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GIBON

Opto-electronic Integration for 100 Gigabit Ethernet Optical Networks

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Project Coordinator Organisation:
Alcatel-Thales III-V Lab (ATL)
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Revision V4

Abstract

This Deliverable is the Final Activity Report for project GIBON, giving an overview of the objectives and achievements of GIBON.

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PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Table of Contents

Glossary of Abbreviations

BER	Bit Error Rate
BERT	Bit Error Rate Test set-up
BCB	Benzo-chloro-butene
CPM	Clock Phase Margin
CPW	CoPlanar Waveguide
DC	Direct Current
DCF	Dispersion Compensating Fibre
DFB	Distributed FeedBack laser
DFF	D-Flip-Flop
DEMUX	Demultiplexor
DER	Dynamic Extinction Ratio
DUT	Device Under Test
EAM	ElectroAbsorption Modulator
EML	Electroabsorption Modulated Laser
ESD	ElectroStatic Discharge
FWHM	Full Width at Half Maximum
HBT	Heterojunction Bipolar Transistor
HEMT	High Electron Mobility Transistor
IC	Integrated Circuit
MBE	Molecular Beam Epitaxy
MOVPE	Metal Organic Vapour Phase Deposition
MZM	Mach Zehnder Modulator
NRZ	Non Return to Zero
OEIC	OptoElectronic Integrated Circuit
OOK	On Off Keying
OSNR	Optical Signal to Noise Ratio
OTDM	Optical Time Division Multiplexing
PD	PhotoDiode
PDL	Polarisation Dispersion Loss
PMD	Polarisation Mode Dispersion
PMMA	Poly Methyl Metacrylate
PRBS	Pseudo Random Bit Sequence
QCSE	Quantum Confined Stark Effect
QPSK (DP-)	Quadrature Phase Shift Keying (Dual Polarization)
QW	Quantum Well
RMS	Root Mean Square
RX	Receiver
RZ	Return to Zero
SDH	Synchronous Digital Hierarchy
SMF	Single Mode Fibre
SIBH	Semi Insulating Buried Heterostructure
TX	Transmitter
TWA	Travelling Wave Amplifier
WDM	Wavelength Division Multiplexing
3R	Reamplifying, Retiming, Reshaping regenerator

1 Executive Summary

GIBON was launched in the frame of IST FP6 on May 1st 2006 and was completed on July 31st 2009. The project addresses the topic of opto-electronic front ends suitable for On-Off Keying optical fibre transmission at 100 Gbit/s, as a solution to fulfil the needs of the emerging 100G Ethernet technology.
During the 39 months of the project, GIBON partners have been collaborating, bringing together their broad and complementary expertise to demonstrate the viability of the proposed technical solutions: compact, Multi-Chip Modules associating very large bandwidth integrated optoelectronics devices (Electro-absorption modulated laser and pin photodiode / Travelling-Wave-Amplifier for transmitter and receiver respectively) and their driving electronics (MUX and DEMUX).

While standards bodies are favouring solutions relying on -almost- available technologies for future 100G Ethernet deployments, GIBON results show that a single lane 100G OOK solution is able to fulfil the transmission requirements.

GIBON Partners

III-V lab ALCATEL-THALES	Alcatel Thales III-V Lab	France
HHI Fraunhofer Institut Nachrichtentechnik Heinrich-Hertz-Institut	Fraunhofer Institute for Telecommunication Heinrich-Hertz Institute	Germany
COM•DTU	Denmark Technical University COM	Denmark
Ørsted•DTU Technical University of Denmark DTU	Denmark Technical University EMI	Denmark

GIBON website: www.ist-gibon.eu

2 Project description

GIBON was addressing the demonstration of very high bit rate opto-electronic transceivers suitable for 100G Ethernet applications, with the objective of demonstrating the highest speed components integrating the optoelectronic transducers (light modulator and photodiode) with their driving electronics (driver and preamplifier respectively). New optoelectronics components were developed based on designs experienced at lower bit rates and their characteristics were optimised in order to match specifications derived from systems considerations.

In order to reach the 100 Gbit/s objective, the integration technology for the transceivers was as important as the optoelectronic devices characteristics. Two parallel paths toward integration were followed in this project for the transmitter and receiver: monolithic integration of the laser and modulator for the transmitter, of the photodiode and electronic preamplifier for the receiver. Moreover a multi-chip integration approach was then retained for the close association with the higher-speed electronic circuits, namely the selector driver and demux stage respectively. Guidelines for the design of integrated devices as well as for the components packaging were given by a supporting Electro-Magnetic simulation activity. This project was completed by an assessment of the fabricated components with respect to the projected application.

To demonstrate the feasibility of transmitters and photoreceivers able to support a 100 Gbit/s OOK modulation, 4 main objectives were identified.

- *Objective 1: extended bandwidth transmitting and receiving opto-electronic components, compatible with a 100G Ethernet ETDM application*
- *Objective 2: compact 100G Ethernet transceiver front-end modules through purposely developed integration / packaging technologies*
- *Objective 3: electro-magnetic modelling of the integration approach and large signal modelling of HBTs for driver applications*
- *Objective 4: 100 Gbit/s test bench for transceivers assessment with respect to the 100G Ethernet applications*

2.1 The GIBON Consortium

In order to address the above objectives, complementary competences were gathered in a 4-partner Consortium:

- 1 Industrial Lab: Alcatel-Thales III-V lab, acting as prime contractor,
- 1 Public Research Center: FhG Heinrich Hertz Institute,
- 1 University: Denmark Technical U. contributing through 2 Departments:
    - DTU-Fotonik (COM)
    - DTU-Elektro (EMI)

2.2 Workpackages description

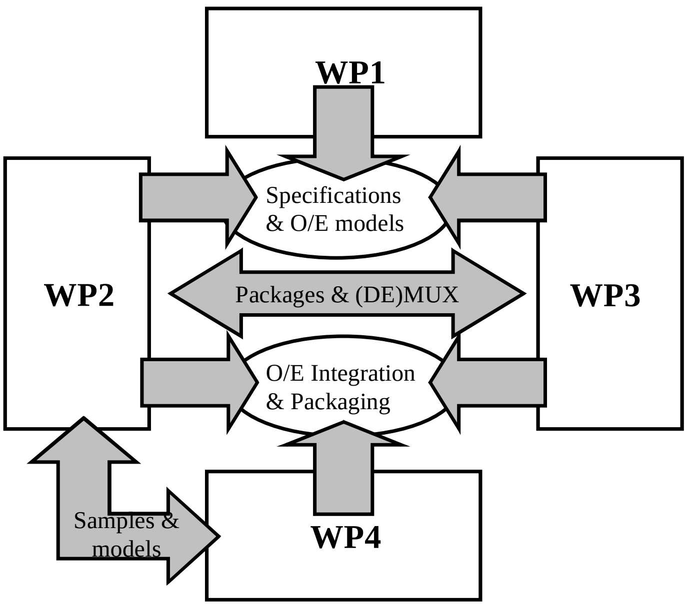
The different tasks identified for GIBON were carried out in 4 technical Work Packages:

- **Work Package 1: Specification & test**
    - Based on current 10G Ethernet specifications, a first set of specifications for the transmitter and receiver was defined. These specifications were further refined, based on the measurements of experimental EML and photodiode samples.
    - Modelling of single mode fibre transmission was performed in order to assess the application area for the components developed in GIBON.
    - A test set-up was assembled and successfully operated for 100G characterization of the transmitter and receiver, using an optical clock transmission.

- **Work Package 2: Transmitter integration**
  - An Electro-absorption Modulated Laser was developed, based on a high modulation efficiency AlGaInAs QW and using a short modulation section so as to allow its operation as a lumped device at 100 Gbit/s.
  - Based on a newly available 0.7 µm InP HBT process, a specific driver, providing a 1V output swing voltage with a negative bias offset (-2.5 V) was designed and fabricated. Other high-speed mixed-signal circuits were designed including 2:1 selector and DFF acting as multiplexor and demultiplexor for their integration within Tx and Rx modules.
  - A Tx module was successfully designed and assembled allowing very close integration of a selector/driver chip with an EML. A 2dB Dynamic Extinction Ratio was measured at 86 Gbit/s, for a -3.5 dBm average power coupled in fibre.

- **Work Package 3: Receiver integration**
  - A very high-speed pin photodiode module was designed, exhibiting a bandwidth larger than 100 GHz.
  - A Receiver OEIC integrating a pin photodiode and a large bandwidth Travelling Wave Amplifier based on an InP HEMT technology was designed. Following an optimization of the HEMT process, pin-TWA chips were successfully fabricated and packaged.
  - Packaged pin and pin-TWA were also developed, with very limited bandwidth degradation when compared to bare dies. Moreover both devices were assembled with demultiplexing ICs in compact Rx packages and characterized up to 107 Gbit/s, exhibiting a record sensitivity of 1.7 dBm.

- **Work Package 4: Device / integration modelling**
  - 3D electromagnetic modelling was developed for characterization and optimization of the photodiode chip/output connector transition.
  - DC characteristics and S-parameters of various emitter length HBTs (0.7 µm emitter width) provided inputs for the development of a scalable HBT model, used by WP2 in their driver design.



Graph of interactions between WPs

The above graphic explains the main interaction between partners:
While the main technological developments for the Tx and Rx were done in WP2 and WP3, with interactions on packaging and integration of MUX/DEMUX functions, specifications and optoelectronic characterization and testing were provided by WP1, with WP4 developing an Electromagnetic simulation activity for the modelling of packaging. In WP4 another activity was devoted to the large-signal scalable models of InP HBT, for the design of drivers.

2.3 Workprogram

The following graph shows the original time breakdown of the different tasks carried out in the 4 technical Work Packages.

GIBON		Leader	Semester 1		Semester 2		Semester 3		Semester 4		Semester 5		Semester 6	
WP1	**Specifications & Test**	COM												
1.1	Specifications for Transceivers		■	■	■	■	■	■	■	■				
1.2	EML with short EAM characteristics			■	■	■	■	■	■	■	■	■		
1.3	pin & pin / TWA characterization				■	■	■	■	■	■	■			
1.4	100 Gb/s TX / RX assessment.								■	■	■	■	■	■
WP2	**Transmitter Integration**	ATL												
2.1	EML for 100 Gb/s applications		■	■	■	■	■	■	■	■	■	■		
2.2	HBT driver for EML			■	■	■	■			■	■	■		
2.3	EML / Driver IC integration			■	■	■	■	■	■	■	■	■	■	
WP3	**Receiver Integration**	HHI												
3.1	pin photodiode module		■	■	■	■								
3.2	pin / TWA module		■	■	■	■	■	■	■	■				
3.3	Receiver with DEMUX function				■	■	■	■			■	■		
WP4	**Device / Integration Modelling**	EMI												
4.1	EM modelling of integration		■	■	■	■	■	■		■	■	■		
4.2	Scalable large signal HBT model		■	■	■	■	■	■	■					

Implementation plan at the start of the project

Actually the technological developments intended during the first two years of GIBON prove more difficult to master than projected, so that a 3 months extension was requested to complete the Tx and Rx chips development, their packaging and the testing of the produced modules.

2.4 GIBON Deliverables

Del.	Deliverable name	WP	Nature	Dissem.	Delivery Date
D0	Project presentation	0	R	PU	3
D1	EML with short EAM in standard module	2	P	CO	4
D2	Preliminary specifications	1	R	PP	6
D3	EML flip-chip process and characterization (BW>50 GHz)	2	R	RE	12
D4	100 Gb/s photodiode module	3	P	CO	12
D5	1st annual report	0	R	PP	12
D6	Driver chip (1st design)	2	P	CO	15
D7	E/O characteristics of short EAM & pin photodiode	1	R	RE	16
D8	EML with 3 dBm output (SAG taper)	2	R	RE	18
D9	Receiver comprising photodiode & DEMUX	3	P	CO	18
D10	EM simulation of interconnects & device parasitics	4	R	PP	18
D11	Scalable HBT large-signal model for circuit simulation	4	O	RE	21
D12	Pin-TWA photoreceiver module	3	P	CO	24
D13	Transceivers final specifications	1	R	PP	24
D14	2nd annual report	0	R	PP	24
D15	Demonstration of the first TX assembly	2	P	CO	27
D16	EM simulation based model of interconnects & packaging	4	O	RE	30
D17	Driver chip (2nd design)	2	P	RE	30
D18	Model & characteristics of EML & pin-TWA	1	R	PP	30
D19	100 Gb/s EML	2	P	CO	30
D20a	RX module including DEMUX	3	P	CO	30

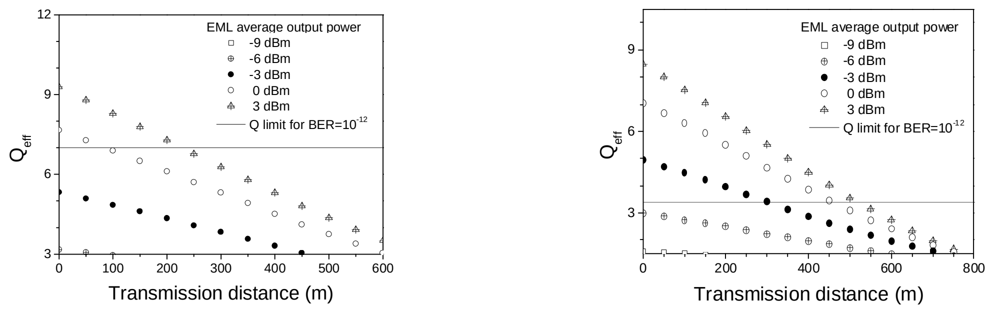
D20b	TX module including MUX	2	P	CO	33
D21	Final report on 100 G TX / RX operation	1	R	PP	36
D22	Final report: technological approach for TX & RX integration	3,2	R	PP	36
D23	Third Annual Report	0	R	PP	36
D24	Final Report	0	R	PU	36
D25	Final Report on dissemination and raising public awareness	0	R	PP	36

3 Highlights of WP achievements

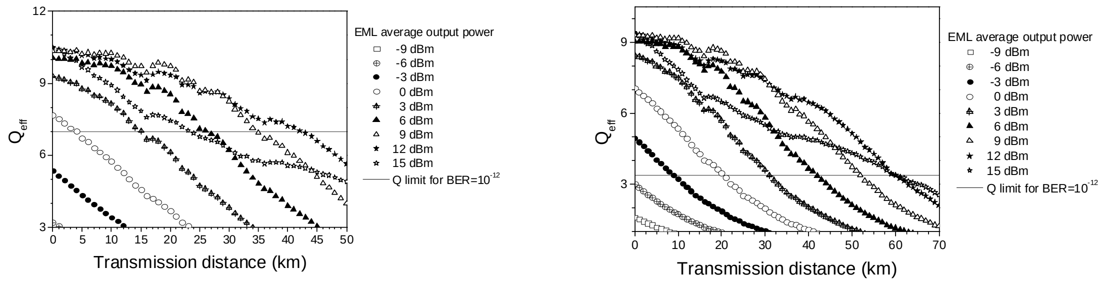
This section gives the highlights of the achievements in the various Work-Packages.

3.1 WP1 Specifications and Test (lead partner: DTU/COM)

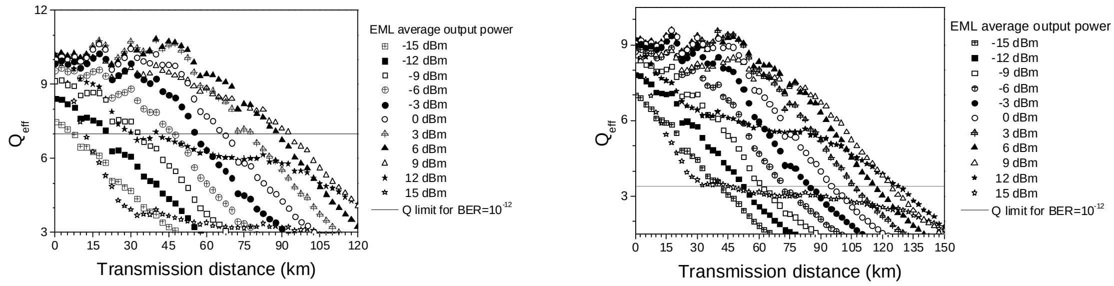
- A comprehensive simulation model has been implemented in order to investigate the transmission performance of the intended transmitter (based on an electro-absorption modulation laser, EML) and photo receiver (based on standard and travelling wave topologies), both for direct and optically pre-amplified receiver. Effects include:
  - EML's frequency response, absorption curve and frequency chirp
  - Expected 100 Gbit/s integrated driver response
  - Dispersion, dispersion slope, PMD and non-linear effects in fibres
  - Optically pre-amplified receiver, including noise, saturation and dynamic gain
  - Photo detector (PD) response based on module measurements
  - Forward-error correction (7%) emulation
  - Simulated results compare with reasonable accuracy to measurements, so the model is believed to offer a high confidence level in the predictions



Expected uncompensated SMF transmission for 100 (left) and FEC'ed 107 Gbit/s (right). Line shows 10^{-12} BER limit

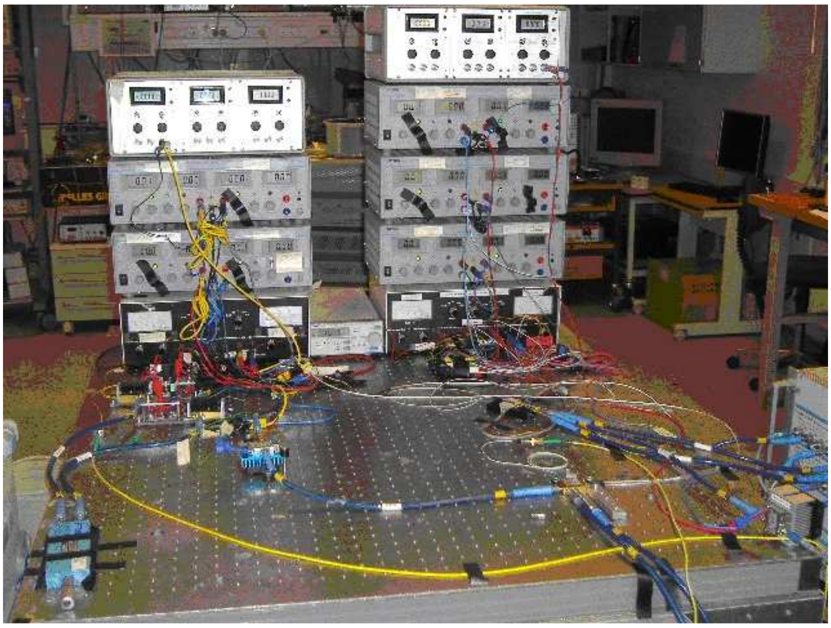


Expected compensated transmission and direct receiver for 100 (left) and FEC'ed 107 Gbit/s (right). Line shows 10^{-12} BER limit.

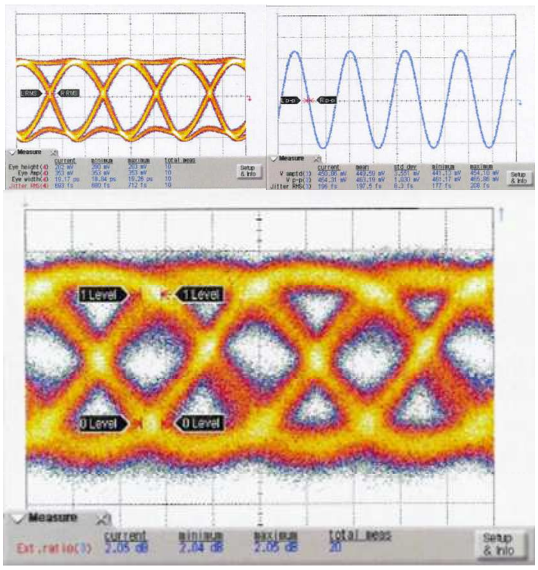


Expected compensated transmission and optically pre-amplified receiver for 100 (left) and FEC'ed 107 Gbit/s (right). Line shows 10^{-12} BER limit.

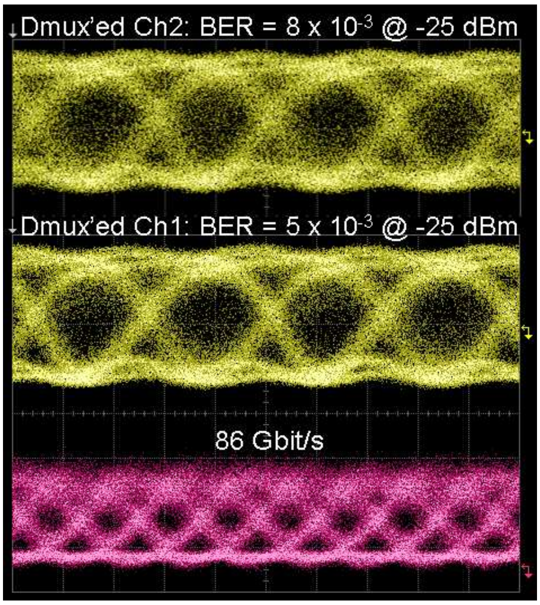
- Based on the simulations a set of tentative specifications has been proposed depending on the intended transmission systems, e.g. compensated, uncompensated, w/ and w/o optical amplification
- Implementation of a 100 Gbit/s test-bed
    - MUX-EML based transmitter
    - PD-DEMUX based receiver
    - Optical clock co-propagated with modulated data
    - Clock recovery scheme for BER measurements at receiver



Clock recovery scheme and PD-DEMUX set-up



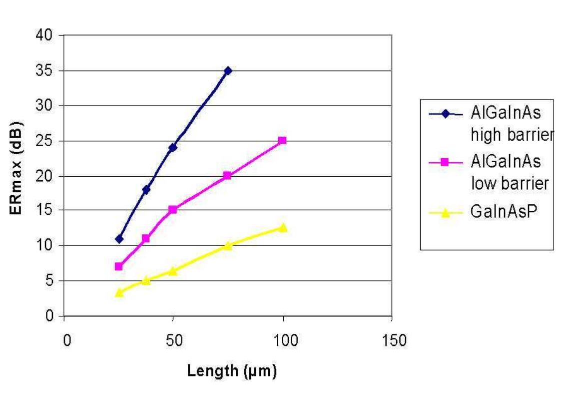
MUX-EML 86 Gbit/s modulated data output



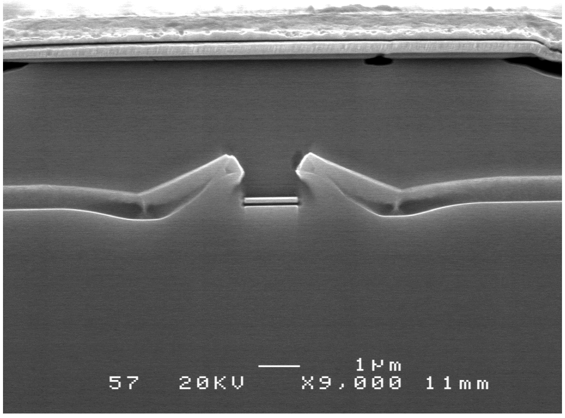
86 and 43 Gbit/s demultiplexed channels after 170 km SMF transmission

3.2 **WP2 Transmitter integration** (Lead partner: ATL)

- Electro-Absorption Modulated Lasers (EML) belong to the Photonic Integrated Circuits family: they integrate a DFB laser with an electro-absorption modulator. The EML developed in GIBON is characterized by specific features:
    - An AlGaInAs QW material structure with enhanced electro-absorption effect and high modulation efficiency. Such a structure allows designing an efficient modulator in spite of a limited length: 12 dB for a 50 µm long modulator, with a DC efficiency of 6 dB/V.
    - A Semi-Insulating Buried Heterostructure (SI-BH) structure with good optical properties (low optical loss) and suitable for large bandwidth applications owing to the low excess capacitance and low series resistance.
    - Single active layer for both the laser and modulator active sections, for simple processing.
    - The overall EML bandwidth goes up to 60 GHz, suitable for the 100 Gbit/s objectives. Ways to improve this bandwidth (reduced capacitance while keeping a constant rsistance) have been identified.

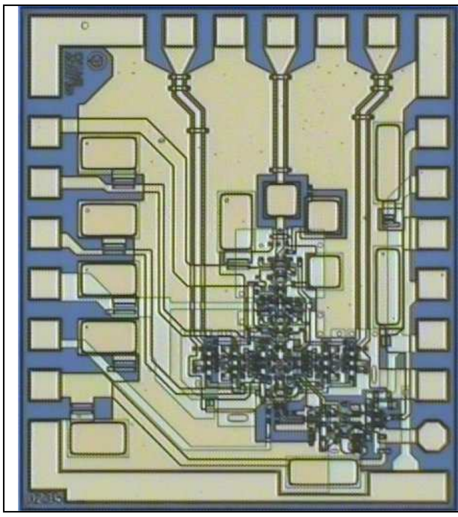


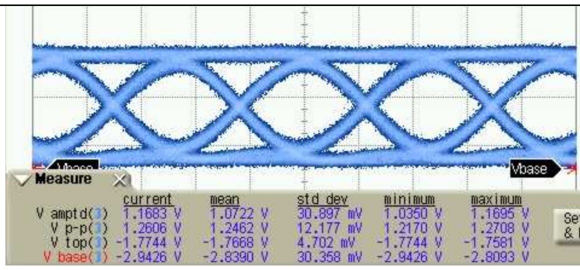
Extinction ratio as a function of EAM length (10 QW, tensile strain), illustrating the superiority of the AlGaInAs system efficiency.



Scanning Electron Microscopy image of a SI-BH waveguide cross-section

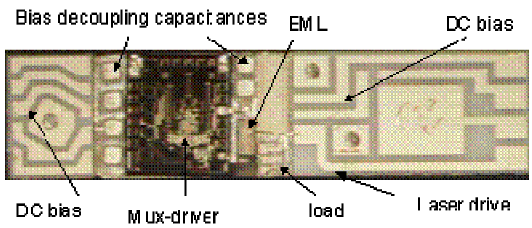
- InP Heterojunction Bipolar Transistors are well suited for the design of high-speed mixed-signal circuits. A processing technology (self-aligned, triple mesa structure, on 3” SI InP substrate) was developed in the early phase of GIBON, with an emitter width of 0.7 µm. HBTs were demonstrated, characterized by cut-off frequencies in the 270-300 GHz range (Fmax and Ft respectively), and breakdown voltage of 4V. Several types of circuits were then designed and fabricated:
    - Amplifiers specifically designed as EML drivers, providing a 1V output swing voltage with an output offset of -2.5 V.
    - Driver amplifiers with larger output voltage. With the lumped amplifier design, output voltage is > 2V, with a maximum differential output voltage reaching > 2x2V using the two complementary outputs.
    - Selector and Flip-Flop ICs were also designed and fabricated for the MUX and DE-MUX needs. Good operation of these circuits was checked at 107 Gbit/s, and were either provided as chips for the GIBON Rx or directly integrated with drivers for the GIBON Tx.



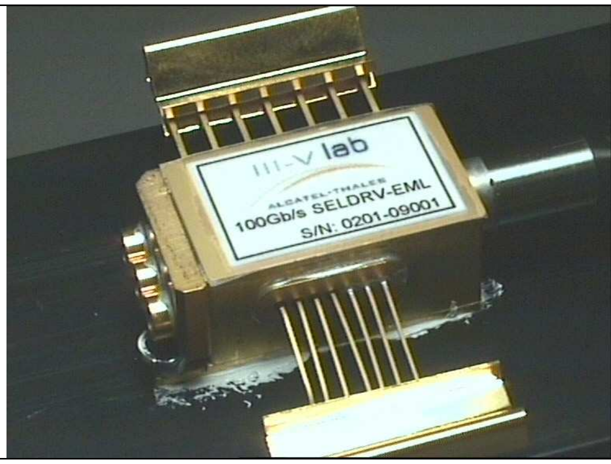


Microphotograph of the selector-driver chip. Input data and clock are coming from the pads at the top; the output signal is generated at the pad in the lower right, to ease the EML pigtail-ing. The eye diagram above is measured at 86 Gbit/s.

- Different schemes for the integration of the EML and the associated selector-driver in the transmitter module were investigated:
  - In a first integration scheme, a bias T is inserted between the driver and the EML to provide the requested bias voltage to the EML. This scheme was used for the 100 Gbit/s demonstration reported at OFC'09. However this approach is prone to possible impairments related to the 100 Gbit/s signal propagation through connectors and lines (losses and jitter).
  - In the retained design, the specific driver (with output voltage offset and output pads in a corner of the die), is mounted next to the EML with a direct wire connection. This assembling approach was checked to introduce minimal losses, and a 2dB Extinction Ratio was measured at 86 Gbit/s.

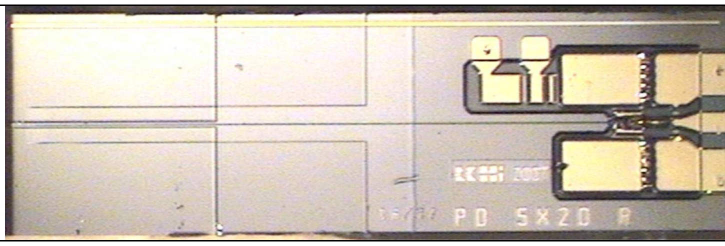


Carrier with interconnected driver, EML and load resistance (above). On the right is the completed module with the 3 input con-nectors and output fiber pigtail



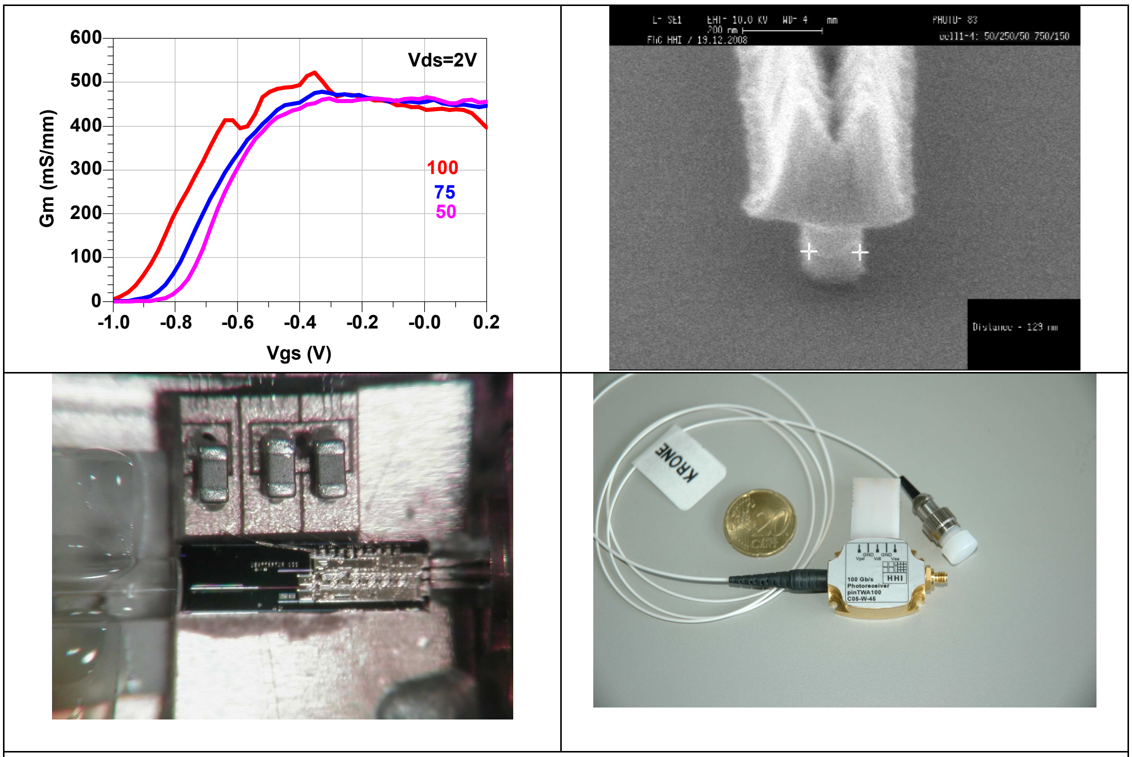
3.3 **WP3 Receiver Integration** (Lead partner: HHI)

- Large bandwidth photodiodes of the waveguide type can be integrated within Photonic Integrated Circuits owing to their waveguide structure; they can also be integrated with electronic preamplifiers owing to the Semi-Insulating InP substrate on which they are grown. In GIBON, such photodiodes have first been optimized for their operation at 100Gbit/s (pin mesa size, steering from the the input waveguide, input taper, electrical termination …).



Passivated waveguide-integrated photodetector with spot-size converter, termination resistor and biasing network. For 5x20 μm^2 sized, AR-coated photodiodes, responsivity >0.6 A/W, bandwidth > 100GHz and polarization loss dispersion < 0.25 dB were achieved.

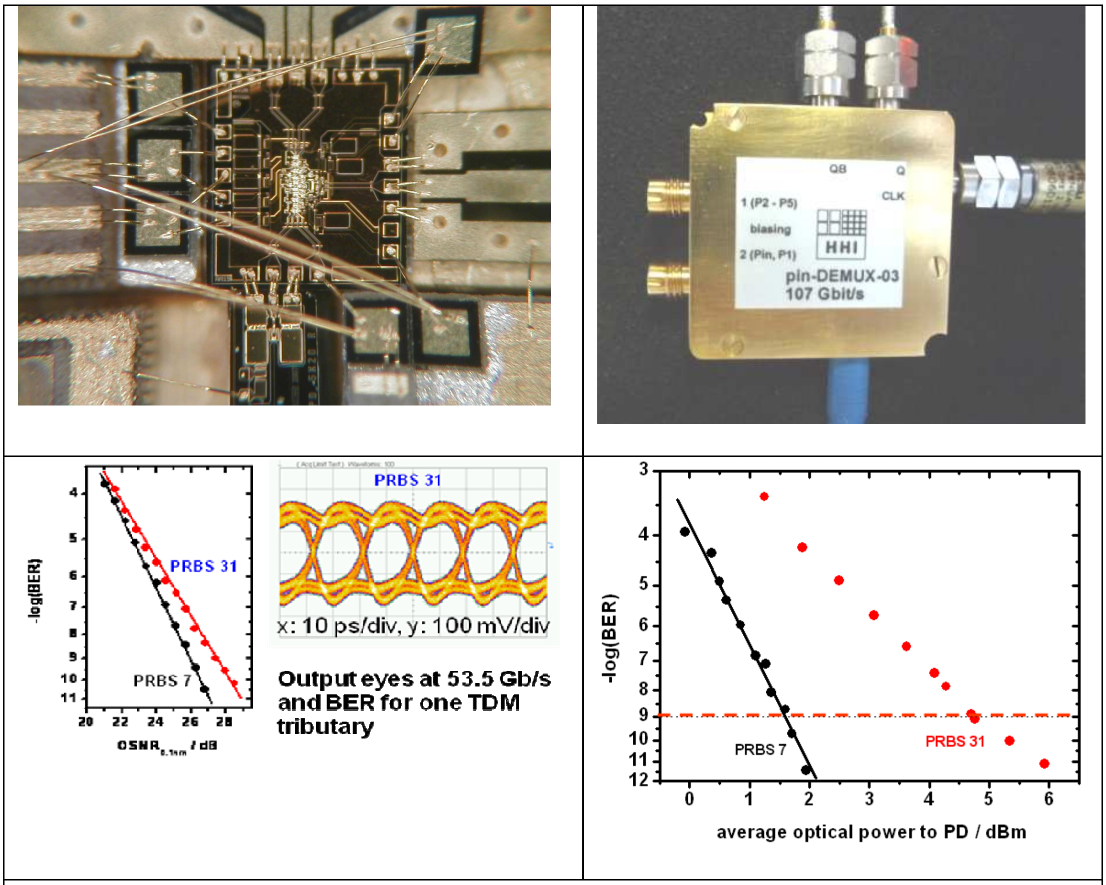
- pin-TWA OEIC (OptoElectronic Integrated Circuit) photoreceivers were designed and fabricated, associating a waveguide type photodiode and a 5-stage travelling wave preamplifier made in the InP HEMT technology. Specific developments were necessary to produce working devices.
  - Tuning the HEMT process, usually performed on the HEMT layer stack directly grown onto the SI substrate, to fit the situation of having the MOVPE grown SI waveguide layers in between.



HEMT transconductance for various gate width & SEM view of the 130nm gate (upper left & right); view of the pigtailed pin-TWA OEIC & packaged photoreceiver (lower left & right)

- Defining a process suited to the non planar OEIC, in particular for the e-beam writing of the short gate (≈ 100 nm length).
- Owing to the high transconductance obtained (750mS/mm intrinsic gain before BCB passivation) the gain provided by the TWA amounted to 4.7 dB.

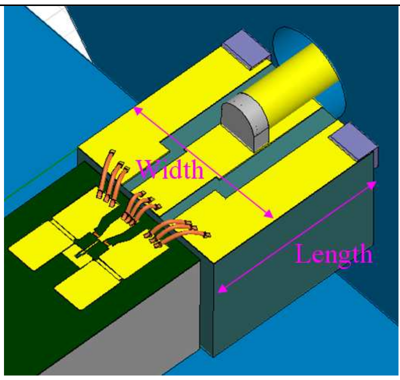
- By combining a high-speed photodiode and a decision Flip-Flop in a same package, a high sensitivity demultiplexing receiver was assembled. The InP-based 1.55 µm high-speed photodiode is of the waveguide-integrated type exceeding 105 GHz bandwidth. The de-multiplexing circuit is a Decision Flip-Flop fabricated in the InP Double heterojunction process. Co-packaging the two devices in a same module greatly reduces electrical losses due to separate housings and interconnections, by roughly 6 dB. World-leading sensitivity can then be obtained (see figure below). A same approach was followed with the co-packaging of a pin-TWA OEIC and decision Flip-Flop; preliminary characterization has shown full functionality, and a 4.7 dBm sensitivity at 10^{-9} BER.

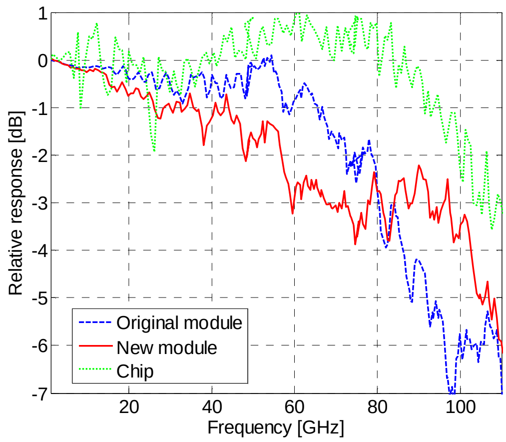


Co-packaging the photodetector chip and the DEMUX chip in one module housing with very short bonding wires (upper left and right) allows recovery of the tributaries without any error floor for the longest sequences, illustrating the good performance of the devices and the quality of the integration process (lower graph and eye diagram). Worth noting are the record sensitivities of +1.7 dBm and + 4.7 dBm at 107 Gbit/s for PRBS of 2^7-1 and 2^{31}-1 respectively.

3.4 **WP4 Device / Integration modelling** (lead partner: DTU/EMI)

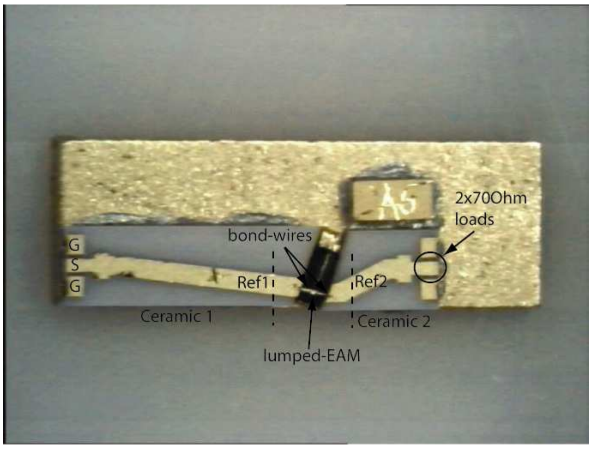
- EM modelling was used to investigate the performance of packaged photodetector modules for the Rx. Potential bandwidth limiting mechanisms have been identified and suggestions for package optimization have been proposed:
    - The transition from 1mm connector to conductor backed CPW was optimized. Guide-lines for via placement for low loss, resonance free transmission to 100 GHz was given.
    - A full 3D electromagnetic model of a photodetector chip, including transit-time ef-fects was developed. The EM model precisely predicts the measured characteristics of photodiode chips with different p-i-n junctions.
    - A new packaged PD module with a thick CPW structure was proposed. The new module exhibits improvement in the measured bandwidth up to 100 GHz and higher relative response over 80 GHz.



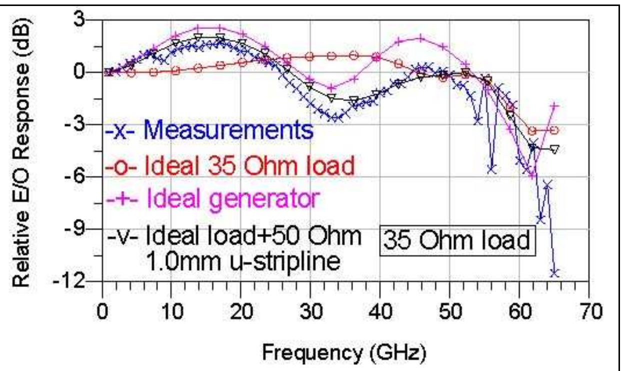


Top figure shows EM model of packaged PD module. Right figure shows the experimental re-sults for the new module exhibiting higher rela-tive response over 80 GHz.

- EM modelling was also used to investigate the performance of EML for the Tx. Methods were established for the EM simulation of electrical to optical transmission properties of EMLs, both on component level and within high-frequency assemblies:
    - Different EML electrode structure options were investigated and suggestions for the best one was given.
    - The cause of the unwanted wave-like effect observed in the measurements of the EML in a microstrip assembly was explained using an EM/circuit co-simulation approach.
    - The wirebond transition from microstrip lines to EML chip on InP was investigated. A step in ground plane height was shown to introduce little additional losses. Equivalent circuit models for wirebond transitions valid to 100 GHz were developed.

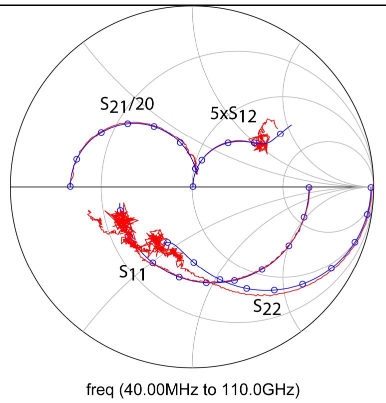


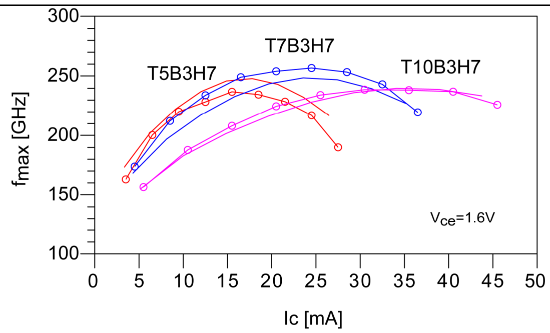
Microphotograph of EML wirebonded onto microstrip lines on ceramic substrate. The EML load is 35 Ohm.

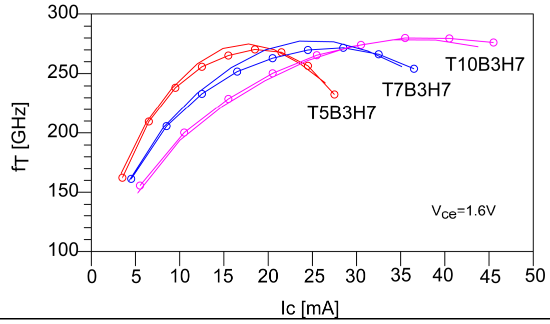


EM-circuit co-simulation of EML u-strip assembly. The wave-like behaviour observed in the measurements is caused by the reflection from the load due to the excessive length of the connecting microstrip line.

- A scalable large-signal model for 0.7µm InP DHBT devices has been developed within the GIBON project. The scalable large-signal model includes thermal effects and predicts the RF performance over bias and geometry:
    - o The large-signal model is based on a modified UCSD HBT model. The scalable model has been made available for both the Agilent ADS and Cadence Spectre simulators with slightly different features.
    - o In order to arrive at an accurate scalable large-signal model novel parameter extraction strategies for the small-signal model of HBT devices have been developed. In particular the fixed base resistance of sub-micron InP DHBT devices proved to be erroneously extracted using traditional methods. A novel extraction technique for the external base resistance developed within the project made the scalability of the models possible.







Top figure shows small-signal model fitting to 110 GHz (emitter length: 10µm; Vce=1.6V, Ic=20.5mA).Right figures show the frequency performance versus current for three 0.7µm InP DHBT device geometries (emitter lengths: 5µm, 7µm, 10µm).

4 Exploitation & Dissemination of knowledge

4.1 Section 1: Exploitable knowledge of GIBON

GIBON has generated a substantial amount of knowledge, which the partners are willing to exploit to a large extent in future R&D activities and projects: technological integration platforms for EAM-based Photonic Integrated Circuits and Photoreceivers for spectral-efficient transmission, but also large bandwidth packaging know-how and high bit rate transmission concepts.

Another path for exploitation of GIBON results is by teaching courses benefiting from activities carried out in GIBON; this holds in particular for DTU partners.

A third path for exploitation is through providing access to the achievements of GIBON to interested parties.
- Parameters for the scalable HBT model have been determined by DTU-EMI associated with the 1.5 and 0.7 µm HBT process developed by ATL. The methodology to determine the parameters is available at DTU-EMI to interested parties (contact T.K. Johansen).
- The EML process has been developed at ATL for several years. During GIBON, this process was further enhanced to provide structures suitable for very high-speed operation. In the frame of the CELTIC project 100GET, EML operating at 100Gbit/s (On-Off-Keying) and packaged with a matched driver will be delivered to Alcatel-Lucent Bell Labs in Stuttgart for assessment of their 100Gbit/s NRZ transmission potential.
- During GIBON, HHI happened to develop a passivation process for their very high-speed pin photodiodes. This process has been made available to u2t, as a GIBON result.
- Several 100Gbit/s mixed signal ICs (selector, full 2:1 MUX, driver, decision circuit, full DEMUX) have been developed in the course of GIBON. Ways to turn some of these ICs into commercial packaged prototypes is now under discussion, with one SME; other interested parties are welcome and should contact ATL (contact J. Godin).
- The demultiplexing pin photodiode (or demultiplexing pin-TWA) was a notable GIBON success. Both ATL and HHI are willing to turn this achievement into commercially available prototypes. As an extension to GIBON, more sensitive demultiplexing ICs and a full 1:2 DEMUX have been designed and fabricated. Following the currently done evaluation process, prototypes will be advertised on the HHI website (contact H-G. Bach).
- During the whole project, packaging of 100 Gbit/s O/E modules has been a topic of interest for ATL, HHI and DTU-EMI. I particular the later has developed a broad expertise which is now available to interested parties (contact T.K. Johansen).

Finally, GIBON partners have developed a broad knowledge about 100GBit/s opto-electronic and electronic technologies; the project is now over, but each partner is working on new developments in the same technical area, and each partner is open to further enquiries from interested parties.

4.2 Section 2: Dissemination of knowledge

Knowledge gained through GIBON has been disseminated by three channels: the first one is the various lessons, courses or presentations given to academic audiences by GIBON partners, using the know-how developed during the project; a second one is associated to publications or presentations during international conferences (see the following list); a third one is the GIBON website reporting on the main achievements.

1. "High-speed Miniaturized Photodiode and Parallel-fed Travelling-Wave Photodetectors Based on InP" *A.Beling, H-G. Bach, G.G. Mekonnen, R.Kunkel, D. Schmidt, IEEE J. Sel.Topics in QE, Vol.13 (2007) pp 15-21.*
2. **"Ultra-fast Efficient Photodiodes Exceeding 100 GHz Bandwidth"** *H-G. Bach, Invited paper, Int'l Conf. on Indium Phosphide & Related Materials, May 14-18 (2007), Matsue, Japan (Proc. pp. 71-76).*
3. **"Wide temperature Range Operation at 43 Gbit/s of 1550 µm InGaAlAs Electroabsorption Modulated Laser with Single Active Layer"** *A.Garreau, M-C. Cuizin, J-G. Provost, F. Jorge, A. Konczykowska, C. Jany, J. Décobert, O. Drisse, F. Blache, D. Carpentier, E. Derouin, F. Martin, N. Lagay, J. Landreau, C. Kazmierski, Int'l Conf. on Indium Phosphide & Related Materials, May 14-18 (2007), Matsue, Japan (Proc. pp. 358-360).*
4. **"Performances and Self-Heating Reduction of Submicron InP/InGaAs/InP heterojunction Bipolar Transistors"** *V. Nodjiadjim, M. Riet, P. Berdaguer, O. Drisse, E. Derouin, A. Scavennec, J. Godin, Workshop On Compound Semiconductor Devices and Circuits in Europe (WOCSDICE), May 20-23 (2007), Venice, Italy.*
5. " **Photoreceivers for 100 Gbit/s applications**" *A. Umbach, G. Unterbörsch, H-G. Bach, C. Schubert, R. Derks, J. Sinsky, IEEE/LEOS Summer Topical Meeting on Ultra-High Data-Rate Transmission, TuE4.2, 23-25 July 2007, Portland, Oregon (USA).*
6. **"**High-speed Integrated Modulators and Receivers**"** *Karl-Otto Velthaus, Heinz-Gunter Bach, invited paper, IPNRA, Salt Lake City, 2007.*
7. **"**Ultrafast Waveguide-integrated pin-Photodiodes and Photonic Mixers from GHz to THz Range" *H-G. Bach, invited paper, paper 5.5.1, 33rd ECOC 2007 (Berlin, Germany).*
8. **"Semi-insulating buried heterostructure 1.55 µm InGaAlAs electro-absorption modulated laser with 60GHz bandwidth"** *Ch. Jany, Ch. Kazmierski, J. Decobert, F. Alexandre, F. Blache, O. Drisse, D. Carpentier, N. Lagay, F. Martin, E. Deroin, T. Johansen, Ch. Jiang, post deadline paper, 33rd ECOC 2007 (Berlin).*
9. "EM Simulation Accuracy Enhancement for Broadband Modeling of On-Wafer Passive Components**"** *T. Johansen, C. Jiang, D. Hadziabdic, V. Krozer, EuMIC, October 8-10, 2007, Munich, (Germany).*
10. "**Optimization of Integrated Electro-Absorption Modulated Laser Structures for 100 Gbit/s Ethernet Using Electromagnetic Simulation**" *T. Johansen, C. Kazmierski, C. Jany, C. Jiang, V. Krozer, IMOC 2007, November, Salvador, Brazil.*
11. "**A Novel Method for HBT Intrinsic Collector Resistance Extraction from S-Parameters**" *T.Johansen, V.Krozer, D.Hadziabdic, C.Jiang, A.Konczykowska, J-Y. Dupuy, APMC 2007, December, Bangkok, Thailand.*
12. "**Optimization of Packaging PIN Photodiode Modules for 100 Gbit/s Ethernet Applications**" *C. Jiang, G.G. Mekonnen, T. Johansen, V. Krozer, H-G. Bach, APMC 2007, December, Bangkok, Thailand.*
13. "Parallel-fed Traveling Wave Photodetector for > 100 GHz Applications**"** *A. Beling, J.C. Campbell, H-G. Bach, G.G. Mekonnen, and D. Schmidt, IEEE J. Lightwave Techn. Vol.26 (2008) pp 16-20.*
14. "A 107-Gbit/s Opto-Electronic Receiver Utilizing Hybrid Integration of a Photodetector and Demultiplexer**"** *J.H. Sinsky, A. Adamiecki, L. Buhl, G. Raybon, P. Winzer, O. Wohlgemuth, M. Duelk, C.R. Doerr, A. Umbach, H-G. Bach, D. Schmidt, IEEE J. Lightwave Techn. Vol.26 (2008) pp 114-120.*
15. "A high conversion gain Q-band InP DHBT sub-harmonic mixer using LO frequency doubler**"** *T.K.Johansen, J.Vikjaer, V.Krozer, A.Konczykowska, M.Riet, F.Jorge, T.Djurhuus, IEEE Trans. Microwave Theory and Techn. Vol56 (2008) pp 613-619.*

16. "Integration potential of Waveguide-integrated Photodiodes: self-powered Photodetectors and sub-THz pin-Antennas" *H-G.Bach, R.Kunkel, G.G.Mekonnen, D.Pech, T.Rosin, D.Schmidt, T.Gaertner, R.Zhang, OFC/NFOEC, Feb 24-28, 2008, San Diego (USA).*
17. "**43 Gb/s operation of a directly connected driver and electro-absorption modulated laser for low-cost packages"** *A.Konczykowska, M.Riet, F.Jorge, F.Blache, C.Jany, J.Décobert, F.Alexandre, C.Kazmierski, OFC/NFOEC, Feb 24-28, 2008, San Diego (USA).*
18. "**Improved Extrinsic Base Resistance Extraction for InP DHBT devices"** *T. Johansen, V. Krozer, V. Nodjiadjim, A. Konczykowska, J.-Y. Dupuy, German Microwave Conference, Hamburg, Germany, March 2008.*
19. "Wireless and photonic high-speed communication technologies for over 100-G applications**"** *A. Konczykowska, V.Krozer, MIKON, 19-23 May (2008) Wroclaw, Invited plenary presentation.*
20. "Millimeter-wave and High-speed MMIC design, interconnects and packaging" T.K. *Johansen, C. Jiang, D. Hadziabdic, V. Krozer, Session WMK on High-speed electronic technologies for 100-G communications, Int'l Microwave Conference, Atlanta (USA), June 15-20 (2008).*
21. "**Preliminary specifications for 100Gigabit Optical Ethernet**" *M. Berger, J. Seoane, C. Jespersen, L. Dittman, Proceedings of Applied Electromagnetics, Wireless and Optical Communications (Electroscience'08) Trondheim (Norway), July 2-4 (2008).*
22. "**High-speed AlGaInAs Electroabsorption Modulated Laser with Optically Equalized Error-Free Operation at 86 Gb/s**" *C. Kazmierski, C. Jany, J. Décobert, F. Alexandre, F. Blache, A. Scavennec, P.J. Winzer, C.R. Doerr, G. Raybon, A. Adamiecki, T. Johansen, European Conference on Optical Communications, Brussels (Belgium) Sept. 21-25 (2008).*
23. "**InP Waveguide-integrated pin-Photodiode Hybrid Packaged with an HBT-DEMUX-Chip for Receiver Modules of 80-100 Gb/s Data Rates**" *G.G. Mekonnen, B. Hüttl, H-G. Bach, D. Pech, T. Rosin, C. Schubert, A. Konczykowska, F. Jorge, M. Riet, European Conference on Optical Communications, Brussels (Belgium) Sept. 21-25 (2008)*
24. "**Submicron InP DHBT technology for high-speed, high-swing mixed signal ICs**" *J.Godin, V. Nodjiadjim, M. Riet, P. Berdaguer, O. Drisse, E. Derouin, A. Konczykowska, J. Moulu, J-Y. Dupuy, F. Jorge, J-L. Gentner, A. Scavennec, T. Johansen, V. Krozer, Compound Semiconductors IC Symposium, Monterey (USA) October 12-15 (2008).*
25. **"**High speed Photodetectors: Self-Biasing and High-Power Behaviour**"**, *H.-G. Bach, invited talk at the 214th Meeting of The Electrochemical Society", Honolulu (Hawaii) October 12-17 (2008).*
26. "A technological platform for 10-100G photonic sources*" Ch. Kazmierski, Invited talk at the OSA Annual meeting, Frontiers in Optics, Rochester (USA) October 19-23 (2008)*
27. " **Packaging aspects of Photodetector Modules for 100 Gbit/s Ethernet Applications**" *C. Jiang, G.G. Mekonnen, V. Krozer, T.K. Johansen, H-G. Bach*, EuMiC, Amsterdam, The Netherlands, Oct. 27-31 (2008).
28. **"Analysis of Hybrid-Integrated High-Speed Electro-Absorption Modulated Lasers Based on EM/Circuit Co-simulation"**, *T. K. Johansen, V. Krozer, C. Kazmierski, C. Jany, F. Blache and C. Jiang, accepted for oral presentation at IEEE MTT-S International Microwave Workshop on Signal Integrity and High-Speed Interconnects, Guadalajara, Mexico, Feb. 2009.*
29. **"100Gb/s Operation of an AlGaInAs Semi-Insulating Buried Heterojunction EML"** *C. Kazmierski, A. Konczykowska, F. Jorge, F. Blache, C. Jany, A. Scavennec, OFC/NFOEC March 22-26, 2009, San Diego (USA).*
30. **"Demultiplexing Photoreceivers Comprising pin- and pin TWA Frontends for 107 Gbit/s ETDM"** *H-G. Bach, G.G. Mekonnen, R. Kunkel, C. Schubert, D. Pech, T. Rosin, A. Konczykowska, F. Jorge, A. Scavennec, M. Riet, OFC/NFOEC, March 22-26, 2009, San Diego (USA).*

31. "**Large Bandwidth Detectors and Receivers for Telecom and Wireless"** *H-G. Bach, invited paper, European Workshop on Photonic Solutions for Wireless, Access and in-House Networks, Duisburg 18-20 May 2009*
32. **"Demultiplexing Photoreceivers Comprising pin- and pinTWA Frontends for 107 Gbit/s ETDM"** *H-G. Bach, G.G. Mekonnen, R. Kunkel, C. Schubert, D. Pech, T. Rosin, A. Konczykowska, F. Jorge, A. Scavennec, M. Riet, European Workshop on Photonic Solutions for Wireless, Access and in-House Networks, Duisburg 18-20 May 2009*
33. **"IST-GIBON"** *C. Kazmierski, A. Konczykowska, F. Jorge, F. Blache, C. Jany, J. Godin, A. Scavennec, H-G. Bach, G.G. Mekonnen, R. Kunkel, D. Schmidt, A. Seeger, D. Pech, M. Berger, J. Seoane, C. Jespersen, V. Krozer, T.K. Johansen, C-H. Jiang, oral & poster presentations, European Workshop on Photonic Solutions for Wireless, Access and in-House Networks, Duisburg 18-20 May 2009*
34. **"Hybrid Co-Packaged Receiver Module with pin-Photodiode Chip and DEMUX-IC for 107 Gb/s Data rates"** *G.G. Mekonnen, H-G. Bach, R. Kunkel, C. Schubert, D. Pech, T. Rosin, A. Konczykowska, F. Jorge, A. Scavennec, M. Riet, ECOC, Vienna, Septembre 2009*
35. **"Packaging of Photodetector Modules for 100Gbit/s Applications Using Electromagnetic Simulations "** *C. Jiang, , V. Krozer, H-G. Bach, G.G. Mekonnen, T.K. Johansen, EuMC, Rome, Italy, Septembre 2009.*
36. **"Electro-absorption modulator laser for cost-effective 40 Gb/s networks with low drive voltage, chirp and temperature dependence"** *G. Aubin, J. Seoane, K. Merghem, M.S. Berger, C.F. Jespersen, A. Garreau, F. Blache, C. Jany, J-G. Provost, C. Kazmierski, P. Jeppesen, Electron. Letters (accepted for publication).*
37. **" InP DHBT selector-driver with 2x2.7 V swing for 100Gbit/s operation"** *A. Konczykowska, J-Y. Dupuy, F. Jorge, M. Riet, J. Moulu, J. Godin, Electron. Letters (accepted for publication)*

5 Conclusion

In the last three years, significant achievements were reported by GIBON, in the area of packaged opto-electronic components for 100 Gbit/s NRZ transmission.

- High-speed optoelectronic transmitters: beyond the first report by GIBON of an EML operating at 100 Gbit/s at last OFC, a major achievement was the demonstration of a suitable packaging technology. The performance achieved (2dB extinction ratio) was limited by the mismatch between the DC characteristics of EML and driver.
- High-speed optoelectronic receivers: very high-speed packaged photodiodes with suitable bandwidth and responsivity have been developed, as well as photodetectors with internal gain provided by an integrated TWA. Moreover demultiplexing photoreceivers were developed, and error-free operation demonstrated at 107 Gbit/s.
- Associated microelectronics: GIBON achievements in high-voltage driver amplifiers based on the InP HBT are also world-leading results.

These achievements are resulting from the close collaboration of partners within GIBON, and the project was instrumental in reaching such results.

While first standards are expected soon, regarding 100G Ethernet and related technologies, trends are towards using available technologies for client interfaces: 10x10 Gbit/s or more likely 4x25 Gbit/s in a multilane approach, or high spectral efficiency coding (e.g. DP-QPSK) for line transport (OIF recently retained DP-QPSK for long haul DWDM transmission). However it was shown through the GIBON project, that 100 Gbit/s OOK transmission has a real potential for transmission over spans of several tens of km. The inherent simplicity of the OOK modulation scheme is still a strong and actual reason to further develop this technology for future standardisation and deployment.