Séminaire Information Communication et Electronique

Self-injected mode-locked lasers for frequency comb generation and application to multi-Tbit/s data transmission

Kamel Merghem

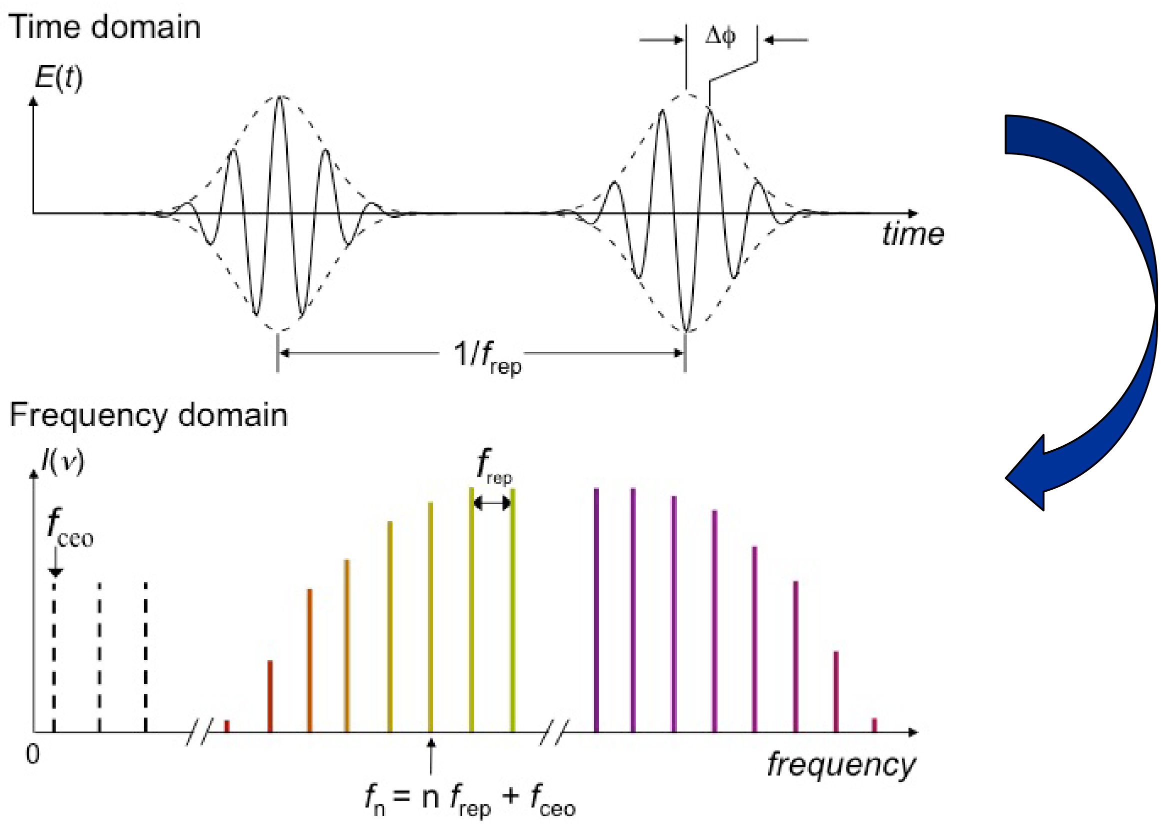
SAMOVAR, IP Paris, Telecom SudParis

Outline

1. Optical Frequency Comb
2. Mode-Locked Laser
    i. Quantum-dash mode-locked laser (MLL)
    ii. MLL characteristics
3. Stabilization schemes
    i. Short-term & long-term frequency stability
    ii. Resonant optical feedback
4. Coherent multi-terabit/s transmission
5. Summary

Optical Frequency Comb (OFC)

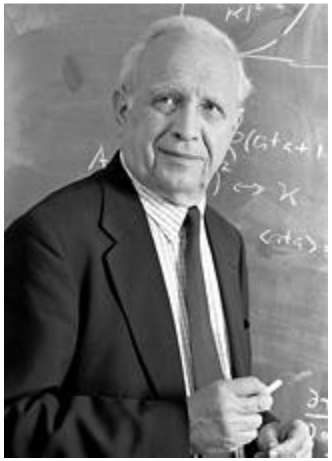
What is an Optical Frequency Comb ?



Fourier transformation

https://www.nist.gov/topics/physics/optical-frequency-combs

The Nobel Prize in Physics 2005



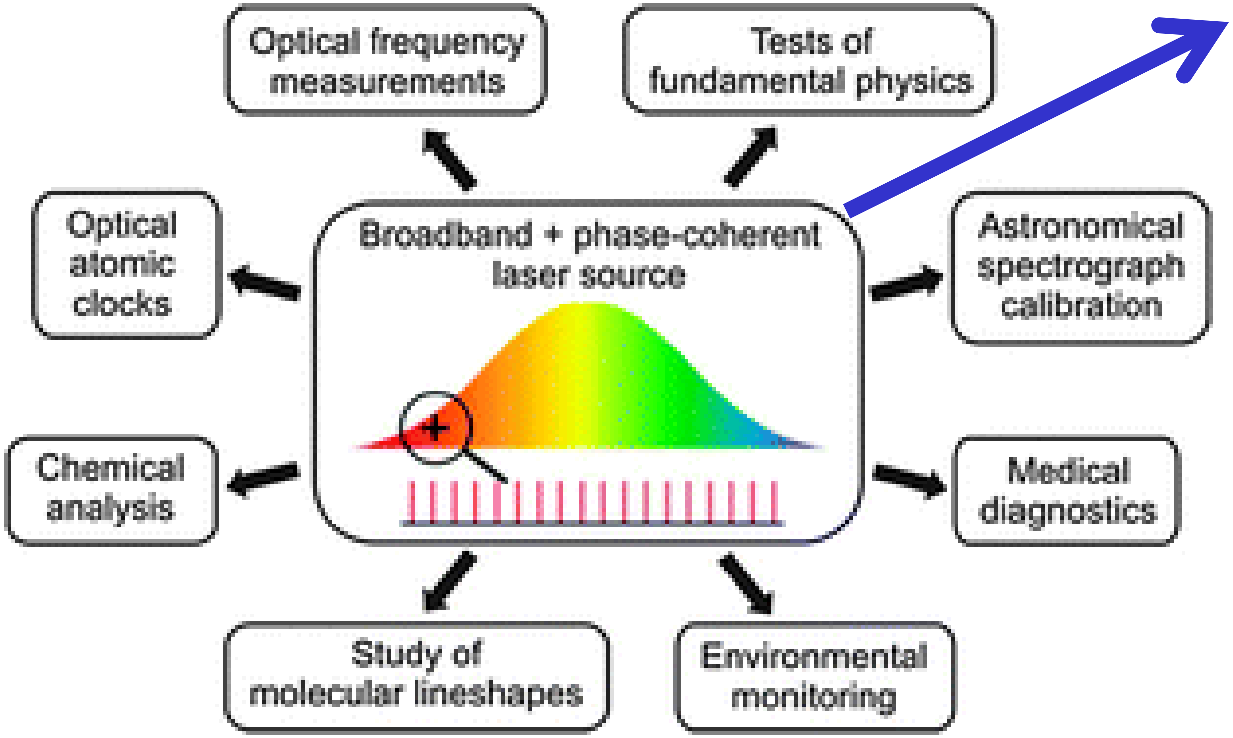
Roy J. Glauber
Prize share: 1/2

John L. Hall
Prize share: 1/4

Theodor W. Hänsch
Prize share: 1/4

The Nobel Prize in Physics 2005 was divided, one half awarded to Roy J. Glauber *"for his contribution to the quantum theory of optical coherence"*, the other half jointly to John L. Hall and Theodor W. Hänsch *"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"*.

Applications

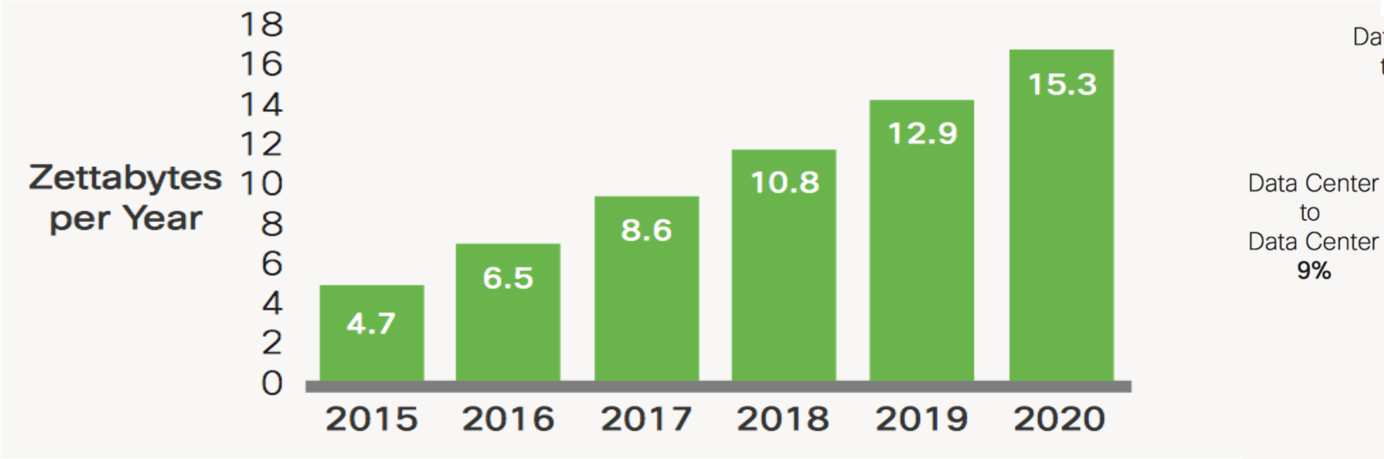


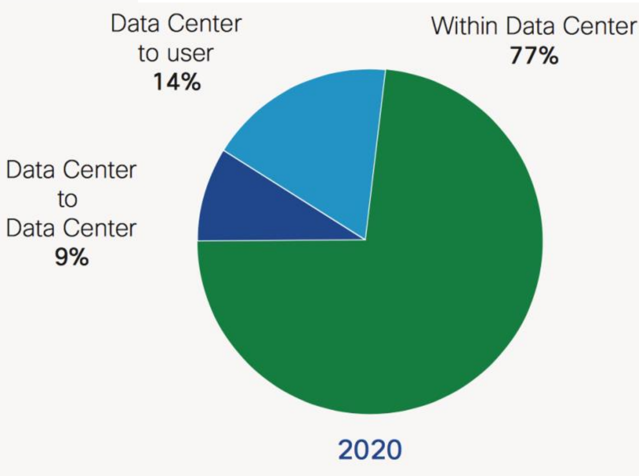
Fiber optic communications

- OFDM superchannels
- Ultra-high capacity WDM

- **Adapted from HS Margolis, Chemical Society Reviews, 15, 2012**

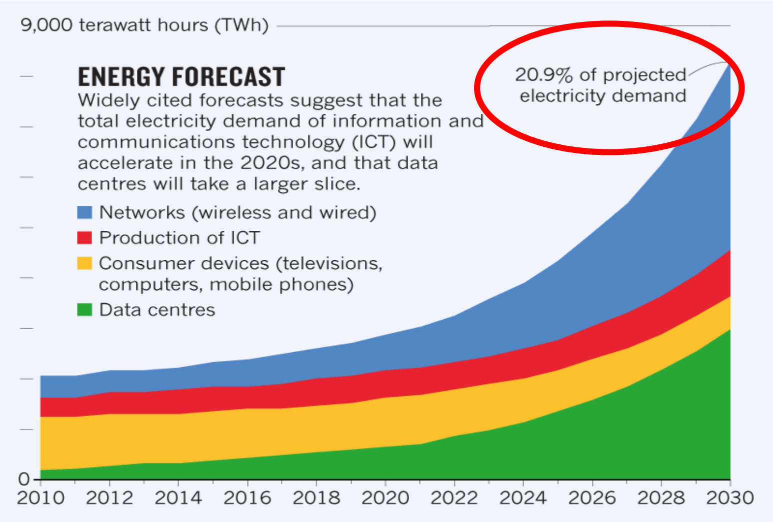
IP Traffic Handling
Source: Cisco Global Cloud Index, 2013–2020





Growth of annual IP traffic from 2015-2020

1 Zettabyte= ~10^{10} Terabyte



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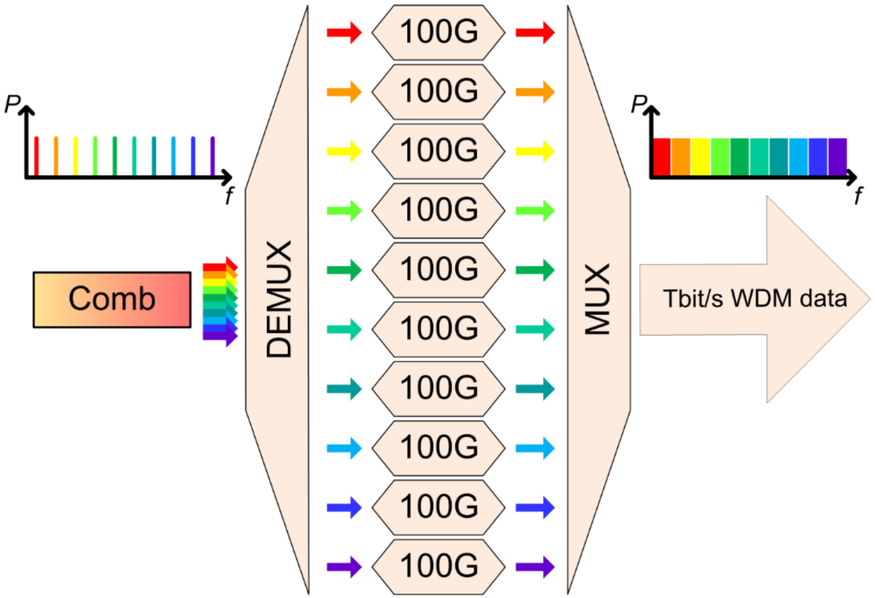
Data center optical interconnects

Requirements 'BIG DATA':
- ***Tb/s data Rates***
- ***Reduced Power Consumption***
- ***High Front Panel Density***
- ***Better Cost Efficiency***

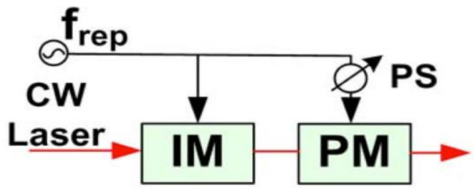
Solution:
Integrated frequency comb sources
- ***energy- efficient and scalable***
- ***Capacity increase w/o compromising footprint and power***

Using comb source vs. individual lasers:
- **Lower power consumption and lower footprint for a higher number of channels**
- **No need for guard-bands between data channels**



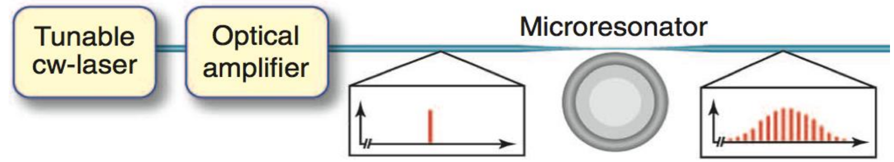
Frequency comb generation

Intensity and Phase Modulation



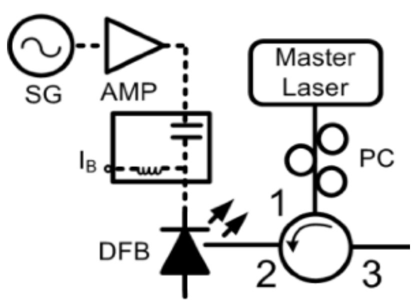
Wu, et al. Opt. Letters(2010)

Cascaded Four-Wave Mixing in High-Q Microresonators



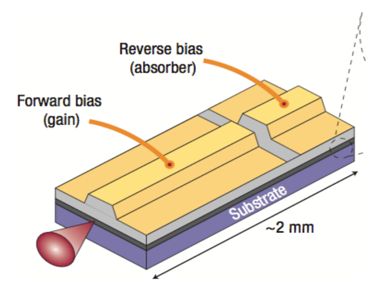
Kippenberg. T, et al. Science (2011)

Injection-Locking and Gain-Switching



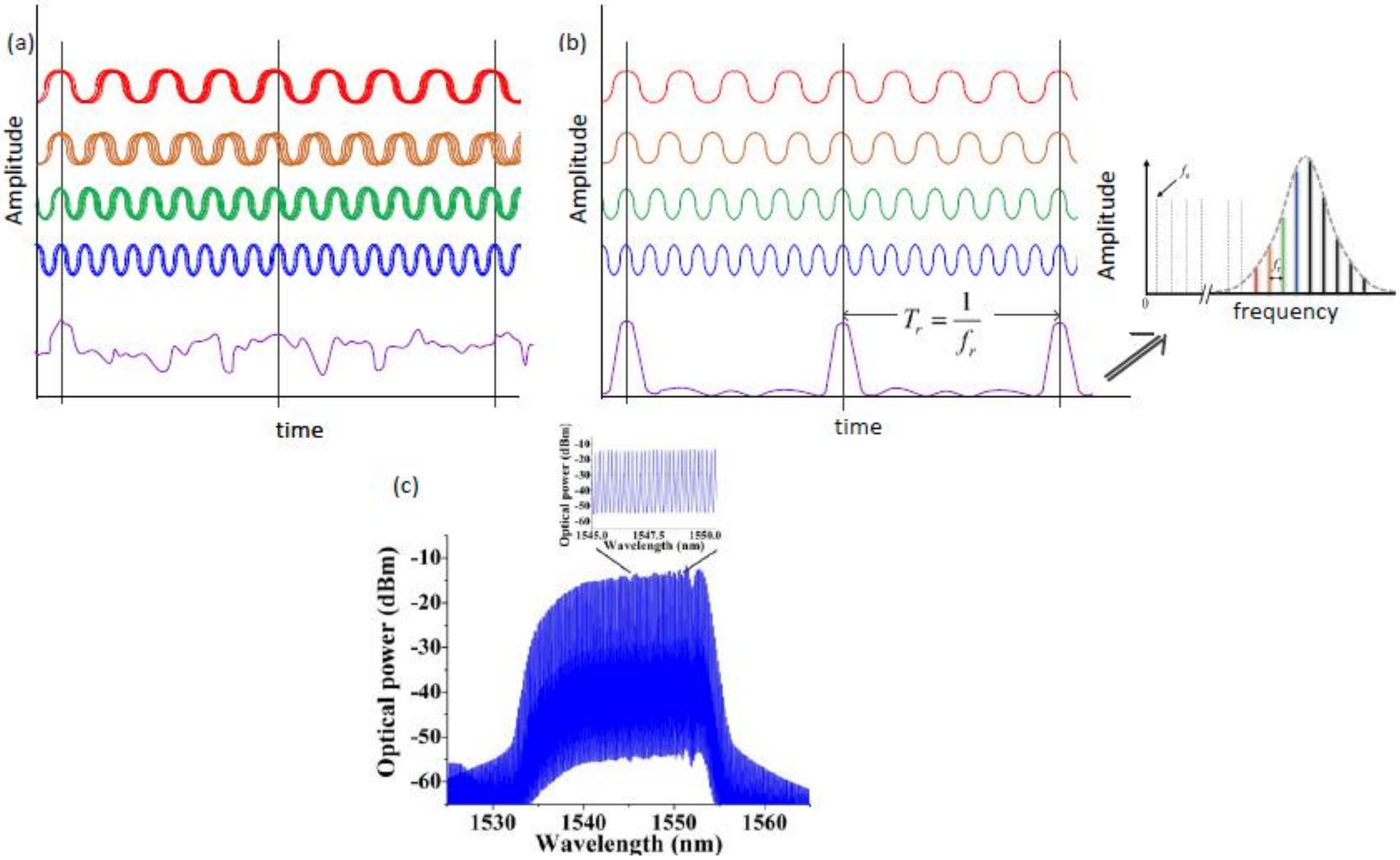
Zhou, et al. Opt. Express (2011)

Laser Mode-Locking

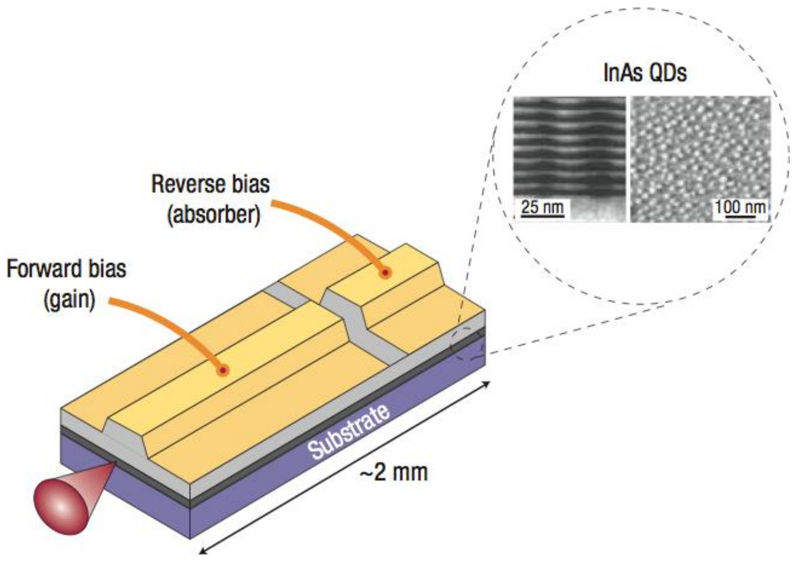


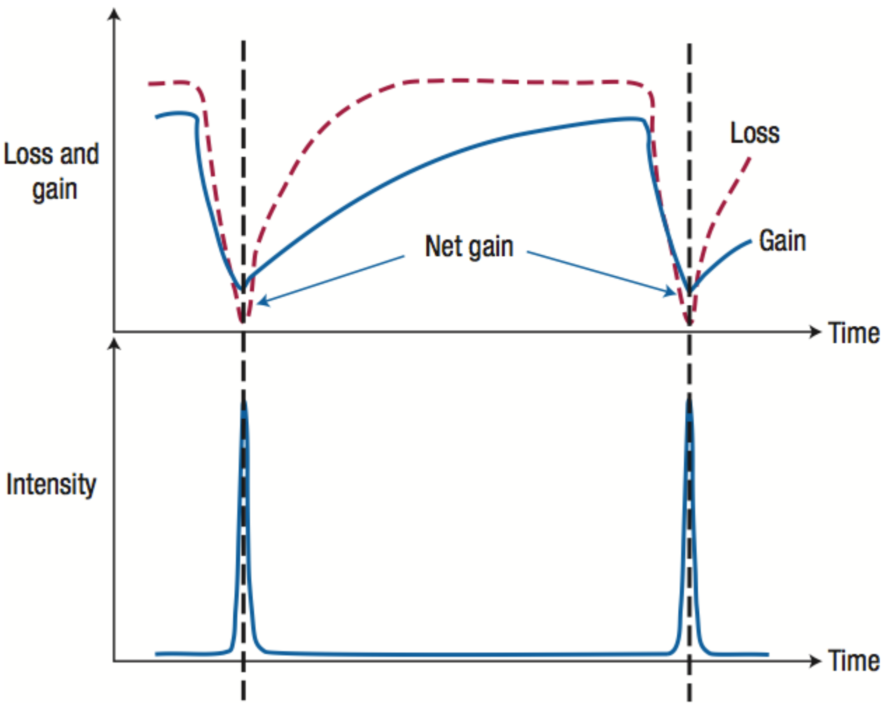
Delfyett, P. J. et al., Elec. Letters (2001)

Mode locking



Monolithic mode locked semiconductor lasers

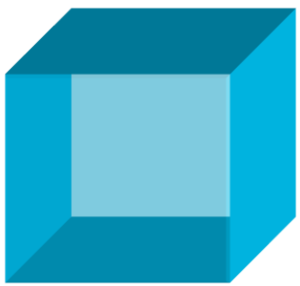


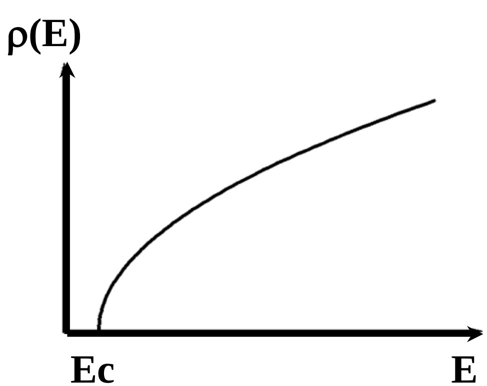


- *The gain section is forward biased*
- *The saturable absorber is reverse biased*
- *Loss and Gain dynamics*

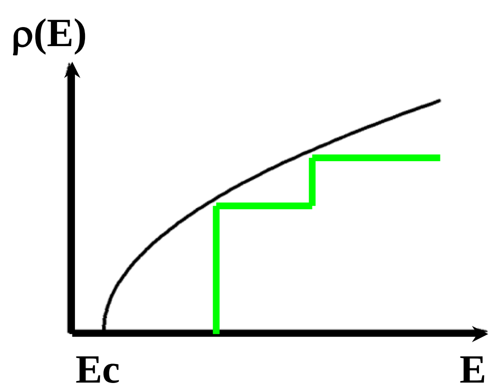
Charge carrier density of states

Bulk semiconductor 3D

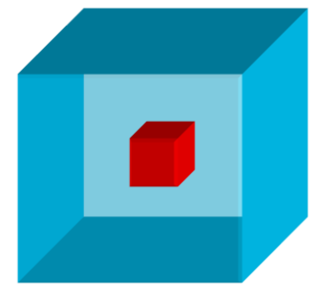


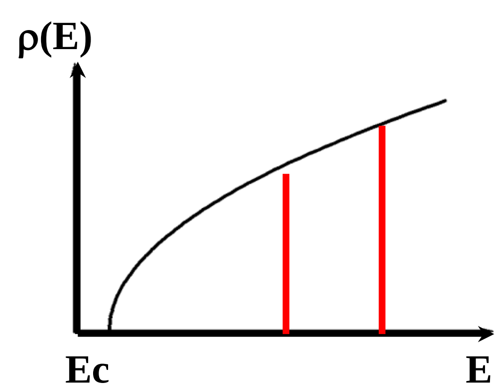


Quantum well 2D



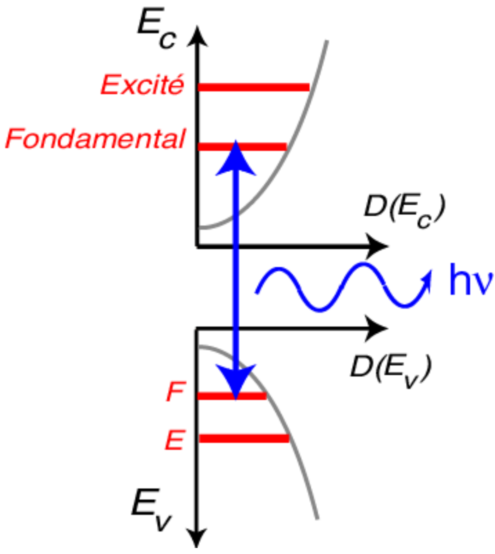
Quantum box 0D





Predicted properties / QD device

- ***Low threshold current density (J_{th})***
- ***High temperature stability (T_0)***
- ***Increased differential gain (dg/dn)***
- ***Small linewidth enhancement factor (α_H)***



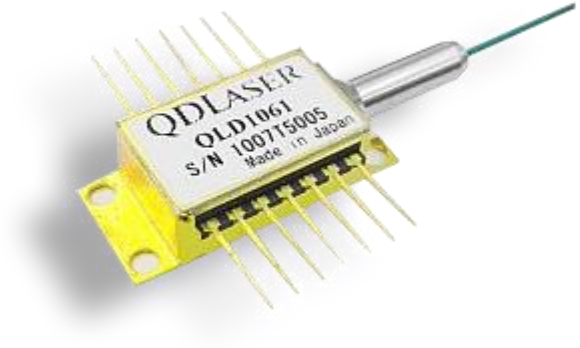
QD-based Mode locked lasers: Interest?

- ***Wide effective optical spectrum***
- ***Fast carrier dynamics***
- ***Small ASE ($n_{sp} \rightarrow 1$)***
- ***Low Γ, low loss waveguide***

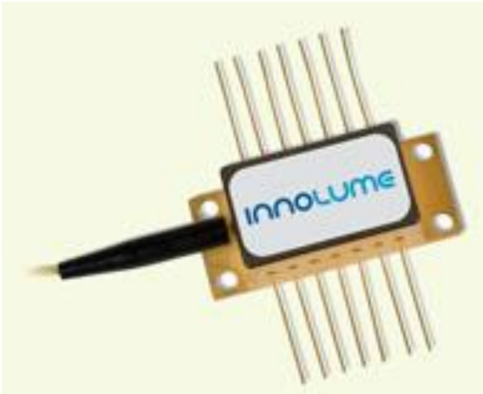
→ ***short pulses***

→ ***low timing jitter***

qdlaser.com/



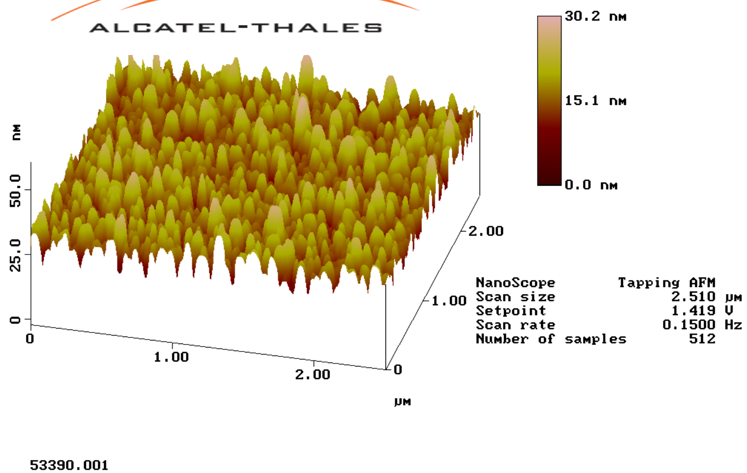
innolume.com/



1.55 µm InAs/InP QDash lasers

► *MBE growth on InP (100) leads to 1D « quantum dash » formation (Univ. of Würzburg, CHTM Albuquerque, …)*

III-V lab
ALCATEL-THALES



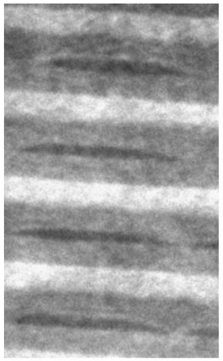
QDs emission at 1.55µm

Height: 2nm, width: 20nm

Length: 50nm→300nm

Qdot→ Qdashes

High density ~5 10^{10} cm^{-2}



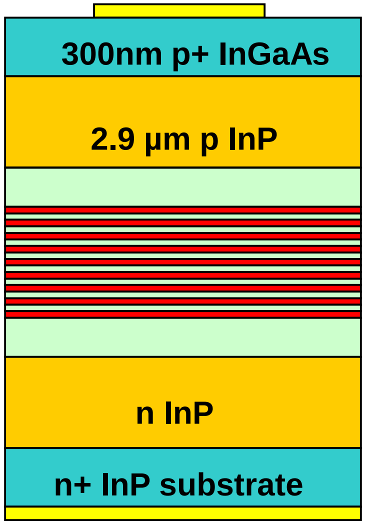
► *MOVPE growth on (100) (Fujitsu, TU Eindhoven, HHI Berlin, LPN) leads to QDs, CBE growth (NRC Ottawa)*

High modal gain InAs/InP (100) Q-Dash lasers

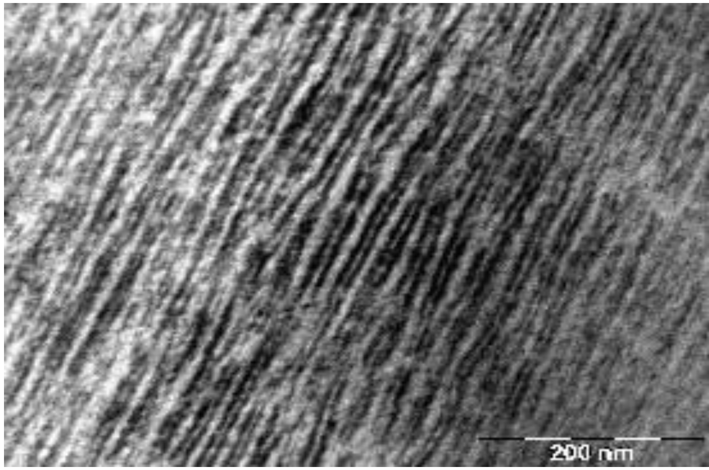
Growth conditions:

- GSMBE on (100) InP substrate
- 6, 9, 12 layers of QDashes

TEM view of active layer



Active layer :
9 InAs/GaInAsP QDash layers
Gg_0= 100 cm^{-1}

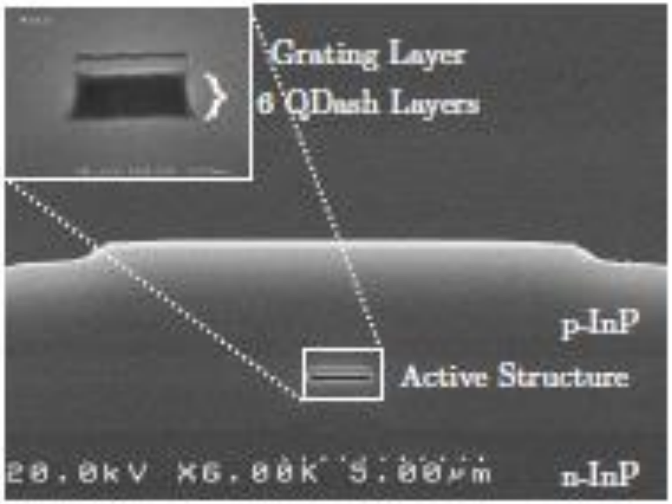


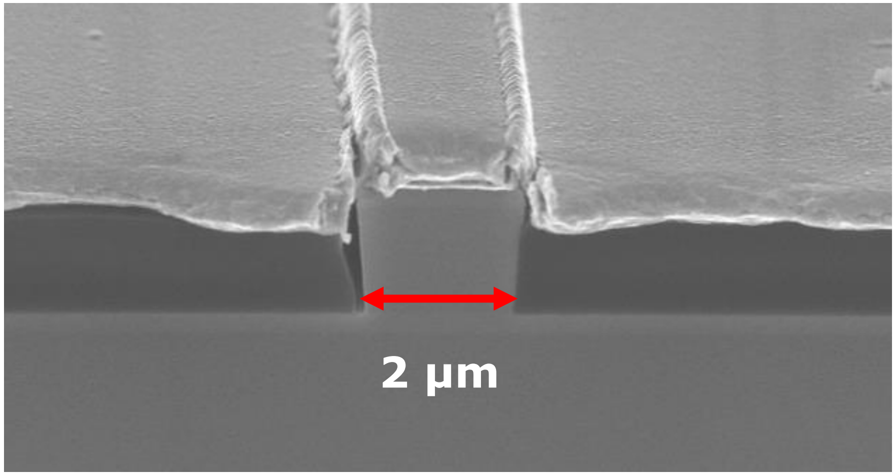
Quantum Dash
(200–400 nm)

G Moreau et al., Applied Physics Letters (2006)

F. Lelarge et al., J. Select. Top. Quant. Electronics (2007)

QDash laser fabrication





- Buried Ridge Stripe (BRS)
- Regrowth step
- Industry fabrication approach

- Ridge waveguide (RWG)
- Standard processing
- Higher injection currents

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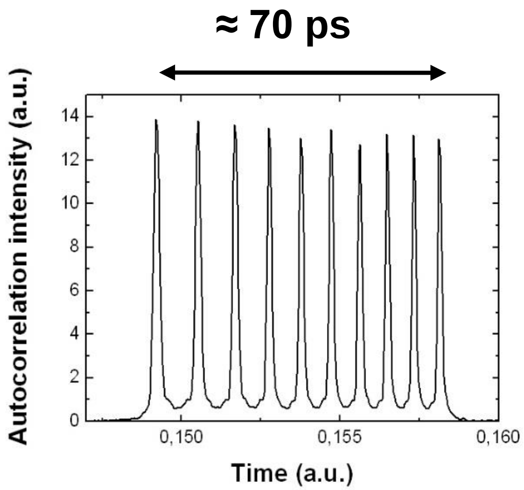
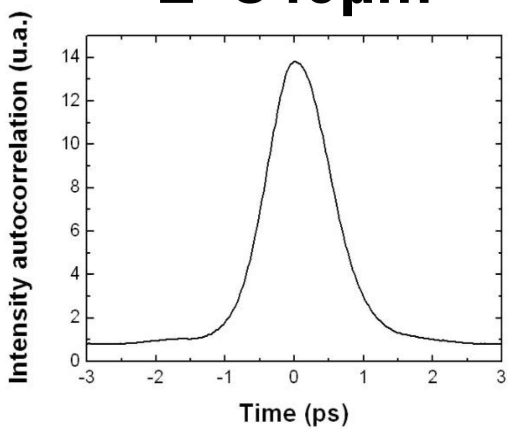
Sub-picosecond pulse generation: 1-section devices

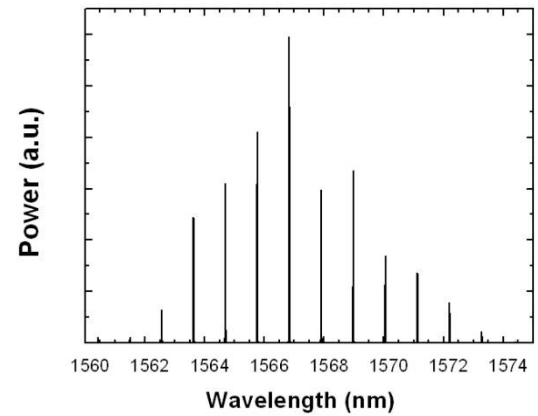
Single section Qdash laser

C Gosset et al., Appl.Phys. Lett. 2006



L=340µm





ER = 13 dB
134 GHz

$\Delta\tau_{AC}$ **= 1.1 ps**

$\Delta\tau_{pulse}$ **= 800 fs**

Hyp: Gaussian shape

$\Delta\nu$ **= 0.54 THz**

$\Delta\tau_{pulse}\Delta\nu$ **= 0.46**

⇒ Enhanced non-linear effects! (FWM)

Nomura et al., Phys Rev A,65,043807,2002

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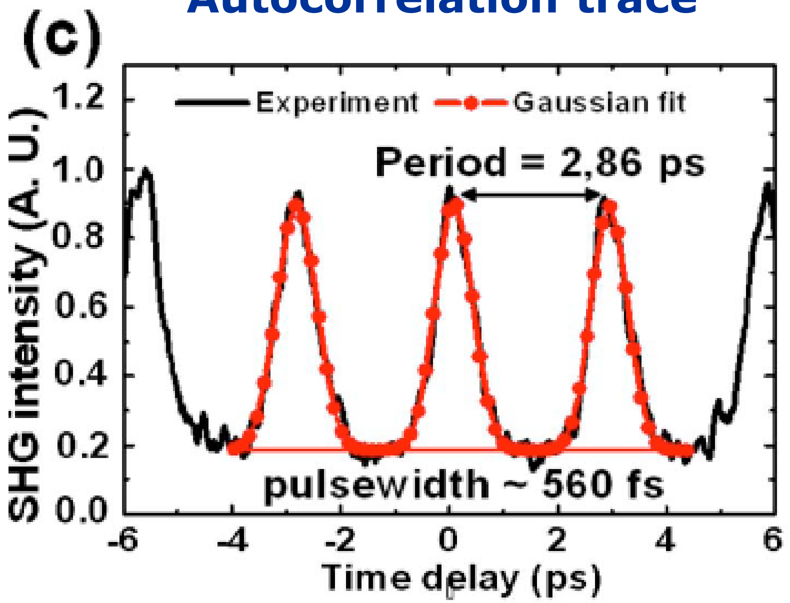
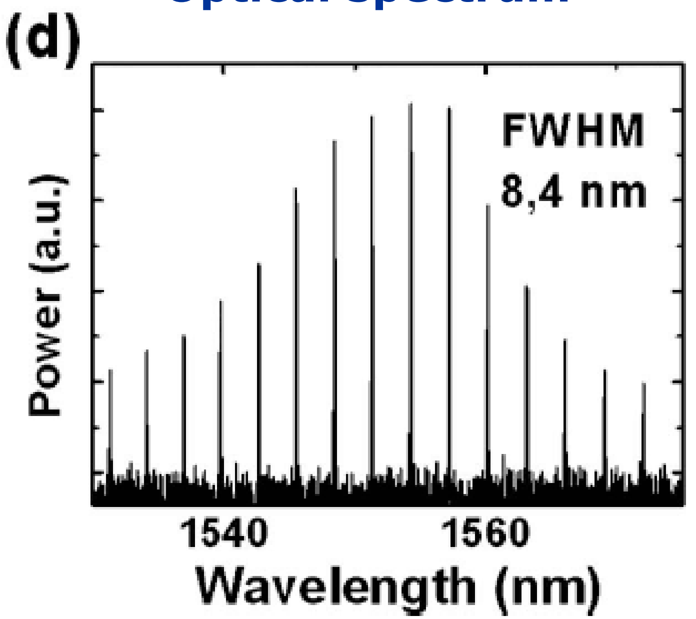
Pulse generation @ 346 GHz

120-µm-long laser (I=217mA)
Pulsewidth 560fs @ 346 GHz

Autocorrelation trace



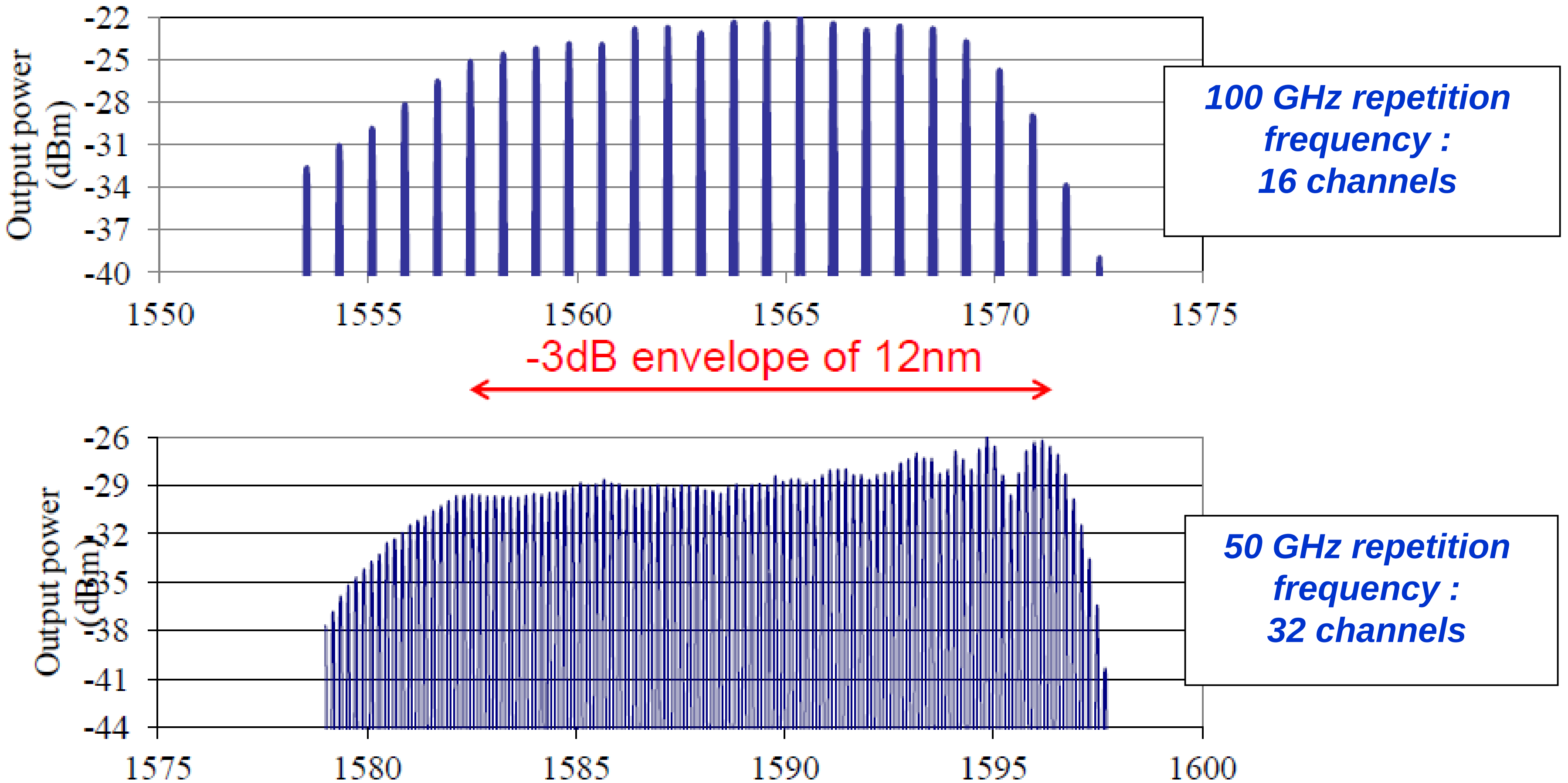
Optical spectrum



K. Merghem et al, Appl. Phys. Lett 2009

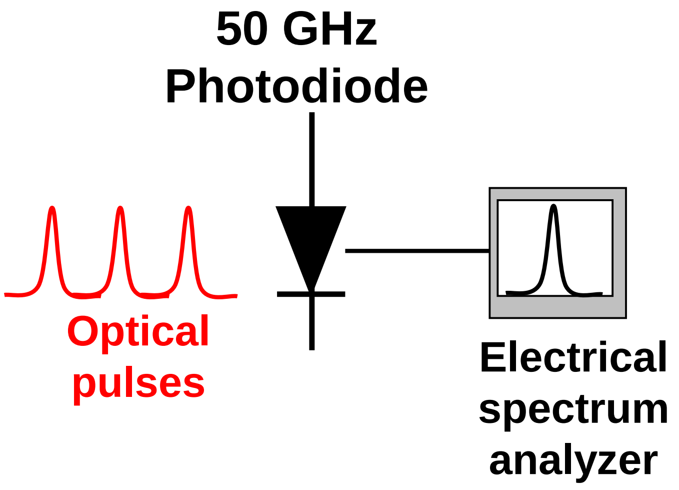
Ultra-high bit rate all-optical signal processing

Optical spectra of QDash based lasers

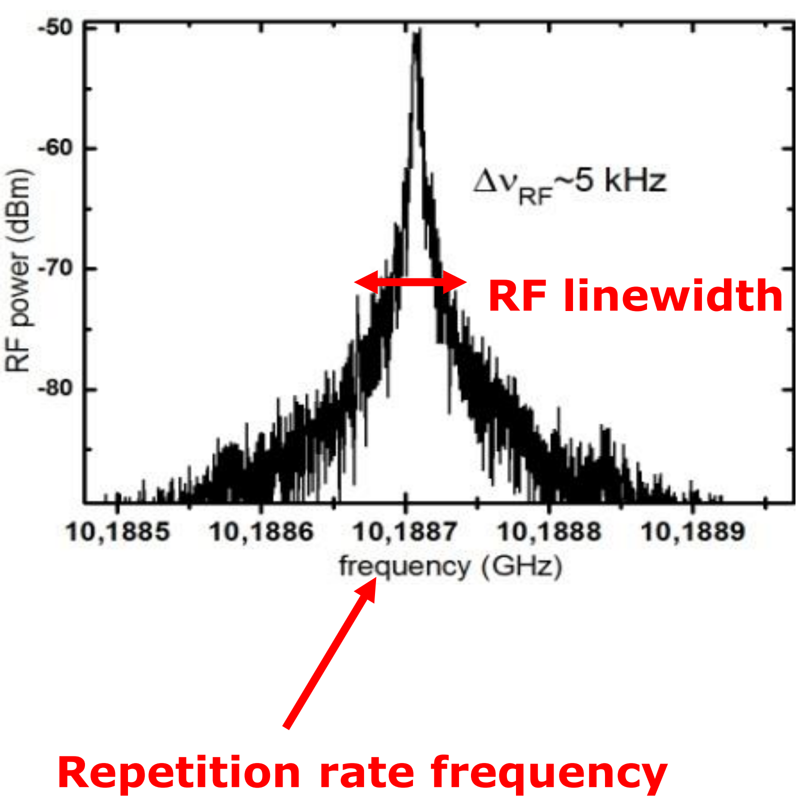


- ***Typical FWHM = 12 nm → 1.5 THz***
- ***Optical bandwidth does not depend on cavity length***

Photocurrent analysis in RF domain

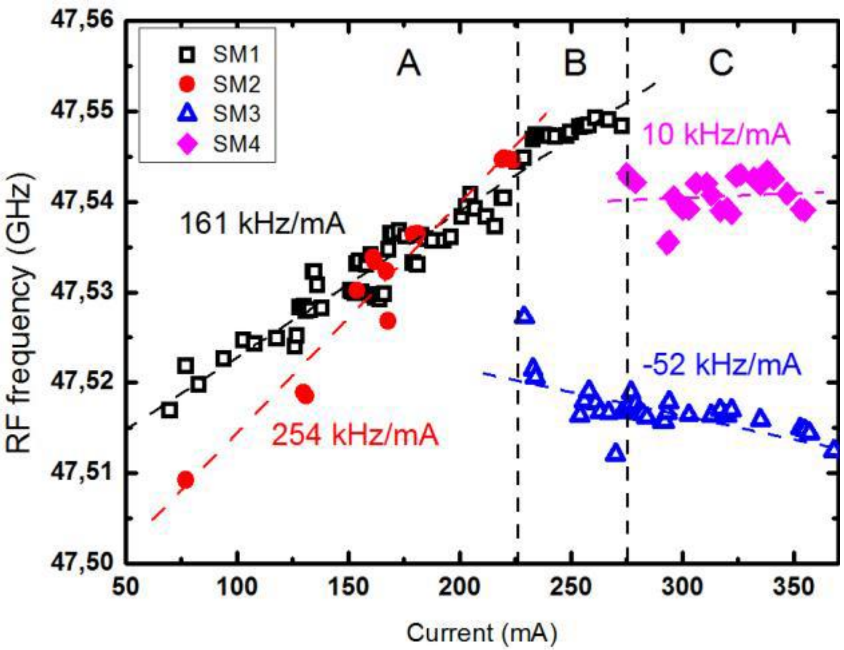


Radio-Frequency spectrum

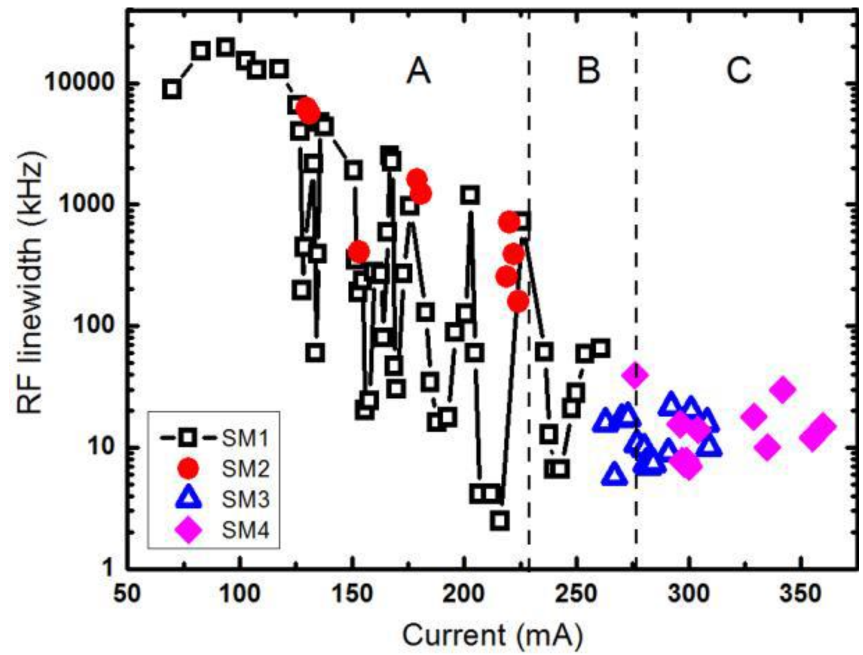


Repetition frequency and RF linewidth evolution with injection current: supermode analysis

Repetition rate frequency



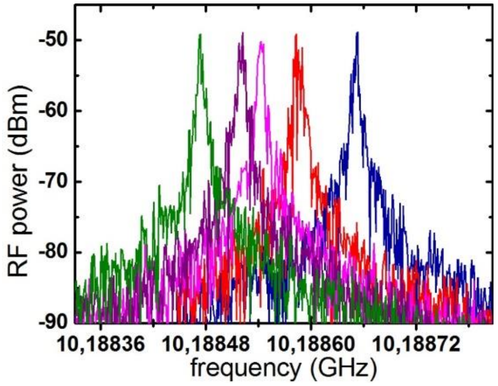
RF linewidth



K Merghem et al., IEEE J. Quant. Electron. 2014

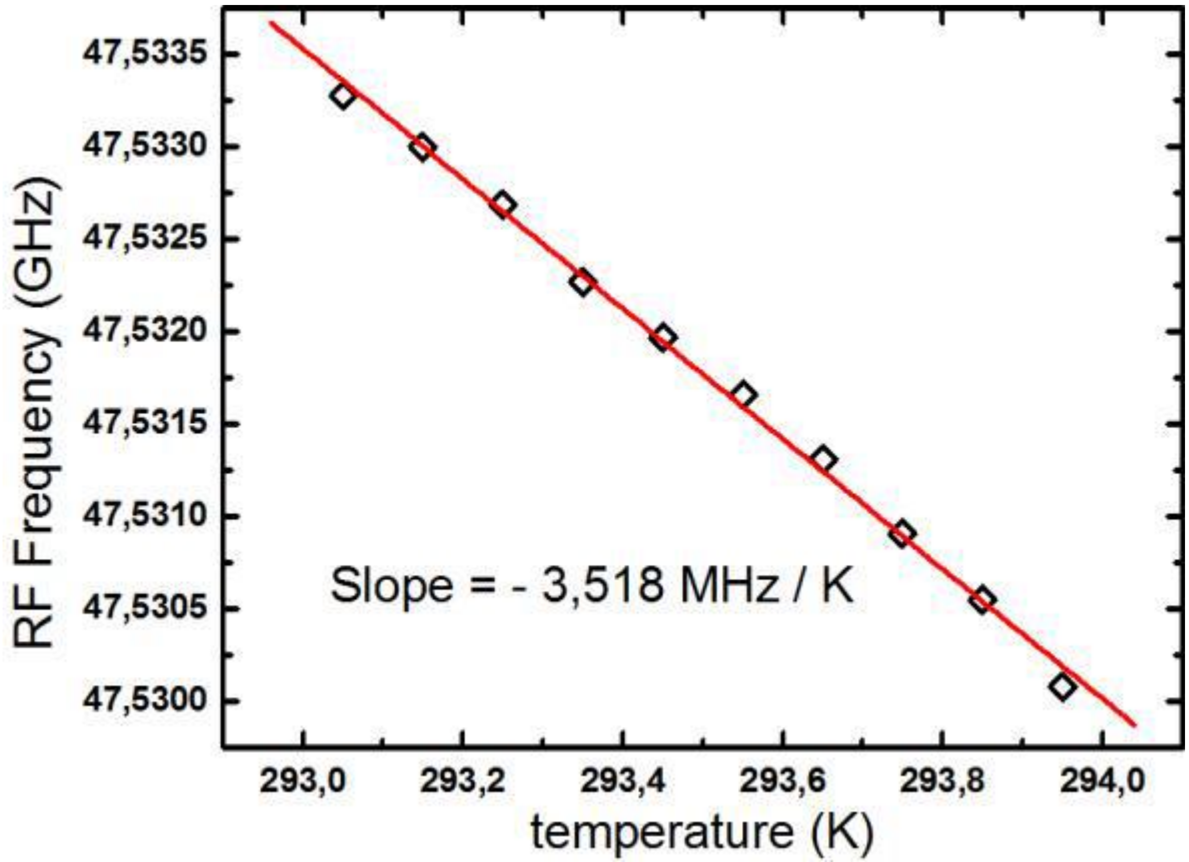
Frequency stability?

- ***Long term RF drift? (environmental noise!)***
  - ***Temperature variations***
  - ***Bias fluctuations***
  - ***Non-controlled optical feedback...***

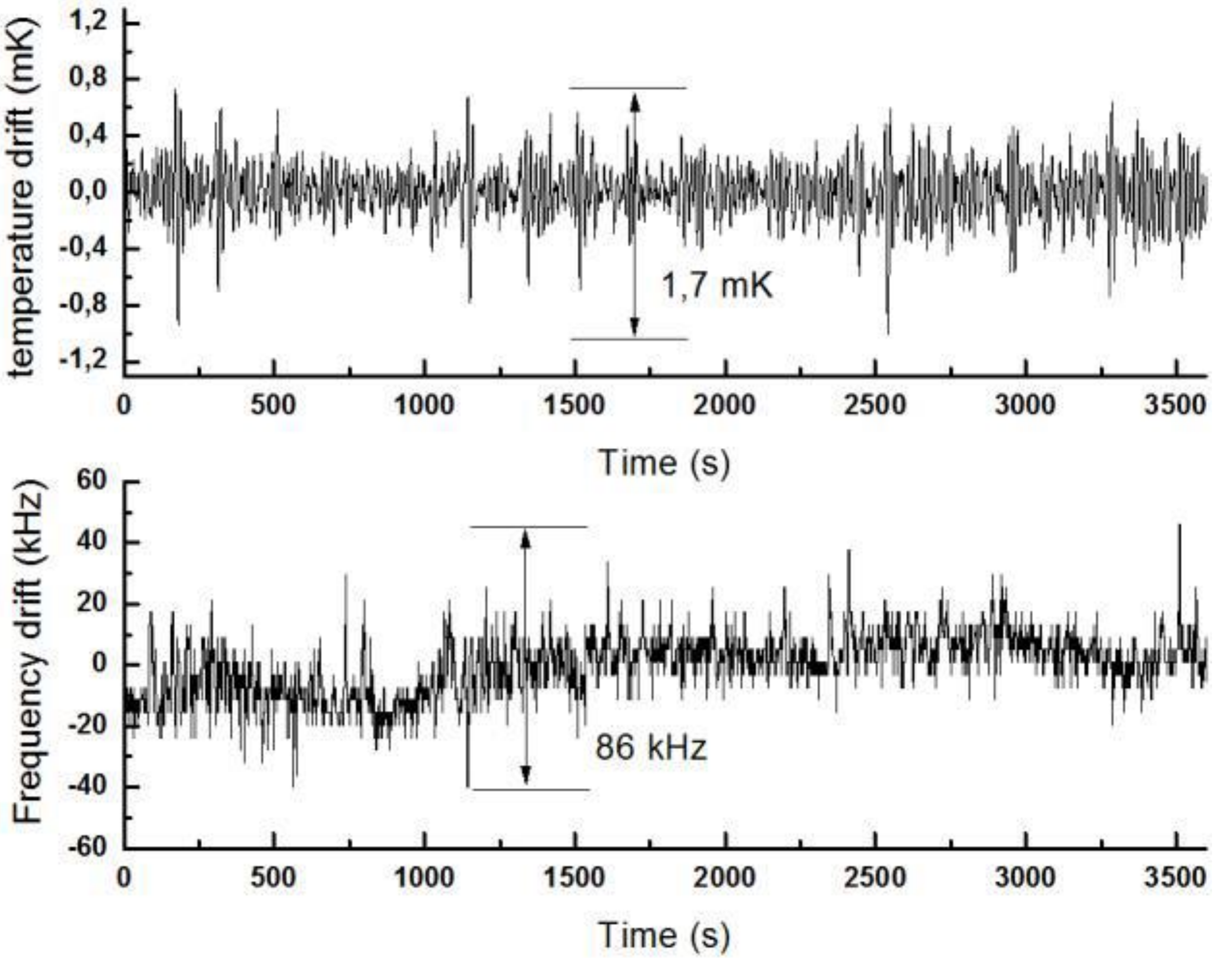


- ***Key point:***
  - ***Specific control depending on application (e.g. Metrology)***

Effect of temperature



Long term temperature drift



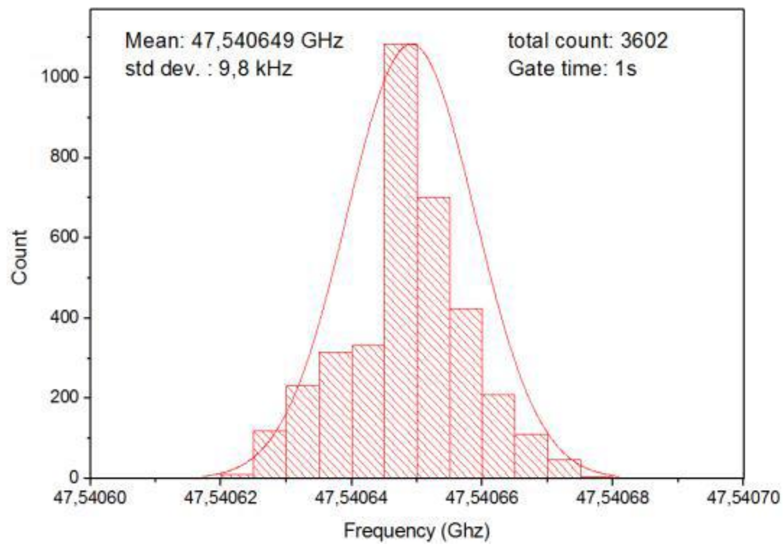
► ***Use low noise battery current source !***

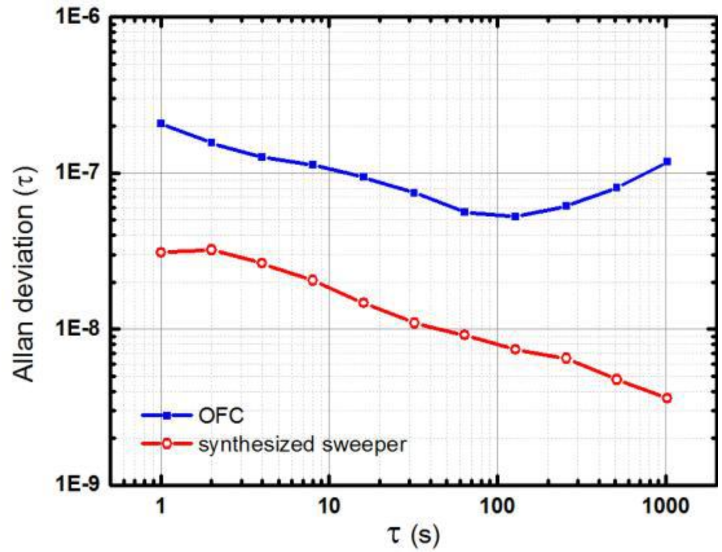
2 mK $\Rightarrow$ 7 kHz variation

Allan deviation (fractional frequency instability)

Allan variance : two-sample variance

Measure of frequency stability using M samples, time T between measures and observation time τ

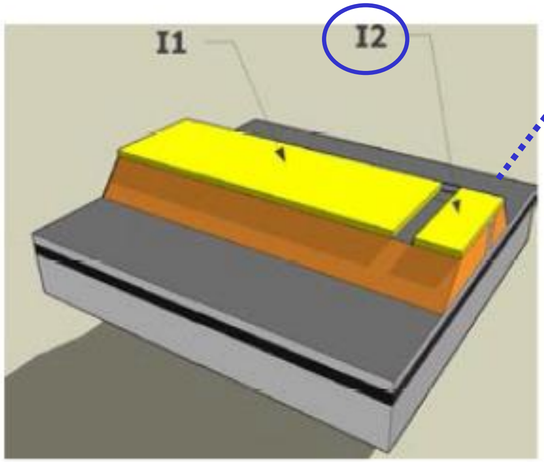




► ***First report for passive mode locked laser***

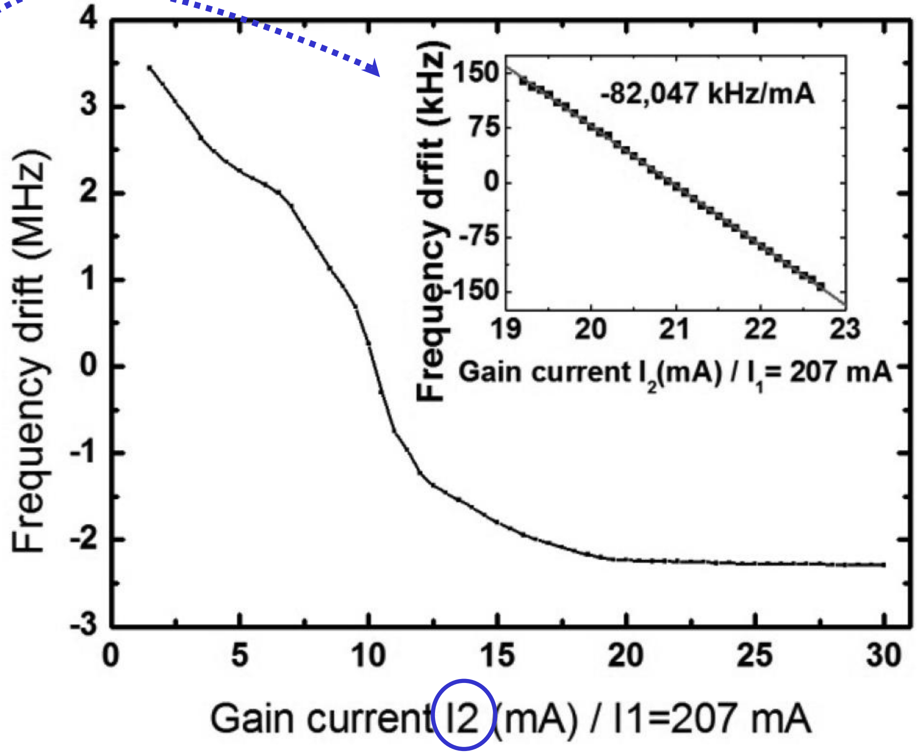
Effect of PID stabilization loop

2-section device



2 gain sections
No absorber section !

Repetition frequency evolution



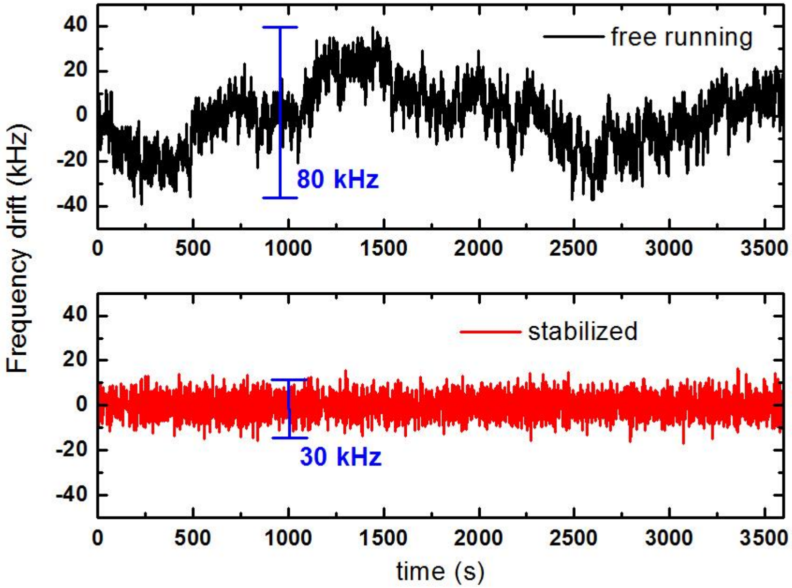
P **I** **D**

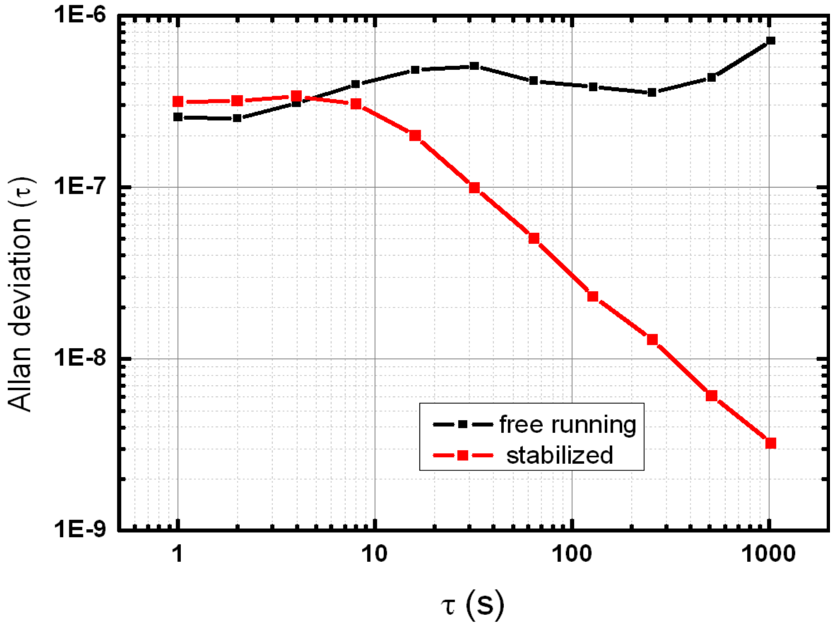
$$u_n = K_p . e_n + K_i \sum_{j=0}^{n} e_j + K_d(e_n - e_{n-1})$$

e_n : Frequency drift

Effect of stabilization loop (2-section device)

► ***gain-gain device at 10 GHz***

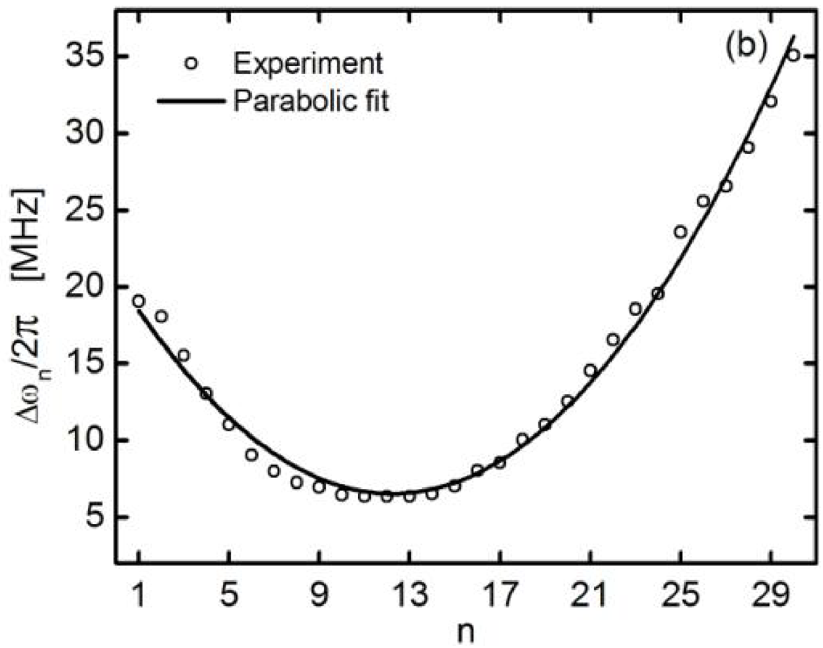




K Merghem et al., IEEE J. Select. Top. Quant. Electron 2015

Typical optical linewidths for passive MLL

Optical linewidth for Qdash MLL ~ 10's MHz



⇒ Need for small optical linewidth (<100 kHz) for high order (>32 QAM) constellations and Gbaud rates in <u>coherent transmission</u>

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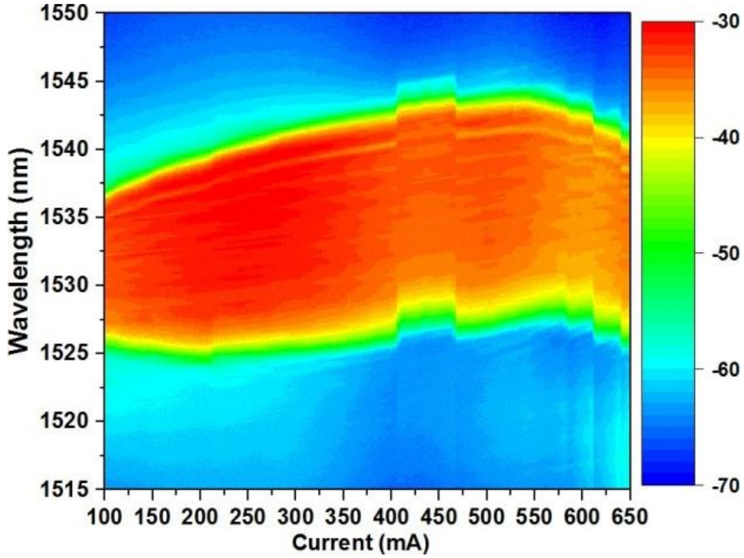
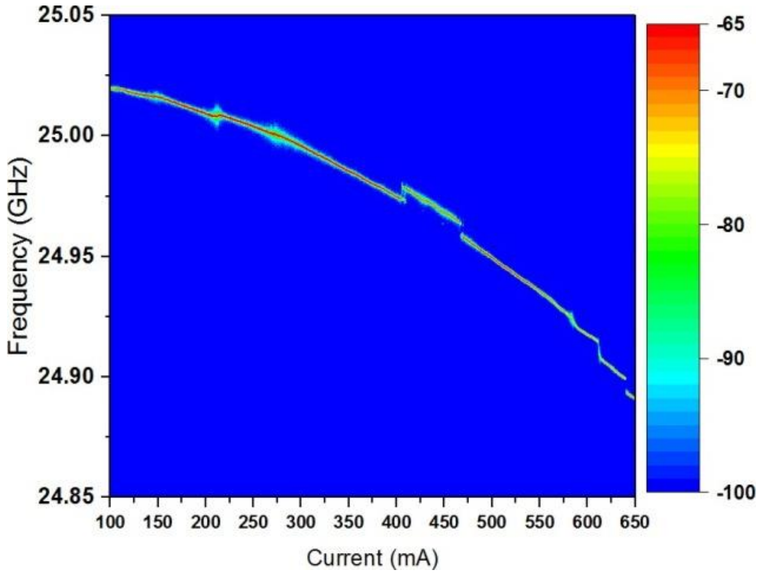
Optical and RF spectra of 3-Qdash device

25GHz Qdash MLL

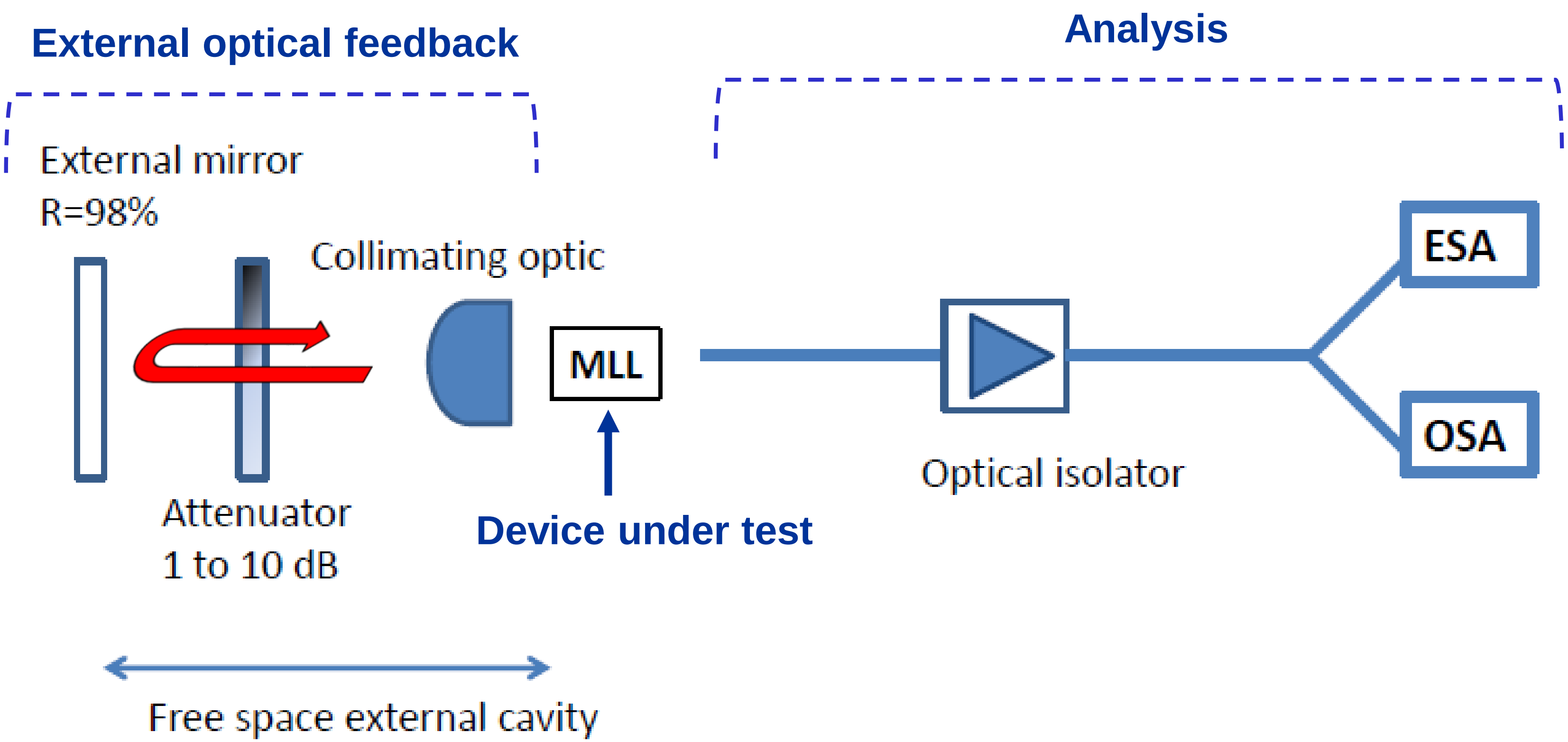
Optical spectrum mapping as a function of current



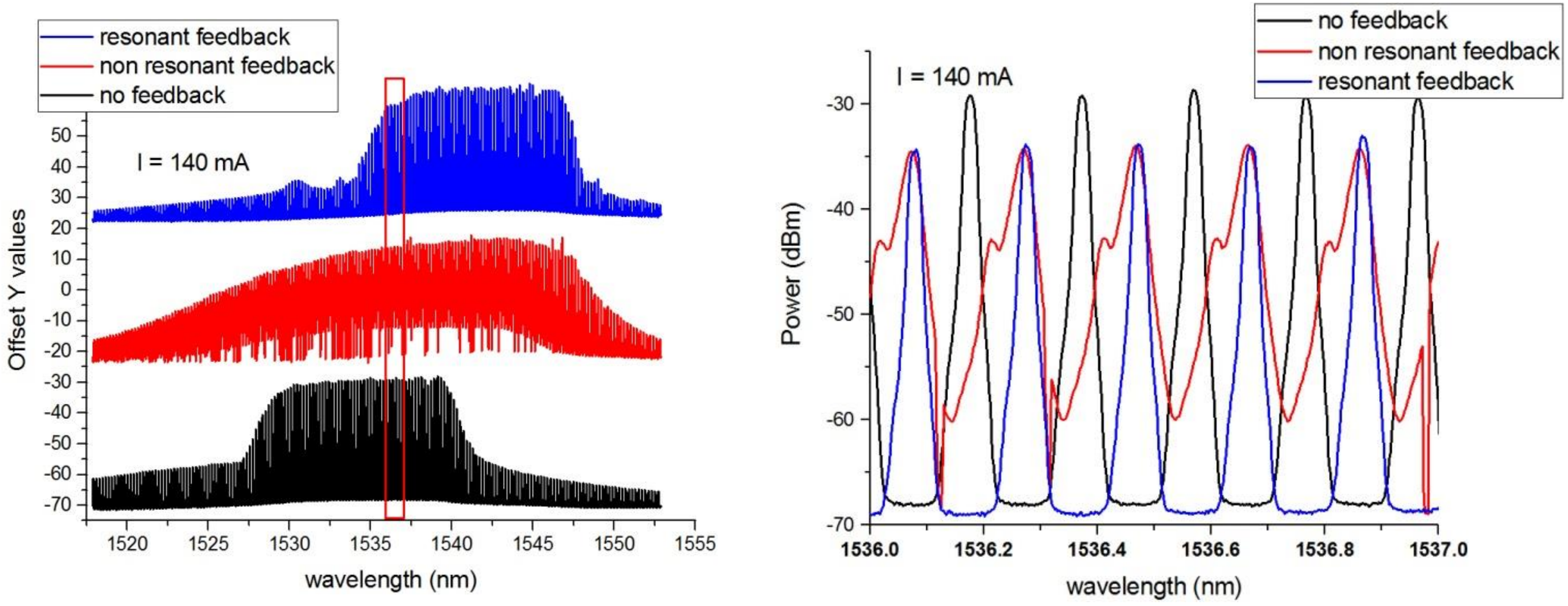
RF spectrum mapping as a function of current



External optical feedback
Free space optical set-up



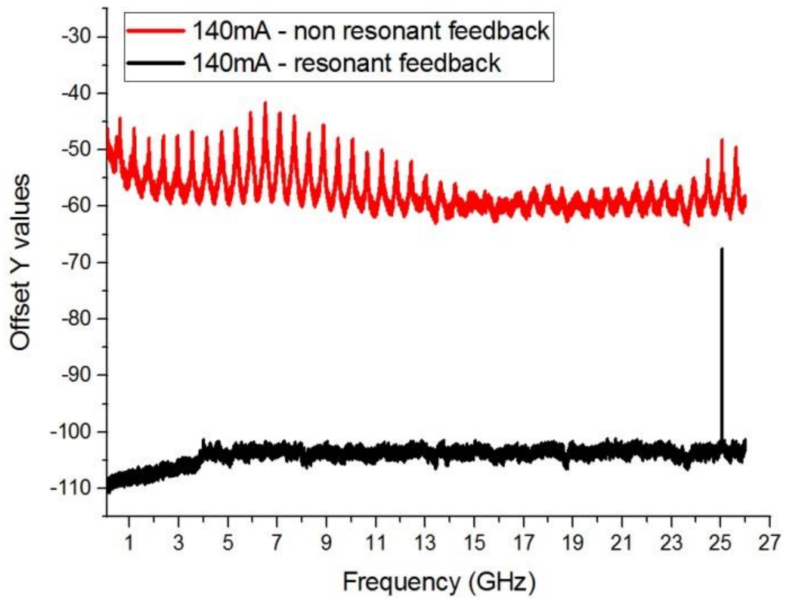
Optical spectrum under feedback

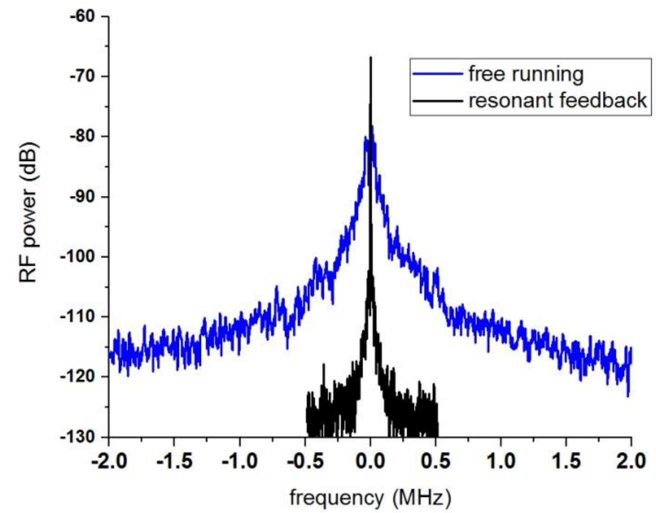


Optical spectrum for the three regimes

- **No feedback**
- **Non-resonant & resonant optical feedback**

RF spectrum under feedback

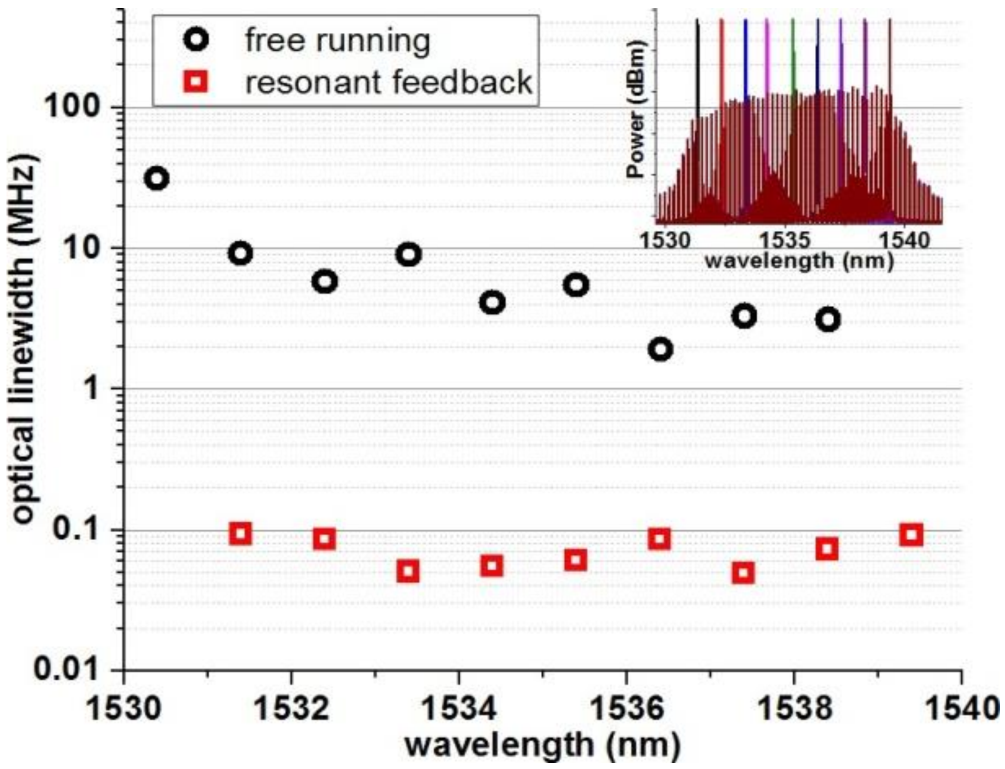




- **Effect of resonant feedback is observed on the RF spectrum**
- **RF Linewidth narrowing from 50 to <1 kHz, no external cavity modes**

T. Verolet et al, IEEE J. Lightwave Technol. 2020 under review

Optical linewidth narrowing by resonant optical feedback



Optical linewidth < 100 kHz !

K. Merghem et al, CLEO 2017

32QAM WDM Transmission Using a Quantum-Dash Passively Mode-Locked Laser with Resonant Feedback

J. N. Kemal[1], P. Marin-Palomo[1], K. Merghem[2], G. Aubin[2], C. Calo[3], R. Brenot[3], F. Lelarge[3], A. Ramdane[2], S. Randel[1], W. Freude[1,4], C. Koos[1,4]

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[2]*Center for Nanosciences and Nanotechnologies (CNRS), Univ. Paris-Sud, Université Paris-Saclay, C2N-Marcoussis, Marcoussis, France*
[3]*III-V Lab, a joint laboratory between Nokia Bell Labs, Thales Research and Technology, and CEA Leti, Marcoussis, France*
[4]*Institute of Microstructure Technology (IMT), Karlsruhe Institute of Technology (KIT), Germany,*
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Abstract: We demonstrate coherent WDM transmission using a quantum-dash mode-locked laser diode with resonant feedback. We report a line rate of 12 Tbit/s (32QAM 60×20 GBd PDM) over 75 km SMF. The spectral efficiency is 7.5 bit/s/Hz.

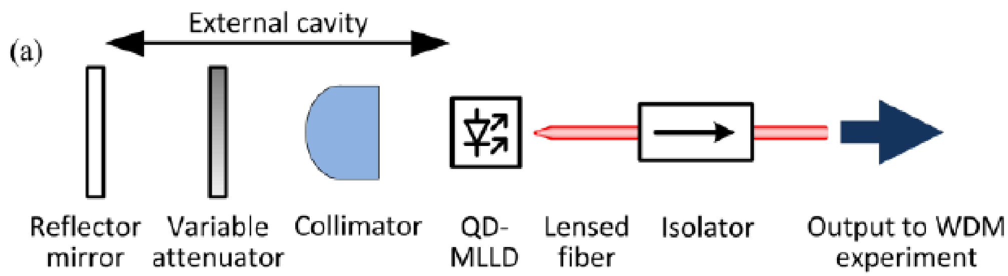
OCIS codes: (060.1660) Coherent communications, (060.2330) Fiber optics communications, (140.4050) Mode-locked lasers

Postdeadline OFC'2017

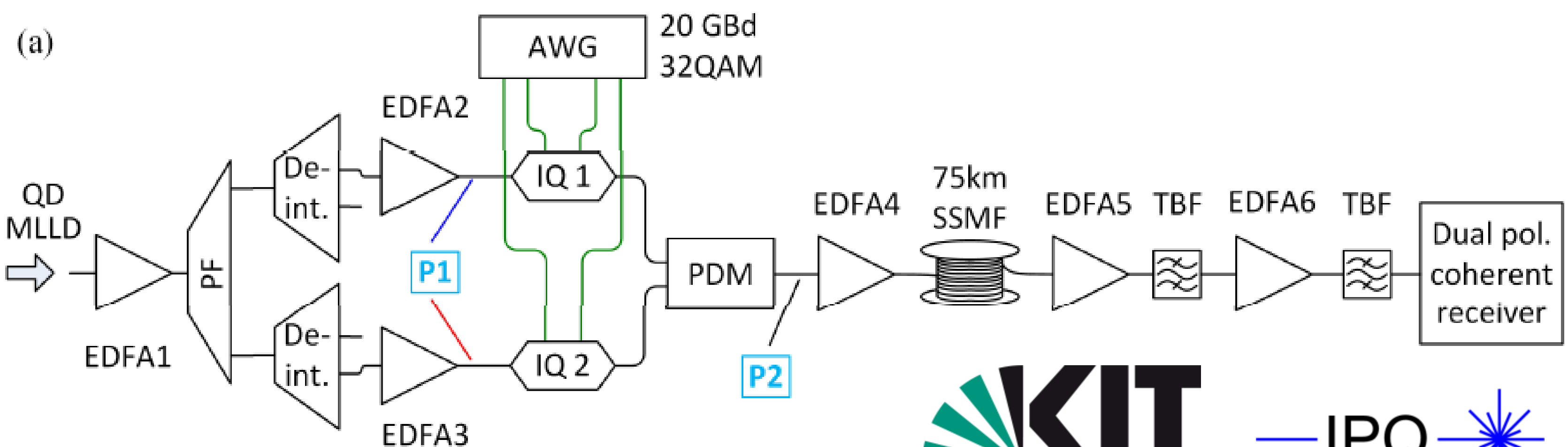
BIG PIPES EC project (2013-2016)

Experimental setup

Optical setup for optical feedback

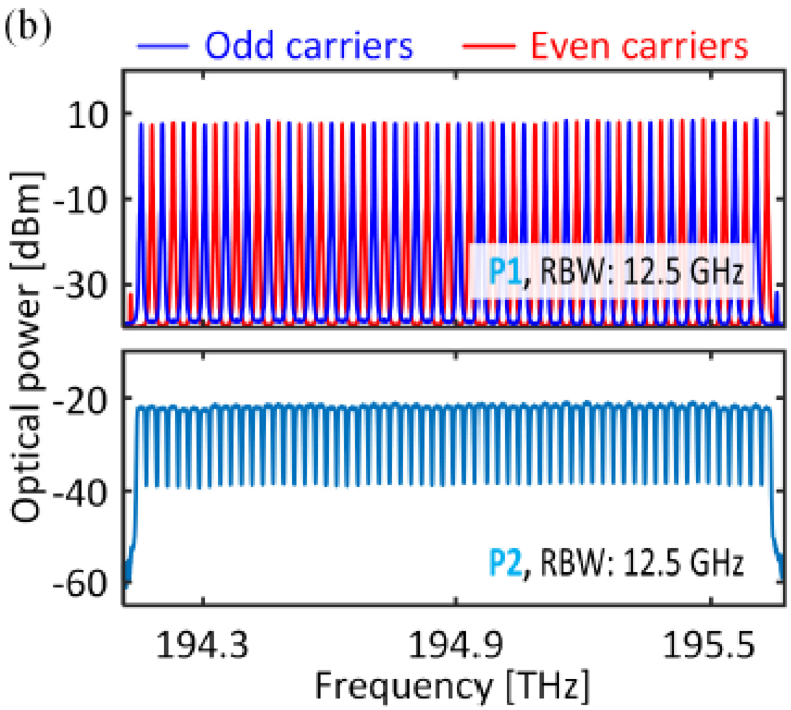


Setup for WDM transmission

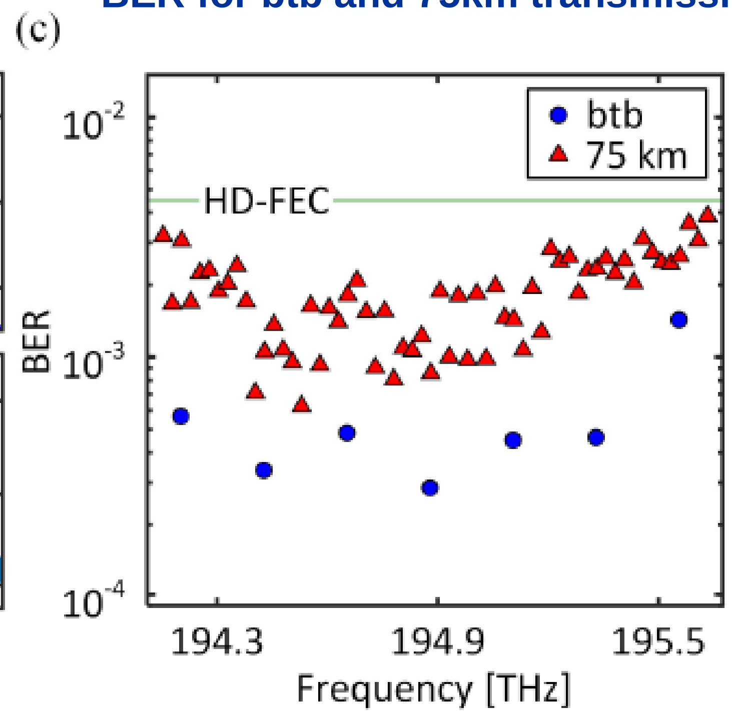


32QAM WDM transmission

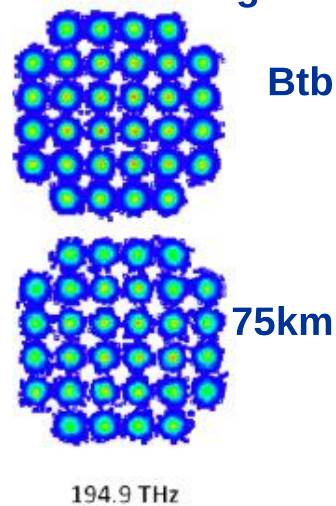
Combined spectra



BER for btb and 75km transmission



Constellation Diagram



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Conclusion

- Quantum-dash MLL for frequency comb generation
- Investigation of long term stability for applications in range finding, dual comb spectroscopy
- Potential for coherent WDM transmission
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Thank you for your attention !