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- OMICS Group signed an agreement with more than 1000 International Societies to make healthcare information Open Access. OMICS Group Conferences make the perfect platform for global networking as it brings together renowned speakers and scientists across the globe to a most exciting and memorable scientific event filled with much enlightening interactive sessions, world class exhibitions and poster presentations
- Omics group has organised 500 conferences, workshops and national symposium across the major cities including SanFrancisco,Omaha,Orlado,Rayleigh,SantaClara,Chicago,Philadelphia,Unitedkingdom,Baltimore,SanAntanio,Dubai,Hyderabad,Bangaluru and Mumbai.

High frequency modulation for injection locking of mid-infrared QCL

Maria Amanti

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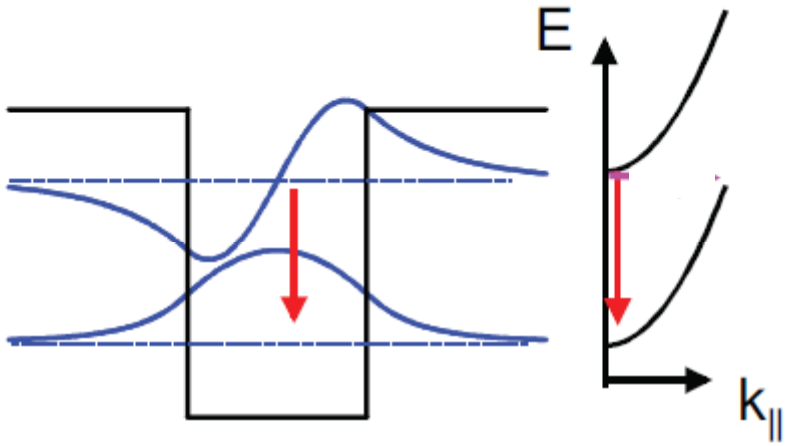
In collaboration with:

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

LABORATOIRE
DE PHOTONIQUE ET
DE NANOSTRUCTURES

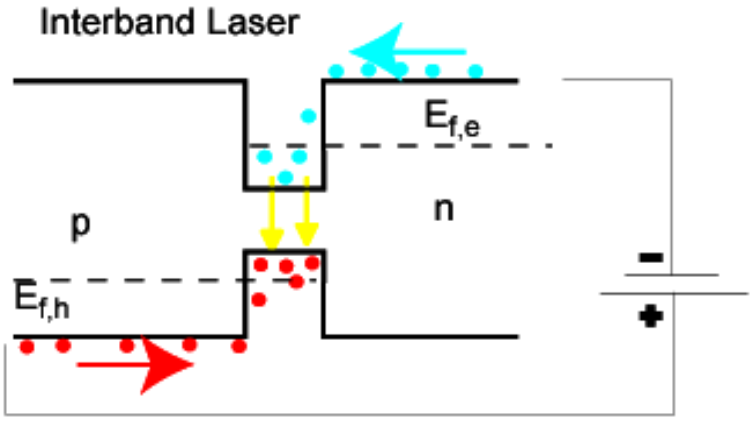
Quantum cascade lasers (QCL): fundamental concepts

1) QCLs are unipolar devices based on intersubband transitions



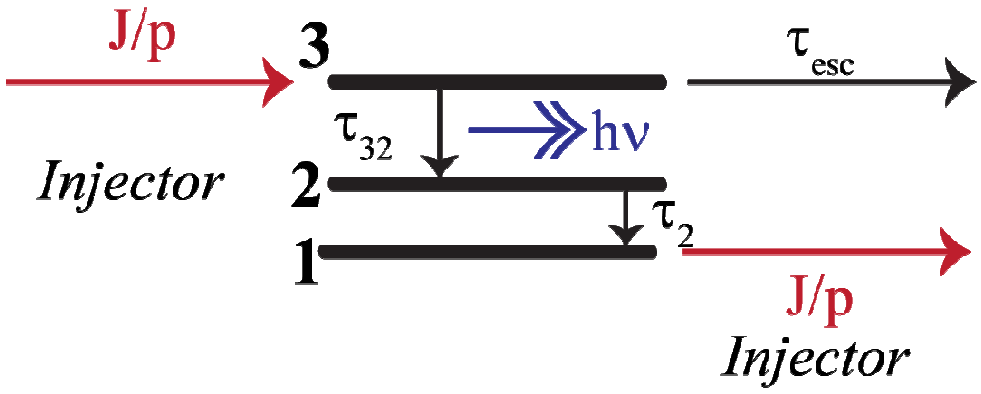
- ✓ Transition energy depends only on layer thickness
- ✓ Ultrafast carrier lifetime (ps)

Laser diode



- Photon energy is fixed by chemistry
- Carrier lifetime of ≈ 100 ps

Dynamical properties of lasers:



Transfer function

Photon population

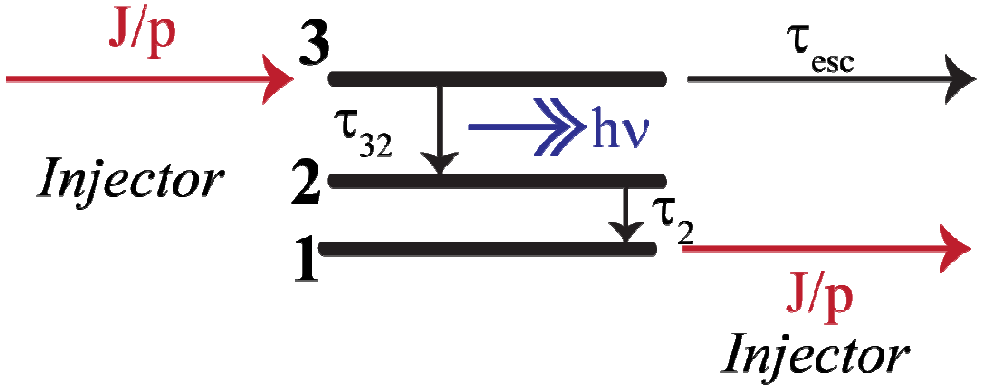
$$\mathbf{S} = h(\omega)\frac{S^{(0)}}{J^{(0)}}\mathbf{J}$$

Current modulation

$$|h(\omega)|^2 = \frac{1}{1+\omega^4\tau_p^2\tau_{stim}^2+\omega^2\tau_{stim}\tau_p(\frac{\tau_p}{\tau_{stim}}+2\frac{\tau_p}{\tau_{up}}+\frac{\tau_p\tau_{stim}}{\tau_{up}^2}-2)}.$$

- $\tau_{stim}^{-1} = (\frac{j}{j_{th}} - 1)\tau_{up}^{-1}$.
- $\tau_{up} = \tau_3$

Dynamical properties of lasers:



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- $\tau_{stim}^{-1} = (\frac{j}{j_{th}} - 1)\tau_{up}^{-1}$.
- $\tau_{up} = \tau_3$

Diode lasers

vs

QCL

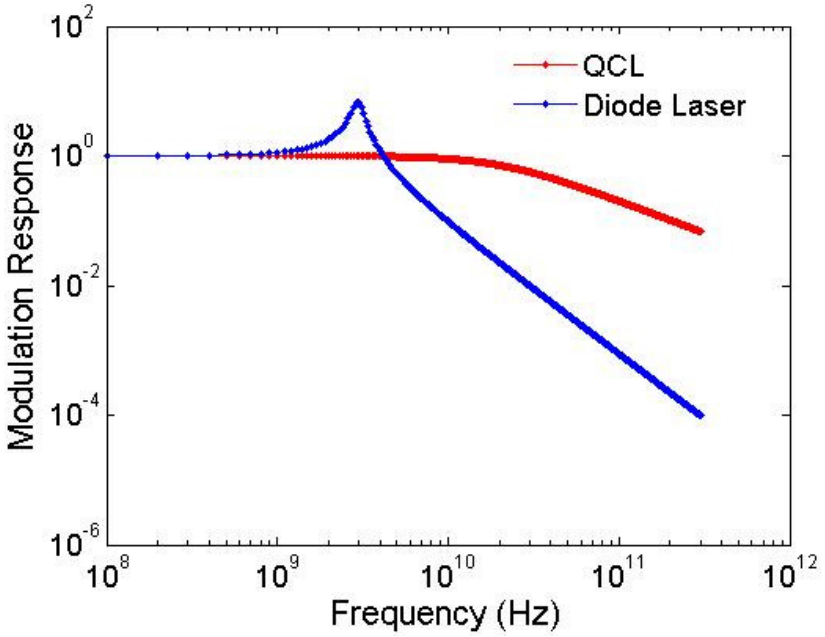
$\alpha_{tot} = 10\ cm^{-1}$

$\tau_{photon} \approx 10\ ps$

$\tau_3 \approx 1\ ns$

$\tau_3 \approx 0.3\ ps$

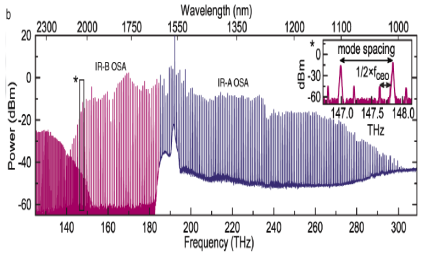
$j/j_{th}=1.3$



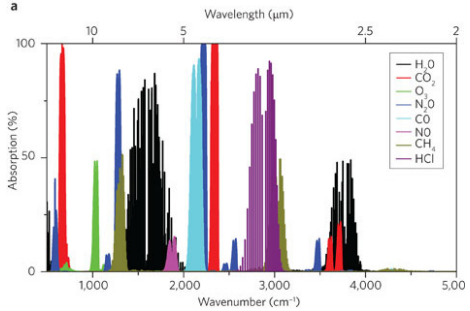
Motivations

- Stabilization and control of the laser modes via direct modulation

- Frequency Combs for spectroscopy

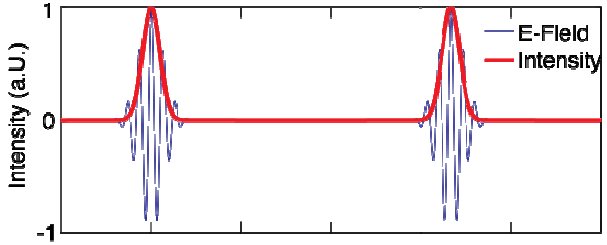


Molecular absorption in the MIR



Nature Photonics 6,440–449 ,(2012).

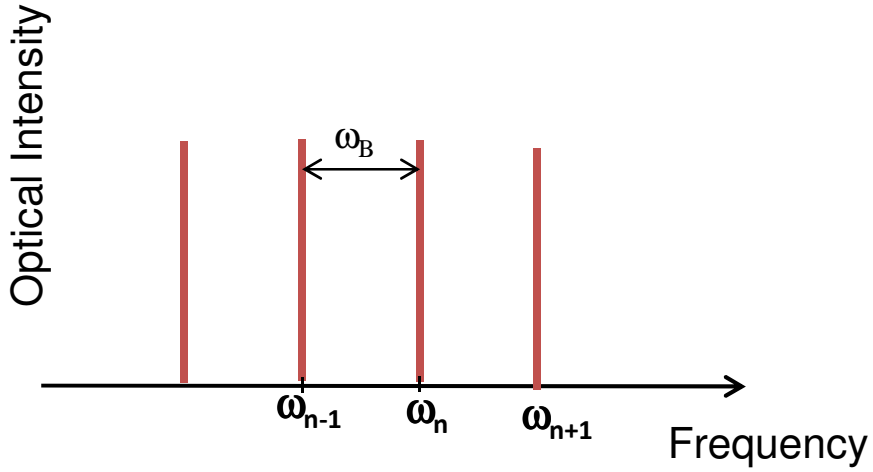
- Mode locking for mid infrared non linear optics



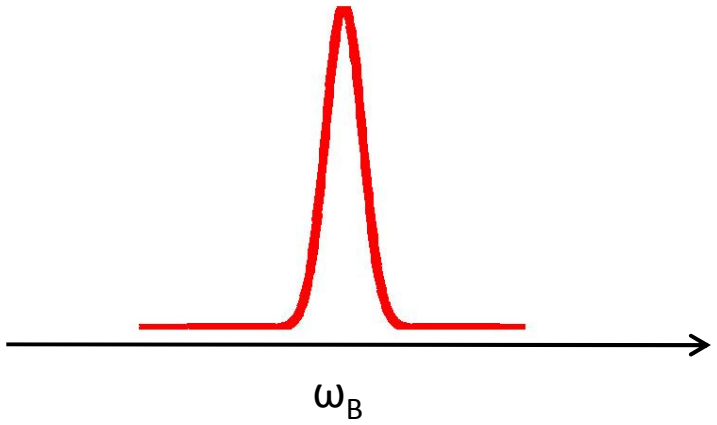
Time

Stabilization of the laser cavity modes: toward frequency combs

Optical spectrum

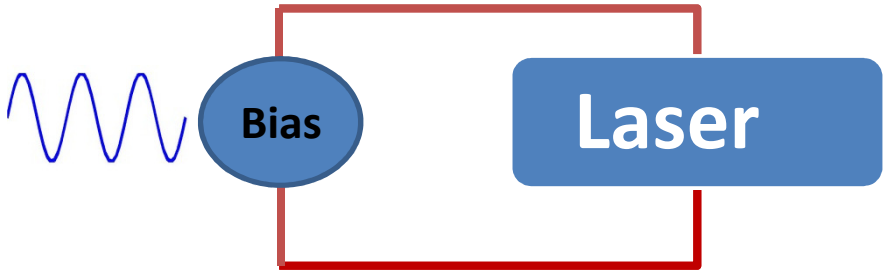


Microwave spectrum



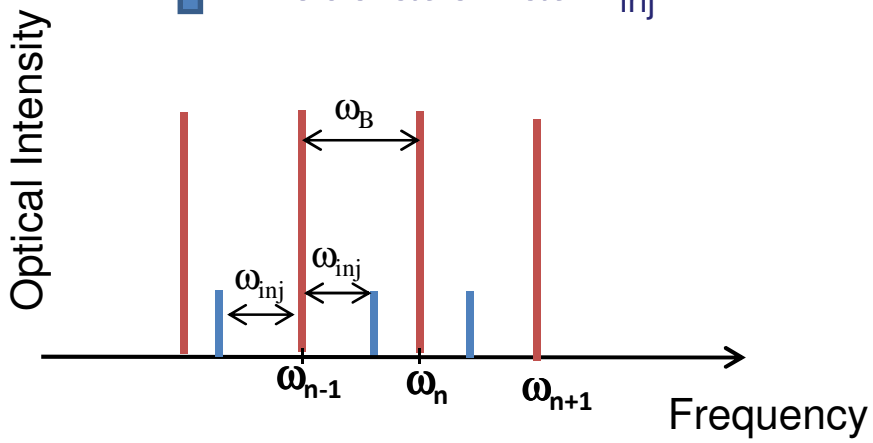
FWHM give an insight on the noise of the cavity modes

Stabilization of the laser cavity modes: toward frequency combs

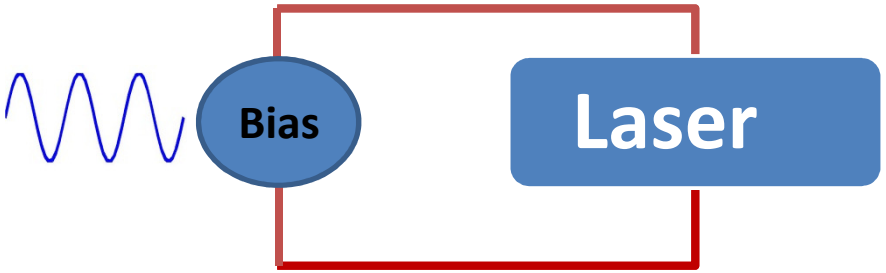


Optical spectrum

Modulation at ω_{inj}:

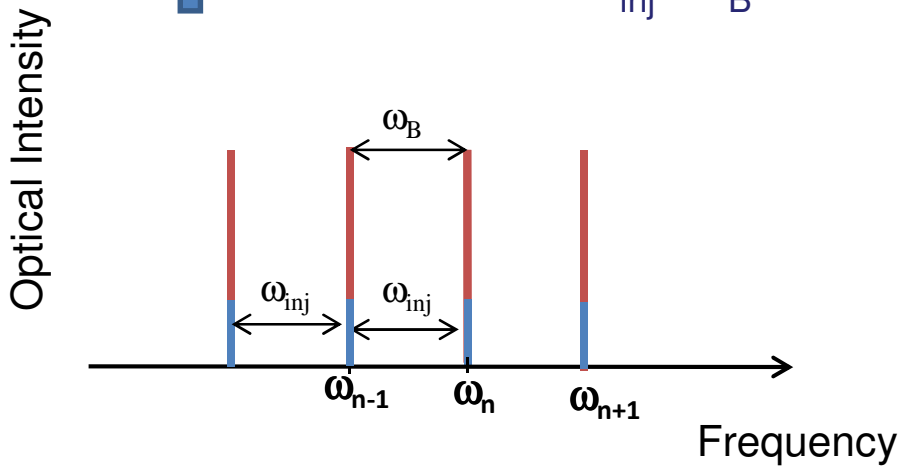


Stabilization of the laser cavity modes: toward frequency combs

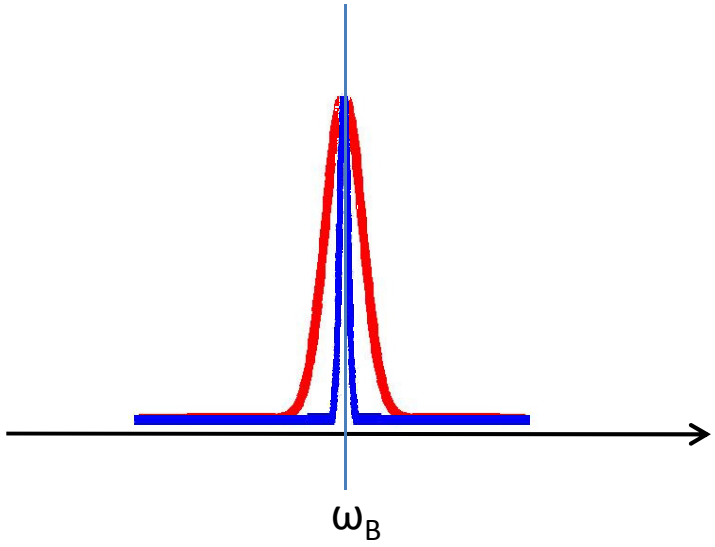


Optical spectrum

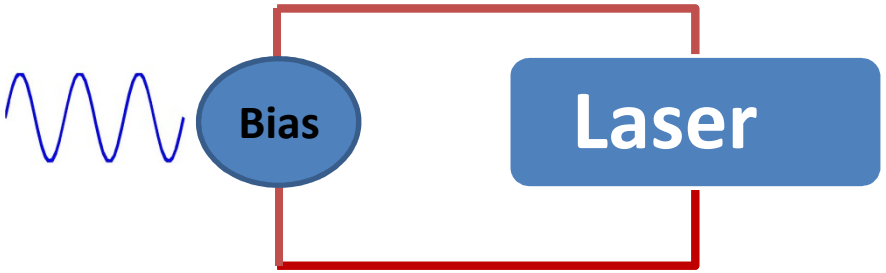
Modulation at $\omega_{inj}=\omega_B$



Microwave spectrum

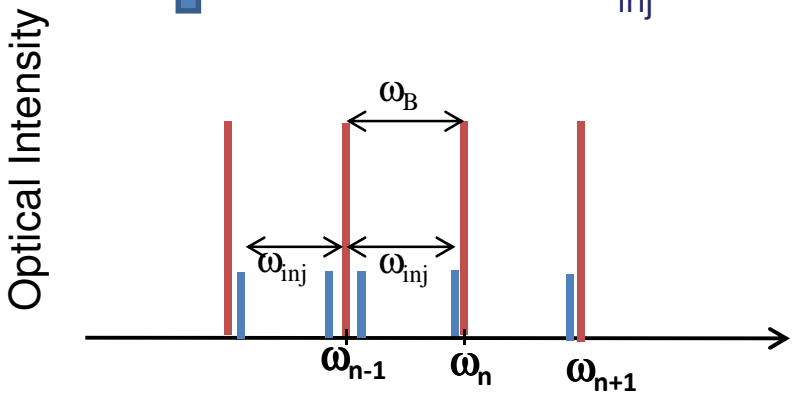


Stabilization of the laser cavity modes: toward frequency combs

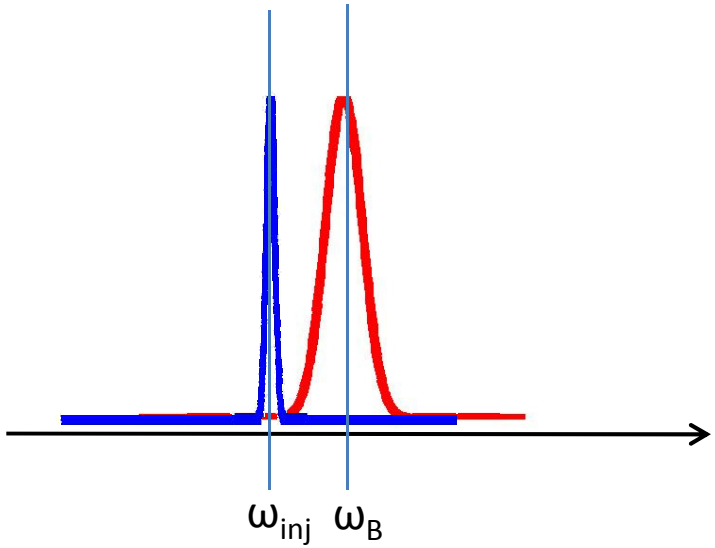


Optical spectrum

Modulation at ω_{inj} close to ω_B

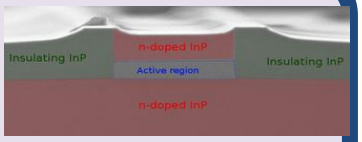


Microwave spectrum

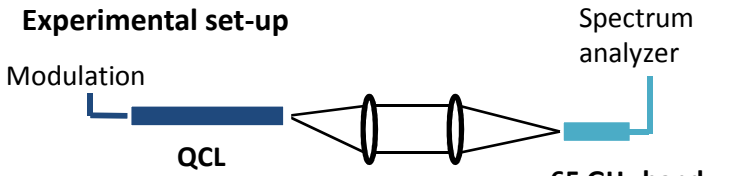


Direct modulation of a QCL @ 9µm

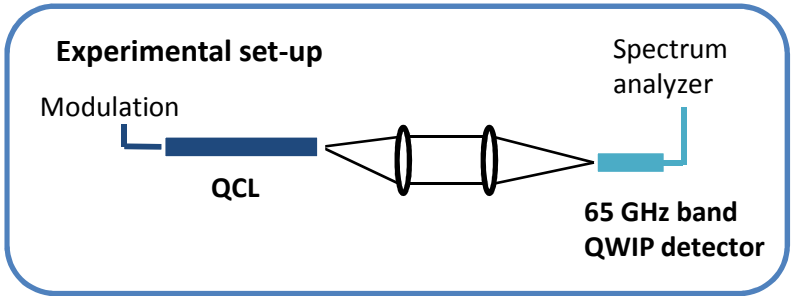
Buried QCL @ 9 µm in InGaAs/AlInAs

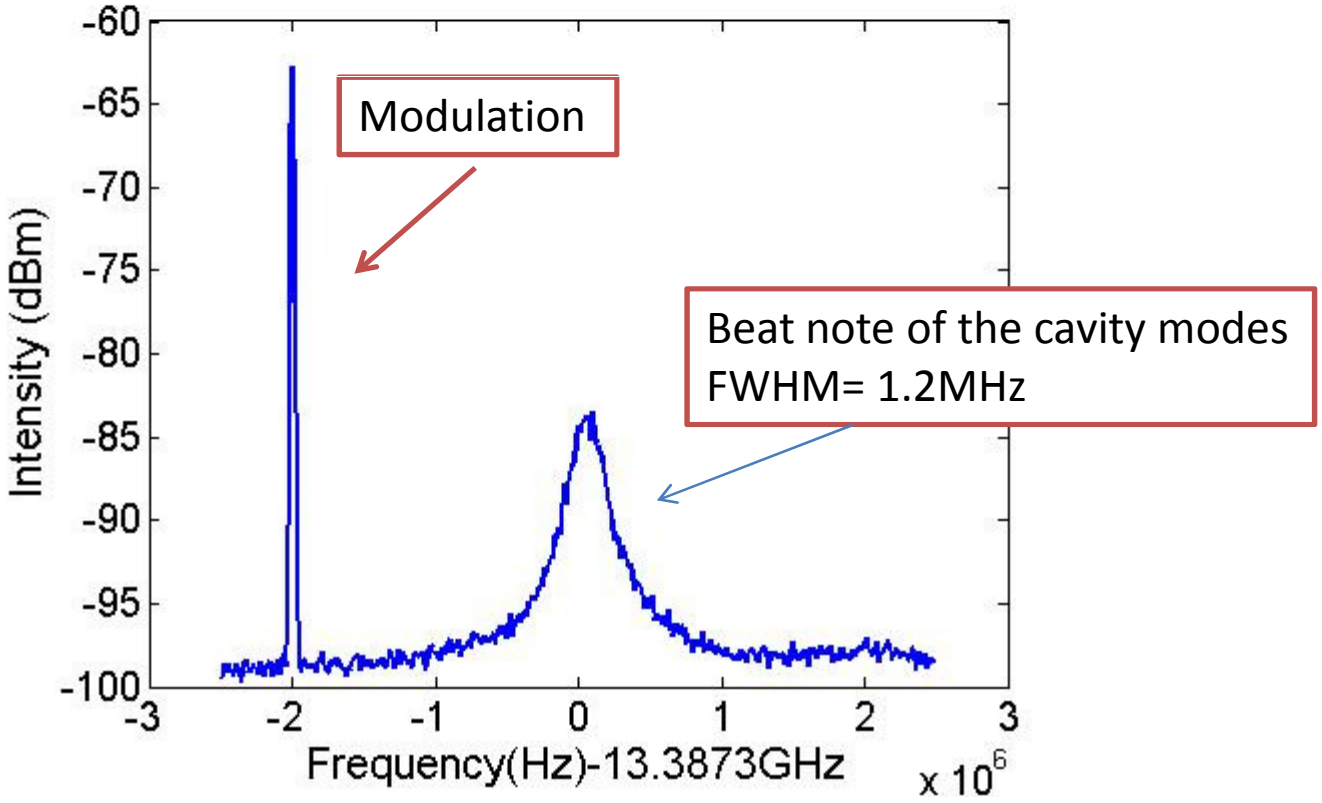


Experimental set-up

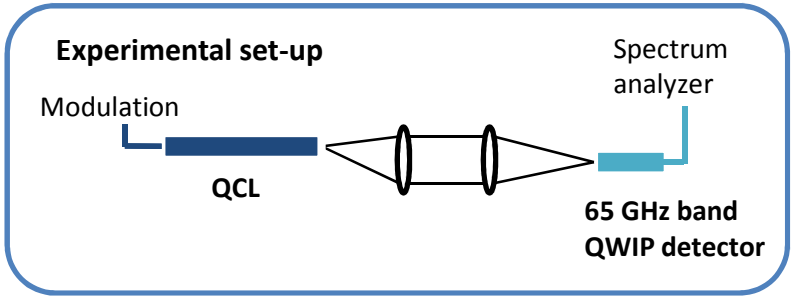


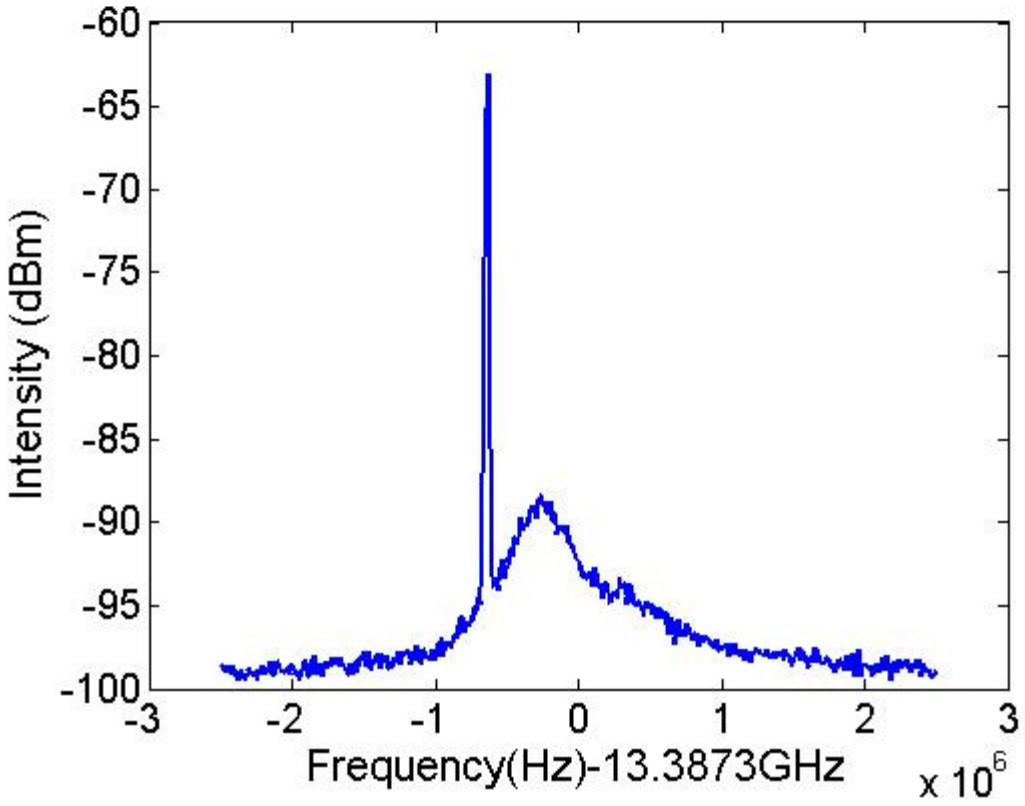
Direct modulation of a QCL @ 9µm



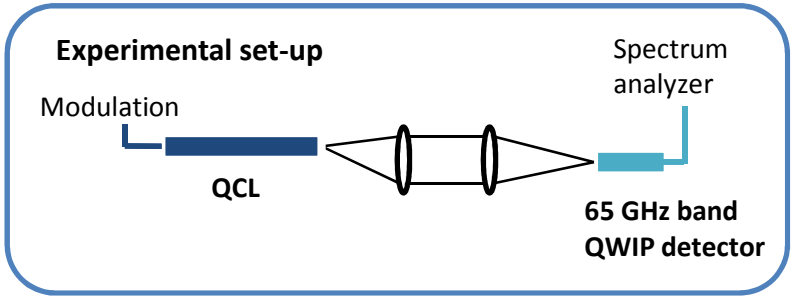


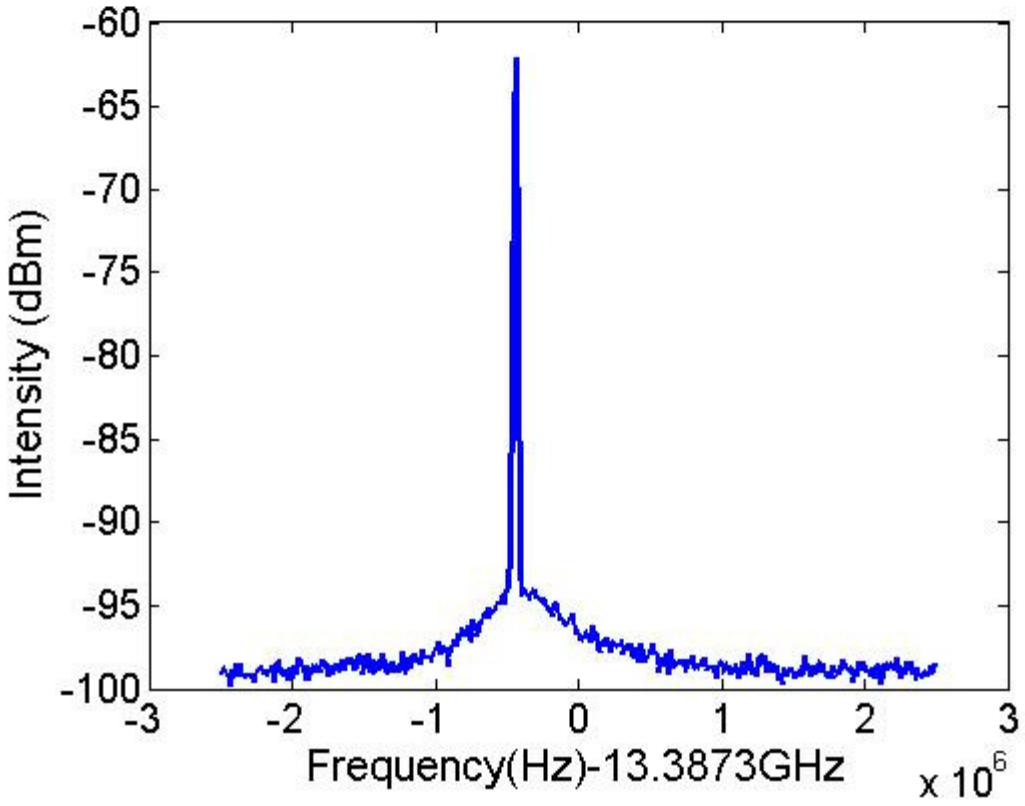
Direct modulation of a QCL @ 9µm



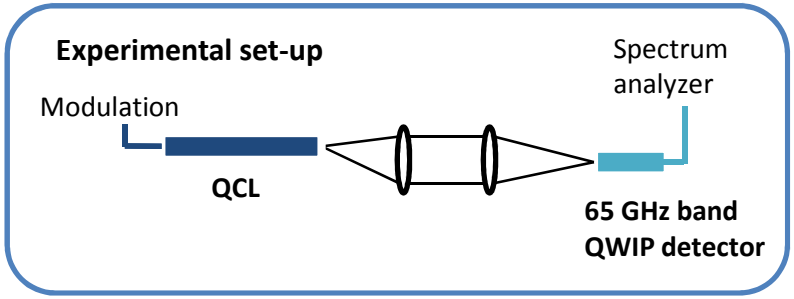


Direct modulation of a QCL @ 9µm

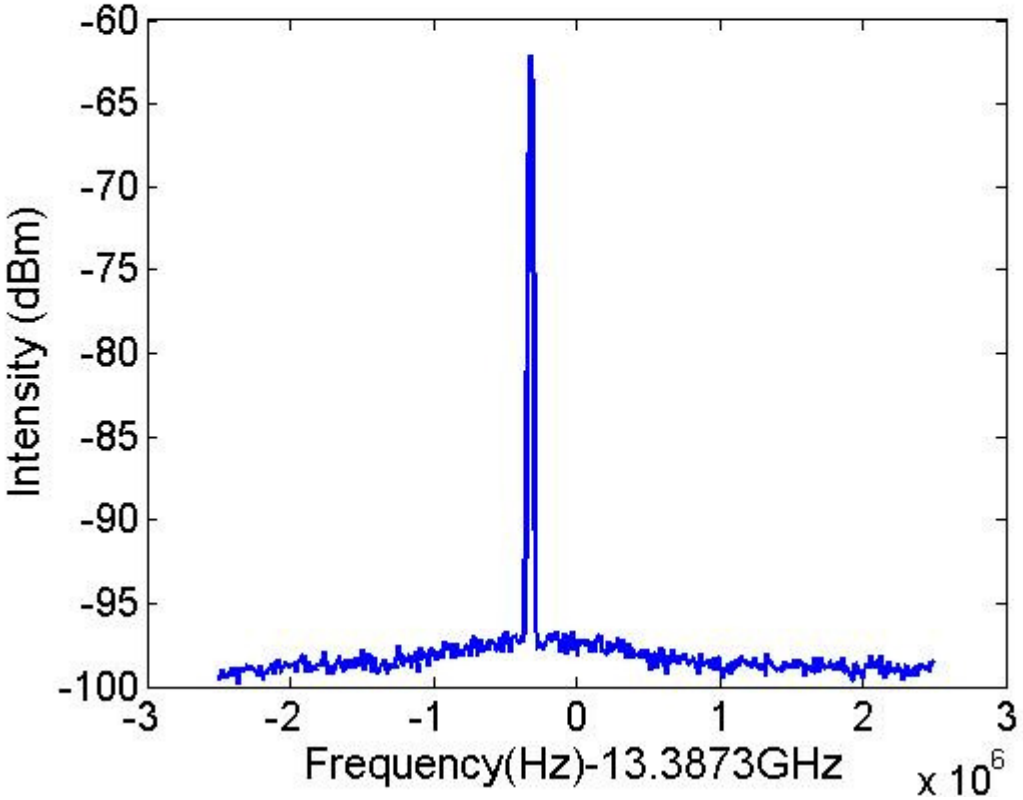




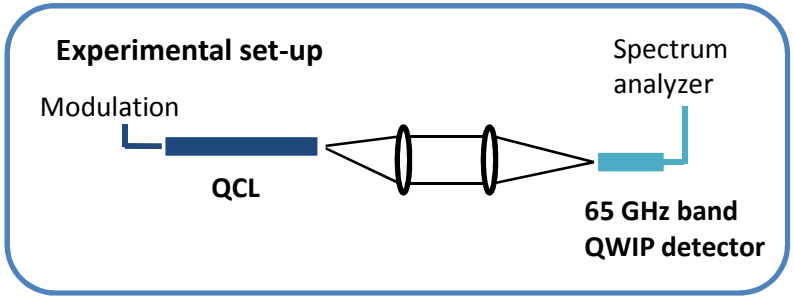
Direct modulation of a QCL @ 9µm



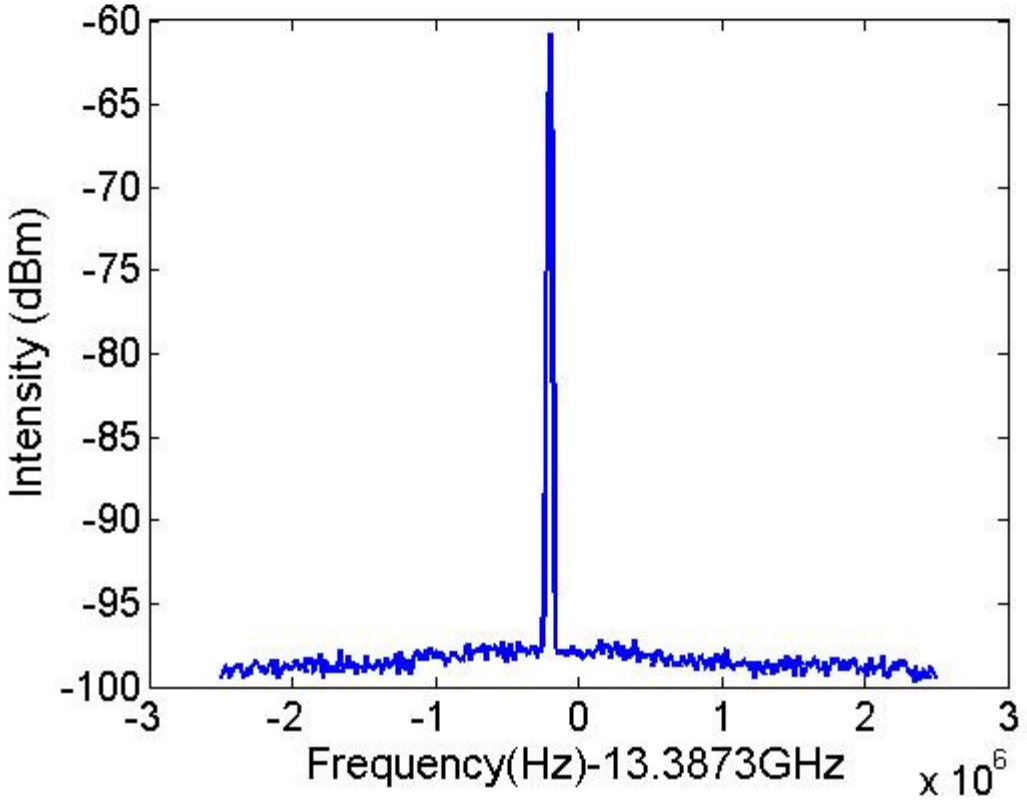
Locking of the optical modes to the external RF source



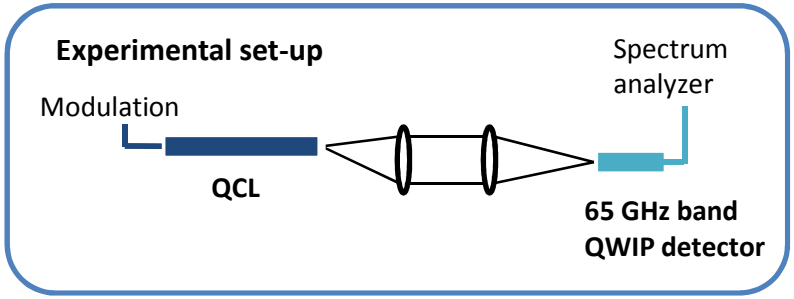
Direct modulation of a QCL @ 9µm



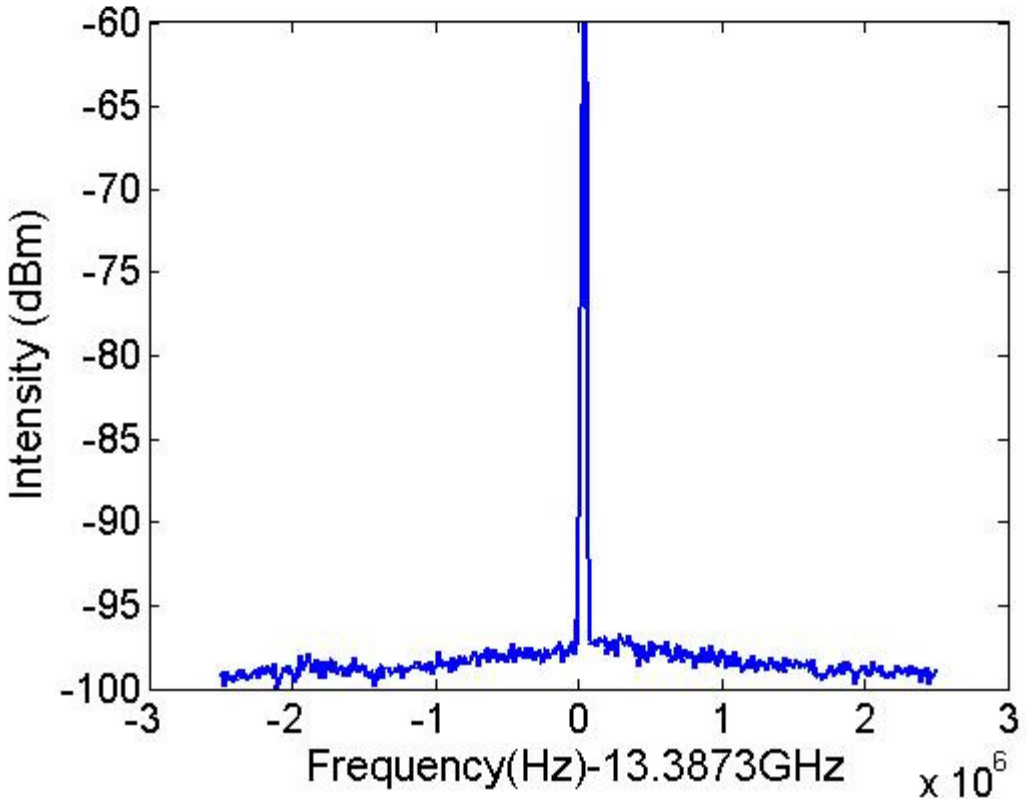
Tuning of the cavity modes with the external modulation



Direct modulation of a QCL @ 9µm



Tuning of the cavity modes with the external modulation



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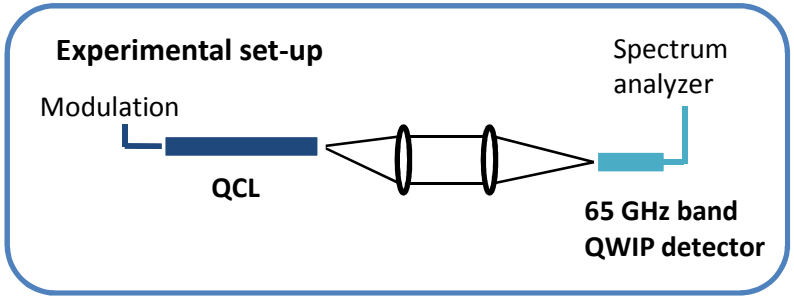

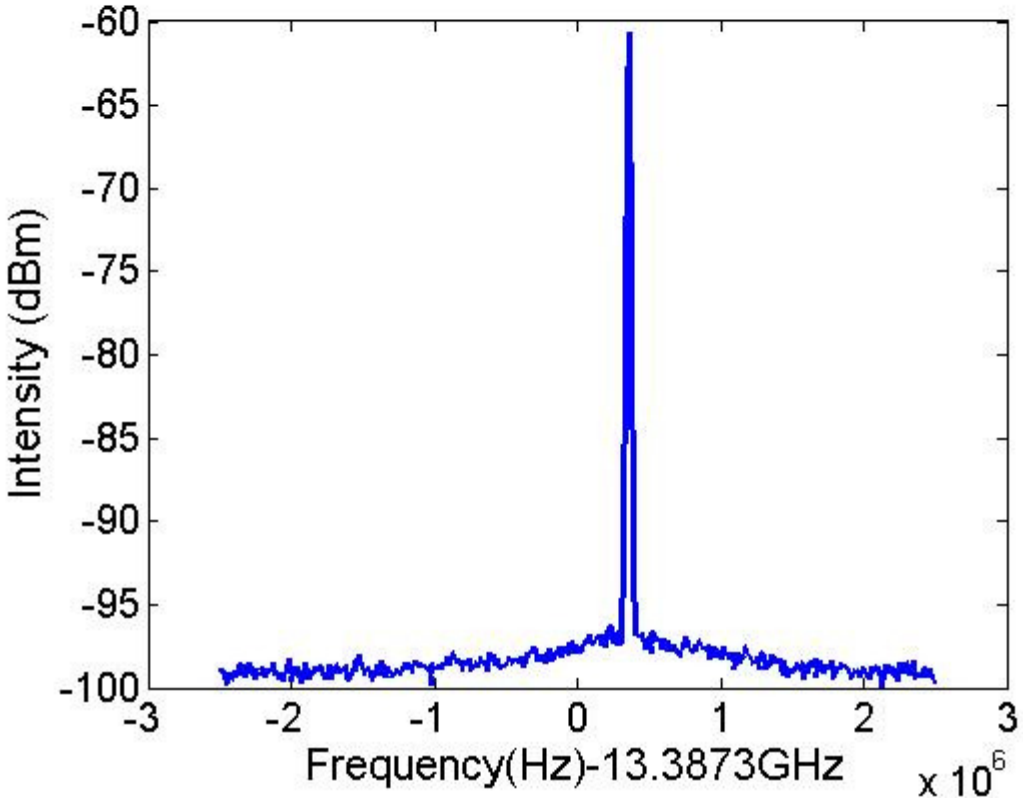

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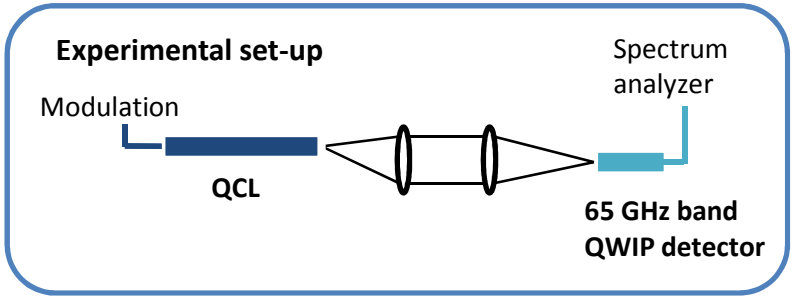
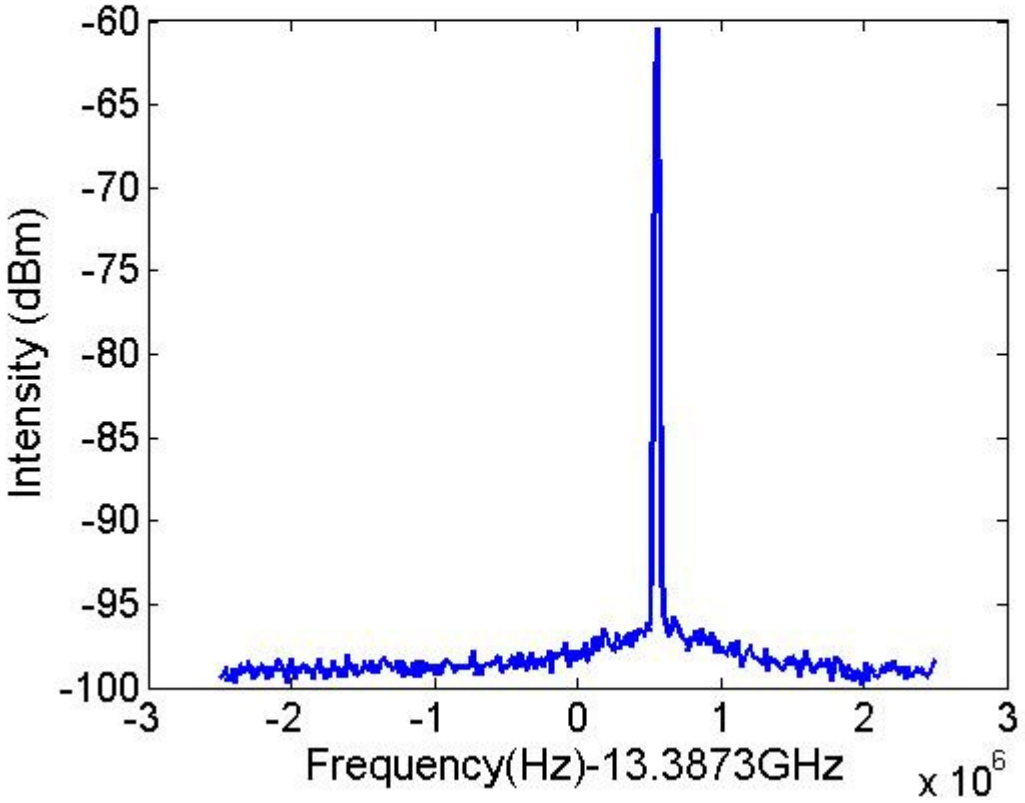
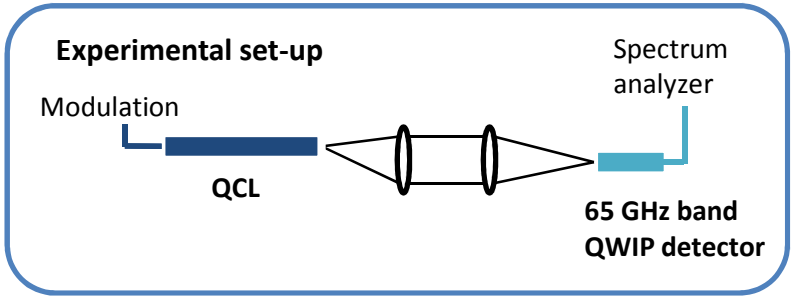
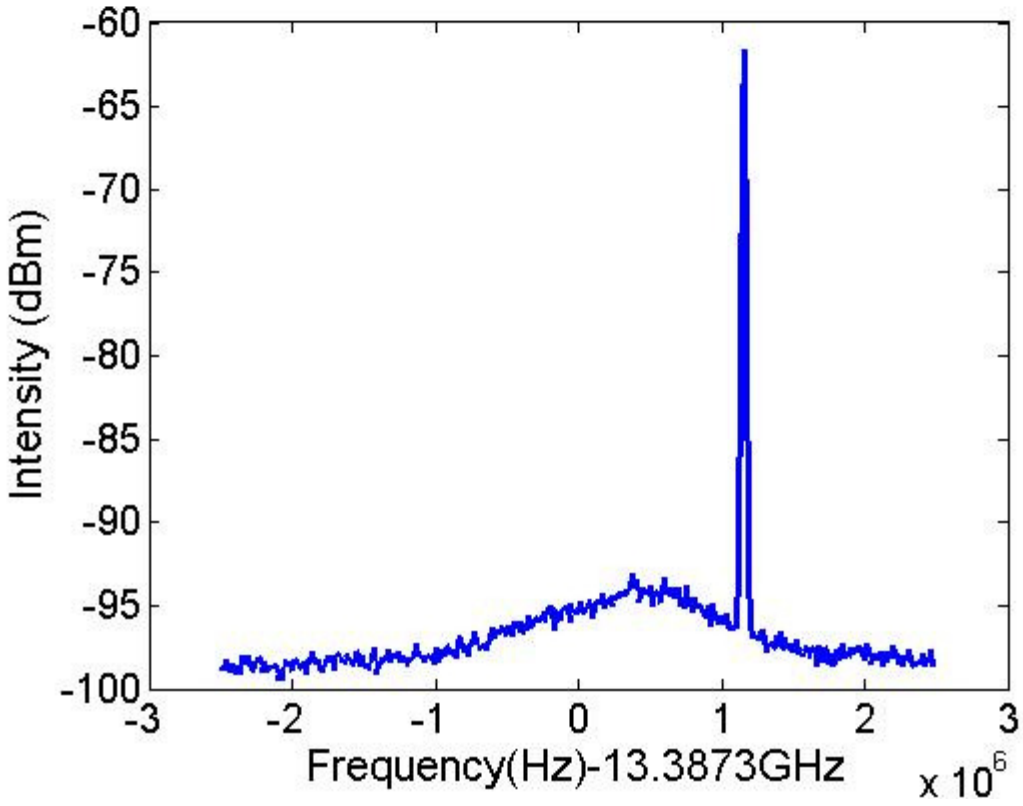


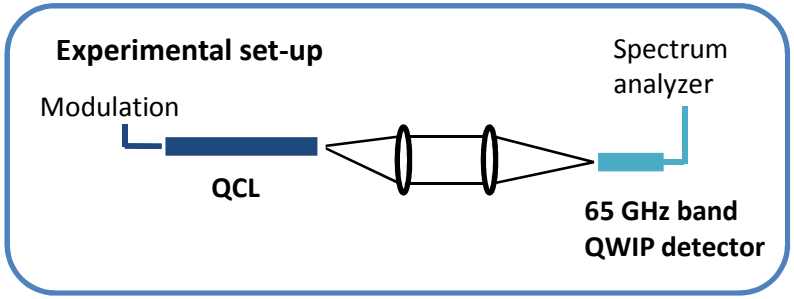


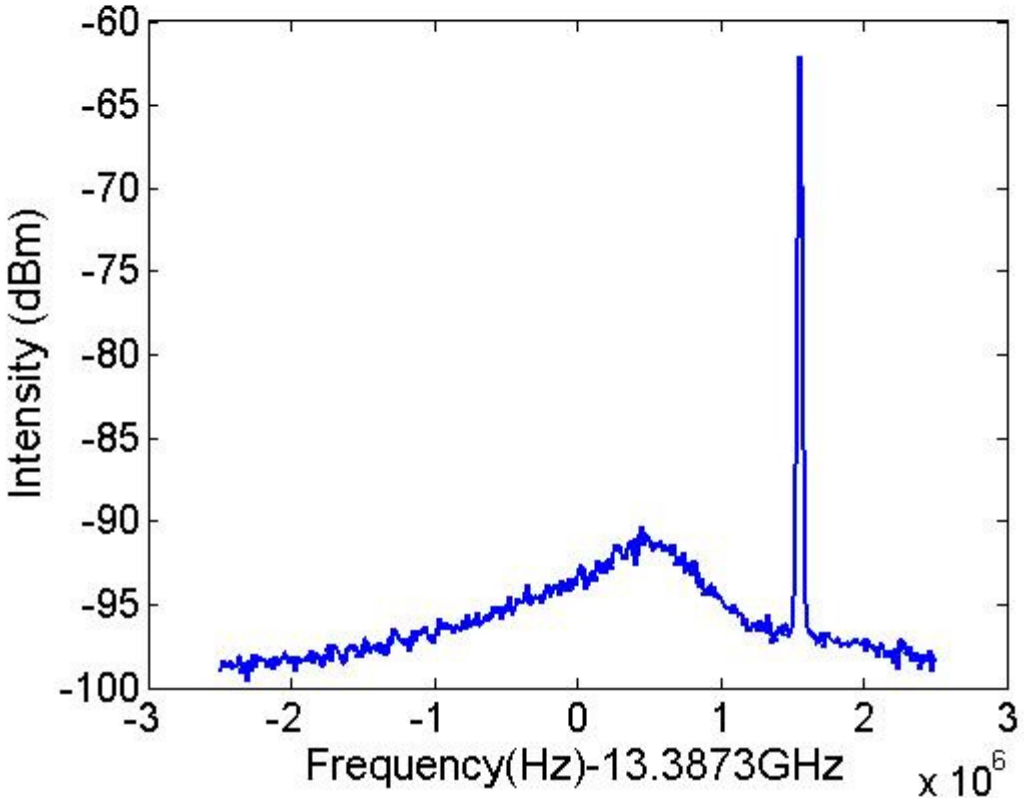
Direct modulation of a QCL @ 9µm



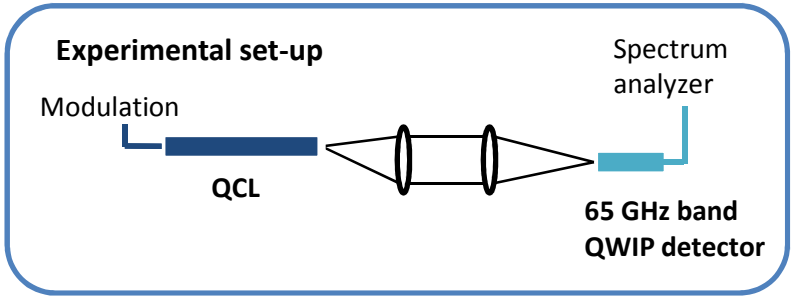


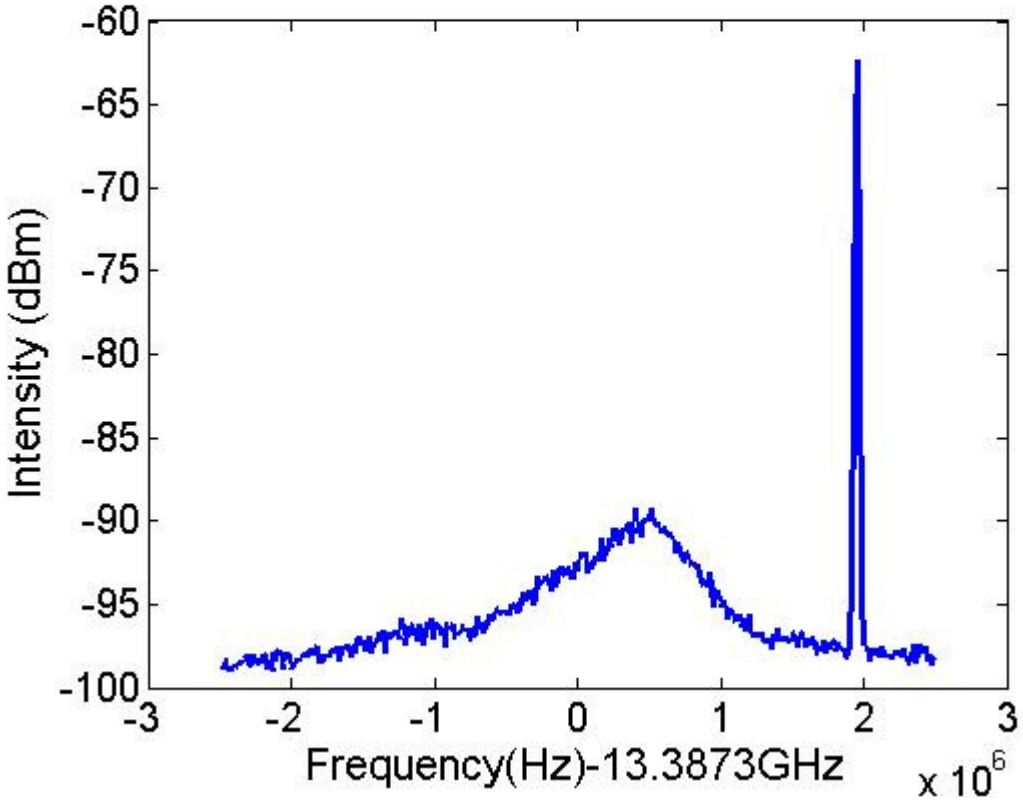
Direct modulation of a QCL @ 9µm



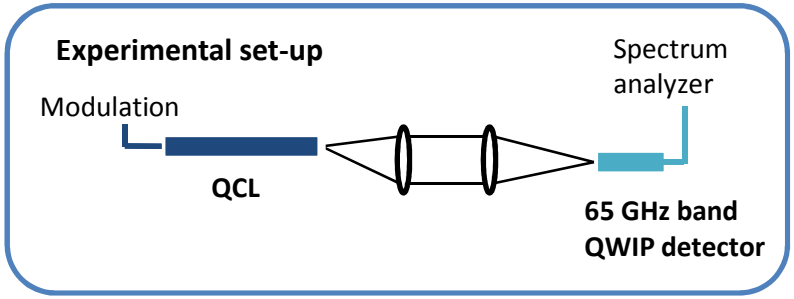


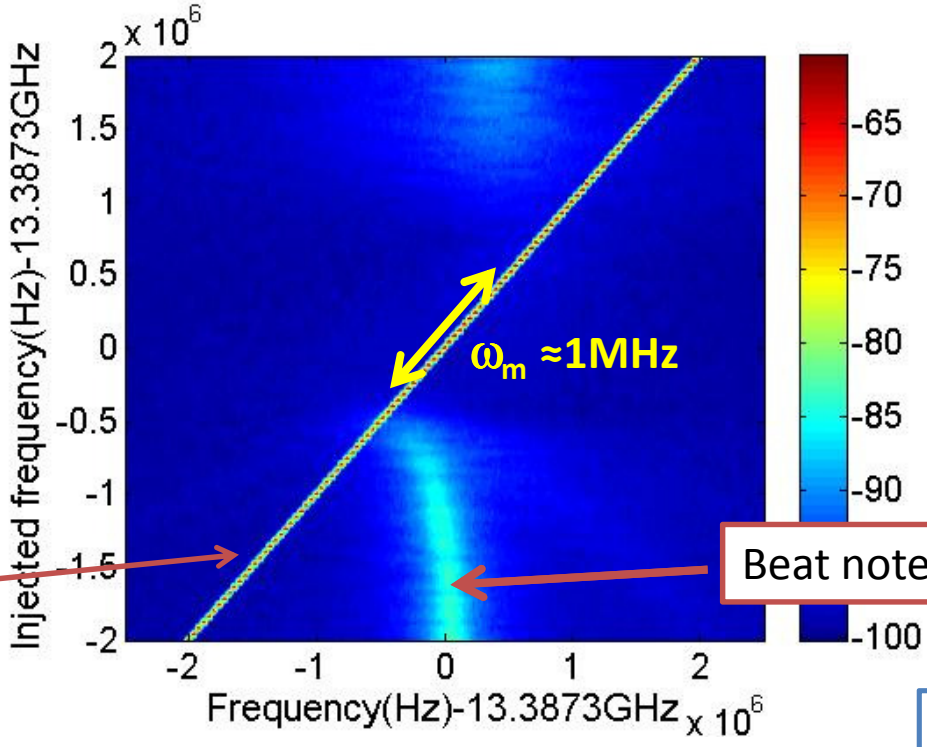
Direct modulation of a QCL @ 9µm





Direct modulation of a QCL @ 9µm





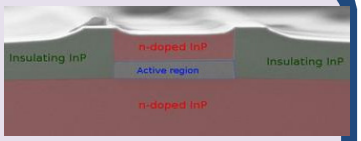
Modulation

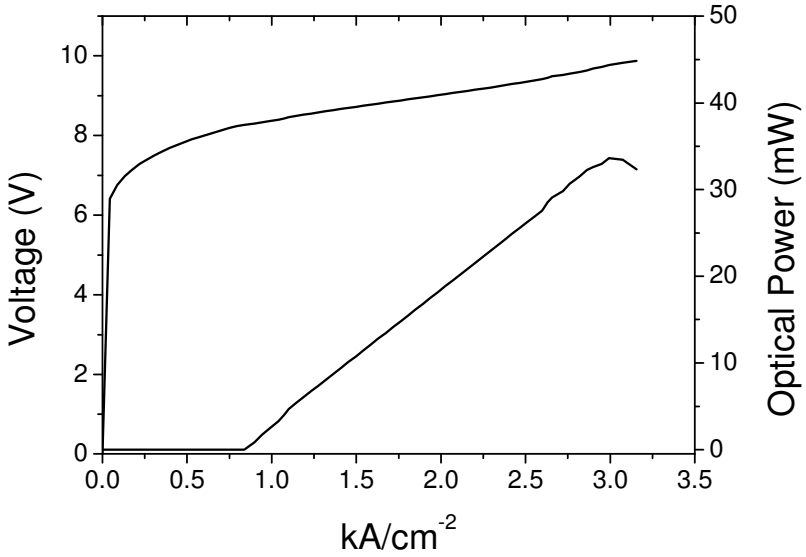
Beat note of the cavity modes

Injected power : 20 dBm

Evolution of the locking with the emitted optical power

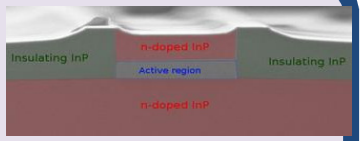
Buried QCL
@ 9 µm in
InGaAs/AlInAs

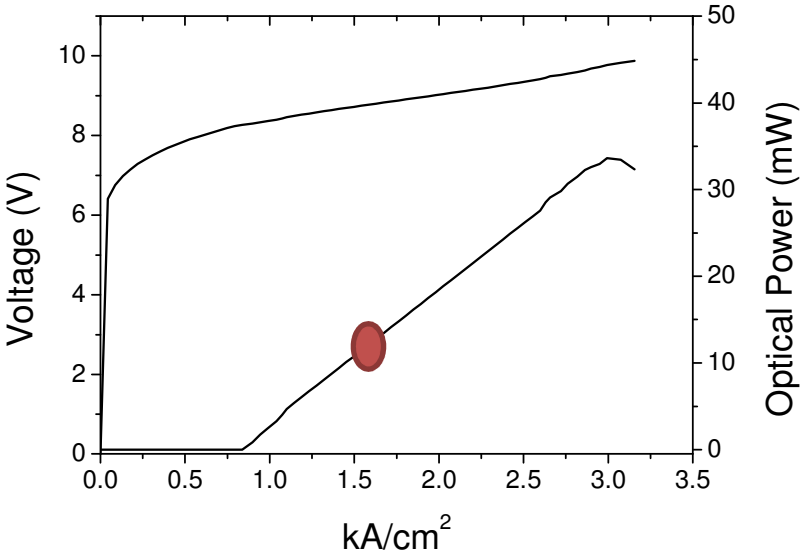




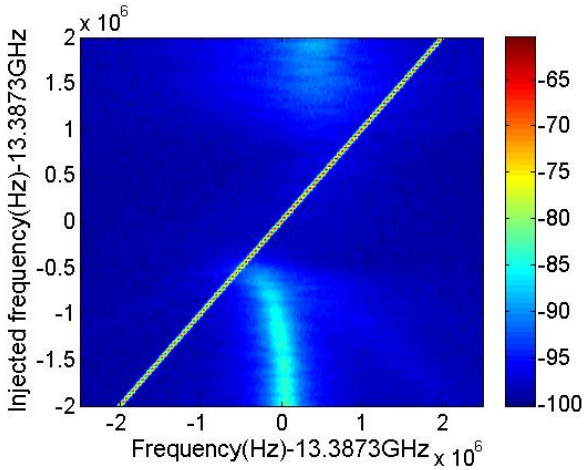
Evolution of the locking with the emitted optical power

Buried QCL
@ 9 µm in
InGaAs/AlInAs



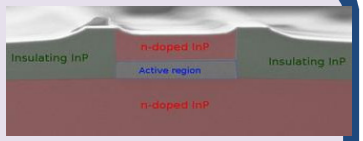


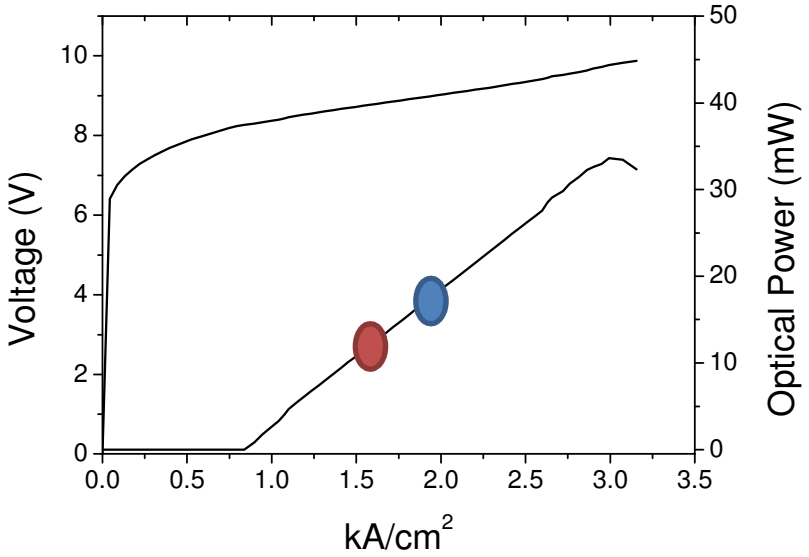
@ 1.7 kA/cm ^{2}



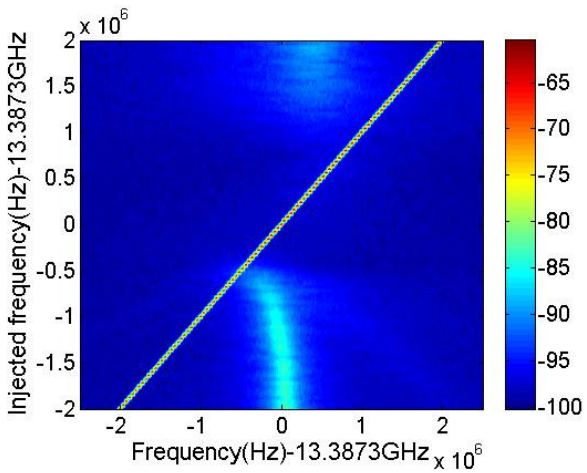
Evolution of the locking with the emitted optical power

Buried QCL
@ 9 µm in
InGaAs/AlInAs

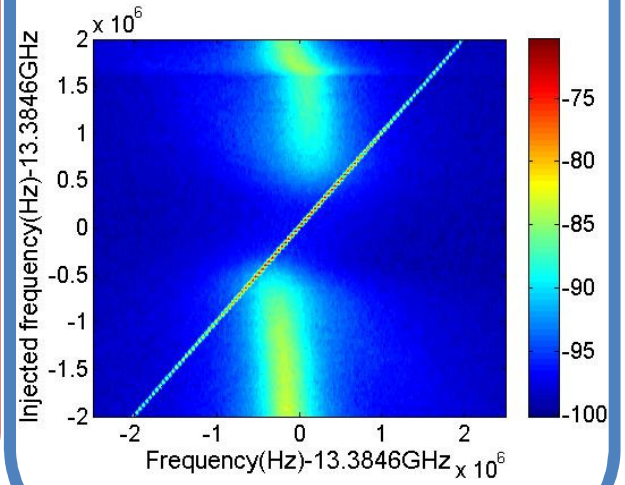




@ 1.7 kA/cm ²

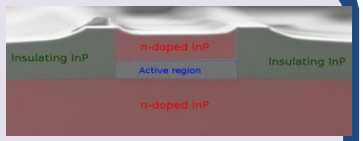


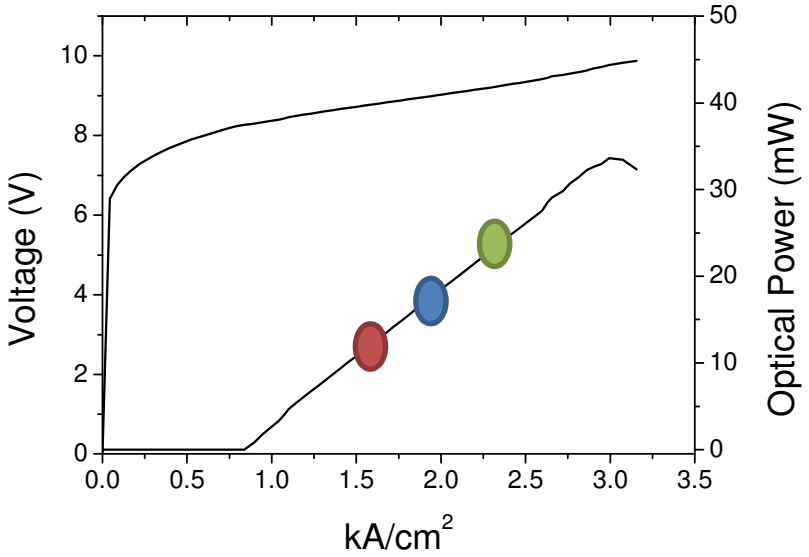
@ 2.0 kA/cm ²



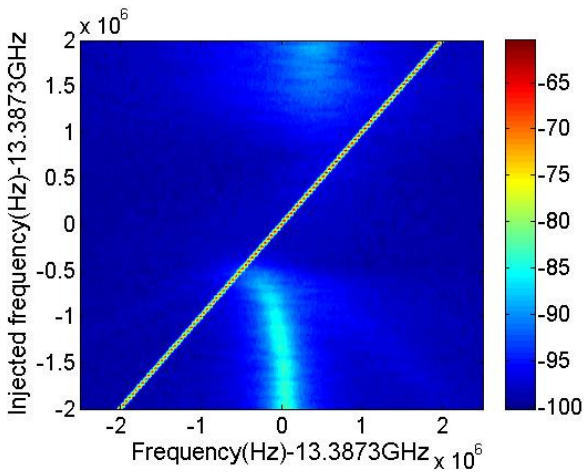
Evolution of the locking with the emitted optical power

Buried QCL
@ 9 µm in
InGaAs/AlInAs

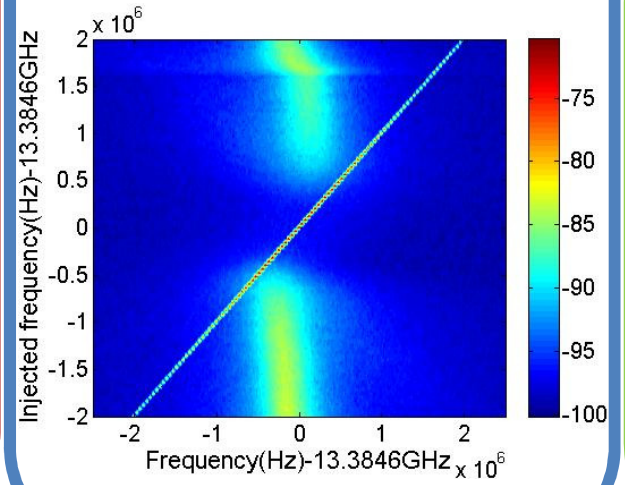




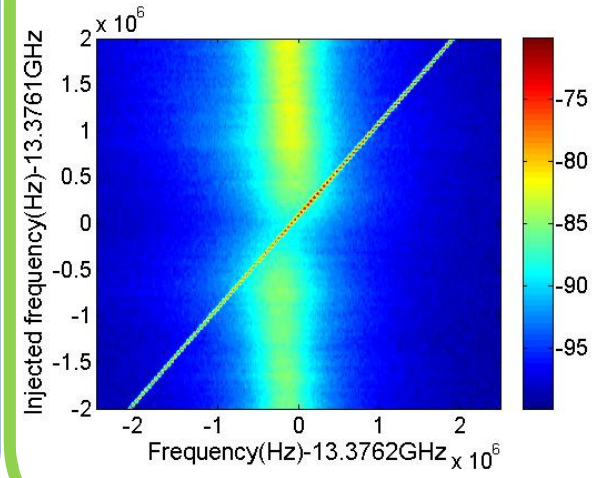
@ 1.7 kA/cm ²



@ 2.0 kA/cm ²



@ 2.4 kA/cm ²



No locking

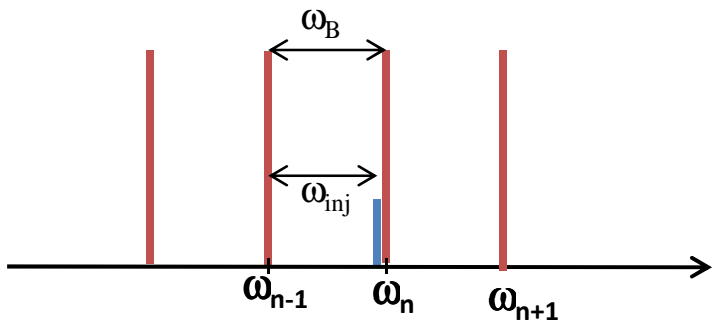
Coupled oscillators Theory

Laser oscillations

Microwave modulation

Cavity field $E_0 e^{[i\omega_n t+\varphi(t)]}$

Modulated signal $\frac{E_{inj}}{\sqrt{losses_{RF}}} e^{[i(\omega_{n-1}+\omega_{inj})t]}$



Coupled oscillators Theory

Laser oscillations

Microwave modulation

Cavity field $E_0 e^{[i\omega_n t+\varphi(t)]}$

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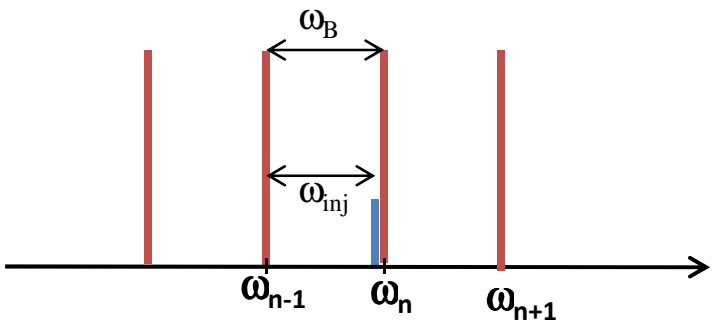


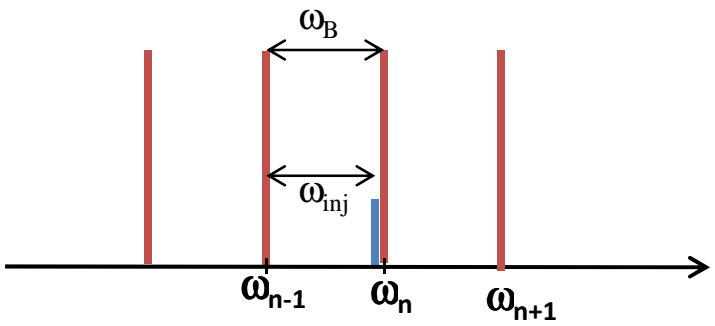
Microwave losses
(propagation losses, impedence mismatch)

Coupled oscillators Theory

Laser oscillations + Microwave modulation

Cavity field $E_0 e^{[i\omega_n t+\varphi(t)]}$

Modulated signal $\frac{E_{inj}}{\sqrt{losses_{RF}}} e^{[i(\omega_{n-1}+\omega_{inj})t]}$



$$\frac{d\varphi}{dt} = \omega_B - \omega_{inj} - \frac{\omega_n}{Q}\frac{E_{inj}}{E_0\sqrt{a}}\sin\varphi$$

$$\frac{\sqrt{I_{inj}}}{\omega_m} = \frac{Q_{ext}}{\omega_0}\sqrt{losses_{RF}}\sqrt{I_0}$$

Locking range

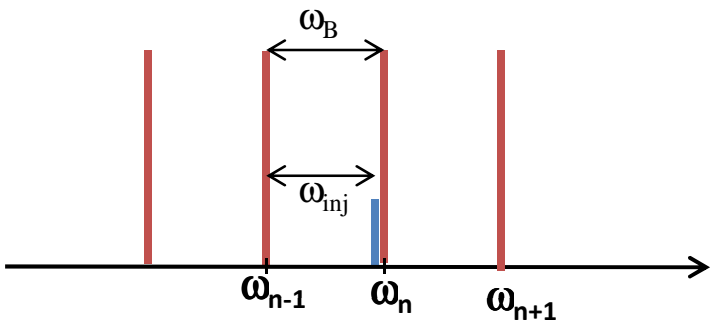
Siegman, A. (1986). Lasers. University Science Book
Razavi, B. (2004). Solid-State Circuits, IEEE, 39(9):1415-424.

Coupled oscillators Theory

Laser oscillations + Microwave modulation

Cavity field $E_0 e^{[i\omega_n t+\varphi(t)]}$

Modulated signal $\frac{E_{inj}}{\sqrt{losses_{RF}}} e^{[i(\omega_{n-1}+\omega_{inj})t]}$



$$\frac{d\varphi}{dt} = \omega_B - \omega_{inj} - \frac{\omega_n}{Q}\frac{E_{inj}}{E_0\sqrt{a}}\sin\varphi$$

Modulation power

Locking range

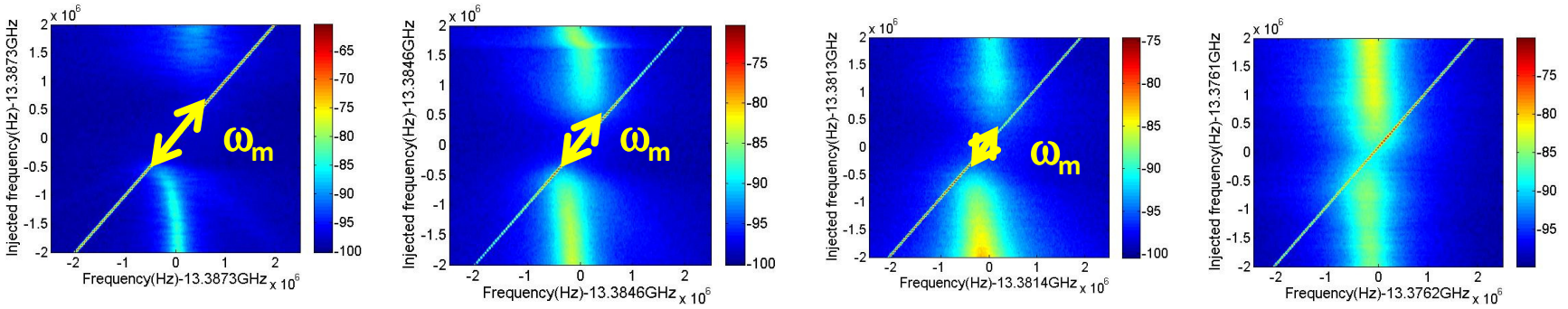
$$\frac{\sqrt{I_{inj}}}{\omega_m} = \frac{Q_{ext}}{\omega_0}\sqrt{losses_{RF}}\sqrt{I_0}$$

Optical power

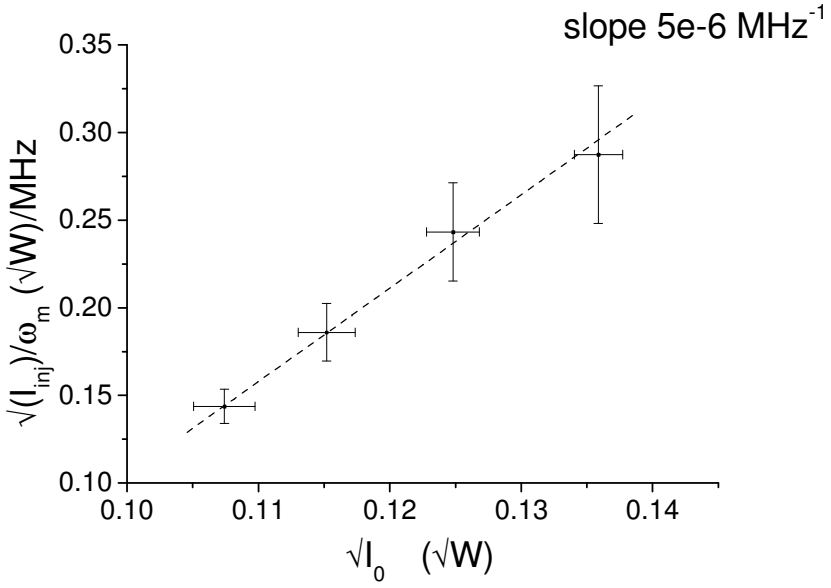
Siegman, A. (1986). Lasers. University Science Book

Razavi, B. (2004). Solid-State Circuits, IEEE, 39(9):1415-424.

Coupled oscillators theory

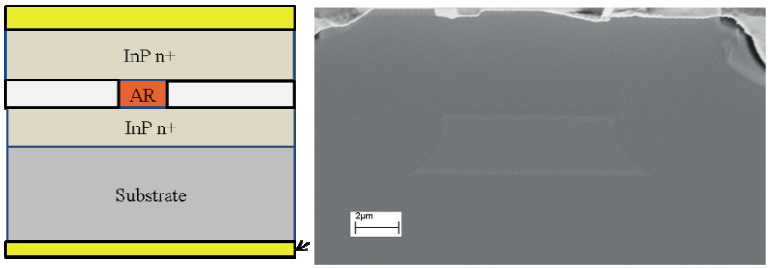


$$\frac{\sqrt{I_{inj}}}{\omega_m} = \frac{Q_{opt}}{\omega_0}\sqrt{losses_{RF}}\sqrt{I_0}$$



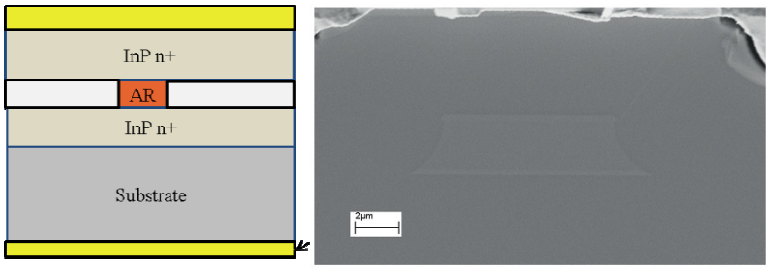
Mir QCL embedded in a microstrip line

MIR QCL guide

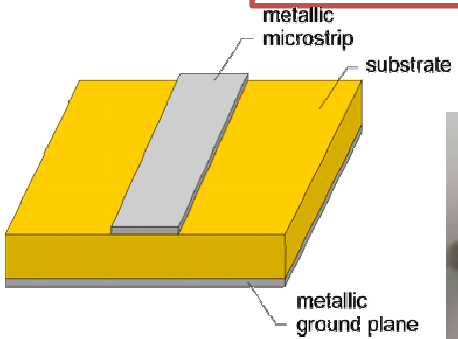


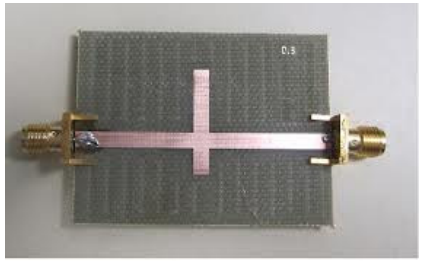
Mir QCL embedded in a microstrip line

MIR QCL guide



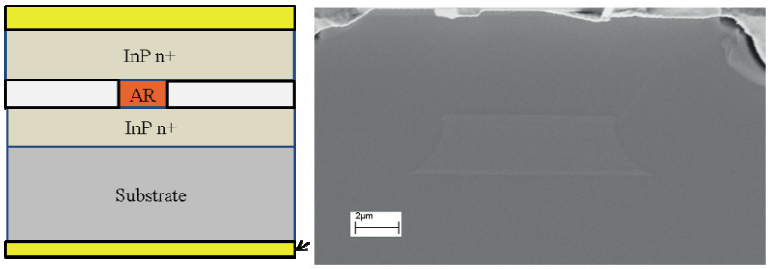
Microwave line



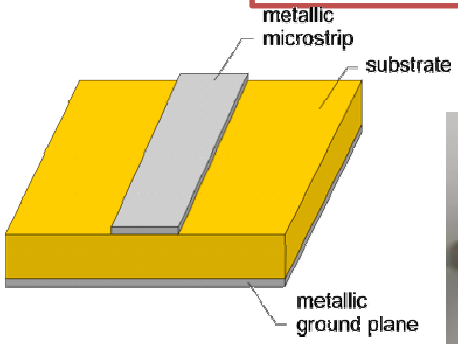


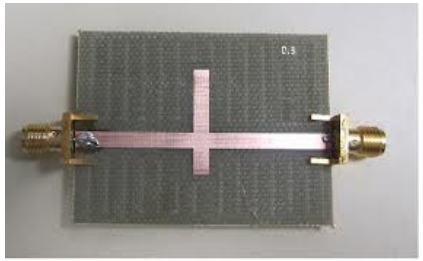
Mir QCL embedded in a microstrip line

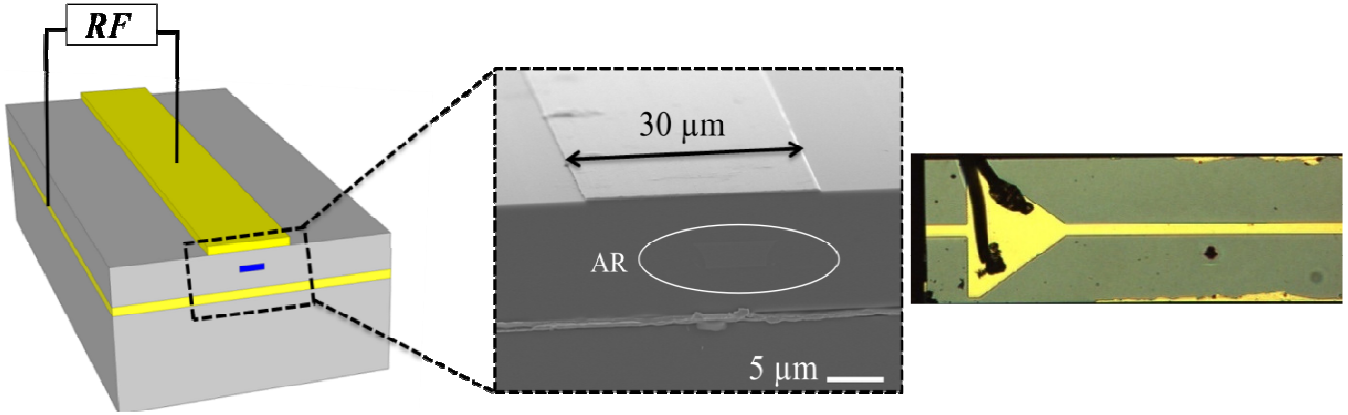
MIR QCL guide



Microwave line





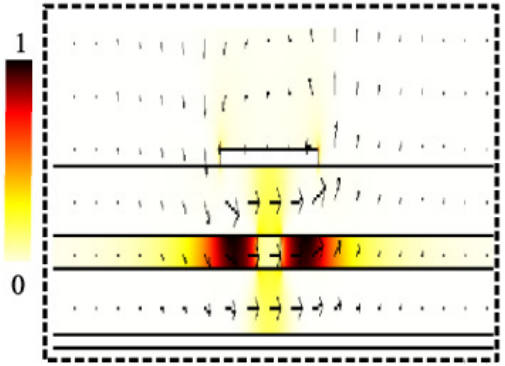


Design:

- Control of the losses in the MIR → Thickness of the InP claddings
- Good overlap of the microwave with the active region → Width of the top contact

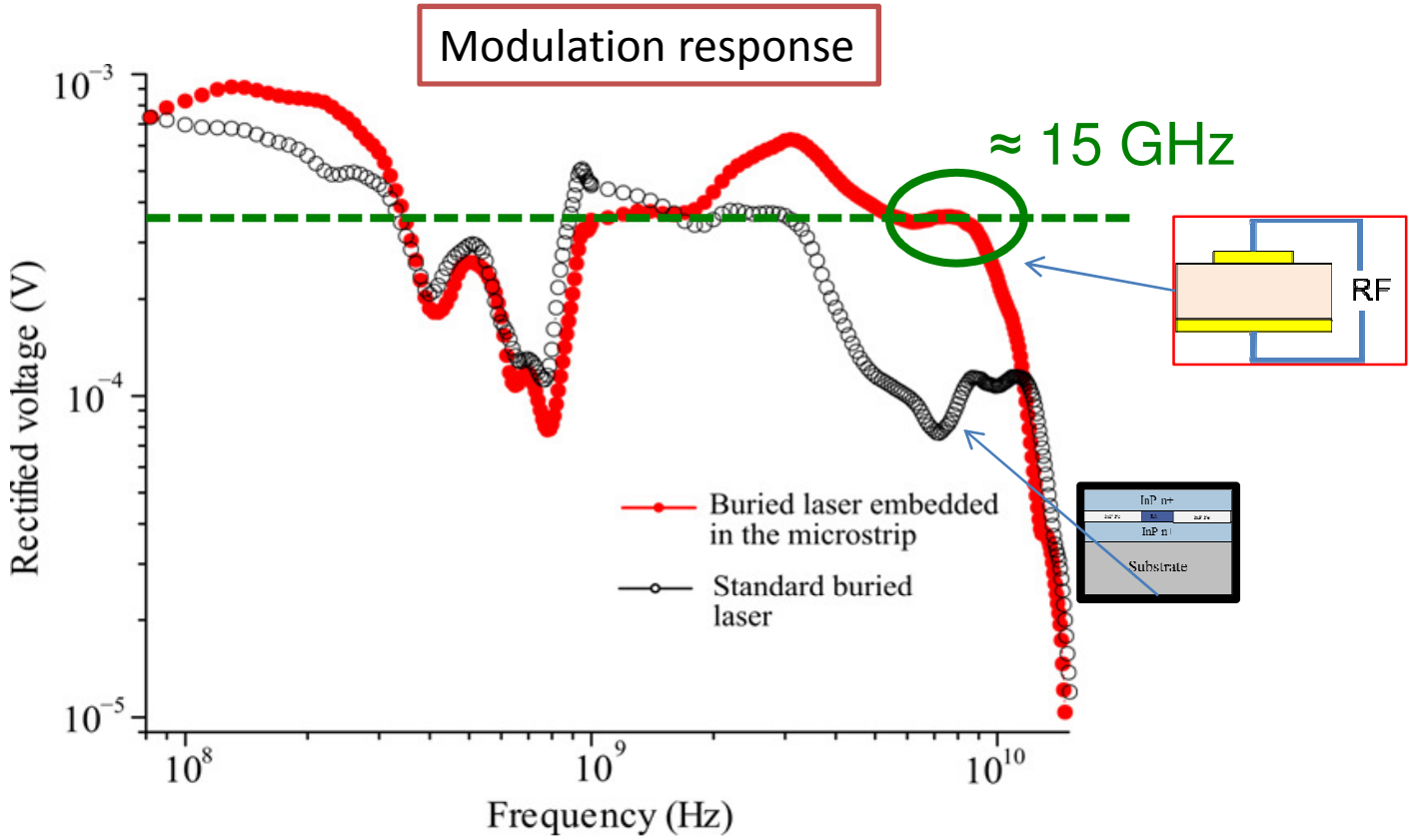
Simulations of the optical and microwave modes

- Drude model for the calculation of the complex refractive index
- Finite element 2D simulation in the plane of the facet



	Microstrip	Standard
Losses @ 33 THz (cm^{-1})	3.5	3.5
Losses @ 13 GHz (cm^{-1})	55	90
Overlap AR @ 13 GHz (%)	1.5	0.6
Figure of merit @ 13 GHz (cm)	0.03	0.006

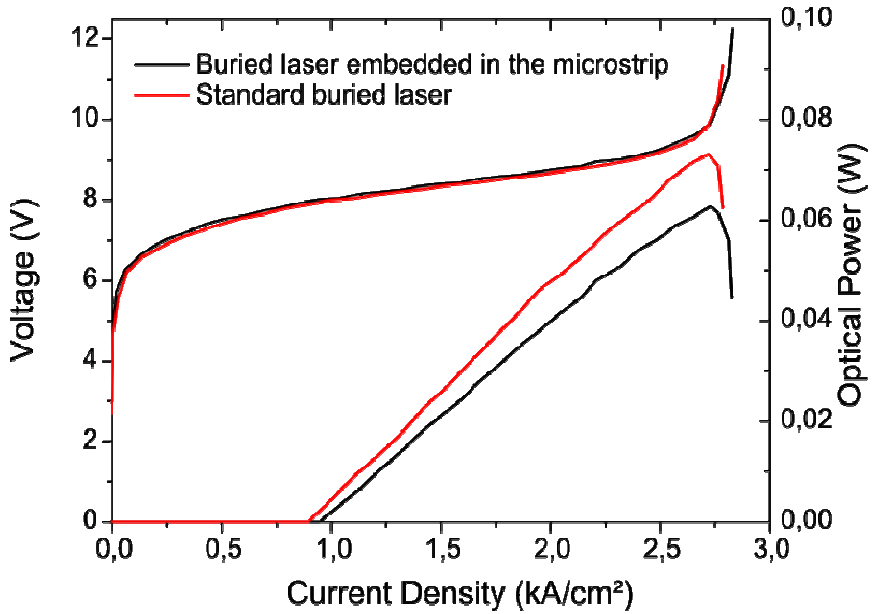
Microstrip vs Standard Buried heterostructure



✔ Improvement of the bandpass up to ~ 15 GHz

Calvar et al Applied Physics Letters 102, 181114 (2013)

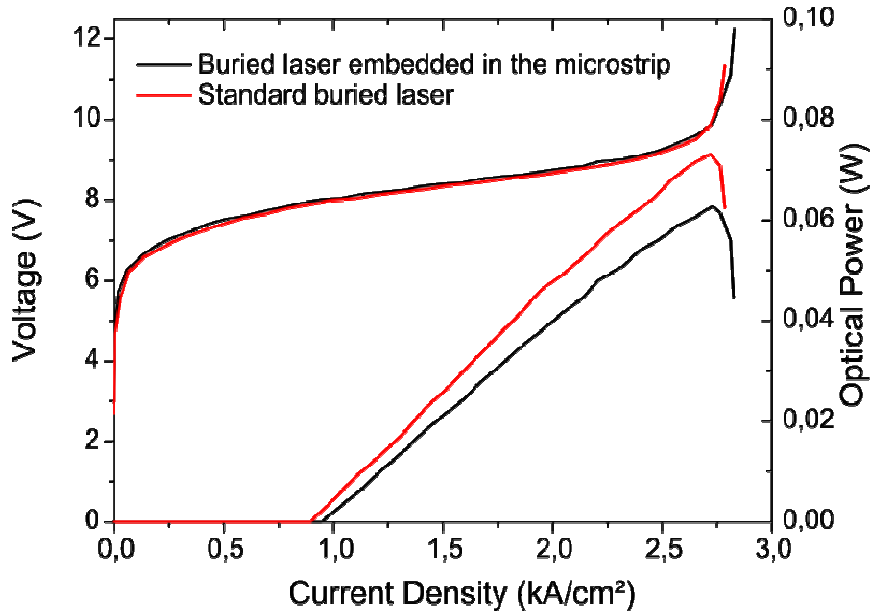
Microstrip vs Standard Buried heterostructure



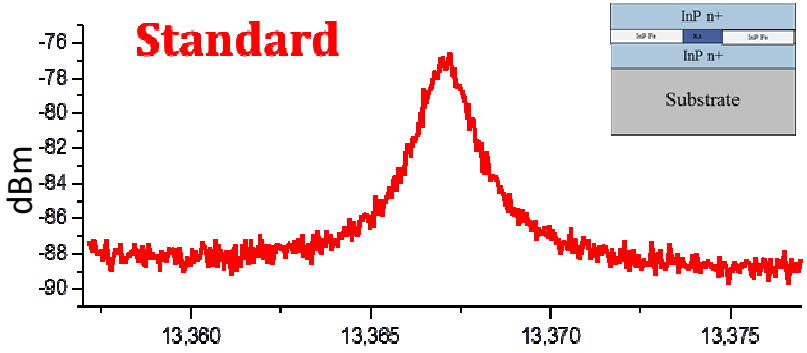
Similar performances

Calvar et al Applied Physics Letters 102, 181114 (2013)

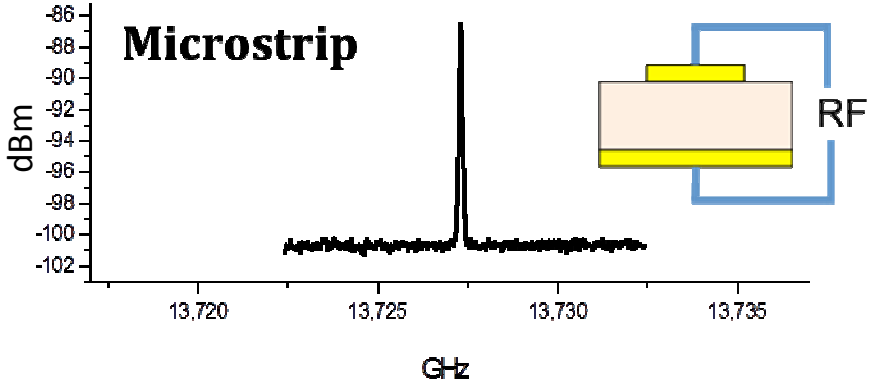
Microstrip vs Standard Buried heterostructure



Similar performances



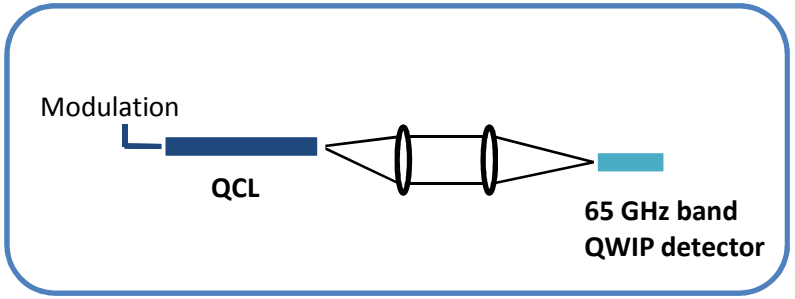
FWHM 1,2 MHz

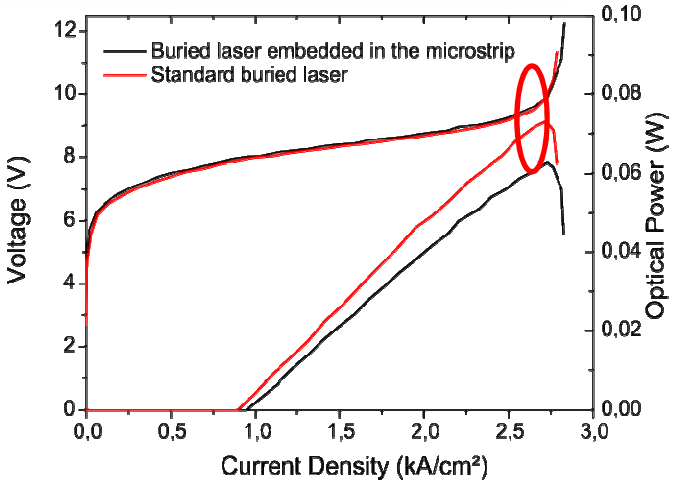


FWHM 100 kHz

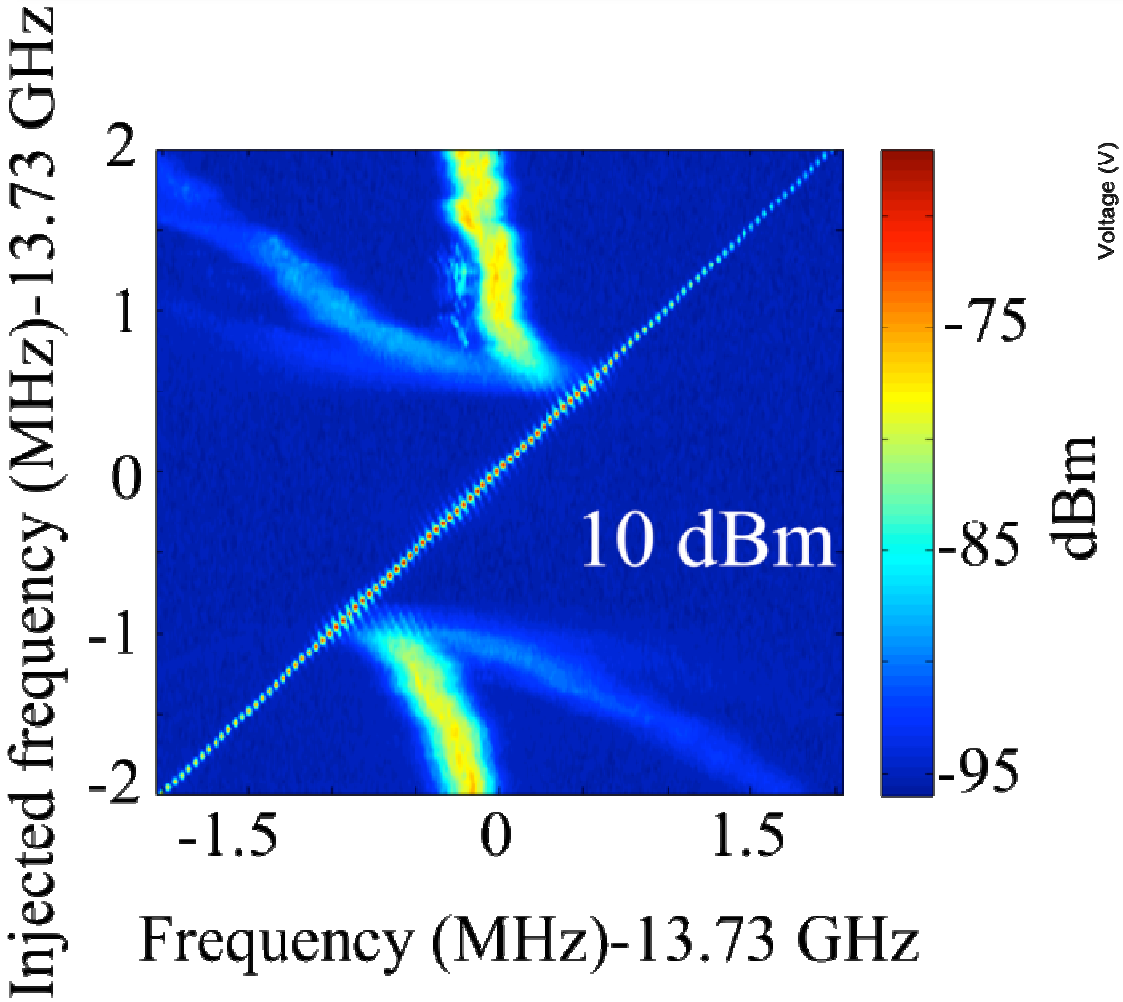
Calvar et al Applied Physics Letters 102, 181114 (2013)

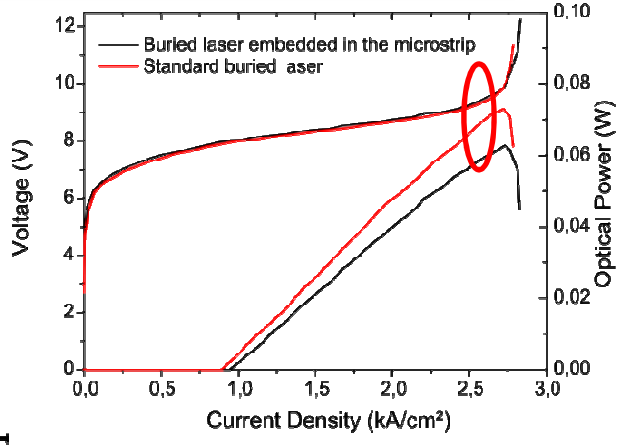
Direct modulation of a microstrip QCL @ 9µm





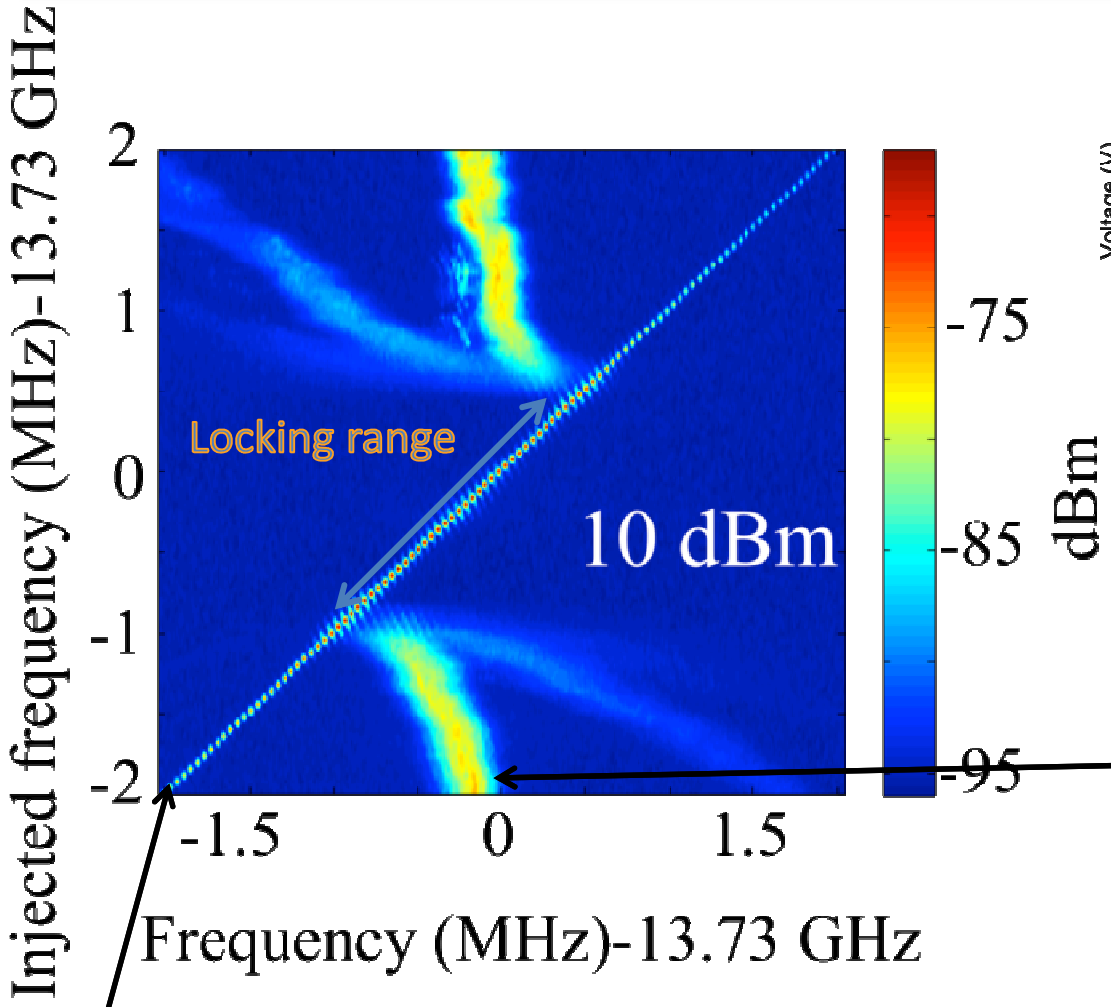
Direct modulation of a microstrip QCL @ 9µm

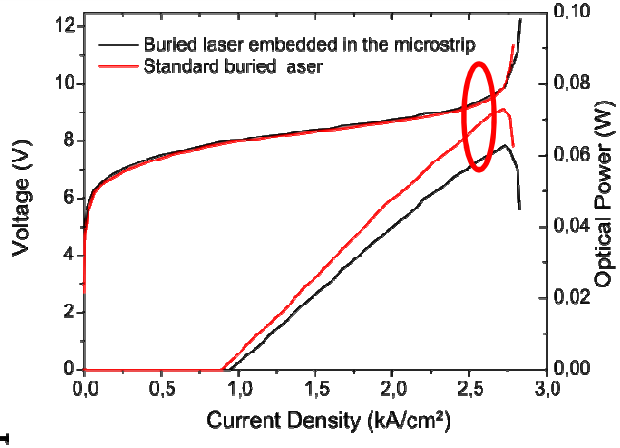




Renaudat Saint-Jean et al Laser & Photonics Reviews 8, 443-449

Direct modulation of a microstrip QCL @ 9µm





Beatnote (Δω)

Signal at the modulation frequency ω_m

Locking over more than 1.5 MHz

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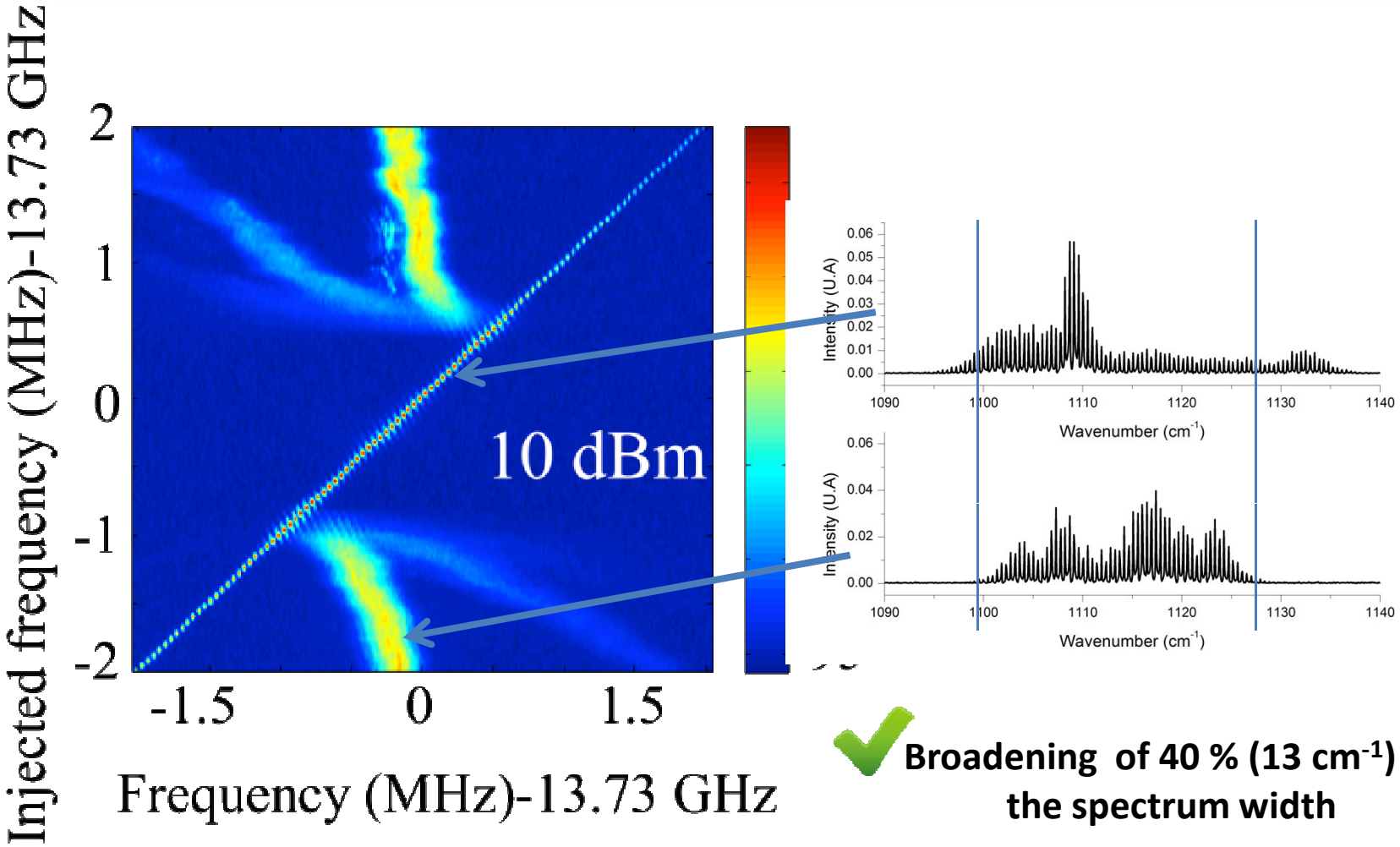
Direct modulation of a microstrip QCL @ 9µm



Broadening of 40 % (13 cm^{-1}) of the spectrum width

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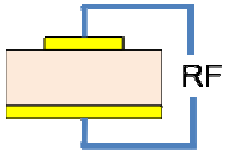
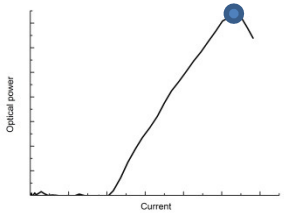
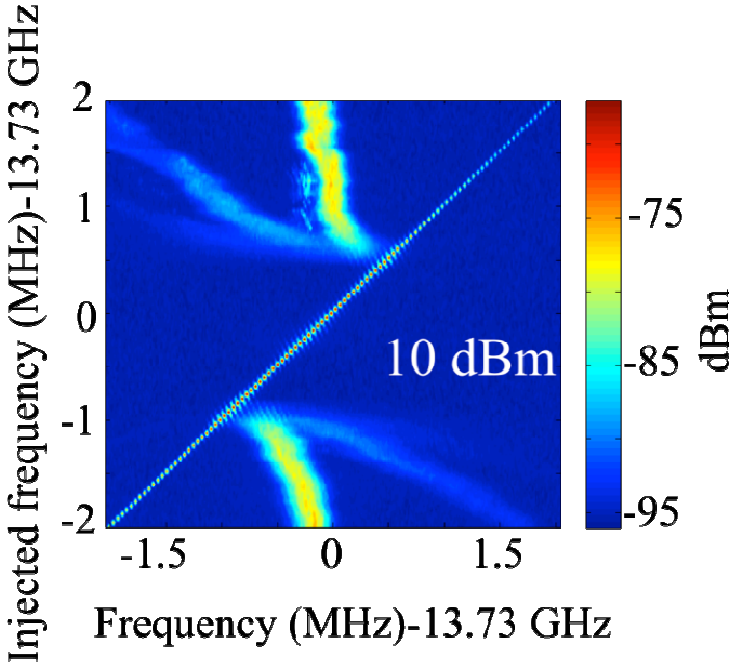
Microstrip vs Standard Buried heterostructure

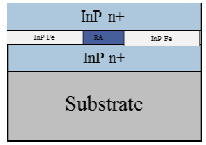
Microstrip laser

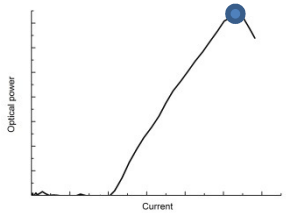


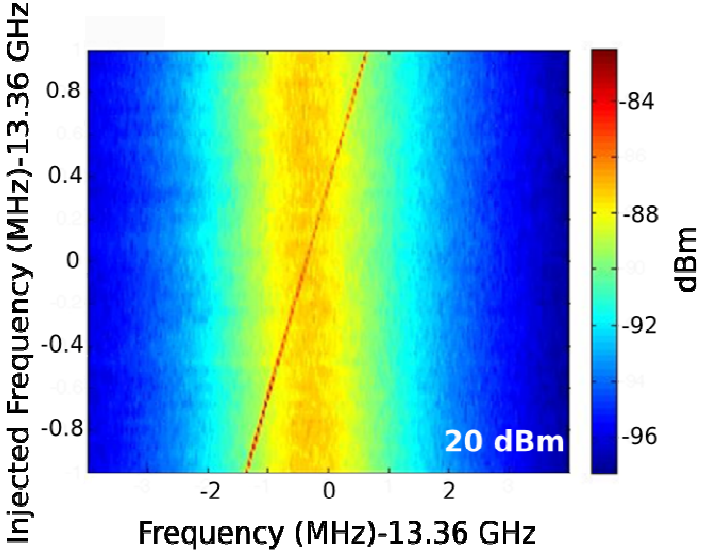




Standard laser



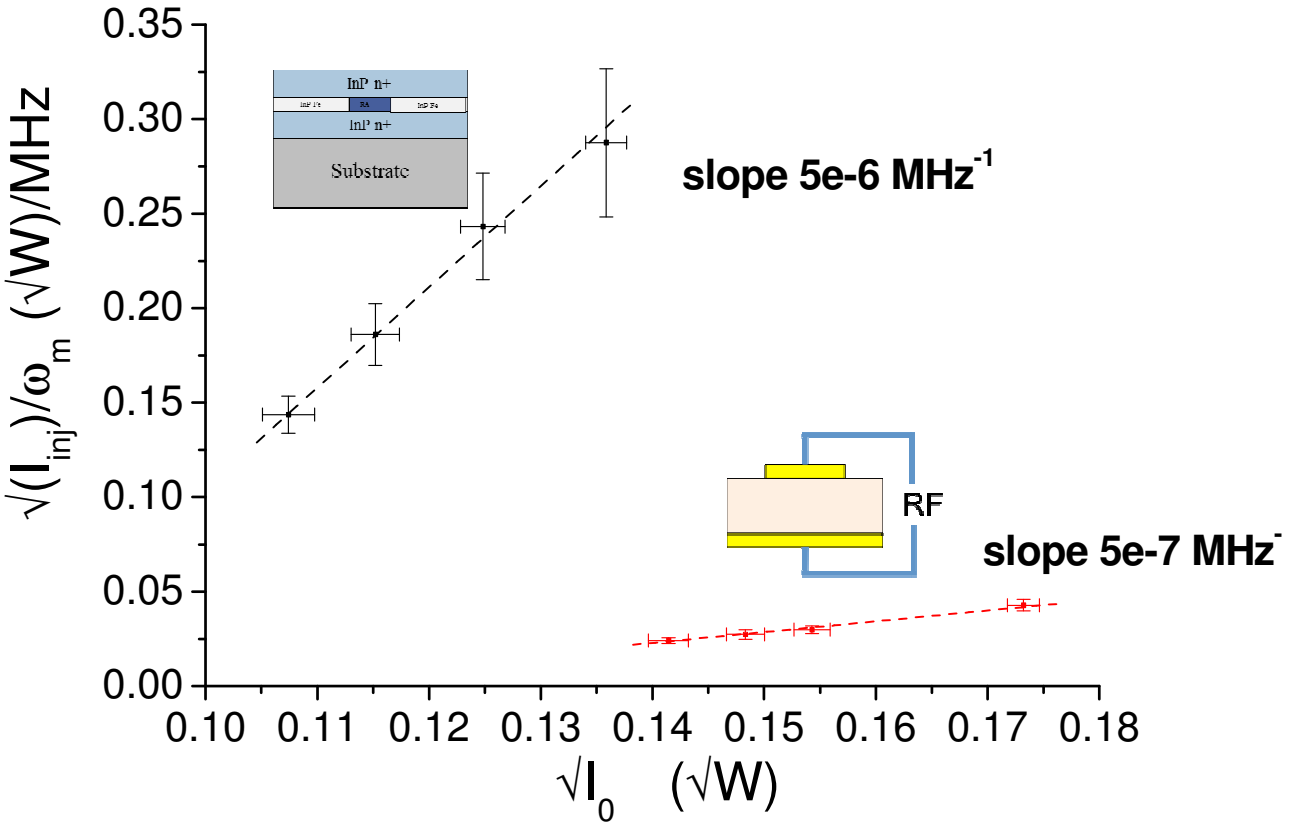




No effect on the beatnote

Coupled oscillators theory

$$\frac{\sqrt{I_{inj}}}{\omega_m} = \frac{Q_{ovt}}{\omega_0}\sqrt{losses_{RF}}\sqrt{I_0}$$



Coupled oscillators theory

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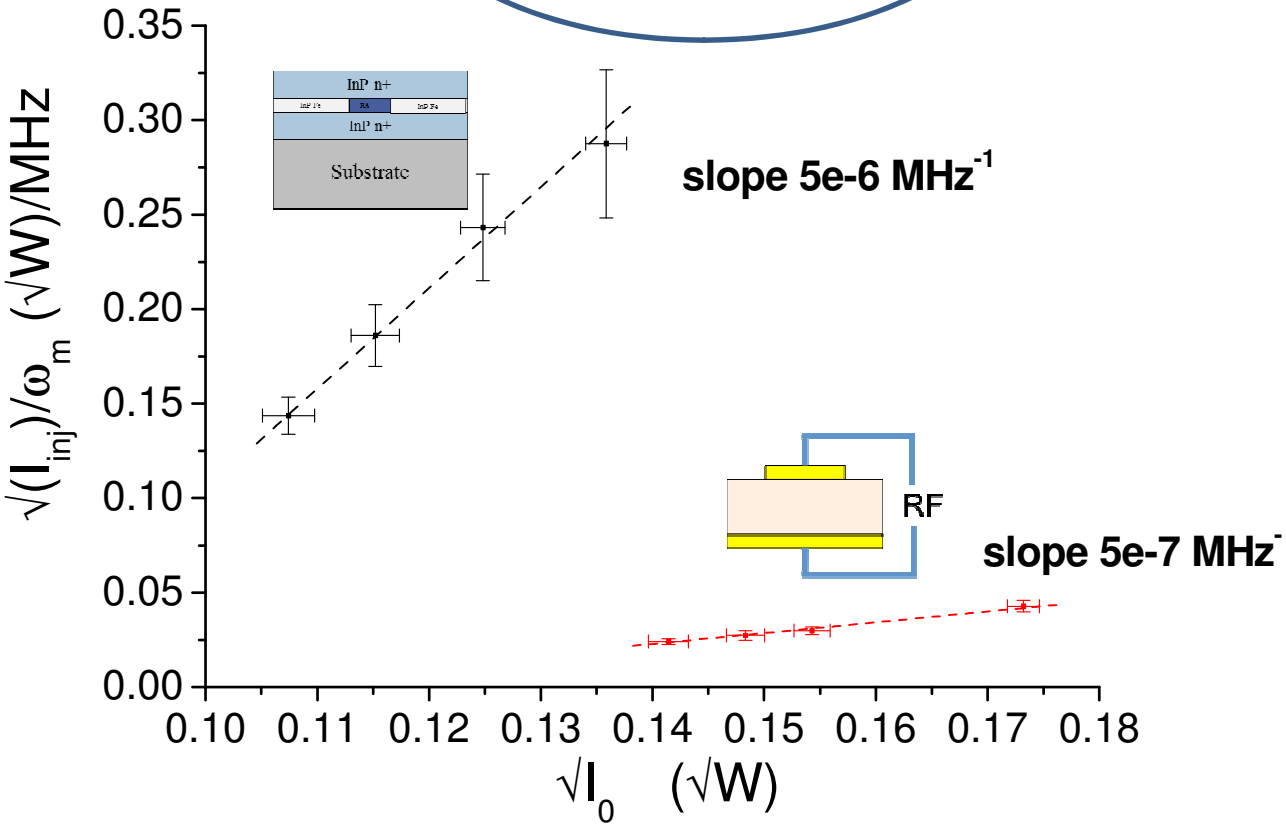


Microwave **losses** for the microstrip **reduced of a factor 10** respect to standard buried

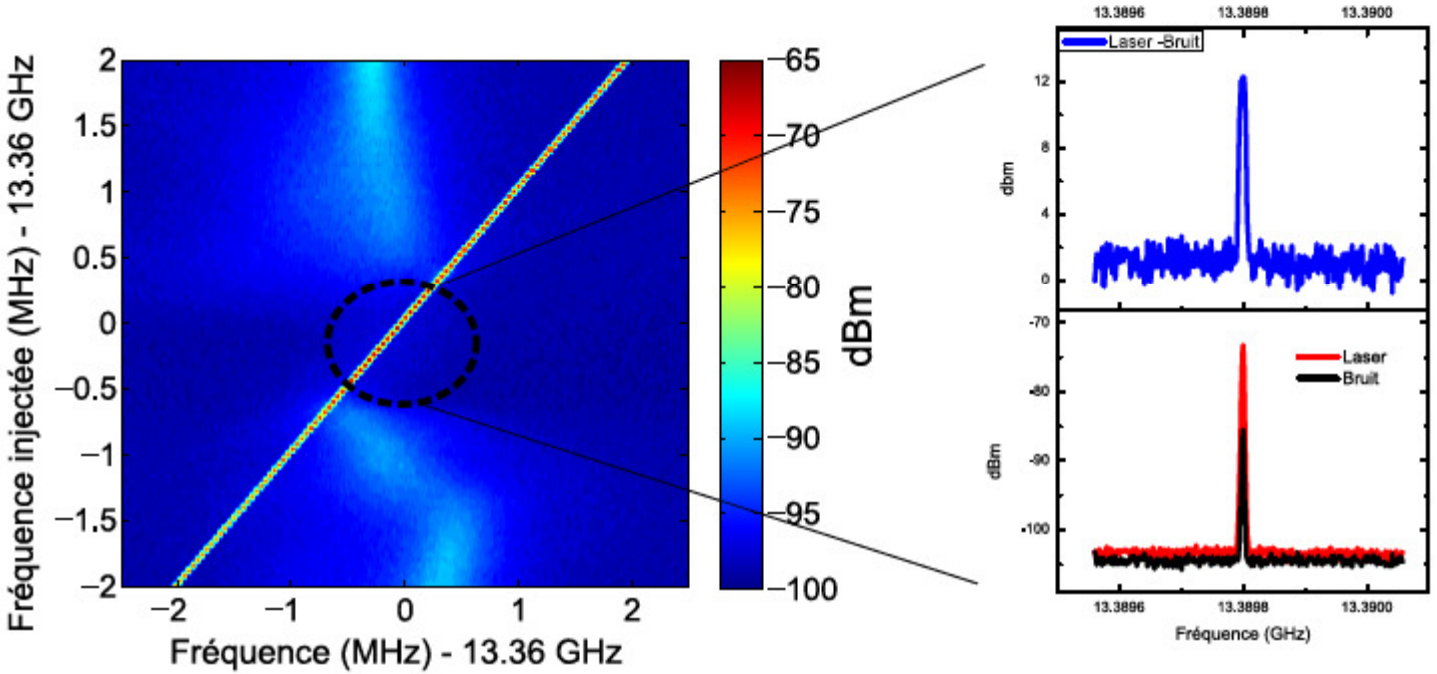
Conclusion:

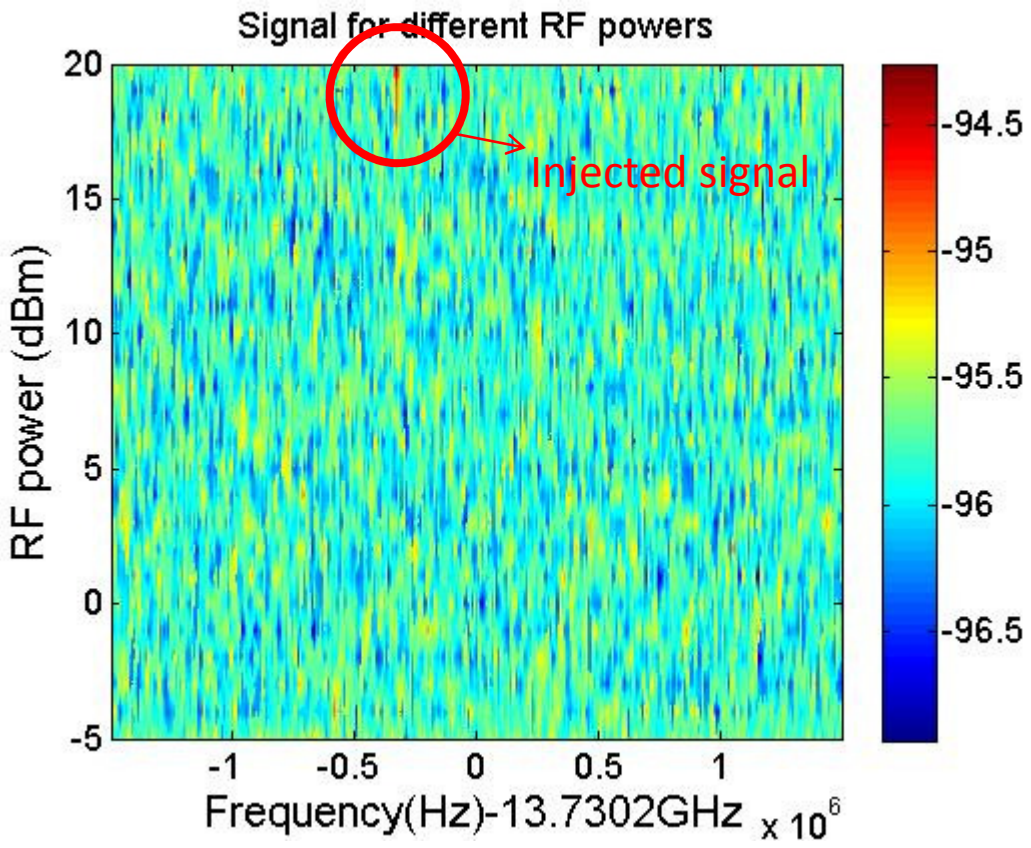
- **Injection locking of QCL emitting in the mid infrared via direct modulation**

- **Design and realization of waveguide embedded in a microstrip line:**

  - ✓ **Reduction of a factor 10 of the microwave losses**
  - ✓ **Locking over more than 1.5 MHz with 10 dBm modulation Power**

THANK YOU FOR YOUR ATTENTION


Fréquence injectée (MHz) - 13.36 GHz
Fréquence (MHz) - 13.36 GHz
dBm
Laser -Bruit
dbm
Laser
Bruit
dBm
Fréquence (GHz)


Signal for different RF powers
Injected signal
RF power (dBm)
20
15
10
5
0
-5
-1
-0.5
0
0.5
1
Frequency(Hz)-13.7302GHz
x 10^6
-94.5
-95
-95.5
-96
-96.5

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