COST

Technical Committee

COST Action 288

Nanoscale and Ultrafast Photonics

FINAL REPORT

Period: from April-2003 to August-2008

(Start date of the Action) (last update)

This Report is prepared by the Management Committee of the Action and presented to the relevant Technical Committee. The report is a "cumulative" report, i.e. it is updated annually and covers the period beginning from the start date of the Action.

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

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14. ABSTRACT

The Final Proceedings for COST 288: Nanoscale and Ultrafast Photonics, 18 May 2008 - 23 May 2008

Materials: Quantum wells (QWs), Quantum Dots(QDs)-to understand how confinement affects properities for various semiconductor materials; Laser Dynamics:understanding carrier dynamics in QWs and QDs and how it impacts in physics and devices; Fabrication: how to fabricate low dimensional structures and devices; Introduction to System Specifications: What do optical systems (communications) chiefly need from devices; Semiconductor Optical Amplifiers: what are they, how are they used in systems, what does low dimensionality give you; Mode-locked lasers: How they work,what determines their performance and how low dimensionality affects them.
Future Applications: Biological, Treahertz and Plasmonics
Report on COST 288 (Eu funded) activities:

15. SUBJECT TERMS
EOARD, Laser physics, Laser dynamics

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CONTENTS

1. **OVERVIEW: ACTION IDENTIFICATION DATA**

Action Identification Data

COST Action ***288*** — ***Title:*** **Nanoscale and Ultrafast Photonics**

TC Recommendation: *(18/10/02)*
CSO Approval: *(02/12/2002)*
Start date: *(04/04/03)* *(1)*
Duration: *48 months*
Extension: *12 months*
End date: *(06/04/08)*

First MC meeting: *(07/04/03)*
Last MC meeting: *(22/05/08)*
Final Report: *(2)*
Evaluation Report: *(2)*
TC Evaluation:

Number of signatories:20

Signatories and date of signature: *(day/month/year)*

Belgium (05/08/03)
Bulgaria (04/04/03)
Czech Rep. (05/08/03)
Denmark (23/05/03
Finland (05/08/03)
France (12/05/05
Germany (17/03/03)

Hungary (05/08/03)
Ireland (05/08/03)
Israel (13/09/04)
Italy (14/03/03)
Lithuania (10/11/04)
Malta (11/03/2005)
Netherlands (23/05/03)

Poland (23/05/03)
Spain (25/09/03)
Sweden (17/03/03)
Switzerland (17/04/03)
Turkey (10/06/04)
United Kingdom (17/03/03)

Institutes of non-COST countries:

Area: ICT

Action Web site:http://www.een.bris.ac.uk/cost288/

Chairperson:

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TC Rapporteur: Prof. Michel BLONDEL, Faculté Polytechnique, MONS, Belgium
External Evaluator: Prof. Antonio MECOZZI, University of L'Aquila, Italy

(1) Date of the first MC meeting. 7 April 2003
(2) When the report is received by TC Secretariat

2. **OBJECTIVES**

In the last decade, the technology to fabricate structures on an optical to sub-optical wavelength scale has matured, and opened for a new generation of photonic devices, which are expected to increase the performance of telecom and datacom systems significantly. Wavelength-scale devices, such as vertical-cavity surface-emitting lasers (VCSELs) and Photonic crystal structures have active dimensions of a few hundred nanometers and require growth and fabrication control in the nanometer range. These former devices, which present major advantages in terms of manufacturability and testing, are already dominating the datacom market and may soon penetrate as a viable alternative for telecommunications. The "nano" aspect will be even more crucial in next-generation photonic devices, where strong 3D optical and carrier confinement in the sub-100 nm range will be exploited to provide new functionalities and increased performance, in structures such as photonic crystal integrated circuits and quantum dot lasers and amplifiers. Indeed, nanophotonics may become the key technology to improve data rates in telecommunications and interconnections, as well as the key provider of low-cost optical solutions for high capacity data traffic to the homes.

Within this action the ultimate limits in the performance of quantum dots and quantum well devices in terms of gain, modulation and switching will be investigated. Existing devices will be studied and improvements in design and integration proposed. By the end of the action the quantum dot and quantum well devices will be studied in terms of single device performance and within an integrated photonic systems test-bed.

The COST Action will build on the existing research effort in Europe, strengthen and supplement this effort by a collaborative Action. The present Action will greatly benefit from previous Actions, such as COST 240 on *"Techniques for modelling and measuring advanced photonic telecommunication components",* COST 267 *"Semiconductor devices for high-speed optical signal processing"*, COST 268 *"Wavelength scale photonic components for telecommunication"*. The experience gained by these successful actions, as recognised in all reviews, will be used in the management of this action. The method of work is to catalyse research on nanoscale and ultrafast photonics for telecom applications by improved collaboration and networking.

Year 2 and Midterm Review

The Working Group leaders have had some discussion concerning any changes of direction or emphasis within the action. Generally the aims are the same but the areas have been cut down from the original proposal, with the agreement of the TC-TIST:

Working group 1 Title: *Novel Gain Materials and Fabrication Techniques* – The focus is on QDots and GaInNAs Quantum wells. No work on fabrication of PBGs.

Working Group 2 Title: *Photonic Devices* –The focus is on non-linear and ultrafast physics of devices: GaAs-based and InP-based on edge-emitters and VCSELs. PBGs are included within this WG for modifying active devices.

Working Group 3 Title: *Ultrafast and Non-Linear Photonic Devices*- Focus on systems utilising devices from working groups 1 and 2.

Status: There have been many STSMs this year spread between the Working Groups. Working Group 2 had more STSMs in year 1. There has been strong linking between the working groups developing this year and generally the feedback is that people within the working groups are happy with the development this year. Viewed critically we have not pursued the ultrafast aspects as much as we would have liked due in part to measurement facilities available and suitable devices. Recent devices from Prof Bimberg should allow some interesting measurements in this area to be done. Also viewed critically the round-robin activities have been slow but I think they are generating interactions between groups which are building up well. Generally COST actions start slowly and build up.

Managerial Aspects

On a managerial note COST 288 has a new coordinator for working group 3 Dr. Erwin Bente He has set up a WIKI website with resisted access for COST members and enhanced multi-user access to documents which has proved very useful.

Overall Actions and Summary-Mid Term

The action now has 2 Vice-Chairs to strengthen bridging between the working groups. The Working Groups have had their Management structures enlarged to have 2 vice-chairs for each working group to add breadth and add cross-linking between groups. We are aiming to bring out the ultrafast element more within the programme and to form strong links with working group 3. All the management teams are aware of this aspect and are endeavouring to strengthen links. I need to emphasise that many of the ultrafast aspects such as broad-band SOAs and polarisation feedback effects in VCSELs are good science and ultrafast but may not be seen in systems within this action in its lifetime. We are aiming to have new devices into the systems by the end of the action however.

Year 3

Year 3 has been our most ambitious year as we had three meetings which enabled us to focus on aims and directions discussed in the Midterm assessment. In August we were invited to be the European respresentatives in the second world-wide bi-annual conference on Utrafast Photonics held in St Andrews, U.K.,at which we joined scientists and government policy makers from Japan, the USA and Britain to discuss science, technology and the view forward for ultrafast photonics. The commitment of the Japanese was impressive to all-fibre to the home. It WILL happen and they are considering government funding to follow the significant FESTA programme to deal with speeds higher than femto-second. This 2 day meeting was followed by a COST 288 MC and working group meetings where emphasis was on WG3. In February we had our second series of WG meetings and MC meeting. This focussed chiefly on reporting measurements and exchanging results from round-robin activities. The alpha-factor round-robin exercise of WG2 was found to be going well with devices being circulated and results being compared. It was proposed to do a multi-way STSM based on people going to labs to do measurements. This was discussed at the meeting and approved by the MC through e-mail. The QDot mode-locked laser round-robin has keen participants who are awaiting a mode locked laser from Zia (US) or Nanosemiconductor (Germany) to test the results on modelling predictions. It was decided to chase these possible suppliers and achieve delivery of 2 devices for circulation. The third and final meeting of year 3 will be held in collaboration with the International Conference on Transparent Optical Networks (ICTON) in Nottingham with the COST meeting being June 22/23 while the ICTON meeting will be June 19-22. This meeting will facilitate discussions between COST 291 and COST P11 members. COST 288 has organised a session at the conference and is heavily involved in organisation of the meeting. This meeting will focus on further exchanging results of round-robins and on reporting on STSMs.

The enlargement of the management of the Working Groups to having 2 Vice Chairs has helped to broaden and coordinate the action.

Year 4

We heard during year 4 that we would receive a one year extension chiefly to enable us to fully test and expoit the quantum dot multi-section laser diodes ordered in year 3. These have been received and are to be used in a large STSM based in Eindoven which will happen soon (at the end of Year 4) to which 6 participants from different institutes will go and exchange techniques. In year 4 we have had 2 meetings in Vilnius on October 5/6 and Metz on March 26/27. In the Vilnius meeting results and STSMs were discussed in detail while the Metz meeting preceeded a PHASE workshop conference, partially supported by COST 288 where international experts were invited for presentation and discussion. The proceedings will be published in journal form, as in the previous PHASE meeting. We are planning to hold our next meeting in July in Rome co-located with the the International Conference on Transparent Optical Networks (ICTON) meeting. This meeting will facilitate discussions between COST 291 and COST P11 members. COST 288 has organised a session at the conference and is heavily involved in organisation of the meeting. This meeting will focus on further exchanging results of round-robins and on reporting on STSMs.

In year 4 we have had a number of STSMs including a STSM (connected to the alpha-factor activity in working group 2) involving several members going to one site (Athens) to exchange techniques and learn new methods which was highly successful. A further large multi-group STSM based in Eindoven is scheduled at the end of Year 4 to investigate the purchased QDot devices.

Year 5 –Extension

The extension time was used to fully exploit the testing of the two pig-tailed mode-locked quantum dot multi-section mode-locked lasers purchased from Innolume (formally Nanosemiconductor which took over Zia lasers in the US). At the end of year 4 (June 2007) a major multi-group STSM look place in Eindoven to fully test these devices and compare test measurement techniques. In the extension year a further STSM was held in Eindoven to extend this study (June 2008). Both of these activities were very valuable and they provided excellent training of young researchers into this area. In addition, one of these devices was used by other members of COST 288 to look at optical feedback. In year 5 we have had 3 meetings.The first in July was co-located with the ICTON conference in Rome where COST 288 coordinated the NAON session. At the COST MC meeting initial results of the multi-group QDot measurements were discussed and the possibility of holding a training school. A second meeting was held in Zaragoza, Spain on October 15/16 where STSMs and other results were presented and the details for the training school was finalised. The final meeting and final review for the action was held in Centaro, Italy on May 22, 2008 following the very successful Training school. At the final meeting STSM reports were given, with particular discussion involving the QDot mode-locked multi-group STSM which was to be held in Eindoven following the final review. In addition two new COST proposals related to this action and put forward by members of this action were discussed (both have been invited to submit into Phase 2- one on tunable gain media for solar cells arising from WG1 Activities and one on dynamics of lasers arising from WG2). In addition a possible publication or book was discussed and the final report.

A Training school was held for PhD students and young RAs in Centaro Italy May 18-22 2008. About 40 students attended a series of lectures on the 2 major themes: Materials and Dynamics, supplemented by talks on Fabrication, Mode-locking, Plasmonics, Terahertz radiation and Systems specifications. This represented a cross-section of COST 288 activities. The talks were chiefly given by World and European experts outside the COST activity. This was followed by our final review meeting on May 22 2008 to which the students were also invited.

Summary at the Close of the Action

The action has been very successful in that the number of attendees at the meetings has maintained constant throughout the action with the number of people being strongly involved increasing throughout the action. In particular many young researchers got strongly involved in the action and started to initiate and lead activities (such as the multi-group alpha-factor round-robin activity.) The initial aims of the action to integrate novel materials and novel physics into usable devices towards systems has been realised with qdot devices proving to have been successfully integrated into mode-locked lasers and broad band SOAs. Several FP7 activities FAST-DOTS (successful Strep) and Eurodot (un-successful integrated project) were assisted by COST interactions and 2 new cost proposals arising from COST interactions has been invited to submit into the second stage.In addition a large number of small, two and three centre, interaction have been established resulting in a large number of joint publications directly arising out of the COST interactions.

3. TECHNICAL DESCRIPTION AND IMPLEMENTATION

The Action is very broad linking systems groups with basic physics group which is one of the actions strengths. The action is divided into 3 working packages:

WG.1 Novel Gain Materials and Fabrication Techniques

WG.2 Photonic Devices

WG.3 Ultrafast and Non-linear Photonic Devices

In Working Group 1 new materials such as quantum dots, GaInNAs and intersubband transitions in GaN –based materials were proposed as novel gain materials while the fabrication/self-oganised growth of photonic band gap structures and gratings were introduced for the control of the optics and the interaction of the material and the light. In addition the investigation of these materials/structures for quantum information (single photon manipulation) was considered. Much effort has focussed on quantum dot and GaInNAs quantum well systems examining lasing behaviour and single photon generation. Some interaction is occurring on photonic bandgap structures but most of that is happening within COST P11-the physics of photonic band gap structures. The aim of this working group is to consider potential candidate materials/systems for telecom window (1.3-1.55 micron wavelength) with high gain and modulation speed or single photon behaviour as candidates for future communications. This may involve using these materials in a similar device design to what is now being used (incremental) or in different device design with different functionality (revolutionary).

Working Group 2 focuses on the physics of devices: semiconductor lasers (SL) such as edge-emitting lasers (EELs), vertical cavity surface emitting lasers (VCSELs) and semiconductor optical amplifiers (SOAs). The aim is to probe the ultimate limits of the devices in terms of performances such as modulation speed, and mode behaviour. Also theoretical and modelling research to explore the high frequency operation limit, and help with the development of new nanostructured devices is performed. In addition novel coding schemes and/or new switching phenomena, involving e.g. polarisation or transverse mode control, complex dynamic multi-mode behaviour, are also being investigated. Physical characterisation of a device often requires complex experimentation (high frequency modulation) and/or rather involved configurations such as external cavity optical feedback, optical injection.

Working Group 3 takes the highly performing devices from working groups 1 and 2 and tests them in a systems environment, In addition they feed back to working group 2 what the systems requirements are. Within WG3 two exercises will be organized, which serve the purpose of stimulating interactions among participants within a clear focus: a round robin exercise where a given mode-locked laser will be tested as to its functionalities in different laboratories and using different testing methods, while the modelling exercise invites partners to compare their modelling results obtained by different methods for a mode-locked laser system with given specifications.

4. PARTICIPATION AND COORDINATION

4.1 Management Committee

Chairperson: Dr. Judy RORISON

Affiliation: University of Bristol (United Kingdom)

Vice-Chairpersons: Prof Geert Morthier

Affiliation: University of Gent (Belgium)

Vice-Chairpersons: Dr. Guido Guiliani

Affiliation: University of Pavia (Italy)

The action is divided into 3 working package each with a chair and vice-chair for each package

Working Package 1

Chair: Prof. Naci BALKAN

Affiliation: University of Essex (United Kingdom)

Vice-Chair*:* Prof Andrea Fiore

Affiliation: ETH Switzerland

Vice-Chair*:* Dr. Mikka Saarinen

Affiliation: University of Tampere (Finland)

Working Package 2

Chair: Dr Jan DANCKAERT

Affiliation: Vrije Universiteit Brussel (Belgium)

Vice-Chair: Dr Marc Sciamanna

Affiliation: SUPELEC-Ecole Supérieure d'Electricité (France)

Vice-Chair: Prof. Wolfgang ELSäßER

Affiliation: Technische Universität Darmstadt (Germany)

Working Package 3

Chair: Dr. Erwin Bente

Affiliation: Technische Universiteit Eindhoven (Netherlands)

Vice-Chair: Dr Cedric Ware

Affiliation: Ecole Nationale Superieure des Telecommunications, Paris

Vice-Chair: Dr Eugene Avrutin

Affiliation: University of York (United Kingdom)

Webmaster/ Secretarial: Mr. Jose Pozo, University of Bristol (years 1-4)

Mr. Nikos Vogiatzis, University of Bristol (year 5)

List of members by country:

- Belgium
  - **Prof. Geert MORTHIER** (Universiteit Gent)
  - **Dr. Jan DANCKAERT** (Vrije Universiteit Brussel)
- ***Bulgaria***
  - **Prof Krasimir PANAYOTOV** (Bulgarian Academy of Sciences)
- ***Czech Republic***
  - **Dr Jiri CTYROKY** (Academy of Sciences , Institute of Radio Eng. and Electronics)
- ***Denmark***

- **Prof Bjarne TROMBORG** (Technical University of Denmark)
- **Dr Kresten YVIND** (Research Centre COM)

- ***Finland***
  - **Prof Markus PESSA** (Tampere University of Technology)
- ***France***
  - **Dr Marc Sciamanna** (l'Universite de Metz et Supelec-Ecole Superieure)
  - **Dr. Cedric Ware** (Ecole Nationale Superieure des Telecommunications, Paris)
- ***Germany***
  - **Prof Dieter BIMBERG** (Technische Universität Berlin)
  - **Prof Wolfgang ELSäßER** (Technische Universität Darmstadt)
- ***Hungary***
  - **Dr Tibor BERCELI** (Budapest University of Technology and Economics)
  - **Mr Tamás MAROZSáK** (Budapest University of Technology and Economics)
- ***Ireland***
  - **Dr John DONEGAN** (Trinity College)
  - **Dr Pascal LANDAIS** (Dublin City University)
- ***Israel***
  - **Prof Meir ORENSTEIN** (Technion)
- ***Italy***
  - **Prof Antonella D ORAZIO** (Dipartimento di Elettrotecnica ed Elettronica Politecnico di Bari)
  - **Dr Concita SIBILIA** (Università di Roma 'la Sapienza')
- ***Lithuania***
  - **Prof Romuald BRAZIS** (Semiconductor Physics Institute)
  - **Dr Raimondas PETRUšKEVICIUS** (Nonlinear Optics and Spectroscopy Laboratory)
- ***Malta***
  - **Mr Ernest CILIA** (Mediterranean Telecommunications Research Institute Ltd)
- ***Netherlands***
  - **Prof Daan LENSTRA** (Vrije Universiteit Amsterdam)
  - **Dr Erwin BENTE** (Technische Universiteit Eindhoven)
- ***Poland***
  - **Dr Marian MARCINIAK** (National Institute of Telecommunications)
  - **Prof Wlodzimierz NAKWASKI** (Technical University of Lodz)

- ***Spain***
  - **Dr Ramon VILASECA** (Universitat Politecnica de Catalunya)
  - **Prof Luis VIÑA** (Universidad Autonoma de Madrid)
  - **Ms Elorz SIMON KATRIN**
- ***Sweden***
  - **Prof Anders LARSSON** (Photonics Laboratory)
  - **Dr Marek Chacinski** (Royal Institute of Technology)
- ***Switzerland***
  - **Prof Georg GUEKOS** (ETH Zürich)
- ***Turkey***
  - **Prof Atilla AYDINLI** (Bilkent University)
  - **Prof Ceyhum BULUTAY** (Bilkent University)
- ***United Kingdom***
  - **Dr Judy M. RORISON** (University of Bristol)
  - **Prof. Naci BALKAN** (University of Essex)

4.2 **Participating Institutions**

- Agilent (Multinational)
- Akdeniz University (Turkey)
- Athens Information Technology (Greece)
- Bilkent University (Turkey)
- Budapest University of Technology and Economics (Hungary)
- Center for Integrated Photonics (United Kingdom)
- Chalmers University of Technology (Sweeden)
- Cumhuriyet University (Turkey)
- Dublin City University, School of Electronic Engineering (Ireland)
- Ecole Nationale d'Ingénieurs de Brest (France)
- École Polytechnique (France)
- Ecole Polytechnique Fédérale de Lausanne (Switzerland)
- ETH Zurich (Switzerland)
- Exalos (Switzerland)
- Faculte Polytechnique de Mons (Belgium)

- FernUniversität in Hagen (Germany)
- Fraunhofer HHI (Germany)
- Friedrich-Schiller-Universität Jena (Germany)
- Helsinki University of Technology (Finland)
- IFM, Linköpings Universitet (Sweeden)
- Imperial College (United Kingdom)
- INSA Toulouse (France)
- Institute of Electronic Structure and Laser, Foundation for Research and Technology (Greece)
- Institute of Physics, Vilnius (Lithuania)
- Institute of Physics. Academy of Sciences of the Czech Republic, Prague (Czech Republic)
- Institute of Radio Engineering and Electronics, Prague (Czech Republic)
- Institute of Solid State Physics (Bulgaria)
- Istanbul University (Turkey)
- Koç University (Turkey)
- Kungliga Tekniska Högskolan (Sweden)
- La Sapienza (Italy)
- LAAS, Toulouse Cedex (France)
- Laboratoire de Photonique et de Nanostructures (France)
- National & Kapodistrian University of Athens (Greece)
- National Institute of Telecommunications (Poland)
- NMRC, ICT (Ireland)
- Paul-Drude-Institut für Festkörperelektronik (Germany)
- Physics Dept. of University of Aveiro (Portugal)
- Politecnico di Bari (Italy)
- Politecnico di Milano (Italy)
- Politecnico di Torino (Italy)
- SUPELEC-Ecole Supérieure d'Electricité (France)
- Tampere University of Technology (Finland)
- Technical University of Denmark (Denmark)
- Technion (Israel)

- Technischen Universität Berlin (Germany)
- Telecom Paris (France)
- Tesnische Universiteit Eindhoven (Netherlands)
- TU Darmstadt (Germany)
- Universidad Autónoma de Madrid (Spain)
- Universidad Carlos III (Spain)
- Universidad de Cantabria (Spain)
- Universidad de Valencia (Spain)
- Universidad de Zaragoza (Spain)
- Universita Degli Studi di Pavia (Italy)
- Universitat de les Illes Balears (Spain)
- Universität Münster (Germany)
- Universität Ulm - Fakultät für Ingenieurwissenschaften (Germany)
- Universitat Würzburg (Germany)
- Universiteit Gent (Belgium)
- University of Bath (United Kingdom)
- University of Bristol (United Kingdom)
- University of Cardiff (United Kingdom)
- University Of Cork (Ireland)
- University of Essex (United Kingdom)
- University of Glasgow (United Kingdom)
- University of Liverpool (United Kingdom)
- University of York (United Kingdom)
- University of Nottingham (United Kingdom)
- University of Sheffield (United Kingdom)
- University of St. Andrews (United Kingdom)
- University of Strathclyde (United Kingdom)
- University of Surrey (United Kingdom)
- University of Warwick (United Kingdom)
- Uniwersytetu Warszawskiego (Poland)

- Vrije Universiteit Amsterdam (Netherlands)
- Vrije Universiteit Brussel (Belgium)
- Weirstrass Institute (Germany)
- Witamy w £odzi (Poland)
- Wroclaw University of Technology (Poland)

4.3 Meetings of the Management Committee

07/04/2003: Brussels, Belgium

18/09/2003: Politecnico di Torino, Italy

02/06/2004: Athens Information Technology, Greece

20/10/2004: Rome, Italy

01/04/2005: Metz, France

03/08/2005: St Andrews, U.K.

03/02/2006: Crete, Greece

23/06/2006 Nottingham, U.K.

06/10/2006 Vilnius,Lithuania

27/03/2007 Metz, France

06 /07/2007 Rome, Italy

16/10/2007 Zaragoza, Spain

22/05/2008 Centaro, Italy

4.4 Meetings of the Working Groups

07/04/2003: Brussels, Belgium

17-18/09/2003: Politecnico di Torino, Italy

01-02/06/2004: Athens Information Technology, Greece

18-20/10/2004: Rome, Italy

31/03/01/04/2005: Metz, France

02/08/05-03/08/05: St Andrews, U.K.

02/02/06-03/02/06: Crete, Greece

22/06/06-23/07/06: Nottingham, U.K.

05/10/06-06/10/06: Vilnius,Lithuania

26/03/07- 27/03/07: Metz, France

05/07/07-06/07/07: Rome, Italy

15/10/07-16/10/07: Zaragoza, Spain

22/05/2008: Centaro, Italy

4.5 Short-term scientific missions:
All proposals and reports and publications for STSMs are available on the COST 288 website.

Year 1

1**. August 19, 2003-August 30, 2003**:Dr. Tamas Marozsak (Hungarian) (Budapest University of Technology and Economicsm Budapset, Hungary) visted Prof. Anders Larsson (Swedish) (Chalmers University of Technology, Chalmers, Sweden) to work on *Vertical cavity surface emitting laser dynamics modelling and measurements* (WP2-approved by MC).

2**. March 28, 2004-April 7 2004**: Prof W.Elsaesser (German)(Darmstadt University of Technology, Darmstad, Germany) visited Prof. G. Giulani, (Italiaan) (University di Pavia, Pavia, Italy) to work on the *Exploration of new experimental techniques for the investigations of the alpha-parameter of semiconductor lasers-perpective for quantum cascade lasers*. (WP2-approved by MC)

3.**May 3, 2004-May 13,2004**: Dr. G. Van der Sande (Belgium) (Vrije Universiteit Brussel, Brussel, Belgium) visited Prof. S. Balle (Spanish) (Instituto Mediterraneo de Estudios Avanzados, Spain) to work on *Analytical approximation for the quantum well gain and refractive index spectra of vertical cavity surface-emitting lasers including the effect of uniaxial planar-strain (*WP2-approved by MC)

4**. Summer 2004**: Mr. Andrzej Tabaka (Polish –PhD student) (Vrije Universiteit, Brussel, Belgium) will visit Prof W. Elsaesser(German)(Darmstadt University of Technology, Darmstad, Germany) to work on *Investigation of the RPP regime in vertical cavity surface emitting lasers subject to short external cavity optical feedback* (WP2-approved by MC).

Year 2

5. **September 1-10, 2004** Miss Yun Sun (Chinese PhD student at the University of Essex, Colchester, UK) visited Prof Marie Xavier **(**Laboratoire de Nanophysique, Magnétisme et Optoélectronique (LNMO) (INSA)Toulouse France) to work on *Experimental PLE measurements on GaInNAs Quantum Well Materials.* (WG1-approved by MC)

6. **December 6-18, 2004**-Dr. Maria Cristina Frassanito (Italian - National Nanotechnology Laboratory Distretto tecnologico, Lecce,Italy) visited Prof Andrea Fiore (Institute of Photonics and Quantum

Electronics, EPFL-FSB-IPEQ, Lausaunne,Switzerland) to work on *Spectroscopic characterization of single InAs/GaAs quantum dots emitting at 1.3μm* (WG1- approved by MC)

7. **January 17-February 11, 2005** Daniel Owens (American PhD student at the Athens Institute of Technology, Athens, Greece) visited Prof HJS Dorren (Eindhoven University of Technology, COBRA Research Institute Eindoven, The Netherlands) to work on *All-optical Flip-Flop Devices* (WG3-approved by MC).

8**. January 24-February 2, 2005**- Dr.Ceyhun Bulutay (Turkish) visited Prof Dieter Bimberg (Technical University of Berlin, Berlin Germany) to *Model Electronic states in Quantum Dot systems* (WG1-approved by MC).

9. **April 14-24, 2005** Dr. Francesco Marin (Italian) visited Dr. Krassimir Panajotov (Bulgarian) at the Vrije Universiteit Brussels to work on *Experimental studies of the strain induced birefringence and dichroism in VCSELs by optical linewidth heterodyne measurements* (WG2-approved by MC)

10**. June 20-July 1, 2005** -Dr. Angel Valle (Spanish) (Instituto de Fisica de Cantabria, Santander, Spain) visited Dr. Krassimir Panajotov (Bulgarian) at the Vrije Universiteit Brussels to work *on Experimental and Theoretical Studies of the nonlinear polarisation Dynamics in gain switched VCSELs* (WG2-approved by MC*)*

11. **July 13- July 20, 2005**- Dr. Dimitris Alexandropoulos (Greek) (Optical Communications Laboratory, University of Athens, Athens) visited Dr. Judy Rorison (University of Bristol, Bristol, U.K.) to work on a *Comparative study on the multi-wavelength amplification properties of GaInNAs quantum wells and quantum dots for broad-band SOAs*. (WG1-approved by MC)

Year 3

12. **October 24-November 4 2005** Ms. Yingning Qiu,(Chinese) at the University of Bristol,Bristol, UK, visited Prof. George.P.Papaioannou (Greek) at the University of Athens, Atherns, Greece, to work on *Ion irradiation induced N redistribution on InGaNAs/GaAs quantum wells* (WG1-approved by MC)

13. **December 7-22 2005** Dr. Marek Chacinski (Polish) from KTH, Sweden visited Prof Geert Mortier (Belgium), Ghent University, Belgium to work on *Optical signal processing using a new*

widely tunable laser diode (the MG-Y laser) with integrated optical amplifier (WG3-approved by MC)

14**. May 8-13th 2006** Prof Guido Guiliani (Italian) from University of Padua, Italy, visited Dr. Yousefi Mirvais, Technical University of Eindhoven, The Netherlands to investigate the *Alpha Factor Measurements* contected with the alpha factor Round-Robin for WG2. (WG2-approved by MC) (This is part of the larger STSM alpha factor round-robin measurement exercise)

Year 4

15**. July 16-30th 2006** Mr. Noam Gross (Israeli) from Ilam University, Israel visited Prof Wolfgang Elsasser at the TU, Darmstadt, Germany to investigate *Chaos Synchronization* (WG2-approved by MC).

16. **12-18 November 2006** Dr Pascal Landais from Dublin City University (Ireland) visited Prof Ioannis Tomkos at Athens Information Technology (Greece) to do round-robin series of *Measurements for the Alpha Factor in Lasers* (WG2-approved by MC).

17. **14-18 November 2006** Dr. Guido Guiliani from the University of Pavia (Italy) visited Prof Ioannis Tomkos at Athens Information Technology (Greece) to do round-robin series of *Measurements for the Alpha Factor in Lasers* (WG2-approved by MC).

18. **14-18 November 2006** Dr. Marek Chacinski from KTH (Sweden) visited Prof Ioannis Tomkos at Athens Information Technology (Greece) to do round-robin series of *Measurements for the Alpha Factor in Lasers* (WG2-approved by MC).

19. **14-18 November 2006** Dr. Raul Escorihuela from Aragon Photonics, Zaragoza (Spain) visited Prof Ioannis Tomkos at Athens Information Technology (Greece) to do round-robin series of *Measurements for the Alpha Factor in Lasers* (WG2-approved by MC).

20**. 14-18 November 2006** Dr. Asier Villafranca from the University of Zaragoza, Zaragoza (Spain) visited Prof Ioannis Tomkos at Athens Information Technology (Greece) to do round-robin series of *Measurements for the Alpha Factor in Lasers* (WG2-approved by MC).

21. **February 19-23 2007** Dr. Giovanna Tissoni from the Universita dell'Insubria (Italy) visited Prof Krassimir Panayotov at the Vrije Universiteit Brussels (Belgium) to investigate *Spatial polarisation dynamics and cavity solitons in broad area VCSELs.*
(WG2-approved by MC)

22. **February 20-28 2007** Dr. Dimitris Alexandropoulos from the University of Athens (Greece) visited Prof Mike Adams (University of Essex, U.K.), to investigate the *Spin Dynamics of dilute nitrides* (WG1-approved by MC)

23. **June 25-29 2007** Dr Angel Valle from the Universidad de Cantabria (Spain) visited Dr. Krassimir Panayotov at the Vrije Universiteit Brussel (Belgium) to investigate *Measurements of the nonlinear polarization dynamics in gain switched single-mode VCSELs* (WG2-approved by MC)

24. **June 4-8 2007** Stefan Breuer from the Darmstadt University of Technology, Darstadt, Germany to visit Profs Smit and Bente at Eindoven University of Technology, Eindoven, The Netherlands, to *Investigate Optical Characterization of Quantum dot Mode-locked lasers* (WG3-MC approved by MC).

25. **June 11-15 2007** Dr Krestin Yvind from the Depatment of Communications optics and Materials technology, Technical University of Denmark, Denmark, to visit Profs Smit and Bente at Eindoven University of Technology, Eindoven, The Netherlands, to *Investigate Optical Characterization of Quantum dot Mode-locked lasers* (WG3-MC approved by MC).

26. **June 4-15 2007** Prof John McInerney from the University of Cork, Ireland , to visit Profs Smit and Bente at Eindoven University of Technology, Eindoven, The Netherlands, to *Investigate Optical Characterization of Quantum dot Mode-locked lasers* (WG3-MC approved by MC).
McInerney

27. **June 4-15 2007** Dr. Jose Pozo from the University of Bristol UK and Eindoven to visit Profs Smit and Bente at Eindoven University of Technology, Eindoven, The Netherlands, to *Investigate Optical Characterization of Quantum dot Mode-locked lasers* (WG3-MC approved by MC).

Year 5

28. **August 1-31 2007** Ben Royall from the University of Essex (UK) visited Dr Mika Saarinen at Tampere University of Technology, (Finland) to investigate the *Design and Growth of Dilute nitride/GaAs solar cells* (WG1-approved by MC)

29**. October 18-27 2007** Krassimir Panayotov from the Institute of Solid State Physics, Sofia

(BUL) visited Dr. Jorge Tredicce at the InstituteNon lineaire de Nice, Nice (FR) to investigate *Experimental and theoretical studies on localized structrures in broad area VCSELs* (WG2-approved by MC)

30. **November 5-9 2007** Prof Romuald Brazis from the Semiconductor Physics Institute, Vilnius Lithuania visited Prof Marek Godlewski at the Institute of Physics of the Polish Academy of Sciences, Warszawa, Poland to investigate *Light emission from crystals with magnetic ions* (WG1-approved by MC)

31. **June 2008** Stefan Breuer from the Darmstadt University of Technology, Darstadt, Germany to visit Profs Smit and Bente at Eindoven University of Technology, Eindoven, The Netherlands, to *Investigate Optical Characterization of Quantum dot Mode-locked lasers* (WG3-MC approved by MC).

32. **June 2008** Prof John McInerney from the University of Cork, Ireland , to visit Profs Smit and Bente at Eindoven University of Technology, Eindoven, The Netherlands, to *Investigate Optical Characterization of Quantum dot Mode-locked lasers* (WG3-MC approved by MC).

33. **June 2008** Dr Asier Villafranca , to visit Profs Smit and Bente at Eindoven University of Technology, Eindoven, The Netherlands, to *Investigate Optical Characterization of Quantum dot Mode-locked lasers* (WG3-MC approved by MC).

34. **June 2008** Dr. Nikos Vogiatzis from the University of Bristol,, Bristol, UK, to visity frofs Smit and Bente at Eindoven University of Technology, Eindoven, The Netherlands, to *Investigate Optical Characterization of Quantum dot Mode-locked lasers* (WG3-MC approved by MC).

5. RESULTS

Working Group 1

WG1-Year 1

In Working Group 1 initial effort was dedicated to discussing the key issues in materials and device fabrication techniques for the next generation of optical devices for telecommunications. Key materials, such as quantum dots on GaAs and InP and GaInNAs quantum wells on GaAs, were identified for their possible impact on ultrafast applications in particular broad band SOAs and lasers. Many participating groups are active in this area and some collaborations were quickly initiated, specifically for the growth and characterisation on GaInNAs quantum wells, with sample exchange between the groups in Univ. Essex, INSA Toulouse, LAAS Toulouse, Technical University of Tampere, and Univ. Instanbul. A common activity between WG1 and WG2 was established on the characterisation of the linewidth enhancement factor, where EPF Lausanne (WG1) has provided quantum dot laser samples for round-robin characterisation in different WG2 groups. On the dissemination side, two speakers were invited to present ongoing research activities on position-controlled quantum dot growth (Dr. E. Pelucchi from EPFL) and on the electronic structure of diluted nitrides (Prof. E. O'Reilly from EMRC). Also, a summer school on semiconductor quantum dots (to be held in Ascona, Switzerland, Sep. 5-10 2004) has been organised by some of the groups participating in WG1 with a high participation expected from all groups participating in the action.

Some activities on GaN have been presented at the COST meeting but none on GaAsSb/GaAs so far. The discussion of Photonic Crystal structures (PBGs) are contained in devices in WG2.

WG1-Year 2

The activities in WG1 continued to focus on quantum dots and dilute nitride (GaInNAs) quantum well systems focusing on basic optical properties, lasing properties, gain properties for SOAs, modulation studies and transport measurements.

- *Quantum Dot Activities*

The Ecole Polytechnique Fédérale de Lausanne EPFL have supplied a number of quantum dot samples for activities in WG1 and WG2. One quantum dot sample was sent to Vrije Universiteit Brussel (Dr. Danckaert) for measurement of the alpha factor. One quantum dot sample was sent to Bilkent University, Ankara (Prof. Aydinli) for measurement as electro-optical modulators. EPFL has supplied one QDot laser sample to be used by several groups in the round-robin alpha factor measurement. EPFL has undertaken to host one short-term-mission from Univ. Lecce on measurement of micro-photoluminescence of single QDs.(STSM #6). Prof Bimberg's group in Berlin hosted Dr. Ceyhun Bulutay from Bilkent University, Ankara on a short term mission STSM #8) modelling the energy levels in quantum dots. EPFL and the SME EXALOS AG have interacted on the realisation and characterisation of quantum dot super luminescent diodes which has resulted in several publications.[papers 1,2,3,4]

- *GaInNAs Quantum Wells*

Professor M. Pessa's group at the University of Technology in Tampere has made available a number of EELs and VCSELs for round robin measurements by the research groups in WP1. These devices are being looked at Essex and Istanbul Universities. As soon as contacting problem is sorted out they will be passed on to other groups. Professor M. Pessa's and Professor Chantal Fontaine's group at Tampere and LAAS- Toulouse respectively have made available a number of undoped dilute nitride quantum well samples. These will be used in round robin measurements. Professor M. Sopanen's group has grown modulation doped GaInNAs/GaAs quantum wells for hot electron transport measurements. These are currently being investigated at Essex.

Prof X. Marie will be sending a series of GaNAs/GaAs QWs for magneto transport measurements to Essex

Professor X. Marie's group at INSA-Toulouse has hosted Ms.Yun Sun from the University of Essex on a short term mission investigating GaInNAs quantum well samples using PLE experiments(STSM #5) This work has resulted in a understanding of the role of localisation in the GaInNAs quantum wells somehow related to the incorporation of N within the InGaAs.

A further STSM (STSM #11) has taken place with Dr. Dimitris Alexandropoulos visiting Dr. Rorison at the University of Bristol. The work involved investigating if broad band gain in

InGaNAs quantum well and localisation centres believed to exist in these quantum wells could be exploited for simultaneous multi-wavelength amplification as in quantum dots. It involved sharing computer models and initial results look promising.

WG1-Year 3

The activities in WG1 continued on Quantum dots and dilute nitride (GaInNAs) and (GaNAs) quantum well systems focusing on basic optical properties, lasing properties of VCSELs and FP lasers, gain properties for SOAs, modulation studies and transport measurements.

A number of strong collaborations have been established between groups of participating academic organizations. A brief summary of the collaborative and COST 288 related activities of the participating groups are:

Quantum Dot Related

Collaboration between Technische Universität Berlin TUB and Vrije Universiteit Brussels

Investigation of the static and dynamic polarization properties of quantum dot VCSELs.

Quantum dot VCSEL with different active regions for emission at 980, 1100 and 1275 nm and different designs have been fabricated by the TUB. Measurements of polarization properties have been done by the Vrije Universiteit Brussels, the work is still in progress.

Other COST 288 related activities at Berlin

QD-SOA [4,5]:

Quantum dot (QD) based photonic devices are promising for the wavelength range of 1.3 µm. Semiconductor optical amplifiers (SOAs) based on QDs show ultrafast gain dynamics and pattern effect free amplification both theoretically and experimentally. Mode-locked lasers (MLL) used as optical comb generators operating in the 5-80 GHz range for high frequency applications such as time domain multiplexing benefit from the low alpha factor and the broad spontaneous emission spectrum of the QD gain medium.

We have presented mode-locked lasers and semiconductor optical amplifiers based on the same quantum dot material. Ultrafast optical combs emitted by QD MLLs at 20, 40 and 80 GHz are amplified without significant distortion of the pulses in the QD SOA. A jitter analysis showed no increase of the rms jitter (Root Mean Squared) by the SOA. These results demonstrate the importance of the ultrafast gain dynamics in QD SOAs for applications in ultrahigh-bitrate transmission systems.

QD-SPS [6]:

Self organized semiconductor quantum dots (*QDs*) represent a potentially important source of triggered single photons and entangled photon pairs, because the excitons and biexcitons recombine by emitting only a single photon at a time.

We demonstrate uncharged exciton and biexciton emission from an single electrically pumped InAs *QD* in a *pin*-diode with submicron oxide current aperture. This *QD-LED* allows reliable pumping of just one InAs *QD* and demonstrates strongly monochromatic polarized emission of a single *QD*. No other emission is observed across a spectral range of 500 nm, proving that indeed just one single *QD* is contributing. Thus, this structure is well suited for practical implementation of an effective linear polarised *SPSs*.

QD-VCSEL[7,8]:

QD-VCSEL with different active regions and device concepts were fabricated and investigated statically and dynamically.

For the first time electrically driven QD-VCSELs grown using metalorganic vapor phase epitaxy (MOCVD), the widely-used growth method for VCSEL production, were realized. Lasing was achived on the ground-state transistion. The devices use stacked InGaAs QD layers, placed in the field intensity antinodes of the cavity formed by selectively oxidized distributed Bragg reflectors. Devices with 3(3 QD layers demonstrate at 20 °C a cw output power of 1.45 mW at 1.1 µm emission wavelength. The peak external efficiency was 45 %, limited by lateral carrier spreading within the 4 □-cavity and a reduction of the internal efficiency above 60 °C. A minimum threshold current of 85 µA was obtained from a device with a 1 µm aperture.

At 1.3 µm emission wavelength a conventionally doped semiconductor DBR QD-VCSEL grown by MBE, containing 17 p-modulation doped QD layers placed in 5 field intensity antinodes demonstrated a cw output power of 1.8 mW (pulsed 8 mW) and a differential efficiency of 20 % at 20 °C. The maximum –3dB modulation bandwidth at 25 °C was 4 GHz.

As an alternative to InGaAs quantum wells and Stranski-Krastanow grown quantum dots (SK-QDs) for the wavelength range around one micrometer, we investigated also stacked submonolayer MBE grown quantum dots (SML QDs) as active medium in VCSELs. The very temperature robust devices emitting at 980 nm show with 0.8 mW single-mode emission at 20 °C a small signal modulation bandwidth of 16.6 GHz and a record high modulation current efficiency factor of 19 GHz/ mA1/2. For multimode lasers the small signal modulation bandwidth decreases only from 15 GHz at 25 °C to 13 GHz at 85 °C. For 20 Gb/s non-return-to-zero pseudo random bit signals the devices have shown clearly open eyes and error free operation with a bit error rate better than 10-12 at 25 and 85 °C.

Collaboration between Ecole Polytechnique Fédérale de Lausanne EPFL and Vrije Universiteit Brussel and Bilkent, Ankara

EPFL have supplied a number of quantum dot samples for activities in WG1 and WG2. One quantum dot sample was sent to for measurement of the alpha factor. One quantum dot sample was sent to Bilkent University, Ankara (Prof. Aydinli) for measurement as electro-optical modulators. EPFL has supplied one QDot laser sample to be used by several groups in the round-robin alpha factor measurement.

Dilute Nitride Related

Collaboration between University of Essex, UK, Helsinki Technical University of Technology, Tampere University of Technology, LAAS-Toulouse, and INSA-Toulouse, Akdeniz University, Antalya , University of Athens on the
Optical characterization of GaInNAs quantum wells [9,10,11,12,13]
Activities continued to establish the effect of nitrogen/Indium concentration and growth/ rapid thermal annealing on the optical quality. The samples and devices supplied by the growth groups are now listed together with their parameters at the COST 288 WEB site This “sample information bank” is intended to give information about samples and devices to be used in round robin measurements together with a list of the investigations completed and the up-to-date coordinates of the devices. It has helped to increase collaborative activities between the groups active in the field. Undoped single and double quantum well samples provided by Helsinki, Tampere and LAAS have been circulated between the collaborating groups for round-robin measurements.
Prof. G. Papaiouannou at Athens university and Prof. M. C. Arikan at Istanbul University have started working on Spectral PC and IPV and radiation effects on optical properties. Prof. George Papaioannou and Prof M. C. Arikan have also decided to extend the collaboration and to apply jointly for a bilateral research programme between the Turkish and Greek Science and technology ministries.
University of Essex has provided Prof. Ulug’s group at Akdeniz university with equipment donation to set up new optical assessment facilities to investigate PL and lasing characteristics of the dilute nitride material supplied within the cost -288 programme.
Dr. Chantal Fontaine’s group at LAAS, and Dr. M. Saponen’ group at Helsinki Technical University provided the modulation doped GaInNAs quantum wells with good electrical quality. . Hot Electron measurements on modulation doped GaInNAs/GaAs QWs for the first time were performed on these samples by Essex. The results will be published shortly.

Collaboration between Universities of Athens and Bristol [14,15]
Yingning Qiu, a PhD student from Dr. Rorison’s group at the University of Bristol, visited Prof. G. Papaiouannou, University of Athens within the frame of a short term mission (STSM #12). She performed ion irradiation and low temperature annealing experiments on QW lasers provided by the Tampere group in an attempt to control the N position within the quantum well as modeling she has

done has predicted that N located at the centre of the quantum well produces a larger red-shift in emission. She observed a red shift in lasing after irradiation and low temperature annealing and the results will be submitted for publication shortly. This initial STSM visit was followed by another visit of Y.Qiu to Athens (not COST funded) to study laser loss coefficients as a function of temperature.

Dr. Rorison's group is also pursuing continuing interactions with Dr. Dimitris Alexandropoulos at the Optical Communications Laboratory, University of Athens, on broad-band amplification of SOAs.

Collaboration between Universities of Bristol, Essex, and Tampere University of Technology
This has led to an application by M. Saarinen, J. Rorison and N. Balkan to organize a symposium on dilute nitrides at the next EMRS meeting (2007- Strasbourg). This application has received very positive feedback and the outcome will be known very shortly.(note added later-proposal granted.)

Collaboration between Universities of Bristol, University of Pavia, EPFL Lausanne, and Tampere University of Technology, Modulight

Alpha factor Round-Robin measurements as well as dynamic
measurements with optical feedback are carried out using the following devices.

<u>FABRY-PEROT:</u>

6 x 650nm AlGaInP/GaAs in chip

6 x 630nm AlGaInP/GaAs in chip

2 x 1329nm AlGaInAs/InP in chip

4 x 1560nm InGaAsP/InP in chip

<u>DFB</u>

2 x ML-T-1310-DFB-2G5 AlGaInAs/InP 1310 nm, packaged, TO can

2 x ML-T-1490-DFB-2G5 AlGaInAs/InP 1490 nm, packaged, TO can

4 x ML-C-1550-DFB-2G5 AlGaInAs/InP 1550 nm, in chip

The packaged DFB are used for alpha factor RR.

Two sets of <u>QD</u> ridge and broad area bar devices from EPFL Lausanne are used for alpha factor RR measurements. The Round Robin activity, which encompasses both WG1 and WG2, has expanded and an interim summary of some collaborative results is included in Appendix 1 of this document and is also accessible on the COST 288 website.

The group at University of Lodz led by Prof. W. Nakwaski has started up a collaborative

simulation project for the COST 2888 participants [16, 17,18,19,20]

These are:

"/Designing and optimisation of diode lasers for their new emerging applications: Part A – Edge-emitting diode lasers", /Modelling exercise within the COST 288 (Nanoscale and ultrafast photonics), http://www.een.bristol.ac.uk/cost288/pdf/nakmod1.pdf.//

"/Designing and optimisation of diode lasers for their new emerging applications: Part B – Vertical-cavity surface-emitting diode lasers", /Modelling exercise within the COST 288 (Nanoscale and ultrafast photonics), http://www.een.bristol.ac.uk/cost288/pdf/nakmod2.pdf.

WG1-Year 4

The activities in WG1 continued on Quantum dots and dilute nitride (GaInNAs) and (GaNAs) quantum well systems focusing on basic optical properties, lasing properties of VCSELs and FP lasers, gain properties for SOAs, modulation studies and transport measurements.

Collaborations that were established between groups of participating academic organizations have continued with increasing strength as evidenced by the number of joint publications and the presentations at the Vilnius and Metz meetings

There was one WG1 STSM [#22] this year. Dr D. Alexandropoulos from the Optical Communications Laboratory in Department of Informatics and Telecommunications of University Of Athens, visited Prof. M.J. Adams research group at the University of Essex, Department of Electronic Systems Engineering, Wivenhoe Park, Colchester, CO4 3SQ, UK. The purpose of the visit was to study Spin Dynamics of Dilute Nitrides to explore theoretically the spin relaxation process in GaInNAs. The effort concentrated on GaInNAs-based Vertical Cavity Surface Emitting Lasers (VCSELs). The work involved the theoretical studies the polarization switching of GaInNAs based VCSELs. To this end Dimitris Alexandropoulos calculated from first principles the electronic structure to provide input data for the VCSEL polarization-switching model of Professor Adams' group.

Collaborations

1. University of Essex, UK , Helsinki Technical University of Technology, Tampere University of Technology, LAAS-Toulouse, and INSA-Toulouse, Akdeniz University, Antalya , University of Athens

Optical and electrical characterisation of GaInNAs quantum wells:

Undoped single and double quantum well samples of dilute nitride quantum wells provided by Helsinki, Tampere and LAAS have been circulated between the collaborating groups for round-robin measurements which led to presentations at Phase 2007 and EMRS-2007 conferences and a number of publications

2. University of Bristol and Athens

Work has continued on investigating how the N position within the qw can be controlled by alpha particle bombardment follwed by low temperature annealing.

3. INSA, Toulouse and University of Essex

The collaboration on the optical properties of In-rich dilute nitrides have started through the exchange of samples. The groups intend to submit a STREP proposal in the FP-7 programme

4. Bristol and Essex

Work on dilute nitrides will be submitted as two research proposals to EPSRC. One is on novel optical amplifiers and the other is hot carrier transport.

5. Tampere University of Technology, and Istanbul University

Dr. M. Saarinen has recently provided Prof. Arikan's group with a selection of doped and undoped QWs of GaInNAs/GaAs for optical studies

6. Institute of Quantum Electronics and Photonics, Ecole Polytechnique Fédérale de Lausanne and Bilkent University, Ankara

Sample exchange, fabrication and measurements of QD waveguides

7. Tampere University of Technology and Essex

Recent collaboration on the growth and assessment of dilute nitride multiple quantum wells with variable nitrogen composition in a GaAs p-n junction

8. J. Rorison (Bristol), M. Saarinen (Tampere), N. Balkan (Essex) and C. Bulutay (Bilkent)

Organization of symposium entitled "Novel Gain Materials based on III-N-V compounds". EMRS-07 international meeting, Strasbourg 29 May- 01 June 2007

WG1-Year 5

The final year of the COST action has continued to focus on quantum dots and dilute nitride (GaInNAs) and (GaNAs) quantum wells. WG1 activities have investigated basic optical properties, lasing properties of VCSELs and FP lasers, gain properties for SOAs, modulation studies and transport measurements. In addition different themes were introduced: InGaN alloys and Quantum Cascade Lasers. The GaInN material was developed at the MRS nitride meeting in Strasbourg last year and has developed further. It was developed into a new cost proposal which was successful in the first round and is submitting into the second round. It has arisen from collaborations within WG1 and is headed by Prof Naci, Dr Rorison and Dr Saarinen. Work on quantum cascade lasers for Terahertz applications (Darmstadt and Sheffield-Hallam) was developed aided by COST within WG1 (physics modelling) and WG2 (alpha-factor round-robin). (A new proposal was submitted in Terahettz from COST 288 members but was not successful past round one.)
Collaborations that were established between groups of participating academic organizations have continued with increasing strength as evidenced by the number of joint publications and the presentations at the Zaragoza and Cetraro Meetings.

At the Zaragoza Meeting WG1 contributions were made by Ben Royall reporting on a STSM (#28) collaboration between Finland and Essex on 'Dilute Nitride Solar Cells', Nikos Vogiatzis reporting results on modelling dilute nitrides going beyond the BAC model 'Band anticrossing and impurity Anderson model in the GaInNAs/GaAs material", Mika Saarinen reporting initial experimental results on VECSELs results and red wavelengths: '1 W at 617 nm generation in GaInAsN disk laser by intracavity frequency conversion'" and '2 wavelength VECSELs', Romuald Brazis reporting on "Monte Carlo studies of the transient response of electrons and phonons in cubic InN",and "Metamaterials for microwave photonics",and Guilhem Almuneau who reported "Technological alternatives for VCSEL devices designed for new applications" . Many of these talks were going beyond the aims of COST 288 and reporting on new activities: solar cells and new wavelengths. A new COST proposal based on dilute nitrides,tunable wavelengths and solar cells was discussed and has passed stage one of the new COST proposal submissions.

At the Centaro meeting Mika Saarinen reported on the WG1 activities: "WG1 - Novel Gain Materials and Fabrication Techniques".At the Final review Ben Royall also repeated and updated his report on his STSM as a young researcher benefiting from COST 288.Romuald Brazis reported on his STSM to Poland at the final meeting as well.

Two WG1 STSMs were done in year 5:

1) Ben Royall from the University of Essex to Tampere University of Technology

"*Design and Growth of Dilute nitride/GaAs solar cells*" (STSM #28)

2) Romuald Brazis from the Semiconductor Physics Institute, Vilnius Lithuania to the Institute of Physics of the Polish Academy of Sciences, Warszawa, Poland (STSM #30)
'*Light emission from crystals with magnetic ions*'

Collaborations
Collaborative activities were strengthen and extended in year 5.

1. *University of Essex, UK , Helsinki Technical University of Technology, LAAS-Toulouse, , Akdeniz University, Antalya , University of Athens, Istanbul University*

Optical and electrical characterisation of GaInNAs quantum wells:
Undoped single and double quantum well samples of dilute nitride quantum wells provided by Helsinki, and LAAS have been circulated between the collaborating groups for round-robin measurements which led to presentations at Research Workshop "Recent Advances in Low Dimensional Structures and Devices" Nottingham, UK (7-9 April 2008) and a number of publications.

2. *INSA, Toulouse and University of Essex*
The collaboration on the optical properties of In-rich dilute nitrides has started through the exchange of samples. Two papers are in preparation for submission for publication

3 *Bristol and Essex*
The work on dilute nitrides has been submitted as two research proposals to EPSRC. One
is on novel optical amplifiers and the other is hot carrier transport.

4 *Tampere University of Technology, and Istanbul University*
Optical spectroscopy work has continued on a selection of doped and undoped QWs of GaInNAs/GaAs which Tampere supplied to Istanbul.

5. *Institute of Quantum Electronics and Photonics, Ecole Polytechnique Fédérale de Lausanne and Bilkent University, Ankara*
Work continued at Bilkent on fabrication and measurements of QD waveguides at Bilkent on Lausanne samples.

6. *Tampere University of Technology and Essex*
Collaboration on the growth and assessment of dilute nitride/ GaAs multiple quantum well tandem

solar cells has started

7. *Members of WG1:* Joint submission of COST Action Open call, proposal entitled "Novel Gain Materials and devices based on III-V-N compounds". This has had favourable feedback and has been invited to submit into Phase 2.

A number of joint publications are included in the publication list in Appendix 1C. A number of devices were provided through WG1 to the COST action:

1) GaInAsN strained MQW-samples for carrier mobility studies to Istanbul University (Prof. Cetin Arikan-WG1).
2) Laser wafer for N-implantiation studies to University of Bristol UK (Dr. Judy Rorison-WG1).
3) Laser devices for surface gratings and splitted contacts studies to University of Bristol (Dr. Jose Pozo-WG1)
4) Laser devices for the COST-288 aplha-parameter Round Robin by Modulight, Inc. Tampere and Tampere University of Technology (WG2).
5) Pigtailed DFB-laser for the interferometric studies to KTH, Sweden (Dr. Marek Chacinski-WG3

Working Group 2

WG2-Year 1

In its first year of activity, the activities of WG2 focused on the following proposals:

- compare measurements of alpha-factor or linewidth enhancement factor by different methods on different devices: QD devices, VCSELs, quantum cascade lasers,... Methods proposed:
  - direct method (sub threshold)
  - linewidth measurement (+ other laser parameters)
  - optical feedback
  - optical injection
  - high frequency modulation and chirp
- study (numerical & theoretical) of the high frequency dynamics of VCSELs, more specifically when subject to optical feedback
- Spatio-temporal modelling of VCSELs.
- Modelling and experiments (if possible) on self-pulsing VCSELs

- *Linewidth Enhancement Factor*

The linewidth enhancement factor (LEF), also known as α–factor, is of utmost importance in semiconductor lasers (SLs). It is indeed one of the main features that distinguishes the behaviour of SLs with respect to other types of lasers. The α–factor influences several fundamental aspects of SLs, such as the linewidth, the chirp under current modulation, the mode stability, the filamentation in broad–area devices, ... More details on the LEF and the way(s) in which it can be measured can be found in the overview that was specially produced for the WG by Guido Giuliani (U. Pavia) and that can be downloaded from the COST288 website and is attached to this report as Appendix 1. Guido Giuliani (U. Pavia) will also act as the coordinator of this activity (STSM #2)

- *Dynamics of Semiconductor Lasers.*

We plan to study the dynamics of semiconductor lasers and new laser structures (Coordinator: Marc Sciamanna, Supélec, France) in the case where the laser is subject to optical feedback with a very small delay time, i.e. in the so-called short external cavity (EC) regime (where the external cavity round-trip time is (much) smaller than the relaxation oscillation period of the semiconductor laser). The dynamical instabilities occurring in the short EC regime are not well known. Their understanding is however of great interest for new applications of laser diodes in compact disk data readout and integrated devices for all-optical, high frequency signal processing and telecom applications.

Another topic that will be considered is related to the study of the dynamics of new laser structures with (presumably) very small alpha factor, such as quantum dot devices. This work on small alpha lasers will be performed in synchronisation with round-robin measurements of alpha factor in new laser structures using different techniques. (STSM # 4)

- *Spacio-temporal Dynamics in VCSELs*

Several groups within WG2 expressed an interest in modelling and measuring the spatio-temporal dynamics in VCSELs (also self-pulsing in VCSELs). Several groups have indeed developed models with a varying degree of sophistication (effective index method, mode expansion, FDTD, direct integration, …). Also new measurement techniques have been proposed such as the TRIDA method (W. Elsässer, TUD). Of course the ultimate aim will be to compare the results of the modelling with the experimental ones. This task is still under definition. Coordinator will be P. Debernardi (Politecnico de Torino). (STSM #1,3)[21, 22,23]

WG2-Year 2

In the second year of activity, the working group 2 has coordinated and extended the results on the following research topics, which have been suggested during the first year of activity.

1. Theoretical and experimental study of nonlinear dynamics of semiconductor lasers, including polarization dynamics of VCSELs. (Coordinator: Marc Sciamanna, LMOPS CNRS UMR-7132, Supélec, France)

As mentioned in our previous report, several participants to COST 288 have expressed their interest in studying theoretically and/or experimentally the nonlinear dynamics of semiconductor lasers and new laser structures when they are subject to a time-delayed optical feedback, optical injection or large current modulation. Particular attention shall be paid to the polarization dynamics of VCSELs in such laser configurations. Moreover, these laser studies ask for new investigations on the modelling of polarization properties and polarization switching of VCSELs, which will also be undertaken in collaboration between several groups.

Optical feedback in VCSELs - A. Tabaka, K. Panajotov, H. Thienpont (Vrije Universiteit Brussel, Belgium), M. Peil, I. Fischer, W. Elsäßer (TU Darmstadt, Germany), and M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France) have collaborated on the study of nonlinear polarization dynamics in VCSELs subject to optical feedback with a very small delay time, i.e. in the so-called short external cavity (EC) regime [where the external cavity round-trip time is (much) smaller than the relaxation oscillation period of the semiconductor laser]. The dynamical instabilities occurring in the short EC regime are not well known, while being of great interest for new applications of laser diodes in compact disk data readout and integrated devices for all-optical, high frequency signal processing and telecom applications. Experiments have been performed during a Short Term Scientific Mission (STSM) in July 2004 (STSM #4) and have unveiled the first evidence of regular pulse package dynamics in the total intensity of VCSELs, i.e. the emission of fast pulses at the EC frequency which repeat regularly like groups of pulses at a much smaller frequency. Spectral and correlation properties of the pulse package dynamics have been analyzed in depth. Striking differences are observed with respect to the pulse package dynamics in edge-emitting lasers, and these differences have been interpreted as resulting from the polarization mode competition in VCSELs. Results have been presented during our COST meeting in Roma (October 2004) and have since been published in proceedings of international conferences.

M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France) and A. Tabaka, K. Panajotov, H. Thienpont (Vrije Universiteit Brussel, Belgium) have also collaborated on new theoretical insights into the regular pulse package dynamics in edge-emitting lasers. Results have motivated new theoretical and experimental studies in VCSELs and have been published in international journals [24,25].

Optical feedback in VCSELs – J. Albert, M. C. Soriano, I. Veretennicoff, J. Danckaert and K. Panajotov (Vrije Universiteit Brussel, Belgium) have collaborated with P. A. Porta, D. P. Curtin, and J. G. McInerney (UCC, Ireland) on the application of the polarization properties of VCSELs subject to Doppler shifted optical feedback to laser Doppler velocimetry. Recent experimental work has shown that the polarisation bistability often observed in VCSELs can be exploited to enhance the responsivity of these semiconductor lasers in speed-sensing applications. Experimental results are reviewed and are compared with simulations on a rate equation model. Results have been published in an international journal [23].

M. C. Soriano, M. Yousefi, J. Danckaert (Vrije Universiteit Brussel, Belgium) have collaborated with S. Barland, M. Romanelli, G. Giacomelli and F. Marin (Univ. di Firenze, Italy) on the study of low-frequency fluctuations in VCSELs with polarized optical feedback. The system shows Low Frequency Fluctuations (LFF) in the selected polarization mode (PM). Below solitary laser threshold, the orthogonal PM remains silent, while it only responds after a dropout event in the main mode above threshold. Calculations show good agreement with the measurements and identify a type of synchronization between the low frequency dynamics of the two polarization modes. Results have been published in an international journal [26]. (STSM #9)

M. Sciamanna, I. Gatare (LMOPS CNRS UMR-7132, Supélec, France) and K. Panajotov, J. Buesa (Vrije Universiteit Brussel, Belgium) have collaborated on the experimental and theoretical study of polarization switching induced by optical injection in VCSELs. I. Gatare is working towards a PhD thesis on this topic, in collaboration between the two universities. Experimental results have unveiled for the first time a rich nonlinear dynamics including wave mixing, time-periodic and possibly chaotic regimes. An in depth mapping of the polarization dynamics has been performed in the plane of the injection parameters (frequency detuning between master and slave lasers and injected power). Theoretical investigations are in progress and aim at comparing experimental results with numerical simulations on different rate equation models for VCSELs. A detailed bifurcation analysis is undertaken with the use of modern techniques such as continuation tools for teady-state and time-periodic dynamical solutions. Results have been published in proceedings of international conferences [27].(STSM # 9).

Large current modulation in VCSELs - A. Valle (Instituto de Fisica de Cantabria, Spain), K. Panajotov (Vrije Universiteit Brussel) and M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France) have collaborated on the theoretical study of gain switching in multi-transverse-mode

VCSELs. Preliminary results unveil complex nonlinear dynamics resulting from the mode competition.

Polarization switching properties of VCSELs - G. Van der Sande, J. Danckaert, I. Veretennicoff, K. Panajotov (Vrije Universiteit Brussel, Belgium) have collaborated with S. Balle (UIB, Spain) on the rate equation modelling of VCSELs including the effect of uniaxial planar stress. Starting from a microscopic model in the free-carrier approximation, they derive an analytical approximation for the optical susceptibility of uniaxially stressed quantum well lasers at low temperatures by neglecting second-order contributions of the band mixing phenomenon. The resulting polarization dependent peak gains, differential peak gains, transparency carrier densities and line width enhancement factors as induced by the uniaxial planar stress are discussed. Results have been published in international journal [28].

Current modulation and polarization switching in VCSELs - The TONA Department at VUB (Belgium) and F. Marin, G. Giacomelli (Univ. di Firenze, Italy) have extended their STSM (STSM #10) to study of modulation frequency response in VCSELs to new insights into the general theory of bistable systems with noise. They have also compared experiments and theoretical results on the stochastic polarization switching in VCSELs. Results have been published in international journals [29,22].

Ghost stochastic resonance in VCSELs - G. Van der Sande, G. Verschaffelt, J. Danckaert (Vrije Universiteit Brussel, Belgium) and C. Mirasso (UIB, Spain) have reported on ghost stochastic resonance in VCSELs. To this end, they study the polarization response of a vertical-cavity surface-emitting laser, driven simultaneously by noise and two (or more) weak periodic signals. In the bistable regime, they observe experimentally the occurrence of stochastic resonance at a frequency that is absent in the input driving signal. The presence of this so called ghost resonance is then confirmed theoretically. Results have been submitted to an international conference.

2. Comparison of measurements of alpha-factor (linewidth enhancement factor) by different methods on different semiconductor laser devices (including quantum dot, VCSELs, quantum cascade lasers) (Coordinator: Guido Giuliani, Univ. Pavia, Italy)

The linewidth enhancement factor (LEF), also known as α–factor, is of utmost importance in semiconductor lasers (SLs). It is indeed one of the main features that distinguishes the behaviour of SLs with respect to other types of lasers. The α–factor influences several fundamental aspects of SLs, such as the linewidth, the chirp under current modulation, the mode stability, the filamentation in broad–area devices, ...G. Giuliani (Univ. Pavia, Italy) has produced for COST 288 a detailed report on the definition of the LEF and the way(s) in which it can be measured. The report can be downloaded from the COST288 website and is Appendix 1 in this report.

The round-robin measurement of linewidth enhancement factor in semiconductor lasers has now started with a large number of groups being involved. Guido Giuliani has distributed a form among COST 288 participantas to be filled by those interested in contributing to the round-robin measurements. This form specifies which method people are ready to apply (direct, subthreshold method, linewidth measurement, optical feedback, optical injection, high frequency modulation and chirp) and which kind of device they would like to analyze. Several devices are distributed, among which VCSELs, quantum dot lasers, long wavelength VCSELs, quantum cascade lasers, DFB lasers at 1550 nm emitting with large output power etc. Several methods should be investigated but we have decided to ask each group to apply a common method to the device, for example the Hakki-Paoli method. Each device will have a "device passport", which would summarize the measurements already performed on the device and its specifications. Some SMEs have expressed that the results of their devices are not published outside the action without their approval.

Besides the round-robin measurement, several collaborations between two or three groups have already been performed and have yielded published results. G. Giuliani (Univ. Pavia) and W. Elsäßer (TU Darmstadt, Germany) have carried out experimental investigations about the linewidth enhancement factor (alpha-factor) of different types of semiconductor lasers exploiting the self-mixing interferometric effect with optical feedback. This technique has been reported in our COST meetings. Part of the experiments has been performed thanks to a STSM. For an external cavity semiconductor laser, the alpha-factor and the linewidth have been measured simultaneously for different tuning positions of the external grating. The alpha-factor is shown to vary between 2 and 5, while the linewidth changes accordingly. This is an evidence of the fact that the alpha-factor in complex-cavity semiconductor lasers is not constant. Also, investigations have been carried out to determine possible dependence of the alpha-factor with the emitted power in 50 mW Fabry-Perot lasers, and measurements on Quantum-Cascade lasers are under way. Results have been published in proceedings of international conferences.

Another topic that will be considered is related to the study of the dynamics of new laser structures with (presumably) very small alpha factor, such as quantum dot devices. This work on small alpha lasers will be performed in synchronisation with round-robin measurements of alpha factor in new laser structures using different techniques.

3. Spatio-temporal dynamics of VCSELs (Coordinator: P. Debernardi, Politecnico di Torino)

During the first year of activity, several groups within WG2 expressed an interest in modelling and measuring the spatio-temporal dynamics in VCSELs. Several groups have indeed developed models with a varying degree of sophistication (effective index method, mode expansion, FDTD, direct integration, …). Also new measurement techniques have been proposed such as the TRIDA method (W. Elsäßer, TU Darmstadt, Germany) and several results have been reported on this topic during our COST meetings. Of course the ultimate aim will be to compare the results of the modelling with the experimental ones. Several modelling exercises have been recently proposed but groups have now to express their interest in such a collaborative task.

WG2-Year 3

In the third year of activity, the working group 2 has coordinated and extended results on the following research topics, making the core of the "physics of devices" activities. These results have led to publications in peer-reviewed journals and international conferences, with acknowledgment to COST 288. They have also led to short term missions between different working group 2 participants. The combination of interactions at WG2 meetings, workshops organized in the frame of COST 288, and short term scientific missions (STSMs), has therefore made possible to bring significant advances to different topics related to physics of nanophotonic devices. The Round Robin activity, which encompasses both WG1 and WG2, has expanded and an interim summary of some collaborative results is included in Appendix 1 of this document and is also accessible on the COST 288 website.

1. Theoretical and experimental study of nonlinear dynamics of semiconductor lasers, including polarization dynamics of VCSELs. (Coordinator: Marc Sciamanna, LMOPS CNRS UMR-7132, Supélec, France)

As already mentioned in our previous reports, several participants to COST 288 have expressed their interest in studying theoretically and/or experimentally the nonlinear dynamics of semiconductor lasers and new laser structures. Particular attention shall be paid to the polarization dynamics of VCSELs. Moreover, these laser studies ask for new investigations on the modelling of polarization properties and polarization switching of VCSELs, which will also be undertaken in collaboration between several groups.

Optical feedback in VCSELs - A. Tabaka, K. Panajotov, H. Thienpont (Vrije Universiteit Brussel, Belgium), M. Peil, I. Fischer, W. Elsäßer (TU Darmstadt, Germany), and M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France) have collaborated on the study of nonlinear polarization dynamics in VCSELs subject to optical feedback with a very small delay time, i.e. in the so-called short external cavity (EC) regime [where the external cavity round-trip time is (much) smaller than the relaxation oscillation period of the semiconductor laser]. The dynamical instabilities occurring in the short EC regime are not well known, while being of great interest for new applications of laser diodes in compact disk data readout and integrated devices for all-optical, high frequency signal processing and telecom applications. Experiments have been performed during a Short Term Scientific Mission (STSM #4) in July 2004 and have unveiled the first evidence of regular pulse package dynamics in the total intensity of VCSELs, i.e. the emission of fast pulses at the EC frequency which repeat regularly like groups of pulses at a much smaller frequency. The detailed results from the collaboration and from the STSM have been published this year in an international journal [30]

Optical injection in VCSELs - M. Sciamanna, I. Gatare (LMOPS CNRS UMR-7132, Supélec, France) and K. Panajotov, J. Buesa (Vrije Universiteit Brussel, Belgium) have collaborated on the experimental and theoretical study of polarization switching induced by optical injection in VCSELs. I. Gatare is working towards a PhD thesis on this topic, in cotutelle between the two universities. Experimental results have unveiled for the first time a rich nonlinear dynamics including wave mixing, time-periodic and possibly chaotic regimes. An in depth mapping of the polarization dynamics has been performed in the plane of the injection parameters (frequency detuning between master and slave lasers and injected power). Experimental results from the collaboration have been published in international journals [31,32].

M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France) and K. Panajotov (Vrije Universiteit Brussel, Belgium) have collaborated on the theoretical modelling of polarization switching in VCSELs induced by orthogonal optical injection. Such a laser configuration is expected to induce a fast (ps) polarization switching in VCSELs. Results give insight into the bifurcation scenarios accompanying the polarization switching induced by optical injection, and into the conditions leading to optical chaos. Results have been published in two international journals [33,34].

Large current modulation in VCSELs - A. Valle (Instituto de Fisica de Cantabria, Spain), has performed a STSM in collaboration with K. Panajotov (Vrije Universiteit Brussel) and with M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France), on the topic of gain switching in multi-transverse-mode VCSELs. Preliminary results unveil complex nonlinear dynamics resulting from the mode competition and are currently analyzed for publication in journal and conference proceedings.

Mutually coupled VCSELs - R. Vicente, J. Mulet, and C.R. Mirasso (Universitat de les Illes Baleares, Spain) and M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France) have collaborated on the theoretical modelling of mutually coupled VCSELs. Polarization switching induced by mutually coupling two otherwise polarization stable VCSELs has been demonstrated and analyzed. The bistability properties of such a laser configuration are thought of great interest for all-optical switching applications. Results have been published in an international journal [35].

Broad area VCSELs - T. Ackemann (University of Strathclyde, UK), M. Schultz-Ruthenberg (Univ.

of Munster, Germany), I.V. Babushkin, N. Loiko (Institute of Physics, Belarus), and K.F. Huang (National Chiao Tung University, Taiwan) have collaborated on the length-scale selection in complex emission patterns spontaneously arising in broad area VCSELs. Results have been published in an international journal [36].

Physics of quantum wells / photonic crystal heterostructures / current modulated lasers- The group of V. Kononenko (Stepanov Institute of Physics NASB and Belarussian State University) has contributed to several new physics of quantum well semiconductor lasers, but also physics of photonic crystal heterostructures and nonlinear dynamics of current modulated lasers. Some of these studies have been performed in collaboration with P. Christol, A. Joullie (University of Montpellier 2, France) and A. Pisarchik (CIO, Mexico). The corresponding results have been published in international journals [37-42]. Van der Sande, M.C. Soriano, M. Yousefi, G. Verschaffelt, M. Peeters, J. Danckaert, and D. Lenstra have considered the influence of current noise on the relaxation oscillation dynamics of semiconductor lasers [43] while J. Rorison's group at Bristol has investigated the role of photonic band gap structures incorporated into VCSEL aperatures in controlling mode interactions and dynamics [44].

2. Comparison of measurements of alpha-factor (linewidth enhancement factor) by different methods on different semiconductor laser devices (including quantum dot, VCSELs, quantum cascade lasers) (Coordinator: Guido Giuliani, Univ. Pavia, Italy) (The Round Robin activity, which encompasses both WG1 and WG2 has expanded, and an interim summary of some collaborative results is included in Appendix 1 in this document and is also accessible on the COST 288 website.)

The linewidth enhancement factor (LEF), also known as α–factor, is of utmost importance in semiconductor lasers (SLs). It is indeed one of the main features that distinguishes the behaviour of SLs with respect to other types of lasers. The α–factor influences several fundamental aspects of SLs, such as the linewidth, the chirp under current modulation, the mode stability and the filamentation in broad–area devices. G. Giuliani (Univ. Pavia, Italy) has produced for COST 288 a detailed report on the definition of the LEF and the way(s) in which it can be measured. The report can be downloaded from the COST288 website and is attached in Appendix 1.

As discussed during the COST 288 Meeting in Crete (2-3 February, 2006), it is highly desirable that a special framework for Short Term Scientific Missions (STSMs #16-20) be created to support the experimental activity related to the Round–Robin measurement on the Linewidth Enhancement Factor of Semiconductor Lasers (Alpha–Factor).

The scope of the Round–Robin is twofold:

1. Compare different measuring method for the alpha-factor by applying those to the same set of devices of common types (such as 1550 nm F-P and DFB lasers, and 780/850/1550 nm VCSELs). In this activity, the largest possible number of participating laboratories is seeked.
2. Apply a few methods (with emphasis on the Hakki-Paoli method where applicable) and critically analyze the results of measurements on devices of new type, for which the alpha-factor measurement is either difficult or has to be considered in detail from a theoretical point of view. In these category of devices are: QD's lasers, dilute nitride lasers, quantum cascade lasers.

To successfully address the above points, an intense exchange of information and common sessions of measurements involving scientists from different Laboratories are required. Hence, it suggested that the exchange of experts between different laboratories also accompany the exchange of devices, for a joint critical analysis of the measurement procedures and of experimental results. To this purpose, a special framework for STSMs has been established, allowing scientists to benefit from a simplified implementation plan. Details about the STSM application rules and implementations have been included in a specific document, available on COST 288, and approved by COST 288 Management Committee. A list of institutions eligible for special Round–Robin STSMs framework has been established on the basis of expressed interests. Any new Institution joining the alpha–factor Round–Robin with an active role can be included, after approval of the COST 288 MC.

The special STSM plan for round-robin measurement of linewidth enhancement factor has already started, devices are being circulated and first results are expected by the end of Summer 2006, to be reported during the Fall meeting of COST 288. Among the first results obtained in the frame of round-robin activities, we can mention the following ones:

- J. V. Staden, T. Genty, Ch. Mann, W. Elsässer (TU Darmstadt, Germany) and G. Giuliani (University of Pavia, Italy) have collaborated on applying the self mixing technique using optical feedback for the measurement of alpha factor of DFB quantum cascade laser. Results have been published in international conferences [45].

- G. Giuliani (University of Pavia, Italy) performed a STSM in TU Eindhoven on May 10-14, 2006, (STSM #14) with the topic "Measurement of the Linewidth enhancement factor of semiconductor lasers with conventional and filtered optical feedback methods". The goal was to experimentally measure the alpha-factor of several semiconductor lasers using two different methods based on optical feedback: one method using conventional optical feedback (self-mixing method), and one method using filtered optical feedback (FOF). A FOF experimental set-up was mounted around a DFB laser (supplied by Modulight, from COST288 WG1). The self-mixing technique was used to monitor the amplitude of each (spurious) reflection coming from the optical elements of the loop cavity (mirrors, attenuators, isolator). A self-mixing signal was then observed using the unidirectional external cavity loop, by generating a wavelength modulation through laser diode current modulation. By introducing FOF, a characteristic multistable signal was observed with longer stable branches, as predicted by the theory of filtered optical feedback. The fruitful exchange of practical know-how on both the self-mixing and FOF techniques, will enable the Pavia and Eindhoven Groups to carry out new measurements in the future, that will enable to characterize some parameters of the semiconductor laser under test.

- Asier Villafranca and Ignacio Garcies (University of Zaragoza) shall report about their first results on round-robin measurements during Nottingham COST 288 meeting in June 2006. They have focused on trying to measure the power dependence of alpha, for two high-power DFB lasers. FM/AM, linewidth and fiber transfer function methods have been applied to measure alpha. They also obtained some results from the measurement of other devices, including VCSEL and MQW lasers. (an interim summary of some collaborative results is included in Appendix 1 of this document and is also accessible on the COST 288 website.)

<u>Dissemination of results</u>

Special issue of OQE journal

M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France) and K. Panajotov (Vrije Universiteit Brussel, Belgium) have co-edited the special issue of the international journal "Optical and Quantum Electronics" (Springer-Verlag) related to "Physics and Applications of Semiconductor Lasers". This special issue includes 22 contributions mostly from collaborations performed in the frame of COST 288. All published articles can be found in Ref. [46].

WG2-Year 4

Working group 2 has continued on the themes developed in years 2 and 3. A lot of effort has gone into the alpha-factor round robin with with a large multi-group STSM (#16, #17, #18, #19, #20) which has been completed at the beginning of this year. The work on the alpha factor has concluded with a report on the large multi-group STSM which has been added as Appendix 1C. In addition 3 other STSM related to WG2 activities were held this year: Noah Gross on *Chaos Synchronization* (#15), Giovanna Tissoni on *Spatial Polarisation Dynamics and Cavity Solitons in Broad area VCSELs* (#21) and Angel Valle on *Measurements of non-linear polarisation dynamics in gain-switched single-mode VCSELs* (#23). The PHASE 2007 international workshop organized in Supélec, Metz, France on March 28-30, followed by a COST 288 Workshop and MC,was strongly related to activities happening in WG2. Detailed results have been published in the technical digest and full-length manuscripts should appear soon in a special issue of Optical and Quantum Electronics international journal, edited by Springer, with many contributions from COST 288 participants

Collaborations between several groups have been very successful in WG2 this year. In paticular work on VCSELs has brought new insight into the physics and applications of VCSEL devices. Here are some more detailed comments on two research activities performed this year concerning VCSEL dynamics.

Spatio-temporal turn-on dynamics of grating relief VCSELs.

Within a joint collaboration of modeling, technology and experiments between the Institute of Applied Physics, Darmstadt University of Technology, the IEIITI-CNR at the Politecnico di Torino, the Institute of Optoelectronics at Ulm University, and the Photonics Laboratory, Microtechnology and Nanoscience at Chalmers University of Technology, we studied the spatio-temporal turn-on dynamics of grating relief VCSELs (vertical-cavity surface-emitting lasers).

Spatio-temporal phenomena and in particular VCSELs play an important in the investigations of working group 2, but in some sense are also linked to the ultrafast dynamics investigations of working group 3. The sophisticated structure makes VCSELs at the same time a very interesting subject of actual basic and application-oriented research. The manifold interactions between the optical field and the semiconductor material results in spatio-temporal phenomena, a complex polarization behavior due to their circular symmetric structure, including a particularly interesting behavior under optical feedback and quite unique and sophisticated noise properties. Among all those phenomena, the concurrence of both polarization and mode stabilization are of particular interest in many applications, such as, e.g., optical data communication and sensing. Here, by our

fast imaging investigations we addressed the question, if polarization suppression and modal selection can be obtained simultaneously also on short time scales.
For this aim, the collaboration investigated the polarization-resolved spatial emission and turn-on dynamics of oxide-confined vertical-cavity surface-emitting lasers (VCSELs) with an integrated surface-relief grating. By applying a time-resolved imaging technique we demonstrated in concordance with the modeling results that the introduced high dichroism also maintains dynamically its influence thus leading to highly polarization-stable spatially fundamental Gaussian mode emission on a hundred picosecond timescale. Finally, the achieved progress, but also the limits of this in-technology-realized promising stabilization scheme have been discussed.

Chaos Synchronization

In STSM #15 Noah Gross, from Bar-Ilan University in Israel, visited Wolfgang Elsaesser at Darmstadt and performed a set of experiments aimed at testing a novel scheme of chaos synchronization for encrypted communications. Communication via chaotic signals has drawn much attention in the last two decades. The fundamental idea for realization of encrypted communications with semiconductor lasers relies on the property that a SLs subject to external feedback can exhibit complex chaotic behavior. Such chaotic signals can be harnessed for the encryption of messages while simultaneously serving as carriers for the encrypted messages. Furthermore, the possibility to synchronize the emission dynamics of a second laser system to the transmitted chaotic signal, carrying the encrypted message, allows for extraction of the encrypted message. These properties describe the essential ingredients that allow realization of a secure communication system, based on nonlinear dynamics. So far no simple practical system has been proposed which allows for bi-directional communications ensuring high quality of security. Therefore, we have proposed a current scheme whose novelty is in its simplicity. Two nearly identical lasers are optically coupled in a face-to-face configuration, whereas a semi-permeable mirror situated in between them serves as the source of self-feedback for each of them. This setup promises robust synchronization according to simulations and it may be easily implemented in an existing optical network by introducing an element that serves as a mirror somewhere along the coupling path; hence, it is very attracting for the application of a commercial optical cryptosystem. Two different types of lasers were tested for synchronization in the described configuration:a pair of 1550nm DFB lasers.and pair of 1570nm Fabry-Perot multi-mode lasers.

The first pair did not show good synchronization properties. The latter pair, however, could be well synchronized, because of almost perfectly agreeing parameters, The existence of synchronization for the case of different external cavity lengths is very important. It reduces significantly the constraint regarding the location of the mirror, making it easier to be implemented in real cryptosystem applications. Therefore, the performed experiments that give evidence for the existence of the identical synchronization solution represent a promising first step toward realization of a functional bi-directional cryptosystem.

Transverse mode switching and locking in VCSELs. Within a joint collaboration of modeling and experiments between Supélec, LMOPS CNRS UMR-7132, France, TONA Dpt, Vrije Universiteit Brussel, Belgium, and IFC-CSIC, Spain, which involved a STSM (#23) we studied the dynamics of the transverse modes and polarization modes of a VCSEL subject to optical injection.
Injection locking of VCSELs is an important issue and has recently been suggested as a way to enhance VCSEL modulation bandwidth and to develop new all-optical signal processing applications. The VCSEL peculiar polarization and transverse mode properties combined with the optical-injection-induced nonlinear dynamics make this laser problem interesting both on the physics point of view and for applications using optical chaos and optical switching. In our laser configuration an external light is injected with a polarization orthogonal to that of the light emitted by the free-running VCSEL. In this orthogonal optical injection scheme, the increase of injection strength leads to polarization switching. Moreover, when the frequency detuning becomes very large, i.e. when the injected light is detuned such that its frequency is close to the transverse mode frequency splitting, then the polarization switching is accompanied by transverse mode switching and transverse mode competition behaviors. We have analyzed these dynamics theoretically and experimentally and mapped them in the plane of the injection parameters (frequency detuning, injection strength).

Polarization synchronization between coupled VCSELs. In collaboration between Supélec, LMOPS CNRS UMR-7132, France, and TONA Dpt, Vrije Universiteit Brussel, Belgium, we have shown that the polarization dynamics of two unidirectionally coupled VCSELs can be synchronized but that the synchronization regimes and conditions may significantly differ from those observed in conventional edge-emitting lasers. In particular we have shown the possibility to synchronize the polarization dynamics in a large range of frequency detunings and injection strength. Chaos synchronization is an interesting property for applications such as chaos cryptography. These new synchronization mechanisms using VCSELs open the path towards new chaos communication schemes.

Spatial Polarisation Dynamics and Solitons in VCSELs

Givanna Tissoni investigated Spatial polarisation dynamics and cavity solitons in broad area VCSELs in STSM #21 in a collaboration with Krassimir Panayotov. They started theoretical investigations on the role of the polarization of light for pattern and cavity solitons formation in broad area Vertical-Cavity Surface-Emitting Lasers (VCSELs). Usually, no particular attention is paid to the polarization properties of the solitons and a linear polarization is a priori assumed. However, it is well established both experimentally and theoretically that small- and medium-area VCSELs are prone to polarization instabilities and polarization switching. Different models are known in the literature that successfully explain this behavior in different region of parameters, such as the spectral shift of the gain/losses, thermal lensing and spatial hole burning, spin-flip phenomena, etc. With this STSM we started exploring the applicability of these well established models for small area VCSELs for studying the polarization dynamics of patterns and cavity solitons in broad area VCSELs.

Polarization bistability in VCSELs with optical injection. In collaboration between Supélec, LMOPS CNRS UMR-7132, France, and TONA Dpt, Vrije Universiteit Brussel, Belgium, we have studied the possibility to observe polarization bistability induced by optical injection in VCSELs. The increase of injection strength for a fixed detuning or a sweep of frequency detuning for a fixed injection strength are two ways to induce polarization switching with bistability. The characteristics of the bistability, such as the hysteresis width and the underlying non-linear dynamics, have been analyzed theoretically and compared with experiments.

Irregular pulsating dynamics in VCSELs with large current modulation. In collaboration between Supélec, LMOPS CNRS UMR-7132, France, TONA Dpt, Vrije Universiteit Brussel, Belgium, and IFC-CSIC, Spain, we have observed experimentally irregular pulsating dynamics in the polarization modes of a VCSEL subject to a large current modulation, although the total intensity dynamics is pulsating very regularly. We have analyzed the statistics of the pulsating polarization dynamics and compared these with the statistics of polarization dynamics as well known in free-running VCSELs.

WG2-Year 5

Working group 2 has continued on the themes developed in years 2, 3 and 4 although the alpha-factor study was completed in year 4. Activities of spatio-temporal phenomena in Vertical-Cavity Surface-Emitting Lasers (VCSELs) have continued with one STSM (#29) being done by Krassimir Panajotov on *Experimental and theoretical studies on localised structures in broad area VCSELs*.

At the final review meeting in Centraro Wolfgang Elsaesser and Krassimir Panajotov gave an overview of WG2 activities throughout the action. A proposal for a new cost action on mastering the dynamics of semiconductor lasers has resulted from discussions and collaborations within WG2. It has been submitted into phase 2 of the COST proposal scheme and links the laser dynamics and soliton dynamics groups in the EU.

Polarisation Dynamics in VCSELs

STSM (#29) was dedicated to measurements of the nonlinear polarization dynamics in gain-switched single-mode VCSELs resulted in clarifying the effect of the boundary conditions in medium size Vertical-Cavity Surface-Emitting Lasers (VCSELs) when taking into account the light polarization in the framework of the rate equation model. As it has been well established both experimentally and theoretically, small-area VCSELs have the tendency to polarization instabilities and polarization switching. Polarization properties of medium- and broad-area VCSELs have been not that well investigated and understood. Therefore, using the elaborated set-up available at INLN, the experimental studies of broad area VCSELs for two orthogonal orientations of the linear polarization of the holding beam revealed a strong interplay between the light polarization and the VCSELs spatially local properties which is responsible for the formation of localized structures.

Working Group 3

WG3-Year 1

- *Short Optical Pulse Sources*

The work in Eindhoven (Bente, Lenstra, Dorren) concentrated on short optical pulse mode-locked sources. One project concerns the development of an all-optical clock extraction circuit for the recovery of a 40 GHz signal from a 160 Gb/s incoming optical data input signal. A series of integrated extended cavity ring and linear lasers with saturable absorbers has been produced that is currently characterised. A second project concerns research into the development of an integrated mode-locked semiconductor laser that can produce femtosecond pulses. Indications from the modelling have shown the feasibility of using arrayed waveguide gratings inside the cavity for intra-cavity dispersion compensation and that significant pulse shaping needs to be applied.

A novel method for sub-picosecond optical pulse generation has been demonstrated using a semiconductor optical amplifier (SOA) and a linear polarizer placed in a ring-laser configuration. Nonlinear polarization rotation in the SOA serves as the passive mode-locking mechanism. The ring cavity generates pulses with duration below 800 fs (FWHM) at a repetition rate of 14 MHz. The pulse time-bandwidth product is 0.48. Simulations results are in good agreement with the experimental results are presented [47].

The group of Morthier in Gent has so far mainly helped in organizing the round robin exercise and the modelling exercise. They have contacted the IST-MONOPLA project to see if mode locked lasers for the round robin exercise can be received and were involved in the planning of the modelling exercise through discussions at the COST288 meeting.

- *Pulse Propagation in non-linear Optical Fibre*

In the Weierstrass Institute for Applied Analysis and Stochastics in Berlin, the contribution of Bandelow within WG3 has focused on pulse propagation in nonlinear optical fibers and on modeling and simulation of mode-locked semiconductor lasers, which will become now an exercise in WG3.[48,49]

- *Electron Occupancy*

  In the group of Kral (Prague) the processes of electronic occupancy up-conversion and of incomplete electronic depopulation have been studied in the context of quantum computing. The results were found to be relevant also for light sources and light detectors used in optical communications[50]

WG3-Year 2

The following institutions and researchers have participated in the COST 288 action in the WG3 area, either through contributions at the meeting, publications or through discussions at the meetings and workshop.

- *Mode-locked semiconductor lasers*

Many activities in this package focus on mode-locked laser devices and the area keeps on attracting new participants in the COST action.

Work at the Technical University of Denmark in the group by Prof Mork by Dr K. Yvind focuses on hybridly mode-locked quantum well lasers with one, two or three quantum wells. In the last period most attention has been given on the jitter and noise properties of the lasers and stability maps for the devices have been recorded in great detail.

The devices have been successfully simulated by Bandelow and Radziumas of the Weierstrass Institute in Berlin, Germany, and this has been reported upon. A travelling wave model of the devices was developed and a mode analysis of the different operating regimes could be performed. The work has shown the importance of limiting the gain in the amplifying section of the lasers. Based on this work, researchers at the Heinrich Hertz Institute in Berlin are currently re-evaluating the design of their 40GHz hybridly mode-locked semiconductor lasers through reduction of the number of quantum wells.

The COBRA Institute in Eindhoven, the Netherlands has presented their results on modelling and designs for ultra-fast integrated passively mode-locked lasers as well as experimental work on ps lasers for all-optical clock recovery. Modelling shows that an integrated femtosecond laser may be realised through using the frequency chirp in the optical output pulses. The chirped pulses can be compressed down to 300fs using compression circuits with the laser. Results obtained with a 27GHz integrated passively mode-locked ring laser that was realised with active passive integration were presented.

- *Mode-locked VCSELs*

Dr J. Mulet and Prof. S. Balle of IMEDEA, Palma de Mallorca, Spain have reported upon the successful modelling of electrically pumped, passively mode-locked Vertical Extended Cavity Surface Emitting Lasers. The bidirectional optical propagation in the gain region can be treated analytically which made an analytical model possible. Experimental results that were reported upon in literature were reproduced.

- *Quantum Dot Mode-Locked Lasers & a Round-Robin Exercise*

In the last meeting in Metz, a report were presented on passively and hybridly mode-locked quantum dot lasers produced by Prof Bimberg's group from the Technical University in Berlin, Germany. Prof Bimberg has decided that he will make such devices available for Round-Robin exercise on the subject of mode-locked laser characterisation that we are currently organising. Currently 4 groups have registered interest in taking part in this exercise.

Quantum dot theory

From the Institute of Physics at the Academy of Sciences of Czech Republic work is reported upon by K. Kral. It concerns a non-Gibbsian behavior of zero-dimensional semiconductor nanostructures, which appears to be manifested in experiments by an effect of incomplete depopulation from electronic excited states or by an effect of up-conversion of electronic level occupation after preparing the system in the ground state of electronic excitation. The effect is currently interpreted with help of electron-LO-phonon interaction, which is supposed to play a role in these structures in the form of multiple-scattering of electron on the optical phonons. Quantum kinetic equation describing the process of electronic relaxation with the inclusion of electronic multiple scattering on phonons is considered. The multiple electron scattering interpretation of the effect is supported by pointing out a considerable degree of agreement between the theoretical picture presented and a rather extensive amount of existing experimental data [51].

- *Emission Dynamics*

From the University of Darmstad, Germany, Prof W. Elsäßer presented combined experimental and theoretical investigations of the picosecond emission dynamics of broad-area semiconductor lasers (BALs)[52]. Here the weak longitudinal self-mode-locking that is inherent to BALs in enhanced by injecting a single optical 50-ps-pulse, which triggers the output of a distinct regular train of 13-ps-pulses. Modelling based on multi-mode Maxwell-Bloch equations illustrates how the dynamic interaction of the injected pulse with the internal laser field efficiently couples the
longitudinal modes and synchronizes the output across the laser stripe. Thus, the results reveal insight into the complex interplay between lateral and longitudinal dynamics in BALs, at the same time indicating their potential for short optical pulse generation..

- *Four-Wave Mixing*

Clock recovery experiments at subharmonic frequencies have been reported upon by Dr C. Ware in the group of prof Erasme at the ENST Paris, France. Here four wave mixing in a semiconductor optical amplifier has been used to lock a local optical 10 GHz oscillator to an incoming 30GHz optical data signal.

- *All optical switching*

In the group of Morthier at the University of Gent, Belgium results were reported upon on a new optical decision or thresholding circuit, composed of an SOA and a DFB laser diode in an optical feedback scheme is proposed. This new circuit has been studied both by simulations and experiments[53].Simulations show a very steep optical decision characteristic that rises 15mW over an input power range of 0.5mW. It is also demonstrated that the decision point can easily be shifted by tuning the drive currents of both the laser diode or the SOA or the feedback ratio between them. The principle has been experimentally verified as well, using a discrete SOA and DFB laser diode. A good agreement with the simulation results was obtained. Again a very steep optical decision characteristic, combined with the possibility to adjust the decision point was obtained. Also at the COBRA Institute in Eindhoven, Netherlands investigations are reported on all-optical switching in a multi-quantum-well semiconductor optical amplifier-based nonlinear polarization switch using optical pulses with duration of 200 fs at a central wavelength of 1520 nm. It is shown that full recovery of the switch is within 600 fs, in both the gain and absorption regime. Numerical simulations are in qualitatively good agreement with our experimental data [54].

Short term mission-Optical Switching (STSM #7)

The COBRA Institute has also hosted a short term mission of Daniel Owens, a student at AIT, Athens, Greece. The subject was on an optical bistable laser device: a Multimode Interference Bistable Laser Diode. This is a four port device (two in, two out). The output can be switched between the two output ports using optical pulses. The work will be reported upon in the coming COST 288 meeting and the report is available on the COST 288 website.

- *Systems*

In the systems oriented devices research work The National Technical University of Athens, the group of Prof. Avramopoulos, and Swiss Federal Institute of Technology, the group of Prof Guekos, have reported work on all-optical burst mode receiver at 10Gb/s and optical transparency in packet formatting and network traffic offered by all-optical switching devices.[55].

Project collaboration web-site

A wiki website has gone on-line to support collaborative work in the COST288 action.

WG3-Year 3

The following institutions and researchers have participated in the COST 288 action specifically in the WP3 area, either through contributions at the meeting, publications or through discussions at the meetings and workshop.

All optical signal processing and clock recovery

Clock recovery is a critical function of any digital communications system. Dr C. Ware in the group of prof Erasme at the ENST Paris, France is working to replace the classical electronic phase-locked loops (PLLs) at higher bit rates. Several all-optical or opto-electronic clock recovery methods are being studied. He has presented an opto-electronic PLL where three-wave mixing in a periodically-poled lithium niobate device (PPLN) provides the phase comparator. Since PPLN is passive, it generates no amplified spontaneous emission noise; also, the error signal is in the visible (763 nm), therefore easily separated from infrared input signals. Clock recovery is performed on a 10-GHz sinusoidal optical signal. Being based on ultrafast nonlinear effects, this scheme should be able to reach still higher bit rates, on the order of several hundred GHz. Also, sub-clock extraction (e.g. 40-to-10 GHz) should be possible without modifications.

In the group of prof. Morthier at the University of Gent, Belgium, work was performed on bistable behaviour of integrated DFB – SOA devices. Optical bistability induced by the feedback into the laser was investigated in a DFB laser diode connected with an SOA. Broadband operation and tunability of the domain of bistable responses was investigated and shown. Such a device can readily serve as an all-optical flip-flop.

At the Athens Institute for Telecommunication in Greece work was performed by Kouloumentas, prof Tzanakaki, prof I. Tomkos on all-optical clock recovery and the use of self-phase modulation for the generation of multiple frequencies. A simple all-optical clock recovery technique is proposed for short data bursts at 160 Gbit/s, and beyond, which is based on the concept of the use of a Fabry-Pérot filter for partially filling the “0s” of the incoming data stream. The novel feature of the technique is the use of a highly nonlinear fiber followed by an optical band-pass filter at the signal’s carrier wavelength that acts as an ultra-fast limiter, removing drastically the amplitude modulation of the Fabry-Pérot filter’s output and providing a clock signal of high quality.

Through a detailed simulation study it the suitability of a subsystem was investigated, based on self-phase modulation induced spectral broadening, to provide multicasting functionality in optical networks. A return-to-zero 40 Gbit/s signal is replicated into seven different output channels with 200 GHz channel spacing under different noise loading conditions. Due to the operating principle three of the produced channels exhibit regenerative performance, while other three undergo only low performance degradation. Q-factor calculations are performed for different input power levels in order to verify and maximize this effect.

Modelocked semiconductor lasers

At the COBRA Institute in Eindhoven, The Netherlands in work by M. Heck and E. Bente a model was developed for the simulation of integrated passively mode-locked InP–InGaAsP ring laser systems that include active components such as an amplifier and saturable absorber, and passive components that can be frequency dispersive. These dispersive components can have a complex frequency dependence, such as arrayed waveguide gratings (AWGs). The model is a lumped-element model that is used as a design tool for developing integrated femtosecond pulse sources with internal dispersion control. Simulations based on an InP/InGaAsP amplifier and absorber show the possibility of laser designs that are able to generate pulses with pulse durations down to 300 fs in the 1550-nm wavelength range. The designs are based on femtosecond laser systems in bulk and fiber optics that are published in the literature. The femtosecond laser sources envisaged can be realized using existing InP–InGaAsP active-passive integration technology.

All-active integrated passively modelocked ring lasers fabricated at the COBRA Institute in the Netherlands (Y. Bararin and E. Bente) have been characterised in detail and data are being compared with results from simulation software developed at the Weierstrass Institute, Berlin, Germany by Mindaugas Radziunas. Pubications of this work are expected later this year.

At IMEDEA, Palma de Mallorca, Spain, Josep Mulet and Salvador Balle have developed a novel description of electrically driven vertical-external-cavity surface-emitting semiconductor lasers (VECSELs) mode-locked by saturable absorber mirrors. Their approach is based on an analytical solution of the bidirectional traveling-wave equations for fundamental transverse mode operation. The resulting time-domain equations describe the evolution of the electric fields and carrier-densities at the quantum well layers of the emitter and absorber structures which are coupled through delayed boundary conditions. For the design considered, stable mode-locked pulses of few tens of picoseconds at 15 GHz repetition rate are obtained which is in agreement with recently reported experimental results.

Quantum dot theory and devices

Work was done on quantum dot devices at 1.3 micron in a collaboration by the Technische Universität Berlin, Germany, the group of prof Bimberg, Nanosemiconductor GmbH, Dortmund, Germany, the Fraunhofer-Institut für Nachrichtentechnik, Heinrich-Hertz-Institut, Berlin, and u2t Photonics AG, Berlin, Germany. They presented results on directly modulated lasers with high-reflectivity coating, mode-locked lasers with a gain and absorber section, and semiconductor optical amplifiers (SOA) with anti-reflection coating, all based on InGaAs/GaAs quantum dot (QD) material emitting at 1.3 µm. Error free 8 and 10 Gb/s data modulation is presented. 80 GHz passive mode-locking of two-section QD lasers is reported. Hybrid mode-locking was achieved at 40 GHz. The minimum pulse width at 80 GHz was 1.5 ps, with a timebandwidth product of 1.7. QD SOAs are shown to have a chip gain larger than 26 dB. Modelling of the gain characteristics of these devices predicts 40 dB amplification under ideal biasing and input power. QD-VCSEL with 17 p-modulation doped QD layers placed in 5 field intensity antinodes and fully doped GaAs/AlGaAs DBRs show a peak multimode RT cw output power of 1.8 mW and differential efficiency of 20 %. The maximum -3dB bandwidth is 3 GHz.

At the COBRA Institute, Eindhoven, Netherlands, the group of H. Dorren has examined ultrafast carrier dynamics in a quantum-dot (QD) semiconductor optical amplifier with a rate equation model. The model includes two-photon absorption (TPA) and gain bleaching during the propagation of 120 fs optical pulses at the wavelength near telecommunication wavebands. The TPA-generated carriers in the bulk region of the waveguide relax to the QDs via the wetting layer, which occurs synchronously in time and space with QD carrier depletion. This leads to efficient enhancement of the rate of carrier capture into the QDs, reducing the pattern effects for ultra high-speed optical signal processing.

Dr Karel Kral at the Institute of Physics, Academy of Sciences of the Czech Republic, Prague has presented theoretical work in which he shows that the usual approach to the kinetics of electrons and phonons in quantum dot systems may need some additional extension. He has used longitudinal optical phonons to interpret the electronic energy relaxation in quantum dots and at the same time they served as a reservoir, with which the electronic subsystem is in contact. Such a phonon subsystem is expected to be passive, namely, in a long-time limit the whole system should be able to achieve such a stationary state, in which statistical distributions of both subsystems do not change in time. Attention was given in his work to this property of the LO phonon bath. He has shown that the passivity property of the so far used approximations to electronic transport in quantum dots. He has also shown a way how to improve the passivity of LO phonon bath using canonical Lang-Firsov transformation.

Short term missions

In December 2005 a short term mission was hosted by the group of Prof Morthier at the University of Gent to Marek Chacinski from the KTH Stockholm (STSM #13). The subject of this short term mission was 'optical signal processing using an MG Y-laser'.

Round-Robin exercise

The search for devices that are suitable for a Round-Robin exercise on the characterisation of modelocked lasers continues. At Photonics West a contact was made with ZIA Laser from the U.S. in order to obtain experimental 5 GHz passively modelocked quantum dot devices. Since these devices are packaged they are particularly suitable for such an exercise. Currently prof. McInerney (University College Cork, Ireland) and Dr J. Rorison, (Bristol University UK) are handling negotiations. Dr E. Avrutin is in contact with Nanosemiconductor GmbH for a similar option.

Work package organisation

In order to stimulate the activities in WP 3 Dr E Avrutin from the University of York in the U.K. and Dr C. Ware from at the ENST Paris, France have joined the WP 3 team as vice chairmen in December 2005.

WG3-Year 4

All optical signal processing and clock recovery

Clock recovery is a critical function of any digital communications system. Dr C. Ware in the group of prof Erasme at GET/Telecom Paris, France is working to replace the classical electronic phase-locked loops (PLLs) at higher bit rates. They have demonstrated successful sub-clock extraction and clock synchronization respectively for a sinusoidal intensity modulated signal at 30 GHz and for a digital intensity modulated signal at 10 Gbps. The three-wave-mixing-based phase comparator operates if the signal frequency is a multiple of the clock frequency; therefore it is anticipated that this scheme will be capable of sub-clock extraction at higher rates. Corresponding experiments as well as BER performance testing, remain to be done.

In the group of prof. Morthier at the University of Gent, Belgium, progress has been made on the dynamic all-optical flip-flop (AOFF) operation of an optical feedback scheme consisting of a semiconductor optical amplifier (SOA) and a distributed feedback laser diode (DFB-LD), bidirectionally coupled to each other. The operation of the AOFF relies on the interplay between the optical powers in both the DFB-LD and the SOA. Switching times as low as 150 ps for switch pulse energies of around 6 pJ and a repetition rate of 500 MHz have been measured. The contrast ratio was measured to be above 12 dB.

At the COBRA Institute, Eindhoven, Netherlands, Martijn Heck and E. Bente have worked on the amplification of picosecond pulses with greatly reduced amplified spontaneous emission compared to a standard semiconductor amplifier (up to 30dB). A large increase in coherent spectral bandwidth is demonstrated in devices that have been fabricated. It can be concluded that the increased spectral broadening, the strongly reduced ASE levels and the compatibility of the fabrication technology, make that the IRIS device is most suitable for integration on a chip in more complex systems where a large optical bandwidth is needed, such as O-CDMA systems.

At the Budapest University of Technology and Economics, Budapest, Hungary, in the group of Tibor Berceli, a research poject is concerned with providing a generally applicable optimization method for harnessing the low-phasenoise microwave–millimeter-wave signal generation capabilities of optoelectronic oscillator (OEO) structures. The gained benefits include the possibility of using inexpensive, commercially available bandpass filters; single-mode operation; equidistant spacing of modes; and total cancellation of spurious content in the output signal. The theoretical ascertainments and simulation data are underlined by numerous experimental results, which were gained through measurements on OEO setups containing one, two, or three parallel connected optical loops. This design method also makes it possible to improve the oscillator's performance, obviating the need for a filter of outstanding performance, ultimately of an unreachably high Q value and low thermal sensitivity.

At ITEAM, Universidad Politécnica de Valencia, Spain the group of J. Capmany in a collaboration with M. Popov from Acreo AB, Sweden and T. Banky of BUTE, Hungary,
have proposed and experimentally demonstrated a very compact technique to perform ultradense WDM (50GHz) generation and detection of Label Swapping channels (10Gb/s Payload and 622Mb/s Label conveyed into a Single Side Band subcarrier at 17GHz). Only two Fibre Bragg Gratings Arrays (three band each) were employed at TRx and RCx nodes. FBG Arrays simultaneously accomplish at the TRx: DWDM multiplexing by interleaving the 100GHz spaced bands to 50GHz, SSB generation and strong rejection of the optical carrier of the label signal and finally combination of Payload and SCM-SSB Label. At the RCx: 50GHz to 100GHz de-interleaving and Payload + SCML-SSB optimum separation for further demultiplexing at standard 100GHz AWGs.

Modelocked semiconductor lasers

At the COBRA Institute in Eindhoven, The Netherlands in work by B. Barbarin, M. Heck and E. Bente report on an extensive characterization of a 15GHz integrated bulk InGaAsP passively modelocked ring laser at 1530 nm. The laser is modelocked for a wide range of amplifier currents and reverse bias voltages on the saturable absorber. They have measured a timing jitter of 7.1 ps (20 kHz – 80 MHz), which is low for an all-active device using bulk material and due to the ring configuration. Measured output pulses are highly chirped, a FWHM bandwidth is obtained of up to 4.5 nm. Such lasers with high bandwidth pulses and compatible with active-passive integration are of great interest for OCDMA applications.

In collaboration between the University of Bristol (J. Pozo and J. Rorison), and the COBRA Institute (Y. Barbarin and E. Bente), bulk InP/InGaAsP 1.5 μm monolithically integrated extended cavity CW lasers have been processed using a Focussed Ion Beam technique to fabricate saturable absorbers in the cavity. In this way they succeeded in producing modelocked laser devices that show improved noise properties with respect to lasers that are of the same length but with a gain material over the full length of the cavity.

Quantum dot theory and devices

Work was done on quantum dot devices at 1.3 micron in a collaboration by the Technische Universität Berlin, Germany, the group of prof Bimberg, Institute of Semiconductor Physics, Novosibirsk, Russia, Institut für Physik, Humboldt Universität zu Berlin. They report on a miniature solid state emitter structure, which allows electrical pumping of only one single InAs quantum dot (QD) grown in the Stranski-Krastanow mode. The emitter demonstrates a strongly monochromatic polarized emission of a single QD exciton. Correlation measurements of the emitted photons show a clear antibunching behavior. The structure is thus attractive for practical implementation as effective single photon source for quantum cryptography.

Also in a collaboration of the group of prof Bimberg in Berlin with the Fachbereich Physik, Universität Duisburg-Essen, Germany, and the Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany a systematic study of the impact of annealing on the electronic properties of single InAs/GaAs quantum dots QDs is performed. Single QD cathodoluminescence spectra are recorded to trace the evolution of one and the same QD over several steps of annealing. A substantial reduction of the excitonic fine-structure splitting upon annealing is observed. In addition, the binding energies of different excitonic complexes change dramatically. The results have been compared to model calculations within 8-band k·p theory and the configuration interaction method, suggesting a change of electron and hole wave function shape and relative position.

Short term missions

A group of short term scientific missions is in preparation for June 2007 concerning the investigation of effects of feedback on modelocked quantum dot lasers.

Round-Robin exercise

For a Round-Robin exercise 1.3 micron quantum dot modelocked lasers have been acquired. There are two packaged devices and ten devices on a submount. Six partners have registered to take part in this exercise. Next to standard characterisation using the established techniques such as auto-correlation, spectral measurements and phase-noise measurements using an RF analyser, attention will be given optical feedback on passively modelocked devices to reduce jitter. This is on the basis of varying reports from several researchers that have worked with similar devices. A special workshop is currently in preparation to perform experiments in this area in the laboratory involving a group of researchers from the Round-Robin partners. This is planned for June 2007 at the COBRA institute in Eindhoven.

WG3-Year 5

The following institutions and researchers have participated in the COST288 action, especially in the WP3 area, either through contributions at the meetings and workshops.

Single distributed feedback experiments

All optical flip flops as optical memory elements

Since there is an increasing demand for fast networks and switches, the electronic data processing imposes a severe bottleneck and all-optical processing techniques will be required in the future. The group of Prof. Geert Morthier at the University of Ghent, Belgium is working in the design and fabrication of all-optical flip-flops, since they are one of the key components because they can act as temporary memory elements. Although several designs have already been demonstrated in the past, they are often relatively slow or complex to fabricate. Recently, they have demonstrated experimentally fast flip-flop operation in a single DFB laser diode which is one of the standard elements in today’s telecommunication industry. Injecting continuous wave light in the laser diode, a bistability is obtained due to the spatial hole burning effect. They can switch between the two states by using pulses with energies below 200 fJ resulting in flip-flop operation with switching times below 75 ps and repetition rates of up to 2 GHz [56].

Modelling work in Semiconductor Saturable Absorver Mirrors

The group of Prof. Eugene Avrutin at the University of York, United Kingdom is working on the modelling of a Semiconductor Saturable Absorber Mirror utilising the electroabsorption effect in a self-biased stack of extremely shallow quantum wells. The saturation flux and recovery time of the proposed device when operated with picosecond incident pulses has been shown in order to compare very favourably with existing all-optical constructions [57].

Quantum Dot theory and devices

The group of Prof. Bimberg at TU Berlin, Germany, has been working in the design and fabrication of Quantum Dot devices, amongst them are single q-bit emitters, nano-flash memories, ultrafast lasers and amplifiers enabling a wealth of advanced systems [58].

All optical signal processing and clock recovery

Clock recovery is a critical function in digital communication systems. The work of Dr. Ware in the group of Prof. Erasme at GET/Telecom Paris, France, has resulted in the successful extraction of a 10 GHz clock from single-wavelength 160 and 320 Gbps OTDM data streams, using an opto-electronic phase-locked loop based on three-wave mixing in periodically-poled lithium niobate as a phase comparator. [59] In addition, using periodically-poled Lithium Niobate for signal processing at 640 Gbit/s, clock recovery is performed successfully with no pattern dependence and less than 1 dB transmission penalty after 50 km fiber.

Modulation of quantum-well lasers

The group of Prof. Marian Marciniak, at the National Institute of Telecommunications, Poland, is working in the numerical modeling of quantum-well semiconductor lasers in order to study the nonlinear dynamics occurring due to current modulation and the tuning of the generation frequency within the gain band. It has been examined the sweeping of the “instantaneous” frequency of radiation connected with the change in the refractive index of the active medium resulted from variations of the non-equilibrium current carrier concentration. Conditionally one can determine limit cases of rather low and high frequencies of current modulation were the sweeping of the radiation frequency approaches to zero. Maximum values (» 1 000 GHz) of the sweeping at emitting of the impulse reach in the intermediate range of the modulation frequencies. They have concluded that the principal features of changes in the sweeping value within the gain band correspond practically to the form of the envelope of the variable component of the laser response [60].

Optical interconnects

The group of Prof. Marciniak is also working on chip and chip-to-chip galvanic links replacement by optical interconnects. The compatibility of optical interconnects with existing CMOS technology has been addressed. In addition, an optical model of a transmission-type vertical-cavity electro-absorption modulator (EA) on Si/SiO2 for high speed intra/inter-chip interconnects has been developed and analyzed by the method of single expression (MSE). As an external radiation source a wideband light source is suggested for avoiding the problem of usage of Si emitter. Transmission properties of symmetrical structure of a modulator consisting of Si p-n junction embedded between Si/SiO2 DBRs have been analysed versus the values of imaginary part of p-n junction permittivity. Corresponding distributions of electric field amplitude and power flow density along the structure and surrounding half-spaces have been presented for high and low transmission state. The transparency of the structure permits to have a cascade of modulators which can be installed in special trunks on chips for connection between different layers of an integrated circuit.

Micro-ring resonators

Finally Prof. Marciniak's group is working towards in the field of micro-ring resonators. They have proposed a novel concept of image converter from an infrared range into a visible range of electromagnetic waves by the use of waveguide resonator structures of a micron size as a sensitive element. Their method is based on the modulation of the resonator proper equidistant spectrum under the influence of the external electromagnetic radiation of the infrared spectral range, which changes the optical properties of the sensitive element material. The structure and principles of operation of the matrix converter of infrared images into visible ones on the base of a matrix of the waveguide micro-ring resonators have been investigated. It is shown that sensitivity of such converter to the variation of infrared radiation power can be as low as 2.6·10−12 W.

Short Term Scientific Missions

A group of experts formed by Mr Nikolaos Vogiatzis (University of Bristol, United Kingdom), Mr Stephan Breuer (TU Darmstadt, Germany), Prof. John McInerney (University College Cork, Ireland) and Mr. Asier Villafranca (University of Zaragoza, Spain) gathered for a week at the TU Eindhoven hosted by Dr. Jose Pozo (STSMs #31-34). Their goal was to continue the investigation carried out in June 2007 (STSMs #24-27). They focused on extended amplitude and timing jitter characterization of packaged QD laser modules subject to optical feedback. For the timing jitter analysis, a direct detection setup was applied consisting of a high-speed photodetector and an electrical broadband spectrum analyser. Significant improvement of the stability of the carrier sidebands was observed.

6. DISSEMINATION OF RESULTS

YEAR 1

6.1 Publications and Reports

07 (+ 20 Additional publications)

6.2 Conferences and Workshops

The opening meeting was held in Brussels April 7 where members were elected, WG structures discussed and groups introduced. A second MC and WG meetings were held in Turin, 17,18 September where further introductions and strategies were decided. It was planned to hold a GaInNAs workshop in Turkey in September 2004, (jointly funded by Turkish Government) but due to illness of WP1 Chair and the political climate this has been postponed. The joint meeting was planned for September/October in Rome with COST P11.

6.3 Web site

The Website of COST 288 is situated at the University of Bristol and is maintained by Jose Pozo. Currently the site is fully open to the public but a section accessible to only COST members will be implemented shortly so that pre-publication results and round-robin measurements can be exchanged. There is a general section and WP sections and each participant has links to their own website.

6.4 Scientific and Technical Co-operation

Cost 288 is closely related to COST action P11 on the Physics of Photonic Bandgap (PBG) Structures. Many groups are members of both actions. It is envisioned that COST P11 will investigate the basic physics and then COST 288 will incorporate PBGs into active devices (WP1 and WP2). The actions plan to hold a joint meeting in Rome in September/October 2004.

There will be close interactions with a new COST action on the Digital Optical Networks which will link closely with WP3 on systems implementations. A joint meeting with OPTIMIST and EPIC was held in Athens June 2004 where related FW 5 and 6 projects gave overviews.

6.5 Transfer of results

A joint meeting with OPTIMIST and EPIC was held in Athens June 2004 where related FW 5 and 6 projects gave overviews.

It is anticipated that there will be future interactions with other actions and with standardisation bodies as the project develops.

Year 2

6.1 **Publications and Reports**

15 (+ 3 additional publications) + Appendix 1A

6.2 **Conferences and Workshops**

A joint meeting was held 18-20 October 2004 in Rome with COST P11 which contained a workshop. A PHASE workshop was held in Metz in March 29-30 2005 immediately followed, 31 March-April 1 2005, by COST 288 and COST P11 meetings.

6.3 **Web site**

The Website of COST 288 is situated at the University of Bristol and has been maintained by Jose Pozo. Currently this site is fully open to the public.A section accessible to only COST members has been implemented by Dr. Bente so that pre-publication results and round-robin measurements can be exchanged-the Wikki site

6.4 **Scientific and Technical Co-operation**

Cost 288 is closely related to COST action P11 on the Physics of Photonic Bandgap (PBG) Structures. Many groups are members of both actions. It is envisioned that COST P11 will investigate the basic physics and then COST 288 will incorporate PBGs into active devices (WP2). The actions held 2 joint meeting last year.

There will be close interactions with a new COST action on the Digital Optical Networks which will link closely with WP3 on systems implementations.

It is planned to hold a world-wide Ultrafast meeting with the Japanese FESTA programme and the US and UK (Ultrafast Physics Consortium) followed by a COST 288 meeting in St Andrews Scotland August 2005.

6.5 **Transfer of results**.

PHASE workshop and special issue of OQE journal

M. Sciamanna (LMOPS CNRS UMR-7132, Supélec, France) and K. Panajotov (Vrije Universiteit Brussel, Belgium) have co-chaired the international workshop called PHASE (PHysics and Applications of SEmiconductor LASERs), held in Metz (France) on March 29-30, 2005 and followed by a two-day meeting of COST 288 and COST P11 actions. The workshop was financially partially supported by COST 288. The workshop has been a great success, with 4 invited talks by keynote speakers (including two US speakers), more than 30 oral contributions and 25 poster contributions. One page abstracts have been published in a technical digest and full-length contributions can be submitted to a special issue of the international journal "Optical and Quantum Electronics" (Springer-Verlag) for which M.

Sciamanna and K. Panajotov will act as guest editors. Both the technical digest and the special issue of a journal are thought to greatly contribute to the publicity of COST 288 collaborative results

It is anticipated that there will be future interactions with other actions and with standardisation bodies as the project develops.

Year 3

6.1 **Publications and Reports**

33 (+26 additional publications) + Appendix 1B

6.2 **Conferences and Workshops**

A joint meeting was held August 1,2 with the FESTA (Japan) USA and UPC (UK) Ultrafast Photonics groups at St. Andrews, UK followed by a COST 288 MC and WG meetings on August 3,4.. A second MC and WG meetings were held in Crete, February 2, 3 to focus on round-robin measurements and exchange of results. The third meeting is about to be held in Nottingham June 22/23. This meeting will follow the ICTON conference held June 19-22 in which COST 288 is very active and is partially sponsoring a session.COST 291 and COST P11 will also be involved with the ICTON meeting fostering exchange of ideas.

6.3 **Web site**

The Website of COST 288 is situated at the University of Bristol and has been maintained by Jose Pozo. Currently this site is fully open to the public.A section accessible to only COST members has been implemented and maintained by Dr. Bente (WG3) so that pre-publication results and round-robin measurements can be exchanged-the Wikki site

6.4 **Scientific and Technical Co-operation**

COST P11 and COST 291 will meet at the ICTON conference June 18-22 2006 held in Nottingham.

6.5 Transfer of results.

The PHASE workshop and special issue of OQE journal has now been published.

Year 4

6.1 **Publications and Reports**

0 (+ 21 additonal publications) + Appendix 1C + Appendix 2(I)

6.2 **Conferences and Workshops**

A COST 288 working group and management committee meeting was held October 5,6 2006 in Vilnius Lithuania. This meeting focussed on round-robin measurements and the exchange of results. A second set of MC and WG meetings was held in Metz, March 26,27 2007 immediately after a PHASE Workshop/ Conference which also involved COST P11 and was organised by COST 288 WG2..

6.3 **Web site**

The Website of COST 288 is situated at the University of Bristol and has been maintained by Jose Pozo. Currently this site is fully open to the public.A section accessible to only COST members has been implemented and maintained by Dr. Bente (WG3) so that pre-publication results and round-robin measurements can be exchanged-the Wikki site

6.4 **Scientific and Technical Co-operation**

COST P11 and COST 291 met at the Phase Workshop/Conference at Metz.

Drs Rorison, Balkan and Saarinen were chairs of an EMRS session on Novel Gain III-N-V materials at the EMRS meeting held in June 2007 in Strasbourg.

6.5 Transfer of results.

The PHASE workshop and special issue of OQE journal from the Metz meeting is in preparation.

Year 5

6.1 **Publications and Reports**

5 (+ 23 additonal publications) + Appendix 1D + Appendix 1E + Appendix 2(II)

6.2 **Conferences and Workshops**

A COST 288 working group and management committee meeting was held July 5,6 2007 in Rome, Italy. This meeting followed the ICTON conference held July1-5 2007 in which COST 288 is very active, chairing and organising the NAON workshop. COST P11 and COST 291 also held meetings at the ICTON meeting which allowed the COST actions to exchange discussion. A second set of working group and management committee meeting was held at Zaragoza, Spain October 15-16 October 2007. At this meeting the details for the COST training school were finalised. The Training school was held in Centraro, Italy 18-22 May 2008 and was a great success with International lecturers and 40 students attending. This was followed by the COST final meeting and final review.

6.3 **Web site**

The Website of COST 288 is situated at the University of Bristol and has been maintained by Jose Pozo (years 1-4) and Nikos Vogiatzis (year 5). It has been re-organised so that all publically accessible information is readily available. The invited talks from the training school are password protected for access for the lectures, students and COST 288 members.Pre-publication results and round-robin measurements can be exchanged using the the Wikki site

6.4 **Scientific and Technical Co-operation**

COST P11 and COST 291 met at the ICTON meeting in July in Rome.

6.5 Transfer of results.

The PHASE workshop and special issue of OQE journal from the Metz meeting is about to come out.Discussion is on-going about a final book for the action.

7. ECONOMIC DIMENSION

Estimated number of signatories:	50

Cost (kECU) per signatory per year:

Estimated nr. Person years per year and signatory involved in action	2
Estimated cost/personyear (average of engineer/student) (this would include Lab. overhead etc.)	40 kEuro
Materials, equipment, computing, consumables	60 kEuro
Travel	10 kEuro
Short term missions, additional costs	10 kEuro
Average Cost per signatory per year:	160 kEuro

Economic dimension:

Total over 4 years for all signatories (1 decimal)	32.0 MEuro
+ 10% overhead for running/operational costs	3.2 MEuro
Total cost to national funds	---- MEuro
EU overhead (over 4 years) _90_kECU	0.09 MEuro
Total Economic Dimension:	35.3 MEuro

Budget:

Year 1

Prior to Split:

Brussels: Travel Expenses	12,000 (estimate)	Euros	(paid by COST centrally)
Turin Meeting: Travel Expenses	18,000	Euros	(paid by COST centrally)

Post–split :

(1)	SECRETARIAT	**3,000**	**Euros**
(2)	WORKSHOPS AND SEMINARS	**0**	**Euros**
(3)	MEETINGS (Athens)	**29,000 (estimate)**	**Euros**
(4)	SHORT-TERM SCIENTIFIC MISSIONS (4)	**8,000 (estimate)**	**Euros**
(5)	PUBLICATIONS SEPARATE	**0**	**Euros**
(6)	Other: (Dr. Rorison trip to Brussels to meet Afonso Ferreira)	**300**	**Euros**
(6)	**TOTAL**	**40,300**	**Euros**

Year 2

(1)	SECRETARIAT	**EURO**	**10,000**
(2)	WORKSHOPS AND SEMINARS (Metz)	**EURO**	**5,000**
(3)	MEETINGS Rome (16,785 Euros) Metz (16,624 Euros)	**EURO**	**33,409,-**
(4)	SHORT-TERM SCIENTIFIC MISSIONS	**EURO**	**11,395,-**
(5)	PUBLICATIONS SEPARATE	**EURO**	**0**
(6)	Other	**EURO**	**0,-**
(7)	**TOTAL**	**EURO**	**59,804**

Year 3

(1)	SECRETARIAT	**EURO**	**12,600**
(2)	WORKSHOPS AND SEMINARS (Nottingham,Crete)	**EURO**	**8,461**
(3)	MEETINGS St Andrews (14, 727 Euros) Crete (14, 073 Euros) Nottingham (15,237 Euros)		
		EURO	**44,038**
(4)	SHORT-TERM SCIENTIFIC MISSIONS	**EURO**	**10,900**
(5)	PUBLICATIONS SEPARATE	**EURO**	**0**
(6)	Other		
	Devices :2 Pig-tailed QDot Mode locked lasers from NL Semiconductor		**5,000**
	Devices:2 DFB lasers for round-robin activity		**1,500**
	Dr. Rorison trip to Brussels for TIST review October 2005	**EURO**	**686**
(7)	**TOTAL**	**EURO**	**83,185.35**

Year 4

(1)	SECRETARIAT	**EURO**	**8,959.80**
(2)	WORKSHOPS AND SEMINARS (Metz)	**EURO**	**7,307.26**
(3)	MEETINGS Vilnius (17, 044.82 Euros) Metz (17,583,08 Euros)		
		EURO	**34,627.90**
(4)	SHORT-TERM SCIENTIFIC MISSIONS	**EURO**	**16,703.81**
(5)	PUBLICATIONS SEPARATE	**EURO**	**0**
(6)	Other: Dr. Rorison trip to Helsinki for TIST review Nov 2006	**EURO**	**1,093.04**

(7)	**TOTAL**	**EURO**	**68,691.81**

Year 5

(1)	SECRETARIAT	**EURO**	**10,559.18**
(2)	WORKSHOPS AND SEMINARS (Metz)	**EURO**	**866.00**
(3)	MEETINGS Rome (10,914.01 Euros) Zarogoza (15,067.76 Euros) Centraro (9,957.79 Euros)		
		EURO	**35,939.56**
(4)	SHORT-TERM SCIENTIFIC MISSIONS	**EURO**	**6,884.39**
(5)	PUBLICATIONS SEPARATE	**EURO**	**3,000.00**
(6)	Other: Training School	**EURO**	**23,452.00**
(7)	**TOTAL**	**EURO**	**80,953.73**

8. SELF-EVALUATION

COST 288 started in April 2003 and ended May 2008 after being awarded a 12 month extension to enable the action to fully examine quantum dot multi-section laser devices.

The original aim of the action was to investigate sub-wavelength scale feature size for optical confinement and control and nanoscale carrier confinement for novel opto-electronic devices for photonic devices for communication devices at the 1.3 and 1.5 micron wavelength ranges. The action was divided into 3 Working Groups:

- WG1: *Novel Gain Materials and Fabrication Techniques*,
- WG2: *Photonic Devices*
- WG3: *Ultrafast and Non-linear Photonic Devices*.

Obviously this was a very broad remit and during the first year it was honed down to consider quantum well (QW) and quantum dot (QD) carrier confinement in InGaNAs/GaAs and GaInAsP/InP QWs and InAs/GaAs QDs in WG1. The fabrication and physics of photonic crystal structures was considered in detail in COST P11 so was removed from WG1 in this action. The optical physics of edge-emitters and VCSELs in these devices plus GaAs VCSELs was considered in WG2 .The influence of photonic crystal structures in VCSELs and edge-emitting devices was considered within this WG. The influence of these devices under optical feedback was considered in detail. In WG3 standard GaInAsP devices were investigated initially and then the novel devices of WG1, were considered particularly for short pulse generation through mode-locking. Ring lasers were also considered. In WG3 modelling was originally considered and then experimental work was done.

The action had a large number (34) of 2 and 3 centre STSMs and had two large round robin-STSM activities: one on the alpha factor of devices (coordinated by Guido Giuliani-involving 7 STSMs) and the other on QD multi-section devices for mode-locking (coordinated by Erwin Bente –involving 8 STSMs). Two Phase Conference/Workshop meeting were organised in Metz hosted by Marc Sciamanna and a Training school and Final Review was organised in Italy in May 2008. In addition COST 288 was involved in coordinating several workshops: the NAON workshop at the ICTON conference series from 2005-2008 and a Novel Gain III-N-V materials symposium at the EMRS meeting Strasbourg in 2007. COST 288 was the European representative at a US-Japan-UK-EU meeting held in St Andrews Scotland, August 2005 on Photonics. Journal publications resulted from the 2 Phase meetings and a joint CLEO-US and CLEO-Europe presentation as made on the alpha-factor round robin. In general there were a large number of COST activated joint partner publications. COST 288 had significant interactions with COST P11 (having a shared meeting in Rome in 2004) and COST 291 (sharing meeting locations at the ICTON conferences).A joint meeting with OPTIMIST and EPIC was held in Athens June 2004 where related FW 5 and 6 projects gave overviews.

The action management originally had the structure of a general chair and vice chair of the action and the same for each WG. At the mid-term review the management was enlarged so that for each vice chair position was enlarged into 2 vice-chairs. The second vice chairs were young researchers who had been active in the action. The young researchers in management positions were: Dr. Guido Giuliani, the Vice chair of the action, Dr. Mikka Saarinen, the Vice Chair of WG1: Dr. Marc Sciamanna, the Vice Chair of WG2, Dr. Cedric Ware the Vice Chair of WG3. These young researchers became very active in the action with Guido Giuliani organising the alpha factor round robin, Mikka Saarinen organising device coordination in WG1, and both Marc Sciamanna and Cedric Ware putting organisational input into WGs 2 and 3 respectively.

Several EU projects were assisted by COST 288: FastDots (successful-Strep), EuroDots (a finalist but un-successful integrated project). Two new COST proposals have been invited to submit into the second phase: one on wavelength tunable gain media (from WG1) and the other on dynamics in lasers (from WG2). These proposals are entitled, “Gain materials and Devices based on III-N-V Compunds”, coordinated by Dr. Naci Balkan from Essex (WG1) and “Mastering Nonlinear effects in Semiconductor Light Sources”, coordinated by Dr. Stephane Barland from Nice (WG2). There has been interaction with a number of SMEs: Exalos: investigating QDot LEDs for broad band emission and Innolume on QDot lasers.

Summary

Overall the action was a success with many European groups meeting through COST 288 and continuing their interaction. Of particular success was the interaction of young researchers and their strong role within the action. The focus on quantum dot nanoscale materials was very ahead of its time and the pull-through of these devices from the exploratory physics in WG1 to the systems in WG3 through the mode-locked activity has been a successful highlight. The alpha factor study was also a success with the renewed interest in alpha-factors with the advent of QD devices with their tunable alpha-factors.

Some particular high-lights and World-class results:

- QD for broad-band gain and multi-wavelength lasing and unusual alpha factors

- Studies of Optical feedback in VCSELs with variable external cavity lengths and under different conditions: exploring the range of dynamics possible
- Modelling active media and design for short pulse generation in mode locking
- Experimental Analysis of mode-locking in QDot multi-section devices

The area of this action was very fundamental and this action will have helped to yield qualified researchers with a deep physical understanding of how the physics links with the devices and the systems which will be required for: photonic devices and systems for the future, for novel optical devices for medical and photo-voltaic applications and other applications.

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APPENDIX 1

THE ALPHA-FACTOR ROUND ROBIN-headed by WG2

APPENDIX 1A

Linewidth Enhancement Factor in Semiconductor Lasers

Review and action proposal

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Motivation – This document presents a short review about the linewidth enhancement factor in semiconductor lasers, with the aim of stimulating discussions and/or action proposals within the WG2 of COST 288.

Summary

1. INTRODUCTION

The linewidth enhancement factor (LEF), also known as α–factor, has a great importance for semiconductor lasers (SLs), as it is one of the main features that distinguishes the behavior of SLs with respect to other types of lasers. The α–factor influences several fundamental aspects of SLs, such as the linewidth, the chirp under current modulation, the mode stability, the occurrence of filamentation in broad–area devices. In synthesis, the dynamics of SLs is greatly influenced by the α–factor, which is of particular interest for the study of injection phenomena, optical feedback effects, and mode coupling as occurring in VCSELs.

2. HISTORICAL PERSPECTIVE

The birth of the α–factor traces back to the early '80s, when first measurements revealed that the SL linewidth was much broader than what predicted by the Shawlow–Townes theory [1981-01]. A theoretical explanation soon came from Henry [1982-02], who developed a theory that ascribes the excess linewidth to the joint action of spontaneous emission events and population inversion (i.e. carrier) relaxation, through the mechanism of index–gain coupling. The latter represents the fact that in a semiconductor medium both the optical gain and the refractive index depend on the actual carrier density. Since then, a number of theoretical and experimental works were carried out, with the aim of calculating the dependence of the α–factor on SL material parameters, and measuring its value in practical devices. An exhaustive review of the early works was presented by Osinski and Buus [1987-03]. Up to now, relevant evolution occurred in the SL field, namely with the appearance of new types of lasers and structures (VCSELs, Quantum Cascade, Complex–Coupled DFB [1992-07], slotted lasers), the advent of new materials (Quantum Dots, Quantum Dash, InGaNAs/GaAs InGaAs/InAlGaAs, long–wavelength InAsSb and InAs/GaInSb [2000-01]), and a growing interest for SL dynamics.

3. THEORY

The α–factor is defined as the ration of the partial derivatives of the real and complex parts of the complex susceptibility $\chi = \chi_r + i\chi_i$ with respect to carrier density N:

$$\alpha = -\frac{\partial \chi_r / \partial N}{\partial \chi_i / \partial N} = -\frac{4\pi}{\lambda} \cdot \frac{dn}{dg} \quad (1)$$

where dn and dg are the small index and optical gain variations that occur for a carrier density variation dN. According to the definition, theoretical models describing the optical properties of the semiconductor medium were used to numerically evaluate the α–factor by calculating the differential gain and differential refractive index [1983-02]. More accurate models also take into account the effect of free carriers. In a linear approximation, only one among the spectral dependence of the differential gain and differential refractive index shall be calculated, as the other can be obtained through Kramers–Kronig transformations [1984-01]. Estimated/measured values for α lie in the range 0.5–8.0, with more common values in the range 2.0–6.0. Typically, α increases for decreasing photon energy and for increasing carrier density [1987-03]. The analysis of different material reveals that, generally, the α–factor is smaller in MQW than in bulk, and it is even further reduced in strained materials [1989-04, 1990-01,1994-04, 1994-05, 1993-01], Q–Wires [2001- 05] and Q–Dots [1999-03]. Also, novel materials such as InGaNAs/GaAs are very promising for having α values around unity [2003-01].
Some authors [1984-03, 1987-01, 1989-02, 1990-02, 1993-03, 1996-01] suggested that non–linear gain and/or carrier heating should have a non negligible effect on α, which in turn should be considered as an optical power dependent parameter (the effective α should increase with increasing power, and deviation from linearity should occur for Pout ≈ 10 mW [1989-02, 1990-02]). Some authors also attribute the effect of high power linewidth floor/rebroadening to the power dependence of α, while others suggested different mechanisms [1983-03, 1983-04]. As a matter of fact, at present no clear experimental and systematic evidence of the power dependence of the α–factor has been reported. In fact, as it will be clear from section 4, the different measurements techniques have not yet proved capable of elucidating this point further. By considering the SL dynamics in its generality, it could be said intuitively that there is a "material" linewidth enhancement factor, which is typical of the semiconductor medium and its value can be measured by the sub–threshold spontaneous emission technique (i.e., the Hakki–Paoli method described in section 4.1). Besides this, there exists a "device" linewidth enhancement factor which is typical of the specific laser under study, and depends on non–linear phenomena, non–uniform carrier density and on loading effects caused by the laser cavity [1984-04,1985-01,1985-02, 1985-03, 1990-06, 1990-07, 1990-08, 1990-10, 1992-07, 1993-05, 1993-06, 1993-07,1994-02,1998-01].

4. MEASUREMENT TECHNIQUES

According to the above definition, measurements techniques can broadly be classified as: 1) techniques capable to measure the "material" linewidth enhancement factor; 2) methods capable to measure the "device" LEF. Methods of class 1 are based on sub–threshold gain / refractive index measurements, and their results might not be closely matched to the behavior of lasers in operating conditions. Conversely, class 2 methods perform the measurement above threshold, and can account for more complex effects. Throughout the scientific literature about linewidth enhancement factor (far more than 100 papers on refereed international journals), no systematic comparison of measurement results obtained from different methods on the same devices has been carried out. Only a few works [1991-07,1994-03, 1994-04, 2001-01] report the comparison between two methods. So, little progress on this point has been gained since the Osinski and Buus review [1987-03], which concluded saying "... thus far no attempts have been made to measure α on the same laser by different methods. Such measurements are likely to provide significant information both on the actual α value and on the relative merits of the various methods". It should be pointed out that not all methods are applicable to all types of SL devices. For example, the common "Hakki–Paoli" method (section 4.1) cannot be applied to VCSELs for the absence of multiple longitudinal modes, and to date no method has been applied to measure the α–factor in Quantum–Cascade SLs, and only a few reports are available about the α–factor of external cavity semiconductor lasers [2000- 03].
It follows here a brief review of different measurement methods for the linewidth enhancement factor proposed and demonstrated in the scientific literature. For each method, advantages and drawbacks are listed, from the point of view of simplicity of the experimental arrangement and accuracy.

4.1 ASE–gain spectrum + Fabry–Perot frequency shift ("Hakki–Paoli" method)

This technique (conventionally called the "Hakki–Paoli" or H–P method) [1983-05, 1985-05] relies on direct measurement of dg and dn as the carrier density is varied by an unknown amount dN by slightly changing the current of a SL in sub–threshold operation. The measurement is performed using a monochromator–based optical spectrum analyzer. The quantity dn is measured through detection of the frequency shift of longitudinal Fabry–Perot mode resonances, while dg is obtained via the Hakki–Paoli method by measuring the fringe contrast (Peak to valley ratio) of the amplified spontaneous emission filtered by the Fabry–Perot cavity [1975-01].
This method is the most common in investigations about α–factor, it is of straightforward implementation, and it can be

easily automated via computer–controlled procedure. Critical points concern the resolution of the spectrum analyzer for the case of closely spaced longitudinal modes, and the fact that the thermal peakshift drift occurring in CW measurements shall be subtracted to reveal the net carrier effect. This is a sub–threshold technique, and it measures the "material" linewidth enhancement factor as a function of injected current and photon energy (while the exact carrier density must be evaluated by other techniques). Hence, there is no chance to measure the possible dependence of α on optical power. It should be noted that this technique and the following (4.2) one are the only that allow to measure α at different photon energies, because methods in which the laser is operated above threshold only give information about α at the lasing wavelength.
This technique cannot be applied to VCSELs, because these devices have one single longitudinal mode beneath the useful gain bandwidth. It is also difficult to be applied to edge–emitting devices with AR–coated facets (such as some DFBs) due to reduced fringe contrast, and to complex–coupled DFBs [1998-01]. The accuracy of the method is generally good.

4.2 Gain spectrum + Kramers–Kronig
Another (typically sub–threshold) technique that measures the "material" linewidth enhancement factor as a function of photon energy and injected current is based on accurate gain spectral measurements as a function of the injected carrier density, from which the spectral differential gain can be obtained. Subsequently, Kramers–Kronig relations allow to retrieve the differential refractive index and the calculation of α [1981-02]. The gain spectrum is typically measured from sub–threshold "pure" spontaneous emission spectra, that must be collected without the effect of cavity amplified spontaneous emission. Hence, light cannot be collected from the output facet of edge–emitting devices, and windows opening must be purposely fabricated on the top or the side of devices [1991-09, 1995-03]. Otherwise, direct measurement of the differential gain can be obtained by ultrafast pump–probe techniques [1994-01]. This method is generally complex, as it involves some experimental difficulties and relevant post–processing of collected data. Its accuracy is moderate.

4.3 Linewidth
According to Henry theory, the α–factor directly influences the linewidth Δν of a SL, and hence linewidth measurements could give information about α. The theoretical linewidth formula reads:

$$\Delta\nu = -\frac{v_g \cdot h\nu \cdot g_{th} \cdot n_{sp} \cdot \alpha_m}{8\pi \cdot P} \cdot \left(1+\alpha^2\right) + \Delta\nu_0 \quad (2)$$

where v_g is group velocity, g_{th} is threshold gain, n_{sp} is the spontaneous emission factor, α_m is mirror loss, P is the output power per facet, and $\Delta\nu_0$ is a power independent linewidth term. In linewidth methods [1992-01, 1992-06] the SL linewidth is typically measured as function of emitted power, and the slope of Δν vs. inverse power is used to compute the linewidth enhancement factor using eq. (2). Obviously, the accuracy of this method is greatly influenced by the degree of accuracy that affects the knowledge of other device parameter that appear in eq. (2). In particular, "difficult" parameters are the spontaneous emission rate (included in n_{sp}) and the internal losses α_{int}. Knowledge of the above parameters usually require a thorough characterization of the specific device under test, together with the knowledge of some fabrication parameters (such as facets reflectivities). Hence, this method is hardly applicable to commercial SLs, or to "black box" devices.
This technique has been often used to measure the α–factor of VCSELs [1992-06, 1994-04, 1995-01].
The method is of general straightforward implementation, but its accuracy has to be regarded as poor, due to the above mentioned complex dependence of Δν on several parameters.

4.4 FM/AM modulation
This method [1983-01, 1985-06] relies on high–frequency SL current modulation which, according to theory, generates both amplitude (AM) and optical frequency (FM) modulation. The ratio of the FM over AM components gives a direct measurement of the linewidth enhancement factor. The AM term can be measured by direct detection via a high speed photodiode, while the FM term is related to sidebands intensity that can be measured using a high resolution Fabry–Perot filter. This technique allows the measurement of the "device" α–factor, it can be applied to all types of SLs, and it has been often deployed to characterize VCSELs [1994-04, 1995-02, 1996-02, 2001-04, 2004-01].
The modulation frequency f_{mod} must be larger than the laser relaxation frequency (f_R), because for $f_{mod} < f_R$ the FM/AM ratio is frequency dependent [1988-03, 1995-02, 1996-02, 2001-04]. This fact poses some experimental difficulties for devices with high f_R, requiring very high–speed RF generators and instrumentation.
This method is reliable in the hypothesis that the susceptibility is linear and the carrier density is longitudinally uniform [1984-02], and apart from the above mentioned frequency dependence, has a good accuracy. A modified method is based on the measurement of the chirp of light pulses emitted under large signal modulation [1987-03,1997-04]. This technique is useful for assessing the real performance of a SL when application to practical telecommunication system is of importance. However, its accuracy for the determination of the α–factor is only moderate.

4.5 FM/AM noise
Based on the same theoretical principle of the FM/AM modulation, the FM/AM noise method [1984-02, 1985-04] relies

on measurement of the phase correlation and the ratio between the spectral dependence of SL FM noise and AM excess noise. The AM noise can be measured by usual techniques (direct detection + RF spectrum analysis), while FM noise has to be measured by Fabry–Perot filters or other techniques. This method is of complex experimental implementation, but does not require active current modulation. Its accuracy is moderate.

4.6 Injection Locking

Injection of light from a master SL into a slave SL causes locking of the slave optical oscillation frequency to that of the master. Typically, the locking region is characterized in terms of the injection level and frequency detuning, showing an asymmetry in frequency due to the non–zero α–factor. Several methods have been presented for the measurement of the α–factor based on injection locking experiments [1990-11, 1991-02, 2001-01, 2003-02].

These methods are capable of giving the effective value for α in operating conditions, and are based on the complex theory of injection locking dynamics, that can however be simplified to give the analytic dependence of measurable quantities (such as asymmetric detuning range) on α–factor. These methods can be divided into two classes: 1) methods requiring the measurement of the injection level, and 2) methods that do not require the knowledge of injection level. An accurate measurement of the effective injection level is generally difficult, because there always exists a mode profile mismatch between the master beam projected onto the slave laser facet and the slave guided mode. Such mismatch can reduce the effective injection to a value that is 10% to 50% of the total facet power. As a consequence, the accuracy of methods requiring the measurement of the injection level is poor, while class 1 methods can have a good or moderate accuracy.

These techniques are of complicated experimental realization, and have mainly been tested with DFB laser. The applicability to Fabry-Perot lasers and VCSELs is still to be investigated.

4.7 Optical Feedback

Similarly to injection phenomena, the behavior of SL subjected to optical feedback exhibits some dependence on the actual value of the linewidth enhancement factor, and hence the α value can be determined from such experiments [1989-01, 2000-03]. Most of the theoretical analysis of the dynamics and properties of SL in presence of feedback are based on the well–known Lang–Kobayashi (L–K) equations [1980-01]. In early works, experimental observations on SL with optical feedback have been compared to theoretical results, and the linewidth enhancement factor was used as fitting parameter to achieve agreement between experiment and theory. The determination of the value of the α–factor was often an additional outcome, as these works were not mainly focussed on this point. Similarly to injection methods, the measurement of α is less accurate where the knowledge of the effective feedback level is required. An optical feedback method purposely devoted to the measurement of the α–factor was presented recently [2004-02] based on the so–called self–mixing interferometry. According to the L–K theory, α is determined from the measurement of specific parameters of the resulting interferometric waveform, without the need for the measurement of feedback level.

Optical feedback methods offer different experimental complexities, depending on the specific feature of the SL subjected to feedback that is measured to determine α. The measured value for α is the effective value in operating conditions, and non–linear effects could be revealed at high power. However, this point shall be carefully checked because non–linearities should possibly be included also in the L–K model [1997-01]. As a rule of thumb, methods requiring the knowledge of the feedback level have a poor accuracy, while methods that are independent from this parameter are more accurate.

4.8 SOA devices

Semiconductor Optical Amplifiers (SOAs) represent another type of active semiconductor devices that are affected by the non–zero value of the linewidth enhancement factor. Measurements of α–factor in SOAs have been carried out with methods that are similar in principle to the H–P technique. SOAs allow for higher injected carrier densities, and hence the α–factor can be characterized over an extended range of this parameter.

The more accurate technique [1991-01, 1992-04] relies on the measurement of dn via an interferometer that includes the SOA in one arm, and on dg evaluation via chip gain measurement. The accuracy of this method is good, and the results are related to the "material" α.

5. OPEN ISSUES

As it is clear from the analysis of published results, the great interest in the value of the linewidth enhancement factor in SLs is not supported by sufficient investigation about the consistency of different measurement methods, and about the agreement between measured α values and actual device dynamical behavior.

Concerning the experiments/theory agreement, this seems generally good when results obtained by the Hakki–Paoli methods are compared with theoretical calculations of the wavelength dependence of α. However, this agreement about the "material" α–factor might give poor information regarding the actual agreement between theory and experiments when laser dynamics is concerned, i.e. when the "device" α– factor is of importance.

Open issues concerning the linewidth enhancement factor could be summarized as follows.

- **Comparison between different experimental methods for the measurement of the α–factor**

  A thorough comparison between α measurements on the same devices using different methods has not yet been carried out.

A “standard method” for the measurement of the linewidth enhancement factor has not been defined to date. A good candidate could to be the AM/FM method (4.4), but a simpler and more versatile technique would be advisable.

Consistency between measured α–factors and the degree of agreement between experimental and theoretical predictions for SL dynamics more complicated than the simple FM/AM modulations has to be evaluated.

- **Dependence of α–factor on optical power**

It is not yet clear whether the predicted dependence of the linewidth enhancement factor on optical power in a SL has been experimentally verified [1991-02]. Experiments reporting linewidth floor/rebroadening do not seem to be decisive in assessing the α dependence on emitted power. Effects on SL dynamics caused by non–linear α–factor have to be evaluated experimentally and theoretically

6. POSSIBLE COST 288–WG2 ACTIONS

Some actions could be carried out within COST 288 – WG2 with the aim to clarify some of the previously explained open issues, as well as to provide interested members with experimental/theoretical support about the α–factor issues.

- **Round–Robin test measurements on linewidth enhancement factor**

A Round–Robin test measurement could be activated with the aim to compare different measurement methods for the α–factor on different devices types.

Measurements methods could include:

  - the H–P method (4.1) or gain spectrum method (4.2)
  - the FM/AM method
  - the self–mixing optical feedback method (4.7)
  - other methods

Devices under test can include:

  - Fabry–Perot lasers emitting at different wavelengths (from visible to third window)
  - DFB lasers (possibly with different detuning of the Bragg grating with respect to peak material gain)
  - VCSELs
  - Quantum–Dots / Quantum–Dash lasers
  - New material lasers (InGaNAs/GaAs, InGaAs/InAlGaAs)
  - A specific method could be applied to investigate the α–factor value in Quantum Cascade lasers

- **Experimental/Theoretical investigation about the dependence of α–factor on optical power**

Besides, or within the Round–Robin test, experimental investigations could be directed at determining the dependence of the linewidth enhancement factor on the emitted power, through a suitable experimental method.

Theoretical analyses could be developed.

- **Consistency of measured α–factor with experimental/theoretical SL dynamics**

The effectiveness of the measured α–factor values should be evaluated with respect to the agreement between theoretical/experimental results on SL dynamics (i.e., optical injection, optical feedback, mode coupling in VCSELs, etc.).

The effective prediction capabilities of the Lang–Kobayashi model could be tested against non–linear effects related to the α–factor.

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APPENDIX 1B

Round-Robin on Linewidth Enhancement Factor of Semiconductor Lasers

Progress Report - November 2006

1. COST 288 ROUND-ROBIN ON LINEWIDTH ENHANCEMENT FACTOR OF SEMICONDUCTOR LASERS

Within Working Group 2 of Action COST 288, it was decided to start a Round-Robin measurement activity on the linewidth enhancement factor parameter of semiconductor lasers (also known as alpha-factor). More than 15 Groups expressed their interest in this activity, that is coordinated by Guido Giuliani (University of Pavia, Italy, *guido.giuliani@unipv.it*).

2. GOALS

After a preliminary study and discussions among participating Partners, during the COST 288 Crete meeting (February 2006) goals for the RR activity were defined.

The activity originates from the consideration that the alpha-factor is a very important parameter for a semiconductor laser, and that in the scientific literature many different measuring methods have been applied to different laser, without an accepted comparison between methods, and a critical assessment of the validity of the obtained results.

The two main goals for the RR activity are:

1. compare different measuring method for the alpha-factor by applying those to the same set of devices of common types (1550 nm F-P and DFB lasers, 780/850/1550 nm VCSELs). In this activity, the largest possible number of participating laboratories is sought. The applicability of newly devised methods (modified linewidth – Univ. Zaragoza, optical feedback – Univ. Pavia) will be analyzed. The consistency / repeatability of the different methods will be assessed.
2. Apply a few methods and critically analyze the results of measurements on devices of new type, for which the alpha-factor measurement is either difficult or has to be considered in detail from a theoretical point of view. In these category of devices are: QD's lasers, dilute nitride lasers, quantum cascade lasers (QCLs).

3. STATUS AND PLANNED ACTIONS

Operations are organized in three tasks.

Task 1 - Common laser devices

Status

- Devices made available for being circulated among partners:
  - 2 x 1540 nm high power DFB, butterfly package, manufacturer JDSU, supplied by University of Pavia (replaced by substitute lasers bought on COST funds)
  - 2 x 850 nm single-mode VCSELs, TO package, manufacturer Kodenshi, supplied by University of Pavia
  - Several DFBs and Fabry-Perot @ 1310 nm, 1490 nm, 1550 nm, manufactured and supplied by Modulight, Finland

- Measurement sessions completed for 1550 nm devices:
  - University of Zaragoza, Zaragoza, Spain
  - KTH, Stockholm, Sweden
  - AIT, Athens, Greece
- Special STSM to AIT Athens, Greece (15-17 November 2006), involving participants from University of Zaragoza, KTH, University of Pavia, Dublin City University, Aragon Photonics.
- Results:
  - First comparison of methods reveals that the fiber transfer method gives reliable and repeatable results. Other methods (FM/AM, digital modulation, Hakki-Paoli) seems more critical. Modified linewidth and optical feedback methods are being assessed.

Planned activities

- New measurement sessions for 1550 nm devices
  - University of Pavia, Italy
  - Dublin City University, Ireland
  - Darmstadt University, Germany
  - Others to be added

Task 2 – Quantum dots laser devices

Status

- Devices made available for being circulated among partners:
  - Several QD Fabry-Perot lasers of different lengths emitting around 1290-1320 nm, manufactured and supplied by EPFL, Lausanne, Switzerland
  - Discussion on main features of the alpha-factor for QD devices (see G. Huyet review presentation, COST 288 meeting, Crete, Feb. 2006)

Planned activities

- Measurement sessions for QD devices
  - University of Pavia, Italy
  - Darmstadt University, Germany
  - University College Cork, Ireland
  - EPFL, Lausanne, Switzerland
  - LPN-CNRS, Marcoussis, France
- Special STSM to University College Cork, Ireland (February 2007), involving participants from University of Zaragoza, KTH, University of Pavia, Dublin City University, Darmstadt University, LPN-CNRS, EPFL.

Task 3 - Quantum cascade laser devices

Status

- At present stage devices are unlikely to be circulated, because only a few partners are equipped to measure QCLs.
- Measurements have been carried out at Darmstadt University (collaboration with University of Pavia) on MIR QCL emitting at 5 μm, using the optical feedback method obtaining interesting results (low alpha at threshold, large increase above threshold)
- Preliminary measurements carried out on QCL emitting in the THz range (wavelength 120 μm) with optical feedback method in a collaboration between University of Pavia and Scuola Normale Superiore, Pisa, Italy

Planned activities (still to be discussed / approved)

- Involvement of a larger number of Laboratories (possible in case of COST 288 being extended for 1 more year)
- Set-up of a Round-Robin activity on QCLs ?

4. CONCLUSION

The activities related to the Round-Robin on alpha factor have stimulated a good and collaborative cooperation between several different Groups.

Obtained results are very interesting, and it appears that the goal of the activity can be fulfilled.

The number of Groups/Laboratories effectively involved in measurements can be increased to improve the added value of the activity.

After completion of the measuring and analysis activities, dissemination of results will be made in the form of international journal paper publications, with at least one reporting the COST 288 citation in the title. Conference presentations of the RR results will also be done.

5. PUBLICATIONS LIST

G. Giuliani, S. Donati, W. Elsässer, "Investigation of Linewidth Enhancement Factor Variations in External Cavity and Fabry-Perot Semiconductor Lasers", Technical Digest of CLEO/QELS 2005, May 22-27, 2005, Baltimore, Maryland (poster presentation).

G. Giuliani, S. Donati, W. Elsässer, "Measurement of Linewidth Enhancement Factor Variations in External Cavity Semiconductor Lasers", Technical Digest of CLEO Europe/EQEC 2005, 13-17 June 2005, Munich, Germany (oral presentation).

J. V. Staden, T. Gensty, W. Elsäßer, G. Giuliani, Ch. Mann, “Measurements of the α-factor of a DFB-quantum cascade laser by optical feedback self-mixing technique”, Optics Letters, vol 31, p. 2574, Sept 2006.

J. V. Staden, T. Gensty, M. Peil, W. Elsäßer, G. Giuliani, Ch. Mann, “Measurement of the linewidth enhancement factor of quantum cascade lasers by the self-mixing technique” in "Semiconductor Lasers and Laser Dynamics II", edited by D. Lenstra, M. Pessa, I. H. White, Proc. SPIE Vol. 6184, 425-434, 2006 (invited presentation).

Appendix 1C

Linewidth Enhancement Factor of Semiconductor Lasers

Progress Report - May 2007

1. COST 288 ROUND-ROBIN ON LINEWIDTH ENHANCEMENT FACTOR OF SEMICONDUCTOR LASERS

Within Working Group 2 of Action COST 288, it was decided to start a Round-Robin measurement activity on the linewidth enhancement factor parameter of semiconductor lasers (also known as alpha-factor). More than 15 Groups expressed their interest in this activity, that is coordinated by Guido Giuliani (University of Pavia, Italy, *guido.giuliani@unipv.it*).

2. GOALS

After a preliminary study and discussions among participating Partners, during the COST 288 Crete meeting (February 2006) goals for the RR activity were defined.

The activity originates from the consideration that the alpha-factor is a very important parameter for a semiconductor laser, and that in the scientific literature many different measuring methods have been applied to different laser, without an accepted comparison between methods, and a critical assessment of the validity of the obtained results.

The two main goals for the RR activity are:

3. compare different measuring method for the alpha-factor by applying those to the same set of devices of common types (1550 nm F-P and DFB lasers, 780/850/1550 nm VCSELs). In this activity, the largest possible number of participating laboratories is sought. The applicability of newly devised methods (modified linewidth – Univ. Zaragoza, optical feedback – Univ. Pavia) will be analyzed. The consistency / repeatability of the different methods will be assessed.
4. Apply a few methods and critically analyze the results of measurements on devices of new type, for which the alpha-factor measurement is either difficult or has to be considered in detail from a theoretical point of view. In these category of devices are: QD's lasers, dilute nitride lasers, quantum cascade lasers (QCLs).

3. STATUS AND PLANNED ACTIONS

Operations are organized in three tasks.

Task 1 - Common laser devices

Status

- *Devices made available for being circulated among partners:*
  - 2 x 1540 nm high power DFB, butterfly package, manufacturer JDSU, supplied by University of Pavia
  - 2 x 850 nm single-mode VCSELs, TO package, manufacturer Kodenshi, supplied by University of Pavia

        - Several DFBs and Fabry-Perot @ 1310 nm, 1490 nm, 1550 nm, manufactured and supplied by Modulight, Finland
- *Measurement sessions completed for 1550 nm devices:*
    - University of Zaragoza, Zaragoza, Spain
    - KTH, Stockholm, Sweden
    - AIT, Athens, Greece
    - University of Pavia, Pavia, Italy
- *Special STSM to AIT Athens, Greece* (15-17 November 2006), involving participants from University of Zaragoza, KTH, University of Pavia, Dublin City University, Aragon Photonics.
- *Results*:
    - 8 methods have been applied to date, and each laser has been measured for 6 different values of the injected current, totalling more than 150 individual measurements
    - The applied methods can be broadly classified as follows, depending on the underlying physical effect or laser / alpha factor model:
        - Static Methods: Gain spectrum ("Hakki-Paoli"); Linewidth-power relation
        - Direct Modulation: FM/AM; Fiber Transfer Function, dynamic chirp; digital modulation
        - Lang-Kobayashi model: Optical Feedback (Self-Mixing); Injection locking
    - The comparison of the results reveals that the fiber transfer method gives the most reliable and repeatable results. Other methods (FM/AM, digital modulation, Hakki-Paoli) seems more critical. Modified linewidth and optical feedback methods are interesting as they give quite consisten results.
- *Dissemination*: the results have been presented at two major International Conferences (see Publication List). Involvement of interested Groups is being seeked, also autside the COST 288 Community

Planned activities

- New measurement sessions for 1550 nm devices
    - Dublin City University, Ireland
    - Technical University of Eindhoven, The Netherlands
    - Others to be added

Task 2 – Quantum dots laser devices

Status

- Devices made available for being circulated among partners:
    - Several QD Fabry-Perot lasers of different lengths emitting around 1290-1320 nm, manufactured and supplied by EPFL, Lausanne, Switzerland
    - Discussion on main features of the alpha-factor for QD devices (see G. Huyet review presentation, COST 288 meeting, Crete, Feb. 2006)

Planned activities

- Measurement sessions for QD devices
    - University of Pavia, Italy
    - Darmstadt University, Germany
    - University College Cork, Ireland
    - EPFL, Lausanne, Switzerland
    - LPN-CNRS, Marcoussis, France
- Special STSM to University College Cork, Ireland (Autumn 2007), involving participants from University of Zaragoza, KTH, University of Pavia, Dublin City University, Darmstadt University, LPN-CNRS, EPFL.

Task 3 - Quantum cascade laser devices

Status

- At present stage devices are unlikely to be circulated, because only a few partners are equipped to measure QCLs.
- Measurements have been carried out at Darmstadt University (collaboration with University of Pavia) on MIR QCL emitting at 5 μm, using the optical feedback method obtaining interesting results (low alpha at threshold, large increase above threshold)
- Preliminary measurements carried out on QCL emitting in the THz range (wavelength 120 μm) with optical feedback method in a collaboration between University of Pavia and Scuola Normale Superiore, Pisa, Italy

Planned activities (still to be discussed / approved)

- Involvement of a larger number of Laboratories
- Set-up of a Round-Robin activity on QCLs ?

4. CONCLUSION

The activities related to the Round-Robin on alpha factor have stimulated a good and collaborative cooperation between several different Groups.

Obtained results are very interesting, and it appears that the goal of the activity can be fulfilled.

The number of Groups/Laboratories effectively involved in measurements can be increased to improve the added value of the activity.

After completion of the measuring and analysis activities, dissemination of results will be made in the form of international journal paper publications, with at least one reporting the COST 288 citation in the title. Conference presentations of the RR results will also be done.

5. PUBLICATION LIST

G. Giuliani, S. Donati, W. Elsässer, "Investigation of Linewidth Enhancement Factor Variations in External Cavity and Fabry-Perot Semiconductor Lasers", Technical Digest of CLEO/QELS 2005, May 22-27, 2005, Baltimore, Maryland (poster presentation).

G. Giuliani, S. Donati, W. Elsässer, "Measurement of Linewidth Enhancement Factor Variations in External Cavity Semiconductor Lasers", Technical Digest of CLEO Europe/EQEC 2005, 13-17 June 2005, Munich, Germany (oral presentation).

J. V. Staden, T. Gensty, W. Elsäßer, G. Giuliani, Ch. Mann, “Measurements of the α-factor of a DFB-quantum cascade laser by optical feedback self-mixing technique”, Optics Letters, vol 31, p. 2574, Sept 2006.

J. V. Staden, T. Gensty, M. Peil, W. Elsäßer, G. Giuliani, Ch. Mann, “Measurement of the linewidth

enhancement factor of quantum cascade lasers by the self-mixing technique” in "Semiconductor Lasers and Laser Dynamics II", edited by D. Lenstra, M. Pessa, I. H. White, Proc. SPIE Vol. 6184, 425-434, 2006 (invited presentation).

Asier Villafranca, Javier Lasobras, Ignacio Garces, Guido Giuliani, Silvano Donati, Marek Chacinski, Richard Schatz, Christos Kouloumentas, Dimitrios Klonidis, Ioannis Tomkos, Pascal Landais, Raul Escorihuela, Judy Rorison, Jose Pozo, Andrea Fiore, Pablo Moreno, Marco Rossetti, Wolfgang Elsässer, Jens Von Staden, Guillaume Huyet, Mika Saarinen, Markus Pessa, Pirjo Leinonen, Ville Vilokkinen, Marc Sciamanna, Jan Danckaert, Krassimir Panajotov, Thomas Fordell, Asa Lindberg, J-F. Hayau, J. Poette, P. Besnard, F. Grillot,
“Linewidth Enhancement Factor of Semiconductor Lasers: Results from Round-Robin Measurements in COST 288”
Technical Digest of CLEO/QELS 2007, Baltimore (USA) 8-10 May 2007, paper CThK1 (oral presentation)

Guido Giuliani, Silvano Donati, Asier Villafranca, Javier Lasobras, Ignacio Garces, Marek Chacinski, Richard Schatz, Christos Kouloumentas, Dimitrios Klonidis, Ioannis Tomkos, Pascal Landais, Raul Escorihuela, Judy Rorison, Jose Pozo, Andrea Fiore, Pablo Moreno, Marco Rossetti, Wolfgang Elsässer, Jens Von Staden, Guillaume Huyet, Mika Saarinen, Markus Pessa, Pirjo Leinonen, Ville Vilokkinen, Marc Sciamanna, Jan Danckaert, Krassimir Panajotov, Thomas Fordell, Asa Lindberg, Jean-François Hayau, Julien Poette, Pascal Besnard, Frédéric Grillot, Mauro F. Pereira, Rikard Nelander, Andreas Wacker, Alessandro Tredicucci, Richard Green,
“Round-Robin measurements of linewidth enhancement factor of semiconductor lasers in COST 288 action”
Technical Digest of CLEO Europe/IQEC 2007, Munich (Germany) 17-22 June 2007, paper CB9-2-WED (oral presentation)

Guido Giuliani, Silvano Donati, Asier Villafranca, Javier Lasobras, Ignacio Garces, Marek Chacinski, Richard Schatz, Christos Kouloumentas, Dimitrios Klonidis, Ioannis Tomkos, Pascal Landais, Raul Escorihuela, Judy Rorison, Jose Pozo, Andrea Fiore, Pablo Moreno, Marco Rossetti, Wolfgang Elsässer, Jens Von Staden, Guillaume Huyet, Mika Saarinen, Markus Pessa, Pirjo Leinonen, Ville Vilokkinen, Marc Sciamanna, Jan Danckaert, Krassimir Panajotov, Thomas Fordell, Asa Lindberg, Jean-François Hayau, Julien Poette, Pascal Besnard, Frédéric Grillot, Mauro F. Pereira, Rikard Nelander, Andreas Wacker, Alessandro Tredicucci, Richard Green,
“Misura del fattore di allargamento di riga di laser a semiconduttore:attività round–robin

nell'ambito dell'azione COST 288",
Technical Digest of Fotonica 2007, Mantova (Italy) 21-23 May 2007, paper B3-4 (oral presentation, paper in italian)

Appendix 1D

STSM: AIT, Athens, Greece, 15-17 Nov 2007

Final Report

1. PARTICIPANTS & HOST INSTITUTION

Marek Chacinski – KTH, Stockholm – Sweden

Raul Escorihuela – Aragon Photonics, Zaragoza – Spain

Guido Giuliani – University of Pavia, Pavia – Italy

Pascal Landais – Dublin City University – Ireland

Asier Villafranca – University of Zaragoza – Spain

Dimitrios Klonidis – Athens Information Technology, Athens – Greece

Christos Kouloumentas – Athens Information Technology, Athens – Greece

Ioannis Tomkos – Athens Information Technology, Athens – Greece

Host institution:

AIT - Athens Information Technology, P.O. Box 68, Markopoulo Ave., GR-19002 Peania, Athens, Greece

2. INTRODUCTION

This STSM involves 5 scientists from 5 different Institutions, travelling to AIT (Greece) to carry out joint measurements within the frame of the Round-Robin measurement activity on the linewidth enhancement factor parameter of semiconductor lasers, taking place within Working Group 2 of Action COST 288.

This report is written jointly by the 5 travelling scientists + host scientists from AIT.

The goal of the STSM is to carry out alpha-factor measurements on two commercial DFB laser samples (that are being circulated among different laboratories) using different methods, namely: the Fiber Transfer Function method, the FM/AM technique, the Digital Modulation method, the Modified Lienwidth method, and the Optical Feedback Self-Mixing technique.

3. FIBER TRANSFER FUNCTION MEASUREMENT

The fiber transfer function measurement with a network analyzer is one of the most common methods to calculate the chirp parameter. Although it had been previously performed at University of Zaragoza and KTH, the AIT offered better conditions to test this method, mainly a longer span of fiber (up to 275 km) and precise control of the power with EDFA and attenuator before each span of fiber.

The network analyzer was unable to record the traces and a programming manual for the GPIB could not be found, so we had to rely on the direct measurement of the dips, which is the method described in [1], and not the full fitting to the transfer function as in [2], that was applied in previous experiments in Zaragoza. Applying this method to directly modulated lasers has the inconvenience that it neglects the adiabatic chirp term, that affects strongly to the first dip, not allowing us to use it for those measurements.

Previous experiments at Zaragoza showed a certain dependence of the measurement of alpha with the emitted power of the DFBs. The first experiment was consequently to check if that change was caused by a real change of the alpha parameter with emitted power, a self-phase modulation effect due to the high power, or some combination of both. The fiber transfer function of two spans of fiber with a total length of 203,9 km was measured modulating one of the DFBs with an external Mach-Zehnder modulator (Agilent 834338) up to 13.5 GHz with -10dBm electrical power coming from the 13 GHz Hewlett Packard network analyzer, using a high speed detector (Discovery Semiconductors DSCR402HR). The laser (butterfly package) was mounted onto the Thorlabs mount, using the optional bias-T. This arrangement makes a poor quality high frequency electrical connection to the laser pins. However, using such a non-ideal bias-T serves as strong a test for the high-frequency modulation measuring methods.

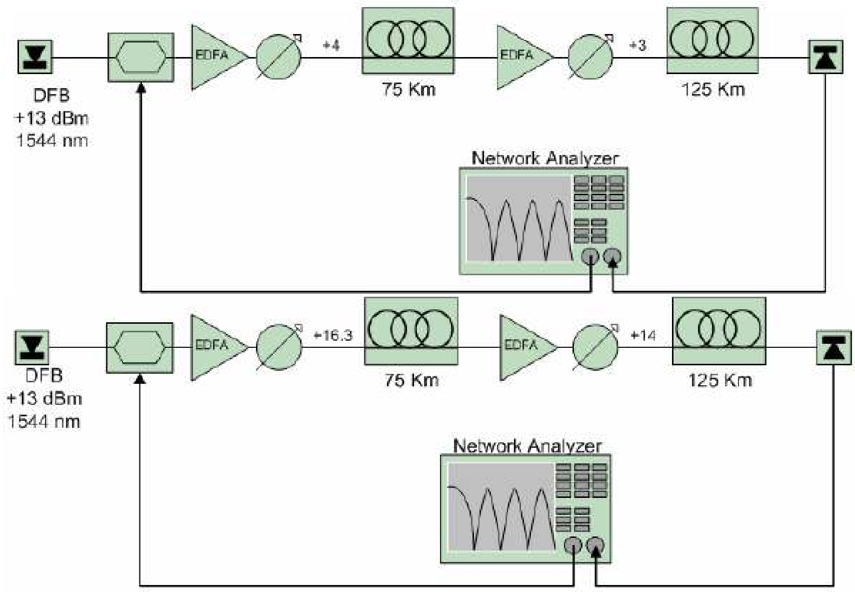

Fig. 1: Experimental setup for the measurement of the fiber dispersion

Two measurements were performed, varying the power entering the fiber spans between the EDFAs from +4 dBm to +16.3 dBm.

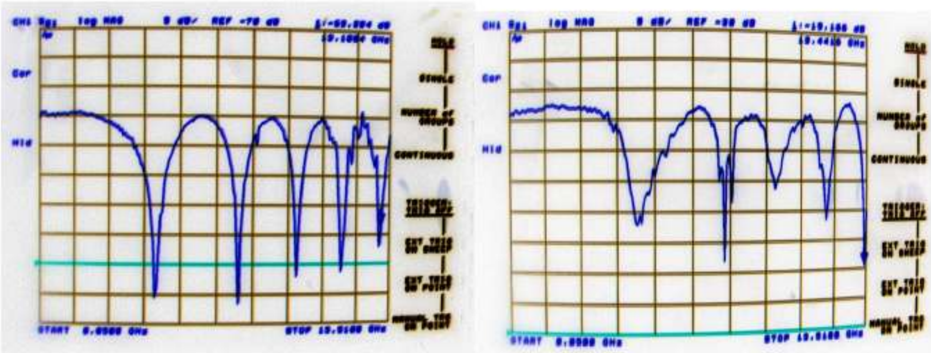

Fig. 2: Measured transfer functions for medium power (left) and high power (right). Start frequency is 0 Hz; Stop frequency is 13 GHz.

	1st dip	2nd dip	3rd dip	4th dip	5th dip	D	α
+4 dBm	4,52	7,65	9,82	11,55	13,18	16,26	-0.09
+16 dBm	4,85	7,93	9,83	11,84	13,44	15,85	-0.24

Varying the power using amplification and attenuation of the optical signal should not alter the chirp characteristics, but there is a frequency shift of the dips of around 300 MHz. This was assumed to be caused by nonlinear effects in the fiber at high powers, mainly self-phase modulation (SPM). It was agreed to control the power entering the fiber for the measurement of the DFBs and keep it at a constant level of +3dBm for all fiber spans.

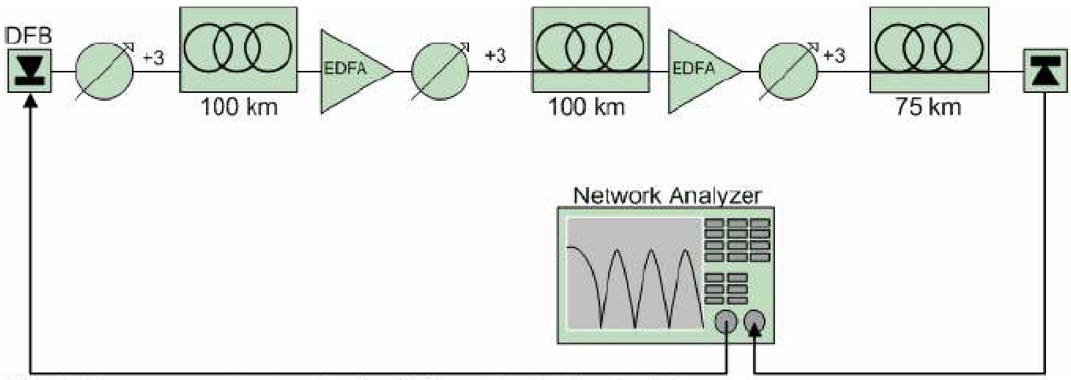

Fig. 3: Measurement setup for the FTF method of the DFB lasers

Due to the reduced bandwidth of the laser and its modulation port, it was hard to locate the 3rd dip with enough precision, so an additional span of fiber was included to reach a total of 280,4 km, getting a cleaner 3rd dip. Results for laser with S/N:4415121 are summarized in the next table. As the fitting to both _ and D had a very high variance, the measurements were also fitted to only _ using the value of D obtained from the measurement with the external modulator, and also to a value of D given by the AIT from previous measurements.

I_{BIAS} [mA]	Frequency dips [GHz]			2 param. fitting		α fitting	
	1st dip	2nd dip	3rd dip	α	D	D=16,3	D=16,8
50	1,42	5,57	7,71	4,24	15,71	2,74	1,53
100	-	5,564	7,72	3,85	15,75	2,27	1,51
200	-	5,5	7,67	5,38	15,78	2,90	1,84
300	-	5,56	7,72	4,01	15,73	2,28	1,52
400	-	5,48	7,76	-61,3	14,94	2,38	1,57
500	-	5,5	7,65	4,48	15,96	3,07	1,91
Average				4,4±0,6	15,79±0,35	2,61±0,35	1,65±0,18

For the other laser (S/N:4415125) the measurements were even more difficult and the 3rd dip was only measurable for low power (below 200 mA).

I_{BIAS} [mA]	Frequency dips [GHz]			2 param. fitting		α fitting	
	1st dip	2nd dip	3rd dip	α	D	D=16,3	D=16,8
50	1,68	5,7	7,72	2,66	15,89	2,12	1,60
100	-	5,68	7,68	1,31	16,88	2,05	1,39
200	-	5,64	7,78	2,84	15,71	1,76	1,21
300	-	5,56	7,72	4,01	15,73	2,28	1,52
400	-	5,57				3,77	2,57
Average				2,71±1,11	16,05±0,56	2,39±0,79	1,66±0,53

The results show that using the fiber transfer function without fitting to the full function and taking adiabatic chirp into account leads to a very imprecise value. This is due to the much higher specific weight of the dispersion term in the fitting. Maybe some different weighting of the parameters could be tried.

The length of fiber used and the measurement conditions seem pretty good but it is a real pity not having been able to get the full traces, which would have lead to much stabler values.

4. BOSA DEMONSTRATION

A high resolution Optical Spectrum Analyzer based on the Brillouin effect was supplied by Aragon Photonics (http://www.aragonphotonics.com) and its functionalities were demonstrated. The instrument was model BOSA-C. The main characteristic of the BOSA is the ultra high optical resolution (10 MHz), that allows to reveal many interesting features of the optical spectrum of semiconductor laser sources that can be alternatively measured only with more complex experimental set-ups, involving RF measurements (i.e., the relaxation frequency). The laser RIN can be displayed directly in the optical domain, even for very low powers emitted by the laser (around threshold), by using a boosting EDFA. The high resolution of the BOSA allows to perform such measurements with a good RIN-to-ASE ratio.

The BOSA have then been used to carry out alpha-factor measurement with the FM/AM method, the digital modulation method and the modified linewidth method.

5. FM/AM METHOD

The FM/AM method is another very common method for the measurement of the linewidth enhancement factor, relying on the measurement of the intensity modulation index in the electrical domain and the sideband to carrier relative strength on the optical spectrum. The setup used at the AIT is depicted in the next figure:

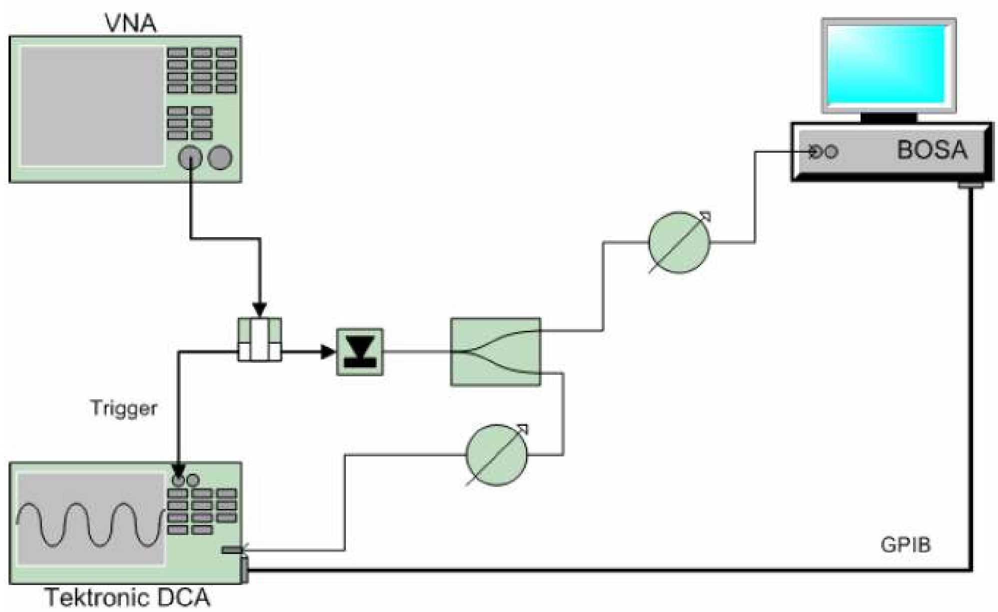

Fig. 4: Measurement setup for the FM/AM method

The low performance of the modulation adapter (Bias-T) of the laser mount made it hard to achieve normal AM indexes for high frequencies. Also, some frequencies corresponded to notch frequencies in the transfer function of the Bias-T - laser system, and had to be skipped. As a solution, a RF amplifier was used to increase the modulation factor. When an electrical high-frequency amplifier is used in front of the laser, care must be taken to avoid any possible saturation of the amplifier, which would make the measurement inaccurate.

The modulation index was measured by a Tektronix digital communication analyser (DCA) with an optical bandwidth of 20 GHz, which resulted being even too large for the measurement at high power, as the modulation index was very small (<1%), and the measurements were noisy. An Aragon Photonics BOSA-C high resolution optical spectrum analyzer was used to measure the carrier-to-sideband ratio. The BOSA was running a script that took the data from the Tektronix DCA (average and peak-to-peak amplitude), but for those noisy measurements the peak-to-peak value showed a considerable deviation from the correct value, so it was measured manually. The script also measures the carrier and peaks in the spectrum.

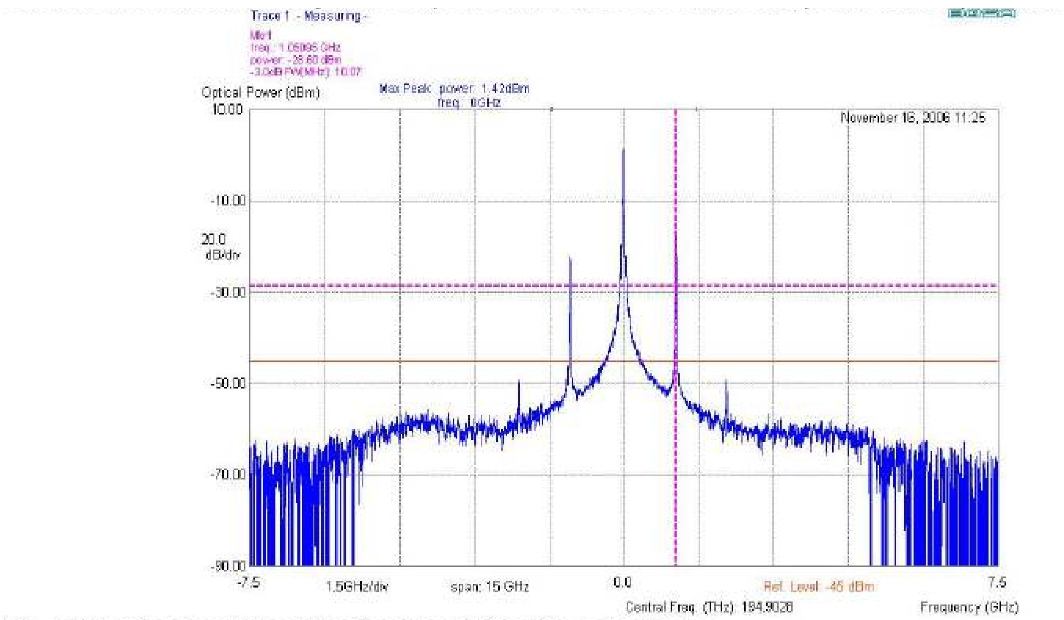

Fig. 5: Sample spectrum of the laser modulated by a sine wave.

Due to the complications in the measurements only laser S/N: 4415125 was measured, and only for two bias currents. The results for α and the adiabatic chirp frequency are shown in next table.

Bias current (mA)	α	f_c (MHz)
47,4	2,45	1915
400	2,90	10135

For the low current measurements, an amplifier was introduced to achieve good modulation over 4

GHz, but it was operated in saturation an altered the measurements. For the fitting only frequencies up to 4 GHz have been considered. For the high current, 4.5, 5.5 and 10 GHz were measured manually, as the noise present in the DCA trace was altering the automatic measurement.
It was concluded that a more reliable method for the estimation of the amplitude modulation index was needed. Possible alternatives are the use of an electrical spectrum analyzer, or a calibrated photodetector with smaller bandwidth to avoid the excess of noise.

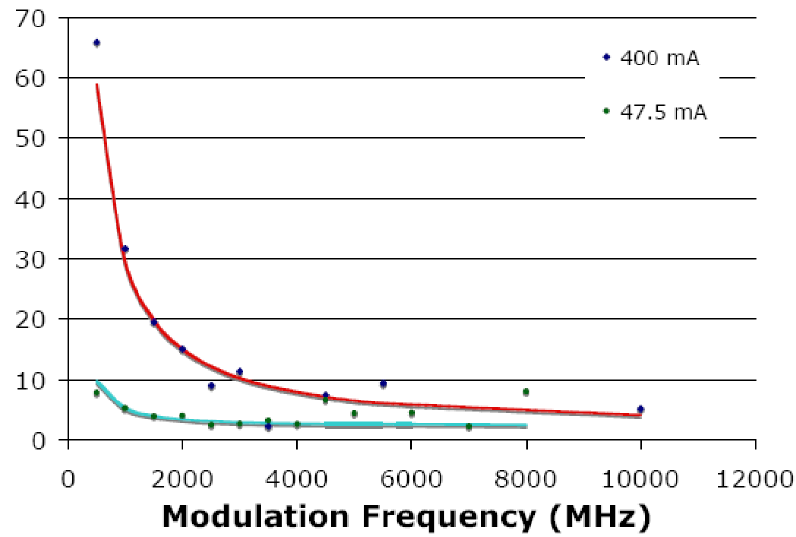

Fig. 6: Measured 2p/m values for tested bias currents.

6. DIGITAL MODULATION

The splitting of the carrier under digital modulation was demonstrated for several modulation rates and power levels. An example measurement using a BOSA is shown in the next figure.

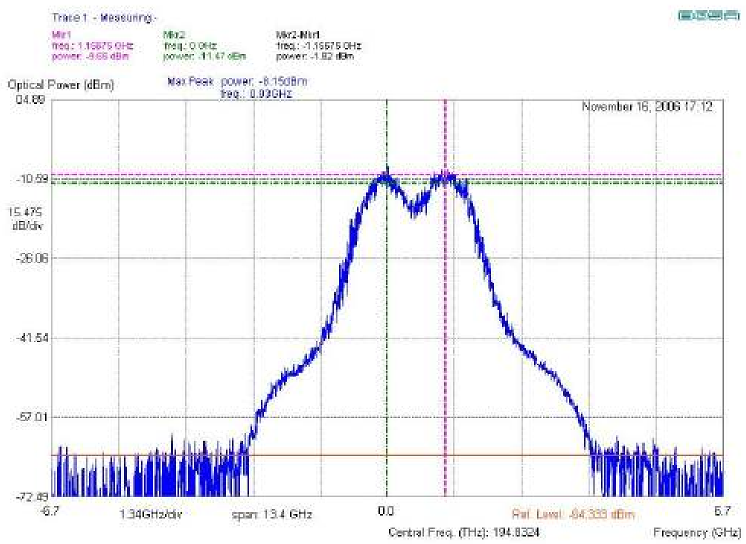

Fig. 7: Spectrum of a digitally modulated DFB laser at 1 Gpbs.

This is a direct measurement of the wavelength shift between the '0' and '1' state. Another way to this measurement would be a FROG system. A 1.16 GHz shift was measured for a 5.6 mW carrier with 10% modulation. This measurement shows that the shift is constant for different carrier powers, but cannot provide the value of α.

7. MODIFIED LINEWIDTH METHOD

The modified linewidth method using the BOSA was also implemented and illustrated to the participants of the STSM. The method relies in the measurement of the linewidth of the laser under CW operation around the threshold and the change in the power dependence between the spontaneous regime (sub-threshold) and the stimulated regime (over threshold).

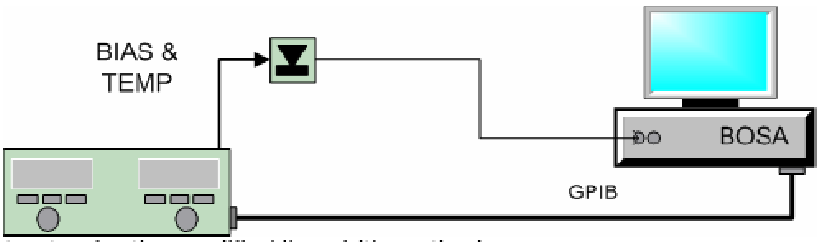

Fig. 8: Measurement setup for the modified linewidth method

This experiment was a replica with the same equipment as the one performed in Zaragoza during the round-robin activities.

The implementation of the method with other spectral measurement techniques was suggested. An option could be the use of Fabry-Perot spectrum analyzers. The importance of a good measurement of the mode power was discussed.

8. MODIFIED HAKKI-PAOLI METHOD

This method is based on sub-threshold measurement, where the simultaneous increase of the power resulting from larger gain Δg and the shift of the peaks positions in the wavelength $\Delta\lambda$ domain are investigated under a small increase of the carrier ΔN. The DFB parameters are extracted using the method described in [3], from the spectra measured with the BOSA (see Fig. 9)

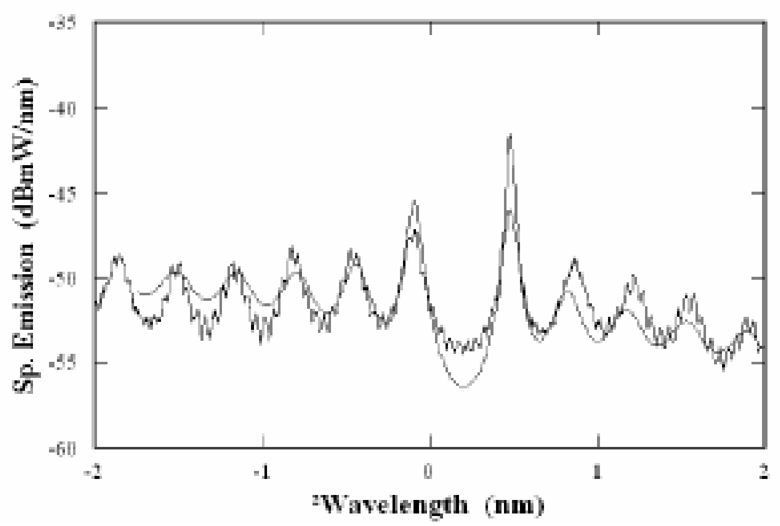

Fig. 9: Optical spectrum for I = 19 mA (around threshold) – Experiment and fitting

The fitted alpha-factor values (for laser with S/N:4415121) are α=1.76 for the transition 18.3mA-19mA and α =1.56 for the transition 19mA-20mA.

As already noted, subthreshold methods are hard to implement for DFB lasers, and the estimated accuracy is not generally satisfactory.

9. OPTICAL FEEDBACK SELF-MIXING METHOD

The optical feedback method based on the so-called Self-Mixing regime was illustrated and discussed. This method was applied only to laser with S/N:4415121, and not to S/N:4415124 because in the latter the monitor photodiode is disconnected.

The experimental set-up is shown in Fig. 10.

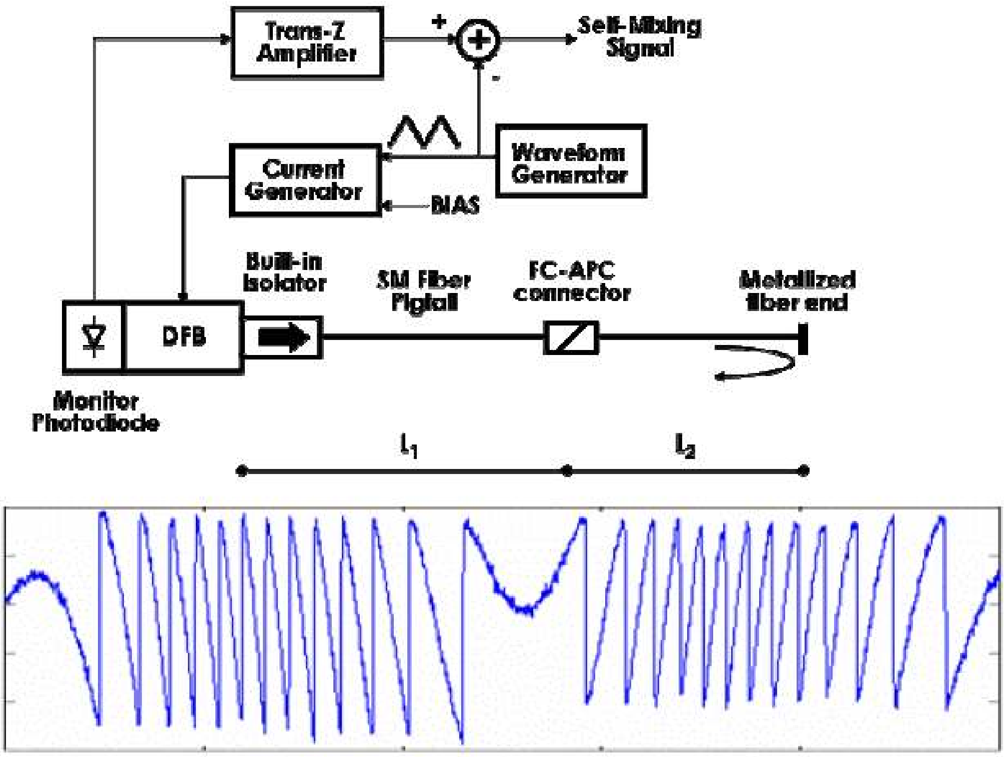

Fig. 10: Experimental set-up for Self-Mixing measurements, and a sample self-mixing signal

The laser is connected via a FC-APC connector to a fiber with a metallized end (reflection > 98%). The reflected light is attenuated by the built-in optical isolator, but the sensitivity of the Self-Mixing configuration is sufficient to obtain an optical feedback configuration with a C factor larger than unity. The laser wavelength is modulated through injection current modulation (low frequency triangular waveform, 50 Hz), and the Self- Mixing signal is obtained from the monitor photodiode through a trans-impedance amplifier (and subsequent subtraction of the residual triangular modulation). The signal is then acquired, and the C factor and the alpha parameter can be obtained following the procedure explained in [4].

The method proved to be usable also for DFB lasers with built-in isolator, and was successfully tested also on a packaged DFB laser emitting at 1310 nm, manufactured by Modulight. Thorough measurements for the alpha factor will be presented in the next RR report by University of Pavia.

10. CONCLUSIONS

The Special STSM within the Round-Robin activity on Alpha-Factor of COST288–WG2 proved to be an efficient way to exchange knowledge and information about the topic under study. The measurements were carried out jointly by researchers from different laboratories, and the strong interaction yielded an appreciable amount of added value.

The schedule was well planned, and it was successfully followed in the STSM implementation. It is suggested that similar initiatives do not last less than three days.

The hosting laboratory (High Speed Networks and Optical Communication – AIT Athens, head Ioannis Tomkos) was very well equipped for the measurements, and people from Optical Networks Group helped in creating a warm and collaborative atmosphere.

As the main RR measurements session are foreseen to be concluded by April 2007, a plan for dissemination of the results has been also discussed at the end of the measurement sessions.

Results about the RR on the two DFB lasers will be conveyed in at least one joint paper to be addressed to a peer-reviewed international journal. A possible target journal for this first work can be the IEEE Journal of Quantum Electronics.

Dissemination of results at International Conferences is also foreseen. At the time of delivery of the present report, contributions with more than 30 Authors from COST 288 have been submitted CLEO USA 2007 and CLEO–Europe 2007.

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Appendix 1E

COST 288 - Round-Robin on
Linewidth Enhancement Factor of Semiconductor Lasers

Final Report - July 2008

1. COST 288 ROUND-ROBIN ON LINEWIDTH ENHANCEMENT FACTOR OF SEMICONDUCTOR LASERS

Within Working Group 2 of Action COST 288, it was decided to start a Round-Robin measurement activity on the linewidth enhancement factor parameter of semiconductor lasers (also known as alpha-factor). More than 15 Groups expressed their interest in this activity, that was coordinated by Guido Giuliani (University of Pavia, Italy, *guido.giuliani@unipv.it*).

2. GOALS

The alpha factor topic was discussed during many COST 288 meetings (starting at Athens, 2004) and during Crete meeting (February 2006) main goals for the RR activity were defined as follows:

5. Comparison of different measuring methods for the alpha-factor by applying those to the same set of devices of common types (1550 nm F-P and DFB lasers, 780/850/1550 nm VCSELs). In this activity, the largest possible number of participating laboratories is sought. The applicability of newly devised methods will be analyzed. The consistency / repeatability of the different methods will be assessed.
6. Application of a few methods and critical analysis of the results of measurements on devices of new type, for which the alpha-factor measurement is either difficult or has to be considered in detail from a theoretical point of view. This category includes: QD's lasers, dilute nitride lasers, quantum cascade lasers (QCLs).

3. ACHIEVEMENTS

The complete Round-Robin excercise could be carried out for 2 telecom DFB lasers, that were measured by scientists from 5 different groups applying 8 different methods.

The Round-Robin activity on "non-conventional" laser devices was not carried out because of the lack of samples and of the unsuitable emission wavelength for many measuring set-ups (QD's lasers, dilute nitride lasers), or for the instrinsic difficulties in operating the devices in laboratory conditions (QC lasers). To solve for the above problems, a strategy was defined and implemented where "spot" measurements were carried out, accompanied by joint discussions and analysis of the results.

In addition, new measuring methods were proposed and implemented, with possible applications also to QD lasers.

Details of the achieved results are given in the following paragraphs.

3.1 Round-Robin measurements on 2 x 1540 nm high power DFB lasers

- *Devices*: 2 x 1540 nm high power DFB, butterfly package, manufacturer JDSU, supplied by University of Pavia
- *Measurement sessions completed:*
  - University of Zaragoza, Zaragoza, Spain
  - KTH, Stockholm, Sweden
  - AIT, Athens, Greece (Special STSM to AIT Athens, Greece (15-17 November 2006), involving participants from University of Zaragoza, KTH, University of Pavia, Dublin City University, Aragon Photonics.)
  - University of Pavia, Pavia, Italy
- *Results*:
  - 8 methods have been applied, and each laser has been measured for 6 different values of the injected current, totalling more than 150 individual measurements
  - The applied methods can be broadly classified as follows, depending on the underlying physical effect or laser / alpha factor model:
    - Static Methods: Gain spectrum ("Hakki-Paoli"); Linewidth-power relation
    - Direct Modulation: FM/AM; Fiber Transfer Function, dynamic chirp; digital modulation
    - Lang-Kobayashi model: Optical Feedback (Self-Mixing); Injection locking
  - The comparison of the results reveals that the fiber transfer method gives the most reliable and repeatable results. Other methods (FM/AM, digital modulation, Hakki-Paoli) seems more critical. Modified linewidth and optical feedback methods are interesting as they give quite consistent results.
- *Dissemination*: the results have been presented at major International Conferences (among which: CLEO 2007, CLEO-Europe 2007), and a long journal paper summarizing the results is being submitted.
- *Future activity*: it was agreed that collaboration on this topic will be continued in the future, by implementing new measuring methods, exchanging devices and comparing the results.

3.2 Alpha-factor measurements on QD lasers

- Review presentations were given at meetings in Rome (2004) and Crete (2006). The following discussions stimulated new measuring activities that were not implemented in the form of Round-Robin because of the unsuitable emission wavelength of the QD devices (made available by EPFL, Lausanne) for many of the experimental set-ups available at laboratories that took part in the RR for 1550 nm lasers.
- New measuring methods have been proposed and tested by University of Zaragoza and University of Pavia on multiple longitudinal mode lasers (that are equivalent to QD lasers), namely: 1) the filtered optical feedback method; 2) the filtered Fiber Transfer Function method (reference: A. Villafranca, I. Garces, G. Giuliani, S. Donati, "Investigation on the linewidth enhancement factor of multiple longitudinal mode semiconductor lasers", SPIE Photonics Europe, Strasbourg, paper 6997-44, 2008).These methods will be futher studied and optimized, ad they will be also applied to QD lasers, in collaboration with Cork University.

3.3 Alpha-factor measurements on Quantum Cascade lasers

- QC laser devices were unlikely to be circulated, because only a very limited number of laboratories were equipped to measure these devices.
- Specific measurement sessions have been jointly set-up by Darmstadt University and University of Pavia, and University of Pavia and Scuola Normale Superiore Pisa, to measure QCLs emitting respectively at 5 μm and 120 μm (THz range). In both cases, very interesting results were obtained:
  - For the MIR QCL, a low value for alpha was measured close to threshold (also exhibiting a change of sign), while a large increase above threshold was observed
  - For the THz QCL, and alpha value between 0.25 and 0.45 was measured, still showing an increase with the emitted power
  - The above results allowed to gain further insight into the QCL gain mechanism, and raised interest in the scientific community

4. DETAIL FOR YEAR 2007-2008

The alpha-factor-related activities carried out during the last year of the COST 288 Action (July 2007 – June 2008) have been the following:

- *Study and implementation of methods for the measurement of alpha factor on multiple longitudinal mode lasers*.
    1. A two-months visit by Asier Villafranca (Univ. of Zaragoza) to University of Pavia allowed to implement a set-up where only a single longitudinal mode of a 1.3 μm Fabry-Perot laser was back-injected into the laser cavity, thus realizing the optical feedback measuring method (bulk experimental set-up, i.e. the filter was implemented using a grating). The Self-mixing interferometric signal was successfully recorded, and the alpha factor measured. A large spread in the measured values for different longitudinal modes suggests that the method be further optimized. A good potential is foreseen in the application to QD lasers.
    2. A modified version of the Fiber Transfer Method was studied by University of Zaragoza, for the application to a 1550 Fabry-Perot laser. The standard method gave a transfer function trace that could not be corecltly intepreted. On the contrary, when a single longitudinal mode of the laser was filtered out, a clear trace could be obtained, from which tha alpha factor could be determined. Measurements are in progress to compare the alpha value with those obtained using other methods.
- *Implementation of a modified version of the Fiber Transfer Method for the measurements of the alpha factor of monolithic ring lasers (and other lasers that cannot be directly modulated)*. It is worth to cosider the application of the FTF method to the largest possible number of laser types, because the Round-Robin activity proved that the FTF is the most accurate method available. However, there is a number of semiconductor lasers that cannot be directly modulated up to high frequencies, due to the large parasitics of the device or the package. This is, in particular, the case for semiconductor monolithic ring lasers. To overcome this limitation, at University of Pavia a new method was demonstrated where the laser was optically modulated by injecting an external light that was modulated by a MZ modulator. In this way, a small carrier density modulation is generated within the laser under test, which is sufficient to produce an amplitude/phase modulation that allows the implementation of the FTF method. This methd was successfully demonstrated for ring lasers and also for DFB lasers, for which a very good comparison was found with results obtained using the conventional FTF method.

5. PUBLICATION LIST

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"Linewidth Enhancement Factor of Semiconductor Lasers: Results from Round-Robin Measurements in COST 288"
Technical Digest of CLEO/QELS 2007, Baltimore (USA) 8-10 May 2007, paper CThK1 (oral presentation)

Guido Giuliani, Silvano Donati, Asier Villafranca, Javier Lasobras, Ignacio Garces, Marek Chacinski, Richard Schatz, Christos Kouloumentas, Dimitrios Klonidis, Ioannis Tomkos, Pascal Landais, Raul Escorihuela, Judy Rorison, Jose Pozo, Andrea Fiore, Pablo Moreno, Marco Rossetti, Wolfgang Elsässer, Jens Von Staden, Guillaume Huyet, Mika Saarinen, Markus Pessa, Pirjo Leinonen, Ville Vilokkinen, Marc Sciamanna, Jan Danckaert, Krassimir Panajotov, Thomas

Fordell, Asa Lindberg, Jean-François Hayau, Julien Poette, Pascal Besnard, Frédéric Grillot, Mauro F. Pereira, Rikard Nelander, Andreas Wacker, Alessandro Tredicucci, Richard Green,
"Round-Robin measurements of linewidth enhancement factor of semiconductor lasers in COST 288 action"
Technical Digest of CLEO Europe/IQEC 2007, Munich (Germany) 17-22 June 2007, paper CB9-2-WED (oral presentation)

Guido Giuliani, Silvano Donati, Asier Villafranca, Javier Lasobras, Ignacio Garces, Marek Chacinski, Richard Schatz, Christos Kouloumentas, Dimitrios Klonidis, Ioannis Tomkos, Pascal Landais, Raul Escorihuela, Judy Rorison, Jose Pozo, Andrea Fiore, Pablo Moreno, Marco Rossetti, Wolfgang Elsässer, Jens Von Staden, Guillaume Huyet, Mika Saarinen, Markus Pessa, Pirjo Leinonen, Ville Vilokkinen, Marc Sciamanna, Jan Danckaert, Krassimir Panajotov, Thomas Fordell, Asa Lindberg, Jean-François Hayau, Julien Poette, Pascal Besnard, Frédéric Grillot, Mauro F. Pereira, Rikard Nelander, Andreas Wacker, Alessandro Tredicucci, Richard Green,
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APPENDIX 2

Mode Locked Quantum Dot Laser Round Robin Activity-headed by WG3

STSM REPORT (I)

Measurements on passive mode-locked QD-MLL under long-cavity feedback

Participants: Prof. John McInerney (University College Cork, Ireland)
Dr. Jose Pozo (University of Bristol, UK and COBRA Institute Eindhoven, The Netherlands)
Dr. Kresten Yvind (COM Institute, Denmark)
Stefan Breuer (Darmstadt University of Technology, Germany)

Hosts: Prof. Meint Smit (COBRA Institute Eindhoven, The Netherlands)
Dr. Erwin Bente (COBRA Institute Eindhoven, The Netherlands)
Dr. Mirvais Yousefi (COBRA Institute Eindhoven, Netherlands and TMC Physics, The Netherlands)

Dates: 28-05-07 - 17-06-07

I. Introduction

Modelocked diode lasers based on InAs/GaAs QDs emitting at 1.3 μm have been acquired from Nanolase GmbH (former NL Nanosemiconductor GmbH, now Innolume GmbH) by the COST288 action. These prototype devices are suitable for use in a Round-Robin exercise. We focused on packaged devices with a cavity length of ~9 mm according to a ~5 GHz rep rate. Fig. 1 depicts a scheme of the bonded chip consisting of 16 sections. Optical pulses as short as 5 to 10 ps are emitted, as measured with an autocorrelation technique. Full specifications of the device under investigation provided by the manufacturer can be found in appendix iia.

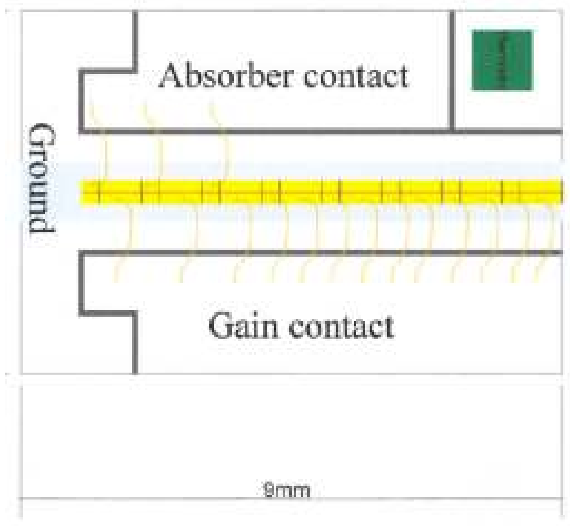


Figure 1 Schematic of the device under investigation: Module A (Innolume GmbH)

The purpose of this STSM is to perform experiments in which we attempt to reduce the large specified timing jitter of these passively modelocked devices which will make them more useful for applications. We will mainly focus on using optical feedback from the laser to achieve this. Occasional observations of very significant reduction in the timing jitter of similar devices from the same manufacturer have been mentioned in private communications with Cambridge University and Alctatel-Thales III-V laboratories. No specific experiments to look into this have yet been performed.

The plan is to investigate this issue in a period of in total 2 weeks at the host institution COBRA Research Institute at the Technische Universiteit Eindhoven (TU/e). In this period four researchers will visit Eindhoven and together with three researchers from COBRA collaboratively perform the experiments. Work will start with standard characterisation of the devices and the adaptation of the set-up for optical feedback. Two directions will be followed in parallel. The first direction is to use optical feedback over a length that is much longer than the laser cavity. This work will be done in the characterisation lab of the Opto-Electronics Devices group in COBRA. The second direction is to attempt to hybridly modelock one or two of the devices to use the optical pulse train to transmit data and perform transmission experiments. This will be done in the neighbouring transmission labs of the Electro-Optical Communication group in COBRA.

II. Measurements performed

Experimental set-up

In order to characterize the devices, the experimental setup shown in Fig. 2 has been used. In order to achieve an optical feedback phenomena, the laser output was split into two branches, one branch to provide long-cavity optical feedback by 80 meters of dispersion-shifted fiber, the other to analyze the emission dynamics. A four percent reflection of the FC-PC connectorised fiber together with an high precision optical attenuator provided the possibility of controlling the amount of feedback. An effective reflection was derived that takes into account the different losses in the setup:

$$R_{eff}[dB] = -30.5dB - 2 \cdot \alpha$$

where R_{eff} is the effective reflectivity of the feedback branch and α the current setting for the optical attenuator.

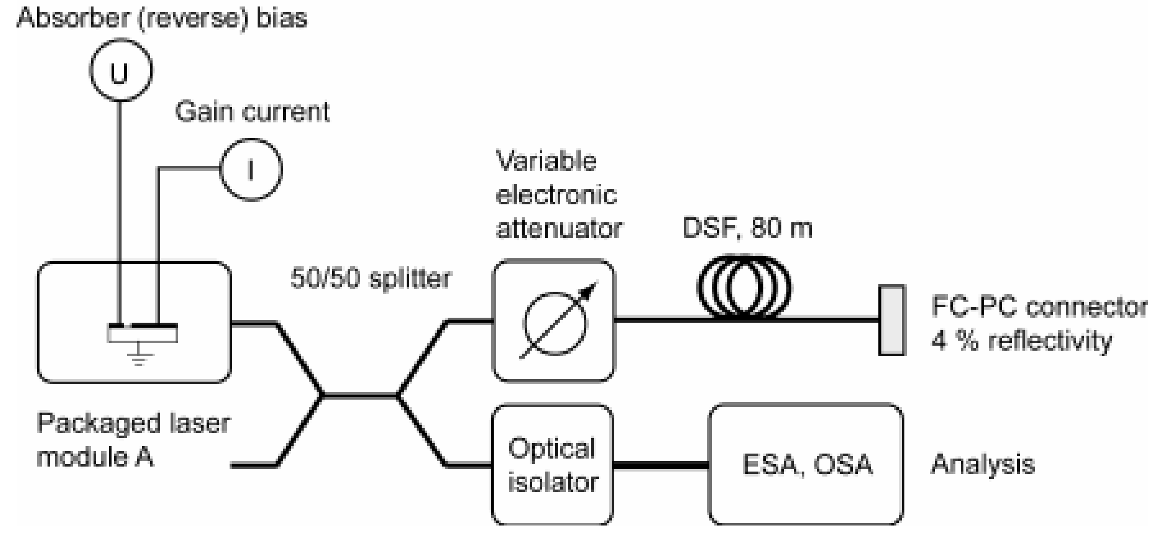


Figure 2 Experimental setup used for long-distance feedback investigations

The second arm was used for the analysis of the feedback induced effects allowing for the simultaneous observation of RF domain and spectral domain characterisations as well as output power characterisations. By variation of gain section current, the reverse bias voltage on the saturable absorber section as well as the optical attenutation, substantial investigations of the output power, spectral- and RF domain as well as the timing jitter were possible.

a. Output power and spectral characteristics

Initial characterization of the device included the PI curves (Fig. 3) and the optical spectra (Fig. 4) as a function of bias current of the gain section as well as different reverse bias voltages applied to the saturable absorber. Fig 3 shows a strong influence of the reverse biasing on the output power characteristics of the laser module. By increasing the reverse bias an increase of the threshold current is observed, as expected due to increasing absorption.

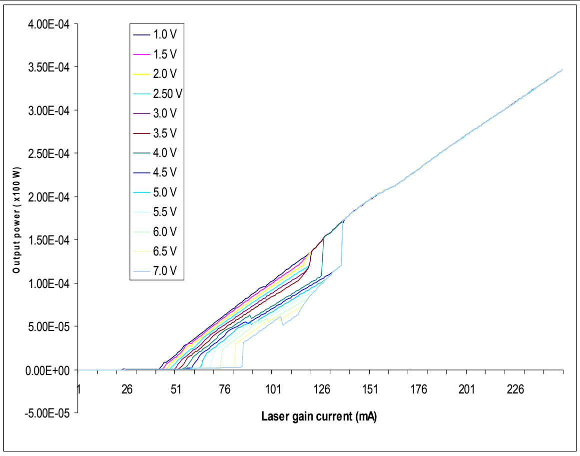


Figure 3 Laser output power as function of gain current and reverse bias blocked Attenuator in feedback arm (20 °C)

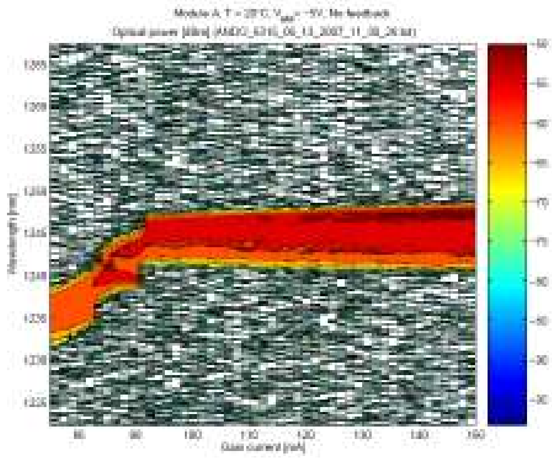


Figure 4 Laser emission spectra, exemplarily shown at -5 V RB and 20 °C

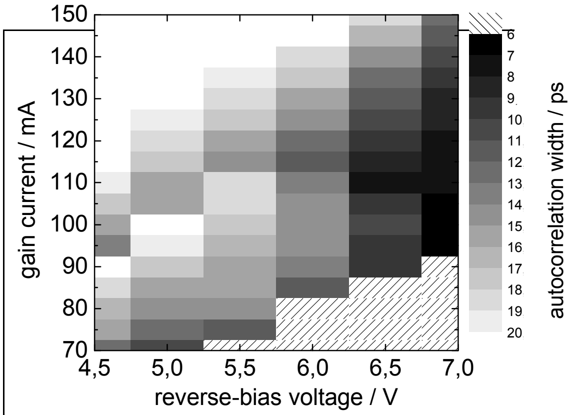


Figure 5 Map of the autocorrelation widths (Module A)

In addition to PI and spectral domain plots, Fig. 5 depicts a map of the emitted optical pulse widths. The grey-colored data represent the measured pulse widths as a function of gain current and reverse-bias voltage using a second-harmonic generation autocorrelation technique.

b. RF spectra characteristics

Using a high-speed photodetector (bandwidth > 45 GHz) together with an electrical spectrum analyzer (bandwidth > 50 GHz) in the analysis arm of the setup, the mode-locking frequency was determined as a function of the current in the gain section (Fig. 6).

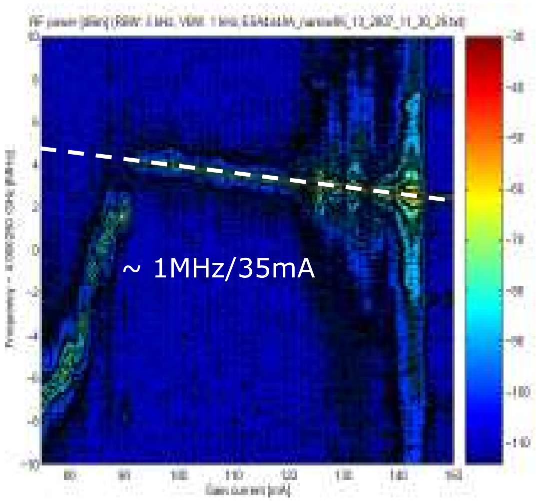


Figure 6 RF spectra at -5 V RB (20 °C)

It can be observed that a strong RF peak indicates a wide range of mode-locked operation. In addition, with increasing gain current and at a fixed reverse bias of -5 V, a slope of 1 MHz/ 35 mA is observed. As this is non-desirable, the use of optical feedback is expected to improve this behaviour.

c. Pulse jitter characteristics

The pulse jitter was investigated by analysing the single-sideband (SSB) phase noise around the carrier RF signal, displayed exemplarily in Fig. 7. A very low jitter of ~ 700fs (20 kHz – 40 MHz) was measured.

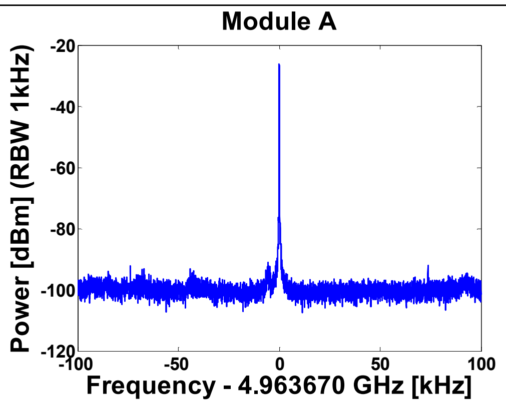


Figure 7 Carrier signal in the RF spectrum (20 °C)

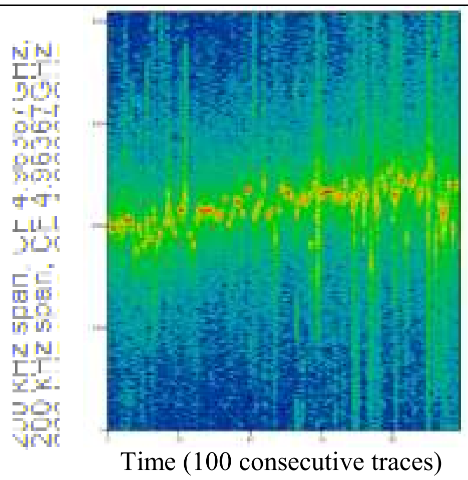


Figure 8 Wander of the timing-jitter (90 mA gain current, -5 V RB, 20 °C)

Besides that, there is still a `significant` wander observed, as shown in Fig. 8. Wander in this context means the jitter occurs at a frequency < 10 Hz.

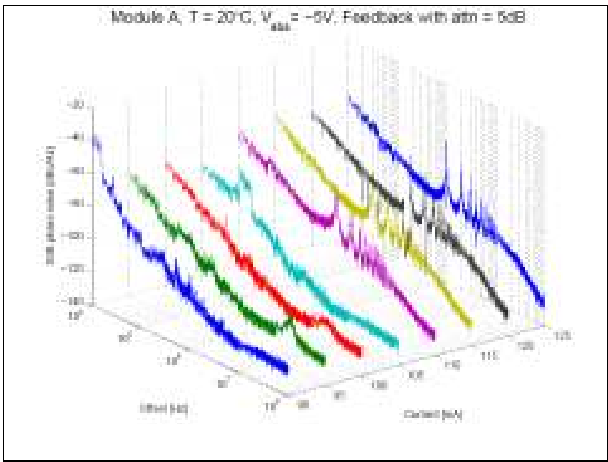


Figure 9 SSB phase noise spectra as a function of gain section current (-5 V RB, $\alpha = 0$ dB, 20 °C)

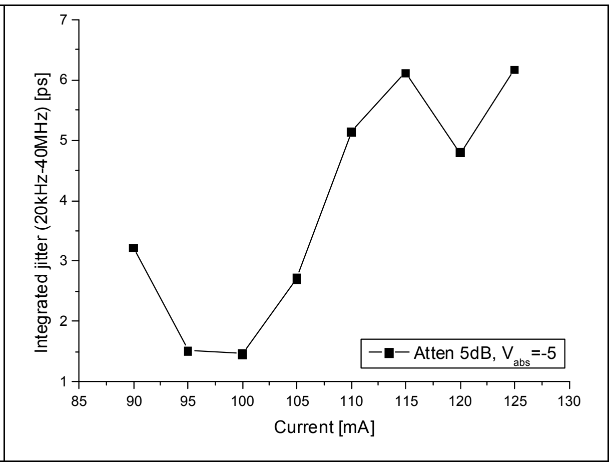


Figure 10 Integrated timing jitter (-5 V RB, $\alpha = 0$ dB, 20 °C)

Extensive characterisations of the SSB phase noise and the timing jitter, repsectively, have been done for various gain section currents and at a fixed reverse bias voltage of -5 V, as depicted in the evolution of SSB phase noise spectra in Fig 9. Exemplarily, Fig. 10 shows the evolution of the timing-jitter plotted as a function of current on the gain section current. In Fig. 10, the integrated jitter is plotted as well as a function of gain section current. At around 98 mA of gain current, the lowest jitter of ~1 ps (20 kHz - 40 MHz) is observed.

d. Feedback characteristics

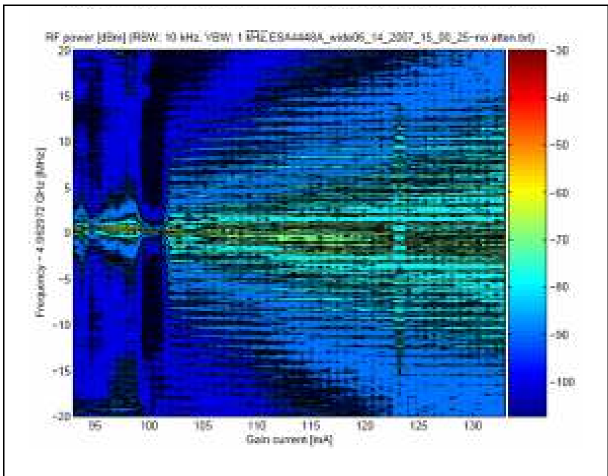


Figure 11 RF signal evolution at a reverse bias of - 5 V (40 MHz span, $\alpha = 0$ dB, 20 °C)

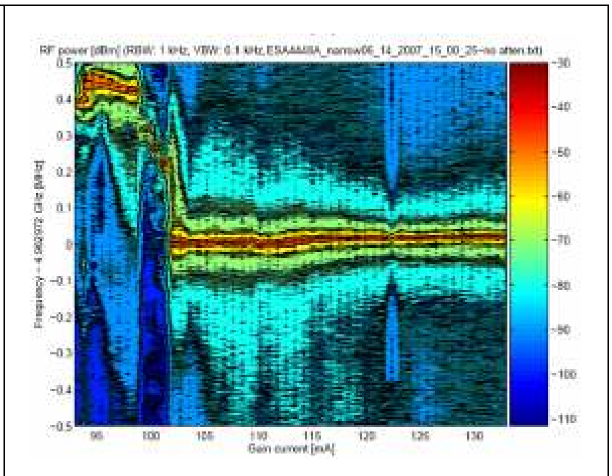


Figure 12 RF signal evolution (1 MHz span, -5 V RB, $\alpha = 0$ dB, 20 °C)

Using the setup shown in Fig. 2, the improvement of the performance of the module by additional optical feedback was under investigation. Fig. 11 and 12 depict the RF spectra as a function of the gain current at a fixed reverse bias voltage of -5 V, and feedback settings (α) of 0 dB. It can be observed, how the frequency of mode-locking has been fixed with the gain current. Also due to this feedback, sidebands have appeared on both sides of the carrier frequency that can be attributed to low-frequency fluctuations (LFFs).

Additionally to that improvement in RF carrier stability through long-cavity feedback, the influence of electronic feedback on the laser is expected to enhance damping of the sideband peaks to a certain degree. The existing set-up was extended to an optoelectronic feedback configuration (Fig. 13). The detected, inverted and amplified optical output signal, hence negative electronic feedback, is used to modulate the absorbing section of the laser module.

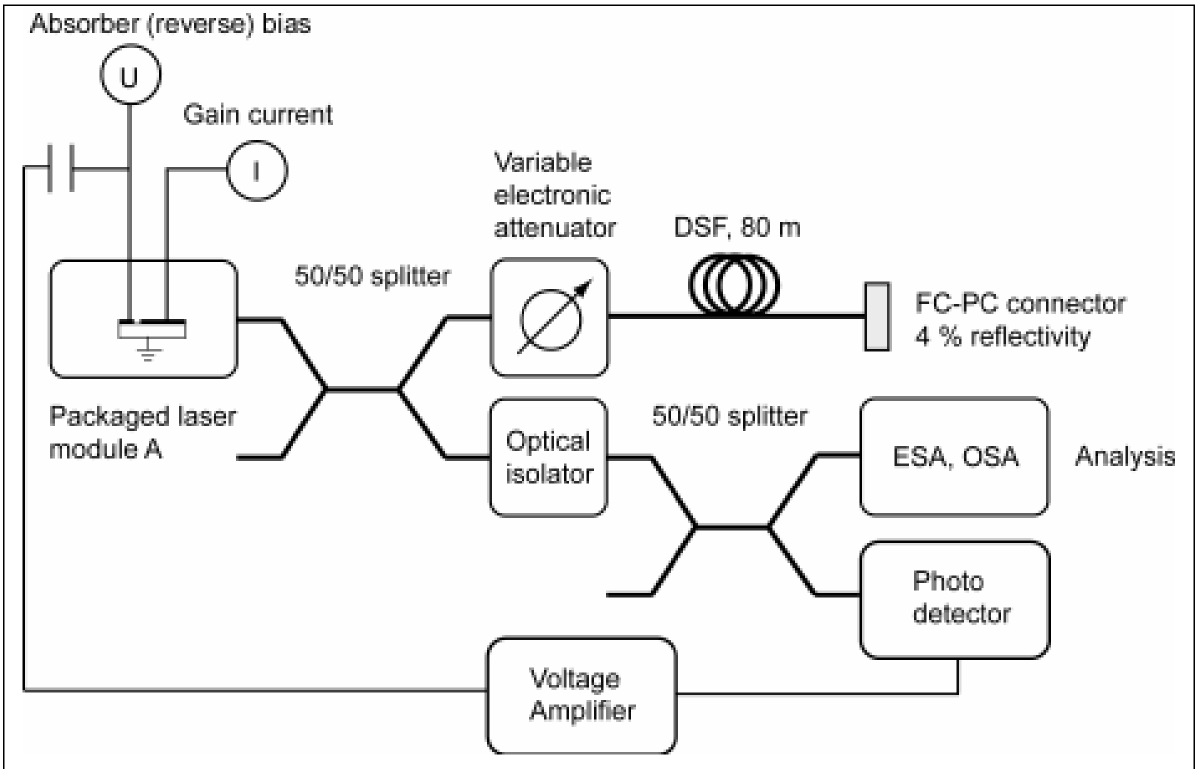


Figure 13 Experimental setup to investigate the influence of electronic feedback, in addition to long-cavity optical feedback

Additionally to the setup presented in Fig. 2, an fiber splitter and a fiber-coupled photodetector with sufficient bandwidth (1 GHz) was used to detect thes LFFs. A voltage amplifier with variable gain settings was used prior to feeding the detected laser signal into the laser. As reported in literature, the modulation of the absorbing section seems more efficient that the modulation of the gain section. As depicted in Fig. 13, we superimposed the reverse bias voltage with the detected optoelectronic feedback signal.

To verify the potential influence of a small modulation voltage on the biased saturable absorber section, a sinusoidial voltage signal with an amplitude of 0.08 Vp-p at a repetition frequency of 3 MHz was applied on the biased saturable absorber section. As depicted in Fig. 14, a clear indication of the modulation signal is observed in the RF spectrum besides LFFs with a repetition rate of ~ 2 MHz. Fig. 15 shows the RF spectrum where the modulation frequency was matched to the observed LFF frequency (2.2 MHz). An increase in RF power is observed in that configuration.

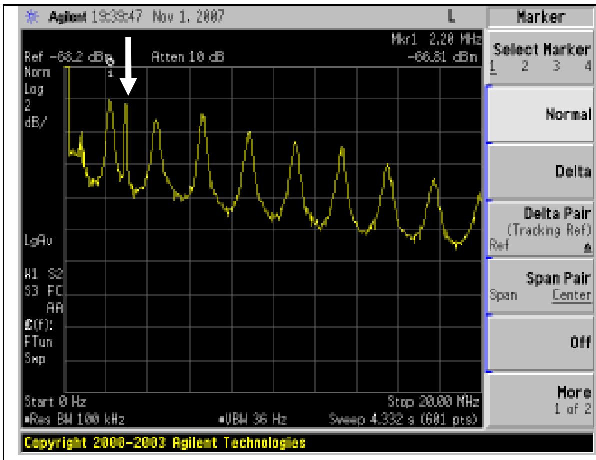


Figure 14: Influence of a sinusoidal voltage modulation (0.08 Vp-p, 3 MHz) on the biased saturable absorber (α = 5 dB, 130 mA gain current, -5 V RB, 20 °C) in the low-frequency regime

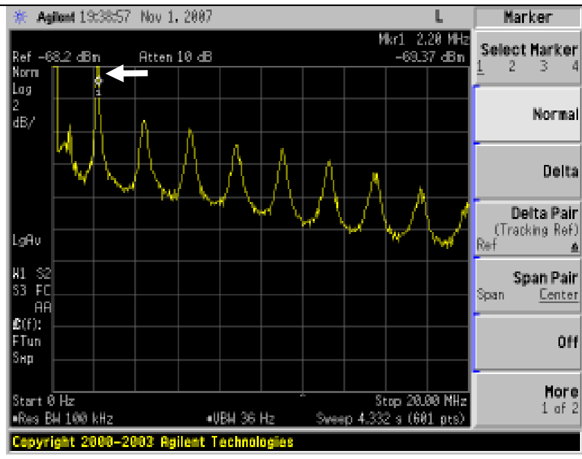


Figure 15 Influence of a sinusoidal voltage modulation (0.08 Vp-p, 2.2 MHz) on the biased saturable absorber (α = 5 dB, 130 mA gain current, -5 V RB, 20 °C) in the low-frequency regime

The following Fig. 16 and Fig. 17 show the influence of applied electronic feedback in the low-frequency regime. Fig. 16 depicts the detected RF signal with optical feedback (α = 5 dB) at a gain section current of 115 mA gain current and a reverse bias of -5 V. Additionally, the electronic feedback was switched on. The corresponding RF spectrum is shown in Fig. 17 indicating an influence on the LFFs but not clearly improving the signal-to-noise ratio of the observed oscillations.

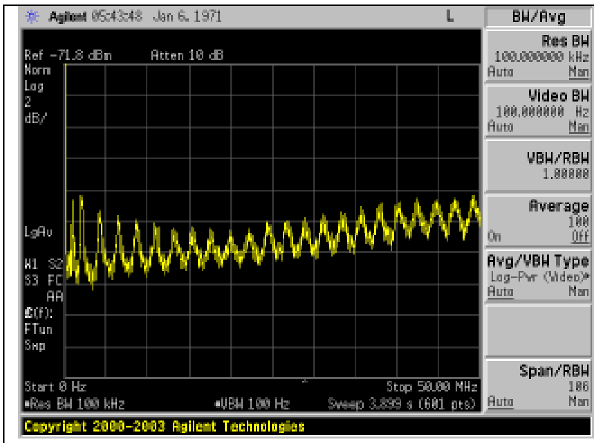


Figure 16: RF spectrum of the low-frequency regime (α = 5 dB, 115 mA gain current, -5 V RB, 20 °C) without electronic feedback

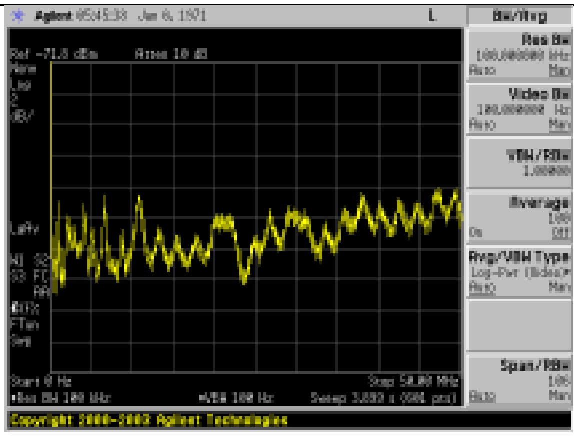


Figure 17 RF spectrum of the low-frequency regime (α = 5 dB, 115 mA gain current, -5 V RB, 20 °C) with electronic feedback

Analysing the effect on the RF carrier, Fig. 18 shows the RF spectrum with α = 5 dB at a gain current of 115 mA and a reverse bias of -5 V RB without electronic feedback. Fig. 19 shows the RF carrier with active electronic feedback, indicating a neglectable influence of the combined optical and electronic feedback on the sideband powers at these operating parameters of the laser.

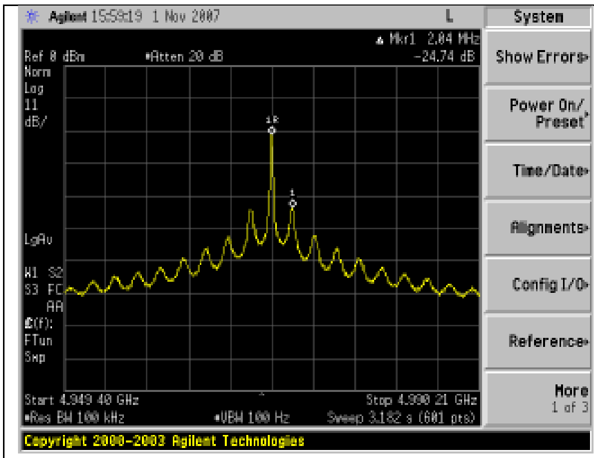


Figure 18: RF spectrum of the carrier signal (α = 5 dB, 115 mA gain current, -5 V RB, 20 °C) without electronic feedback

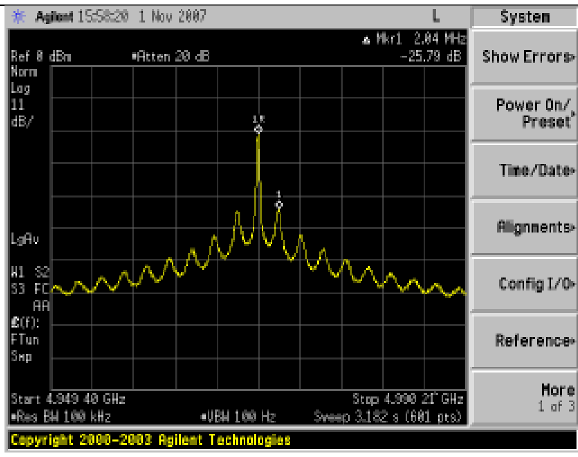


Figure 19: RF spectrum of the carrier signal (α = 5 dB, 115 mA gain current, -5 V RB, 20 °C) with electronic feedback

Interestingly, by decreasing the gain section current from 115 mA to 106 mA, a drastic change can be observed, as depicted in Fig. 20. Here, nearly all sideband power is reduced. By increasing the gain section current to 110 and 115 mA, the sideband modulation again becomes more apparent.

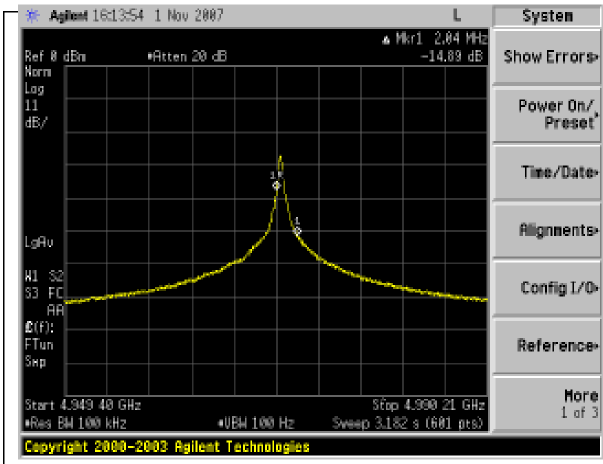


Figure 20: RF spectrum of the carrier signal ($\alpha = 5$ dB, 106 mA gain current, -5 V RB, 20 °C) with electronic feedback

Further investigations on this very interesting effect of the combined opto- and electronic feedback were limited by the available time within the STSM. Prospective work could address issues as noise of the detection and amplification part of the electronic feedback loop as well as the control of the delay of the slow frequency fluctuations in respect to the laser emission. Also, the influence of higher AC amplification of the feedback-signal could be further investigated. Further practical issues that could be considered include enhanced optical isolation could be considered, for example in the analysis arm (Fig. 2) as well as in the feedback arm (Fig. 13). Furthermore, the modulation of the gain section and simultaneously the saturable absorber section could probably improve the influence of electronic feedback.

Also due to the weak influence of the combined optoelectronic feedback on the carrier and sideband peak suppression, substantial investigations focused on the SSB phase noise characterisations in the case of applied optical feedback. For various gain section currents and at a fixed reverse bias voltage of -5 V and a large variety of attenuation settings in the feedback arm of the set-up, close investigations on the evolution of the phase noise were performed. For comparison, Fig. 21 shows the SSB phase noise spectra (as already shown in Fig. 9) without optical feedback. In the case of applied feedback, Fig. 22 displays the observed evolution of the SSB phase noise as a function of attenuation setting.

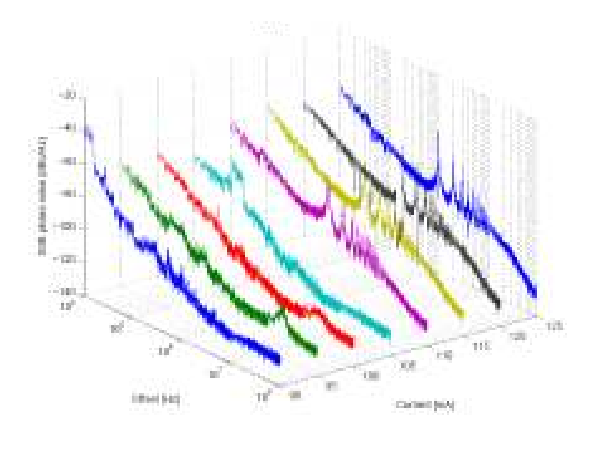


Figure 21 SSB phase noise spectra as a function of gain section current (-5 V RB, α = 0 dB, 20 °C)

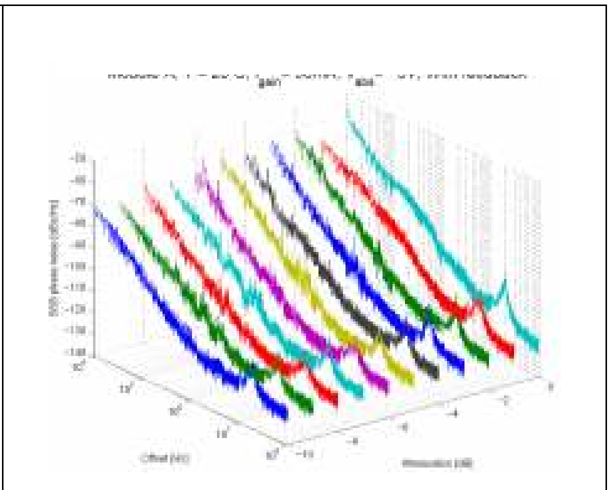


Figure 22 SSB phase noise spectra as a function of attentuation setting (98 mA gain current, -5 V RB, with feedback, 20 °C)

As can be clearly seen, a strong reduction of the wander (Fig. 21) is achieved by applying optical feedback to the laser. The integrated timing jitter as a function of attenuation setting, plotted in Fig. 23, yields a lowest jitter of around < 1 ps (20 kHz - 40 MHz). Compared to the results presented in Fig. 10, a slight improvement of the timing jitter is achieved at a gain section current of 98 mA and a reverse bias voltage of -5 V.

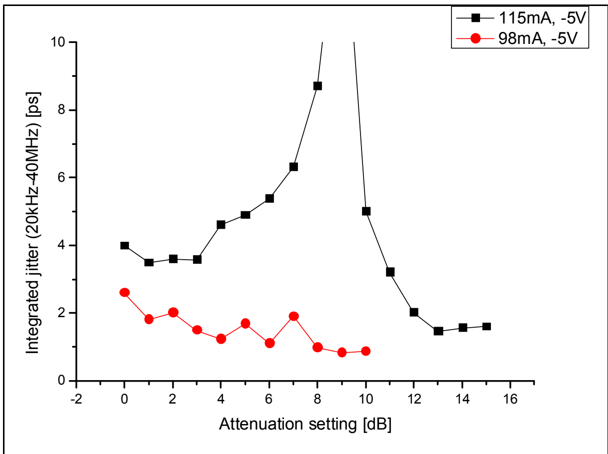


Figure 23 Integrated timing jitter as a function of attenuation setting (-5 V RB, 20 °C)

With increasing attentuation, the timing jitter tends to decrease, however, strong optical feedback should enable a decrease of the SSB phase noise. In order to investigate this effect, further scans of gain section current and reverse bias voltages as well as intensified of the applied attentuation could be performed.

However, closer investigations on this very interesting effect of the combined opto- and electronic feedback were limited by the available time within the STSM.

III. Conclusions and future work

Within this two-week STSM, several achievements could be made that turn this mission into a scientific success.

At first, the excellent measurement techniques available at TU/e made a comprehensive standard characterisation of a prototype 1.3 μm QD InAs/GaAs modelocked diode laser possible. Detailed output power, spectral domain as well as temporal domain analysis could be performed to study the picosecond pulsed emission properties of this prototype laser. Without applying long-cavity feedback, a decrease of the RF carrier frequency at ~ 5 GHz of ~ 1 MHz/ 35 mA with increasing gain current was initially observed in the RF domain.

At second, a long-cavity optical feedback set-up was realised. A significant improvement of the stability of the carrier sidebands of the passively mode-locked multi-section QD laser over a wide range of gain current and at a fixed reverse bias, making the device under investigation more useful for applications, was achieved. Substantial SSB phase noise analysis was done to observe especially the timing jitter of the emitted picosecond short optical pulses were possible. A wander in the timing jitter was observed and closely investigated with the available ultra-high bandwidth RF detection system.

Making use of the high differential gain in the saturable absorber section, leading to a fast absorption of the carriers, initial direct modulation of the saturable absorber section with a sinusoidial voltage was performed. A distinct influence of absorber voltage modulation on the laser emission in the low frequency regime was demonstrated in the RF domain.

The combined optical and opto-electronic feedback configuration on the RF spectra both in the low-frequency as well around the carrier regime was subsequently investigated. Only slight perturbations on the LFFs were observed, more systematic investigations are necessary to do a detailed analysis of the complex influence on the RF spectra of the laser.

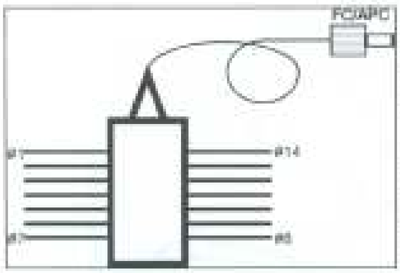
However, by applying solely long-cavity optical feedback, a significant reduction of the wander of the timing jitter was achieved. Several ideas evolved during the course of this STSM to further enhance the influence of opto- and electronic feedback to especially control the RF carrier stability as well as the potential of suppression the observed LFFs. These issues could perhaps be addressed in prospective work.

IV. Appendix iia

Attached are the specifications of the device under investigation and standard characterisation results, made available by the manufacturer NL Nanosemiconductor GmbH (former Nanolase GmbH, now Innolume GmbH).

nano semiconductor

MODULE A

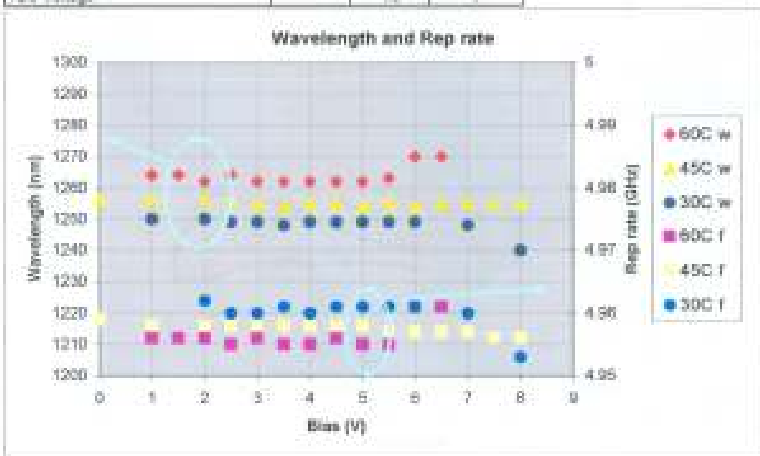


Pin	Connection
1	10kOhm Thermistor
2	10kOhm Thermistor
3	Gain Section
5	Absorber Section
6	TEC(+)
7	TEC(-)

Fiber	SMF-28
Connector	FC/PC

Absolute Maximum Ratings:

Parameter	MIN	MAX	Unit
Storage Temperature	-40	85	ºC
Operating Case Temperature	5	70	ºC
Operating Chip Temperature	30	60	ºC
Gain Section Current		500	mA
Absorber Reverse Voltage		8	V
TEC Current		1.4	A
TEC Voltage		4.3	V



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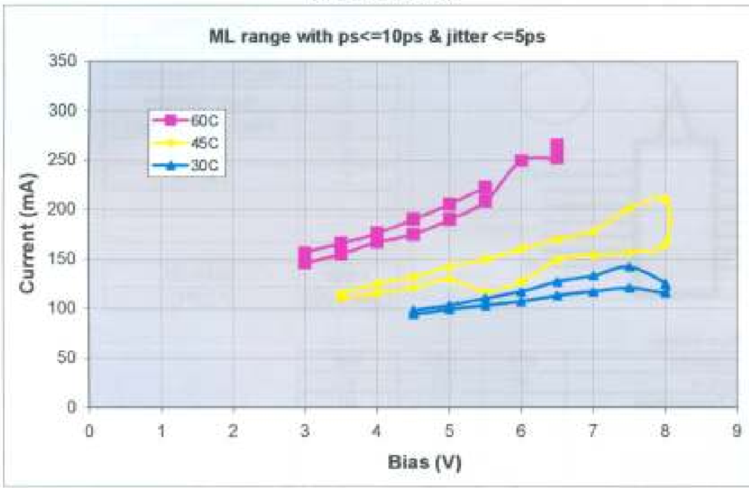
MODULE A



STSM REPORT (2)

Measurements on passive mode-locked QD-MLL under long-cavity feedback

Participants: Prof. John McInerney (University College Cork, Ireland)
Dr. Jose Pozo (Technical University of Eindhoven, The Netherlands)
Dr. Kresten Yvind (Technical University of Denmark, Denmark)
Dr. Nikos Vogiatzis (Bristol University, United Kingdom)
Asier Villafranca (University of Zaragoza, Spain)
Stefan Breuer (Darmstadt University of Technology, Germany)

Hosts: Prof. Meint Smit (Technical University of Eindhoven The Netherlands)
Dr. Erwin Bente (Technical University of Eindhoven The Netherlands)
Dr. Mirvais Yousefi (Technical University of Eindhoven, Netherlands and TMC Physics, The Netherlands)

Dates: 26-05-08 - 30-05-08

V. Introduction

Within the previous STSM action it was demonstrated that the passive jitter of the investigated modelocked diode lasers based on InAs/GaAs QDs is low, but some wander exists. Optical feedback (FB) in the investigated regimes did lower the timing jitter. This was the motivation to investigate further the potential of lowering of the timing jitter through optical feedback. We were glad to have the chance of continuing within another week of intense, joint research. The purpose of this STSM was to perform experiments in which we pursued to reduce the specified timing jitter of passively modelocked devices which will make them more useful for applications. This was especially be done by investigating the potential of optical feedback and simultaneous modulation of specific laser sections. The joint work was done again in the excellent emission characterisation laboratories of the Opto-Electronics Devices group as well as the labs of the Electro-Optical Communication group in COBRA at TU Eindhoven.

VI. Measurements performed

Prior to feedback and absorber modulation experiments, we investigated the pulsed emission behaviour of the second available packaged laser module (Nanosemiconductor module B). Fig. 1 shows the layout of the laser module's chip under investigation. Fig. 2 depicts a sketch of the optical feedback setup used for the characterisations within this STSM. In order to take into account the different attenuated reflections from several components in the setup, an effective reflection coefficient was derived.

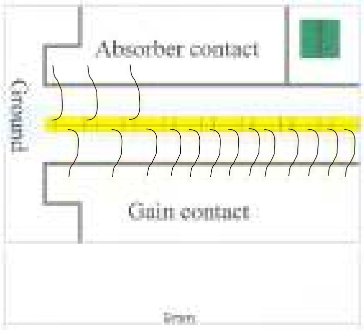


Figure 1 Schematic of the device under investigation: Module B (Innolume GmbH)

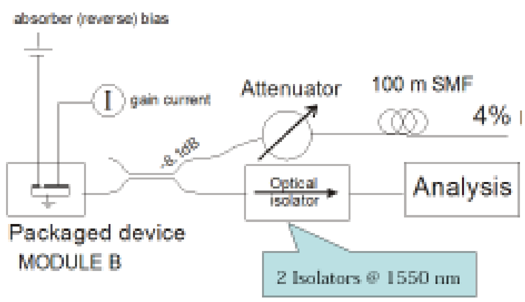


Figure 2 Sketch of the opto-mechanical setup applied for investigating the influence on the modelocked module B

Emitting at a center wavelength of 1230 nm, we observed mode-locking (ML) within the specified region of ML, provided by Innolume (see Appendix A). We started with L-I characterisations, with and without FB (80 m DS SMF) at different reverse bias voltages. The L-I performance without feedback and for varying reverse bias (RB) voltage is shown in Fig. 3.

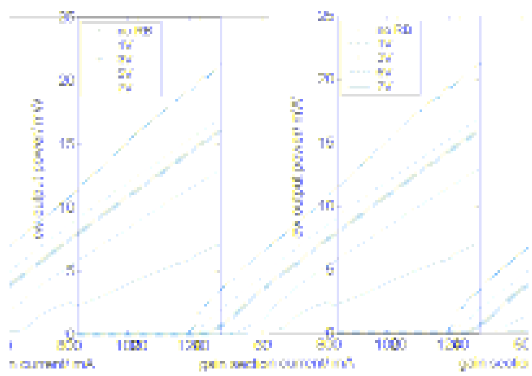


Figure 3 L-I of Nanosemiconductor module B (20 °C) for different RB voltages, without feedback

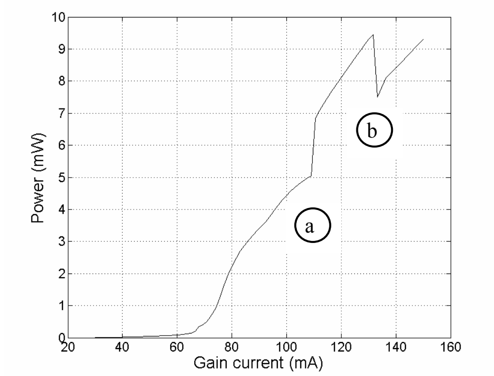


Figure 4 L-I of Nanosemiconductor module B (30 °C), 6 V RB voltage, without feedback

Fig. 4 exemplarily depicts an L-I curve showing a pronounced dip starting at 110 mA (30 °C), which we denote as transition (a) up to 135 mA, transition (b). A further increase of gain section pump current did not lead to a 'joint' cw output power level. Applying optical feedback did not influence the onset of transition (a) and (b).

Mode locking regimes were identified by numerous scans of radio-frequency (RF) spectra at 5 V reverse bias voltage without optical feedback and with 1, 3 and 5 dB ATT settings of optical feedback. Optical spectra evolution within that regimes were studied with a high resolution optical spectrum analyser (0.05 nm resolution) at 5 V reverse bias voltage.

Detailed investigations of the RF spectra evolution were performed at 5 V and 30 °C, well within the module's specifications by the manufacturer. Fig. 5 depicts the RF power in different regimes of mode-locking with increasing gain section pump current. We relate regime (1) to no-ML operation, regime (2) showing a transition to ML, (3) was assigned to ML, which is followed by regime (4), indicating a broadening of the spectra and the frequency evolution of regime (5) was related to temperature effects within the laser cavity.

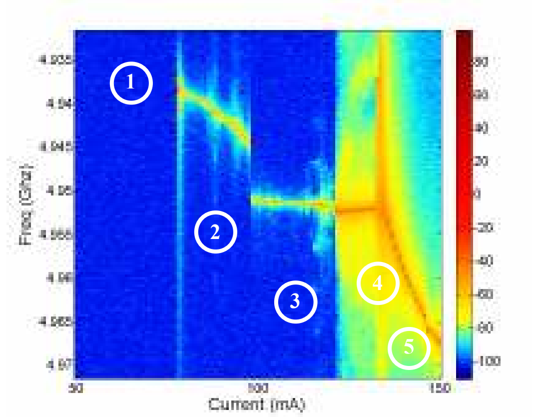


Figure 5 Evolution of RF spectra with increasing gain section current, 6 V reverse bias voltage (30 °C), without feedback

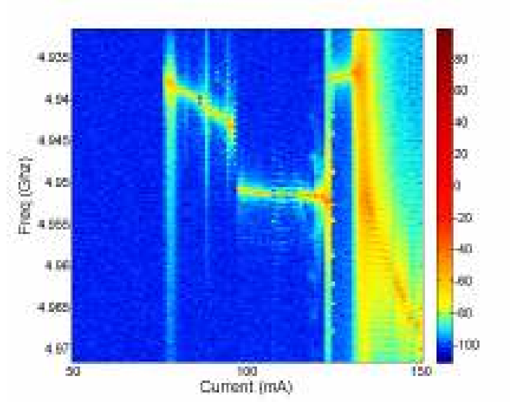


Figure 6 Evolution of RF spectra with increasing gain section current, 6 V reverse bias voltage (30 °C), with 0 dB of feedback

Fig. 6 shows the RF spectra under influence of 0 dB of optical feedback. Modulation sidebands of the long external fiber cavity become prominent. At around 100 mA and 5 V reverse bias, a stable, narrow RF carrier evolution was observed.

In order to better interpret the effects in the emission caused by optical feedback, such as sideband appearances or shifting of the RF center frequency within distinct regimes of gain section pump current, we tried to correlate the effects in the static (L-I) domain and the regime (3) in Fig. 5 of ML operation. It was found that the distinct transitions in the L-I characteristics in Fig. 4 and the RF spectra regime show a weak correlation, also accompanied by a simultaneous strong hysteresis. High resolution scans of the L-I characterisation around the two transitions were performed and supported the observation of strong hysteresis behaviour. Interestingly, no changes (spectral power and bandwidth) in optical spectra were observed within that region of output power hysteresis. A spectral width (-3dB) of 8.5 nm was observed starting at 80 mA up to 140 mA of gain section pump current and 30 °C.

Simultaneously we monitored the width of the autocorrelation signal and power, obtained with an commercially available autocorrelator, with respect to the L-I transition regime.

Fig. 7 depicts the obtained autocorrelation traces for gain section pump currents ranging from 80 to 140 mA, well covering the two transitions in the L-I behaviour (Fig. 4). The trace with the lowest AC power corresponds to 80 mA, the AC trace with the highest AC power corresponds to 140 mA. Interestingly, also two transitions, (a') and (b'), regarding the autocorrelation width and power, respectively, were observed. This behaviour might give rise to estimate the amplitude of an optical pulse, solely by experimentally observing the cw L-I characteristics of a ML laser.

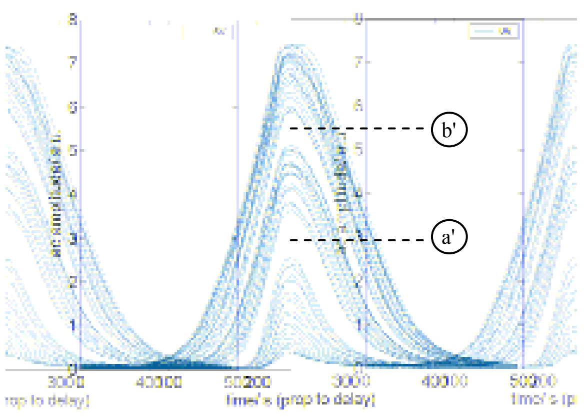


Figure 7 Evolution of autocorrelation traces with increasing gain section current, 6 V reverse bias voltage (30 °C), without feedback

Especially understanding the complex interaction of L-I, RF and autocorrelation behaviour demanded a major amount of the time available during the STSM. We regarded this understanding indispersable in order to be able to properly investigate the feedback behaviour of the laser module.

During the course of the last STSM in October 2007, is was observed, that a modulation of the absorber section influenced the RF spectra dynamics (high differential gain). However, no clear improvement of the signal-to-noise ratio of both low frequency fluctuations and RF carrier oscillations within the investigated feedback parameters was observed at that time.

For that reason, in the following we focused on the experimental investigations of applying both optical feedback through a long DSF and additional modulation of the absorbing section of the laser module. The goal was to modulate the absorber voltage with low/high frequencies in order to perform 'hybrid' ML experiments. The applied optical setup is sketched in Fig. 7. A frequency synthesiser was used to generate a sinusoidial RF signal that was matched to the observed RF carrier frequency. This RF signal was combined with a DC voltage for saturable absorption via a high-bandwidth bias-T and was fed into the absorber section of the laser module.

At a feedback level of 0 dB and an additional, external, sinusoidal modulation of Vpp at a frequency of 5 GHz, numerous traces of RF spectra were obtained.

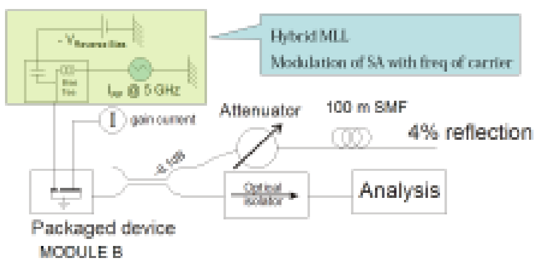


Figure 7 Evolution of RF spectra with increasing gain section current, 6 V reverse bias voltage (30 °C), without feedback

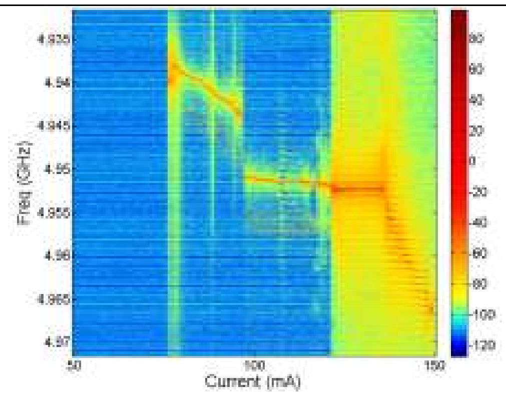


Figure 8 0 dB FB and hybrid ML, 6 V reverse bias voltage (30 °C)

A complete map of these RF spectra is shown in Fig. 8. It can be seen, that, additional to the sidebands caused by the optical feedback, a further set of sidebands appear. Despite this additional set of sidebands, essentially the RF evolution plotted in Fig. 4 is reproduced. No significant influence of the combined modulation and optical feedback on the sideband power was observed. However, an increase in additional sidebands is observed.

By changing the module's operation parameters such as gain section pump current, reverse bias voltage, optical feedback strength as well as the operating temperature, no significant changes regarding the presented performance was obtained.

VII. Conclusion

Several successful experimental investigations could be carried out during the course of this, extended, STSM that helped to improve the understanding of mode-locked QD lasers.

Again, the outstanding measurement techniques available at TU/e made a detailed characterisation of a second prototype of a 1.3 μm QD InAs/GaAs modelocked diode laser possible. Prior to feedback and modulation experiments, we investigated the pulsed emission in terms of L-I and especially RF spectra characteristics of the Nanosemiconductor module A. A decrease of the RF carrier frequency at ~ 5 GHz of ~ 1 MHz/ 35 mA with increasing gain current was initially observed with Nanosemiconductor module A, but quite a different behaviour was observed on module B within this STSM. With module A, an increase of the RF carrier at ~ 5 GHz of 1.5 MHz / 25 mA was observed within the region of ML operation.

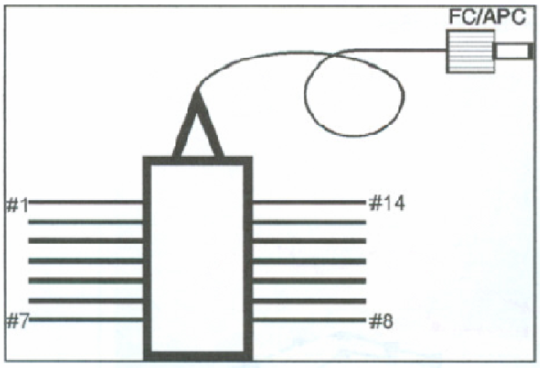
As it was reported in the previous STSM, applying solely long-cavity optical feedback led to a significant reduction of the wander of the timing jitter.

Supported by this highly promising observation, we applied long-cavity optical feedback at different strenghts to the module. We observed the appearance of sidebands, the sideband spacing being proportional to the optical pathlength of the fiber-based feedback setup. Interestingly, the RF carrier stability was not significantly influenced by applying feedback to module A.

Hence, we concentrated on improving the understanding of the complex interaction of L-I behaviour, optical-, RF- and autocorrelation spectra evolution. Distinct interconnects between transitions in the L-I curves, afflicted with strong hysteresis, and autocorrelation amplitudes were observed.

A further approach during this STSM comprised of performing 'hybrid' ML experiments. By modulating the absorber voltage with low/high frequencies, combined with optical feedback to the module, we observed only a minor influence of this modulation technique on the timing jitter. We assigned the strong observed L-I hysteresis of the module under investigation as the major limiting point for performing detailed, reproducible timing jitter studies, within the complex operating regime of the laser module.

VIII. Appendix iib

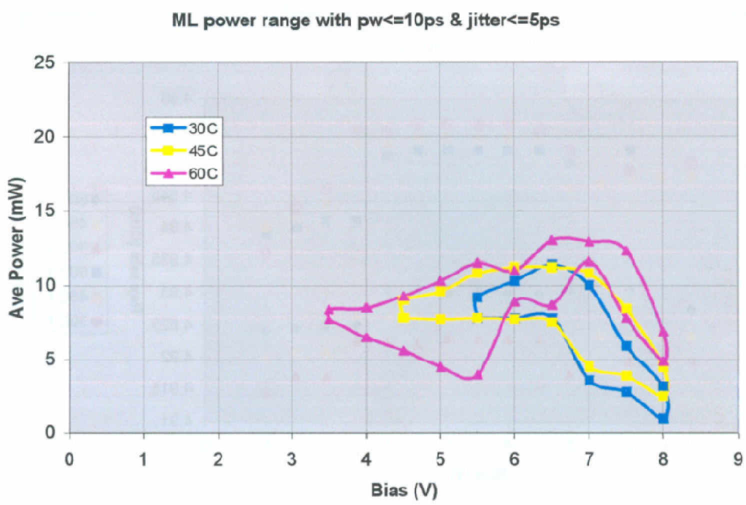


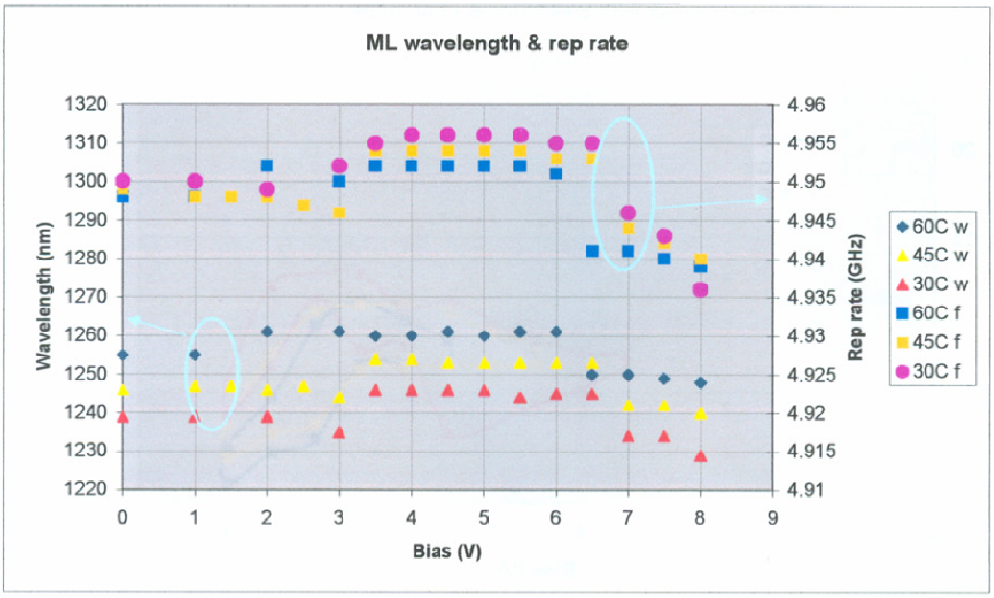
Pin	Connection
1	10kOhm Thermistor
2	10kOhm Thermistor
3	Gain Section
5	Absorber Section
6	TEC(+)
7	TEC(-)

Fiber	SMF-28
Connector	FC/PC

Absolute Maximum Ratings:

Parameter	MIN	MAX	Unit
Storage Temperature	-40	85	eC
Operating Case Temperature	5	70	eC
Operating Chip Temperature	30	60	eC
Gain Section Current		500	mA
Absorber Reverse Voltage		8	V
TEC Current		1.4	A
TEC Voltage		4.3	V




ML wavelength & rep rate
Wavelength (nm)
Rep rate (GHz)
Bias (V)
60C w
45C w
30C w
60C f
45C f
30C f
1320
1310
1300
1290
1280
1270
1260
1250
1240
1230
1220
4.96
4.955
4.95
4.945
4.94
4.935
4.93
4.925
4.92
4.915
4.91
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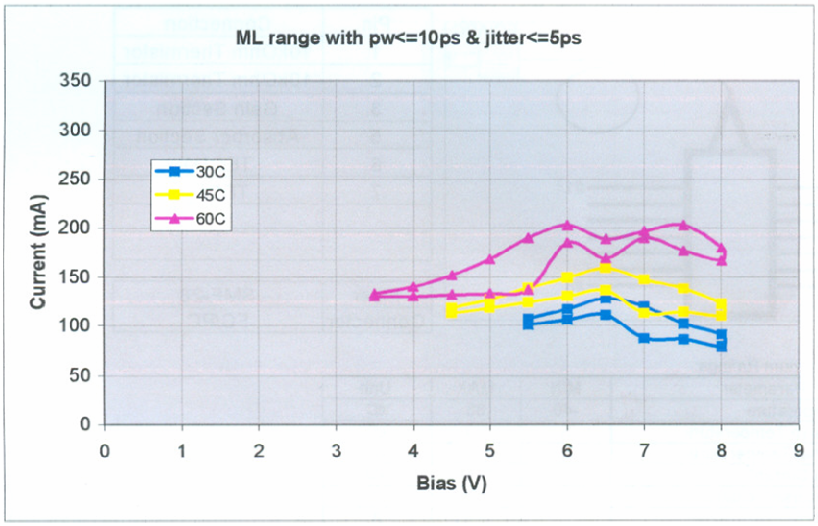
1
2
3
4
5
6
7
8
9


ML range with pw<=10ps & jitter<=5ps
Current (mA)
Bias (V)
30C
45C
60C
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9

Appendix 3

Additional Publications

WP1

Year 1

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Year 3

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