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

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Outline

1. Optical Frequency Comb
2. Mode-Locked Laser
   i. Quantum-dash mode-lockd 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?

https://www.nist.gov/topics/physics/optical-frequency-combs
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".
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 $\approx 10^{10}$ Terabyte

*Source: Cisco Global Cloud Index, 2013–2020*

**Energy Forecast**
Widely cited forecasts suggest that the total electricity demand of information and communications technology (ICT) will accelerate in the 2020s, and that data centres will take a larger slice.

- Networks (wireless and wired)
- Production of ICT
- Consumer devices (televisions, computers, mobile phones)
- Data centres

20.9% of projected electricity demand
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

\[ f_{\text{rep}} \]

CW Laser \rightarrow IM \rightarrow PM


Injection-Locking and Gain-Switching

\[ \text{SG} \rightarrow \text{AMP} \rightarrow \text{Master Laser} \]


Cascaded Four-Wave Mixing in High-Q Microresonators

Tunable cw-laser \rightarrow Optical amplifier


Laser Mode-Locking

Forward bias (gain)

Reverse bias (absorber)

Mode locking

(a) Amplitude
(b) Amplitude
(c) Optical power (dBm)

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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**

\[ \rho(E) \]

\[ E \]

\[ E_c \]
Predicted properties / QD device

- Low threshold current density ($J_{th}$)
- High temperature stability ($T_0$)
- Increased differential gain ($\frac{dg}{dn}$)
- Small linewidth enhancement factor ($\alpha_H$)
QD-based Mode locked lasers: Interest?

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

short pulses

low timing jitter
1.55 µm InAs/InP QDash lasers

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

QDs emission at 1.55µm
Height: 2nm, width: 20nm
Length: 50nm→300nm
Qdot→Qdashes
High density ~5 10¹⁰ 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

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

QDash laser fabrication

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

- Ridge waveguide (RWG)
- Standard processing
- Higher injection currents
Sub-picosecond pulse generation: 1-section devices

Single section Qdash laser
C Gosset et al., Appl. Phys. Lett. 2006

$\Delta \tau = 800 \text{ fs}$

$\Delta \nu = 0.54 \text{ THz}$

$\Delta \tau \nu = 0.46$

Hyp: Gaussian shape

ER = 13 dB
134 GHz

$L = 340 \mu m$

$\approx 70 \text{ ps}$

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

$\Rightarrow$ Enhanced non-linear effects! (FWM)
Pulse generation @ 346 GHz

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


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

100 GHz repetition frequency: 16 channels

50 GHz repetition frequency: 32 channels
Photocurrent analysis in RF domain

Radio-Frequency spectrum

50 GHz Photodiode

Optical pulses

Electrical spectrum analyzer

RF linewidth

Repetition rate frequency

\[ \Delta v_{RF} \approx 5 \text{ kHz} \]
Repetition frequency and RF linewidth evolution with injection current: supermode analysis

Repetition rate frequency

RF linewidth

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

![Graph showing the effect of temperature on RF frequency. The graph plots RF Frequency (GHz) against temperature (K). The slope of the graph is -3.518 MHz/K.](image)
Long term temperature drift

- Use low noise battery current source!

2 mK ⇒ 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 $\tau$

- **First report for passive mode locked laser**
Effect of PID stabilization loop

2-section device

Repetition frequency evolution

2 gain sections
No absorber section!

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

\( e_n \): Frequency drift
Effect of stabilization loop (2-section device)

▸ gain-gain device at 10 GHz

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 coherent transmission
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

External optical feedback

External mirror
R=98%

Collimating optic

Attenuator
1 to 10 dB

Device under test

Optical isolator

Free space external cavity

Analysis

ESA

OSA
Optical spectrum under feedback

Optical spectrum for the three regimes
- No feedback
- Non-resonant & resonant optical feedback
Effect of resonant feedback is observed on the RF spectrum.
RF Linewidth narrowing from 50 to <1 kHz, no external cavity modes.

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

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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

\textbf{Postdeadline OFC’2017
BIG PIPES EC project (2013-2016)
Experimental setup

Optical setup for optical feedback

Setup for WDM transmission

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32QAM WDM transmission

Combined spectra

BER for btb and 75km transmission

Constellation Diagram

Kemal et al. Optics Express 2020 under review

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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
Thank you for your attention !