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Chip-scale optical frequency combs for fiber optic communications systems, data processing and fiber optic sensing

Kamel Merghem

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Habilitation à Diriger des Recherches



Chip-scale Optical Frequency Combs for fiber optic communications systems, data processing and fiber optic sensing

Kamel MERGHEM

SAMOVAR, Télécom SudParis, Institut Polytechnique de Paris

Présenté et soutenu le 7 février 2023

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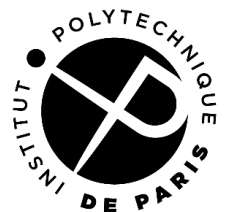
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I. Curriculum Vitae

Name : **Merghem Kamel**
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I.1. Professional experience

Since July 2019 : Associate Professor - SAMOVAR, Télécom SudParis, Institut Polytechnique de Paris, Electronics & Physics Department, Optics & Photonics research group
2017 – 2019 : R&D Project Manager - 3SP Technologies (Nozay)
2002 – 2017 : Research Engineer - Center For Nanosciences and Nanotechnologies CNRS (previously Laboratory for Photonics and Nanostructures) Photonic Device Research Team
2000 – 2002 : Product Engineer - Alcatel Optronics (Nozay)

I.2. Education

Jan 2011 : **PhD thesis from Université des Sciences & Technologies de Lille**
Doctoral school : Sciences de la matière, du rayonnement et de l'environnement
“Semiconductor Mode Locked Laser for high bit rate optical communications”
Sept 2000 : **Master of Science “Lasers & applications” from Université des Sciences & Technologies de Lille (USTL)**
Jun 1999 : **Master Degree of Physics from Université Paris XI (Orsay)**

I.3. Skills

- Physics of photonic devices
- Advanced optoelectronic characterizations
- Optical Frequency Combs
- Dynamics in semiconductor lasers with optical feedback
- Ultra high bit rate transmission experiments
- Design & fabrication of semiconductor devices (clean room)

I.4. Teaching activities

I.4.1. Teaching

Since I took my Associate Professor position, I have been involved in different teaching units of Télécom SudParis Engineering school and Institut Polytechnique Paris (IPP) Masters. The main topics cover optics, digital electronics, photonic devices and optical transmission

systems. My teaching load is ~ 115h/year. Hereafter, I describe my contributions to the different modules :

- Systèmes de transmission optique / Optical transmission systems (PHY3601 - 1st Year of Engineering school)

Since 03/2020 (20h/year)

Tutorials on electromagnetic optics (slab waveguide and optic fiber), optical transmission system (link budget, multiplexing, optical amplification, transmitter, receivers)

- Fonctions électroniques fondamentales / Fundamentals of electronics (PHY3101 - 1st Year of Engineering school)

Since 05/2021 (15h/year)

Tutorials on digital electronics (number system, code conversion, combinational logic ...)

- Physique des télécommunications / Physics of telecommunications (PHY4101 – 2nd Year of Engineering school)

Since 10/2019 (15h/year)

Tutorials on coherent communication systems and flexible optical networks

- Dispositifs optiques & systèmes hyperfréquences / Photonic devices and microwave systems (PHY4102 – 2nd Year of Engineering school)

Since 01/2020 (10h/year)

Lectures on optical modulators (electro-optic and electro-absorption modulators), exams

- Numérique et consommation énergétique / Energy consumption of digital technology (ENV4101 – 2nd Year of Engineering school)

Since 11/2022 (10h/year)

Tutorials on energy consumption in optical communication systems and networks

- Réseaux optiques très haut débit / Ultrahigh bitrate optical networks (NET8623 – 3rd Year of apprenticeship Engineering)

Since 12/2019 (15h/year)

Set-up of a new practical works on reconfigurable optical add-drop multiplexer (ROADM)

- Fundamentals of Fibre-Optic Communications (PHY7002 – Master 1 Electrical Engineering of Communications and Information Processing - EECIP, IP Paris)

Since 09/2020 (15h/year)

Tutorials on electromagnetic optics, exams

- Advanced optoelectronic Devices (PHY7503 – Master 1 EECIP, IP Paris)

Since 04/2020 (15h/year)

New lectures and tutorials on high-speed optical modulators (electro-optic, electro-absorption and silicon-based modulators), exams

I.4.2. Academic responsibilities

I am the coordinator of the following modules for the Engineering School and IP Paris Master:

- Dispositifs optiques et systèmes hyperfréquences / Photonic devices and microwave systems (PHY4102) – Télécom SudParis Engineering school (since 09/2019)
- Fundamentals of Fibre-Optic Communications (PHY7002) - Master IP Paris (since 09/2020)
- Advanced optoelectronic Devices (PHY7503) - Master IP Paris (since 09/2020)

For these modules, the main goal is to coordinate the teachers' team and keep coherent the learning objectives.

Recently, I took the responsibility of the physics-teaching domain. This consists in coordinating all the physics-teaching units for the Engineering School and IP Paris Masters in collaboration with the associate professors. For this purpose, I am also the main contact for the Graduate school and in charge of organizing the teaching domain council between professors and industrial companies to adapt our teachings to the job requirements.

I.5. Collaborations and projects

I list here my main collaborations with industry partners, national and international academic institutions and my contribution in research projects.

Main collaborations:

- Industrial partners: III-V Lab, Almae Technologies, Huawei Technologies, Orange Labs Lannion
- International academic partners: Karlsruhe Institute of Technology, Dublin City University, RWTH Aachen University, ITMO University of St Petersburg, Cork Institute of Technology, Duisburg-Essen University, Weierstrass Institute WIAS Berlin
- National academic partners: CNRS-UPSAclay C2N, CNRS-UCA InPhyNi, UMI Georgia Tech-CNRS Metz, Foton CNRS, Telecom Paris, IES CNRS-Univ. Montpellier

Research projects:

During the last decade, I have been involved in the following projects in different roles:

2022 – 2024 :	ANR-DFG project - HybridCombs
Role :	Coordinator
Goal :	Hybrid chip-scale frequency combs combining III-V quantum-dash mode-locked lasers and high-Q Si ₃ N ₄ microresonators
Partners :	C2N (CNRS-UPSAclay), Institut Physique de Nice (CNRS-UCA), Karlsruhe Institute of Technology (KIT), Weierstrass Institute Berlin
2022 – 2025 :	ANR project - ORCHID
Role :	Work package leader
Goal :	Optical Reservoir Computing with Integrated Devices
Partners :	III-V Lab, CEA-Leti, Femto-ST
2019 – 2020 :	Institut Polytechnique de Paris <i>Prématuration</i> project ' Combs '
Role :	Coordinator
Goal :	Optical frequency Combs for high bit rate optical fiber communication systems
Partners :	C2N (CNRS, UPSaclay)
2017 – 2019 :	Industrial R&D project - 3SP Technologies
Role :	Project manager
Goal :	1550nm DFB laser diode modules for LiDAR in autonomous vehicles
Partners :	O-Net Communications (China & USA)
2017 – 2019 :	Industrial R&D project - 3SP Technologies

Role : Project manager
 Goal : 10G-25Gb/s EML TO-Can modules for telecom applications
 Partners : O-Net Communications (China & USA)

2016 – 2017 : Academic collaboration
 Role : Scientific & technical leader at C2N CNRS UPSaclay
 Goal : Ultra-compact Source for THz Time Domain Spectroscopy
 Partners : J. Balzer - Duisburg-Essen University
 Publications : [J13], [C3], [C8]

2016 – 2017 : Academic collaboration
 Role : Scientific & technical leader at C2N CNRS UPSaclay
 Goal : Quantum-dash laser dynamics
 Partners : E. Viktorov - ITMO University of St Petersburg
 Publications : [C4]

2016 – 2017 : Academic collaboration
 Role : Contributor
 Goal : Multi-GHz chaotic optoelectronic oscillator
 Partners : A. Locquet - UMI Georgia Tech-CNRS Metz
 Publications : [J16], [J23]

2016 – 2017 : CNRS/INSIS Prématuration project
 Role : Partner
 Goal : Resonant Metamaterial grating for DFB Lasers
 Partners : A. Lupu – C2N CNRS UPSaclay

2013 – 2016 : European STREP project **BIG PIPES** (Broadband Integrated and Green Photonic Interconnects for High Performance Computing and Enterprise Systems)
 Role : Partner
 Goal : Optical frequency combs for datacenters optical interconnects
 Partners : RWTH Aachen University, III-V Lab, Pilot Photonics, DCU, KIT, Mellanox, LPN-CNRS
 Publications : [J14], [J18], [J20]-[J22], [J24]-[J26], [C5]-[C7], [C9]-[C18]

2012 – 2015 : ANR project **JASMIN**
 Role : Work package leader
 Goal : Integrated SOA-PIN Detector for High-Speed Short Reach Application (25 – 40 Gbps)
 Partners : III-V Lab, LPN-CNRS UPSaclay, Orange Labs, Advteotec, LPCNO

2012 – 2015 : ANR project **DIQDOT**
 Role : partner
 Goal : Dispersion immune quantum dot based sources for low lost, low consumption and athermal access network
 Partners : III-V Lab, LPN-CNRS, Orange Labs, Foton CNRS, Télécom SudParis
 Publications : [J30], [C23], [C27],

2011 – 2014 : European ITN Marie Curie **PROPHET** (Postgraduate Research on Photonics as an Enabling Technology)

Role : partner

Goal : training of early stage researchers

Partners : Cork Institute of Technology, III-V Lab, LPN-CNRS, TU Berlin, FVB-WIAS, PROCAL, Télécom SudParis, University of Pavia, U2t, Superlum, IMM Catania, NCU, University of York, Lancaster University, St Andrews

Publications : [J27], [J31], [J32], [C24]-[C26]

2011 – 2014 : ANR project **BATGAN**

Role : partner

Goal : Betavoltaic energy converters based on Gallium Nitride semiconductors

Partners : UMI Georgia Tech, LPN-CNRS, CEA LIST

Publications : [J10], [J11]

2010 : Academic collaboration with visiting researcher at LPN-CNRS

Goal : Feedback resistant DFB semiconductor laser

Partners : Q. Zou, Télécom SudParis

Publications : [J47]

2009 – 2013 : ANR project **TELDOT**

Role : partner

Goal : Quantum dot Mode Locked Lasers for WDM transmission and Radio over Fibre

Partners : III-V Lab, LPN-CNRS, Orange Labs, IMEP-LAHC, Foton CNRS

Publications : [J33], [J38], [J39], [J42], [J48], [J51], [J53]

2009 – 2013 : ANR project **MODULE**

Role : partner

Goal : Dual-Electroabsorption Modulated Laser for access and metropolitan networks

Partners : Télécom ParisTech, III-V Lab, LPN-CNRS, XLIM

Publications : [J29], [J40]

2006 – 2009 : **CARRIOCAS**: High bit rate optical networks for simulation of complex systems (Systematic Paris-Region cluster)

Role : partner

Goal : Study and implementation of very high-speed broadband optical networks (up to 40 Gbps per channel)

Partners : Bull, CEA, III-V Lab, LPN-CNRS, Drakka, EDF R&D, Ecole Centrale Paris, Télécom SudParis, Telecom ParisTech, KYLIA, INRIA, Marben products, Université Paris Sud, Université de Versailles St Quentin

Publications : [J49]

I.6. Research impact and visibility

I am author and co-author of one book chapter, 66 publications in international journals, 63 international conferences and 26 invited papers (cf list of publications p.58).

Since 2009, I am reviewer for international journals (Optics Express, Applied Physics Letters, IEEE Journal of Selected Topics in Quantum Electronics and IEEE Photonics Journal) and member of 'Société Française d'Optique' (SFO).

In the past years, I was contacted for several collaboration requests:

- E. Viktorov – ITMO University St Petersburg
- E. Sooudi and G. Huyet – Tyndall National Institute
- M. Achouche – III-V Lab Marcoussis
- O. Acef - Observatoire de Paris SYRTE
- R. Teissier and A.N. Baranov - IES Montpellier
- J. Balzer - Duisburg-Essen University
- A. Gallet - Huawei Technologies France

I.7. Scientific supervision

2022 – 2023 :	Y. Driouche – postdoctoral researcher
Title :	Artificial Neural Networks based on hybrid mode-locked laser
Supervision :	100%, related to the ANR project 'ORCHID'
2022 :	S. Boudghene (Master Internship) - Master M2 Systèmes Communicants en Environnement Complexe (SCEC), Université Gustave Eiffel
Subject :	Etude de la dynamique de lasers à semi-conducteur soumis à une rétroaction optoélectronique contrôlée
Supervision :	100 %
Location :	Télécom SudParis
2021 – 2024 :	A. Souleiman Dabar - PhD thesis in collaboration with 3-5 Lab
Title :	Thermally robust and broadband on-chip lasers and SOAs for optical communications
Supervision :	50%
Publications :	[J1], [C1]
2020 – 2023 :	S. Yu – CIFRE PhD thesis in collaboration with Huawei
Title :	Semiconductor optical amplifier for future telecom systems
Supervision :	50%
2020 – 2021 :	A. Calabrese – postdoctoral researcher
Title :	Semiconductor optical frequency combs for coherent communication systems
Supervision :	100 %, related to the IP Paris Prématuration project 'Combs'

2020 : M. Shabnam (Master Internship) - Electrical Engineering Program, Master M2 Optical Networks and Photonic Systems, Institut Polytechnique de Paris

Subject : Stabilization of a semiconductor laser subjected to optical feedback

Location : Télécom SudParis

Supervision : 100 %

Publications : [C3]

2019 – 2023 : N. Mwamsojo - PhD thesis

Title : Photonic and optoelectronic Reservoir Computing

Supervision : 50%

Publications : [J2],[C2]

2013 – 2016 : V. Panapakkam - PhD thesis

Title : Optical frequency comb generation using InP based quantum-dash/ quantum-well single section mode-locked lasers

Supervision : 30 %, related to the European project BIG PIPES

Publications : [J20]-[J22]

2012 – 2015 : K. Papatryfonos - PhD thesis

Title : 1.6-2.5 μm long wavelength quantum dash-based lasers for gas sensing

Supervision : 15 %, related to the european project PROPHET

Publications : [J17]

2011 – 2014 : C. Calo - PhD thesis

Title : Quantum dot based mode locked lasers for optical frequency combs

Supervision : 30 %, related to the european project PROPHET

Publications : [J27], [J32], [J33]

2009 – 2012 : R. Rosales - PhD thesis

Title : InAs/InP Qdash mode locked lasers for optical communications

Supervision : 30 %, related to the ANR project TELDOT

Publications : [J36], [J38], [J39], [J42]

2006 – 2009 : A. Akrouf – CIFRE PhD thesis in collaboration with III-V Lab

Title : Investigation of Qdash mode locked laser for telecoms applications

Supervision : 15 %

Publications : [J54], [C47], [C48]

II. Introduction

II.1. Foreword

My research journey started as Research Engineer in 2002 at the CNRS *Laboratory for Photonics and Nanostructures* (Now *Center for Nanosciences and Nanostructures CNRS-UPSaclay*). I joined the *Photonics Device* research team that develops innovative photonic components for the next generation optical communication networks. My activities included in particular the design and fabrication of opto-electronic devices in clean room, static and dynamic characterizations, and set-up of advanced characterization optical test benches. I was also involved in high bit rate transmission experiments. During this period, I had the opportunity to valorize my research results in the framework of a PhD thesis from 2008 to 2011. I led investigations on low dimensional semiconductor-based mode locked laser, and in particular, on the sub-picosecond optical pulse generation at very high repetition rates with improved timing jitter performances.

After the completion of my PhD, from 2011 to 2017, I pursued these research activities with a focus on the development of quantum-dash mode locked laser for the generation of optical frequency combs. Then, from 2017 to 2019, I worked for the company 3SP Technologies, provider of opto-electronic components for optical communication market. I led, as R&D project manager in a cross-functional team, the development of new optoelectronic devices (980nm pump lasers and 1550nm DFB laser modules) from the design to the manufacturing. Since July 2019, I have taken the position of Associate Professor at SAMOVAR, *Télécom SudParis, Institut Polytechnique de Paris*, in the '*Optics and Photonics*' research group. The developed know-how during my research career and the previous fruitful scientific collaborations allowed me to engage my research activities in the development of chip-scale optical frequency combs for dedicated applications.

To present my research work, I organize this manuscript as follows.

First, in section II.2, I will briefly give the context and the summary of my PhD research work. Then, in section III, I will present the research performed after my PhD on the development of optical frequency comb generator based on semiconductor mode locked lasers.

Part III consists of six main sections. After an introduction on semiconductor-based mode locked laser (III.1), I will first describe the investigation of self-pulsating mode locked lasers with different gain material systems (III.2) and then discuss the noise features of such lasers and in particular the dynamic behaviors when subjected to optical feedback (section III.3). In section III.4, I will focus on the development of quantum-dash mode locked lasers as comb sources, and shows several demonstrations of WDM data transmission performed in collaboration with either Karlsruhe Institute of Technology (KIT) or Dublin City University (DCU) in the framework of common European projects. To conclude this third chapter, I will summarize my research works and present achievements in other research areas.

The final part IV concludes this '*Habilitation*' manuscript with my on-going and future research projects in optical frequency combs for different applications such as WDM transmission, data processing and optical fiber sensing.

II.2. PhD summary

II.2.1. Context

Before reviewing my investigations I carried out during my PhD, I would like to introduce the general context of this work and in particular the research on low dimensional semiconductor lasers and their particular features.

The introduction of semiconductor nanostructures as active material for lasers has been a major breakthrough in this field. The formation of low dimensional nanostructures such as quantum wire (1D) and quantum dot structures (0D) leads to a subsequent decrease of the degree of freedom of charge carriers. Ideally, 0D systems exhibit an atomic-like density of states hence providing an ultimate carrier confinement. In particular, lasers based on low dimensional structure such as quantum dashes (QDash) and quantum dots (QD) have been predicted to exhibit lower temperature sensitivity [1] and lasing threshold [2], and higher differential gain and direct modulation bandwidth [3] compared to the ones based on bulk and quantum well (QW) material. A picture of QD active layer is illustrated in Fig. 1. The dots are 10-20 nanometers (nm) wide and only a few nm thick, leading to 3D confinement of charge carriers. Over the past years considerable progress had been made over the development of QD lasers allowing improved characteristic features distinguishing them from conventional devices. First characteristic pertains to the laser threshold current, an essential parameter. The strong improvement of the threshold current density with the development of heterostructure lasers (bulk, quantum well and quantum dot based material) is shown in Fig.2. A clear trend was observed in threshold current reduction, from bulk to QW then to QD, showing significant breakthroughs proving that the ultimate carrier confinement can lead to ultra-low threshold currents [4]. This feature arises from the fact that for smaller dimensionalities carriers injected by electrical pumping concentrate in a narrower energy range, and would imply that all the injected carrier contribute to the population inversion at the lasing energy.

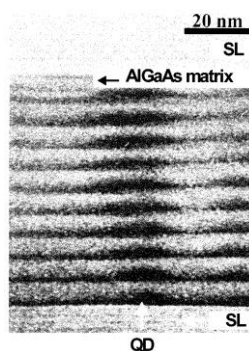


Figure 1 : Transmission electron microscopy image of the active region of high-power Quantum dot laser [4]

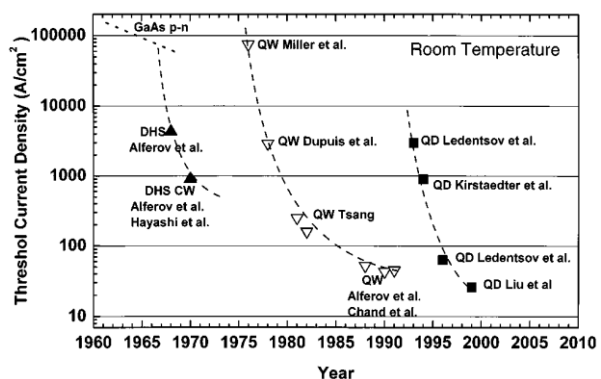


Figure 2 : Chronological progress of the threshold current density for semiconductor lasers [4]

QDs and QDashes have demonstrated other unique features in terms of low temperature sensitivity [5], [6], ultrafast carrier dynamics and recovery of gain and absorption [7], [8], and wide emission spectra [9]. The fast carrier dynamics as well as large gain bandwidth resulting

from the inhomogeneously broadened gain spectrum are very interesting assets for ultrashort pulse generation and motivated my work on these QD/QDash-based laser sources. All of these remarkable features and the technological advances on QD and QDash lasers have opened new perspectives for applications in optical communication networks.

II.2.2. PhD related works

During my PhD, my main works were focused on the ultrashort optical pulse generation at a very high repetition rate based on passive semiconductor mode locked lasers. I investigated two different types of configurations: the standard 2-section mode locked laser including a saturable absorber section and the so-called 'self-pulsating lasers using a single gain section. Using different measurement techniques, I assessed the timing jitter of the generated pulse trains and showed improved performances using external optical feedback.

I started with the investigation of standard two-section mode locked lasers based on a single InGaAsP/InP quantum well structure, especially designed to exhibit a low optical confinement factor Γ . One of the main influenced characteristics is the saturation energy of the gain material E_{sat} which is inversely proportional to the confinement factor Γ . By the use of an optimized single QW layer structure allowing low propagation losses, relatively low modal and differential gains, to achieve high saturation energy, we reported subpicosecond pulse generation without any external pulse compression scheme (Fig. 3) [10]. Depending on bias conditions (current, saturable absorber voltage), we observed a small RF linewidth of 30 kHz for the 21.31 GHz pulse train indicating low timing jitter. This performance is attributed to the small coupled amplified spontaneous emission noise owing to the low optical confinement factor, similar to those obtained on quantum dash based self-pulsating lasers at 1.55 μm [11], emphasizing the importance of optical confinement for achieving low phase noise.

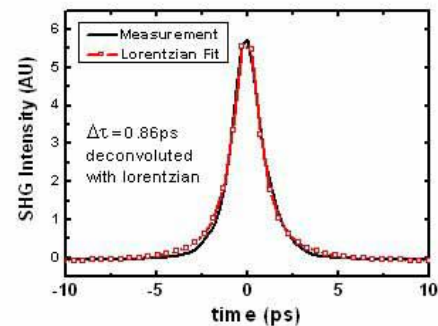


Figure 3: Autocorrelation trace of an isolated pulse for $I=74$ mA and $V=-3.8$ V.

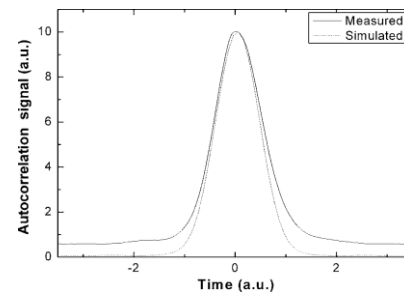


Figure 4 : Autocorrelation signal trace of an isolated pulse at 134 GHz repetition rate

In the second part of my PhD, I initiated the first investigation of Qdash MLLs in strong interaction with the postdoctoral researcher C. Gosset. We investigated single section mode locked laser with cavity length ranging from 340 μm to 990 μm [12]. We demonstrated very narrow mode-beating linewidth for these lasers, of the order of 10's kHz, which is an evidence of efficient mode locking, and the first optical pulse generation at 134 GHz with subpicosecond width in a single section self-pulsating Qdash mode locked laser (see Fig.4).

Following this first demonstration, within several projects, in collaboration with our partner *III-V Lab*, I contributed to the optimization of the quantum dash material that allowed, few years later, the first generation of optical pulses at a record 346 GHz repetition rate using a monolithic

semiconductor mode locked laser [13]. Exploiting the higher optical confinement factor of multilayer active stack, which results in a high modal gain (up to 100cm^{-1}), allowed laser emission for very short cavity lengths [14], [15]. Exploiting the large effective gain bandwidth resulting from the inherently inhomogeneously broadened gain spectrum allowed the demonstration of ultrashort pulse generation at extremely high repetition rates in simple, one-section device configurations. The main results are summarized in the following figures (Fig. 5) [13].

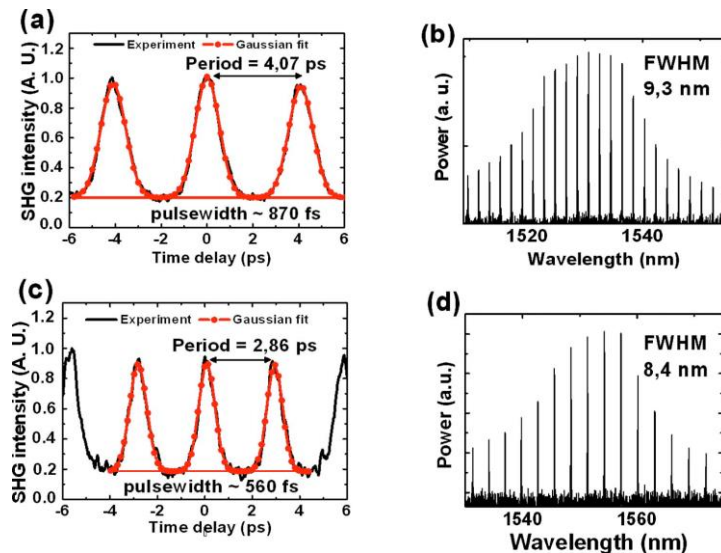


Figure 5 : typical pulse train autocorrelation signal corresponding to a 245 GHz and 346 GHz repetition rate and corresponding optical spectra. After deconvolution, by assuming a Gaussian line shape, we obtained respectively subpicosecond pulse width of 870 fs and 560 fs at the output of the self-pulsating laser without any pulse compression scheme.

During this time, I have also been particularly involved in the assessment of the timing jitter of the generated pulse trains. In the lab, we have set up a specific measurement technique based on optical cross-correlation, that has the advantage to directly yield the pulse-to-pulse timing jitter. This work was carried out in collaboration with the post-doc researcher J.-P. Tourrenc and the PhD student A. Akrouit. We hence evaluated the timing jitter of single QDash MLL showing sub-picosecond values for optimized driving conditions [16].

Another important part of my work was dedicated to the investigation of the effect of external optical feedback on semiconductor devices and in particular on the semiconductor mode locked laser. I did the initial investigations in interaction with S. Azougui during her PhD thesis work. It has been shown both theoretically and experimentally that, depending on operating conditions, optical feedback may improve or degrade MLLs performance [17]–[19]. In 2009, I subsequently started to investigate the beneficial effect of optical feedback in conventional two-section QDash MLLs [20]. In particular, I first evaluated the effect on pulse duration and RF linewidth of two-section passively MLLs at 17 GHz. I showed that, with an amount of feedback of approximately -22 dB (max value for our setup), stable mode locking was still observed, even though a reduction of 25% of the mode locking area was evidenced. The most important result was the reduction of the RF linewidth under optical feedback. This was reduced from an initial value of 370 kHz (without feedback) down to less than 500 Hz with

maximum feedback (see Fig. 6), implying a 27-fold timing jitter reduction [21]. Starting with a noisy MLL, we obtained an RF linewidth comparable to that of high-performance InAs/GaAs QD MLLs [22]. Further work on the improvement of MLLs characteristics under optical feedback will be presented in Section III.3.2.

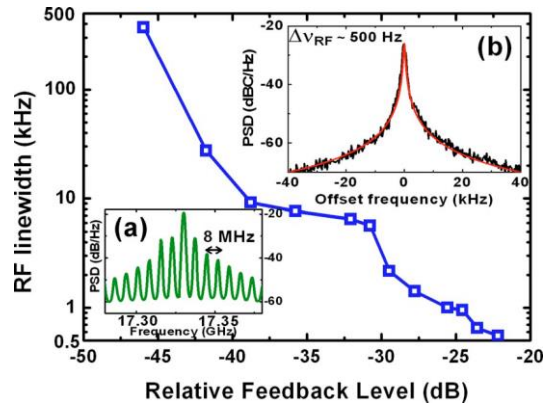


Figure 6: RF linewidth as a function of the feedback level at a current of 110 mA and a voltage of -1.9 V

Inset (a): RF Spectrum showing harmonic modes separated by 8 MHz.

Inset (b): RF spectrum with showing a RF linewidth of ~500 Hz.

III. Frequency comb generation using semiconductor mode-locked lasers

This part of manuscript deals with my post-PhD research I have carried out at the *CNRS Laboratory for Photonic and Nanostructures* (now *Center for Nanoscience and Nanotechnology - C2N*) and at *SAMOVAR, Télécom SudParis, Institut Polytechnique de Paris*.

III.1. Context

As a general introduction, I will present the trend in the area of optical networks and the evolution of my research work in this context.

With the onset of the health crisis in 2020, we have seen that the digital infrastructure and the optical networks become an even more essential part of our personal and professional lives. It allows to exchange information, conduct commerce and more importantly to develop and maintain communication. Today, the optical network data traffic is mainly driven by our usages of mobile devices, video services, cloud computing and machine-to-machine internet. The current trends show a faster growing global IP traffic than the system capacity. As shown in Fig. 7, overall global data traffic has been doubling every 2-3 years over the past years and there is nothing to suggest that this growth rate will slow down [23]. Despite the aforementioned tremendous growth of traffic into and out of the data center, about 75 % of all the IP traffic is being processed within datacenters (Fig. 8). It has

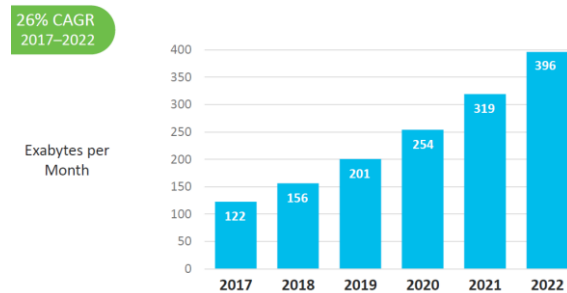


Figure 7: Growth of annual IP traffic from 2017-2022
Source: Cisco Global Cloud Index [23]

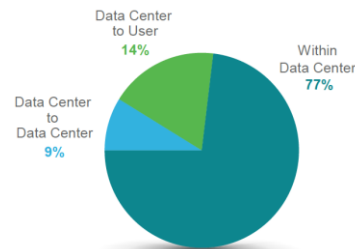


Figure 8: Percentage share in the IP traffic handling with ~77 % residing within datacenters [23]

forced the internet infrastructures to be transformed and placed increased constraints on the datacenter interconnects. Data center power consumption is also a matter of significant importance. With data center traffic consuming nearly 2% of all electricity used today and growing over the last decade, there is an urgent need for a paradigm shift to greener technology.

As shown in Fig 9, the worst-case prediction shows that the information and communication technology (ICT) (including networks, consumer devices and data-centers) is likely to increase by 2030, to 21% of projected global demand [24]. There are also an increased public concerns about climate change and environmental issues, and the ultimate ecological footprint of data center activities [25]. Future data center interconnects (DCIs) will thus be expected to carry more data while consuming less—the energy while transmitting a single bit over a link will have to be reduced to ~1 pJ from several hundreds of pJ today [26]. Moreover, we start to enter in the era of Internet of Things (IoT) with expected trillions of connected objects that will generate

Zettabytes of digital information. All the data will have to be carried across the optical network infrastructure delivering the required performances to manage the unabated growth in data traffic. Extending the capacity of optical networks with minimal increase of costs and energy consumption has become a high-priority task in order to support the current growth of Internet traffic. As transmission bottlenecks approach data centers and metro/access networks, use of wavelength division multiplexing (WDM) with advanced modulation formats in these systems appears

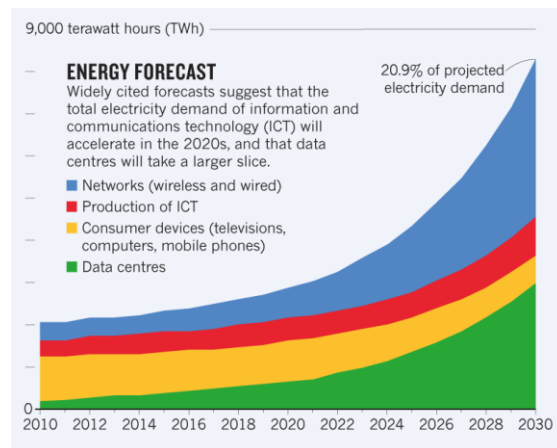


Figure 9: Energy forecast of ICT from [27]

to be more and more attractive. But, the high cost of components and the challenges related to the management of hundreds of channels limit its uses in access networks and intra-/inter-data center communications. However, the availability of low-cost laser sources capable of generating a number of equally-spaced optical frequency channels has the potential to revolutionize future optical communication systems in particular in access networks and in optical interconnects in data-centers. These optical sources, known as optical frequency combs (OFCs) are of great interest and showed their ability to generate a high number of channels for massively parallel WDM transmission at overall data rates of tens of Tbit/s with reduced energy consumption [28]. Therefore, I decided to extend my research work of semiconductor mode locked lasers toward the development of chip-scale OFC sources for their use as compact, high-efficiency, and low-cost light sources in high-speed dense WDM transmissions. The availability of such compact chip-scale comb sources has also started to open a path towards other applications, in which footprint, compactness, and energy consumption are crucial performance parameters, such as high-precision ultra-fast ranging and in light detection and ranging (LiDAR) for autonomous navigation, spectroscopy and gas sensing for environmental monitoring and photonic computing approaches for data intense processing.

My research has been focused on the use of low-dimensional nanostructures, such as quantum dots (QD) and quantum dashes (QDash), as gain material for semiconductor laser sources. The particular properties of these structures have led to improved mode-locking performances of semiconductor lasers, as well as its uses as compact OFC sources with a relatively large optical bandwidth [11]. In the following, I will present my contributions to the development and engineering of optical frequency combs generated thanks to single-section QD and Qdash based lasers and their applications in WDM coherent optical transmission.

III.2. Semiconductor QD/QDash mode-locked lasers

In this section, I will discuss the development of semiconductor QDot/QDash mode-locked lasers and their specific performances. It was part of the works done during the PhDs of Ricardo Rosales (2009-2012) and Cosimo Calo (2011-2014). I will first introduce the state of

the art of InAs/InP Qdot/Qdash MLLs, then, discuss the self-pulsating mechanism in these optical devices and finally show the operating conditions to perform ultrashort pulse generation at high repetition rate using different material systems.

III.2.1. Introduction

Mode-locking is a well-known method that locks the phases of the longitudinal modes of a laser, resulting in the generation of a train of pulses with a repetition rate corresponding to the cavity round-trip time. Semiconductor lasers are ideal candidates for mode-locking owing to their compactness and integrability with direct electrical control that allows the generation of picosecond and high-repetition-rate optical pulses in the near-infrared spectral range. The use of QD/QDash based mode locked lasers, which demonstrate ultra-broad band gain and absorption and ultrafast carrier dynamics, have become one of the most promising material systems for the generation of ultrashort pulses in the sub-picosecond range

The first demonstration of a monolithic passively mode locked laser using InAs/GaAs QD based active layer was reported in 2001 [29]. 17ps wide pulses were generated at a repetition rate of 7.4 GHz using a passive mode locking technique. The performance was limited by the available optical modal gain in a QD layer stack. Advances in material growth allowed to stack several QD layers thus enabling mode-locking with much improved performance in terms of pulse width, repetition rate and noise properties. Sub-picosecond pulse durations were demonstrated later by several groups using InAs/GaAs QDs [30]. This was made possible owing to the wide inhomogeneously broadened optical gain spectrum as well as extremely fast absorption recovery under reverse bias in the saturable absorber section of the devices [31].

A recent paper by Khan et al [32] reviewed the performances progress of Qdash/Qdot based mode locked lasers either in a standard two-section configuration including saturable absorber or in self-pulsating configuration using a single gain section. As illustrated in Fig. 10, single section devices exhibited better performances in terms of pulsewidth with record low values as short as 300 fs with QD based MLL [35]. In these works, the corresponding 3dB spectral bandwidths exceed 10 nm, while these amount to only a few nm for bulk or QW based devices.

My main works were initially focused on the ultrashort-pulse generation using passive mode locking techniques but without the need of saturable absorber. The so-called 'self-pulsating lasers' use a single gain section based either on InAs QDs or quantum dashes (elongated quantum dots) grown on an InP or GaAs substrate. The mode locking phenomena in single section lasers have been demonstrated in different dimensionality of the gain material (i.e bulk material, quantum wells, quantum dashes and quantum dots) [12], [35], [44]–[46]. Single-section devices based on low-

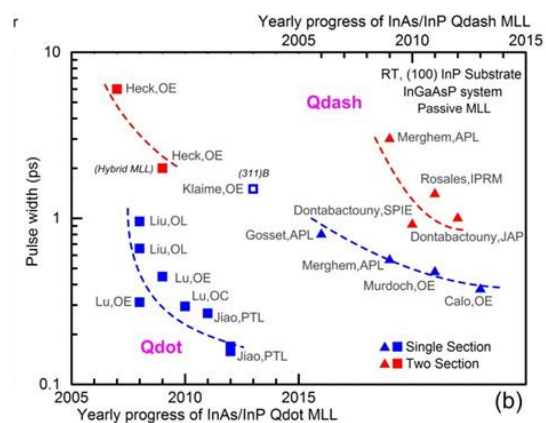


Figure 10 : Chronological progress of spectral bandwidth and pulsewidth of InAs/InP QDot and Qdash MLLs, after [32] (QDot: [33]–[40]; Qdash: [12], [13], [20], [41]–[43])

dimensional nanostructures have readily shown improved performances than conventional bulk or QW based lasers. Additionally, the narrower RF linewidths demonstrated for these materials indicate improved mode coherence. This last property, in particular, has been ascribed to the low optical confinement factor of QD and QDash structures [47], leading to a reduced spontaneous emission noise coupled to the propagating longitudinal modes. In addition, the absence of extra losses from an intracavity absorber allows for larger average output power and reduced optical linewidths compared to two-section passively MLLs with similar characteristics.

III.2.2. Self-pulsating mechanism

The understanding of the fundamental physical effects at the origin of self-pulsating mechanism in Fabry-Perot semiconductor lasers is still a matter of present research. One of the first papers dealing with mode locking in Fabry Perot semiconductor lasers was published in 2002 by Nomura et al. [45]. Using a semiclassical laser model, they demonstrated that a FP QW semiconductor laser can exhibit mode locking depending on the operating conditions and underling the important role of linear and nonlinear chromatic dispersions of the gain material. Many other physical effects are cited in the literature for explaining self-pulsating mechanism in QD and QDash lasers; these are the four wave mixing (FWM), the Kerr effect together with self and cross phase modulation and spatial hole burning (SHB). Similarly to quantum cascade laser case [48], models of QD and Qdash lasers have shown the importance of longitudinal spatial hole burning (SHB), treated as a gain compression term [49], or as a carrier grating term which gives rise to multimode operation because the gain recovery dynamics is much faster than the carrier diffusion process. Another mechanism also considered in [48] is the Kerr effect; this one was included as an instantaneous saturable absorber distributed all over the device length. Several papers attributed also the mode locking mechanism in single section lasers to the enhanced four wave mixing (FWM) in the Qdash/dot gain medium where the nonlinear interaction of adjacent modes through FWM results in the generation of sidebands, that will cause mutual injection locking of the cavity modes, resulting in the mode locking phenomena. It is important to note that the broad optical spectrum often measured in QD and

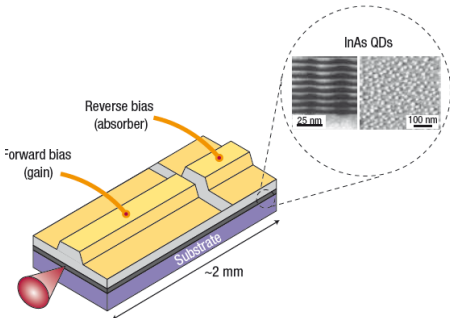


Figure 11 : Schematics of a monolithic two-section QD laser. Inset, transmission electron microscopy (TEM) photographs of QD layers [30]

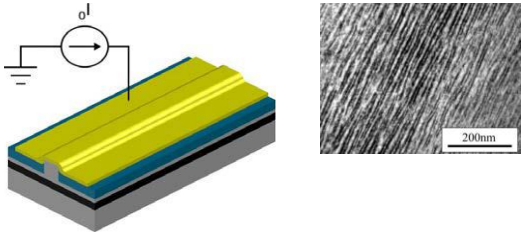


Figure 12 : Schematics of a single-section passively MLL (a) TEM picture of as-grown quantum dashes [47]

QDash lasers does not automatically imply a perfect phase-locking condition and in some cases in order to observe the generation of optical pulses from self-pulsating laser, we need to use some dispersion mitigation techniques such as dispersion compensator or SMF fiber.

III.2.3. Self-pulsating mode locked laser

This section illustrates the investigations we carried out on the self-pulsating mode locked lasers based on different material systems (InAs/InP QDash, InAs/GaAs QD and InGaAsP/InP SQW structures).

The story of InAs/InP QDash Mode locked laser started in 2005 with the first demonstration of self-pulsating regime under DC drive conditions [46]. The demonstration of a very narrow mode-beating linewidth for these lasers, of the order of 10's kHz for the full spectrum was an evidence of mode locking. Later on, we demonstrated ultrashort pulse generation at extremely high repetition rates in simple, one-section device configurations [12], [13]. We assessed the performances of QDash MLL by using the standard measurements techniques, i.e., by measuring their mode beatings in the RF domain in order to determine the ML range as a function of bias conditions and in the time domain to evaluate the pulse trains by means of second harmonic generation (SHG) background-free auto-correlator.

In the framework of the ANR project TELDOT and the European ITN project PROPHET, we aimed to investigate and evaluate the performances of self pulsating MLLs using advanced measurements techniques (stepped heterodyne technique [50] and second-harmonic generation frequency resolved optical gating (FROG) measurements [43]), in order to extract the values of the group delay (GD), group delay dispersion (GDD) and hence give us access to the static phase relation of the lasing modes and spectral phase of the electric field. Having access to the phase as well as the amplitude of the lasing modes allows reconstructing the intensity profile of the mode locked laser, from which the pulse duration can be determined.

If we represent the electric field in the frequency domain, its associated spectral phase can in general be written as a Taylor expansion around a given frequency ω_0 as: $\varphi(\omega) = \varphi^{(0)} + \varphi^{(1)} \frac{\omega - \omega_0}{1!} + \varphi^{(2)} \frac{(\omega - \omega_0)^2}{2!} + \dots$ with the group delay (GD) and the group delay dispersion (GDD) respectively defined as: $GD = \varphi^{(1)} = \frac{d\varphi(\omega)}{d\omega}$ and $GDD = \varphi^{(2)} = \frac{d^2\varphi(\omega)}{d\omega^2}$.

Figure 13 summarizes the measurements done on MLLs with repetition frequency of 48 GHz (cavity length of 890 μm) and 23 GHz (cavity length of 1820 μm) [51]. RF linewidths ranges 10s of kHz to 100kHz, showing efficient mode locking in large operating conditions. Figure 14 (a) represents the measured Group Delay for the 48GHz MLL when biased at 400 mA as a function of offset frequency, spanning about 50 modes of the power spectrum (Fig. 14 (b)). As expected from the ML condition, a linear GD is obtained, the slope of which determines the value of GDD which has been calculated at 1.3 ps². Figure 14 (c) shows the corresponding spectral phase (red plot) obtained after integration of the GD curve.

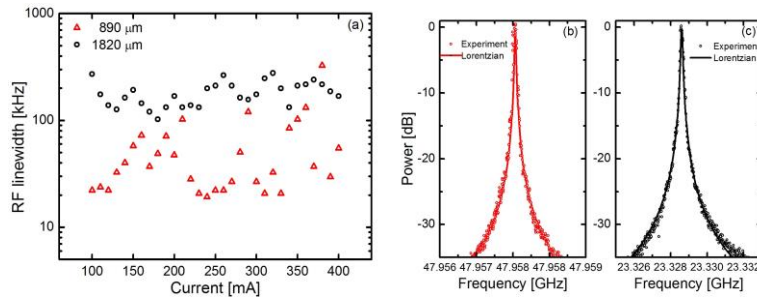


Figure 13 : (a) evolution of the RF linewidth for both lasers from 100 mA to 400 mA, reaching minimum values of 20 kHz and 100 kHz, for the 890 and 1820 μm lasers respectively.

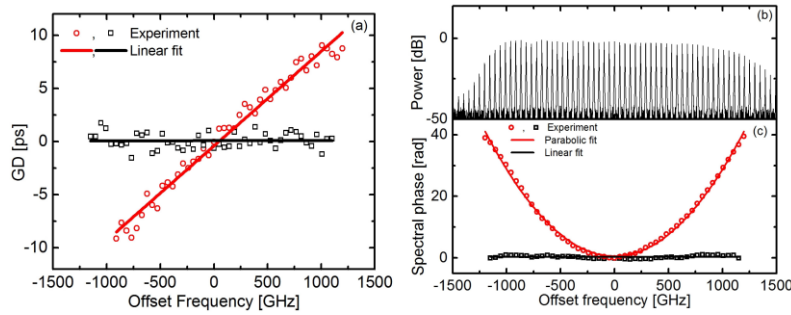


Figure 14 : (a) GD of the 890 μm laser measured at the laser output (red plot) and after 65 m of SMF (black plot) with corresponding (b) optical spectrum and (c) spectral phase at the laser output (red curve) and after 65 m of SMF (black curve) for an injection current of 400 mA.

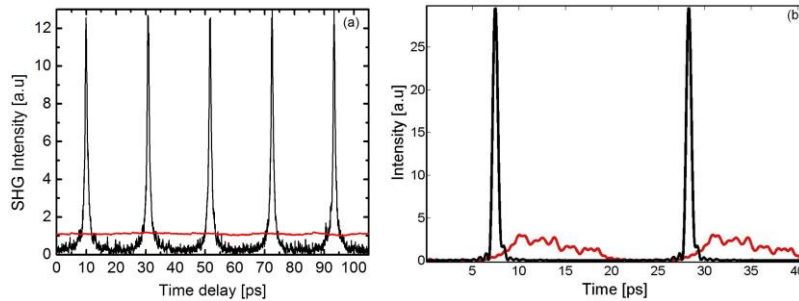


Figure 15 : (a) Intensity autocorrelation for the 890 μm laser at the laser output (red curve) and after 65 m of SMF (black curve) with corresponding (b) reconstructed field intensity profiles at the laser output (red curve) and after 65 m of SMF (black curve) when driven with 400 mA.

Regardless of the perfect locking of the mode beating frequencies and the low RF linewidths, the parabolic spectral phase profile in Fig. 14 (c) does not allow pulse generation. By inserting 65 m of single mode fiber (SMF) at the laser output introducing -1.3 ps^2 of accumulated dispersion, which would compensate for the laser GDD (black curves), the spectral phase, after dispersion compensation, showed negligible value, allowing for nearly Fourier transformed pulse generation. This is evidenced by the clean train of pulses in the intensity autocorrelation trace of Fig. 15 (black curve) which has been measured without using any type of optical amplification. We measured narrow pulse widths of 600 fs after deconvolution (assuming Gaussian pulse shape) and the 40 mW of average output power result in peak powers greater than 1 W. The electric field intensity profile has been reconstructed, yielding 600 fs pulse widths in agreement with the measured autocorrelation trace.

Similarly, we also investigated single section mode locked lasers in other material systems. We, in particular, evidenced the self-pulsating regime in GaAs-based QD lasers emitting in the 1.3 μm fiber window. In [52], we demonstrated the same regime of operation and studied the group delay profile of the laser electric field showing subpicosecond pulse generation by GaAs quantum dot laser (Fig. 16 - 18). After group delay dispersion compensation, pulse durations as short as 770 fs in a 45 GHz repetition rate device have been measured, with 1.9 W of peak power and a narrow RF spectrum of only a few kHz linewidth. This was the first demonstration of sub-picosecond pulses from a single section Fabry Perot InAs/GaAs edge emitting quantum dot (QD) based laser at 1.3 μm under continuous wave operation. These experiments showed evidence of an unexplored mode-locking regime in the InAs/GaAs quantum dot material system.

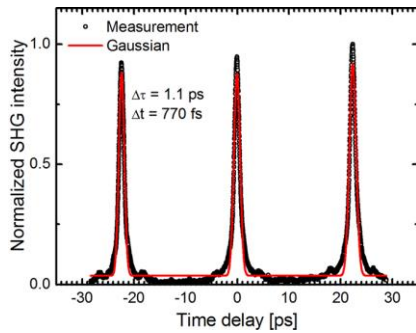


Figure 16 : Autocorrelation trace at $I=300$ mA after GDD compensation. Pulsewidth of 770fs after deconvolution

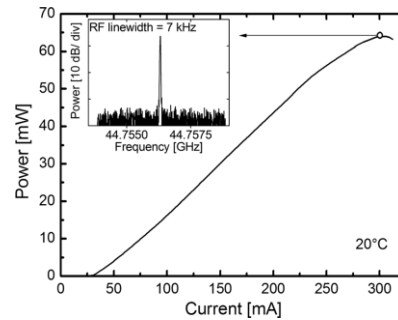


Figure 17 : L-I curve at room temperature
Inset: RF spectrum under 300 mA injection current showing 7 kHz of RF linewidth

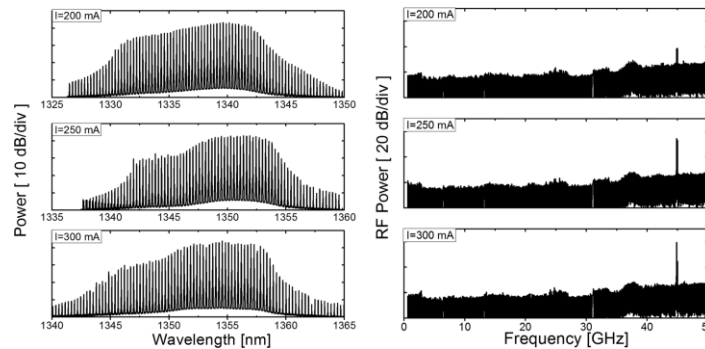


Figure 18 : Optical spectrum and corresponding 50 GHz span RF spectrum under different injection currents for InAs/GaAs QD based lasers

In addition to the QD and QDash material described above, we considered a single quantum well structure especially designed to have an optical confinement factor of 1%, comparable to that of QD/QDash based lasers. The use of relatively low confinement factor is advantageous for reducing the phase noise in the semiconductor mode locked lasers, owing to the small coupling of the amplified spontaneous emission to the propagating mode.

Based on this optimized laser structure, we investigated self-pulsating regimes in single QW-based MLL [53]. We observed a relatively flat comb spectrum with FWHM on the order of 4 to 6 nm (Fig. 19) and phase correlation between the comb lines was also demonstrated by the narrow RF line shape at the MLL repetition frequency. The RF linewidth exhibited by the device was on the order of 100 kHz and below indicating good mode-locking performance (Fig. 20). The main difference with these QW MLL compared to QDash MLL was the limited range of

operation with sharp transitions between different mode-locked states observed with injection current (Fig. 21).

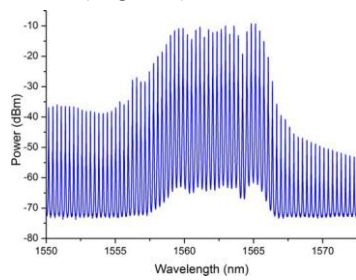


Figure 19: optical spectrum with FWHM of 6nm for 1 QW based MLL

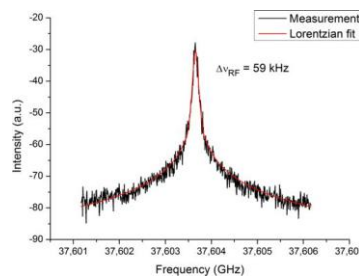


Figure 20: RF spectrum showing 59 kHz linewidth at 37GHz

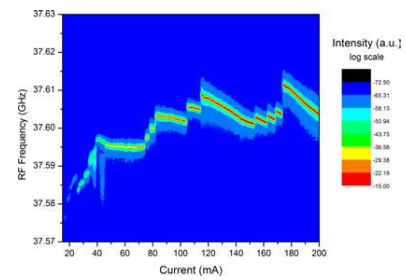


Figure 21: RF spectrum mapping as a function of injection current

In summary, we demonstrated experimentally the self-pulsating mechanism using different types of semiconductor mode locked lasers (Qdash, QD and QW). We achieved sub-picosecond pulse generation after propagation in a proper length of dispersive optical fiber. However, the self-pulsating mechanism seems to be more efficient in nanostructured material thanks to the inhomogeneous broadening of the gain spectrum associated to the enhanced non-linear effects in these Qdash/dot gain medium. It is important to note that the broad optical spectrum often measured in QD and QDash lasers does not automatically imply that a phase-locking condition can be established among all the modes; in [54], we showed that the phase locking is achieved only within separate group of modes depending on the operating conditions.

All of these works have contributed to the theoretical and experimental research in self-pulsating Fabry-Perot Lasers. Following our demonstrations, several groups have been involved in the modeling of the rich dynamics of multimode FP semiconductor lasers [55]–[57] and in the investigation of QD or QW-based self-pulsating lasers [58]–[60]. In particular, the group of P.J. Poole from National Research Council (Ottawa), investigated QD/QDash laser structures with similar performances [35], [37], [38]. More recently, self-pulsating regime was also observed by using a QD laser directly grown on silicon. Generation of 490 fs short optical pulses has been reported at a repetition rate of 31 GHz [61].

III.3. Noise characteristics and external optical feedback effects

In this section, I introduce an important feature of mode locked laser, i.e. the timing jitter. I will present the related measurements techniques we developed during the PhD of Ricardo Rosales (2009-2012). Then I discuss an efficient method based on optical feedback to improve the timing jitter. These experimental investigations are partly done during the PhD of Theo Verolet (2017-2020).

III.3.1. Timing jitter and measurement techniques

A very important figure of merit for MLLs is the timing jitter of the generated pulse trains. For a variety of applications including high bit rate optical time division multiplexing, clock recovery and millimeter wave generation, low timing jitter is necessary in order to fulfill bit error rate and phase noise requirements. I have been particularly involved in the investigation of this fundamental parameter using different schemes [16], [54], [62]–[64].

Timing jitter refers to the random variation of the temporal position of the pulse, with respect to the nominal position established by the pulse repetition frequency f_r . Timing fluctuations are converted into phase variations with respect to the pulse repetition frequency using the following relation: $\varphi_t(t) = 2\pi f_r \Delta t(t)$ where $\varphi_t(t)$ is the timing phase noise. The timing jitter can be quantified in terms of the variance of φ_t , $\sigma_{\varphi_t}^2 = \langle |\varphi_t|^2 \rangle$ which can be written as $\sigma_{\varphi_t}^2 = \int_{-\infty}^{+\infty} S_{\varphi_t}(f) df$. Timing jitter can be expressed by the integrated root-mean-square (rms) timing jitter over the frequency interval $[f_L, f_H]$ as $\sigma_T^i(f_L, f_H) = \frac{T_R}{2\pi} \sqrt{\int_{f_L}^{f_H} S_{\Phi_{RF}}(f) df}$ where T_R is the the period of pulse train and $S_{\Phi_{RF}}$ the single sideband (SSB) power spectral density (PSD) of the RF noise. In the case of the cumulated jitter, the pulse-to-pulse timing jitter is more adapted and is defined as $\sigma_T^{pp}(N) = \frac{T_R}{2\pi} \sqrt{\int_0^{+\infty} \sin^2(\pi f N T_R) S_{\Phi_{RF}}(f) df}$ where N is the number of repetition periods between the pulses considered for calculation.

In passively MLLs, the RF frequency noise is mainly induced by the broadband spontaneous emission leading to a Lorentzian-shaped PSD of the first harmonic of the RF photocurrent, whose linewidth is found to be directly linked to the timing jitter. Consequently, the full-width at half-maximum of the Lorentzian RF linewidth $\Delta\nu_{RF}$ determines completely the SSB PSD of the RF phase noise [65]. A commonly used timing jitter estimation method was developed by Von der Linde [66]. It is based on the measurement of phase noise PSD measured from the power spectrum of the MLL pulses. However, this procedure relies on the assumption that amplitude and timing noises are uncorrelated. Another technique was devised for measuring timing jitter, using the optical spectrum of the longitudinal lasing modes of the passive MLLs [62], [67], [68]. The broadening of the lasing modes is dominated by the contributions of optical phase noise and pulse-to-pulse timing fluctuations for passive MLL. This results in the linewidth of longitudinal modes being a parabolic function of the mode number (wavelength) and reaches a minimum within the lasing spectrum. The scaling of the parabola is proportional to the first harmonic of the RF linewidth, therefore it provides a direct measurement of the timing jitter without requiring fast detection. The figure 22 and 23 illustrate the method to evaluate the timing jitter of single section QDash MLLs.

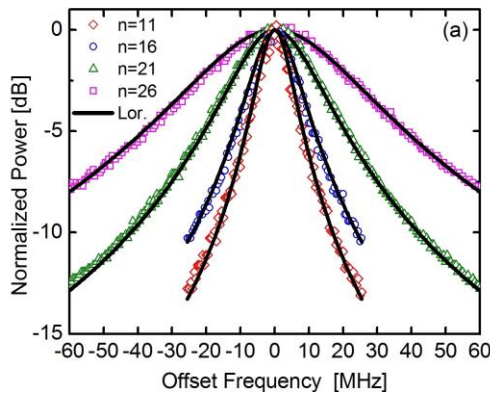


Figure 22: Self-mode beating spectra with Lorentzian fits for modes 11, 16, 21 and 26.

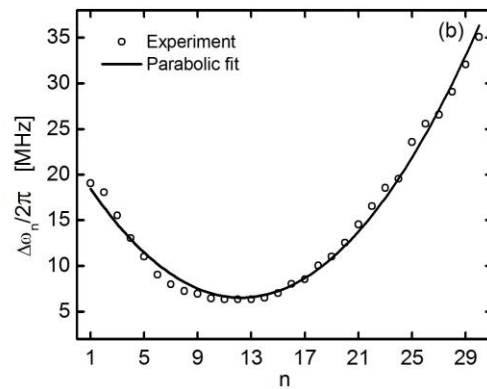


Figure 23: Measured optical linewidth vs mode number and parabolic fit

It was estimated from the optical spectra using the following formula $\Delta\omega_n = \Delta\omega_{min} + \Delta\omega_{RF}(n - n_{min})^2$ where $\Delta\omega$ is the FWHM optical linewidth, $\Delta\omega_{RF}$ is the RF linewidth, n is the

mode number and n_{\min} is the mode number corresponding to the minimum linewidth. By using this measurement technique, we have evaluated the timing jitter of single-section QDash MLLs with repetition frequencies up to 130 GHz [11], [63] and showed improved timing jitter performances down to several 10's of fs.

This technique is particularly interesting at high repetition frequencies where direct measurement of the RF linewidths and the evaluation of the timing jitter is limited by the photodiode and the electronics instrumentation bandwidth.

III.3.2. Mode locked laser performances under optical feedback

Improvement of the timing jitter of semiconductor MLLs are becoming essential for different applications such as DWDM coherent transmission. Significant reductions of the timing jitter have been reported by means of stabilization techniques such as optoelectronic feedback loop [70], optical injection [71] or optical feedback schemes [20], [72], [73]. It has long been shown that optical feedback is an efficient method to narrow the optical linewidth, which is equivalent to reduce the phase noise or timing jitter of a MLL. Depending on operating conditions, optical feedback may improve or degrade MLLs performance [17], [18]. In a numerical investigation, Avrutin et al. [19] have discussed different dynamic regimes for MLLs under optical feedback. A reduction of laser noise was predicted in the resonant case, where the external cavity length is a multiple of the optical length of the laser, whereas in the non-resonant case, optical feedback degraded the mode-locking process. In 2017, for the first time, we investigated experimentally the effect of resonant or coherent optical feedback on the phase noise characteristics of QDash MLL [69]. By exploiting this optical feedback regime in a free space external cavity, we achieved a drastic reduction of phase noise in a single section QDash MLL. To allow the coherent feedback regimes, the external cavity length was adjusted to be near a multiple of the optical length of the laser as simulated in [19]. Figures 24 and 25 illustrate respectively the effect of optical feedback on the RF characteristics and the optical linewidths. We observe a frequency shift by ~ 100 MHz towards high frequency and a RF linewidth reduction from 151 kHz to 3 kHz at a repetition frequency of 25 GHz. The laser implemented a simultaneous decrease of the optical linewidth of all individual longitudinal modes.

The initial optical linewidths of (2 to 10) MHz reduce by nearly two orders of magnitude with

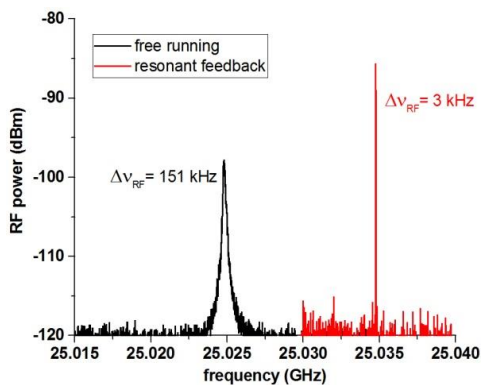


Figure 24 :RF spectrum showing this effect of resonant optical feedback [69]

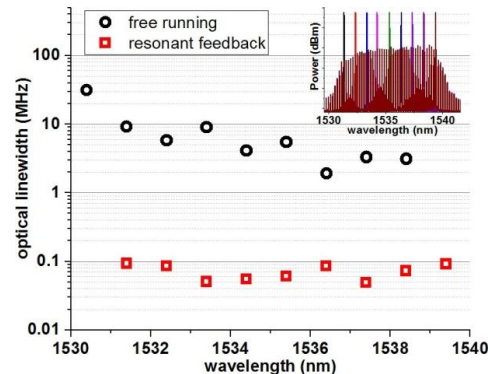


Figure 25: Optical linewidth as a function of wavelength. Inset : Optical spectrum measurement values below 100 kHz.

This first demonstration opened the way for several other investigations

on the beneficial effect of optical feedback on semiconductor MLLs. Subsequently, several research groups used the same techniques to reduce significantly the pulse timing jitter [74]–[79].

During the thesis of Théo Verolet (2018-2020), in [80], we further explored the feedback regimes of a single section MLL as function of feedback strength in resonant or non-resonant cases. We assessed the optical spectrum envelope together with the RF comb beat spectra (Fig. 26). Four feedback regimes were identified as a function of feedback delay and strength: coherence collapse regime (I), detuned feedback (II), coherent feedback regime (III) and weak feedback regime (IV). In the regime I, with high feedback strength (~ -7 dB) the optical spectrum envelope and each longitudinal mode is considerably broadened (optical linewidths >10 GHz) as well as the RF spectra with the presence of harmonics corresponding to the external cavity roundtrip time. In that case, the mode locking mechanism is degraded. This regime was referred to as the coherence collapse regime by similarity with the one observed in single mode lasers. In the regime “II”, the feedback strength is reduced close to -16 dB, which corresponds to a feedback level under the onset for coherence collapse, and the external cavity roundtrip time is not adjusted to a multiple of the MLL one. This feedback regime is also detrimental to mode locking effect. In regime III, the feedback level is similar to the previous case, but the external cavity roundtrip time is set close to a multiple of the MLL roundtrip time to target locking between the MLL and the feedback cavity. In this regime, the comb envelope is similar to that in the non-feedback case, but shifted by few nm to longer wavelengths. The similarity in shape of the comb envelope with the non-feedback case may be related to a similar feedback phase affecting every MLL tone. The beneficial effect of coherent feedback on the noise properties of the MLL, is revealed by the RF linewidth narrowing from 49 kHz to a value of 530 Hz. In the regime ‘IV’ labelled as weak feedback (under -30 dB), the comb envelope is not affected but depending on the feedback delay, the RF beat signal linewidth can be more than ten times wider. Only the coherent feedback regime had beneficial effects on the MLL RF beating signal linewidth. It was obtained for feedback level under the onset for coherence collapse and with an external cavity round-trip frequency adjusted to a sub-harmonic of the MLL RF beat signal frequency. The performances obtained with resonant optical feedback indicates that the

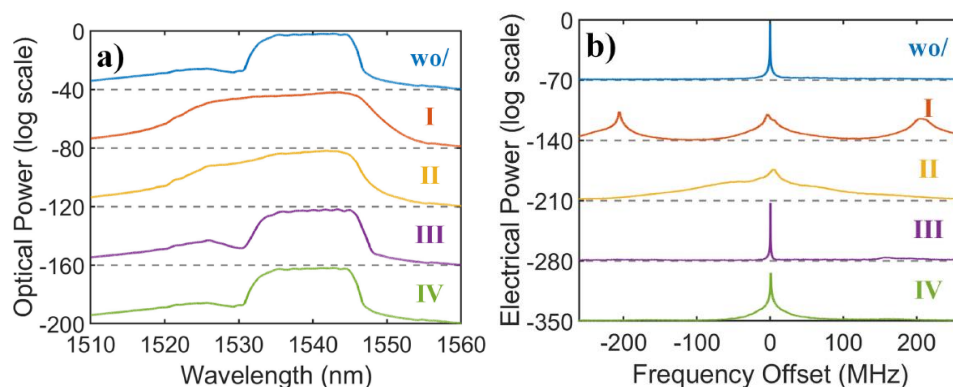


Figure 26 : (a) Optical envelope for different feedback regimes. (b) Electrical spectra of the photodetected entire comb beating, (wo/ without feedback)

external cavity used can successfully play a role to make high correlation between the lasing modes and result in femtosecond timing jitter level. Combined with obtained low optical

linewidths, this makes Qdash MLL suitable for their use in the next generation high-speed coherent transmission systems, and for all-optical signal processing.

III.4. Quantum-dash laser comb sources for multi-terabit/s WDM transmission

Recently, there has been significant interest in optical comb lasers and their benefits as monolithic sources of multiple wavelength channels for DWDM coherent fiber communication systems with net data rates exceeding Terabit/s transmission rates and high spectral efficiency [81], [82]. Such comb lasers can reduce costs and packaging problems by replacing many separate DFB lasers for each channel by a single laser chip. Additionally, these comb sources are very attractive owing to their compactness, low cost, low noise and improved performances [30], [83]. Narrow optical linewidth is also an essential requirement to be used in high data rate coherent communication systems where phase noise impacts signal noise in the coherent detection process, and the maximum data rate is determined by the ratio of signal to noise power.

My research on semiconductor mode locked laser gave me the chance to be involved in the European ITN Marie Curie project PROPHET (2011-2014) and in the European STREP project BIG PIPES (2013-2016) for the development of optical frequency combs for optical interconnects in the datacenters. In this section, I will present a part of works we did during these projects. First, I will introduce the performances of QDash MLL as optical comb sources, and then show several demonstrations of high bitrate WDM data transmission performed in collaboration with KIT and DCU.

III.4.1. Quantum-dash based laser as optical comb sources

An optical frequency comb (OFC) is a light source whose spectrum is composed of a discrete set of equally spaced lines. Optical frequency combs initially attracted attention for their impact on the field of precision measurement where they revolutionized optical frequency metrology and synthesis and enabled optical atomic clocks [84]. The groundbreaking research on OFCs lead to the attribution of one half of the Nobel Prize in Physics 2005 to J. L. Hall and T. W. Hänsch. One of the most popular techniques for the generation of OFC is laser mode locking. As already discussed, mode-locked lasers produce a periodic train of optical pulses at a period equal to the round-trip time of the laser cavity, leading to a spectrum consisting of discrete lines separated by integer multiples of the pulse repetition frequency. For telecom applications, semiconductor MLLs with extremely high repetition rates are promising OFC sources for their use as compact, high-efficiency, and low-cost light sources in high-speed dense wavelength-division multiplexing transmissions.

III.4.1.1. Optical bandwidth

The first important characteristic of optical frequency comb is the optical bandwidth and in particular the envelope full width at half maximum (FWHM) of its optical spectrum. It determines the number of available longitudinal laser modes with respect to the free spectral range (FSR) of the MLL. Qdash lasers generate a broad and flat emission spectra with FWHM in excess of 15 nm (corresponding to >1.5 THz). As illustrated in Fig. 27, the FWHM increases

from a few nanometers at threshold current up to a maximum value of ~ 15 nm at high injection currents, after which it essentially remains constant with increasing current. This parameter depends on the intrinsic material gain spectrum and its broadening effects (homogeneous and inhomogeneous) rather than on the particular ML mechanism (single section or two section). In general, we have found that the maximum spectral FWHM in the QDash MLLs, both in its single and two section configurations, was larger than those reported for QD [35] or QW based devices [85] on InP substrates.

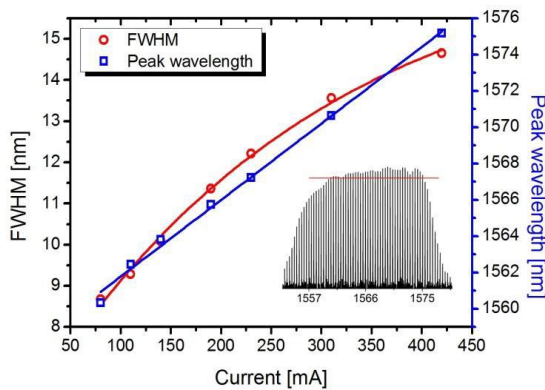


Figure 27 : FWHM and peak wavelength of the optical spectrum as a function of injection current. (Inset: Optical spectrum)

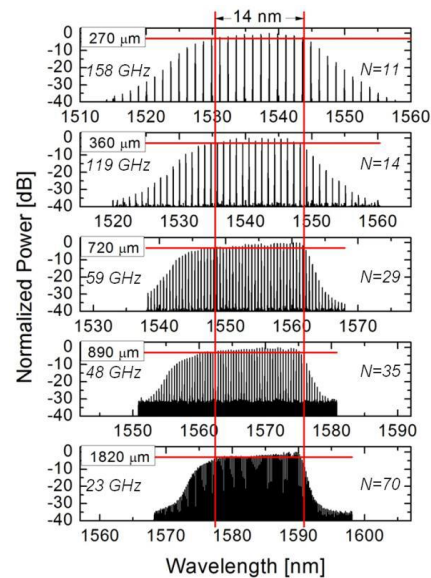


Figure 28 : Optical spectrum and corresponding number of lasing modes (N) for different cavity lengths,

These typical trends were observed for any QDash FP laser and take place independently of its cavity length as shown in Fig 28. The fact that the envelope FWHM of the lasing spectrum is preserved means that the maximum attainable number of longitudinal modes under the spectrum envelope increases proportionally when increasing the laser cavity length. This property can be exploited in applications requiring a large number of equally spaced longitudinal modes, such as in optical Orthogonal Frequency Division Multiplexing (OFDM), allowing for large capacities and improved spectral efficiency through the use of multilevel modulation of tightly-spaced orthogonal subcarriers

III.4.1.2. Repetition frequency stability

The second topic of interest for optical frequency comb is the evolution of repetition frequency as a function of operating conditions. I thoroughly investigated this parameter for QDash MLLs. In fact, depending on Qdash structure design, sharp transitions between different mode-locked states could be observed with injection current [54]. These transitions involve jumps of both the RF frequency and the central wavelength. In particular, shifts of the emission spectrum towards longer wavelengths are accompanied by larger values of the beat-note frequency. Figures 29 - 32 illustrate these behaviors for 10 GHz and 25 GHz QDash MLL.

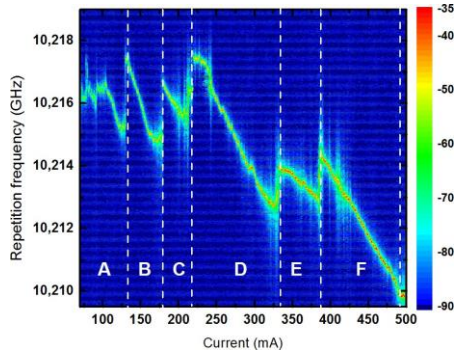


Figure 29 : RF spectrum mapping as a function of current for 10 GHz QDash MLL

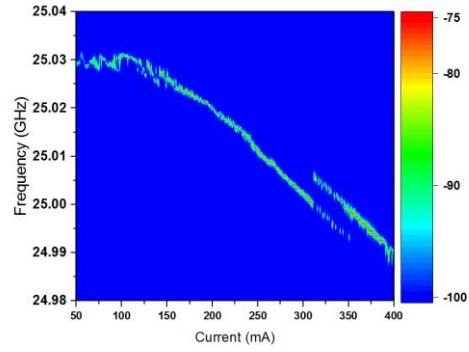


Figure 30 : RF spectrum mapping as a function of current for 25 GHz QDash MLL

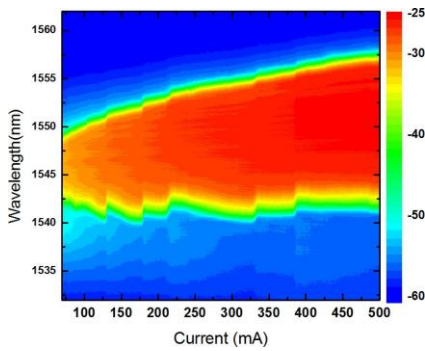


Figure 31 : corresponding optical spectrum mapping as a function of current for 10 GHz QDash MLL

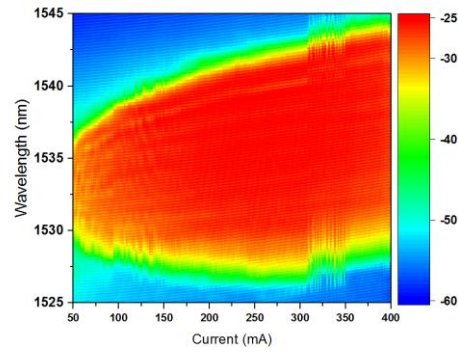


Figure 32 : corresponding optical spectrum mapping as a function of current for 25 GHz QDash MLL

On these figures, for a large range of driving conditions, we observe efficient mode locking with narrow RF linewidths (tens of kHz). The repetition frequency decreases with increasing current accompanied by a change of slope and sudden hops. For single section MLL, we identify different mode locking regimes. The analysis is based on the evolution of RF spectrum and optical spectrum of 10 GHz MLL and could be extended to the 25GHz device. As shown in the Fig 29, from 70 to 100 mA, RF spectrum is instable with large fluctuations. The range of currents between 100 to 133 mA corresponds to the first mode-locking regime where the frequency decreases with current. At 130 mA, the RF frequency starts to broaden and jumps to higher value. At 134 mA, the RF spectrum shows a low RF linewidth (~ 10 kHz) and the RF frequency decreases again until 180 mA. We observe the same succession of regimes with multiples frequency hops. The same behavior was observed for two-section devices. Similar trends were already observed in quantum dot MLLs explained by the presence of different optical supermodes [21]. This concept of supermode was first proposed by Kim and Lau for semiconductor MLLs [86]. This frequency domain approach defines a supermode as a set of phase locked longitudinal modes. It is a solution of the coupled mode equation for the intracavity electric field. Each supermode has a distinct repetition frequency and threshold. In semiconductor lasers, multiple supermodes can coexist with distinct repetition frequency and threshold because of a different group index. In general, a supermode has its own repetition frequency and its own evolution with current and temperature. In case the laser emits light on

multiple super-modes at a certain bias point, these will compete between them for gain, resulting in repetition frequency instability and larger RF linewidths [54].

III.4.1.3. Long-term frequency stability

Another quantity of interest for optical frequency combs from MLLs is the long-term stability of the repetition frequency. The most common time domain measure of frequency stability is the Allan variance ($\sigma_y^2(t)$), as known as two samples variance, which gives a value for the fractional frequency fluctuations $y(t)$ as a function of averaging time t : $y(t) = \Delta f(t)/f_r$ with Δf the frequency fluctuations and f_r the repetition frequency.

The overlapping Allan variance is a form of the normal Allan variance that makes maximum use of a data set by forming all possible fully overlapping samples at each averaging time t . It can be estimated from a set of M frequency measurements for averaging time $t = n\tau_0$, where n is the averaging factor and τ_0 is the basic measurement interval, by the expression defined by:

$$\sigma_y^2(n\tau_0, M) = \frac{1}{2n^2(M-2n+1)} \sum_{j=0}^{M-2n} (\sum_{i=j}^{j+n-1} \bar{y}_{i+n} - \bar{y}_i)^2 \text{ with } \bar{y}_k(t) = (\bar{f}_k(t) - f_r)/f_r$$

In practice, the long-term frequency stability is measured using a frequency counter with highly stable reference typically used for high precision comb sources. To be able to adapt these measurements for Qdash MLL, I developed a very simple approach for monitoring the repetition frequency stability in time by sampling the applied voltage fluctuations [87]. Terminal voltage fluctuations across a laser diode have already been used to characterize the dynamic characteristics such as the chaos in semiconductor lasers subjected to optical feedback [88]. Another application relates to self-mixing interferometry for sensing applications [89]. In that case, the terminal voltage changes play the role of the photodetection function. We applied this technique to the monitoring of long-term frequency stability of QDash-based MLL thanks to its terminal voltage fluctuations. Various noise sources can affect the repetition frequency stability. The main ones arise from temperature fluctuations, laser drive current fluctuations and undesirable optical feedback. The dependence of diode forward voltage on junction temperature had first been investigated. This is related to band gap energy and carrier density variations with temperature. The repetition frequency also decreases with increasing temperature through the refractive index changes. Also several investigations have already shown the sensitivity of semiconductor MLLs to external optical feedback. In our case, a weak optical feedback is generated from the coupling optical fiber end showing frequency instabilities.

To evaluate the long-term stability, we measured the frequency change and the terminal voltage drifts during one hour (Fig. 33) at a fixed current of 250 mA and stable temperature of 19°C. The two parameters follow the same trend. The cumulated

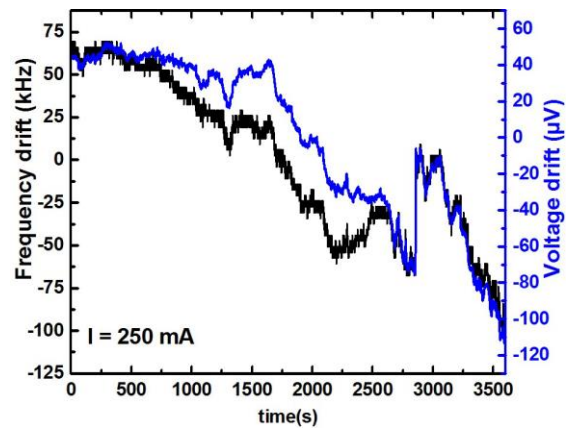


Figure 33 : Frequency and terminal voltage drifts during one hour ($I=250$ mA) [87].

frequency drift reaches a value of 160 kHz and total terminal voltage drifts up to 140 μ V. The origin of the frequency drift is mainly related to environmental noise and in particular fluctuations of fiber position induced by mechanical vibration.

In order to improve this long-term frequency stability, more or less sophisticated stabilization techniques have been proposed for semiconductor MLL. The first method is to operate in active or hybrid mode-locking regime with a high-stability RF signal. The optoelectronic phase-locked loop is another technique based on electrical feedback that allow an improved stability and a phase noise reduction [90]. Stabilization has also been demonstrated by optical injection (coherent or incoherent schemes) [64], [91]. In my research team, we have developed different stabilization schemes based either on electrical feedback loop or optical feedback loop [92]. The scheme based ultra-short optical feedback use the pulling effect on the repetition frequency by variation of the feedback delay to compensate the frequency drift while the electrical scheme use only the control of applied current on the laser for frequency stabilization. Both schemes showed similar improved performances in term of long-term frequency stability. We will discuss here the stabilization scheme based on electrical feedback loop. This scheme is specific to two-section devices working in gain-gain configuration (different injection currents are applied on the gain sections). Figure 34 illustrates the two-section device with a 4mm-long section and a 230 μ m-long section. The applied current on the short section is specifically used for frequency stabilization through the control of its applied current. To perform this stabilization, we used a typical discrete PID controller modeled by the following expression:

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

where e_n represents the n th sample of the error between the reference frequency and measured frequency, u_n is the resultant current I_2 applied to the short section to compensate this drift, and K_p , K_i , K_d are the constant gains assigned to the proportional, integral and derivative components of the controller respectively. We evaluated the long-term drift, by measuring the frequency change during 1 h with and without this stabilization scheme. The results are depicted in Fig. 35. These

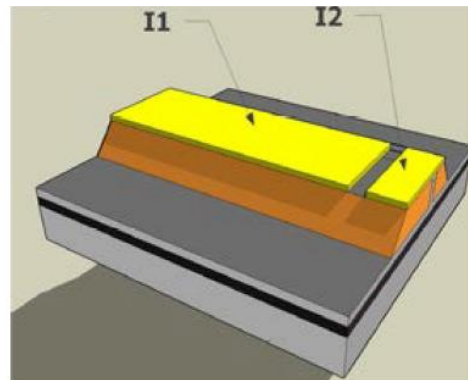


Figure 34 : sketch of two-section self-pulsating MLL.

measures showed the effect of stabilization loop by reducing the total frequency excursion and the standard deviation σ , by almost a factor of three. As a measure of the long-term stability of the generated comb, the overlapping Allan deviation was computed from the frequency time-series reported in fig. 35 (a) and (b) and results are reported in Fig. 35 (e). Starting from 3×10^{-7} at 1s averaging time, it reaches 3×10^{-9} level at 1000s averaging time with the frequency stabilization system whereas in free running operation, the Allan deviation is always greater than 2×10^{-7} . For the first time, we had investigated the long-term frequency stability of semiconductor-based OFC and developed frequency stabilization techniques. This study has led to a successful implementation of electrical control that stabilizes the repetition frequency and reduce the standard deviation down to 4.8 kHz at a 10 GHz repetition frequency, corresponding to a fractional frequency instability of 3×10^{-9} . Combining this stabilization

scheme with the assessment of frequency stability via terminal voltage fluctuations can offer a simple way to develop highly stable OFC generated by QDash MLLs.

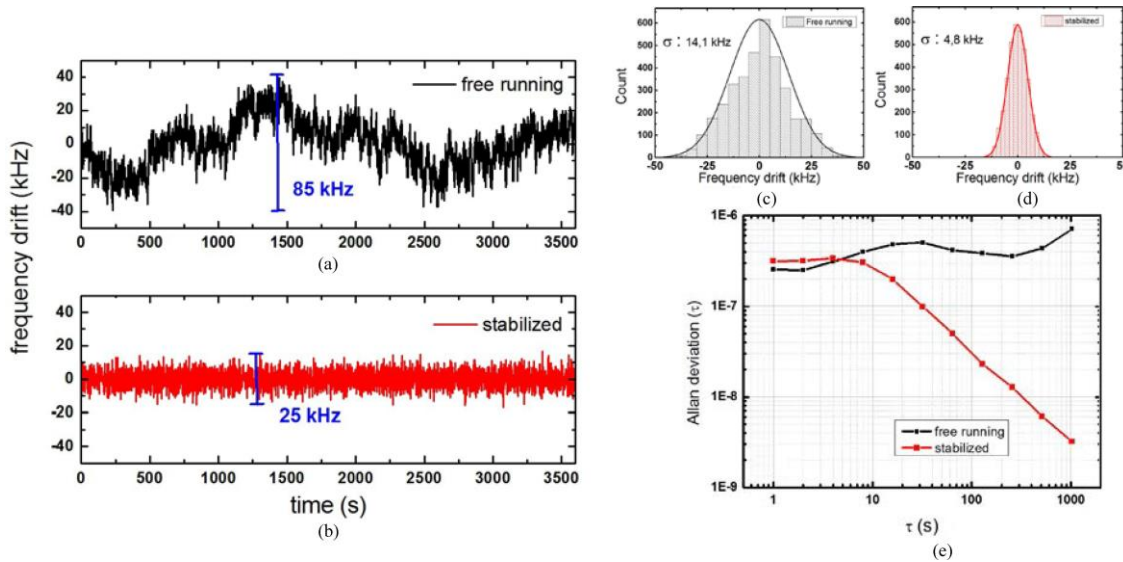


Figure 35 : Frequency drifts during 1 h (a) in free running and (b) with stabilization scheme. Distribution of frequency drift (c) in free running and (d) with stabilization scheme. (e) Allan deviation based on the measured relative frequency drifts

III.4.2. Multi-terabit/s comb-based WDM transmission

In the framework of European projects (ITN Marie Curie project PROPHET and STREP project BIG PIPES) in collaboration with our partners, I had the chance to contribute to the demonstration of WDM transmission experiments implementing QDash MLL as comb sources. To allow these transmission experiments, I was firstly involved in the optimization of QDash devices and devices assessments. For each optimized device, to select the right regime of operation, I did the full mapping of the devices performances in the optical and frequency domain as a function of the injected current. Thereby, devices characteristics could directly be correlated to the transmission performances.

In the section, I will present a selection of multi-terabit/s coherent transmission experiments performed by Karlsruhe Institute of Technology and Dublin City University with different architectures employed.

III.4.2.1. Introduction

Over the last years, various high-speed WDM transmission experiments have been carried out using a wide variety of different chip-scale comb generators that rely, e.g., on Kerr nonlinear high-Q silicon-nitride microresonators [93], on gain switching of semiconductor lasers [94], or on electro-optic modulators [81]. Among the different frequency comb sources, QD/QDash mode-locked laser diodes are particularly interesting owing to their technical simplicity. Driven by a direct current, these devices emit broadband frequency combs consisting of few tens of optical carriers, spaced by free spectral ranges of 10s GHz to 100s GHz. Table 1 summarizes the transmission experiments found in the literature using QD or Qdash frequency combs in the last years and Fig. 36 depicts the related evolution of aggregate data rate in chronological

order. We observe a clear evolution towards high order modulation scheme using different strategies and the use of a large number of channels to perform multi-terabit/s transmission from few km to 100 km of SMF.

Optical source	Modulation scheme	SMF length [km]	#Ch.	Data Rate [Gb/s]	Ref.
MLL	OOK	50	8	1x10	[95]
MLL	DP-QPSK	BtoB	11	1x56	[96]
MLL	OOK	100	4	4x170	[97]
MLL	OOK	100	4	4x28	[98]
MLL	16QAM	BtoB	37	37x72	[99]
MLL	16QAM	75	13	13x72	[99]
MLL	16QAM	3	40	40x28.2	[100]
MLL	16QAM	3	80	80x28.2	[100]
MLL	16QAM	50	16	16x33.6	[83]
MLL	16QAM	50	40	40x33.6	[101]
MLL	16QAM	3	160	160x28	[83]
MLL	DP-QPSK	50	36	36x50	[102]
MLL	DP-QPSK	75	52	52x160	[103]
MLL	16QAM	75	32	32x304	[103]
MLL	DP-QPSK	75	23	23x180	[104]
MLL	PAM4	25	48	48x112	[105]
MLL	16QAM	100	48	48x224	[106]
SIL/MLL	16QAM	BtoB	47	47x256	[107]
MLL	PAM4	1	8	8x56	[108]
SIL/MLL	32QAM	75	60	60x200	[109]
MLL	16QAM	100	56	56x28	[110]

Table 1 : Summary of the implementation of QD/QDash lasers in optical communication in literature (adapted from [32])

MLL: QD/QDash Mode Locked Laser

SIL : self-injection locking

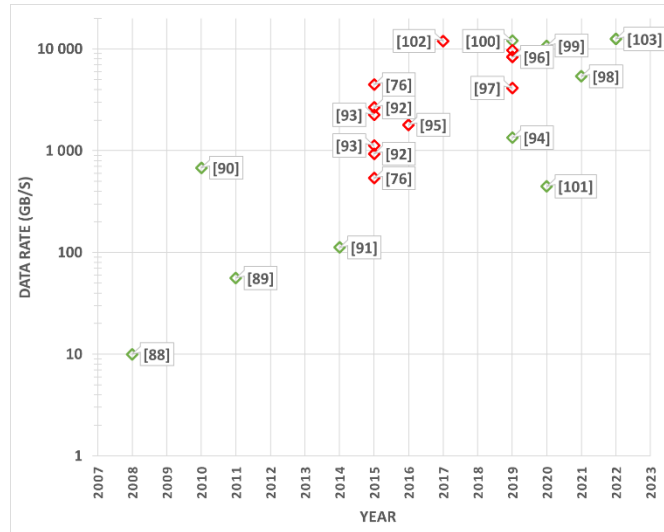


Figure 36 : Summary of the demonstrated aggregate data rates achieved over WDM optical communication incorporating InAs/InP QD/Qdash LD as optical sources. (Red dots corresponding to our contributions)

The First demonstration of WDM transmission implementing a Qdash MLL was done by Akrouf et al [95], [111] in 2008. A Qdash mode-locked device emitting in the C-band was used to generate 8 WDM channels with 100 GHz-mode spacing. Error-free transmission with an On-Off Keying (OOK) modulation scheme (i.e. intensity modulation) was demonstrated at a data rate of 10Gb/s for each channel, over 50-km SMF span. The following report demonstrated phase modulation transmission (DP-QPSK) at a data rate of 56Gb/s using 11 channels generated by similar Qdash devices. These first demonstrations of WDM transmission with QD-MLLD had to rely on intensity modulation or were limited to rather simple modulation formats such as quadrature phase-shift keying. It was challenging to implement 16-state quadrature amplitude modulation (16QAM) transmission due to inherently broad optical linewidths of the FP modes in the order of tens of MHz, which strongly impairs transmission of signals. In the following, I will describe the different strategies were employed to allow coherent WDM transmission using high order modulation schemes.

III.4.2.2. Terabit/s WDM transmission with single QDash mode locked laser

In collaboration with our partners from DCU and KIT, we achieved in 2015 the first Tb/s data-capacity WDM transmission with a single Qdash MLL source, and both using 16QAM modulation scheme. In [99], we transmitted 18 GBd 16QAM signals on 25 spectral lines of QDash MLL, achieving 1.562 Tbit/s aggregate data rate. To overcome the large optical

linewidth of comb lines (typically 10s of MHz), self-homodyne detection were employed, i.e a comb of local oscillator (LO) tones derived from the same comb source used to transmit the signal is sent along with the signal [112]. This specific setup and the data transmission results after 75km of SMF are illustrated in the Fig 37. The BER values were below the 20% FEC limit for all modes after transmission.

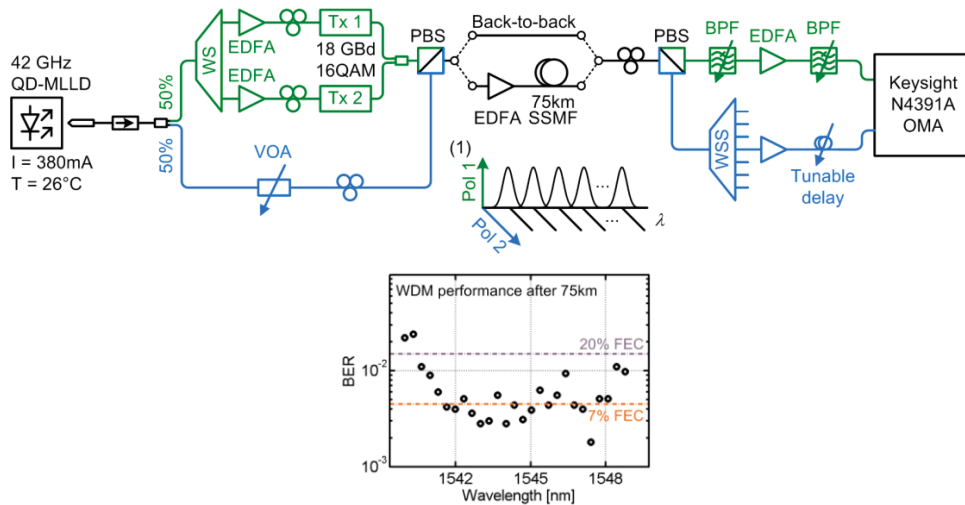


Figure 37: Experimental setup for self-homodyne data transmission and BER vs wavelength for 27 WDM channels after 75km [99]

Concurrently, in collaboration with DCU, successful use of QDash based frequency comb generators for WDM data transmission using high-spectral efficiency 25 Gbit/s optical orthogonal frequency division multiplexing (OFDM) encoding [83], [100]. Aggregate capacities up to 4 Tb/s from a single device using direct detection OFDM (DD-OFDM) were achievable in WDM transmission. The experimental setup for the IM/DD SSB OFDM system is shown in Fig. 38.

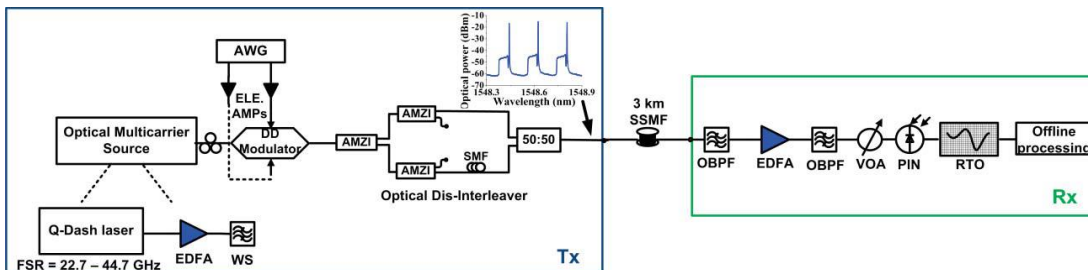


Figure 38: Schematic of the Q-Dash Terabit/s transmitter (Tx) which employs IM, and DD based receiver (Rx). Inset depicts part of the optical spectrum of the transmitted signal, showing SSB-OFDM modulation [83]

The performances of the selected channels after transmission over 3 km of SSMF are given in Fig. 39. The total measured average RIN (DC-10 GHz) for all channels was under -132.5 dB/Hz. The measured constellation diagram for one channel is shown in Fig. 39. The selected channels, which uniformly cover the entire emission spectrum of the 10.2 GHz Q-Dash MLL, all exhibit performance below 7% FEC limit, indicating the possibility of a further increase in aggregate data rate up to 4.5 Tb/s (160 x 28.2 Gb/s IM/DD SSB OFDM).

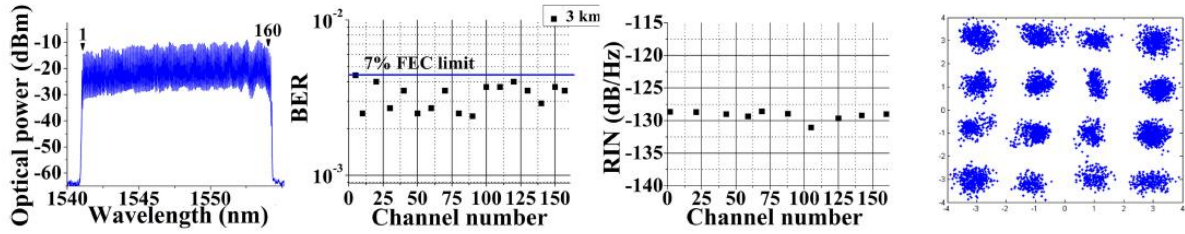


Figure 39: (a) Optical spectrum of filtered Q-Dash PMLL with 10.2 GHz channel spacing (RBW = 0.02 nm), (b) measured BER for selected channels, after transmission over 3 km of SSMF, (c) the measured average RIN (DC-10 GHz) for selected modes, and (d) the measured constellation diagram for the middle channel after 3 km of SSMF

III.4.2.3. Multi-Terabit/s WDM transmission

As already presented in section I.3.2, further performance improvements of Qdash MLL was possible by exploiting coherent feedback from an external cavity to drastically reduce the phase noise and optical linewidth of QD-MLLD tones, thereby greatly improving the transmission performance. In our experiments, we demonstrated for the first time 32QAM WDM transmission on 60 carriers derived from a single QD-MLLD, leading to an aggregate line rate of 12 Tbit/s at a net spectral efficiency of 7.5 bit/s/Hz. For this specific experiment, I personally set up the experimental setup to stabilize the QDash MLL in the KIT lab and ensured that the operating conditions give the required low optical linewidth below 100 kHz allowing coherent transmission.

The transmission experimental setup and performances are illustrated in Fig. 40.

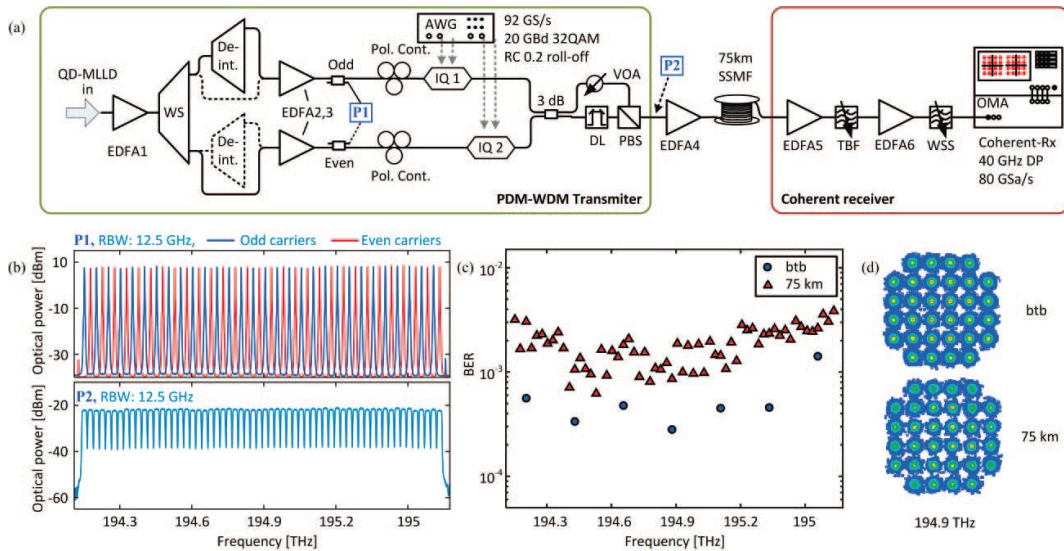


Figure 40: (a) The experimental transmission setup demonstrated. (b) Combined spectra of both unmodulated odd and even carriers taken at position P1 (top) and spectrum of the 60 modulated comb lines measured at position P2 (bottom). (c) BER of the different transmitted channels in BtB and 75 km long SMF links. (d) Example constellation diagrams of the mode at 194.9 THz [109], [113]

The transmitter signal was amplified and modulated in a 32QAM modulation scheme at a symbol rate of 20 Gbaud by a $2^{11}-1$ long PRBS and PDM (200 Gb/s per channel). Figure 40 (b) depicts the combined spectra of both unmodulated odd and even carriers taken at position P1 (top spectrum) and of the 60 modulated comb lines measured at position P2 (bottom

spectrum). Then, after amplification, the recombined and modulated comb lines were transmitted over a 75-km long SMF. The desired comb signal was filtered out at the receiver, amplified, and detected on an optical modulation analyzer. We showed that BER values for all 60 comb lines was below the 7% FEC limit. In [109], simulations were also performed showing that feedback-stabilized QD-MLL should also support 64QAM transmission with a performance close to the theoretical optimum.

Chip-scale frequency comb generators lend themselves as multi-wavelength light sources in highly scalable WDM transmitters and coherent receivers as well as addressing green communication networks by potentially replacing several light sources with a single source in WDM networks. Among different options, QDash mode-locked laser diodes stand out due to their compactness and simple operation along with the ability to provide a flat and broadband comb spectrum tones. The potential of QD-MLLD has been demonstrated by using these devices as optical sources for spectrally efficient high-speed data transmission, achieving aggregate lines rates of more than 10 Tbit/s using advanced modulation formats beyond 16QAM. Different architectures were employed, not all presented here for clarity, allowing coherent transmission, and thus demonstrate the tremendous potential of QDash OFC for the next generation of optical network [83], [53], [99], [100], [102], [113], [103], [104], [108], [109], [80].

Similarly, all of these works have been of interest by the research community and several other groups have been involved in the development of QD-based combs sources for Tbps WDM transmission [107], [114], [115], [105], [110].

III.5. Additional achievements

In this section, I will present other research activities during the same period in different topics related to the developed know-how in mode locked lasers and low dimensional semiconductor lasers. These achievements are the result of fruitful academic collaborations with *Institut d'Electronique et des Systèmes* (IES-Montpellier), *Télécom SudParis* and the *University of Duisburg-Essen* (Germany).

III.5.1. Monolithic mid-infrared mode locked laser

In the past few decades, research on monolithic semiconductor mode-locked lasers was mainly focused on the GaAs and InP material systems and thus was limited to the near infrared spectral range. Recently, a strong interest rose for ultrashort pulsed sources at longer wavelengths above 2 μm . These laser sources as frequency combs represent a promising solution for many applications such as molecular spectroscopy, high resolution gas sensing, advanced telecommunications, and eye-safe light detection and ranging [116], [117].

In collaboration with R. Teissier and A.N. Baranov from *IES Montpellier*, we demonstrated, for the first time, passive mode locking in a monolithic GaSb-based diode laser emitting at 2.1 μm [118]. We studied a standard two-section laser including a saturable absorber with a total length of 1.88mm. The laser active region consisted in two GaInSbAs/GaAlSbAs quantum wells grown on GaSb substrate.

I was mainly involved in the assessment of the GaSb-based mode-locked lasers. The evaluation of the mode locking performances is commonly performed by means of an electrical spectrum analyzer after photodetection of the laser pulse train. The periodic change in the emitted light intensity is transformed into RF electrical oscillations using an external photodetector. In two-section semiconductor lasers, the reverse-biased short section acting as a saturable absorber for mode locking can also be used as an intracavity photodiode. In this configuration, achievement of ML and some

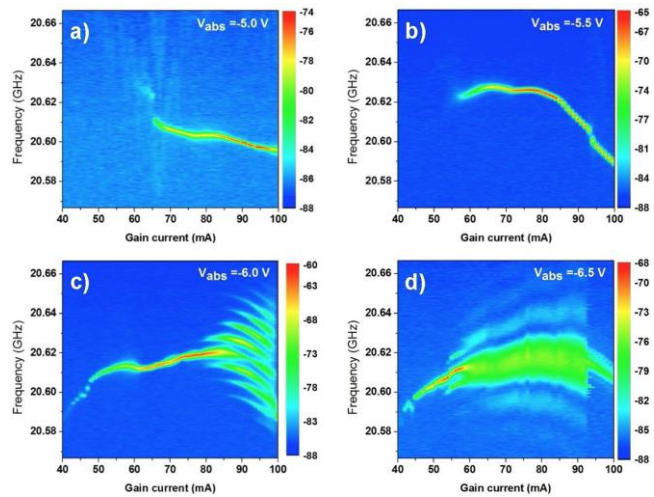


Figure 41: RF spectral maps in dB scale as a function of gain current for different absorber voltages V_{abs}

characteristics of this operating mode can be explored using an all-electrical experimental setup without any external photodetector [119]. I set up this experimental rig and carried out the mode locking characterization of the GaSb-based laser. We showed that the two-section ridge laser exhibits stable mode locking operation with a repetition rate of 20.6 GHz in a large range of operating conditions (see Fig. 41). The RF spectrum of the signal measured in the ML regime in the electrical circuit of the saturable absorber showed linewidths as narrow as 10 kHz at certain operating conditions (Fig. 42), implying a low timing jitter of the generated light pulses. This first demonstration shows the potential of GaSb based lasers as compact pulsed sources in the 2 μm spectral range and has since paved the way to further investigations in this domain [120]–[123].

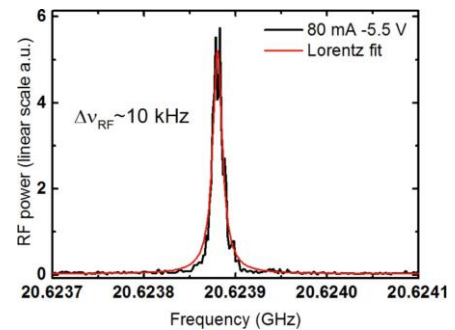


Figure 42: RF spectrum measured at a gain current of 80 mA and $V_{abs} = -5.5$ V.

III.5.2. Quantum-dash based DFB laser for isolator free operation

As presented in III.2.1, QDash and QD lasers have demonstrated unique features distinguishing them from conventional devices and in particular for the development of the so-called isolator free lasers for applications in fiber optic communications. QD based lasers are expected to achieve higher performances owing to their smaller linewidth enhancement factor values (LEF or α -factor) that reduce their sensitivity to external optical feedback. This LEF factor has a great importance for semiconductor lasers, as it is one of the main features that influences several fundamental aspects of semiconductor lasers, such as spectral linewidth, chirp under current modulation, mode stability, laser dynamics, laser behavior in presence of optical feedback and injection locking [124]. The critical optical feedback level marking the onset of coherence collapse or optical instability [125] is described by the following formula :

$$f_{crit} = \frac{\tau_L^2 \gamma^2}{16C^2} \frac{1 + \alpha_H^2}{\alpha_H^4}$$

where τ_L is the roundtrip time in the laser cavity, γ the damping factor which is

proportional to the relaxation oscillation rate f_r , and $C = (1 - R)/2\sqrt{R}$ is the coupling strength from the laser main cavity to the external cavity from a laser facet with reflectivity R . As shown in the latter formula, the critical optical feedback level (f_{crit}) is a strong function of LEF.

When the laser operates in the regime of coherence collapse (see Fig. 43), it is marked by severely broadened laser linewidth and rapidly deteriorated laser relative intensity noise (RIN) [125]. The tolerance to optical feedback also depends on multiple laser parameters such as the injection current, differential gain, and the laser cavity length. A trade off should be made depending on the targeted applications to achieve for instance high output power, low power consumption, temperature stability, good modulation efficiency, and sufficient optical feedback tolerance.

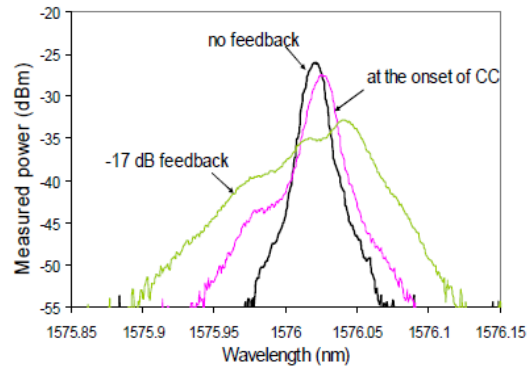


Figure 43: Broadening of the optical spectrum which occurs at the onset of coherence collapse [126]

In the following section, I summarize a part of the investigations we did on optical feedback tolerance of InAs/InP Quantum dash DFB lasers in collaboration with the visiting researcher Q. Zou from Télécom SudParis [127]. Extended works had been done in my research group on QD and QDash DFB lasers [128], [129] but not presented here. One of the main advantages of quantum-dash-based lasers is the higher modal gain compared to that of quantum dots [14]. We have shown in [130] that that the dominant parameter for feedback sensitivity is the differential gain. By using p-doping of the active layer, the higher differential gain results in small values of the linewidth enhancement factor and an increased tolerance to external optical feedback. The investigated DFB lasers here were $\lambda/4$ -shifted, AR-coated on both facets and index-coupled with various values of the normalized coupling coefficient κL (with L the cavity length). Figure 45 illustrates the evolution of the onset of coherence collapse of these lasers as a function of the injection current above threshold for different κL values (1.3 to 4).

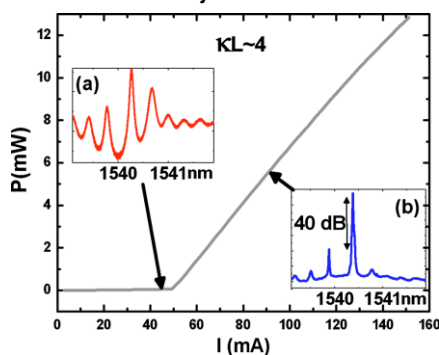


Figure 44 : Typical light-current characteristic of QDash-based 1-mm-long AR/AR DFB lasers with $\kappa L \sim 4$. Inset: optical spectrum at a) $I=46$ mA and at b) $I=90$ mA.

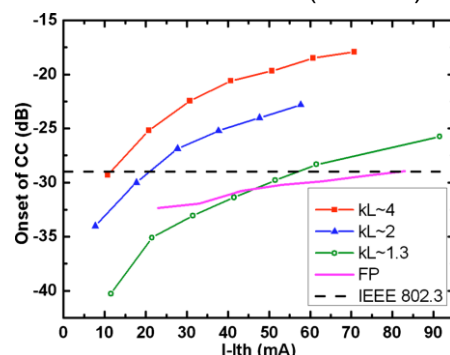


Figure 45 : Measured onset of coherence collapse (CC) of QDash based 1-mm-long DFB lasers as a function of the injection current above threshold, for values of L approximately equal to 1.3, 2, and 4. The dashed line represents the minimum value (-29 dB) of the return loss for isolator free 10 Gb/s transmission, recommended by the IEEE 802.3 standard.

We observed the typical evolution of the onset of coherence collapse of these lasers showing a high tolerance to external feedback of more than -29 dB fully compatible with the IEEE 802.3 standard for isolator free laser operation, the highest tolerance achieved for the higher κL devices.

III.5.3. THz generation using semiconductor mode locked laser

This last section deals with terahertz (THz) generation based on MLL. Over the last few years, THz radiation has been used for several applications including non-destructive testing, medical imaging, and food quality control [131]. The most frequently used technique is terahertz time-domain spectroscopy (THz TDS) based on the excitation of a photoconductive antenna (PCA) with ultrashort optical pulses [132]. In a standard THz TDS system, optical pulses with femtosecond pulse durations are transformed into a THz pulse as probe signal. This technique measures directly the change between time-resolved electric fields of THz pulses propagating through a sample and an equivalent length of free space. This measurement gives access to both the phase and the amplitude of the waveform, and thus provides the information on the absorption coefficient and the refractive index of the sample. For material analysis, the usual way to retrieve material parameters is to perform a Fourier transform of the recorded pulse time-traces with and without a sample. The main figures of merit are the achievable THz-bandwidth and signal-to-noise ratio (SNR). Conventional THz TDS systems are driven by fiber-based mode-locked laser but its high cost limits its deployment in industrial applications. In order to achieve a further spreading of the THz technology, semiconductor mode-locked lasers are a promising alternative for more compact and cost-efficient THz-TDS systems.

In collaboration with J.C. Balzer from University of Duisburg-Essen, we demonstrated for the first time that a monolithically integrated and electrically driven semiconductor laser can be used for THz TDS [133]. For this work, we used a QDash passively MLL at a repetition rate of 41 GHz to drive a conventional fiber coupled THz TDS system. The averaged THz trace in the time domain and the corresponding spectrum in the frequency domain are depicted in Fig. 46. We obtained a THz bandwidth of ~ 0.6 THz with a SNR of 45 dB. Limited performances of our system was attributed to the relatively broad pulses (~ 900 fs), low average optical power (5 mW) at the PCA, and an emitter PCA carrier lifetime of 30 ps, which is long compared to the 25 ps period of the laser pulses. Later, based on this approach called ultra-high repetition-rate THz time-domain spectroscopy (UHRR-THz-TDS), the team of J.C. Balzer showed the potential of this technique in terahertz high-resolution imaging and ranging applications [134], [135] and thin-film characterizations [136].

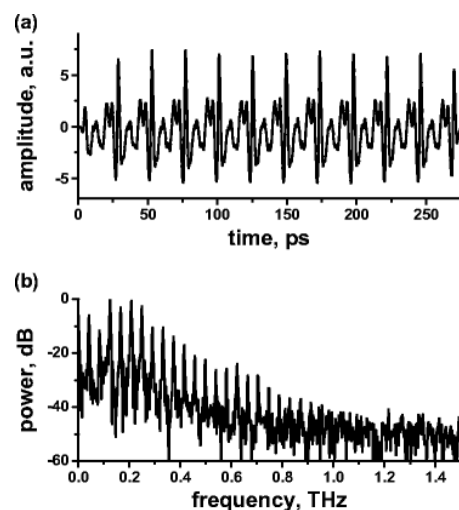


Figure 46 : (a) Measured THz trace in time domain and (b) corresponding spectrum obtained by Fourier transform [133]

III.6. Conclusions

In the previous chapters, I presented my work focused on low dimensional semiconductor laser and their particular characteristics. For the sake of clarity, I decided not to include in detail the technological developments and other research works I carried out through different ANR projects (ANR *MODULE*, ANR *DIQDOT*, ANR *JASMIN*, ANR *BATGAN*). In this manuscript, I mainly describe my contribution to the development of quantum-dash mode locked lasers, especially for the generation of optical frequency combs for WDM transmission. This work ranges from the optical pulse generation thanks to either standard semiconductor mode locked lasers or self-pulsating lasers, optimization of laser structures, noise and stability assessments and WDM transmission demonstrations. I strongly believe that the research achievements have contributed to the development of new type of efficient and broadband OFC generators for the next generation of optical networks. I had been involved in different research projects that allowed me to strongly interact with other researchers from academia and industry. This rich environment and lab facilities largely contributed to these achievements. I would like also to highlight that all of this work was a collaborative work and wouldn't have been possible without the contributions of the PhD students, the Postdoctoral researchers, collaborators and my current and former colleagues. As indicated in the following figure, my work has been supported by European and national projects which opened new avenues to my research works and new collaborations.

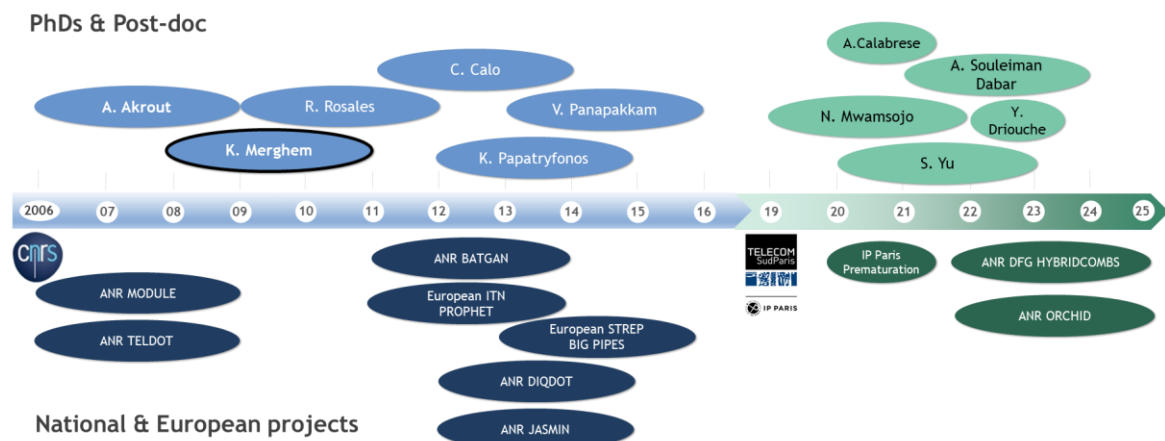


Figure 47 : Timeline of PhD students and postdoctoral researcher supervision, and projects participation.

IV. On-going and future projects

In this final part of the manuscript, I will discuss my on-going and future research projects. My aim is to take advantage of the developed know-hows and the acquired knowledge in the last years to build new type of efficient photonic devices towards dedicated applications described hereafter.

IV.1. Hybrid chip-scale Optical Frequency Comb

Up to now, most of my effort has been devoted to investigations of OFC generated thanks to semiconductor MLL. The development of integrated comb sources is a very active area of research [137]–[140] with many groundbreaking demonstrations in recent years, both on the device and system level. A key step towards widespread use of frequency combs is the availability of chip-scale comb sources that can be efficiently produced in large quantities using highly parallel wafer-level processes and that can be integrated into highly compact and robust miniaturized systems. Several approaches have been developed for chip-based frequency combs including mode-locked laser combs, microresonator-based combs and EO-modulated frequency combs [28]. Among the various approaches to chip-scale comb sources [9], [10], two concepts appear particularly promising: semiconductor mode-locked lasers based on quantum-dash gain materials as shown in section III.4 and so-called Kerr soliton combs that rely on cascaded four-wave mixing in high-Q Kerr-nonlinear optical microresonators [141], [142]. However, while both approaches have successfully been used in selected applications such as ultra-fast data transmission [4]–[8], they still feature distinct weaknesses that impede widespread industrial use. Specifically, Kerr combs offer broadband smooth spectra, comprising hundreds of optical tones with optical linewidths of less than 100 kHz [137], but suffer from the need for high pump powers, intricate pumping schemes, and rather low efficiencies of typically less than 1% for the nonlinear conversion of the continuous-wave pump to the lines of a bright-soliton comb [143]. QDash MLL, in contrast, can be easily operated with a DC drive current and offer wall-plug efficiencies that can well compete with those of conventional CW lasers, but are subject to strong optical bandwidth limitations and to strong phase noise leading, e.g., to optical linewidths in excess of several MHz [103].

To develop a novel class of chip-scale frequency comb sources that combine the distinct advantages of soliton Kerr combs and QDash MLL while overcoming the respective weaknesses, I start a new collaboration in the framework of ANR-DFG project called '*Hybridcombs*' that has recently been funded (2022-2024) gathering five partners (Center for Nanoscience and Nanotechnologies - C2N, Institut Physique de Nice - InPhyNi, Télécom SudParis - TSP, Wierstrass Institute - WIAS and Karlsruhe Institute of Technology - KIT). In this project that I am co-coordinating, we will cover modeling activities (WIAS, InPhyNi), development and characterization of innovative semiconductor devices (C2N, TSP), integrated nonlinear optics and hybrid photonic integration (KIT), as well as system-level application demonstrations in optical communications, metrology, and ultra-broadband signal processing (KIT). The main concepts are illustrated in Fig. 48.

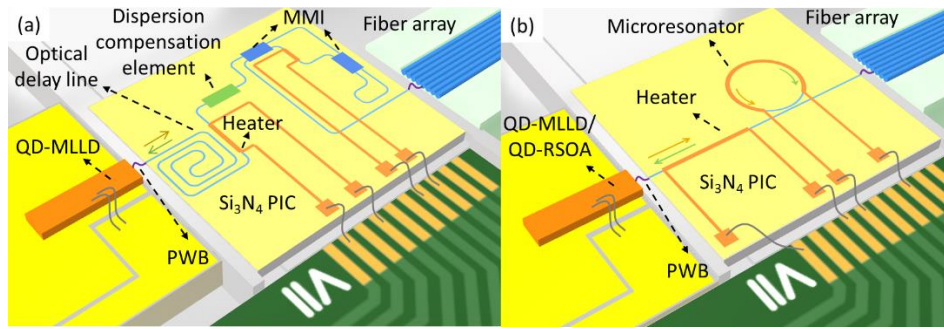


Figure 48 : Illustration of the envisaged hybrid combs sources

- (a) Linear feedback: A QDash MLL is coupled to a passive Si₃N₄ PIC as a simple delay line.
- (b) Nonlinear feedback: A QD-MLLD is combined with an Si₃N₄-based Kerr comb generator.

This consists of the synchronized coupling of QDash MLL and high-Q Kerr-nonlinear microresonators (Fig.48-b), aiming at injection locking of the two comb oscillators in hybrid platform (III-V semiconductor and silicon nitride). We will achieve multi-tone injection locking of the QDash MLL and the Kerr comb source by proper matching of the devices in terms of cavity length (and related FSR), coupling strength and dispersion management. Recently, several groups have investigated theoretically and experimentally the dynamics of nonlinear optical microresonators driven by periodic optical pulses [144], [145] and shown that for pulsed input, solitons remain the fundamental solution of the system and the power requirement is reduced by the duty cycle of the pulse with respect to CW pumping.

By exploring the novel class of chip-scale frequency comb sources developed in the *Hybridcombs* project, we will expect the transfer of the low phase noise of the Kerr comb to the QDash MLL spectrum and, at the same time, the drastic increase of the power conversion efficiency in the Kerr-nonlinear microresonator by generating a perfectly synchronized pulsed pump signal that features much better temporal overlap with the cavity soliton than conventional CW pump. During the project, a preliminary scheme (Fig.48-a) will be also investigated where QDash MLL is coupled to a passive Si₃N₄ PIC, operating as a simple delay line, that provides frequency-selective passive optical feedback to greatly reduce the optical linewidth of the QDash MLL as already demonstrated (cf. III.3.2). In both schemes, the coupling of the QDash MLL and the Si₃N₄ chip will be realized by 3D-printed photonic wire bonds or micro-lenses.

If successful, these comb sources will be of transformative impact on a series of applications, such as ultra-high capacity optical coherent transmission, spectroscopy, gas sensing, optical ranging and light detection and ranging (LiDAR). For coherent transmission, the ability to achieve extremely low phase noise for a high number of channels will readily allow the demonstration of massively parallel WDM transmission at overall data rates of tens to hundred of Tbit/s with reduced energy consumption. In the same way, chip-scale frequency combs have been demonstrated to open new perspectives in high-precision ultra-fast ranging where compact power-efficient comb sources with low phase noise will be key for real-world deployment [146].

IV.2. Optical reservoir computing based on mode locked lasers

The second research topic concerns the optical data processing. In recent years, demand for novel and increasingly powerful Artificial Intelligence (AI) and Machine Learning systems has exploded in order to process the vast, ever-growing amounts of data generated in our society and to deliver increasingly challenging functionalities. Artificial neural networks (ANNs), inspired by the human brain, have achieved unprecedented success in a wide range of applications ranging from image recognition to medical diagnosis [147], [148] owing to their capability for learning to be able to process unknown data intelligently. ANNs are mathematical network models formed by densely interconnected neurons, with the ability to address complicated tasks such as natural language processing, object or face recognition.

Therefore, neuromorphic (brain-like) computing approaches aimed towards novel physical realizations of neural networks have attracted increasing interest for data intense processing tasks. The photonic approaches for neuromorphic information processing are receiving growing attention thanks to their unique attributes, e.g. ultrafast and energy efficient operation, high bandwidths and parallelism allowing processing speeds a thousand times faster than what electronic neural networks can currently deliver.

In collaboration with the PhD student Nickson Mwamsojo (2019-2022) and my colleagues of the ‘*Optics and Photonics*’ research group (Yann Frignac, Qin Zou and Badr-Eddine Benkelfat), I have been engaged in the physical implementation of photonic neuromorphic computing [149], [150]. I intend to contribute in this domain, by capitalizing on my previous works on the non-linear dynamics of photonic devices subjected to delayed optical feedback. We are developing a particular ANN implementation called Reservoir Computing (RC). The major advantage of this implementation is its versatility. It can process any temporal input–output task, and many nonlinear, high-dimensional dynamical systems can be used as a random neural network (“reservoir”). The concept of RC is illustrated in Fig. 49 and consists of three layers as input, reservoir and output of the system. The input $u(n)$ is sent to the reservoir layer by the input layer. The reservoir layer is a nonlinear recurrent dynamical system whose photonic neurons are denoted $x_i(n)$. The output $y(n)$, produced in the output layer, is a linear combination of the photonic neurons. In the RC approach, the reservoir itself does not need to be modified or trained, only the linear output layer is adjusted during the training phase. Often the readout function can be learned through simple linear regression, which is computationally inexpensive to implement on a digital computer connected to the physical reservoir. Owing to its simple, versatile, and efficient framework, physical RC has become one of the leading paradigms for exploiting high-dimensional, nonlinear, dynamical systems for data computation.

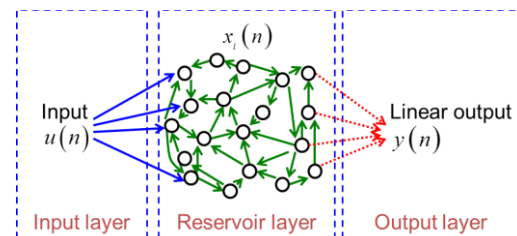


Figure 49 : Schematic of a RC

Photonic RCs have already been successfully realized demonstrating state of the art performances for classifying signals [151], but, in many experiments, only the core (reservoir) of the system was implemented, which severely limits the maximum processing power of the devices. In the framework of ANR project *ORCHID* (2021-2025), we will develop in

collaboration with III-V Lab, CEA Leti and Femto-ST, a RC implementation based on hybrid multimode lasers (MLL for the input layer and multimode laser cavities for the reservoir layer, see Fig. 50). For this project, I lead the workpackage dedicated to the evaluation of the reservoir computers' performances for specific use cases (for instance spoken digit classification, nonlinear channel equalization, chaotic time series forecast). We will, in particular, study the impact of different physical parameters of MLLs on the RC performances [152].

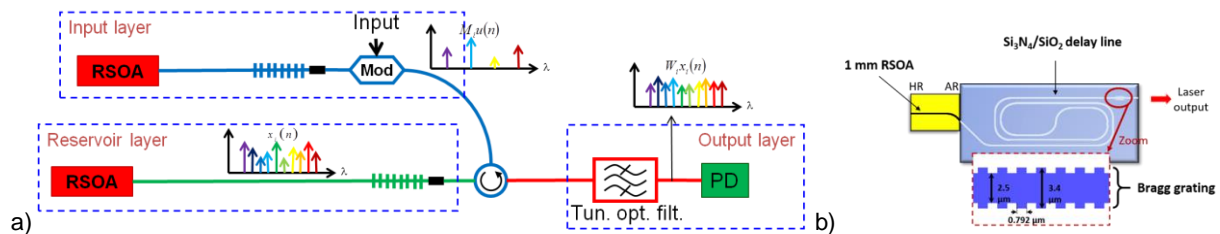


Figure 50: a) Schematic of the RCs planned in the ORCHID project. b) Schematic of an hybrid laser subassembly. In optical RC implementations, the reservoir's dimensionality (the number of "neurons"), i.e. processing capacity, is determined by the number of optical modes that can be addressed by the system. In ORCHID project, we will implement optical RC by using MLL, the photonic neurons being multiplexed in the optical spectrum. This hybrid platform will be able to sustain large reservoir computers, on 45mm² chips, consuming less than 1W, in a technology ready for photonic integration. The development of such reservoir computers able to handle very large number of photonic neurons can be considered as an important step towards the realization of energy efficient optical neuromorphic coprocessor that will be mandatory in the future, especially when considering the amazingly growing demand for such type of computation and the limited amount of energy available for such processing.

IV.3. Distributed optical fiber sensing using optical frequency combs

The last research topic, led in collaboration with A. Khadour from the Université Gustave Eiffel (previously IFSTTAR: the French institute of science and technology for transport, development and networks), will be on the use of optical frequency combs for the distributive fiber optic sensors. Fiber optical sensors are an effective tool adopted by civil, mechanical, and aerospace engineering communities for temperature and strain monitoring in different structures. They offer numerous advantages, such as multiplexing abilities, robustness, easy integration, lightweight and resistance to electromagnetic interference. This technology is today a key ingredient in building the Smart Cities for creating more efficient, sustainable, and eco-friendly living space. Conventionally, the distributive fiber optic sensors make use of some form of light scattering inside an optical fiber, i.e. Rayleigh, Brillouin and Raman scatterings [154]. These mechanisms can be used for both static (strain and temperature) and dynamic (acoustic/vibration) sensing. They usually involve the acquisition of the backscattered light for a range of laser wavelengths and the analysis of frequency shift between the incident and scattered light by using either a

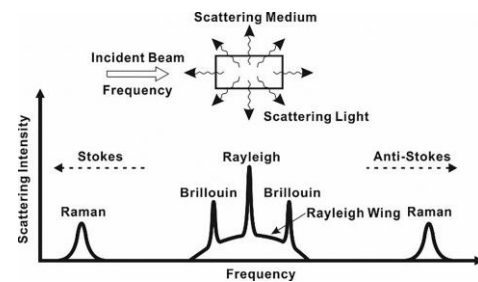


Figure 51: spontaneous light scattering spectrum [153]

broadband light source or coherent light sources such as CW lasers or wavelength-swept lasers. Depending on the chosen solution, a trade-off has to be found between the sensing resolution, response bandwidth, and dynamic range of the FBG sensing system. Moreover, the traditional solutions do not exploit the multiple scattering mechanisms simultaneously on the same fiber for multi-parameter sensing [153]. Broadband coherent sources such as optical frequency combs (OFC) could be an attractive solution for FBG interrogators. OFCs combine the advantages of broadband and tunable laser interrogators as they interrogate the complete optical span with better efficiency. Dual-comb spectroscopy schemes have also been developed for broadband and precise characterization of FBG sensors [155]. For instance, when applied to FBG strain sensing, dual-comb spectroscopy enables the detection of small changes in the FBG spectrum in the static regime with a large dynamic range and potentially can characterized simultaneously multiple FBG sensors with different center wavelengths [156].

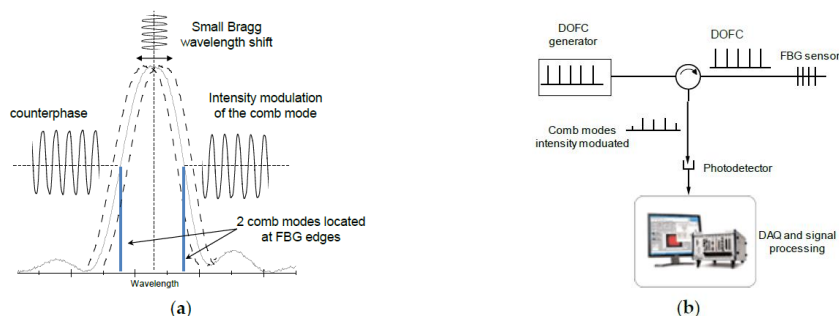


Figure 52: FBG interrogation system based on a dual optical frequency comb [156].

However, the complexity, cost, and size of dual-comb systems are still prohibitive for FBG sensing applications. A promising solution could be the use of chip-scale OFC to develop low-cost, more compact and portable systems for field application. As already demonstrated for optical ranging system [146], QDash-based combs can offer a particularly attractive route towards high-performance chip-scale dual comb system for the interrogation of FBG sensors for structures monitoring. QDash MLLs are compact, can be easily operated by a simple DC drive current, and provide spectrally flat frequency combs with bandwidths in excess of 2 THz. We intend to develop a new type of FBG interrogator based on the use of chip-scale OFC that underpasses the conventional optical time domain reflectometry (OTDR) approaches. We also aim to explore reconfigurable laser sources in order to optimize the sensitivity and resolution of the distributed fiber sensors for the different scattering mechanisms. Depending on the measurements techniques used, narrow to relatively broad optical linewidth is needed. As an example, the phase-sensitive OTDR required a narrow linewidth and stable laser source whose coherence length is much longer than the length of the fiber under test while polarization-sensitive OTDR use a relatively broad linewidth laser to avoid interference induced by Rayleigh backscattered light. Multi-wavelength laser with customizable linewidth and power distribution is great of interest for versatile interrogation of different FBG scattering mechanism. For semiconductor-based laser sources, one simple way to modify the laser characteristics (optical linewidth and spectral bandwidth) is to introduce a small amount of controlled optical feedback. An integrated solution could be a hybrid III-V/SiN chip-scale comb sources that incorporate a SiN PIC within an extended cavity to be able to optimize the comb characteristics. The main challenge for this research work is to develop a versatile optical source that enables the simultaneous and optimized temperature, vibration and strain measurements with combined Brillouin, Rayleigh and Raman scattering.

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List of Publications

I. Book

- [B1] A. Martinez, C. Gosset, **K. Merghem**, G. Moreau, F. Lelarge, and A. Ramdane, "Quantum Dot-based Mode-locked Lasers and Applications," in Handbook of Self Assembled Semiconductor Nanostructures for Novel Devices in Photonics and Electronics, M. Henini, Ed. Amsterdam: Elsevier Science Bv, 2008, pp. 600-619.

II. International journals

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III. International conferences

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- [C2] N. Mwamsojo, et al., "Optoelectronic Reservoir Computer for Early Stage Alzheimer's Disease detection," Conference on Lasers and Electro-Optics Europe European Quantum Electronics Conference (CLEO), 2022.
- [C3] Q. Zou et al, "Bifurcation and Chaotic Behavior of Feedback Semiconductor Lasers Operating in the Full Range of External Reflectivity," 22nd European Conference on Integrated Optics (ECIO), Paris, June 2020

- [C4] A. Gerling et al., "Monolithic Mode-Locked Laser Diode for THz Communication," in 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), sept. 2019.
- [C5] A. V. Kovalev et al., "Symmetry Properties and Coexistence of the Mode-Locked States in Semiconductor Lasers," in 2019 Conference on Lasers and Electro-Optics Europe European Quantum Electronics Conference (CLEO/Europe-EQEC), juin 2019.
- [C6] J. N. Kemal et al., "32QAM WDM Transmission Using a Quantum-Dash Passively Mode-Locked Laser with Resonant Feedback," Optical Fiber Communications Conference and Exhibition (OFC), 2017.
- [C7] J. N. Kemal et al., "WDM Transmission Using Quantum-Dash Mode-Locked Laser Diodes as Multi-Wavelength Source and Local Oscillator," Optical Fiber Communications Conference and Exhibition (OFC), 2017.
- [C8] **K. Merghem** et al., "Narrow linewidth frequency comb source based on self-injected quantum-dash passively mode-locked laser," Conference on Lasers and Electro-Optics (CLEO), 2017
- [C9] J. C. Balzer et al., "Ultra-compact Source for THz Time Domain Spectroscopy," Conference on Lasers and Electro-Optics (CLEO), 2016.
- [C10] **K. Merghem**, V. Panapakham, Q. Gaimard, F. Lelarge, A. Ramdane, "Monitoring the Long-term frequency Stability of InAs/InP Quantum-dash-based Mode Locked Lasers via Terminal Voltage," Compound Semiconductor Week (CSW), 2016.
- [C11] V. Panapakham et al., "Noise investigation of Single Section InAs/InP Quantum-dash Lasers in Active and Passive Mode-locking," Compound Semiconductor Week (CSW), 2016.
- [C12] A. Ramdane et al., "Frequency combs from InAs/InP quantum dash based mode-locked lasers for multi-terabit/s data transmission," International Conference Laser Optics, 2016.
- [C13] V. Vujicic et al., "Tbit/s Optical Interconnects Based on Low Linewidth Quantum-Dash Lasers and Coherent Detection," Conference on Lasers and Electro-Optics (CLEO), 2016.
- [C14] W. Freude et al., "Phase-Noise Compensated Carriers from an Optical Frequency Comb Allowing Terabit Transmission," 17th International Conference on Transparent Optical Networks (ICTON), 2015.
- [C15] A. Martinez et al., "Monolithic optical frequency comb based on quantum dashed mode locked lasers for Tb/s data transmission," Quantum Sensing and Nanophotonic Devices Xii, vol. 9370, M. Razeghi, E. Tournie, and G. J. Brown, Eds. (Proceedings of SPIE), 2015.
- [C16] J. Pfeifle et al., "Coherent Terabit Communications Using a Quantum-Dash Mode-Locked Laser and Self-Homodyne Detection," Optical Fiber Communications Conference and Exhibition (OFC), 2015.
- [C17] J. Pfeifle et al., "Simultaneous Phase Noise Reduction of 30 Comb Lines from a Quantum-Dash Mode-Locked Laser Diode Enabling Coherent Tbit/s Data Transmission," Optical Fiber Communications Conference and Exhibition (OFC), 2015.
- [C18] V. Vujicic et al., "Quantum Dash Passively Mode-Locked Lasers for Tbit/s Data Interconnects," Optical Fiber Communications Conference and Exhibition (OFC), 2015.
- [C19] V. Vujicic et al., "Tbit/s transmission based on mode locked laser frequency comb sources," IEEE Photonics Conference, 2015.
- [C20] C. Calo et al., "Spectral and temporal phase measurement by Optical Frequency-Domain Reflectometry," 26th International Conference on Indium Phosphide and Related Materials (IPRM), 2014
- [C21] A. Martinez et al., "Quantum dot mode locked lasers for coherent frequency comb generation," in Quantum Sensing and Nanophotonic Devices Xi, vol. 8993, M. Razeghi, E. Tournie, and G. J. Brown, Eds. (Proceedings of SPIE), 2014.
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- [C24] O. Mollet et al., "Optimized modulation bandwidth and Henry factor of Fabry-Perot InAs/InP Quantum Dash based ridge waveguide lasers for Access/Metro Networks26," 26th International Conference on Indium Phosphide and Related Materials (IPRM), 2014.
- [C25] K. Papatryfonos et al., "Quantum Dash based lasers for Gas Sensing," 26th International Conference on Indium Phosphide and Related Materials (IPRM), 2014.
- [C26] C. Calo et al., "Optical pulse generation from single-section InAs/GaAs quantum dot edge-emitting lasers," Conference on Lasers and Electro-Optics (CLEO), 2013.
- [C27] C. Calo et al., "Frequency-resolved optical gating measurements of sub-ps pulses from InAs/InP quantum dash based mode-locked lasers," International Conference on Indium Phosphide and Related Materials (IPRM), 2013.
- [C28] N. Chimot et al., "1550nm InAs/InP Quantum Dash Based Directly Modulated Lasers for Next Generation Passive Optical Network," International Conference on Indium Phosphide and Related Materials (IPRM), 2013, pp. 177-180.
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- [C33] R. Rosales et al., "Timing Jitter Measurements of a 130 GHz Passively Mode Locked QDash Laser from its Optical Spectrum," Conference on Lasers and Electro-Optics (CLEO), 2012.
- [C34] R. Rosales et al., "Quantum Dash Mode Locked Lasers as optical comb sources for OFDM superchannels," 38th European Conference and Exhibition on Optical Communications (ECOC), 2012.
- [C35] E. Sooudi et al., "All Optical Passive Stabilization of a Two-Section InAs/InP Based Quantum-Dash Mode-Locked Laser with Simultaneous CW Injection-Locking and Selective Optical Feedback," in 2012 Conference on Lasers and Electro-Optics (CLEO), 2012.
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- [C42] R. Rosales et al., "Effect of Optical Feedback on 17-GHz Quantum Dash Based Mode Locked Lasers," Conference on Lasers and Electro-Optics (CLEO). 2010.
- [C43] E. Sooudi et al., "Generation of Microwave Signal in a Mode-Locked InAs/InP Based Quantum Dash Laser with CW Optical Injection," Conference on Lasers and Electro-Optics (CLEO), 2010.

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- [C47] A. Akrouit et al., "Ultra high repetition rate and very low noise mode locked lasers based on InAs/InP quantum dash active material," IEEE 21st International Conference on Indium Phosphide & Related Materials (IPRM), 2009, pp. 45-47.
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- [C55] G. Moreau et al., "InAs/AnP Quantum Dash based electro optic modulator with over 70 nm bandwidth at 1.55 μm ," International Conference on Indium Phosphide and Related Materials (IPRM), 2007, pp. 271-273.
- [C56] G. Moreau et al., "Demonstration of 1.51 μm InAs/InP(311)B quantum dot single-mode laser operating under continuous wave," *IET Optoelectronics*, vol. 1, no. 6, pp. 255-258, Dec 2007.
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- [C63] A. Bousseksou et al., "Single-transverse-mode emission of RT-CW operating large diameter (50 μm) 1.55 μm InP-based electrically-pumped VECSEL," IEEE LEOS Annual Meeting Conference Proceedings (LEOS) Annual Meeting, 2005, pp. 468-469.

IV. International invited conferences

- [Inv1] C. Koos, T. J. Kippenberg, L. P. Barry, A. Ramdane, R. Brenot, W. Freude, S. Randel, P. Marin, J. N. Kemal, P. Trocha, D. Ganin, C. Weimann, S. Wolf, J. Pfeifle, M. Karpov, A. Kordts, V. Vujcic, **K. Merghem**, "Optical frequency combs and photonic integrated circuits - tools for high-speed communications and advanced distance metrology," Photonics West 2018, San Francisco, USA
- [Inv2] A. Ramdane, V. Panapakkam, Q. Gaimard, **K. Merghem**, G. Aubin, F. Lelarge, V. Vujcic, A. Anthur, R. Zhou, L. P. Barry, P. Marin, J. N. Kemal, J. Pfeifle, C. Koos, "Single section QW and QDash based mode-locked lasers for frequency comb generation allowing multi-Tbit/s fiber optic transmission," International Workshop on Comb Lasers, Torino, Oct 2017
- [Inv3] **K. Merghem**, Q. Gaimard, V. Panapakkam, G. Aubin, A. Ramdane "Quantum dash based mode-locked lasers for ultra-broadband optic communications," 9th Russian-French Workshop on Nanosciences and Nanotechnologies, Suzdal, Dec 2017
- [Inv4] A. Ramdane, V. Panapakkam, Q. Gaimard, **K. Merghem**, G. Aubin, N. Chimot, F. Lelarge, V. Vujcic, A. Anthur, R. Zhou, L. P. Barry, P. Marin, J. N. Kemal, J. Pfeifle, C. Koos, "Frequency comb generation using QD-based mode locked lasers: application to multi-Terabit/s optical fiber transmission," International Nano-Optoelectronics Workshop iNOW-2016, 26 July - 5 August, Munich, Würzburg, Germany (2016)
- [Inv5] A. Ramdane, V. Panapakkam, Q. Gaimard, **K. Merghem**, G. Aubin, N. Chimot, F. Lelarge, V. Vujcic, A. Anthur, R. Zhou, L. P. Barry, P. Marin, J. N. Kemal, J. Pfeifle, C. Koos, "Frequency combs from InAs/InP quantum dash based mode-locked lasers for multi-terabit/s data transmission," Laser Optics' 2016, Saint Petersburg, June 2016
- [Inv6] W. Freude, J. Pfeifle, R. Watts, I. Shkarban, S. Wolf, V. Vujcic, P. Landais, N. Chimot, S. Joshi, **K. Merghem**, C. Calò, M. Weber, A. Ramdane, F. Lelarge, L. Barry, C. Koos "Phase-Noise Compensated Carriers from an Optical Frequency Comb Allowing Terabit Transmission," 17th International Conference on Transparent Optical Networks (ICTON 2015), Budapest, Hungary, July 5-9, 2015
- [Inv7] C. Calo, V. Panappakam, R. Rosales, R. T. Watts, **K. Merghem**, A. Martinez, L. P. Barry, A. Ramdane¹, "Quantum dot based Mode locked lasers and applications," International Nano-Optoelectronics Workshop iNOW'2014, August 2014, St Petersburg, Russia
- [Inv8] A. Martinez, C. Calo, R. Rosales, R.T. Watts, **K. Merghem**, A. Accard, F. Lelarge, L. P. Barry, A. Ramdane, "Quantum dot mode locked lasers for coherent frequency comb generation," Photonics West, February 2014, San Francisco, USA
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Chip-scale Optical Frequency Combs for fiber optic communications systems, data processing and fiber optic sensing

The present report gives an overview of a selection of my research activities conducted at the CNRS Laboratory for Photonics and Nanostructures (Now Center for Nanosciences and Nanostructures CNRS-UPSaclay) and at SAMOVAR, Télécom SudParis, Institut Polytechnique de Paris.

Most of my research has been focused on the use of low-dimensional nanostructures, such as quantum dots (QD) and quantum dashes (QDash), as gain material for semiconductor mode locked laser sources. The particular properties of these structures have led to improved mode-locking performances, as well as its uses as chip-scale optical frequency comb sources. In this manuscript, I will present my contributions to the development and engineering of optical frequency combs generated thanks to single-section QD and Qdash based lasers and their applications in WDM coherent optical transmission and will conclude with my on-going and future research projects in optical frequency combs for extended applications such as data processing and optical fiber sensing

Keywords : Semiconductor Mode Locked Laser, Chip-scale Optical Frequency Comb