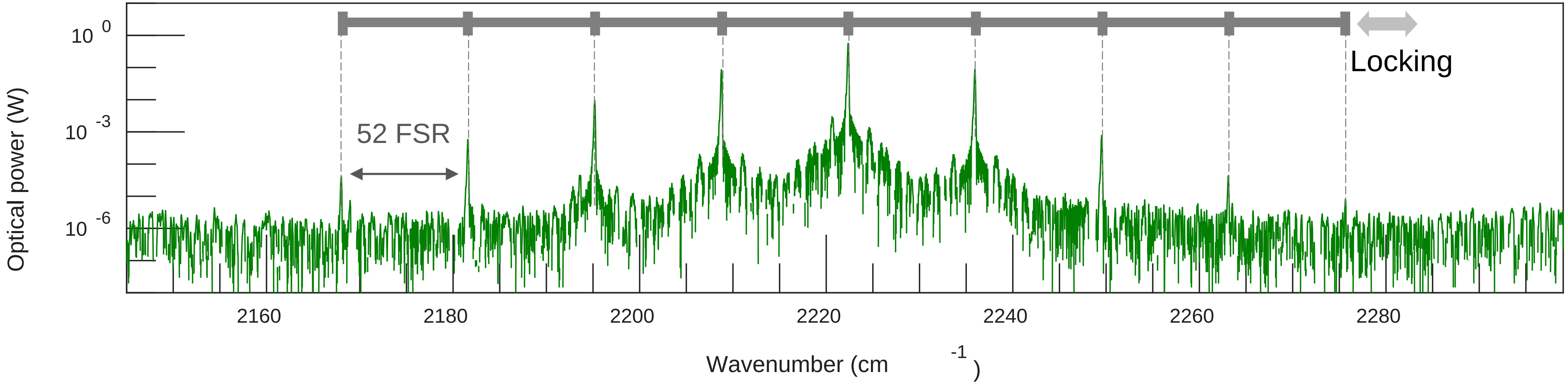


This is not a comb.



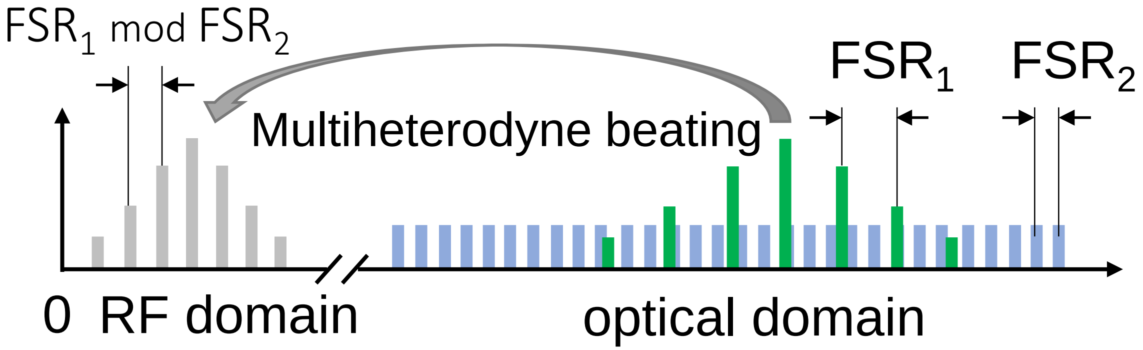
A. E. Siegman, *Lasers*, University Science Books (1986)

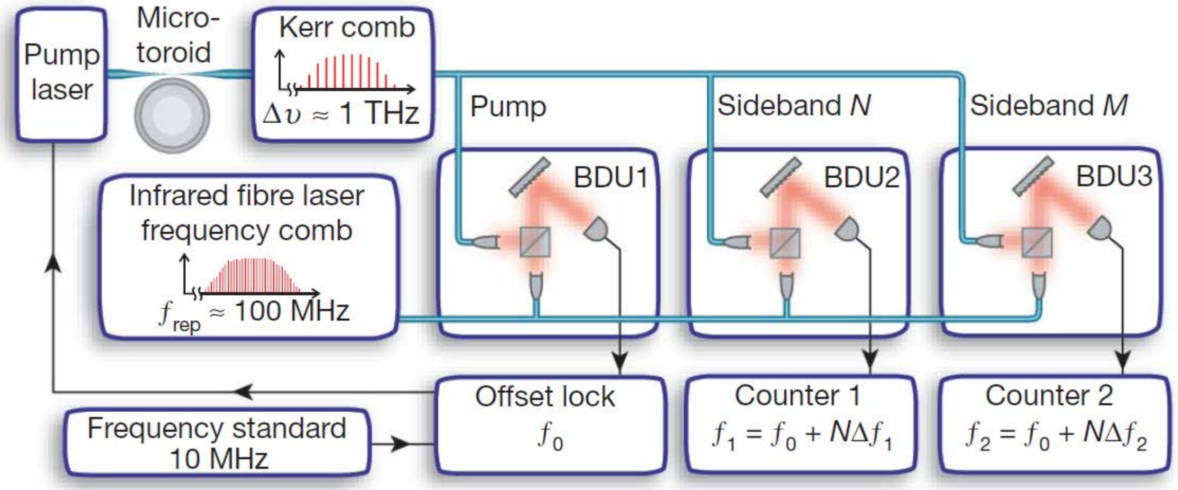
Are the modes locked?



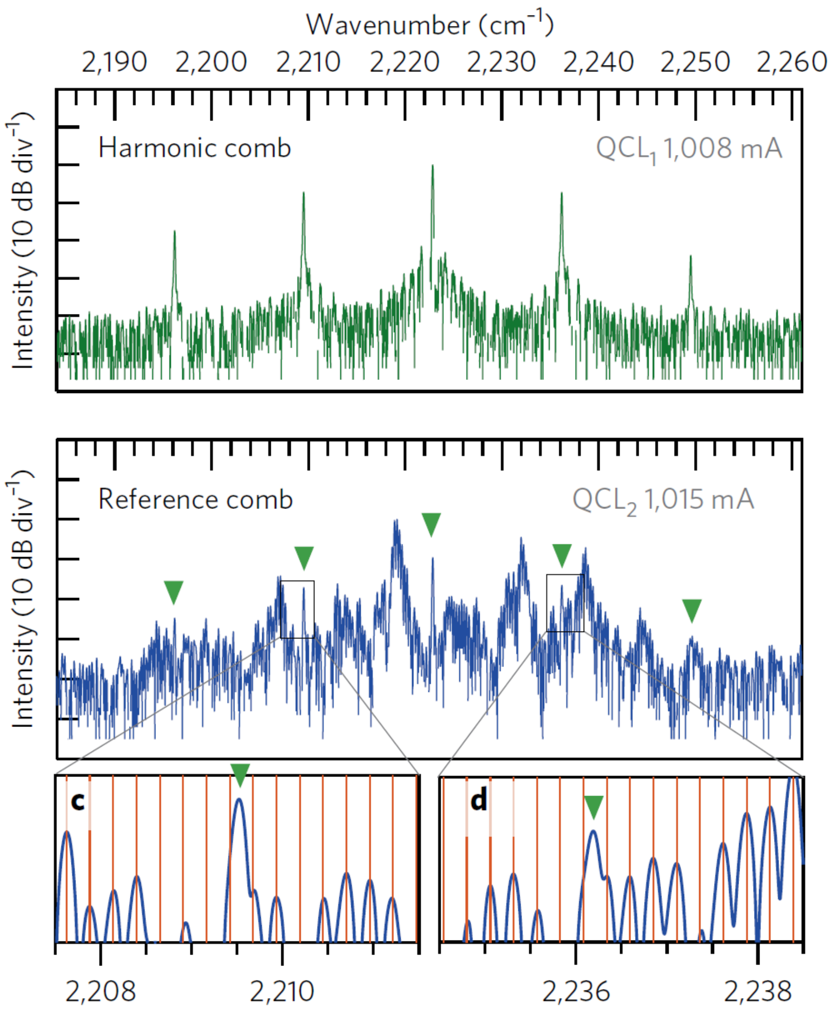
Strategy:

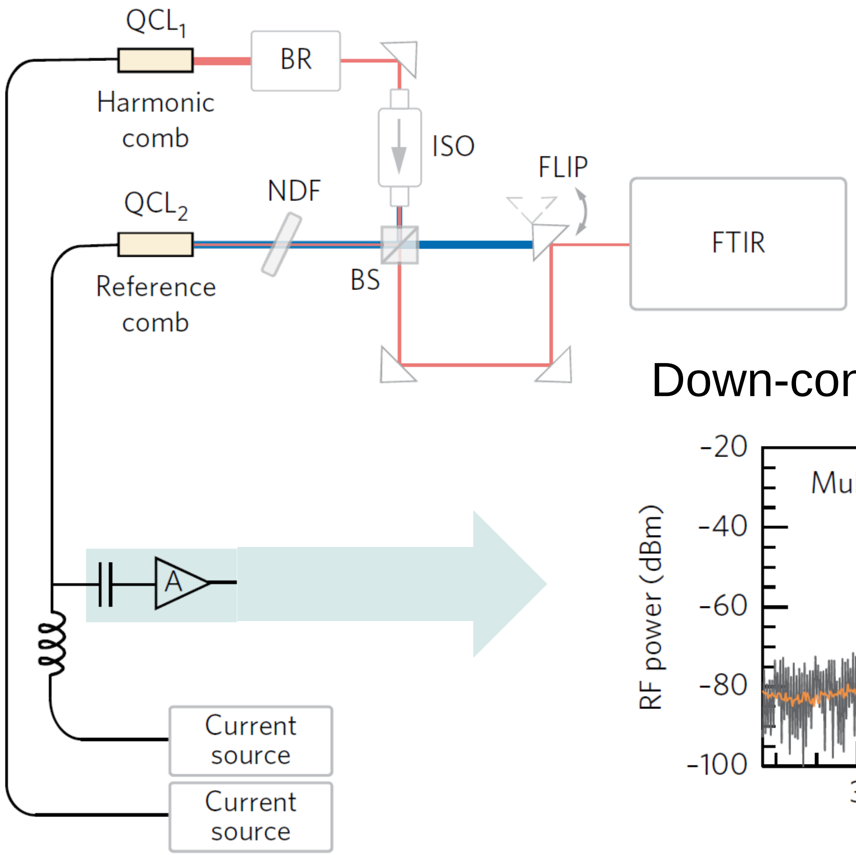
A reference comb can be used to create a down-converted replica of the sample comb



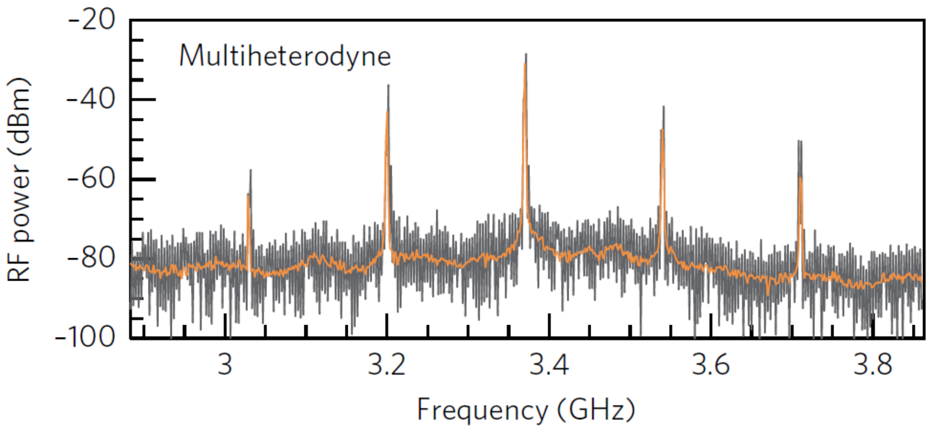


Multi-heterodyne detection

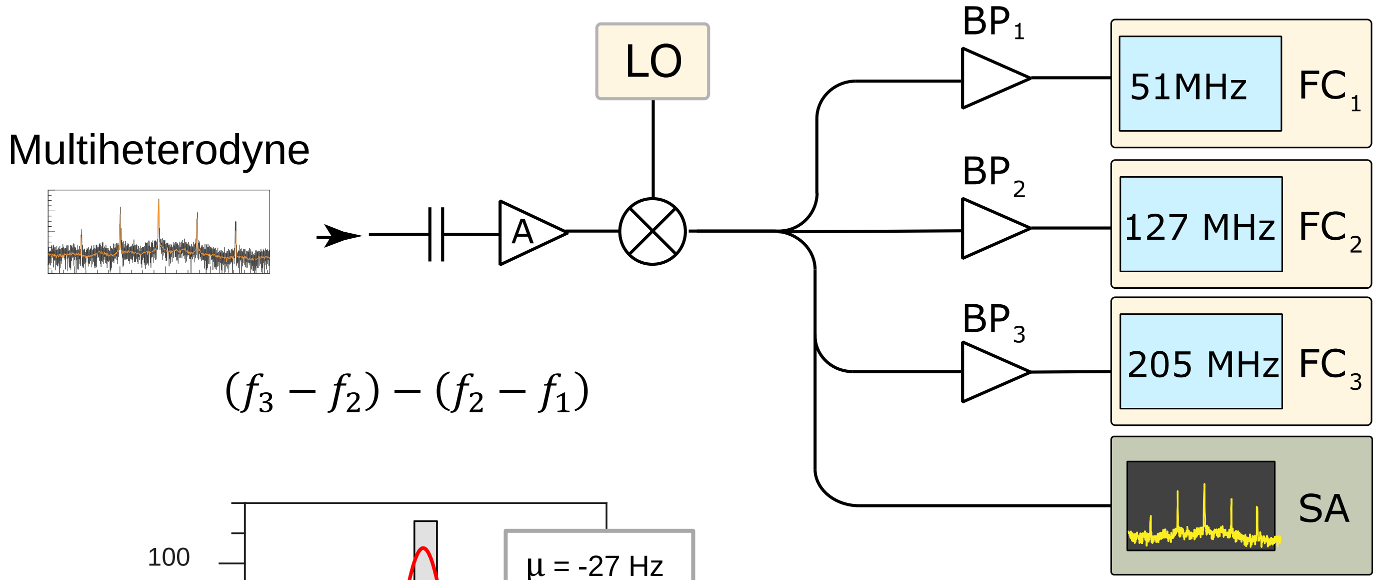




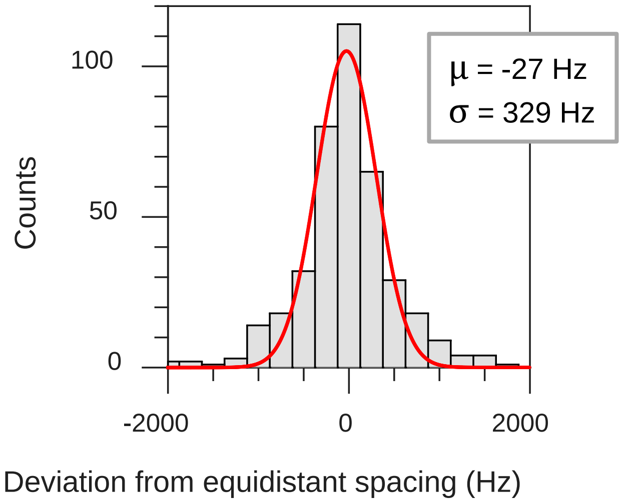
Down-converted replica of the harmonic state

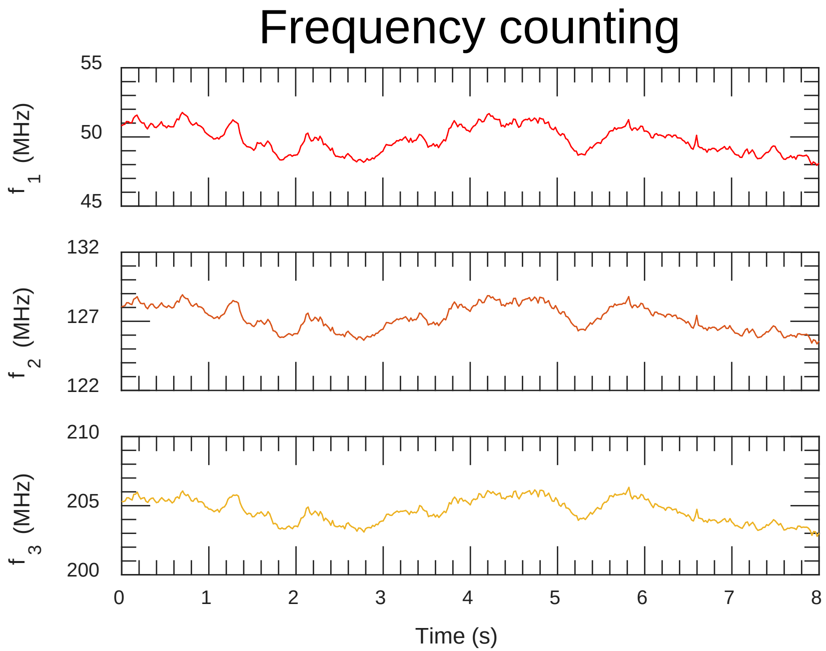


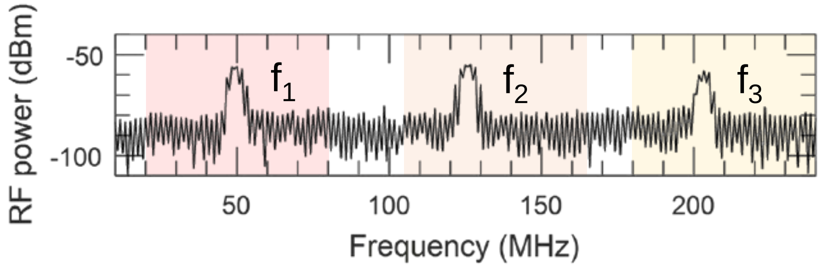
Spacing uniformity of the harmonic comb



$$(f_3 - f_2) - (f_2 - f_1)$$

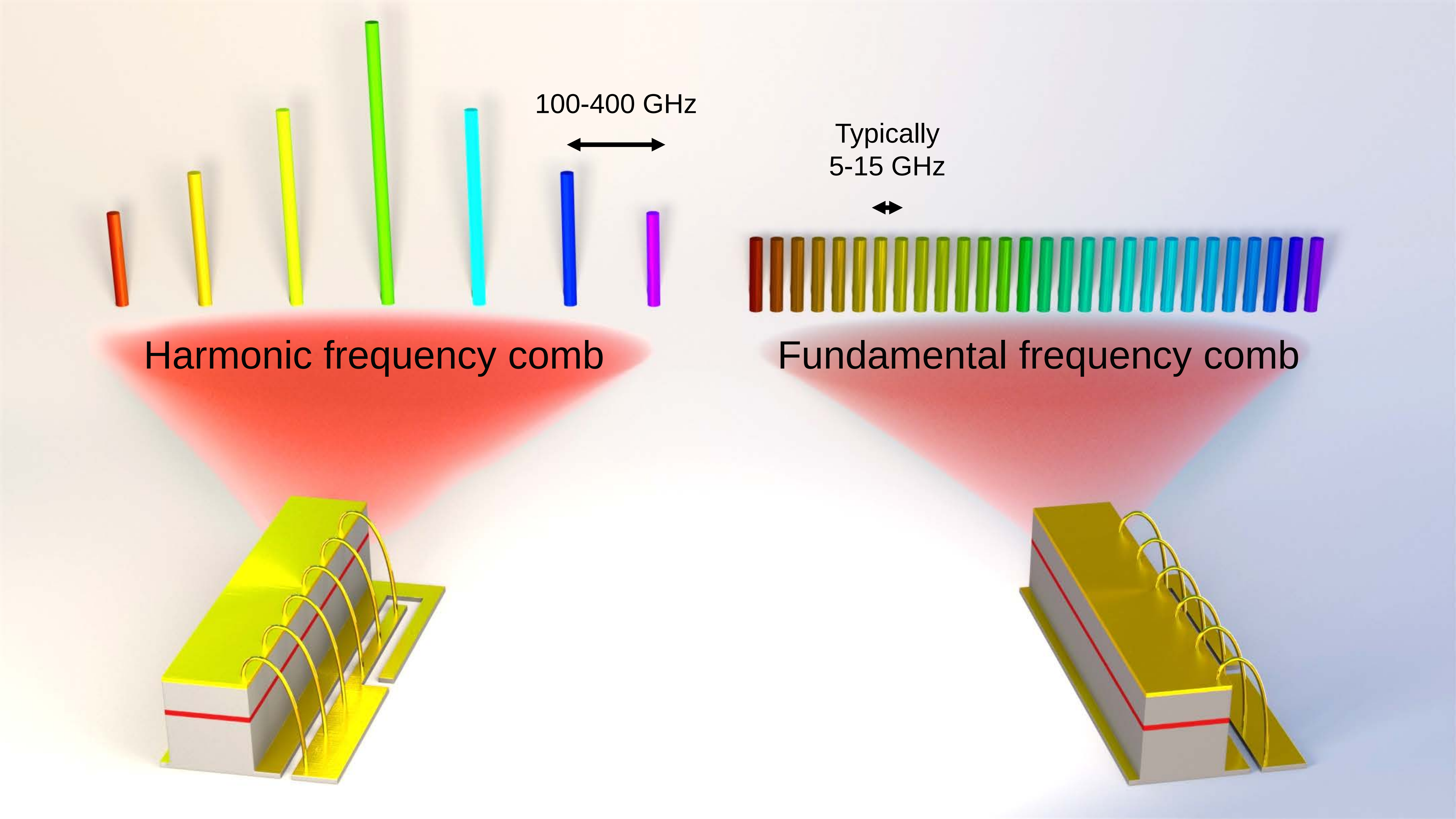


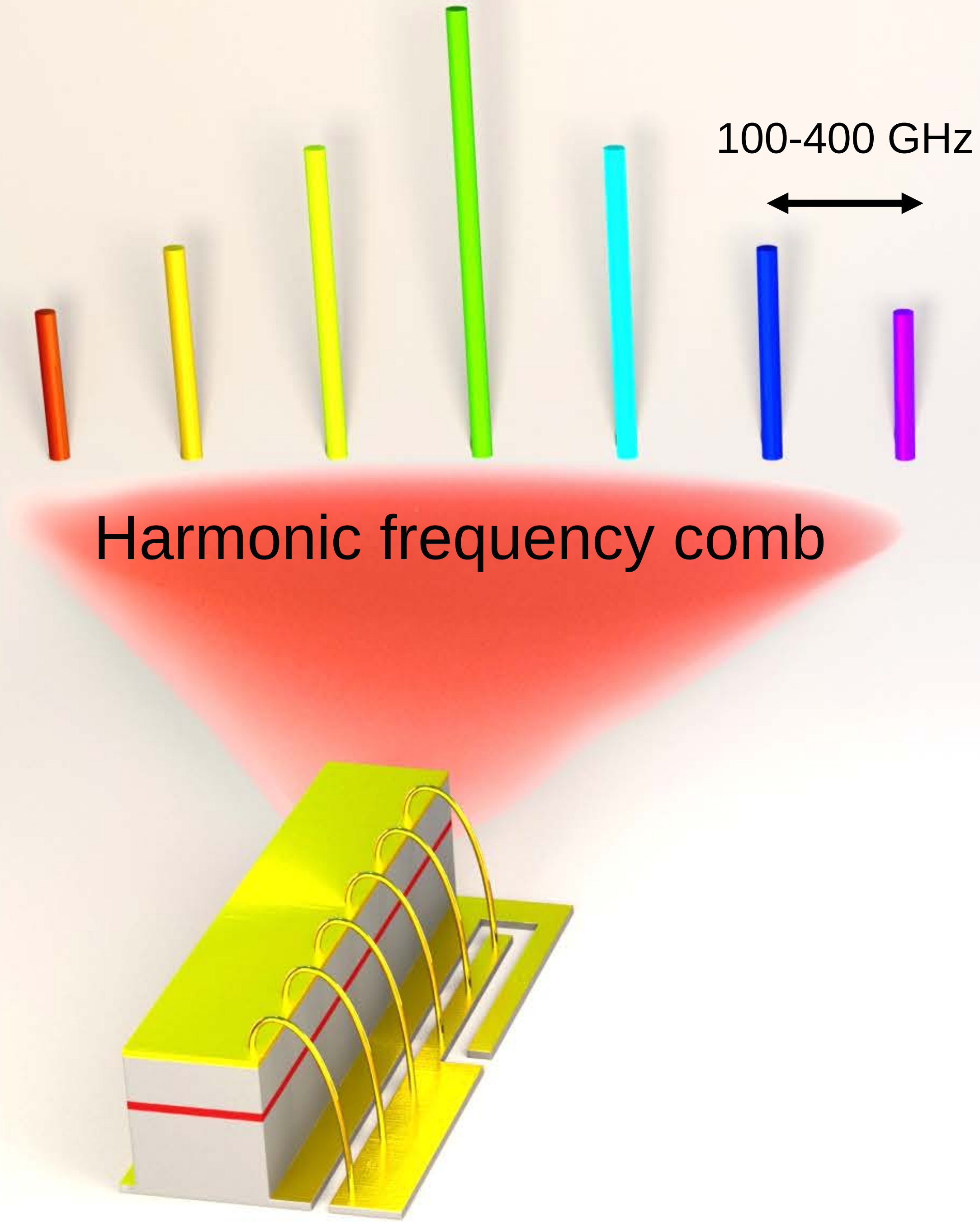




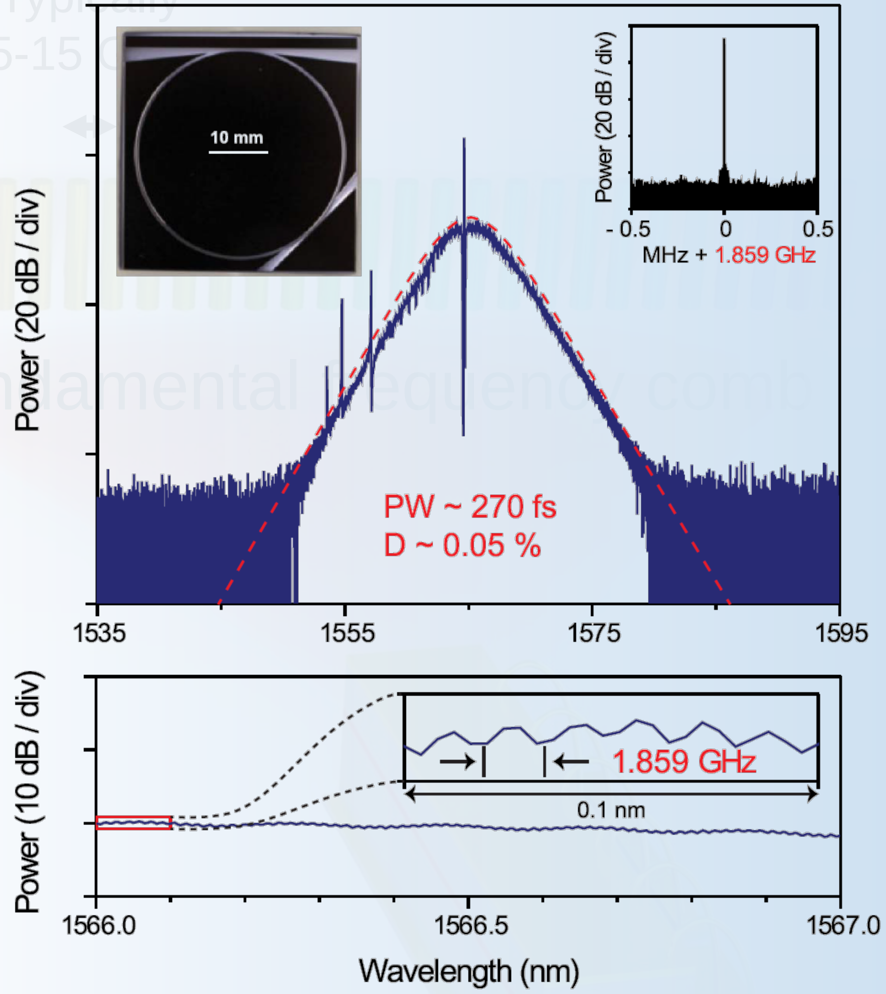
Normalized to the optical carrier frequency (66.7 THz), the spacing uniformity of the harmonic comb is verified with an accuracy of 5×10^{-12}

D. Kazakov, M. Piccardo *et al.*, Nat. Photonics 11, 789–792 (2017)


100-400 GHz
Typically
5-15 GHz
Harmonic frequency comb
Fundamental frequency comb



Gigahertz-repetition-rate microcomb



M-G. Suh and K. Vahala, Optica **5**, 65 (2018)

Outline

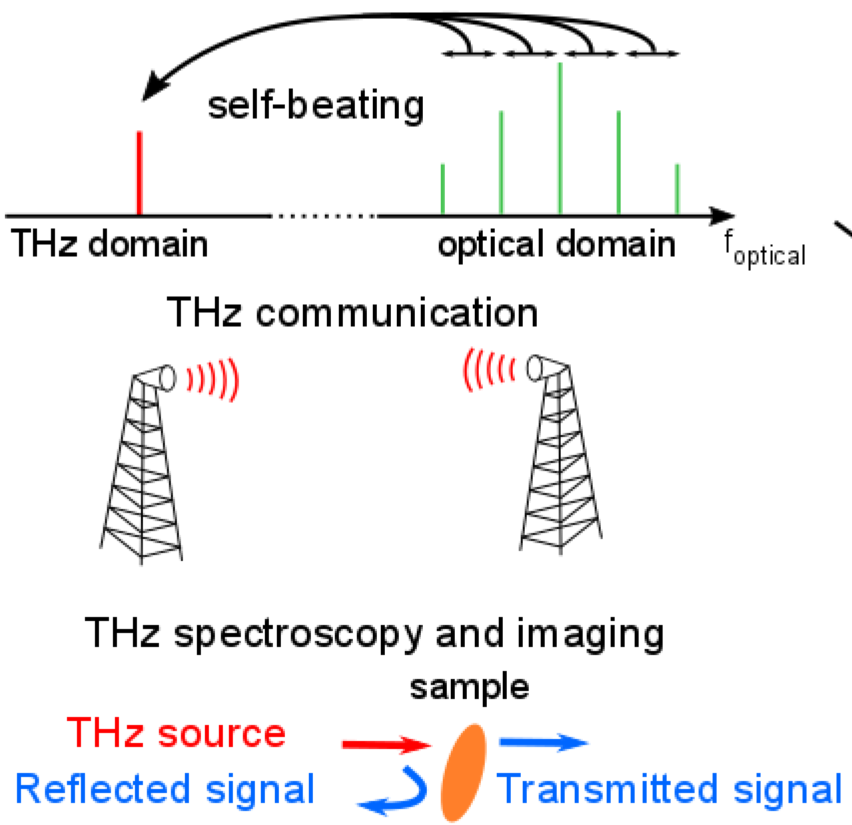
Basic elements: quantum cascade lasers and multimode states

Applications

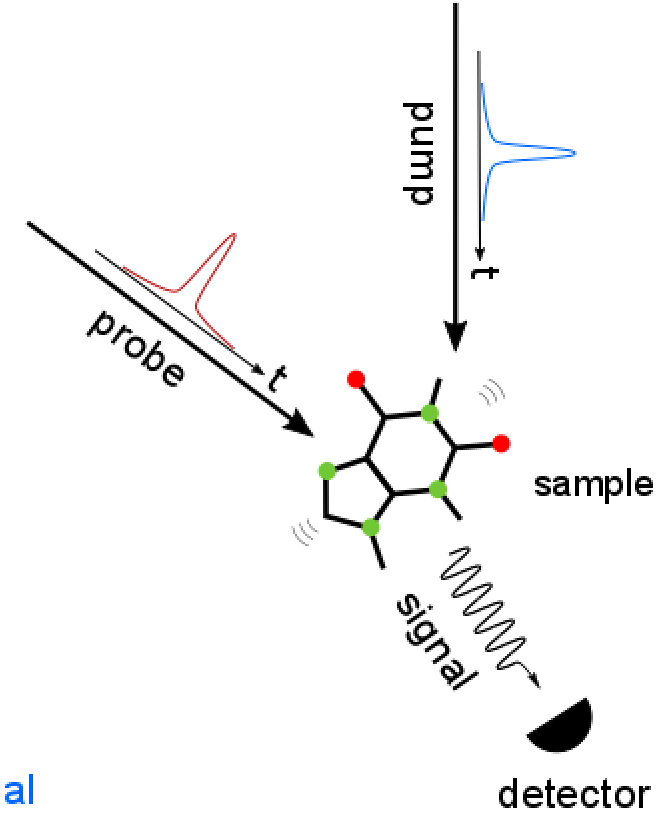
The harmonic state

Prospective applications of the harmonic state

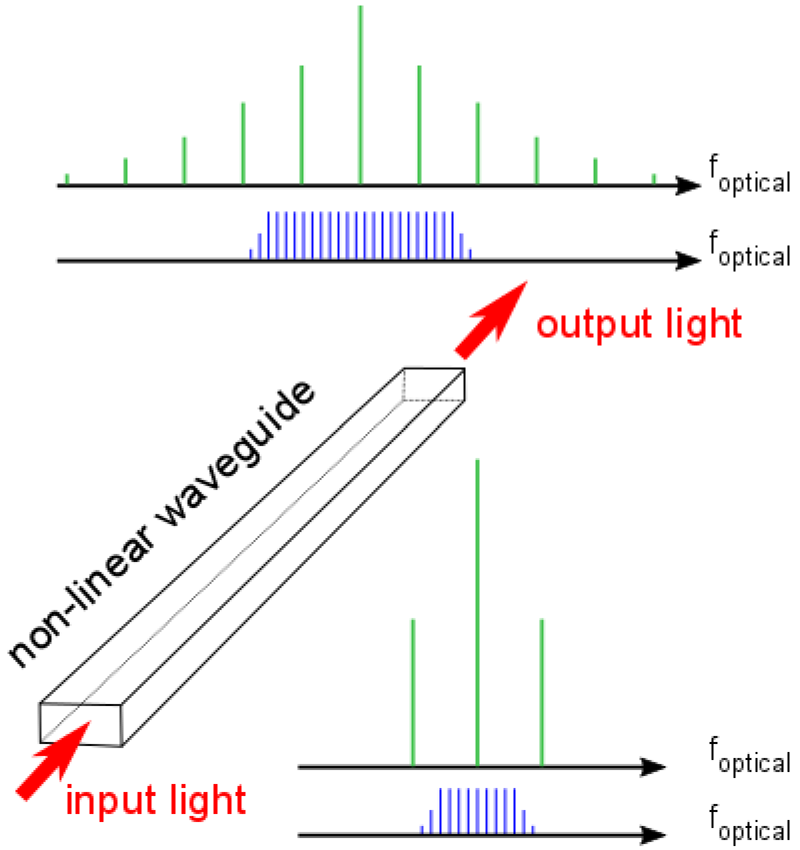
Microwave and THz generation



Pump-probe spectroscopy

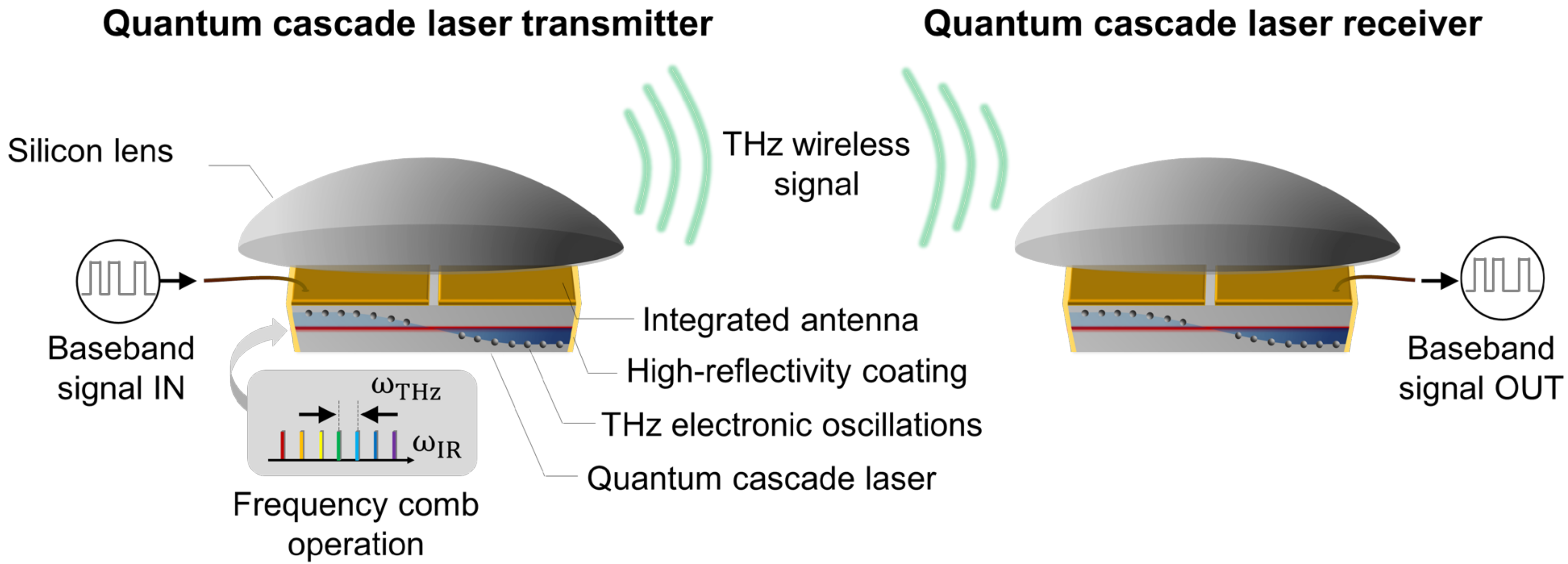


Broadband spectroscopy



M. Piccardo, P. Chevalier *et al*., Opt. Express 26, 9464 (2018)

A new route in QCLs

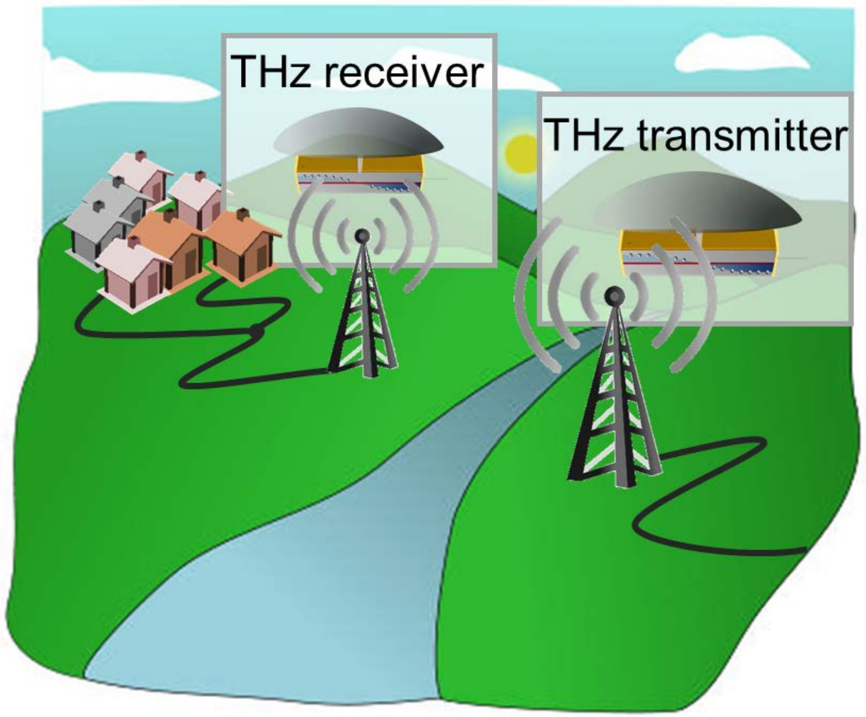


M. Piccardo, D. Kazakov, F. Capasso, Provisional patent submitted (US Patent Application # 62609232)

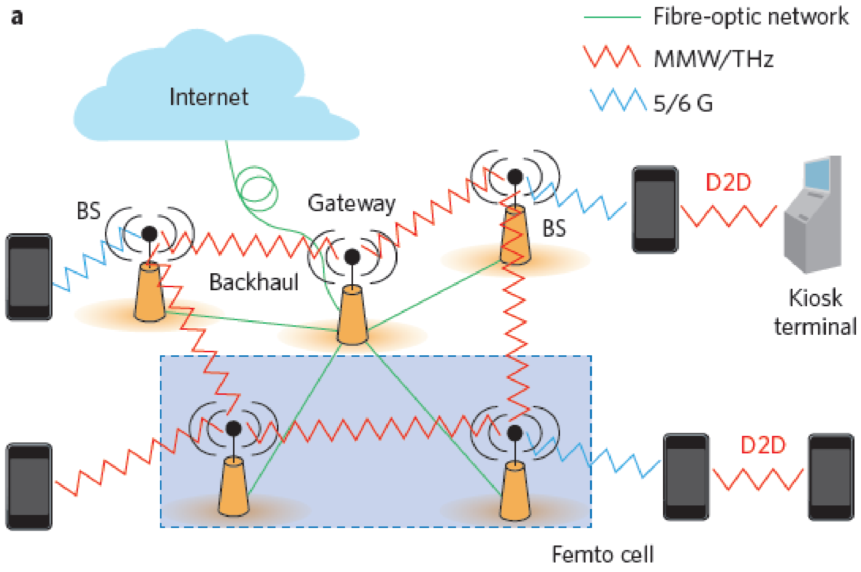
THz wireless communication

THz band: 0.1-10 THz

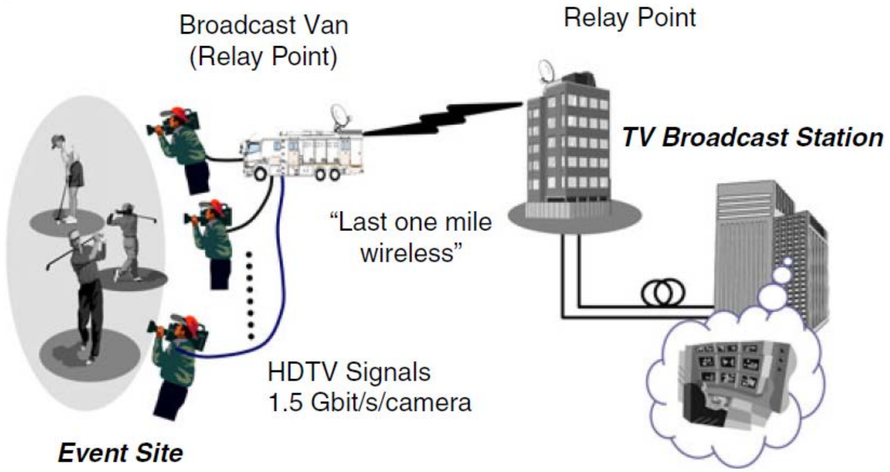
High-speed internet access in remote rural areas



Base station connection, device-to-device communication



Broadcasting of multichannel HDTV data in sport events



S. Koenig *et al*., Nat Photon 7, 977 (2013)
T. Kleine-Ostmann *et al*., J. Infrared Milli Terahz Waves 32, 143 (2011)
T. Nagatsuma *et al*., Nat Photon 10, 371 (2016)

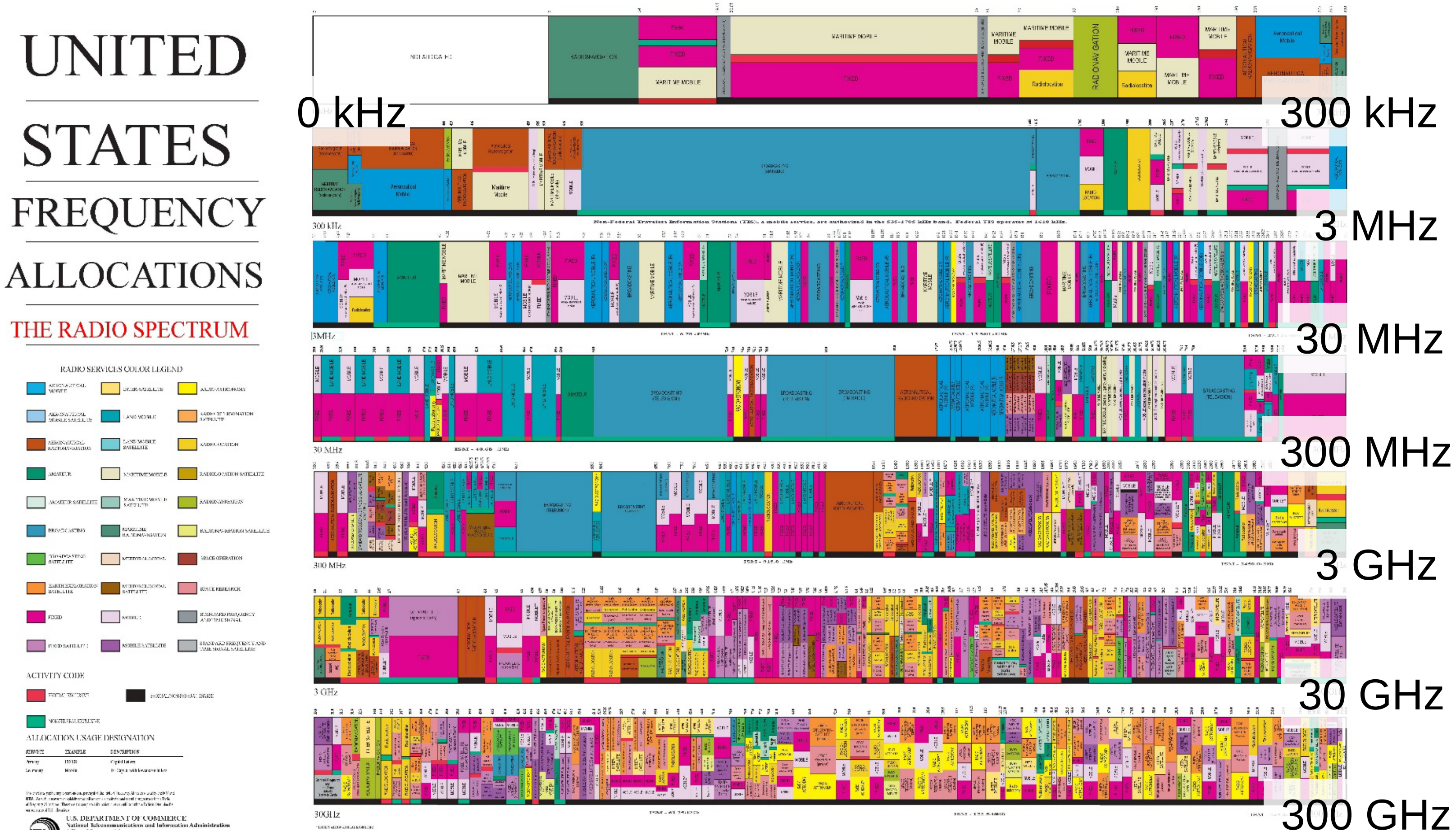
THz wireless communication

Increasing the bandwidth W increases the communication capacity:

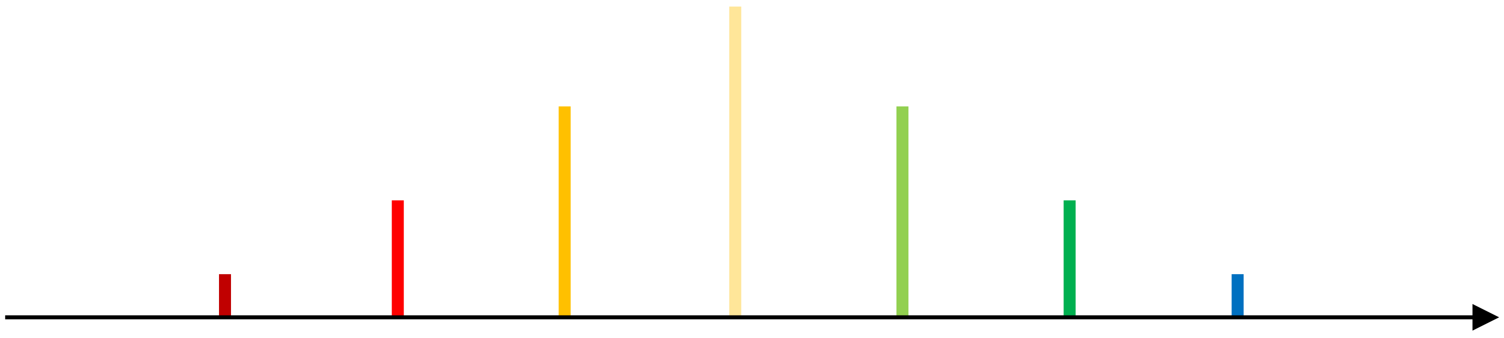
C (bit s^{-1})$=W \log_2(1+S/N)$

THz band: 0.1-10 THz

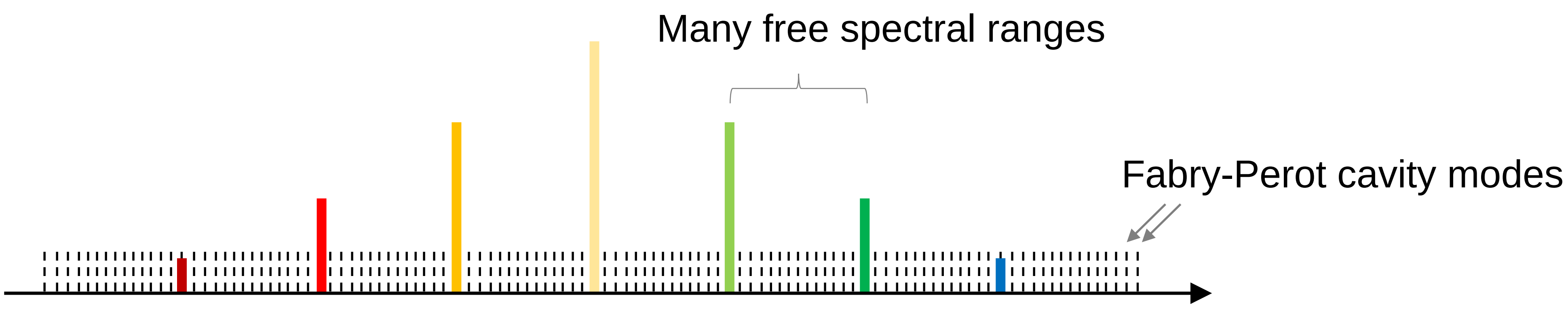
Why THz?



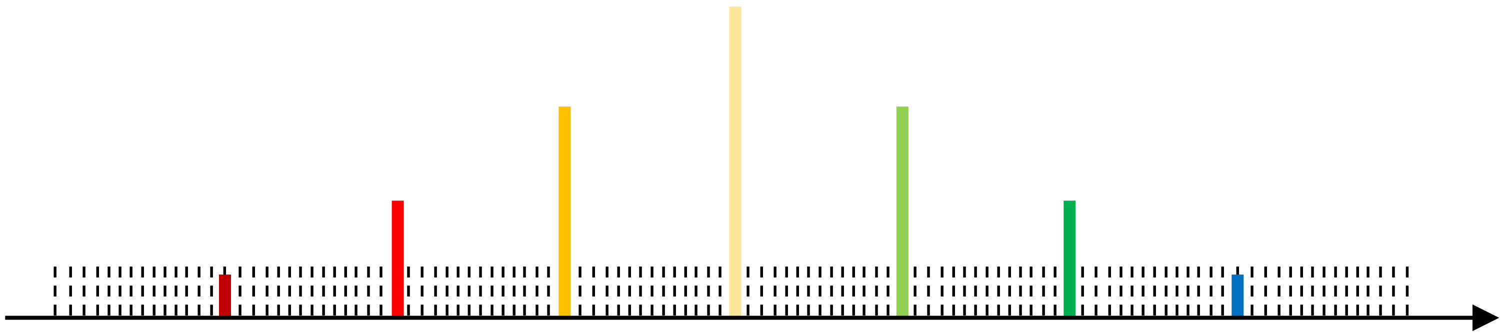
Can we tune the spacing of the harmonic comb?



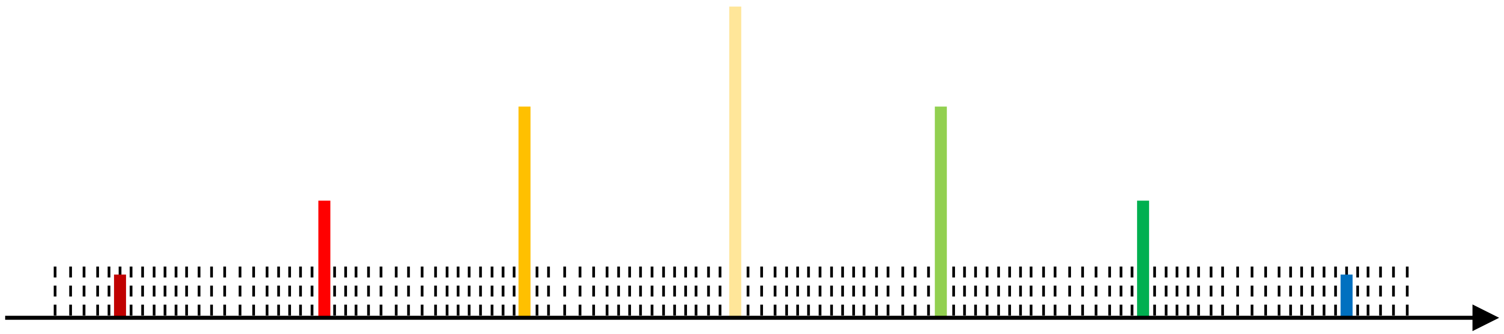
Can we tune the spacing of the harmonic comb?



Can we tune the spacing of the harmonic comb?



Can we tune the spacing of the harmonic comb?



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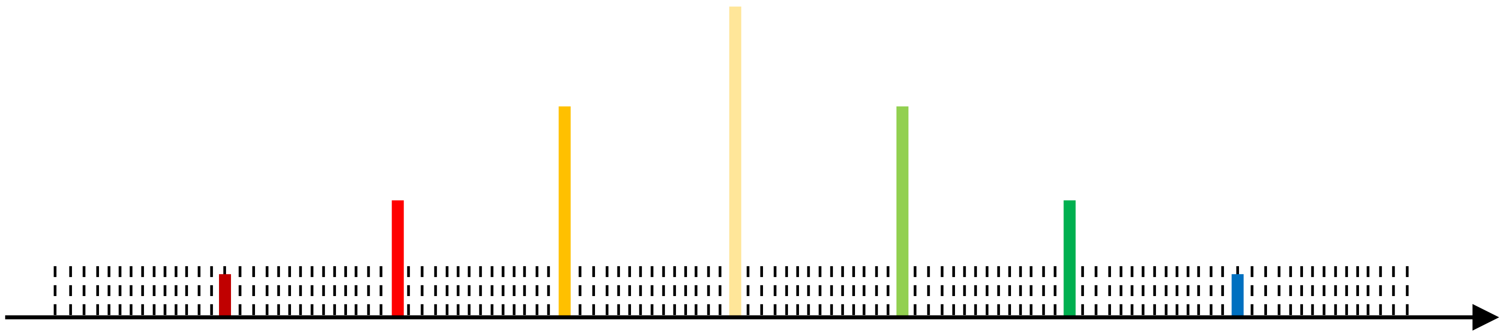

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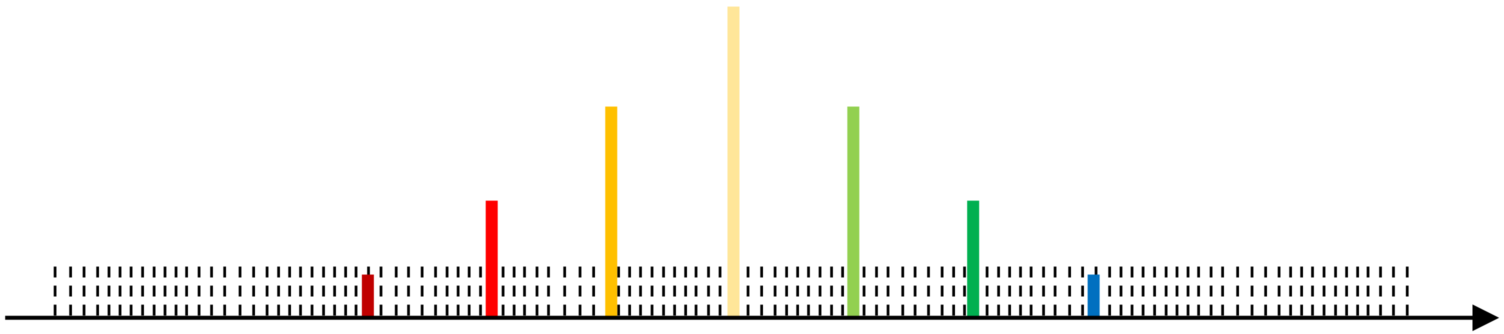
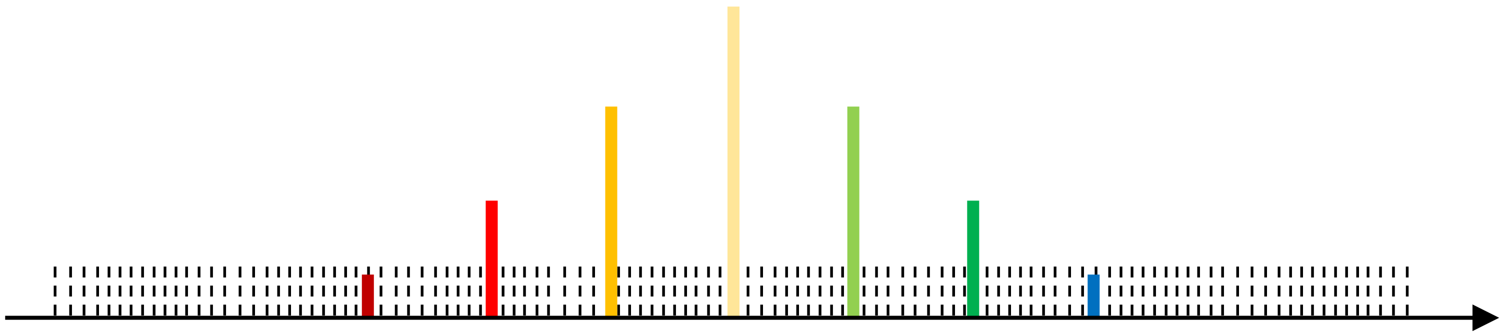


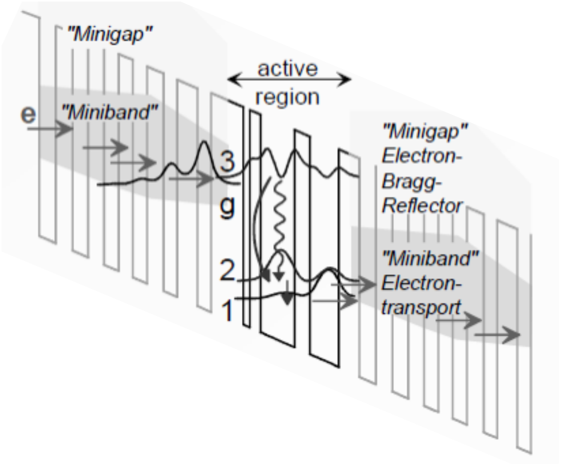
Can we tune the spacing of the harmonic comb?



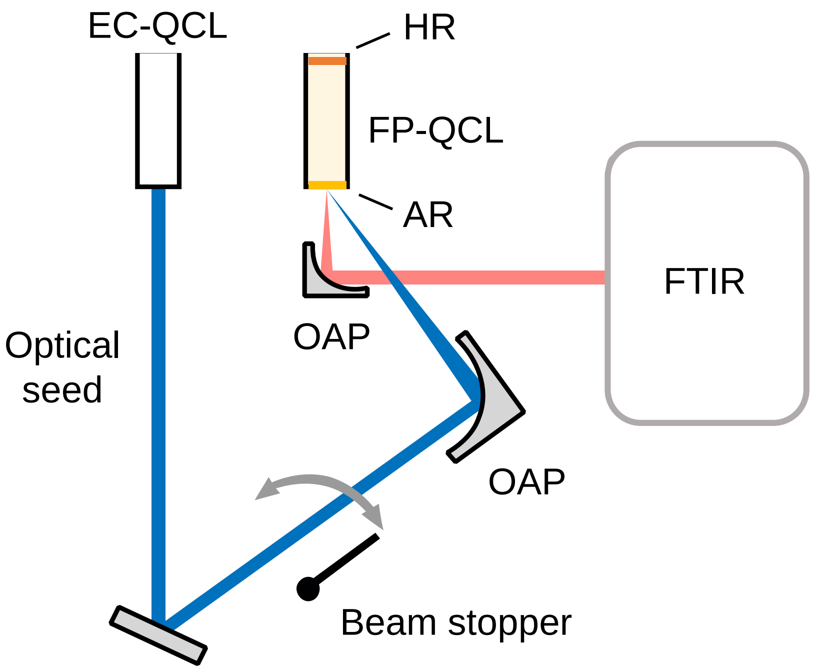
The spacing of *self-starting* harmonic combs is fixed by fundamental laser parameters:

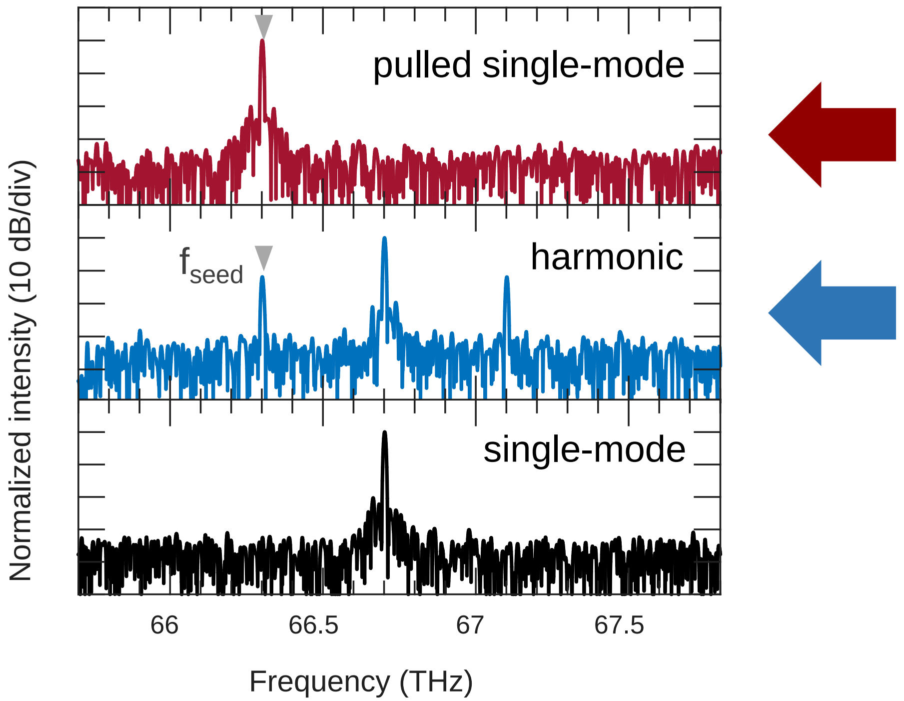
$$\delta\omega^2 = \frac{d|E_0|}{\hbar}\frac{1}{\sqrt{T_2 T_g}} - \frac{1}{T_g^2}$$

- dipole moment
- grating lifetime
- dephasing time



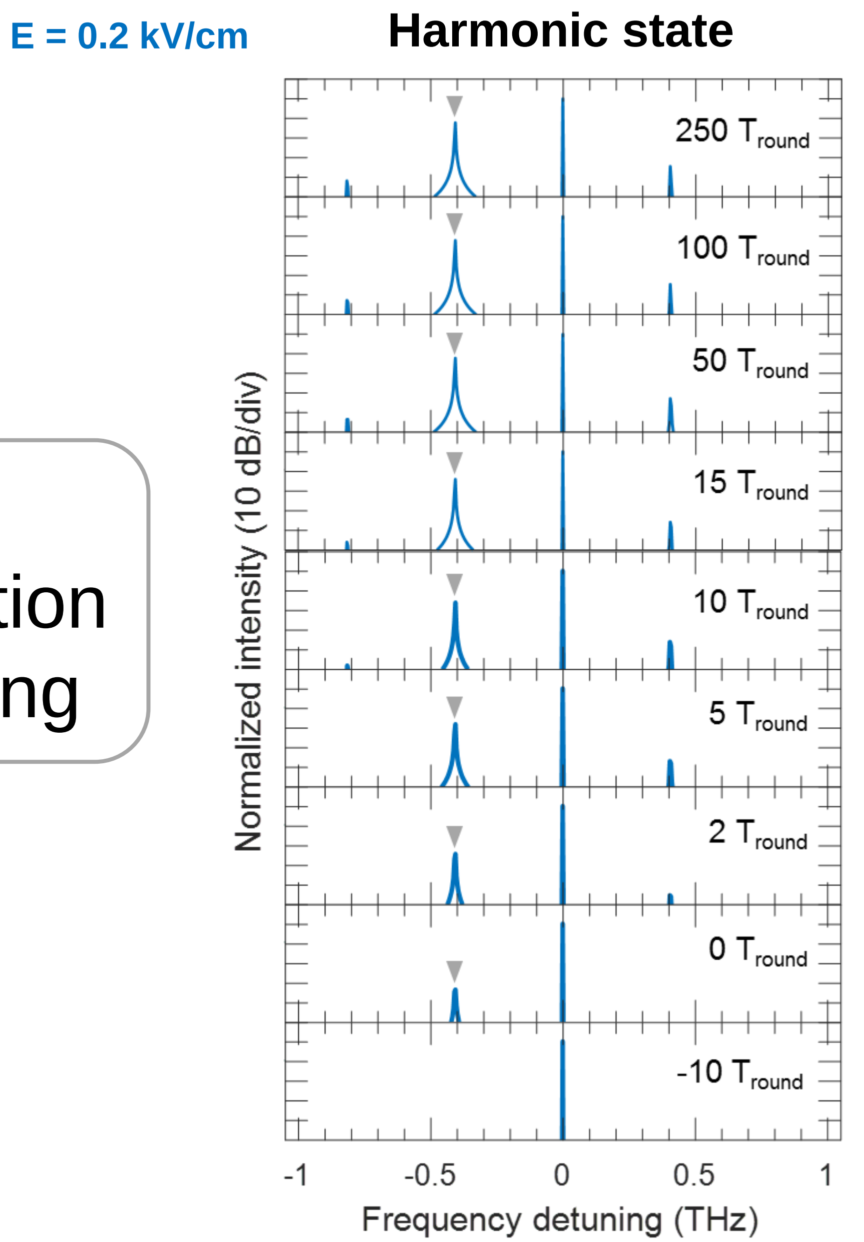
Introducing an optical seed in the cavity

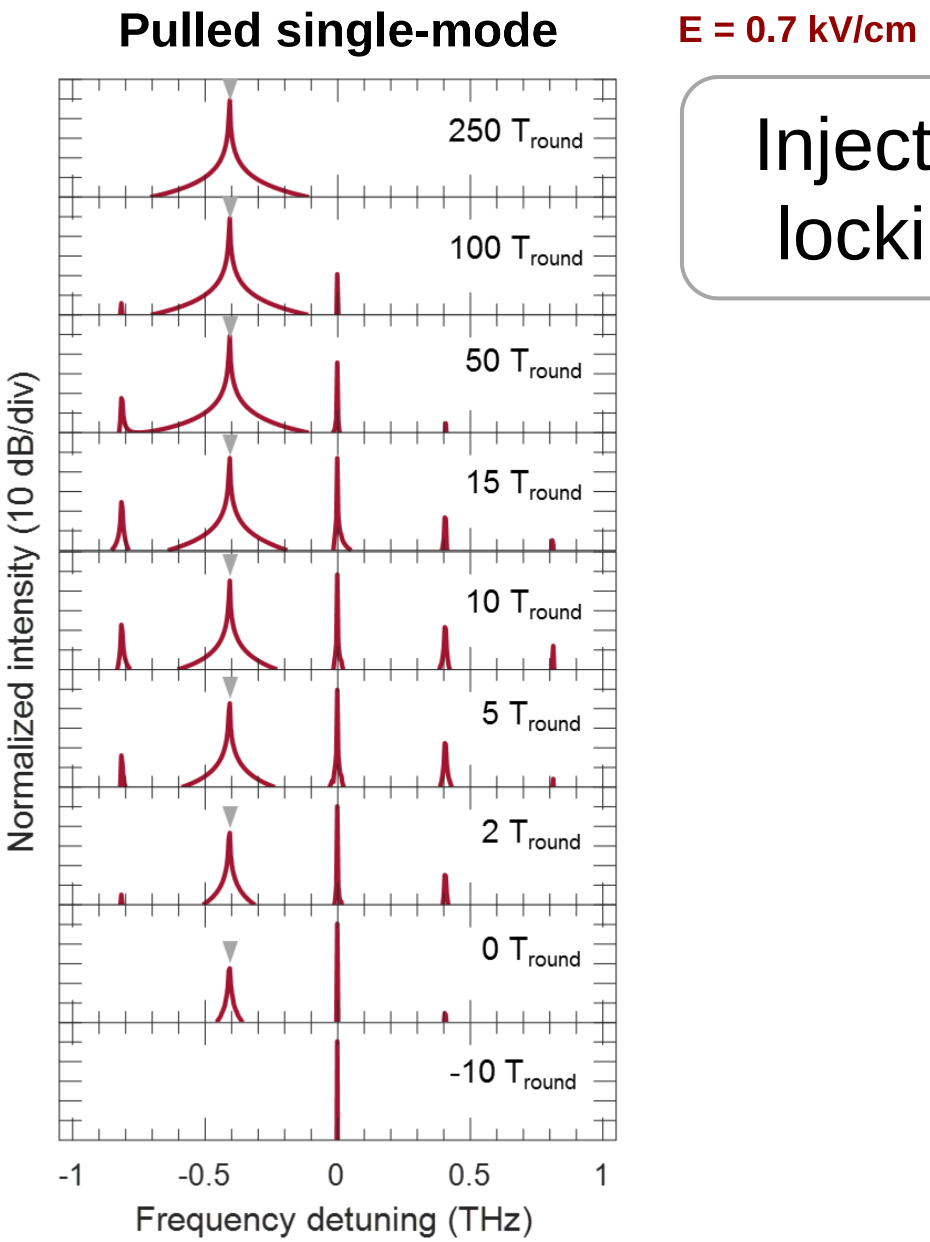




Two different scenarios

P. Chevalier *et al*., Appl. Phys. Lett. 112, 061109 (2018)

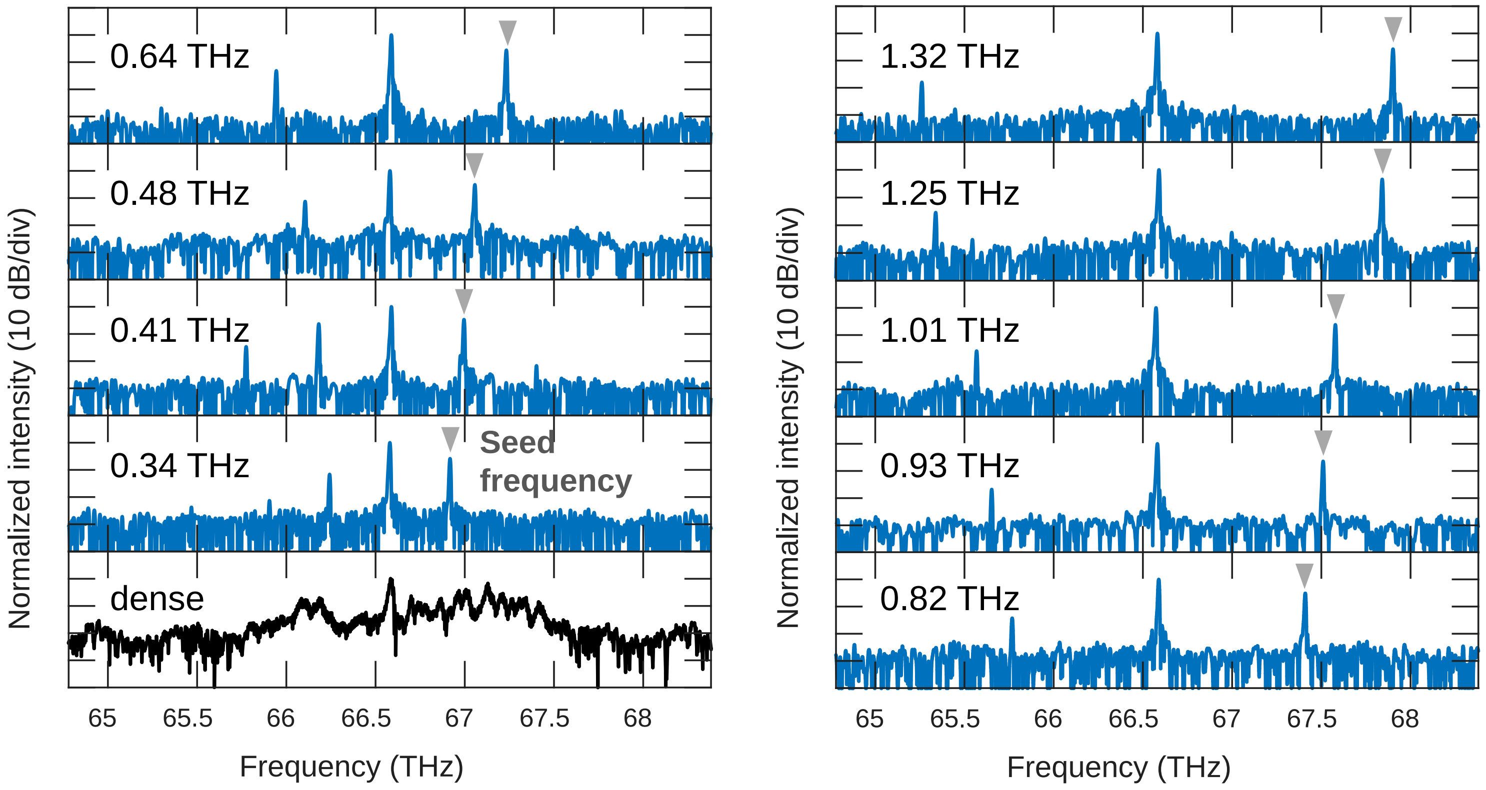


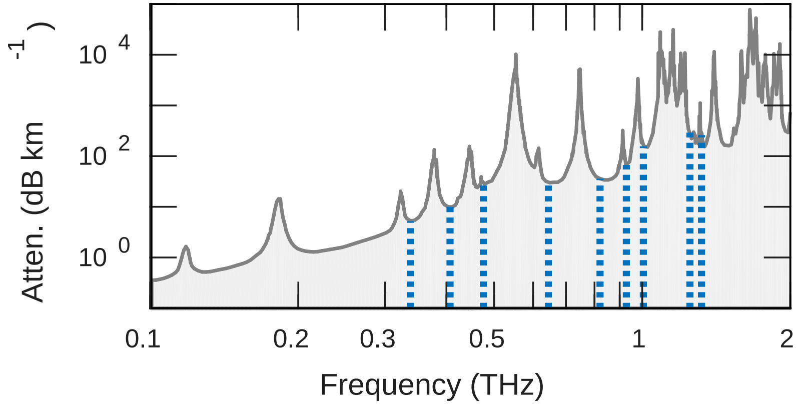


Injection locking

Seed amplification and mixing

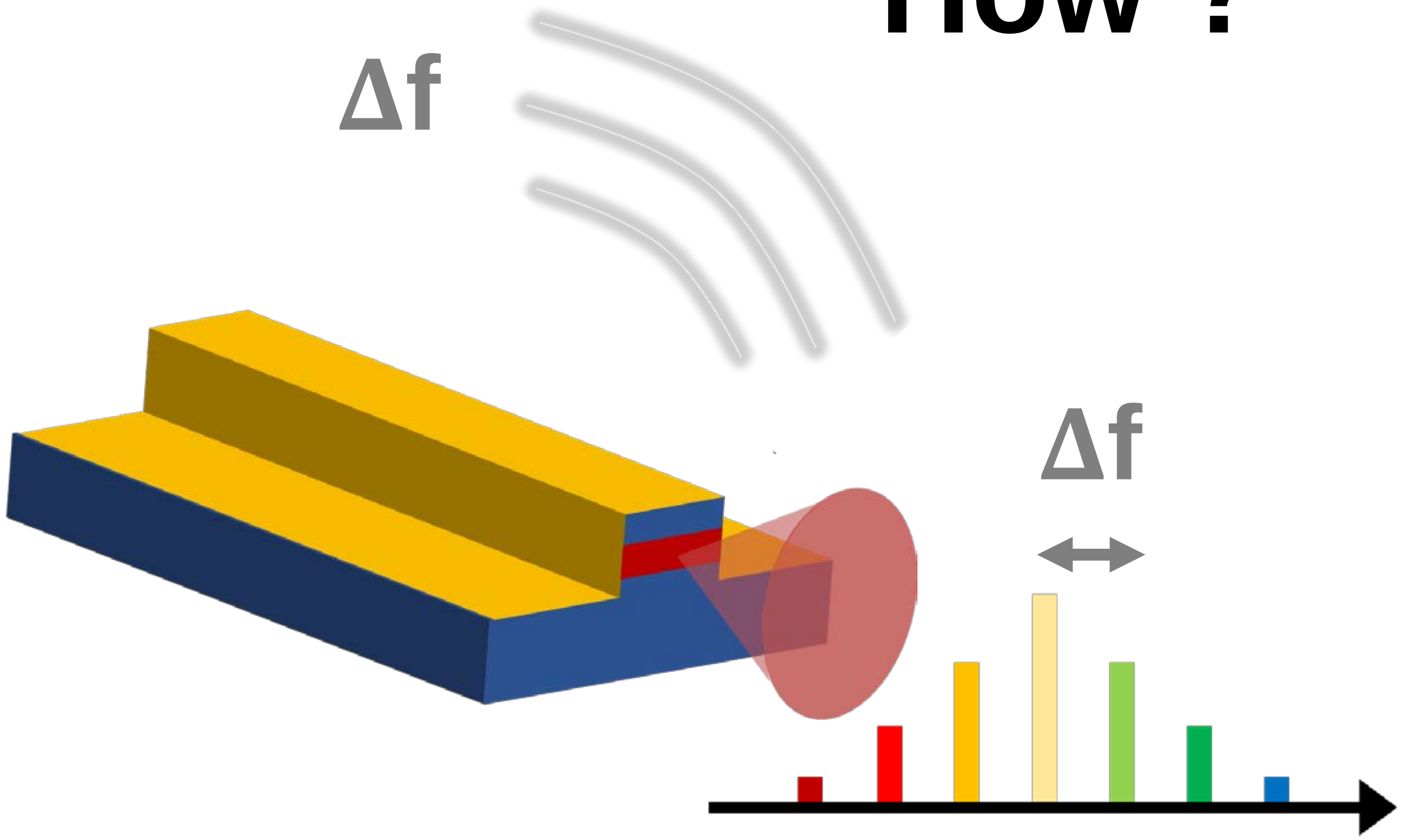
One seed to rule them all





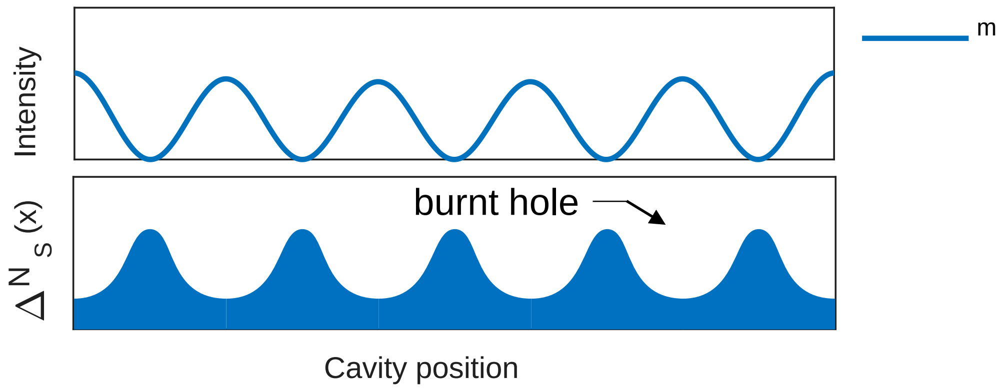
This corresponds to skipping between 44 and 171 longitudinal modes

How ?



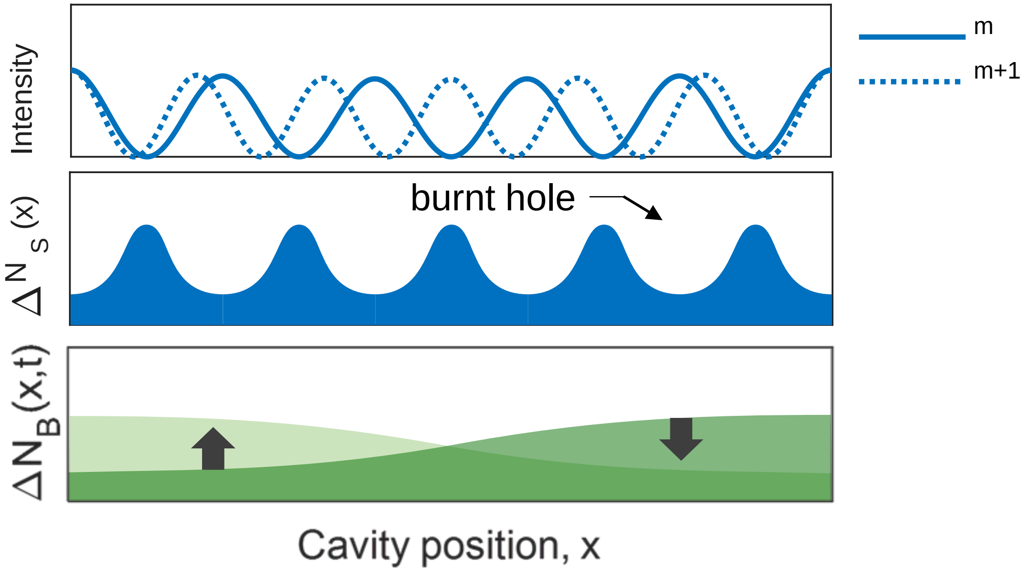
Back to basics

The first lasing mode in a standing-wave laser induces a *static* population grating:



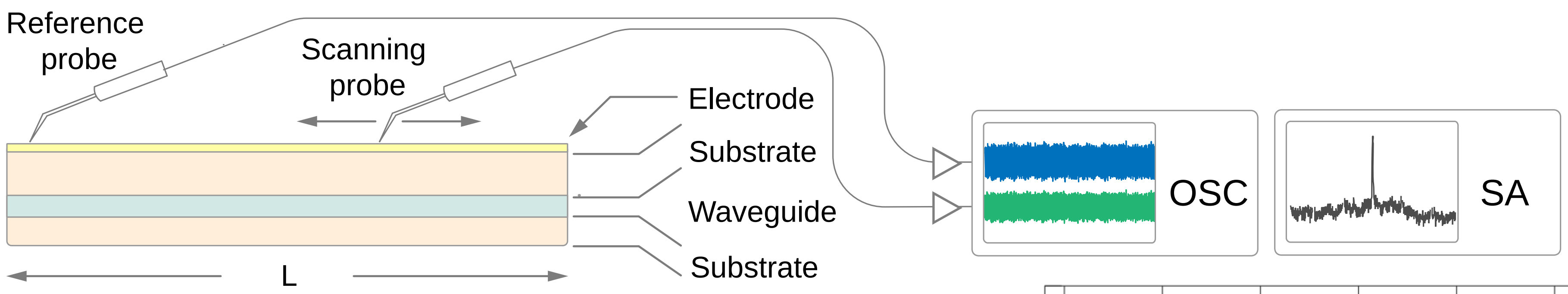
Back to basics

Adjacent cavity modes will be able to extract gain from the medium and start lasing:

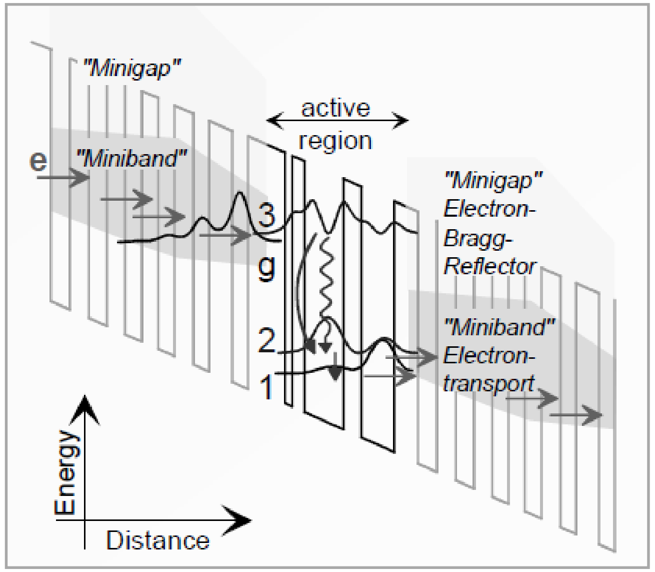


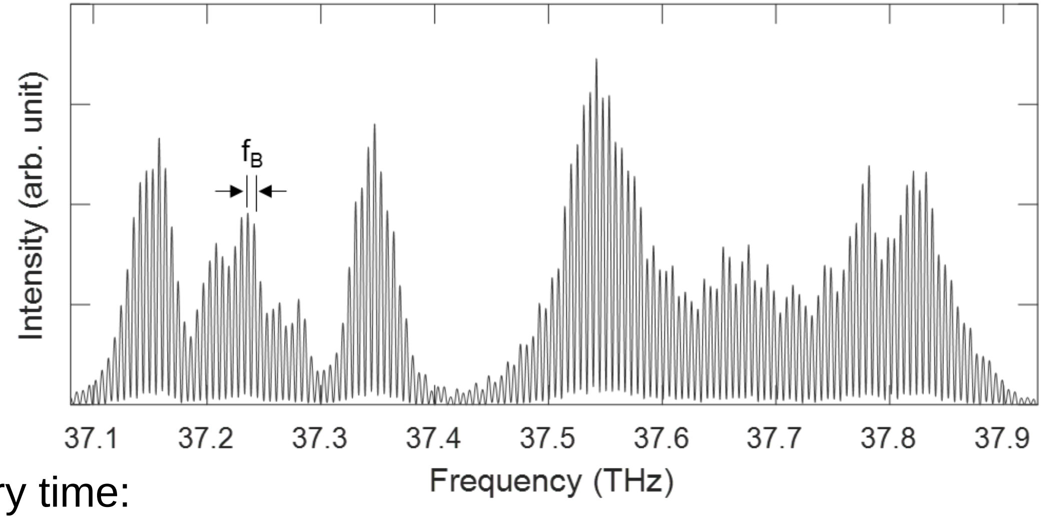
A time-dependent population inversion grating oscillating at the beat frequency is then produced

Probing dynamic population gratings in a QCL



Quantum cascade laser: the ideal platform





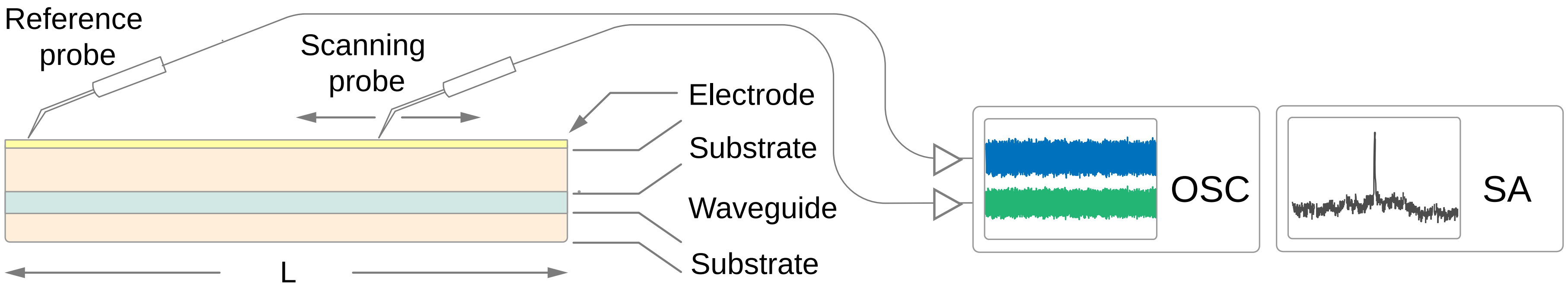
Short picosecond gain recovery time:

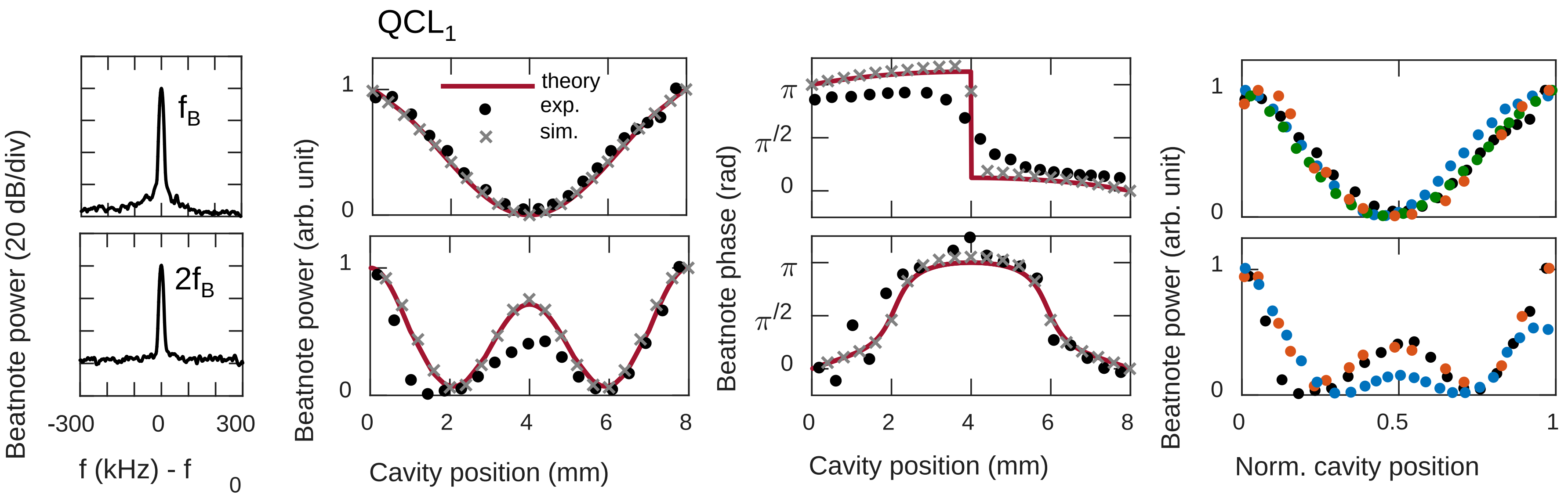
- High-frequency (THz) oscillations of the pop. inv. are allowed
- Excited carriers diffuse within sub-wavelength distances (few 100 nm)

SHB is not washed out

M. Piccardo et al., Optica 5, 475 (2018)

Probing dynamic population gratings in a QCL



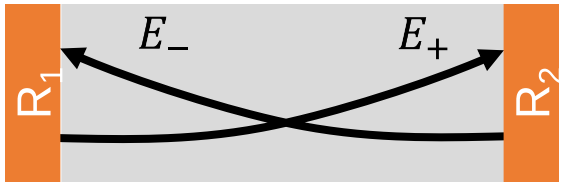


	λ (µm)	L (mm)
● QCL_1	8.0	8
● QCL_2	8.0	8
● QCL_3	7.6	3
● QCL_4	3.8	6

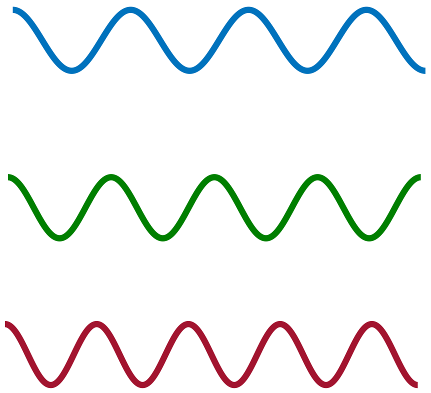
M. Piccardo et al., Optica 5, 475 (2018)

Analytical model of the dynamic gratings

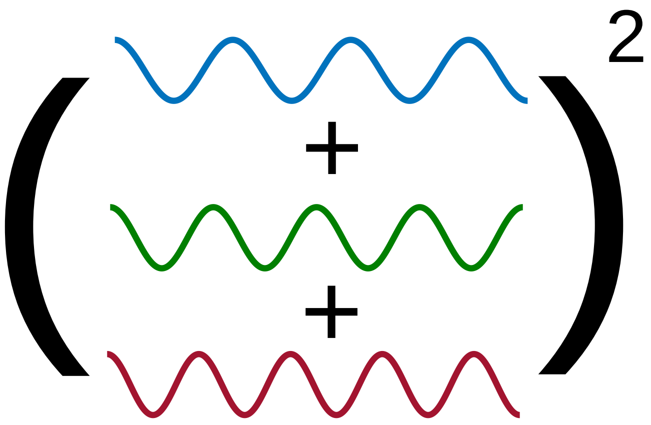
Ingredients:



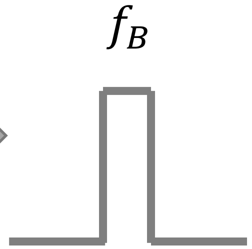
Counter propagating waves



Cavity modes



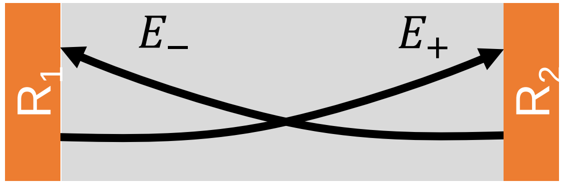
Total field intensity



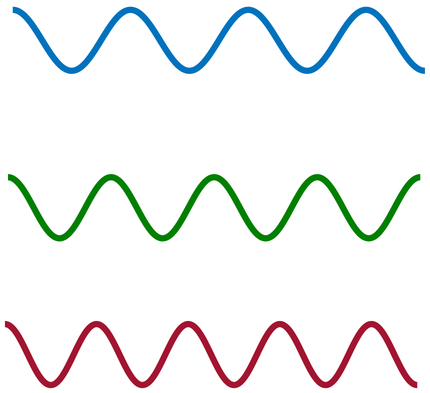
Filter beatnote (Fourier series)

Analytical model of the dynamic gratings

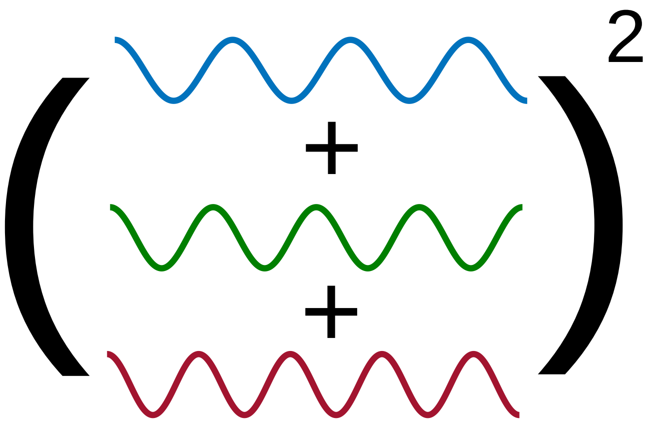
Ingredients:



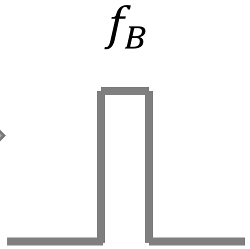
Counter propagating waves



Cavity modes



Total field intensity



Filter beatnote (Fourier series)

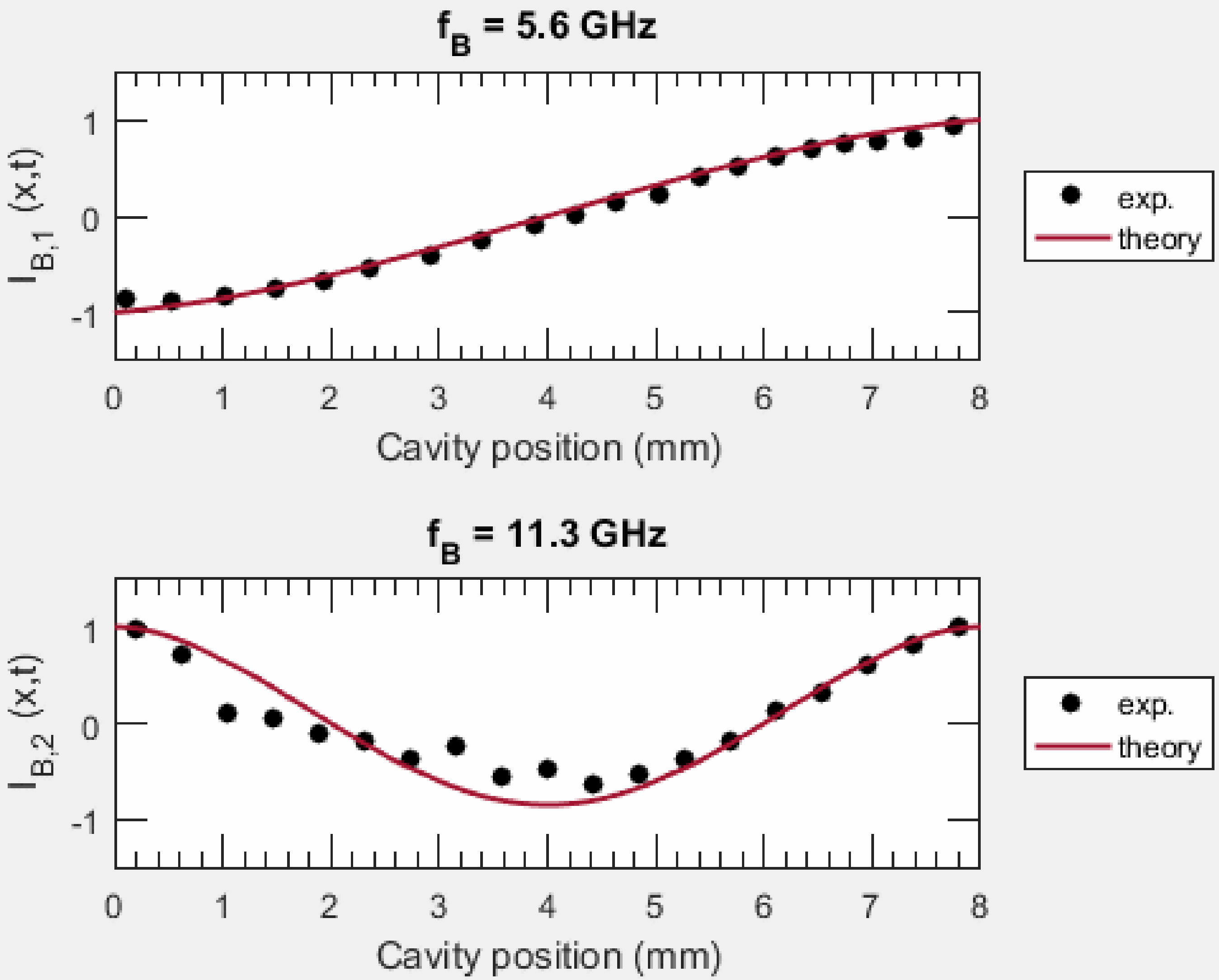
$$I_{B,n}(x,t) = \sum_{m=1}^{N-n} A_m A_{m+n} \Big\{ \cos\left[nk_B x + n\omega_B t + \Delta\phi_{m+n,m}\right] e^{-gx}$$

$$+ 2\sqrt{R_1}\cos\left[(k_{m+n} + k_m)\,x\right]\cos\left[n\omega_B t + \phi_{m+n} + \phi_m\right]$$

$$+ R_1 \cos\left[nk_B x - n\omega_B t - \Delta\phi_{m+n,m}\right] e^{gx} \Big\}$$

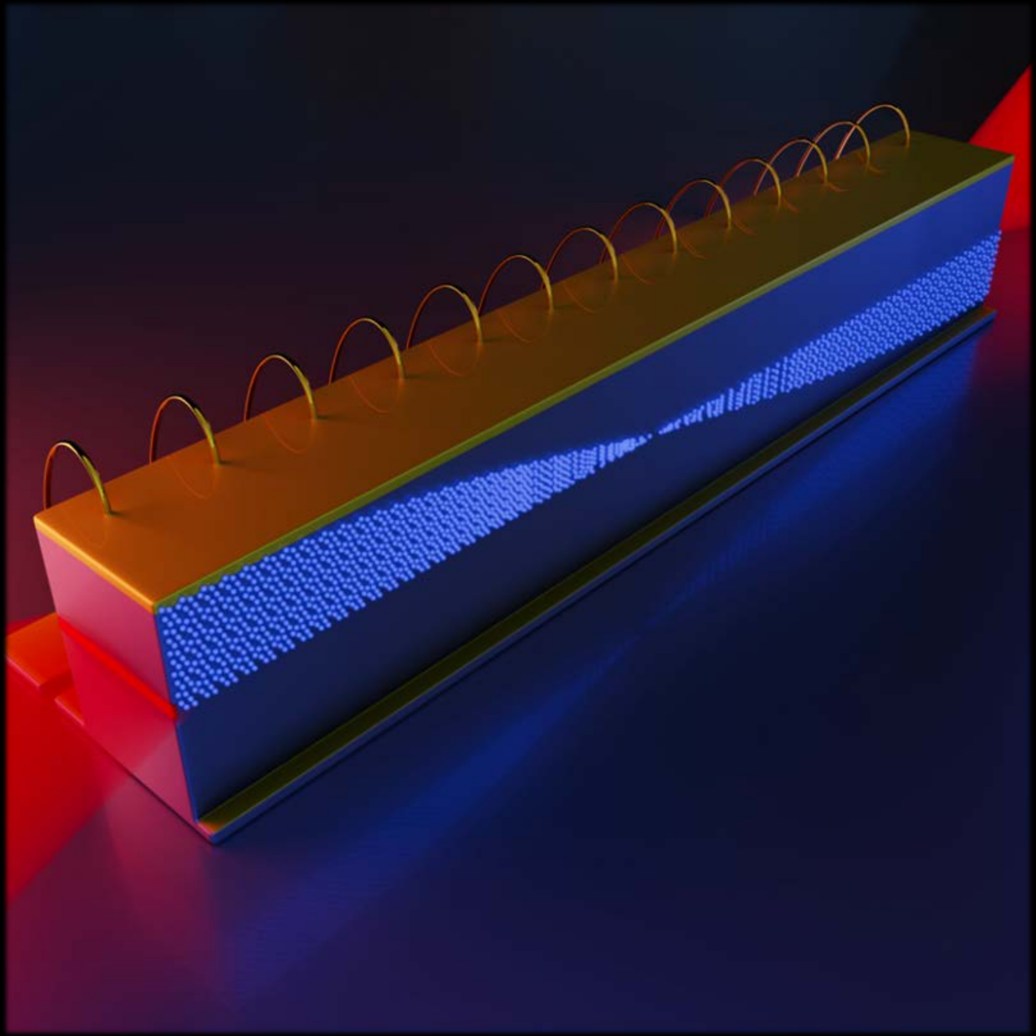
This term is filtered out in the experiments: spatial oscillations of few microns << RF probe size

M. Piccardo et al., Optica 5, 475 (2018)



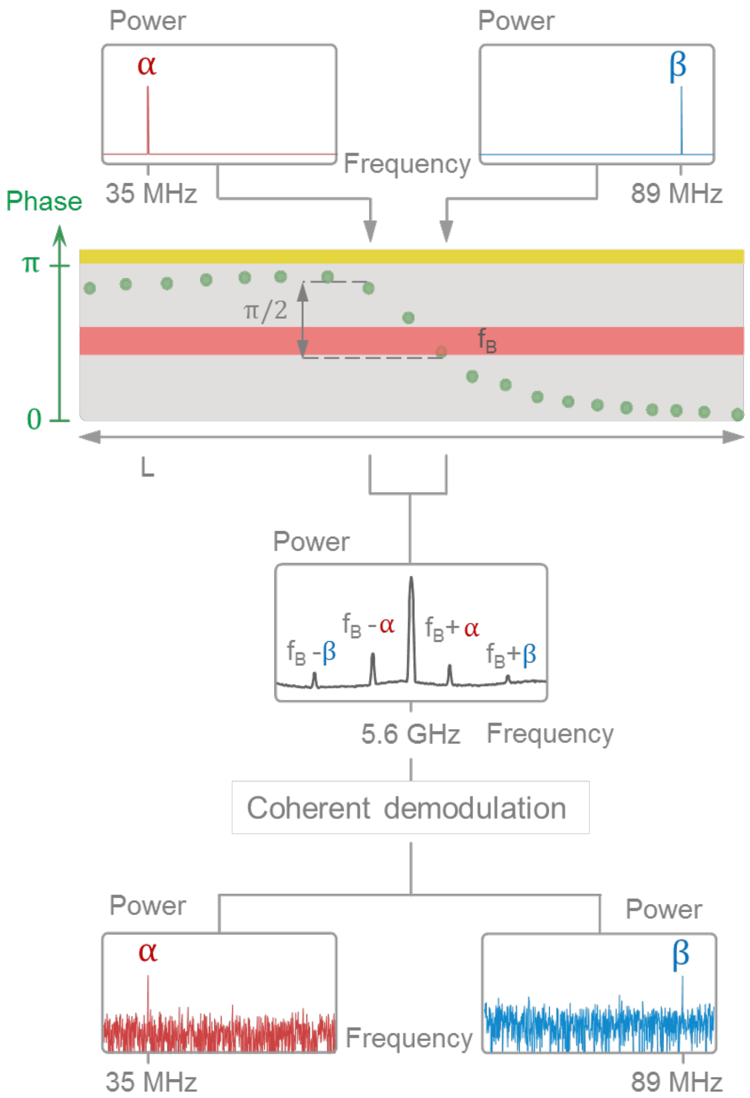
M. Piccardo et al., Optica 5, 475 (2018)

In a device operating at optical frequencies new microwave applications are enabled



M. Piccardo et al., Optica 5, 475 (2018)

The QCL as a microwave quadrature modulator

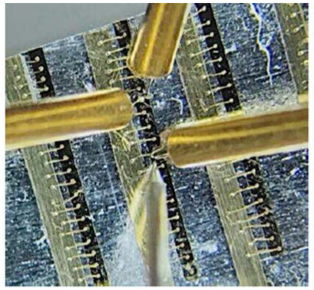


Injection of two microwave signals

Modulation of coherent QCL beatnotes dephased by 90°

Extraction of the modulated orthogonal signals

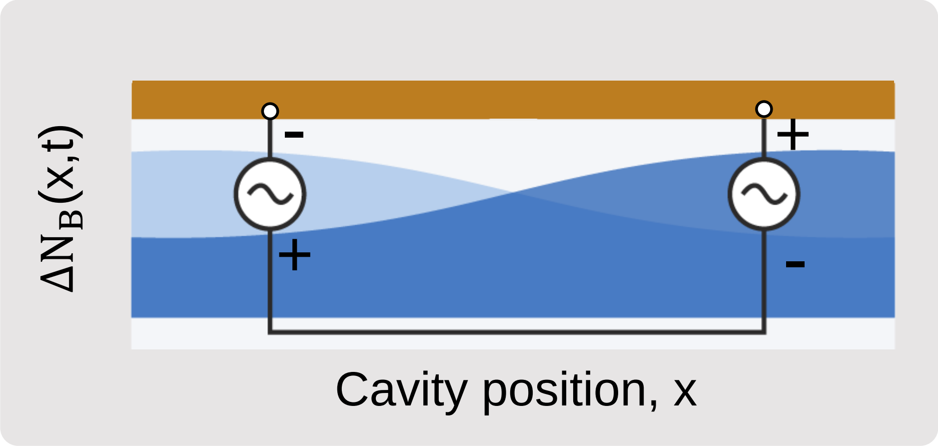
Transmission via a single channel



Original signals retrieved by coherent demodulation

A microwave engineer's perspective

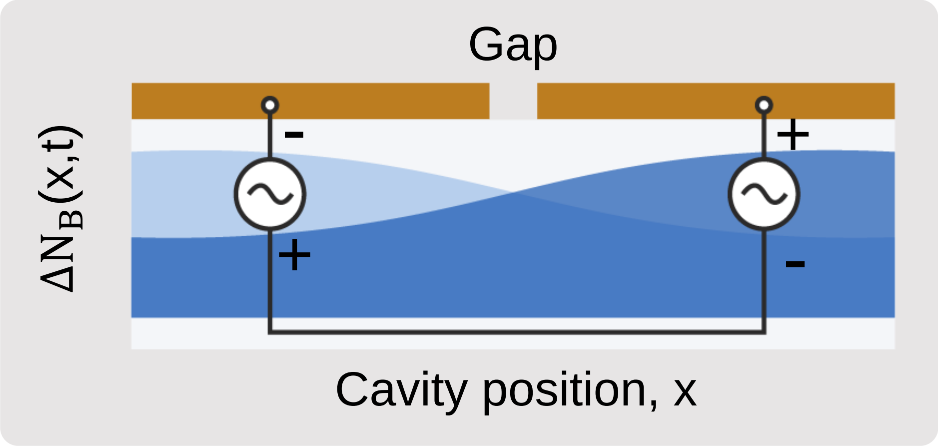
The dynamic grating can be seen as two internal radio frequency generators connected in series



The continuity of the top electrode bounds microwave radiation inside the device

Towards wireless emission…

Introducing a gap in the top contact opens the possibility of radio wave emission



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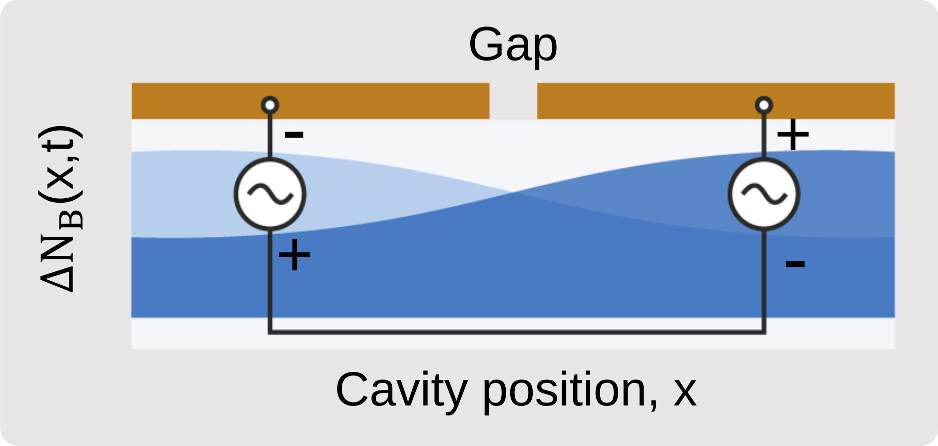
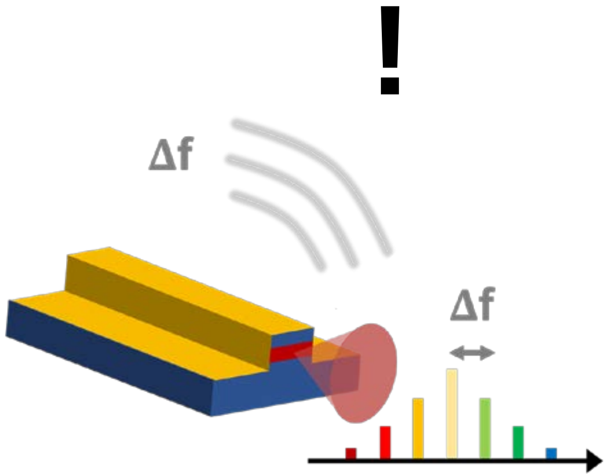
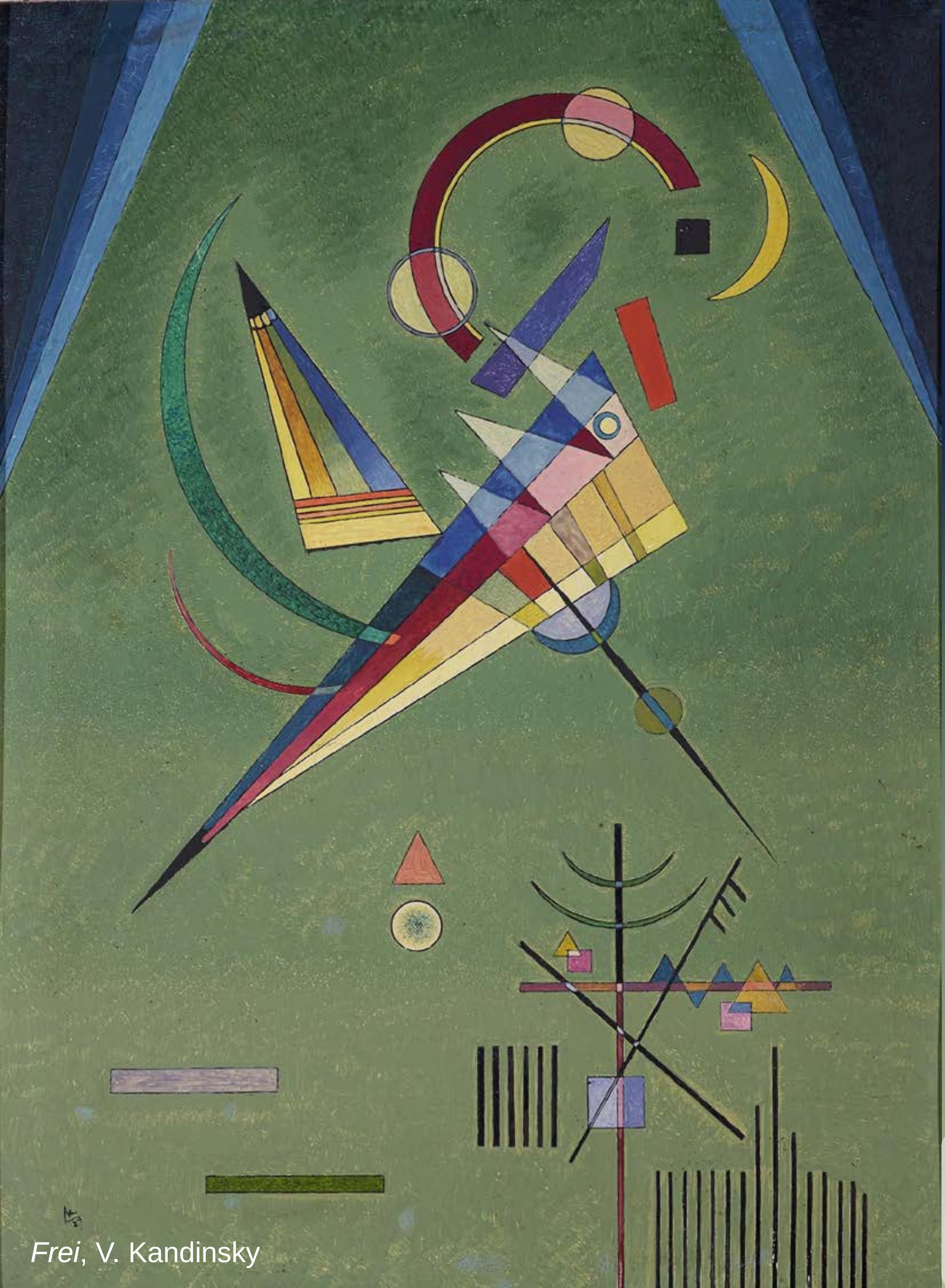
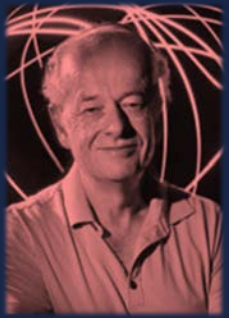




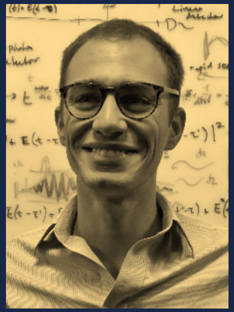


Frei, V. Kandinsky



Federico Capasso

Tobias Mansuripur



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