IPHOBAC

Integrated Photonic mm-Wave Functions For Broadband Connectivity

Publishable Final Activity Report

Reporting period

1 June 2006 – 30 November 2009

Proposal/Contact no. **035317**
Instrument **Integrated Project**
Thematic Priority **Photonic mm-Wave Functions for Broadband Connectivity**
Start date of project **1 June 2006**
Duration **42 months**

Project coordinator name **Dr. Andreas Stöhr**
Project coordinator organization name **Universität Duisburg-Essen**

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0 Publishable Executive Summary

The field of Microwave Photonics has seen tremendous growth recently and is generally considered as a disruptive technology for several radio-frequency applications. By integrating the best out of the photonic and the radiofrequency engineering worlds, Microwave Photonic technologies can enable broadband connectivity with some unique advantages that can not easily be achieved by other competing technologies such as all-electronic systems. Besides the benefits of a low transmission loss and a low weight due to the use of optical fiber for radio-frequency transport, Microwave Photonic technologies furthermore enable low phase noise radio-frequency generation and ultra-wide frequency tunability as well as broadband modulation capabilities over the entire microwave, millimeter-wave, and terahertz bands. Since the early experiments in the late 1970s, the field has expanded significantly, addressing today first substantial commercial applications.

In 2006, at the beginning of the IPHOBAC project, the demand for Microwave Photonic technologies was further fueled by the ever increasing operating frequencies utilized in many applications. This is even more the case today; according to a recent IPHOBAC survey, the interest in Microwave Photonic technologies is especially strong in a growing number of applications utilizing the millimeter-wave frequency range (30-300 GHz).

Main Objectives

It was thus the general aim of the IPHOBAC (Integrated Photonic mm-Wave Functions for Broadband Connectivity) project to foster the development of Microwave Photonic component and system technologies mainly for applications in communications, radar/sensing and instrumentation. IPHOBAC has emerged from the two previous European Network of Excellences NEFERTITI and ISIS. IPHOBAC itself integrated a chain of well-experienced competent partners with a complementary portfolio: From academic research partners over national research institutes to industrial R&D centers, from public technology centers over commercial component manufacturers to end-users. Altogether the IPHOBAC consortium was comprised of 11 partners with the five industrial partners Alcatel-Thales III-V Lab, CIP Technologies Ltd, U2T Photonics AG, Thales Aerospace and France Telecom Orange Labs. The six academic partners were CNRS-Lille, University College London, University Duisburg-Essen, University of Valencia, University of Ljubljana and the Kista Photonics Research Center. The project was coordinated by Andreas Stöhr from University Duisburg-Essen.

IPHOBAC has been an application driven project in the research fields of novel and advanced photonic components, photonic and electronic integration as well as photonic enabled systems. The project had a set of innovative approaches and some very ambitious objectives; aiming at the development of several novel and advanced mm-wave photonic components, two integrated functional sub-systems for the optical generation, modulation and emission of mm-wave signals as well as the demonstration of the component's ability to enabe innovative systems with advanced performances such as super-broadband wireless communications, mm-wave sensors and frequency tunable mm-wave sources for instrumentation applications.

An overview upon its technical objectives is presented in Figure 1. For each addressed application field (communications, radar/sensing and instrumentation), there was at least one challenging system demonstration planned including:

- Super-broadband millimeter-wave wireless link with >10 Gb/s capacity
- Millimeter-wave sensor systems for security applications
- Frequency tunable 30-300 GHz photonic mm-wave source

Those planned system demonstrations provide guidance for the definition of the novel and advanced photonic components as well as integrated modules to be developed. Among them were:

- Hybrid integrated low-phase noise photonic mm-wave sources for DC-110 GHz
- Integrated photonic frequency tunable photonic mm-wave sources for 30-300 GHz
- Advanced high-speed 110 GHz packaged photodiode modules
- Novel high-frequency 30-300 GHz packaged photonic transmitter modules
- Advanced packaged quantum-dash mm-wave mode-locked laser modules
- Novel frequency tunable (30-300 GHz) dual-wavelength DBR and DFB lasers
- Novel reflective-type packaged optical 60 GHz transceiver modules
- Advanced 110 GHz modulators with and without integrated SOA
- Advanced SOI phase shifters for 10 Gb/s operation

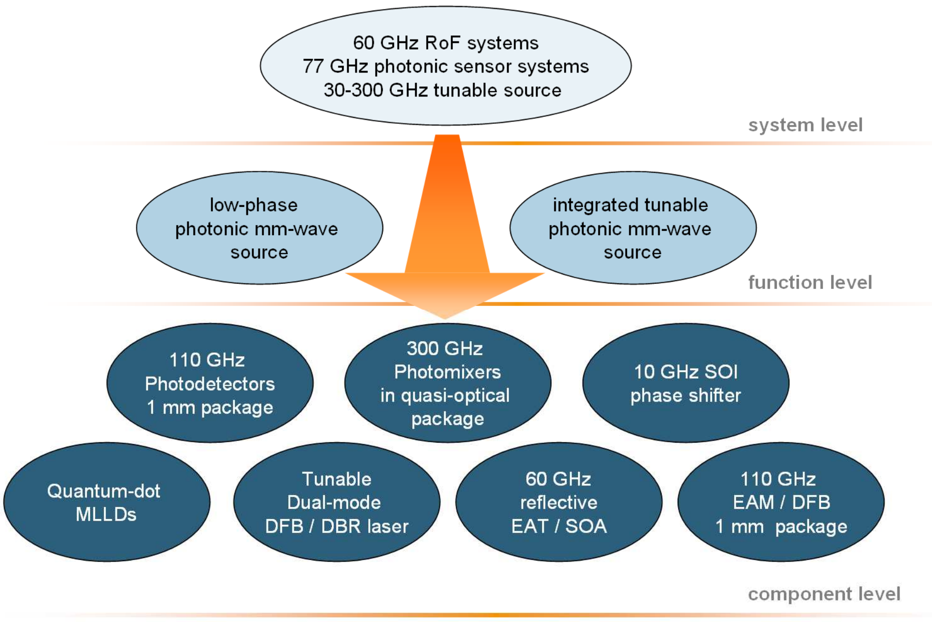

Figure 1 Overview on the technical objectives of the IPHOBAC project on the system level, the functional or sub-system level as well as on the component level.

Key technological and technical achievements

With respect to technological and technical developments, IPHOBAC has achieved several breakthroughs in the fields of photonic component research, photonic integration and photonic enabled systems as compared to the state-of-the-art. In several cases, the project even succeeded in demonstrating world record performances.

For example, the project has successfully designed, fabricated and commercialized packaged broadband (f_{3dB}=110 GHz) 1.55µm photodiode modules with a coaxial W1 output connector. To our knowledge, these high-speed PD modules are the only ones commercially available world wide. This does not only provide proof for the maturity of the technological developments, it also helps in fostering the European position in photonic components. For high-power operation, the project furthermore developed packaged high-speed PD modules with a f_{3dB}~50-75 GHz which has been successfully employed for high-power mm-wave generation with up to +4.5 dBm output power at 110 GHz.

IPHOBAC also succeeded in designing, fabricating and commercializing photonic transceivers for 60 GHz broadband wireless systems. Again, to our knowledge there is no other commercial source for such photonic components.

The project has furthermore developed novel and advanced photonic components which clearly have a potential for commercialization and for which several commercial interests were already received by some of the project partners. Among those components are packaged photonic 30-300 GHz transmitter modules, packaged mode-locked quantum-dash laser modules for fixed frequency mm-wave generation (e.g. at 55, 60 or 77 GHz) and amplified tunable twin lasers (dual-wavelength output) with integrated mode expanders that make them suitable for hybrid integration in 30-300 GHz photonic sources.

IPHOBAC has also worked on the development on 100 GHz travelling-wave modulators with integrated DFB laser chips as well as on reflective 60 GHz transceivers with integrated SOA amplifiers. Because the truly challenging technological fabrication process of the two photonic integrated components has hampered the timely provision of fully-functional chips, the consortium has additionally developed individual reflective transceivers with a 3dB-bandwidth in excess of 60 GHz (simulated bandwidth f_{3dB}~105 GHz) and a 7-8 dB extinction ratio as well as electroabsorptive modulated lasers (EML) with an f_{3dB} of up to 65 GHz and a 5 dB/V modulation efficiency. Those individual components are ready for packaging and were partially packaged.

By employing some of the photonic components invented in IPHOBAC, the consortium has performed a number of system experiments which not only demonstrate the usefulness of the IPHOBAC components but also have allowed the partners to demonstrate systems with record performances.

Among those system demonstrations are 60 GHz wireless indoor systems for up to 15m wireless path links with capacities up to 3 Gb/s, 60 GHz outdoor wireless links for access and mobile backhauling applications with record capacities up to 12.5 Gb/s and experimentally proved wireless distances up to 50 m (expected theoretical maximum wirless link length when also considering heavy rain is expected to be in the km-range). IPHOBAC also demonstrated a 60 GHz wireless link by employing photonic vector modulation with a capacity of 10 Gb/s. Also, compact modules for wireless HDTV transmission in the 60 GHz window were fabricated.

By using an OFDM-16QAM modulation format, the project has even succeeded in demonstrating a photonic wireless system providing world record capacities and efficiencies of up to 27 Gb/s and 3.86 bit/s/Hz, respectively.

With respect to instrumentation and sensor applications, the project has developed several hybrid or fully integrated photonic sources for low-phase noise fixed frequency and frequency tunable mm-wave generation. Ultra-wideband 30-300 GHz frequency-tunable photonic mm-wave generation with output power levels up -11dBm @ 110 GHz has been demonstrated and an advanced optical phase lock loop (OPLL) for 10-300 GHz signal generation with -20 dBm output power @ 300 GHz was also developed. Those photonic mm-wave sources employed different IPHOBAC components including the photonic transmitter, the dual-wavelength lasers, mode-locked lasers as well as advanced electronic phase detectors which were also developed in the project. Also, for W-band operation, a hybrid photonic mm-wave source using external modulation and the IPHOBAC photodetector modules were developed. Using the hybrid photonic mm-wave source, frequency-tunable (75-110 GHz) mm-wave generation with up to 0 dBm output power and phase noise levels of -70 dBc/Hz @ 10kHz offset from a 100 GHz carrier were achieved. When operated in fixed-frequency condition, the phase noise at 100 GHz is as low as -85 dBc/Hz @ 10 kHz offset.

Two patent / patent applications were filed to ensure future exploitations.

To study the usefulness of the developed components in sensing and security applications, several system demonstrations at around 38 GHz and 77 GHz were performed including a continuous-wave (cw) radar experiment, a frequency-modulated (FMCW) radar sensor demonstration as well as a W-band signal remoting and distribution system.

Here, a chirp locking at 38 GHz was realized over 1.3 GHz and a chirped source remoting at a recurrence frequency of a few tens of Hz was demonstrated. The laser additive phase noise was measured to be ~-95 dBc/Hz at 33 GHz and ~-80 dBc/Hz at 77 GHz.

These demonstrations showed that many applications in the field of transportation, security, and sensors could be envisaged. Particularly, the use of IPHOBAC optical links are of great interest as in comparison to state of the art waveguide techniques, losses in optical links are independent of the distance. Therefore, IPHOBAC components could allow new possibilities such as the distribution of a local oscillator in a sensor architecture, or the deployment of a security sensing network over a large area with a central processing unit linked to each radar element by an optical link.

Key dissemination actions

The IPHOBAC consortium has actively disseminated its results and achievements. In total there were more than 100 press releases published world wide which reported on the IPHOBAC achievements in all kind of media. The consortium has published 66 scientific articles (several were invited ones) in high-level journals and at almost each relevant international conference. The project was furthermore invited to report about its achievements to several international organizations and market leading companies. Demonstrations and meetings were organized for the IEICE, the OIDA, Alcatel-Lucent, Ericsson, Nokia-Siemens Networks, Rohde&Schwarz, Siemens to name just a few. In total, 23 presentations were made and altogether 9 meetings with external industrial partners were organized. Furthermore, the consortium presented its developments at four international exhibitions and has organized a well attended workshop with about 80 participants of which more than 60 were no IPHOBAC members.

As regards the awareness of the project in the relevant research and industrial field, it can be concluded that the IPHOBAC achievements are well known and were well perceived internationally. For example, the IPHOBAC demonstration at ICT 2008 was voted by the more than 4000 delegates as one out of the Top 10 demonstrations among 200 present. IPHOBAC itself is even listed among the 10 highlight EC projects out of the last five years among all research disciplines by the European Research Commission.

Further examples of the international awareness of the project and its achievements can be seen e.g. from Science Daily in the US which titled “Breakthrough for Post-4G Communications – New Components from Europe” or the Communications Research Unit of the European Commission who stated with respect to the wireless experiments that **“**This is definitely of high interest to us as this might represent a real breakthrough to go far beyond current state-of-the-art data rate in wireless systems**”** The Pravda in Russia titled **“**Europe demonstrates Photonic Wireless HDTV Transmission**”** and the well known European based Compound Semiconductor magazine titled **“**A new Class of InP Photonic Systems**”.** The US based IEEE Microwave Magazine and THz Network both titled **“**IPHOBAC pushes Microwave Photonic Boundaries”. The “TheNextBigFuture” magazine in the US even stated “While several companies in Japan and the USA have been working on merging optical and radio frequency technologies, IPHOBAC is the world’s first fully integrated effort in the field”.

Main exploitation activities

From project start, the small and medium size enterprises participating in IPHOBAC were building upon the design and prototyping efforts of their own research and of the academic partners to prepare for the commercialization of components in the target markets. The development of products was planned in continuation of the project work both on the level of semiconductors and on the level of packaged products and subsystems. However, first prototypes of targeted components have already been introduced to the market: High-power photodiodes with 100 GHz bandwidth are now commercially available from two IPHOBAC partners and also the 60 GHz reflective type electroabsorption (R-EAT) transceivers are now commercially available.

Furthermore, a patent on novel and innovative high-performance and low-cost PRBS generation was filed with the intention to establish a spin-off company focusing on low-cost and high-performance devices and (sub-) systems and specialized services (modeling and consultancy). A second patent on novel optical mm-wave source was filed with the intention to secure further exploitation of the respective developments in the field of optical low-phase noise mm-wave generation.

The industrial partners did contribute their in depth knowledge on the markets of targeted applications. Their contributions to the project ensured from the very beginning, that the specifications and techno-economical requirements of the market are guiding the technological developments. A current update of the latest application trends and market information in the telecommunications, transport, security and instrumentation markets has been provided as well as an assessment of the technological development status of the different results in terms of an industrial evaluation scheme.

All consortium partners are committed to use all their individual and joint efforts to ensure a solid exploitation of the IPHOBAC results. Depending on the nature of the results achieved, short or long term exploitation scenarios have been defined for the results of the project: A total of 22 exploitable results have been identified by the project partners (see also list above) and first steps to commercialize IPHOBAC components have already been taken.

Apart from providing a direct or indirect path to the end-user markets the industrial partners also benefited directly from the IPHOBAC results. An evidence for this is given by the fact, that some partners have been enabled to apply for the development of a W-band optical mm-wave generation system for the European Space Agency (ESA) supported by the results on low-phase noise optical mm-wave generation achieved within IPHOBAC.

Apart from the wide field of system applications in instrumentation and sensing and as a result of the excellent dissemination of the IPHOBAC results some initial contacts with all European tier 1 system providers for the wireless communications network have been established, undertaking exploitation endeavors outside the consortium. In one case this has already led to joint research activities. These very promising efforts of exploiting the knowledge on broadband photonic wireless links developed within the IPHOBAC project for mobile backhauling applications will be continued between IPHOBAC partners and the world leading system suppliers. In addition to the field of potential applications in the mm-wave photonics area additional exploitation path has been identified in the field of 100 Gigabit Ethernet optical systems.

In conclusion, despite the forward looking nature of the program, the exploitation prospects of the IPHOBAC project are excellent, both by providing direct paths towards the commercialization of products based on IPHOBAC R&D and by enabling new application technologies to support the European industry to gain leadership in photonic-mm-wave systems.

1 Project Execution

1.1 Summary description of the project objectives

IPHOBAC aimed at developing innovative mm-wave photonic components and integrated functions generically based upon the combination of radio and optical technologies. IPHOBAC has had a set of innovative approaches and ambitious objectives for developing altogether seven novel and advanced mm-wave photonic components and two integrated functional sub-systems for the generation, modulation and emission of mm-wave signals. IPHOBAC aimed at bringing mm-wave photonics components and integrated functions to a level of maturity to enable take-up actions by industry. The novel and advanced components as well as the integrated functional sub-systems developed in IPHOBAC were developed to support multiple mm-wave applications in broadband wireless communications, sensor, and instrumentation.

Proposal/Contract no.	035317
Contract type	Integrated Project
Start date	1 June 2006
End date	30 November 2009
Project duration	42 months
Total budget	11M€ (EC contribution 5.83 M€)
Total Effort	798.4 person months
Cluster	SO 2.5.1. Photonic Components

Table 1.1 Project data at a glance

This document summarizes the activities carried out and the related technical achievements reached during the full project duration (1 June 2006 – 30 November 2009).

Overall, IPHOBAC truly had an impressive number of ambitious and very challenging technical and technological goals. The project aimed at developing three system level demonstrators utilizing not less than seven novel or advanced (integrated) photonic components which were not available at the project start. The project further aimed at integrating two functional photonic sub-systems.

The main demonstration activities of IPHOBAC project on the system level were to develop functional and compact demonstrators utilizing IPHOBAC components and sub-systems for the following applications:

- Broadband 60GHz RoF wireless delivery systems
- FMCW mm-wave radar
- Frequency tunable mm-wave synthesizer

The main technological objectives at the (sub-) system level were:

- To develop a very compact and low driving power, tunable optical mm-wave source with integrated antenna, to be used up to 300 GHz
- To develop an integrated optical phase locked loop to achieve high purity mm-wave signals, associated with the mm-wave modulated photonic sources developed in the project.
- To implement photonic vector modulator and demodulator schemes employing the components developed in IPHOBAC and demonstrate the wireless transmission of a 10 Gbit/s signal in a laboratory environment.

The main technological objectives of IPHOBAC on the component and photonic integration level were:

- To develop advanced quantum dot mode-locked DBR laser and dual-mode DFB/DBR lasers for the generation of spectrally pure, low phase noise mm-wave signals with the following properties
- To develop frequency tunable (30 – 300 GHz) for dual-wavelength DFB/DBR lasers
- To develop high-frequency packaged photodiodes based upon advanced TW and UTC approaches with a 3dB bandwidth up to 110 GHz for broadband applications and a target output power level of ~1mW between DC–100GHz.
- To develop ultra-wideband and high output power photomixers with integrated antennas based on TW and UTC approaches for optical mm-wave transmission within the frequency range of 30-300 GHz and a target peak output power level of ~0.1 mW.
- To develop travelling-wave modulators integrated with a DFB laser featuring a 3dB bandwidth of 90 GHz as well as advanced high-frequency 100 GHz modulators.
- To develop a novel 60GHz reflection-type transceiver (R-EAT) integrated with a semiconductor optical amplifier (SOA) as well as advanced 60 GHZ reflection-type transceiver.
- To develop an optical phase shifter on SOI technology for 10Gb/s photonic vector modulation

1.2 Contractors involved

IPHOBAC integrates a chain of partners, from academic research to industrials, from technology centers over component manufacturers to end-users, all known for their previous achievements in microwave photonic components and technologies. All partners of the Consortium are listed in the following table

Particip. Role*	Particip. No.	Participant name	Participant short name	Country
CO	1	Universität Duisburg-Essen	**UDE**	Germany
CR	2	THALES Systemes Aéroportés S.A.	**TAS**	France
CR	3	Alcatel Thales III-V Lab	**III-V Lab**	France
CR	4	Kungliga Tekniska Högskolan[1]	**KPRC**	Sweden
CR	5	Center National de Recherche Scientifique[2]	**IEMN**	France
CR	6	France Telecom	**FT**	France
CR	7	U2T Photonics AG	**U2T**	Germany
CR	8	The Center for Integrated Photonics Limited	**CIP**	United Kingdom
CR	9	University College London	**UCL**	United Kingdom
CR	10	Universidad Politécnica de Valencia	**UPVLC**	Spain
CR	11	Univerza V Ljubljani	**LUB**	Slovenia

* CO = Coordinator
CR = Contractor

[1] KPRC is part of KTH who is the official legal entity participating in IPHOBAC as indicated in the CPF. KPRC is the organization carrying out the work as described in the following.

1.3 Work performed

1.3.1 Overall description of the project structure

The IPHOBAC project was structured into 7 work packages (WP), each WP was subdivided into task(s)

- WP1 - Management
  - T1.1 Scientific and project management

- WP2 - Specification and System Requirement
  - T2.1 End-users requirements
  - T2.2 Function definitions and impact on system applications

- WP3 - Millimeter-wave Photonic Generation
  - T 3.1 Optimization of quantum dots for mode-locked and dual-mode LD
  - T 3.2 New building blocks for the fabrication of ML and dual-mode LD
  - T 3.3 Design and technology of mode-locked QD DBR lasers
  - T 3.4 Design and technology of dual-mode DFB and DBR lasers

- WP4 - Millimeter-wave Photonic Receiver/Transceiver
  - T 4.1 TW-photomixer
  - T 4.2 UTC waveguide coupled detectors
  - T 4.3 TW-EAM with integrated DFB LD for RF signal trans. up to 100GHz
  - T 4.4 Reflective EAT with integrated SOA and antenna for 60GHz apps.
  - T 4.5 110 GHz Package
  - T 4.6 300 GHz Package

- WP5 - Integrated Photonic Functions
  - T 5.1 Tunable integrated mm-wave source
  - T 5.2 Frequency stabilization for phase noise reduction in OEO
  - T 5.3 Vectorial modulation and demodulation of mm-wave signal

- WP6 - Assessment and Exploitation of Results
  - T 6.1 Excellence demonstration of IPHOBAC components
  - T 6.2 Exploitation plan
  - T 6.3 Special Actions

- WP7 - Dissemination and Standardization
  - T 7.1 Website and publications
  - T 7.2 Education and training
  - T 7.3 External contacts and lobbying
  - T 7.4 Contribution to standards

As regards the technological activities, the component and system specifications were identified in WP2. Photonic component developments were mainly carried out in the WPs 3 and 4. Photonic integration as well as photonic-electronic integration was performed in WP5. Demonstration activities, i.e. assessment of the developed components and integrated functions in photonic systems were carried out in WP6. The following figure visualizes the major work package interactions.

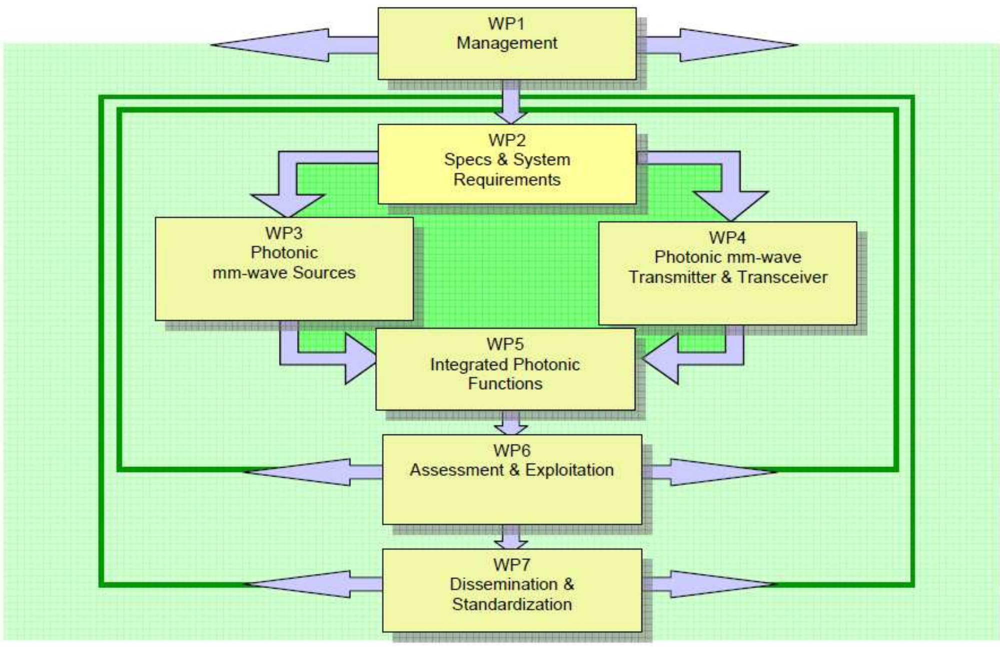

Figure 2 Graphical presentation of work packages

Based on the extensive experience and long-lasting cooperation of the IPHOBAC partners in organizing, managing and participating in international collaborative research activities, including EU and other internationally funded projects, the following management structure has been adopted.

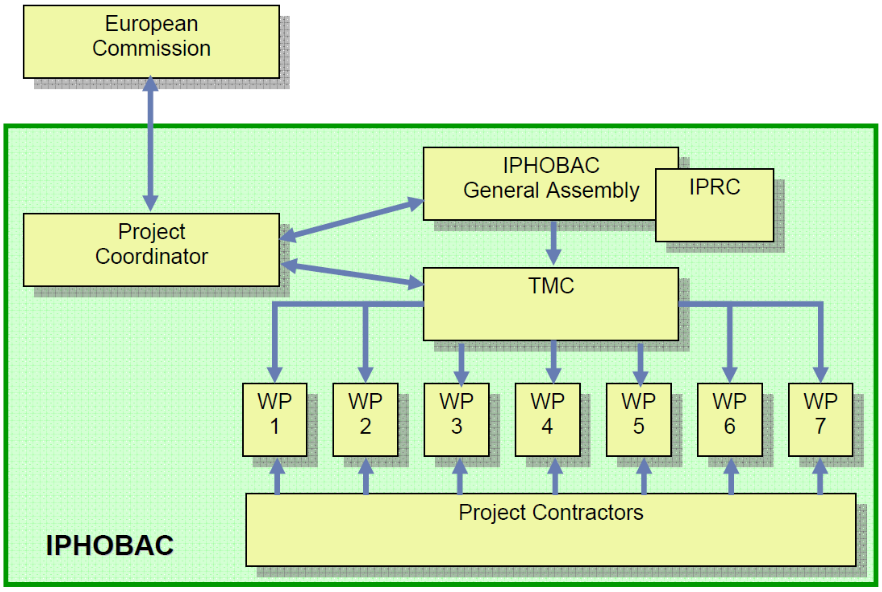

Figure 3 General organizational structure of IPHOBAC

The Project Coordinator and the Work package Leaders form the **Technical Management Committee (TMC)**. The TMC has taken care of the overall management of the technology related work in the project including identification of risks and progress monitoring.

The **General Assembly (GA)** was formed by one representative from each participant. The GA was responsible for the overall supervision of the project and was the consortium arbitration body. Decisions of the GA were binding for the project. The tasks of the GA and the voting procedure were fixed in the Integrated Project Consortium Agreement (IPCA).

Exploitation and IPR were part of work package 6. The **IPR Committee** was formed of one representative from each partner and the IPR regulations were fixed in the Integrated Project Consortium Agreement (IPCA).

1.3.2 Work package objectives, methodologies and approaches

As described above, IPHOBAC aimed at developing innovative microwave photonic components and integrated functions generically based upon the combination of radio and optics technologies. IPHOBAC's set of innovative approaches and ambitious objectives listed in section 1.1 aimed at bringing microwave photonic components and integrated functions to a level of maturity such that take-up actions by industry can be ensured.

Overall, the project had identified key commercial mm-wave application in three different industrial fields which were all addressed in the project:

- Telecommunication
- Security and Radar

- Instrumentation

In order to reach the ambitious goals the IPHOBAC work plan has been defined to:

- Exploit the competences and complementarities of its partners in the most efficient integrative way
- Synchronize the ambitious R&D activities to allow for a short-term progress
- Initiate and support the full commercial exploitation of its developments

The innovation-related R&D work and the demonstration, dissemination, training and management activities of IPHOBAC had been divided into seven work packages (see section 1.3.1) and were distributed among four levels:

A first level of activities addresses the specification and user requirements of each scenario within one work package:

- WP2: Specification and system requirements

  The objective of this work package was to precisely determine the component specifications based on the system requirements established by the industrial project partners. In a first step, the industrial partners fixed the applications to be addressed by the photonic components and integrated functions developed in IPHOBAC. Among the applications foreseen, the end-users had identified the next generation of wireless applications in indoor and outdoor context based on radio systems with higher frequencies and/or with Ultra Wide Band, high frequency radar and sensor applications for transport applications as well as ultra-wideband tunable photonic mm-wave generation for instrumentation. During the course of the project also other application fields, e.g. in the medical domain were studied.

  In order to realize innovative, cost-efficient, large value-added and highly integrated functions based on the technology developed in the project, relevant evaluations had to be defined to quantify both functions and technology progress. Based on the end-users specifications, pre-calculations needed to be carried out to ensure both feasibility of the functions and their application into real systems ensuring both applicability and long-term survivability of the functions and the technology.

A second and core level of the project covered the mm-wave photonic component developments as well as photonic integration and photonic-electronic integration. These activities were subdivided into three work packages which are listed below:

- WP3: mm-wave photonic generation

  This work packe summarized all project activities related to laser developments including: mode-locked and dual-mode lasers using quantum dots (QD) in the active layer for narrow linewidth operation. Planned technological activities in WP3 included vertical grating and spot size converter developments to facilitate the hybrid integration of the lasers with mm-wave photodiodes (WP4) required for the integrated optical phase locked loop studied in WP5. WP3 also concentrated on quantum-dot based mode-locked lasers for generating mm-wave signals at fixed frequencies, e.g. at 60 GHz, with a low spectral linewidth less than 10 kHz and the possibility to allow external modulation. Such lasers are needed for the direct generation of mm-wave signals by locked mode heterodyning. Finally, WP3 aimed at demonstrating an integrated dual-mode laser ensuring a frequency tuning range from 10 to 300 GHz and a low spectral linewidth of about 1MHz and the possibility to allow external tuning within an OPLL to further reduce the phase noise.

- WP4: mm-wave photonic receiver/transceiver

  This work package covered all activities related to the development of high-output power and high-frequency photodetectors, modulators and transceivers needed for the integrated functions in WP5 as well as for the system demonstrations in WP6. The approach was to develop efficient optical heterodyne photomixers based on travelling-wave and UTC structures for high-frequency operation up to 300 GHz. These photomixers were intended to be used in combination with the optical sources of WP3 to create widely tunable photonic microwave and mm-wave sources for the system demonstrations in WP6. The idea was to integrate the photomixers with planar and broadband antennas and a further objective was also to develop a compact package for such photonic mm-wave transmitters. Another objective of WP4 was the development of broadband, high-output power packaged photodiode modules with a cut-off frequency of up to 110GHz. The approach was to focus on travelling-wave and UTC structures as well as photodiodes with partly p-doped active layers. Another objective in that regard was the integration of the photodetectors with passive optical waveguides for high-responsivity fiber-optic coupling as well as the development of a new and compact package featuring a W1 coaxial output connector. To develop high-frequency travelling-wave electroabsorption modulators integrated with DFB lasers. Also within WP4, resonant (60GHz) reflection-type electroabsorption transceivers for broadband wireless systems were to be developed. In order to compensate the high-optical losses, the approach was to integrate the transceivers with SOAs. A final objective of WP4 was the development of high-frequency 100GHz travelling-wave modulators with integrated DFB lasers.

- WP5: Integrated photonic functions

  The overall objective of this work package was to investigate mm-wave photonic system functions using combinations of the components developed in WP3 and WP4. These photonic functions were to be demonstrated either through the use of hybrid integration or by laboratory bench demonstration. One approach was to integrate components from WP3 and WP4 at chip or sub-module level to overcome the problem of bulky and costly approaches reported earlier. The aim was to cover a huge frequency spectrum from 30-300 GHz where there is no other technical solution envisaged to offer such wide tunability. Another objective of this work package was to look at ways of reducing and controlling phase noise by developing a semi-integrated optical phase lock loop (OPLL) and finally, WP5 aimed at studying photonic techniques for optical vector modulation. Here the approach was to develop SOI based optical phase shifter for wireless transmission of up to 10 Gb/s.

A third organizational level was identified to ensure full demonstration and exploitation of the projects achievements both through assessment of results and knowledge dissemination. Activities on the third level also covered the project management, training, education, standardization and other dissemination activities. All those activities were covered in the work packages WP1, WP6 and WP7.

- WP1: Management

  A specific work package (WP1) was devoted to the management of the IPHOBAC project. The management structure was already described in the section above. Overall, the objectives of the work package 1 were to ensure project management and reporting, financial management and reporting as well as contractual and legal management and reporting.

- WP6: Assessment and exploitation of results

  The major aspect of WP6 was in performing convincing proof of IPHOBAC components developments with system oriented experiments and well-defined assessment of the results. The goal was also to ensure the rapid exploitation of the knowledge gained in the project in industrial products and systems, thereby maximizing economic benefits to the European community.

- WP7: Dissemination and standardization.

  The aim of WP7 was to stimulate research and the overall advancement of the field by disseminating scientific knowledge efficiently and effectively and by assuring an efficient spreading within the European Industry of the new opportunities offered by the outcomes of the IPHOBAC project. The latter one was to be achieved e.g. by active participation of the project partners in standardization processes and by organizing technical meetings with system vendors active in the addressed application fields. Furthermore, the good position of mm-wave photonics in National and European R&D programs should be improved and to ensure the further development and exploitation of the components and functions to be developed, the training of scientists and engineers who are expert in the field was within the focus of this work package.

1.4 Project achievements related to the State-of-the-Art

1.4.1 Photonic component developments

1.4.1.1 Quantum-dash mode-locked and dual-mode FP and DBR lasers

Objectives

In task 3.4, the general objective was to develop and fabricate mode-locked QD DBR lasers and assess those QD lasers for use in mm-wave optical sources. The approach was to incorporate quantum dots active layers, studied in task 3.1 and spot size converters as well as vertical gratings studied in task 3.2. The key technical objectives were as follows:

- Reduced linewidth of mode beating spectrum of mode-locked DBR lasers using optimized quantum dot layer structure
- Reduced divergence of the emitted light in order to reduce the coupling losses
- To demonstrate integrated quantum-dot based mode-locked lasers, generating mm-wave signals at frequencies in excess of 60 GHz, with a spectral linewidth less than 10 kHz, and the possibility to allow external tuning and microwave injection control to further reduce the phase noise.

Project work and achievements

The work on very narrow linewidth mode-locked Fabry-Perot laser in the mm-wave range was performed in the frame of T3.1 and all by III-V Lab. It was already found from previous studies that the electrical beat-note linewidth was depending on the type of gain medium that is used with a reduction when the confinement factor is reduced (see Figure 4 (left)). In order to further optimize the gain layers, different types of quantum dash gain layers have been grown and processed in order to get Fabry-Perot lasers. The -3 dB linewidth obtained from these structures are presented in Figure 4 (right). It shows that linewidth below 10 kHz were observed on structures with 3 layers of quantum dash.

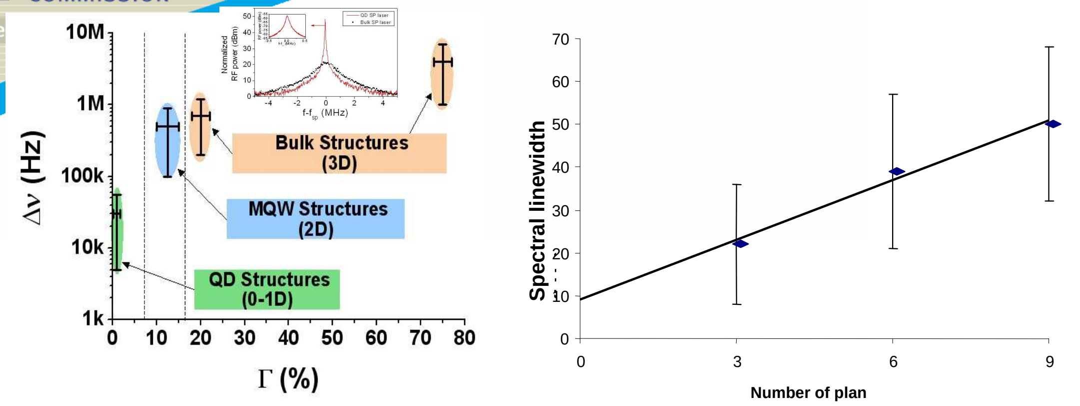

Figure 4 (left) -3dB linewidth measurement of mode-locked lasers with different type of gain region around 40 GHz, (right) -3dB linewidth measurement of mode-locked lasers with different amounts of quantum dash layers around 40 GHz

In order to maintain a good compromise between linewidth and laser output power, structures with 6 quantum dash layers were chosen for the devices to be implemented in system experiments. These results were used in the frame of T3.2 by III-V Lab in order to integrate the chips to be used in the system experiments. The initial goal was to get DBR devices, where a Bragg grating is used for closing the optical cavity in order to filter a limited number of optical modes centered on a given Bragg wavelength. But as can be seen in M331, M332, D331, D332, the Bragg grating has a detrimental effect on the linewidth of the generated tone that could not be inferior to the threshold of 10 kHz initially specified. As the wider optical spectrum that was obtained with the Fabry-Perot chips was not a limit for the system evaluations, it was decided to use them instead of DBR devices. Fabry-Perot chips for generation of 24.5 GHz, 38.5 GHz, 55 GHz, 58.5 GHz tones have been cleaved and packaged. -3dB linewidth of 3 kHz has been obtained with the 55 kHz mode-locked laser (D331) and 4 kHz for the 58.8 GHz mode-locked laser (M332). These results are at the state of the art. They can be compared with results obtained at 10 GHz by University of Cambridge and University of Madrid on mode-locked lasers at 10 GHz emitting around 1.3 µm with a linewidth of 500 Hz (Carpintero et al., IEEE-PTL Volume 21, issue 6, March15, 2009 p389–391) and results obtained by III-V Lab with mode-locked lasers at 10 GHz emitting in the 1.5 µm range with a linewidth of 850 Hz (Akrout et al., post deadline OFC 2009).

As regards the QD materials, a second goal in IPHOBAC was to get devices that would potentially be integrated using the hybrid integration platform developed by CIP. In addition, it is of course desirable to have devices compatible with low cost packaging but this is even more difficult to achieve with quantum dash structures. The reason is, that the QD material highly confines the optical mode in the vertical direction which leads to a large divergence. For these reasons a spot size converter has been developed by III-V Lab with contribution of IEMN. This design has been evaluated on Fabry-Perot lasers. The devices were fabricated by III-V Lab. The divergence of the initial laser waveguide was of 32°x42°. Thanks to the designed spot-size co nverter, adapted to the used shallow ridge fabrication process, it was reduced to 9.4°x1 6.6°. The design work can be found in D321, M322 and M323.

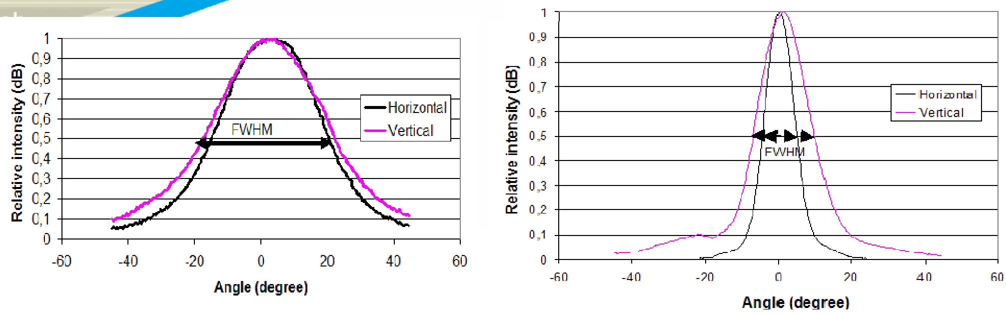

Figure 5 (left) vertical and horizontal divergence of the lasers with no spot-size converter, (right) vertical and horizontal divergence of the lasers with the spot-size converter

It was initially intended to get DBR mode-locked lasers and dual wavelength mode-locked lasers associated with these spot-size converters. Unfortunately, the corresponding fabrication runs didn't succeed due to problems during the fabrication process but this has not affected other activities of the project.

As discussed above, the quantum dash mode-locked lasers are good devices for the delivery of narrow linewidth signals. The final objective thus was to develop and study injection locked quantum dash mode-locked laser for low phase noise mm-wave generation. Here, the phase noise of the generated tone was shown to be low enough to be used as a carrier for wireless transmission at 60 GHz, as demonstrated in WP2 and WP6. For other applications it can be necessary to synchronize the signal with other signals in the laser. For sensing application it is necessary to have a phase noise lower than what is obtained with the free running devices. For these reasons the mode-locked lasers were mounted on sub-mounts with a coplanar line used both for biasing the laser cavity and for directly modulating the signal. They were packaged in modules with a RF connector. We demonstrated that it was possible to lock the beat note of the laser by directly modulating the laser even at very high frequencies. This was in particular shown for the 24.5 GHz comb source that was delivered to UCL in order to injection lock the dual wavelength DBR laser of the OPLL source (D333). A photo of the module and phase noise of the source in free running mode and in electrical injection locking are presented in Figure 6.

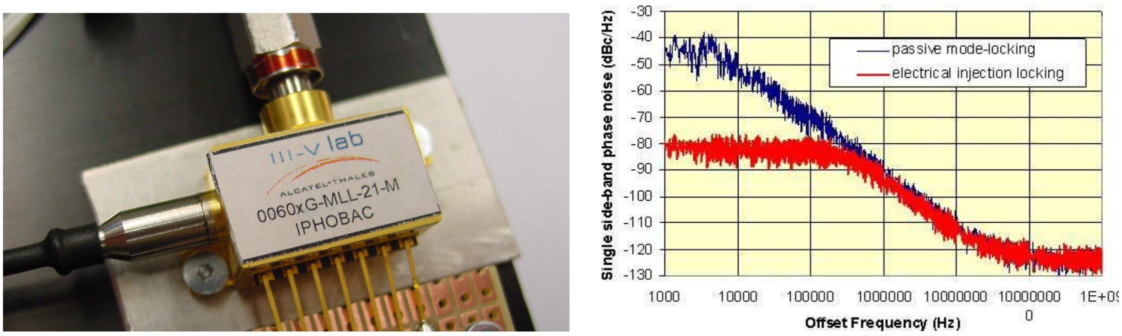

Figure 6 (left) photo of a mode-locked laser module, (right) phase noise measurement of the 24.5 GHz signal in free running mode and in electrical locking mode

The ability of the semiconductor mode-locked lasers to be injection locked was also used in order to realize opto-electronic oscillators. In these architectures the phase noise of the generated tone is reduced thanks to an opto-electronic delayed self-injection loop. Before our work these types of oscillators were integrated at frequencies below 30 GHz and required electrical filters to select one frequency. Thanks to the narrow linewidth of the quantum dash mode-locked lasers, opto-electronic oscillators at 55 and even 58.5 GHz were demonstrated. Figure 7 shows the box containing the active optical elements of the transportable oscillator that was built during the project and the phase noise measurements of the 55 GHz tone.

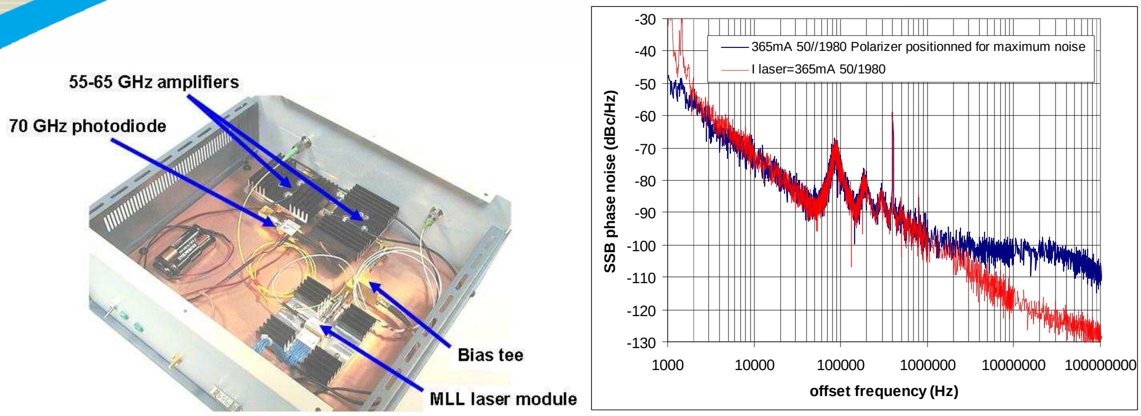

Figure 7 (left) photo of the optical box containing the optical elements of the portable opto-electronic oscillator, (right) phase noise measurement of the 55 GHz mm-wave tone.

Comparison to the State-of-the-Art

- Very narrow linewidth mode-locked Fabry-Perot laser in the mm-wave range

  It is hard to find linewidth measurement results in the mm-wave range. But the results obtained in the frame of IPHOBAC can be compared with results obtained at 10 GHz by University of Cambridge and University of Madrid on mode-locked lasers at 10 GHz emitting around 1.3 µm with a linewidth of 500 Hz (Carpintero et al., IEEE-PTL Volume 21, issue 6, March15, 2009 p389–391) and results obtained by III-V Lab with mode-locked lasers at 10 GHz emitting in the 1.5 µm range with a linewidth of 850 Hz (Akrout et al., post deadline OFC 2009).

- Reduction of the divergence of the shallow ridge quantum dash lasers

  Thanks to the designed spot-size converter, adapted to the used shallow ridge fabrication process, we obtained a divergence of 9.4°x16.6°. These divergences are larger than what has been obtained by other teams with other type of gain layers. But If we compare these results with other quantum dot structures associated with spot-size converter, they are better than the state of the art. The best result we have found in the literature is a divergence of 18°x22° (Pommereau et al., IEEE International Conference Indium Phosphide & Related Materials, 2009. Page(s):339 – 342). It was initially intended to get DBR mode-locked lasers and dual wavelength mode-locked lasers associated with these spot-size converters. Unfortunately the corresponding fabrication runs didn't succeed due to problems during the fabrication process. This has not affect the other activities of the project.

- Injection locked quantum dash mode-locked laser for low phase noise sources

  Since the start of the IPHOBAC project there have been different demonstrations of opto-electronic oscillators at mm-wave frequencies at 39.8 GHz (Myunghun et al.; OFC/NFOEC 2007, p1–3) and 52.8 GHz (Sakamoto et al.; Electronics Letters vol. 43, Issue 19, September 13 2007 Page(s):1031 – 1033). The draw back of these different designs is their complexity with frequency quadrupling schemes and large amount of different elements. The oscillators developed in the frame of IPHOBAC use a very simple architecture with no modulator, no optical or electrical filter, with no optical amplifier. This could be obtained thanks to the direct modulation of the laser and to the filter-type behavior of the laser. But the resulting phase noise still needs to be improved in terms of phase noise. A phase noise of -

100 dBc/Hz was obtained at ~100 kHz frequency offset. Paper with opto-electronic oscillators in the 10 GHz region demonstrate phase noise values below -120 dBc/Hz.

1.4.1.2 Dual-mode and dual-wavelength lasers

Objectives

- New design involving two DFB and DBR lasers with the goal of achieving compact, tunable, high power sources suitable for generation of up to 300 GHz signals.
- To demonstrate an integrated dual-mode laser with a frequency tuning range from 10 to 300 GHz, a low spectral linewidth of about 1 MHz and the possibility to allow external tuning within an OPLL to further reduce the phase noise.

Project work and achievements

The objectives were met.

The twin DBR lasers made at CIP are buried heterostructure lasers fabricated 30 µm apart on a single InP/InGaAsP chip, each stripe having 4 sections: front and rear grating sections of lengths 150 µm and 450 µm respectively, a 400 µm long gain section and a 100 µm long phase section. The waveguide of each stripe was of different width to achieve a wavelength offset between them. Designs included devices with angled facet mode expanded SOAs on each DBR output as well as devices with an MMI coupler to combine output onto a single angle tapered semiconductor optical amplifier (SOA). In both cases the aim of the SOA being to boost the output power while minimizing facet reflections. Measurements at UCL showed that the output from each of the stripes had SMSR greater than 35 dB and a tuning range of 7 – 8 nm with an offset of 6nm between them, giving a heterodyne tuning range of 0 Hz to 1.8 THz. A 50 degree Centigrade change in temperature causes each of the stripes to tune by 60 GHz, however the heterodyne frequency changes only by 2.5 GHz. A linewidth as low as ~1 MHz were measured. These devices were described in D342.

These twin DBRs were assembled into the hybrid integrated OPLL at CIP as described in D527.

Comparison to the State-of-the-Art

We are not aware of any other reports of twin amplified tunable lasers with integrated mode expanders that make them suitable for hybrid integration.

1.4.1.3 Broadband DC-110 GHz Photodetectors

Objectives

The overall goal was the development and fabrication of packaged high-output power mm-wave traveling-wave (T4.1) and UTC-based photodiodes (T4.2) with coplanar 50Ω output transmission lines.

In general, the activities can be separated into two major parts; the development of photodetector chips in the tasks T4.1 and T4.2 and the development of a suitable broadband (DC-110 GHz) package featuring a W1 coaxial output connector which was performed in task T4.5.

The technical objectives can be summarized as follows:

- Development of high peak-power (>1mW) ultra-wideband (DC-110 GHz) travelling-wave and UTC-photodiodes

- Development of a UTC-photodiode module with -3dB bandwidth of ~110 GHz and a responsivity of ~0.4 A/W.
- Development of a coaxial output 110 GHz bandwidth package for the photodetectors.

Project work and achievements

In task T4.1, UDE has designed and developed high-output power broadband travelling-wave photodetectors. A new partially p-doped and partly non-absorbing *pin*-epilayer structure was grown for the TW-PDs which was reported in M411. Regarding the InGaAs(P)/InP layer structure, the amount of slow photo-generated carriers (holes) is significantly reduced which would otherwise contribute to the photocurrent and therefore degrade the RF-performance. Another key benefit is the applied traveling-wave principle which differs from a lumped element in a non-RC time limited response exhibiting superior high-frequency performances. Furthermore, the mask and design fabrication were also presented in M411. First experimental results of the photodetectors with coplanar output transmission lines were reported in M412 and D411. Here, a peak power in excess of 0 dBm could already be shown at 10 GHz. However, high-frequency measurements up to 50 GHz revealed cut-off frequencies of around 10 GHz only. The development of broadband photodetectors for DC-110 GHz operation which had been fabricated to be packaged into the W1-module (T4.5) was presented in D412. As reported in D412, the advance of an enhanced layer structure featuring a top InP cladding layer and further characteristics for preventing from Zn diffusion was necessary (Figure 8). In D414 and M414, processing schemes for implementing an efficient passive optical waveguide (POW) as well as simulations improving the optical and electrical coupling efficiency of the photodetectors have been reported. Here, a chip layout featuring a POW for low-loss fiber-chip coupling was developed and reported (Figure 9).

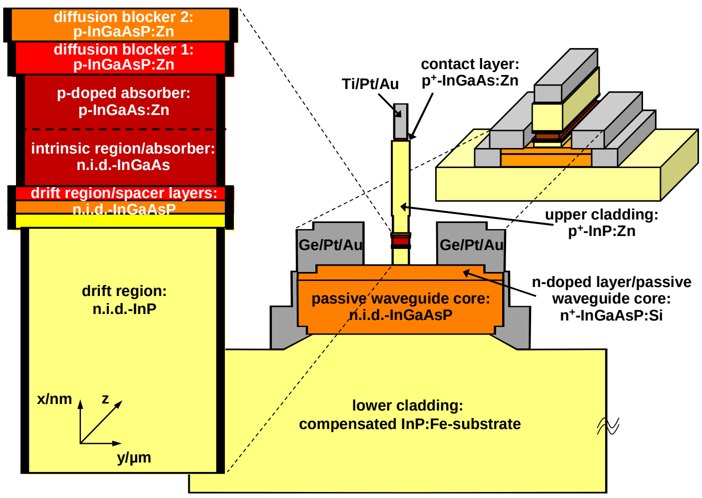

Figure 8 Schematic cross section (middle) of the developed traveling-wave photodetector, enlarged active section (left hand) and 3D model (right hand).

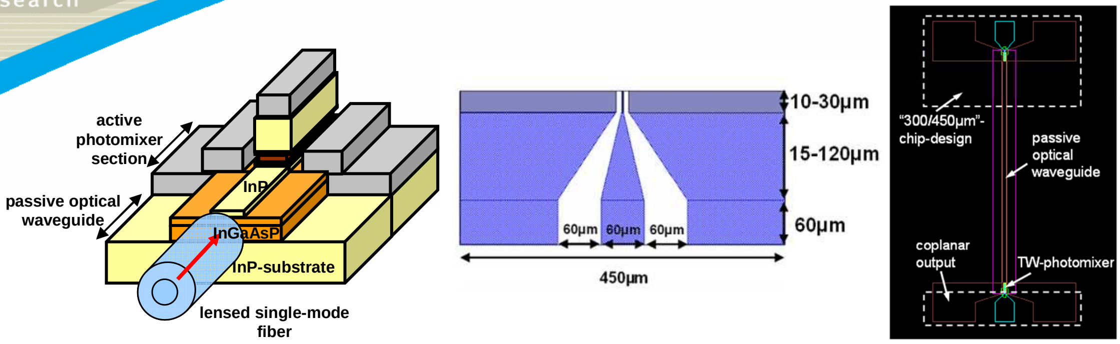

Figure 9 Layout of the POW integrated TW-PD (left hand), top view of the photodetector with coplanar output transmission line varying in taper length (middle) and mask layout for POW integrated TW-photodetectors with compressed coplanar output.

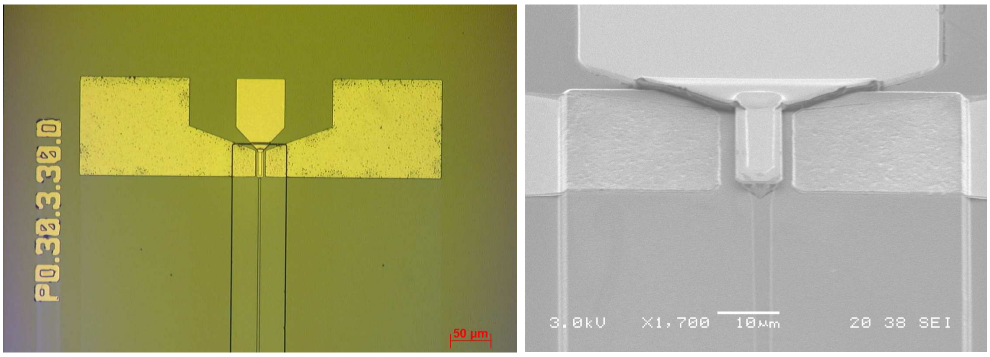

Figure 10 Photographs of the developed photodetector chip (UDE). Top view of the fabricated TW-photodetector with coplanar waveguide circuitry (left hand) and close-up view of the active photomixer section and passive optical waveguide (right hand). The device is further coupled to a 50Ω matched coplanar output.

In task T4.2, CIP has developed waveguide-coupled uni-travelling carrier (UTC) detector which is essentially based on a pin-diode layer structure with a slightly p-doped absorbing layer and a transparent non-intentionally doped (i) depletion layer reported in D421. In the first year of the project some non mode expanded photodiodes were fabricated and after initial assessment at CIP sent for high speed testing at UCL. The high speed results at high optical input power described in M421 as well as D422 were very encouraging. Based upon these results, mode expanding tapers were integrated to the device to make them suitable for hybrid integration in T5.1 and easier to package in T4.5 and T4.6. This was done using the dual ridge taper design described in T3.2 whilst leaving the design of the absorber and contacting layers of the active part of the photodiode almost unchanged from the earlier non-mode expanded design although this time the absorber layer was only partially p-doped. A schematic of the waveguide coupled photodiode as well as a fabricated chip are shown in Figure 11.

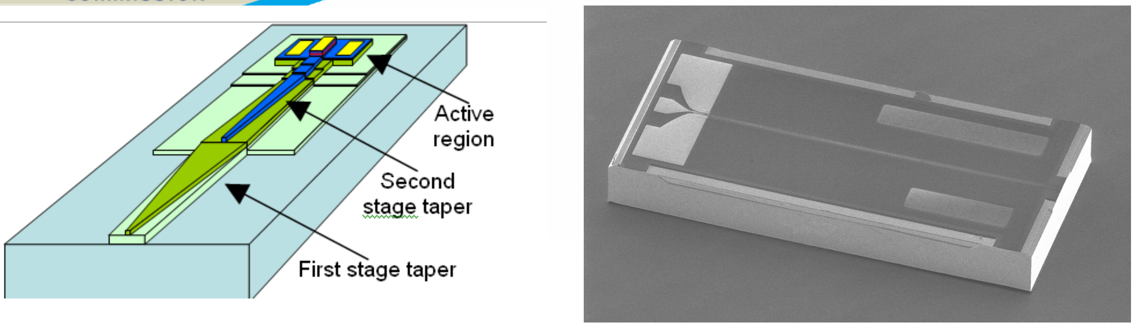

Figure 11 (left) Schematic of the waveguide integrated UTC-photodiode developed at CIP and (right) SEM photo of a fabricated chip.

In task T4.5 U2T had designed a new package featuring a W1 coaxial output connector in the first year and manufactured and packaged first photodetectors modules in second year. This was reported in D451. The third project period focused on the optimization of the design, assembly and full characterization of the final modules. This was reported in D452 and in the Y3 PAR.

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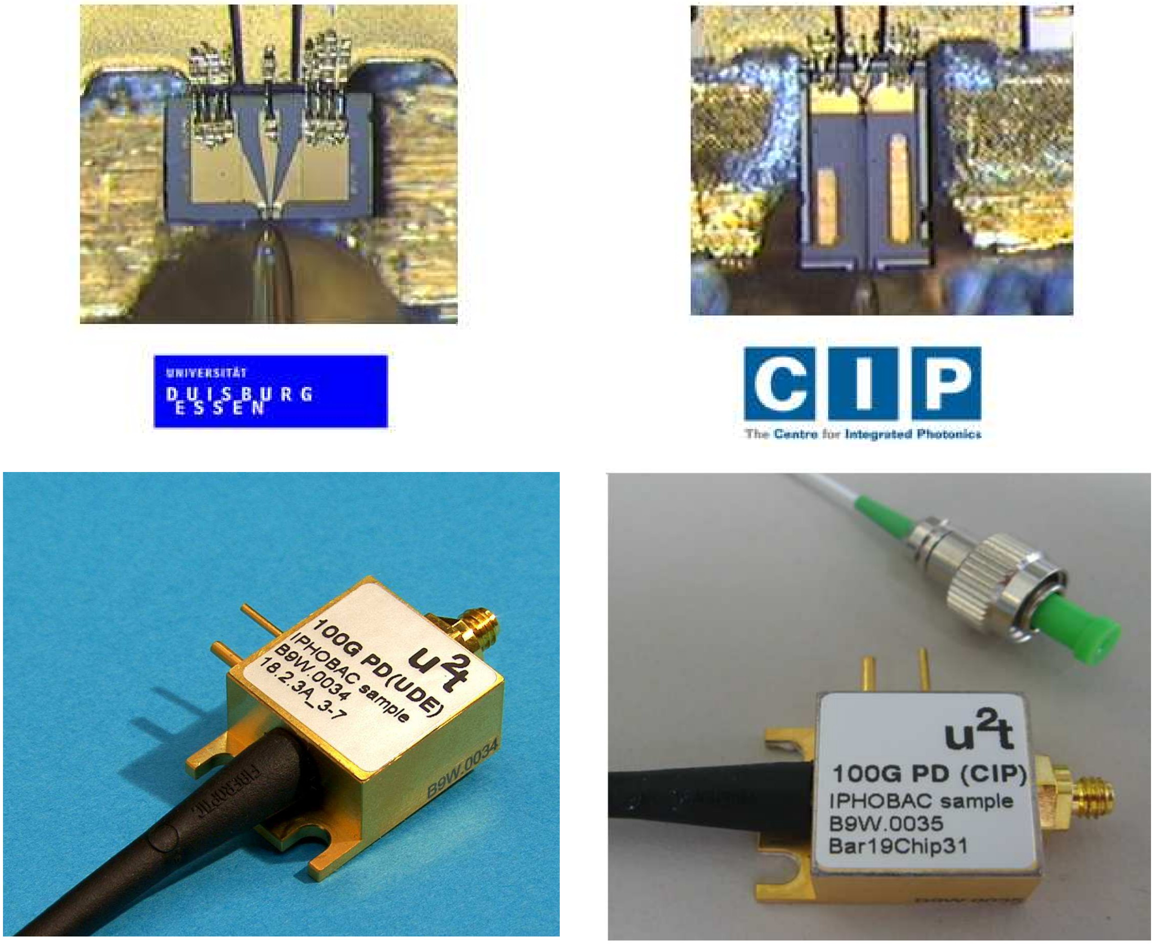

Figure 12 Photos of the packaged photodiode chips from UDE (top left) and CIP (top right) and the corresponding packaged photodetector modules (bottom).

During this project U2T developed a new package accommodating a W1-connector in a non-hermetic fashion, where the W1-connector was soldered in by U2T to achieve fully hermetically sealed modules. Furthermore, several sub-mounts were designed to adapt to the special requirements of the UDE & CIP chips developed in T4.1 and T4.2 and lensed fibers had to be evaluated and designed-in. Figure 12 shows fully assembled 110 GHz modules with chips from UDE and CIP. To accommodate the different photodiode types and lengths of the chips, several different versions of sub-mounts were manufactured and used to fit the different photodetector chips

During the time of this project several batches of UDE and CIP chips were packaged. A detailed description of the packaging efforts and characterization results of the first batches are given in D451 and D452. The DC responsivities, PDL, dark current, and ORL were 0.2-0.3 A/W, ~2dB, ~300-350 nA, and ~25-30 dB, respectively.

After the initial DC-characterization of the chips (before packaging) and the modules, a heterodyne system was used to characterize RF-performance of the photodetector modules assembled in IPHOBAC. A comparison of the normalized o/e-response of a few IPHOBAC modules was presented in D452 and it is also given in Figure 13.

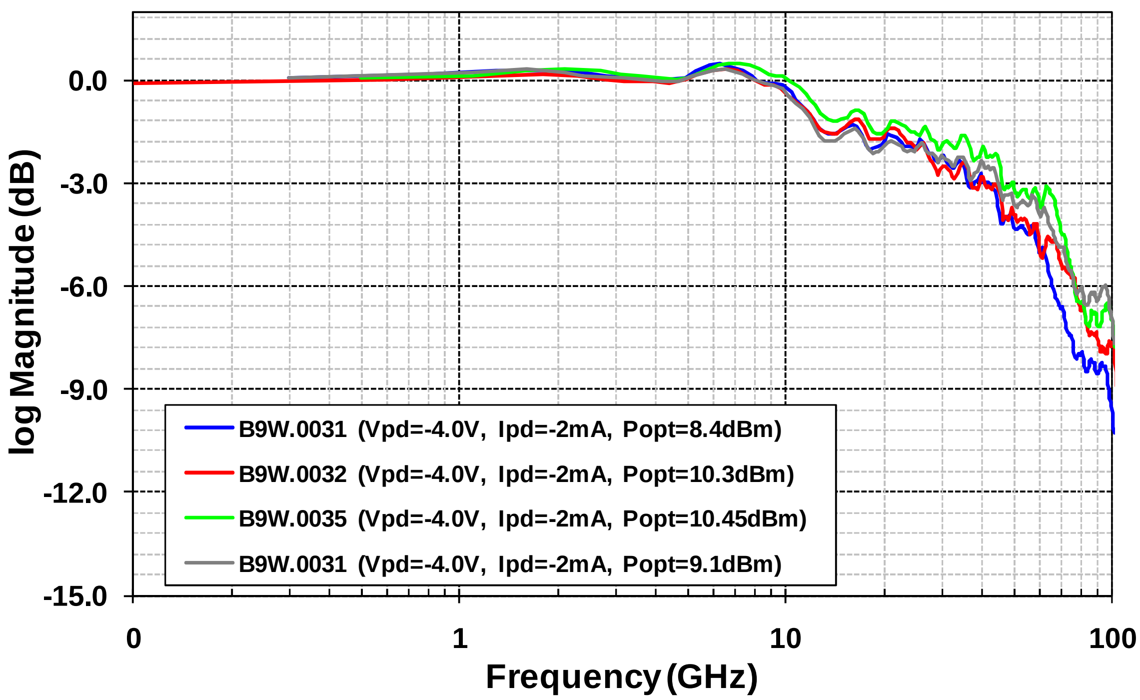

Figure 13 OE-response measurement of packaged photodetector modules.

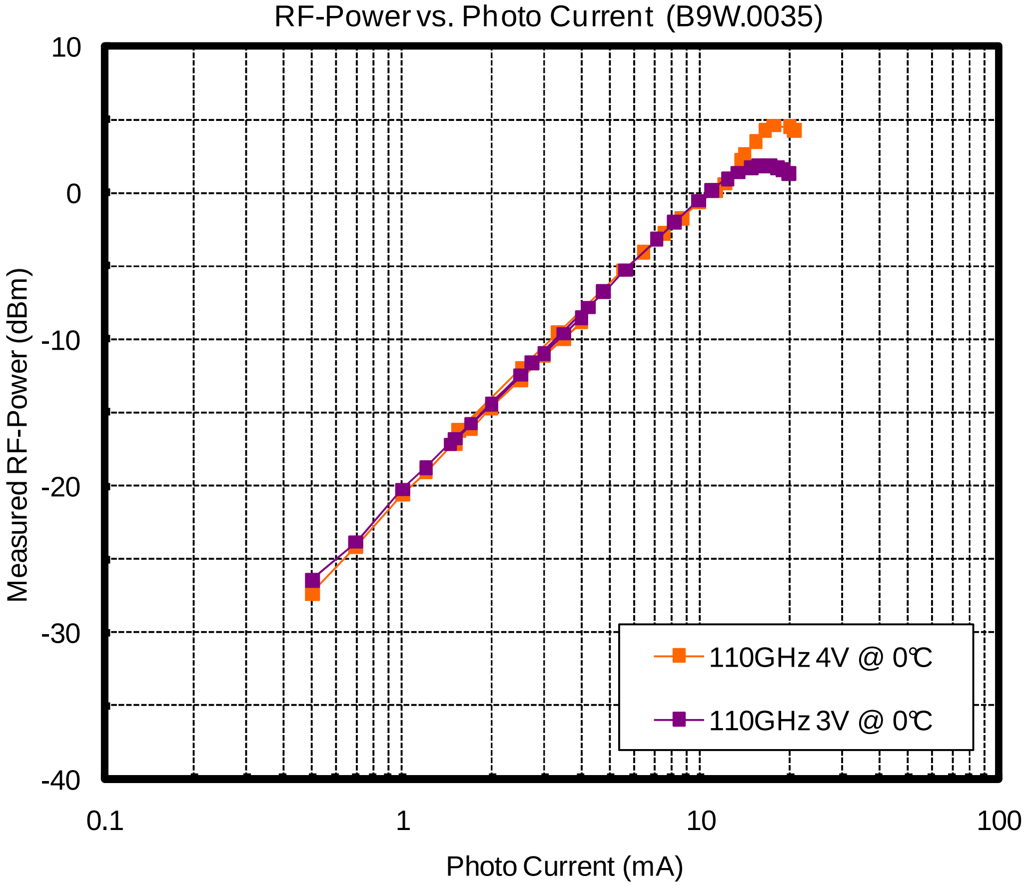

Figure 14 RF-output power at 110 GHz for bias voltages of 3 V and 4 V versus DC-photocurrent of a photodetector module (B9W.0035).

All curves were measured with the same photodiode current of 2 mA, which due to the small variations in the responsivity resulted in measurements with an optical input power between 8.5 dBm and 10.5 dBm. What one can directly see is the smooth curve without much ripple and the relatively smooth roll-off towards higher frequencies with a slight increased slope for frequencies above 70 GHz. Shorted photodiodes with 3dB cut-off frequencies in excess of 110 GHz were also developed and reported, however those PDs exhibit lower saturation photocurrents.

The final characterization of the modules described above was again done with the heterodyne system in the high-power setup to determine the maximal achievable RF-output power of the modules. The curves were measured at two different bias voltages of 3 V and 4 V, respectively. This experiment revealed a clearly linear behavior up to photo current levels of above 10 mA, followed by a peak in the RF-output power and then the decay due to saturation. For bias levels of 3 V this peak appears at slightly lower photocurrent values of around 16.5 mA with a maximal RF-output power of just below 1.8 dBm, whereas for a bias level of 4 V the peak appears at slightly higher photo current values of 18 mA with a remarkable maximal RF-output power of +4.5 dBm (see Figure 14).

In summary, high-frequency packaged photodiode modules with coaxial W1 connector have been fabricated. A remarkable peak output power (from the module!) in excess of 1 mW has even been achieved for PDs with a cut-off of 40-70 GHz and a responsivity of ~0.3 A/W. Furthermore, PDs with a 3 dB cut-off of 110 GHz have been developed and packaged.

Comparison to the State-of-the-Art

The developments in IPHOBAC have enabled the partners U2T and CIP to launch 110 GHz photodiodes as commercial products. To our knowledge, those are the only packaged 110 GHz PD modules available world wide.

1.4.1.4 Wideband 30-300 GHz antenna integrated photodiodes

Objectives

Among the development and fabrication of broadband DC-110 GHz photodetectors presented in the section above, further objectives of T4.1 and T4.2 were to study, simulate and fabricate antenna integrated photomixers using planar broadband antennas which are impedance-matched to the photomixer. The objective was to integrate the planar antennas with the TW-PD and UTC-PD developed in T4.1 and T4.2 for mm-wave signal generation over the entire mm-wave frequency range from 30-300 GHz. According to the project objectives, the peak output power of -10 dBm within the frequency range of 100-300 GHz was expected for the realized antenna-integrated photomixers. The operation principle of the developed 30-300 GHz photonic transmitters is shown in Figure 15.

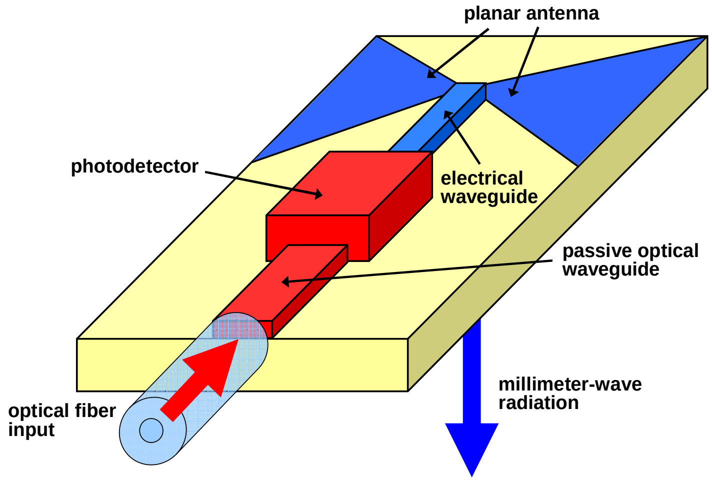

Figure 15 Operation principle of the developed component.

As regards the packaging of the antenna integrated photomixers, the objective of T4.6 was to design and fabricate an advanced compact package for mounting the first prototypes of the 300 GHz bandwidth antenna integrated photomixers developed in T4.1 and T4.2 and thus to fabricate a completely new quasi-optical module for 30-300 GHz operation. The novel fiber-optic package should feature a quasi optical element for focusing the emitted mm-wave radiation within the frequency range from 30-300 GHz. Furthermore, the quasi-optical package should be compliant with the specifications for the hybrid integrated photonic mm-wave generator as defined in T5.1.

Project work and achievements

As described in the section above, the developments of the DC-110 GHz photodetectors was reported by UDE, CIP, and UCL in M411, M412, M421 as well as in D411, D421. As regards the simulation and design of the planar antennas, LUB has been involved in T4.1 and T4.6. Different planar antennas including bow-tie, log-spiral and log-periodic toothed structures have been designed and simulated as reported in D411.

As regards the package for the photonic mm-wave transmitters in T4.6, 300 GHz package geometries and properties have been designed by UDE, U2T in compliance with the end-user specifications provided in T2.1. A study has been carried out to find proper materials for the package itself and for the quasi-optics, and the decision was made to use high-resistive (HR) silicon due to its advanced properties with respect to integration. Simulations have been accomplished to find a solution which is compact on the one side but also allows for a broadband frequency response. In this context, the log-periodic toothed antenna (LPTA) was found to be the optimum solution in conjunction with the specified package geometries. This was reported in D461. Here, UDE was in charge of developing antenna integrated photomixers in task T4.1 for integration with the 300 GHz package developed in T4.6.

Further on, the mask and device fabrication of first antenna integrated photomixers was reported in M413 and M422. For further optimization of T4.1 and T4.2 as well as T4.6 devices, simulations on different antenna structures and the quasi-optics have been carried out by LUB in D413 showing that the package design was not optimum yet, especially with respect to radiation pattern and directivity. With these results, the package has been revised and adapted, which is reported in M461. Here, also packaging procedure was developed and performed for the first time. Already existing measurement setups, comprising electrical spectrum analysis in conjunction with external mixers and a Golay-cell based characterization technique were further reported in M461. However, these setups do either not meet the demand for a calibrated measurement or do not meet the bandwidth requirements.

With D414 and M422, a processing scheme for implementing an efficient passive optical waveguide as well as simulations improving the optical as well as electrical coupling efficiency of the antenna-integrated photomixers have been carried out and realized. Optimized schemes for the photomixers/antenna integration were applied; first chip-level measurements have been performed and described in detail in M414, M422 as well as D415, D423. In order to enhance the coupling efficiency into the photomixer section, the passive optical waveguide of the photomixer was optimized for the UDE devices using an under etched waveguide section in combination with the former stripe loaded waveguide. A maximum theoretical coupling efficiency of 73% has been simulated. To reduce the return loss from the microstrip feeding line and antenna into the photomixer, a new tapered microstrip feeding line between the photomixer and the antenna was designed, resulting in a return loss reduction better than 10 dB for 100-300 GHz and better than 5 dB for frequencies below. Revised photomixers with integrated passive waveguide sections and different integrated planar antenna structures were processed and characterized.

As a solution for a calibrated measurement as well as for meeting the bandwidth requirements, a new measurement setup based upon mm-wave power detectors was designed. Using an array of 6 Schottky power detectors, a power-calibrated measurement within 30-325 GHz was achieved and shown in detail in D462 and Y3 PAR.

The final characterizations of the fabricated antenna integrated photomixers were summarized in the Y3 PAR.

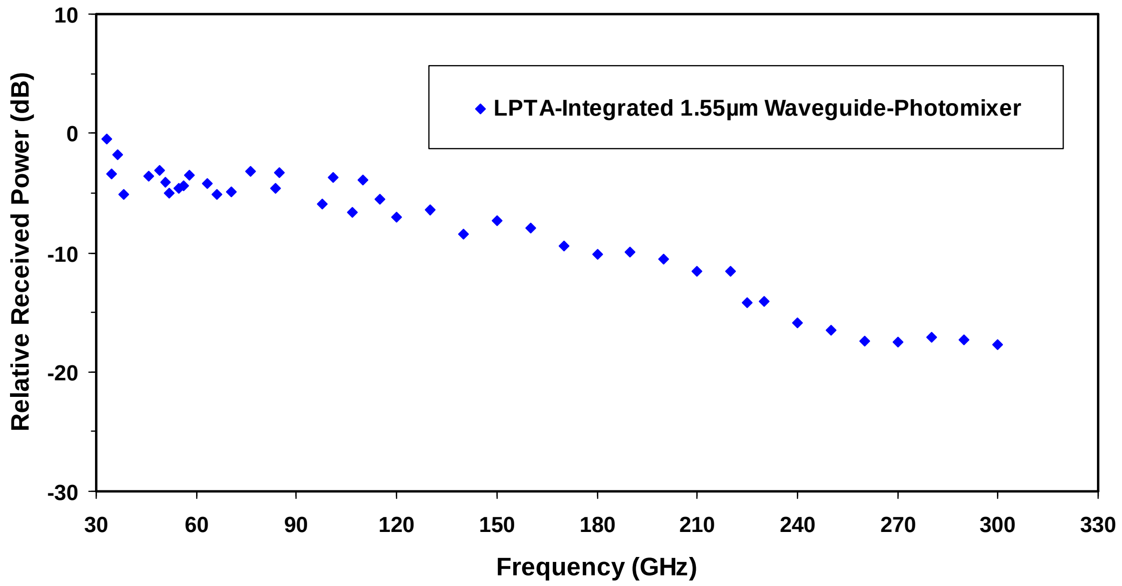

Figure 16 30-300 GHz characterization of the developed UDE photonic transmitter.

In T4.1, operation from 30-300 GHz has been demonstrated by UDE and a peak output power of -11 dBm has been achieved at 100 GHz and for a photocurrent level of 6 mA and -2 V reverse bias. This is in accordance with the overall goal to demonstrate a peak power level of 0.1 mW in the frequency range of 100-300 GHz. The overall power drop from 100-300 GHz is about 10 dB, depending on the antenna structure.

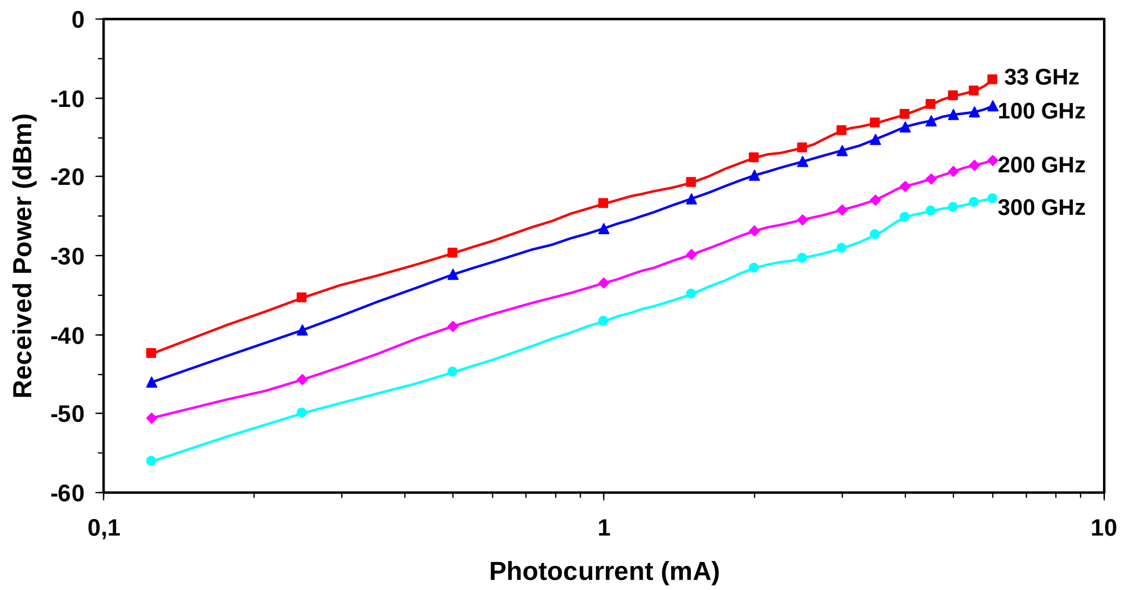

Figure 17 High-power chip-level measurements of a LPTA-integrated photomixer (UDE) at a DC-bias level of -2V and a photocurrent of up to -6 mA.

In T4.2, CIP has also demonstrated mm-wave transmission using antenna integrated photomixers. Operation from 50-300 GHz has been achieved with a peak power level of -17 dBm @ 3.3 mA photocurrent at around 100 GHz. High power measurements at photocurrent levels up to 37 mA confirm that these devices can be used for efficient mm-wave transmitters.

In T4.6, different 1.55 µm TW photomixers with integrated antennas were packaged by UDE, U2T. The experimental characterization setup for calibrated power measurements in the frequency range from 30-325 GHz was completed by UDE. The setup was further extended to allow for polarization dependent measurements. A maximum polarization dependent output power penalty of 3-5 dB has been measured. The packaged mm-wave transmitter shown in Figure 18 was experimentally characterized; operation from 30-325 GHz has been successfully demonstrated. The packed modules exhibited a maximum peak power in the µW range for -1 mA photocurrent and -2 V reverse bias. The power roll-off between 30-100 GHz is only 2.5-5 dB. The roll-off between 100-300 GHz is about 15-20 dB. It was found that the Si-lenses and the Si-spacer in the package cause a power penalty of about 10 dB. Thus about 10 dB higher output power is expected when using low-loss lenses.

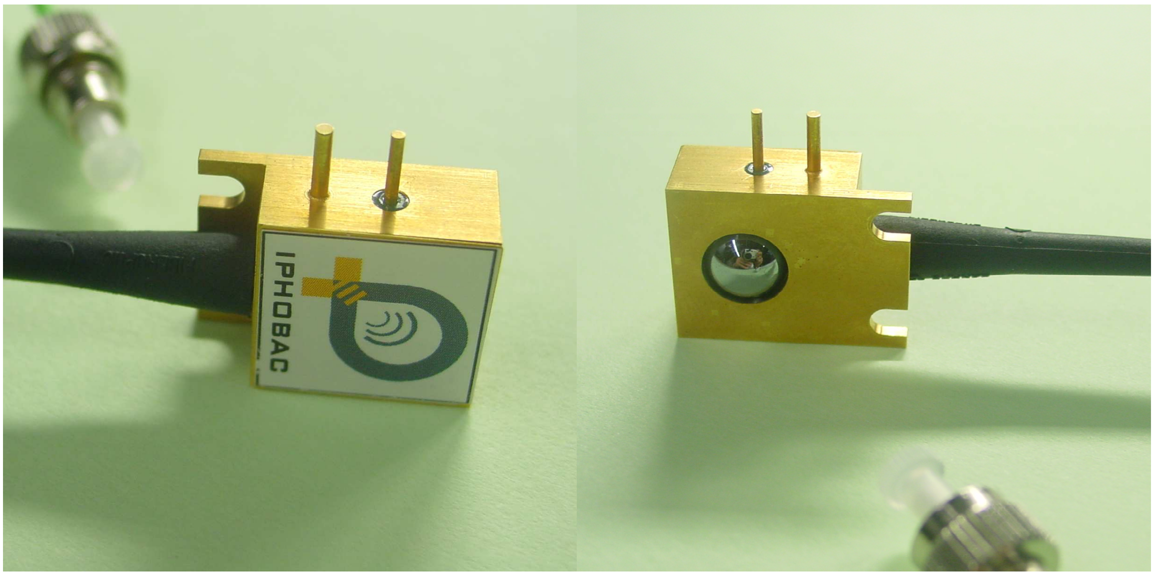

Figure 18 Top view of a packaged antenna-integrated photomixer device (left hand) and bottom view (right hand) showing the quasi-optics.

The work which had been carried out within T4.1 and T4.2 as well as T4.6 regarding to the antenna-integrated photomixers has led to numerous publications including [23], [30], [31], [42], [47]-[49] and [65].

Comparison to the State-of-the-Art

In the course of the IPHOBAC project, two other research groups published on photonic mm-wave and THz photomixers with integrated antenna. In 2008, HHI reported on a comparable photonic mm-wave transmitter by demonstrating optical heterodyne mm-wave generation in the frequency range from 60-300 GHz using a pin-antenna module operated at -2 V reverse bias [R66]. Here, the minimum available received power in the horn antenna attached detector was limited to -35 dBm due to the EM3 power meter. Hence, a reliable measurement could be performed only up to 200 GHz at a photocurrent level of -5 mA. The maximum output power of the transmitter module received in the detector was consequently only around -30 dBm at 200 GHz, which is somewhat lower than the received power from the IPHOBAC photonic transmitter module. Furthermore, the power roll-off between 60-100 GHz is about 15 dB. From 100-200 GHz, the received power fluctuates between -25 and -35 dBm except a total fall-off within around 105 GHz.

Further, high power antenna integrated photomixers (UTC-PD) operating up to 1.6 THz were reported by NTT [R34]. In 2007, a record 3-dB bandwidth of 310 GHz and a high mm-wave output power had been achieved. For generating mm-/sub-mm-wave signals, the research group developed a compact UTC-PD module with a rectangular waveguide output port for operation at up to 325 GHz. The group had also fabricated a quasi-optical module for operation at higher frequencies integrating a UTC-PD and a planar log-periodic antenna. This module can be operated at up to 1.6 THz with a maximum received output power of 2.6 µW at 1.04 THz.

1.4.1.5 Resonant 60 GHz Transceivers with integrated SOA

Objectives

The aim of this task was to integrate a semiconductor optical amplifier (SOA) with an electro-absorption transceiver (EAT) to form an optical transceiver for RF-signals around 60 GHz (see Figure 19). The use of a reflective EAT with only one optical port facilitates the packaging and coupling to the fiber. The integrated SOA works as an optical preamplifier in detection mode and a booster amplifier in transmitter mode.

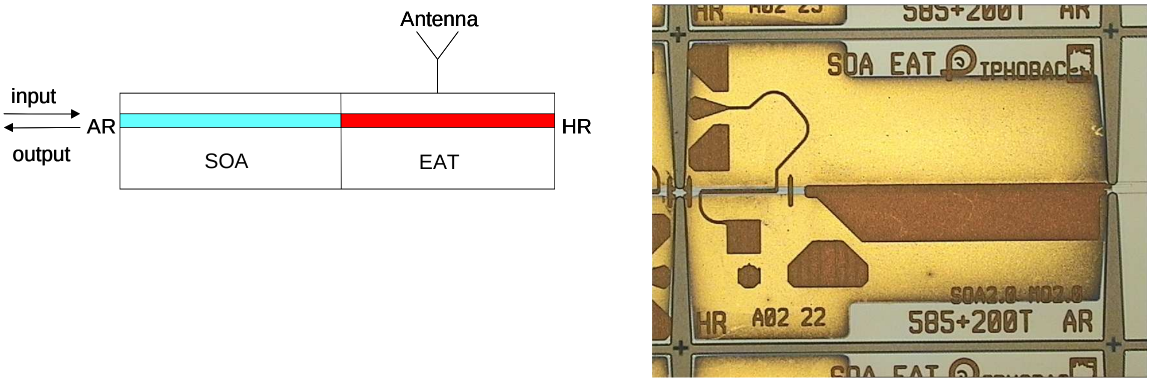

Figure 19 Schematic picture of the integrated SOA-EAT (left) and a photo of a finished device (right). The electrode design was redesigned to fit the package developed by U²T.

The SOA-EAT was designed for maximum response in the 60 GHz region. This was accomplished using a resonant design of the microwave electrodes where an intentional microwave reflection is used to maximize the voltage over the modulation and detection voltage. A 200 µm long bent taper region was used to ease the demands of the antireflection coating. The SOA-EAT was co-fabricated with the DFB-TWEAM of Task 4.3 and both first and second batch components suffered the same problem with the adhesion of the electrical contacts. As for the DFB-TWEAM, three instead of planned two major batches of SOA-EAT were made and a contingency plan with alternative components from CIP was initiated.

The third batch yielded finally, after annealing and coating by CIP, working devices with good performance. The devices exhibited a DC responsivity around 1.5 mA/mW at 70 mA SOA bias and the SOA could hence compensate the large fiber coupling losses in the experimental setup (around 10 dB) and still provide net gain. By comparison with a pigtailed commercial detector, it was deduced that the responsivity at 40 GHz at 100 mA SOA bias was 0.57 mA/mW despite the 10 dB coupling loss.

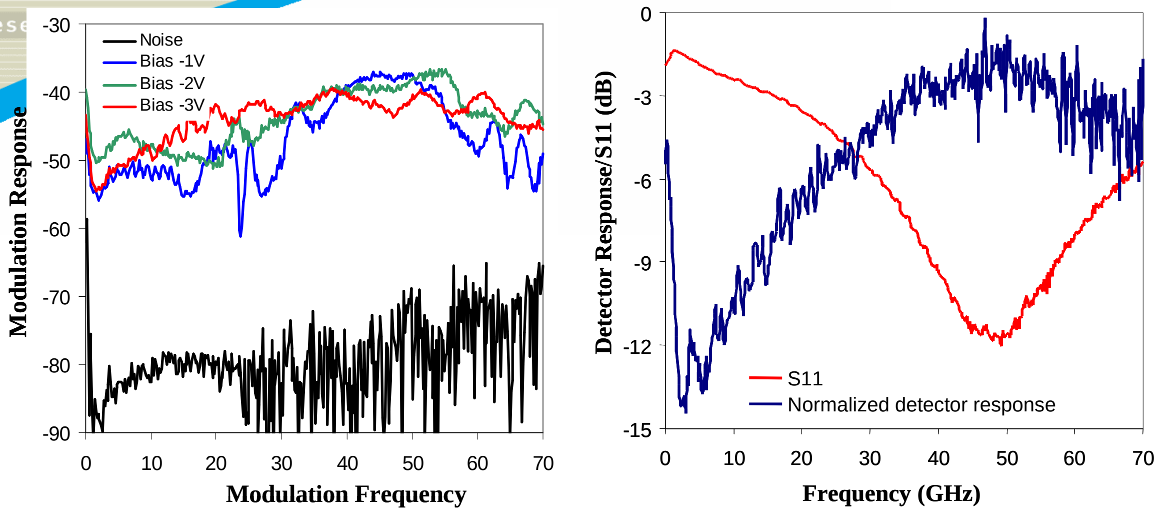

Figure 20 Modulation response of the SOA-EAT used as an optical transmitter for three different bias voltages (left). Detector response for the SOA-EAT used as an optical receiver (right, blue) and its microwave reflection coefficient S11 (right, red).

The frequency response of the SOA-EAT was similar in the transmitter and receiver mode with a maximum response and return loss (S11≅-12 dB) slightly above 50 GHz. A special package and antenna have been developed for the device by U^2T and LUB but due to the fabrication problems at KPRC the devices were severely delayed and the packaging could not be achieved before the end of the project. The estimated responsivity of a packaged component with optimized fiber coupling (2 dB loss) would be around 3 mA/mW for frequencies between 35-70 GHz. A system experiment using an unpackaged component, described in D612, successfully demonstrated transmission of a 2.5 Gbps 60 GHz ASK radio signal over optical fiber.

Comparison to the State-of-the-Art

There have been a few reports of unamplified reflective 60 GHz electroabsorption modulators in the literature [R62][R63] with reported responsivites between 0.8-1 mA/mW. CIP recently reported an integrated reflective EAM with integrated SOA for 10 Gb/s digital signals which, however, only was tested in transmitter mode [R64].

The resonant design in combination with the integrated SOA of the IPHOBAC device increases the responsivity to an estimated 3.0-3.6 mA/mW at 60 GHz. Also the modulation efficiency is, due to the amplification, believed to surpass present state-of-the-art devices. However, additional measurements on a packaged device with optimized fiber coupling are needed to accurately judge and compare the performance of the fabricated component.

1.4.1.6 Broadband DC-110 GHz Modulators with integrated DFB laser

Objectives

The objective of this task was to develop a distributed feedback (DFB) laser with high single mode output power and low phase noise integrated with a traveling-wave electro-absorption modulator (TWEAM) with high modulation efficiency, high linearity and saturation power to optimize its use as a transmitter for radio over fiber applications. The design uses a segmented travelling-wave design to overcome the bandwidth limitation of single section modulators (see Figure 21).

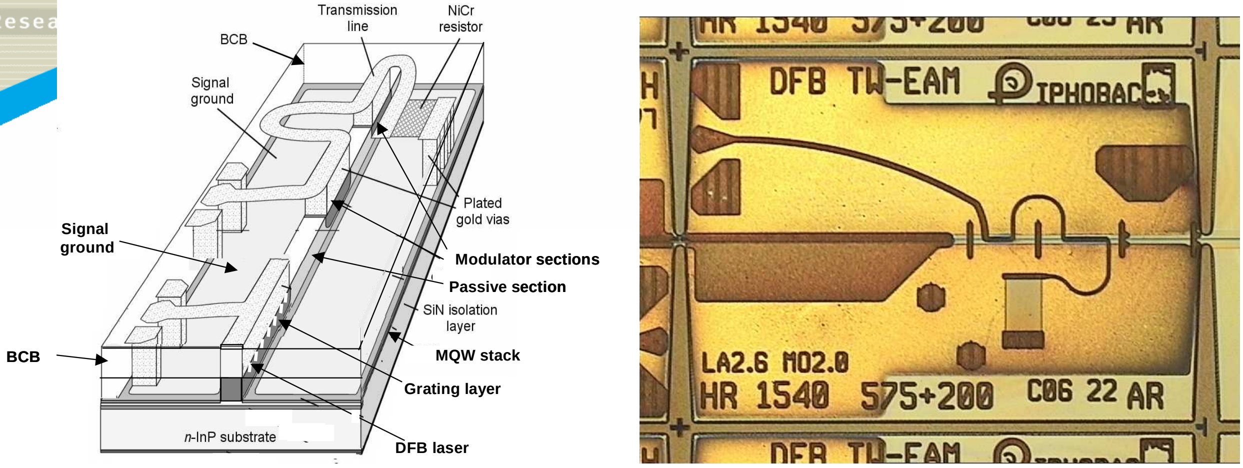

Figure 21 3D-cross section of the integrated DFB-TWEAM (left) and a photo of a finished device (right). The electrode design was redesigned to fit the package developed by U^{2}T.

Project work and achievements

As has been described in D434, both first and second batch components were unusable for system experiments due to a problem with the adhesion of the electrical contacts. Hence, three instead of planned two major batches of DFB-TWEAM were made, all with significant design differences. In addition, due to the delay and uncertain outcome of the third batch, a contingency plan with alternative components from CIP and Alcatel Thales was initiated (see results below). The fabrication problem at KPRC was finally found to be due to an unreliable sputtering machine used to deposit TiW, NiCr and gold layers. A wafer of third batch was therefore sputtered and plated in cooperation with Svedice. After annealing at KPRC and coating by CIP, working integrated DFB-TWEAMs with good steady state characteristics (18-23 mA threshold, SMSR>40 dB and 8-12 mW output power through TWEAM un-mounted) were achieved (Figure 22).

A remaining problem with the third batch was that the sputtered NiCr end resistors, designed to be 35 Ω, became 100-250 Ω. This gave a large microwave reflection which severely hampered the modulation response of the device. The extrapolated modulation efficiency of a device at 100 GHz with 150 Ω was 0.3 mW/V limited by the large value of the matching resistor. Although there existed devices with lower resistance it was concluded that the expected modulation results were not promising enough compared to the contingency plan alternatives to motivate packaging in the specially designed package by U^{2}T. In a simple system experiment with an unpackaged DFB-TWEAM, described in D611, transmission of a 2 Gbps 60 GHz ASK radio signal over an optical fiber was demonstrated.

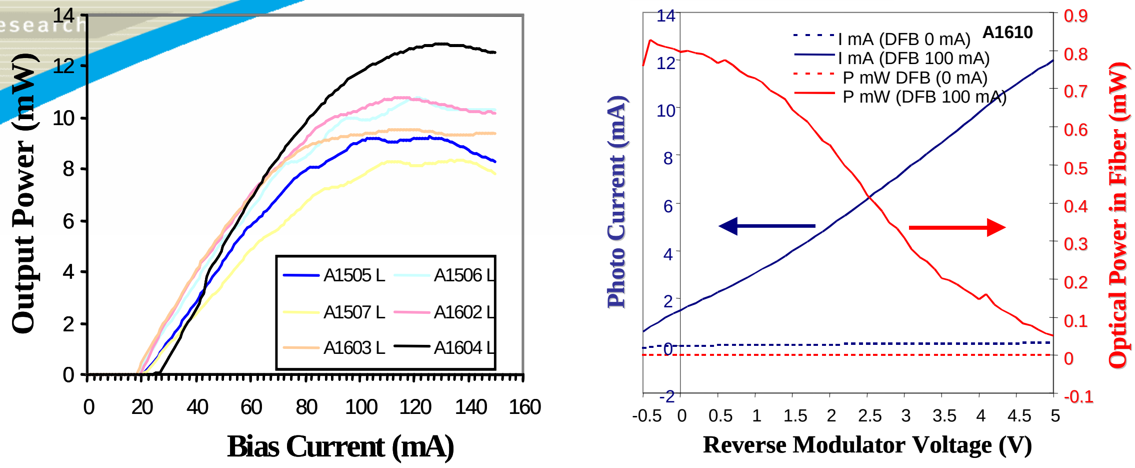

Figure 22 Output power (left) as a function of injection current of six 375 µm long DFB lasers integrated with a TWEAM modulator. Measurements of fiber-coupled power (right, red) and photocurrent (right, blue) versus reverse modulator voltage. Total length of chip is 900 µm.

Comparison to the State-of-the-Art

The device can be compared to the state-of-the-art DFB-TWEAM for 100Gb/s Ethernet which was developed within the Hecto project [R65]. Both devices use a segmented travelling wave modulator. However, since the Hecto device is optimized for use in a digital 100Gb/s Ethernet system it uses a different laser design, epitaxial design, electronic pad design and waveguide design to achieve linear phase response and high extinction ratio. The laser characteristics (threshold, single mode stability and output power) of the IPHOBAC devices were slightly better than for the Hecto devices. The IPHOBAC modulator exhibited similar static modulation efficiency (2.5mW/V) and better linearity. However, due to the fabrication problem with the termination resistor, the modulation efficiency at 100 GHz was almost one order of magnitude lower, only 0.3 mW/V. The system performance of a packaged IPHOBAC DFB-TWEAM would otherwise, due to the design differences, most likely exceed that of the Hecto device which was successfully tested in the IPHOBAC test-bed (see D611).

1.4.1.7 Broadband DC-70 GHz Modulators with integrated DFB laser

Objectives

In the fame of the contingency plan it was decided that III-V Lab will develop wide bandwidth (f_{3dB}~70GHz) integrated DFB/EAM (EML) chips on sub-mount which are ready for packaging in a U2T package.

Project work and achievements

Devices from III-V Lab that were obtained from former fabrications runs were characterized, mounted and packaged by U²T. Devices with different geometries have been cleaved and mounted on specific sub-mounts optimized to work up to mm-wave frequencies. These sub-mounts, developed in collaboration with U²T, were designed in order to be compatible with U²T standard modules. Thanks to the new sub-mount design it was possible to get a flat electro-optical response at up to 65 GHz, the limit of the network analyzer (Figure 23). More details about the mounted chips can be found in

D432. The characterization and use of the modules in system experiments by TAS can be found in D614.

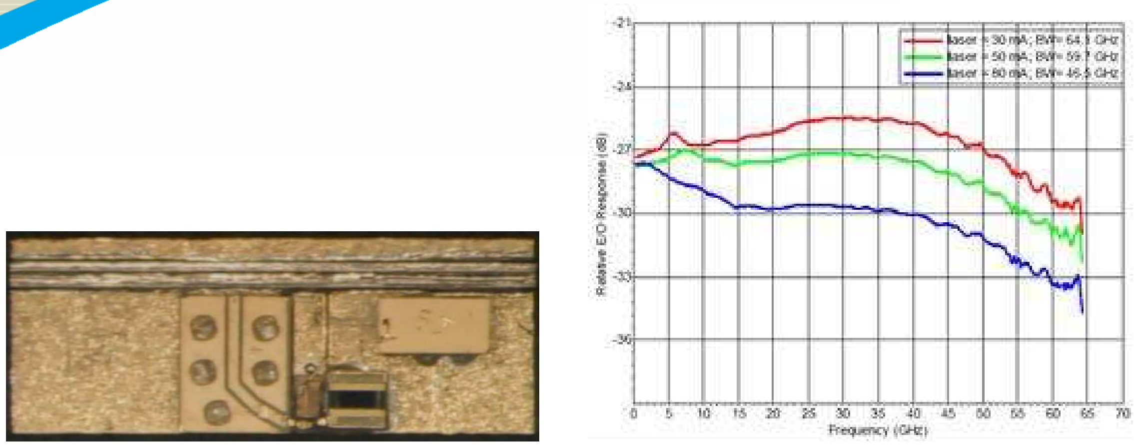

Figure 23 (left) View of the chip on submount and (right) modulation response measurement.

In order to improve the device performance, a new design of the modulation section having a larger electro-optical response has been made and grown. With more efficient absorption layers it is possible to shorten the modulation section while maintaining a good modulation efficiency. This leads to a lower parasitic capacitance and favors the modulation bandwidth. The measurement results of the electro-optic response of the modulator from the new design can be seen in Figure 24. A modulation response of about 5 dB/V has been obtained. More details about this work can be found in M437.

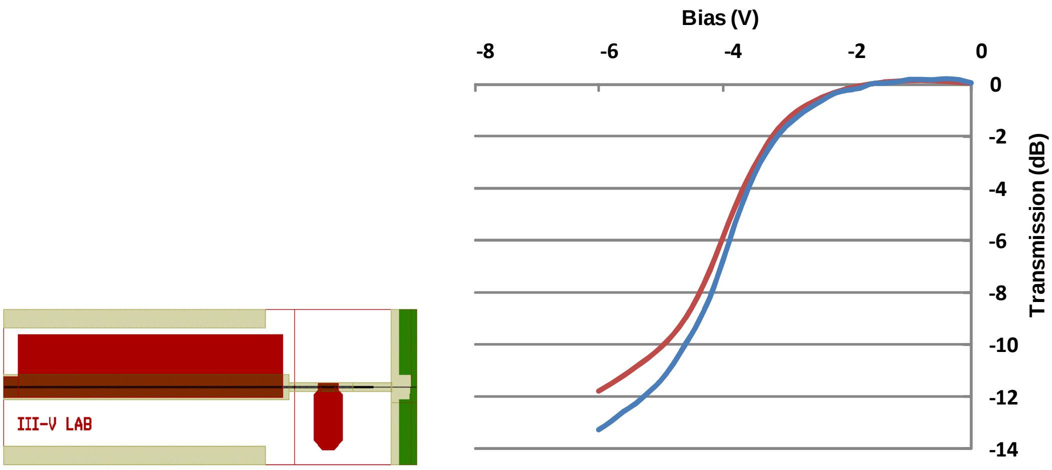

Figure 24 (left) View of the chip design and (right) static electro-optic gain measurement

Comparison to the State-of-the-Art

The results obtained on these devices are very similar to those obtained by KTH in the frame of the IST-Hecto project, where a bandwidth of more than 100 GHz was demonstrated with a maximum static electro-optical response of about 10dB/V (Chacinski et al., Journal of Lightwave Technology, vol. 27, no. 16, August 15, 2009).

1.4.1.8 Broadband DC-100 GHz transmissive and reflective modulators

Objectives

- Development of a wide bandwidth (100GHz, 9dB extinction) reflective-type EAM ready for packaging.

Project work and achievements

The objectives were met, except that the extinction ratio of the 100 GHz devices was fractionally lower than the target.

- Reflective EAMs were fabricated at CIP to a new high speed design. After two fabrication runs devices that had 7-8 dB extinction ratio and >60 GHz bandwidths (measurement limited) were obtained. Their simulated bandwidth based on the measured electrical characteristics was ~ 105 GHz. These devices were supplied for packaging and were described in D433.
- Some very low insertion loss and high responsivity transmissive and reflective EAMs were packaged in 'V'-type connectorised modules at CIP. These were supplied and used in 60 GHz RoF experiments at FT and UPVLC. The devices were described in D442. This work helped CIP to launch a new product – the 60G-R-EAM-1550.

Comparison to the State-of-the-Art

These are thought to be the fastest reflective EAMs ever reported.

1.4.1.9 10 Gb/s SOI phase shifter

Objectives

One objective of the IPHOBAC consortium was to study optical vector modulation techniques for broadband wireless systems for using the mm-wave bandwidth more efficiently. For doing this, a specific component, namely an optical phase shifter was needed. It was the aim of UPVLC in task 5.3 to fabricate such a phase shifting element in silicon-on-insulator (SOI) technology based on ring-resonators that have excellent features (compactness, stability and bandwidth).

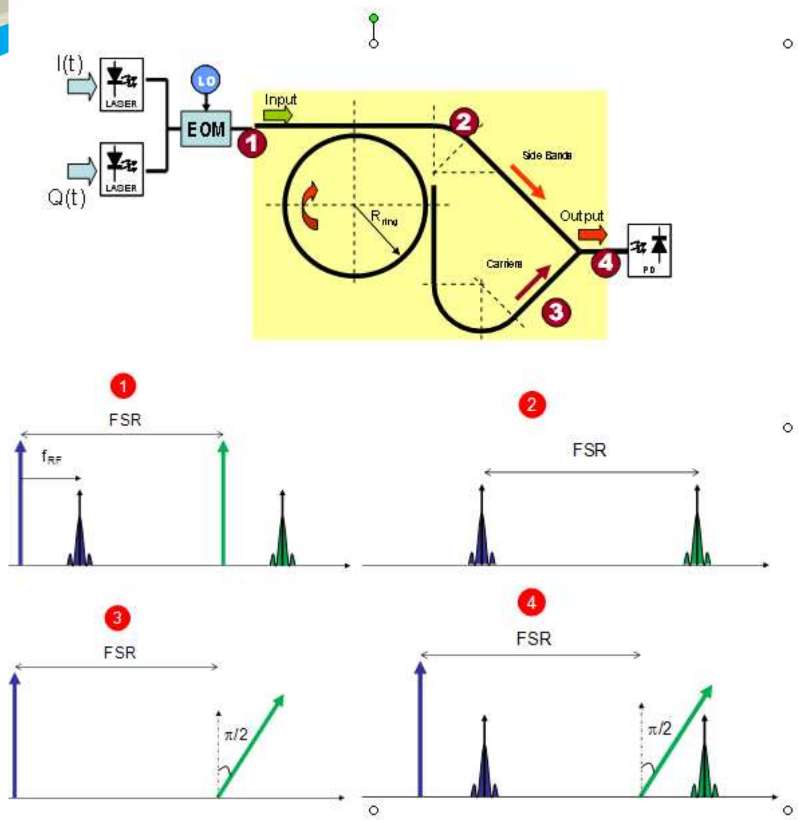

Figure 25 Scheme of the ring-resonator-based phase-shifter. Signal components propagation and relative phase shifts at different points of the RR-PS structure.

It was proposed to design, fabricate and test a compact phase-shifting element in Silicon on Insulator (SOI) technology so that it can be potentially integrated with other elements in SOI photonic technology. The proposed structure was based in a ring-resonator (RR) structure coupled to input and output integrated optical waveguides, as shown in Figure 25(top). The operating principle is the following: an optical signal entering through access 1 couples inside the RR at point B if its wavelengths corresponds to the one of the resonance wavelengths of the RR, and if not, travels to the output. The signal inside the RR can be extracted out by setting a second waveguide close to the RR so that the entire signal can be coupled in the new waveguide. A series of wavelengths spaced with the free-spectral range (FSR) of the RR will be extracted at point 3. Owing to the position of the second output waveguide, the phase shift between adjacent extracted wavelengths will be 90º. If at point 1 we inject to optical carriers spaced the RR FSR with SSB modulation (at a given RF frequency that must be higher than the RR resonance bandwidth) the optical carriers will be extracted towards point 3 and will have a relative 90º phase shift between them. In contrast, the SSB sidebands will not be extracted so they will travel towards point 2 without any relative phase shift (apart from that induced by the silicon waveguide dispersion). At point 4 both branches are combined. If the output optical signal is photodetected at the output we will have a QAM modulation owing to the relative 90º phase shift induced by the RR (see Figure 25, bottom)

Project work and achievements

The development of the 10 Gb/s SOI phase shifter was carried out within task T5.3 and UPVLC was the only contractor involved in this task. The work and achievements were reported in D532, D534 as well as in M532 and M535.

Basically, the methodology consisted of a workflow including these stages: 1. Modeling; 2. Optimized design and calculation of physical parameters; 3. Fabrication run. 4. Measurements. 5. Comparison with simulations and turn to stage 2. Here we describe all the stages as a general summary of the undertaken activities.

We started by modeling the proposed SOI ring-resonator phase-shifter (RR-PS) using a simple transfer-matrix method (TMM). The transfer matrix method (TMM), which is the most commonly used for modeling photonic structures that employ RRs, is based on a simple matrix modeling of the waveguides of the structure and the coupling between them. A typical theoretical response is shown in Figure 26. In the model, we assumed that the waveguide has a certain effective index, which depends on its dimensions and can be obtained by means of the beam propagation method (BPM). A silicon waveguide with core dimensions of 250x450 nm^2 was chosen (n_{eff}=2.6). The waveguide dispersion was also calculated using BPM. It turned out that the total dispersion could be neglected owing to the small dimensions of the circuit (less than 100 microns). We also simulated the RR-PS response using the finite-difference time-domain methods. See D532 for more details about the theoretical analysis and design.

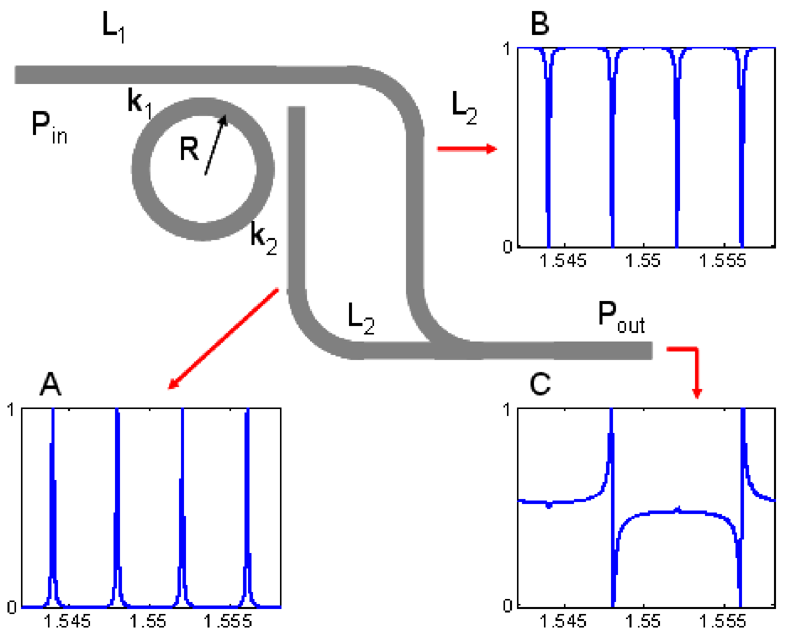

Figure 26 RR-PS configuration. The normalized transfer function of the structure as a function of the wavelength in microns is shown at three critical points of the structure. A, transmission across the RR; B, transmission across the input waveguide; C, Transfer function of the structure.

Once we had the tool to model the response, we proceeded to design the RR-PS to obtain an optimum behavior. The RR-PS element was optimized in order to achieve a total extraction of the resonant wavelengths throughout the C access. The main parameters that were considered for the optimization of the RR structure are the coupling and transmission coefficients of the input coupler (k_1, t_1) and of the output coupler (k_2, t_2). As a conclusion of this study, the coupling coefficient k_2 always has to be equal (if there are no propagation losses) or lower than k_1. When propagation losses increase the optimum k_2 value moves to lower values in order to achieve a maximum extraction of the power of the carriers from the modulated signal. The problem that arises is that the point of the desired 90º phase relation is more difficult to be found and disappears for the case of very high losses.

The TMM approach gave us the optimum coupling ratios but not the physical parameters of the RR-PS. The radius of the RR was chosen to be R=21.2 µm in order to achieve a FSR of 500 GHz. The waveguide-RR gaps (g_1 and g_2) were obtained from the calculated k_1 and k_2 values using the 3D FDTD method. Table 1 shows the optimized parameters. It has to be mentioned that g_1 and g_2 refer to the RR-waveguide spacing in regions 2 and 3 respectively.

Table 1 Optimum parameters of the SOI RR-PS chip

Waveguide width (nm)	500
SOI wafer silicon thickness (nm)	250
FSR (GHz)	500
RR radius (um)	21.2
g_1 (nm)	100
g_2 (nm)	200

In D534 we reported on the measurements of first fabricated samples. Only amplitude measurements were realized owing to the inherent difficulty in the realization of phase measurements. However, after we had completed the complete workflow (stages 1 to 4) with an initial thickness of the silicon layer of 220 nm, our supplier of silicon wafers (SOITEC) stopped the delivery of 220 nm SOI wafers and replaced them by 250 nm ones. This was a serious inconvenience that made us to come back to step 2 and resulted in a delay in the realization of the proposed activities. All parameters and results given in this report refer to a silicon thickness of 250 nm.

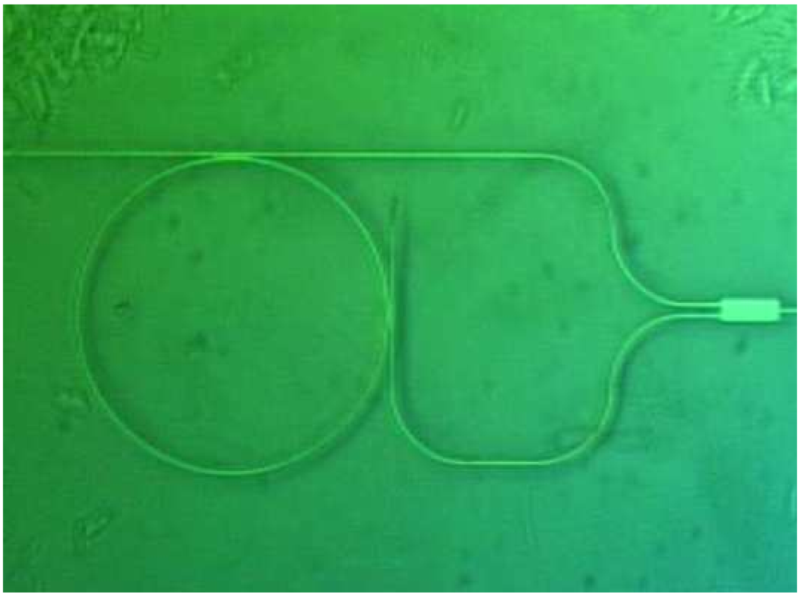

Figure 27 Optical microscope image of the optimized closed IPHOBAC chip with 21.2 um RR, g_1=100nm and g_2=200 nm.

For instance, we fabricated open and closed RR-PS structures with a RR radius of 21.2 um and different values of g_1 and g_2 (close to the optimum values given in Table 1). As combining structure, we used the MMI coupler. Figure 27 shows an optical microscope image of one of the fabricated closed structures with g_1=100nm and g_2=200 nm. We obtained an optimum performance (critical coupling) for these values of the gaps (which satisfies the $|k_2| \leq |k_1|$ condition). The drop and through response of the open RR-PS circuit is shown in Figure 28(a). It can be seen that both transmission dips in the through port and peaks in the drop port are very steep. Moreover, the amplitude of the drop port peaks is similar to the amplitude of the through port at wavelength out of the resonances, which is a requirement for the IPHOBAC chip. The FSR is 4 nm (500 GHz) as expected. The combined response (closed RR-PS) is shown in Figure 28(b). It can be seen that the dropped wavelength is efficiently combined with the through port. This occurs also for adjacent resonant wavelengths.

We fabricated new samples with grating couplers at both the input and the output of the chip to ensure high coupling efficiency from external fibers to the RR-PS chip. The optimized parameters in Table 1 were used. After optical transmission measurements, we obtained an output spectrum (D point) even flatter than that shown in Figure 28 (not reproduced here). In principle, this result encouraged us to carry out measurements of the relative phase between adjacent optical carriers (spaced by the RR FSR). To do that, we modulated two FSR-spaced optical carriers by use of a single RF tone generated by an HP8510C vector network analyzer. The idea was to split up the optical wavelengths (with the RF sidebands) at the chip output and then to detect each path by use of 45-GHz photodetectors. Finally, and after proper amplification, the accumulated phase through each path could be measured in the HP8510C. However, we obtained that the measured phase shift changed strongly both with time (probable as a consequence of index changes in the RR due to temperature drifts) and with wavelengths. In fact, we were aware that since in the relatively-flat output spectrum we were not able to identify the resonance wavelengths, it was not possible to properly tune the optical carriers. Then, we decided to fabricate the same sample but with three outputs: the combined one, as before, but also the B and C point signals before combination. In this case we should be able to identify the resonant wavelengths at the output, and we would also have the combined signal to carry out the phase measurements.

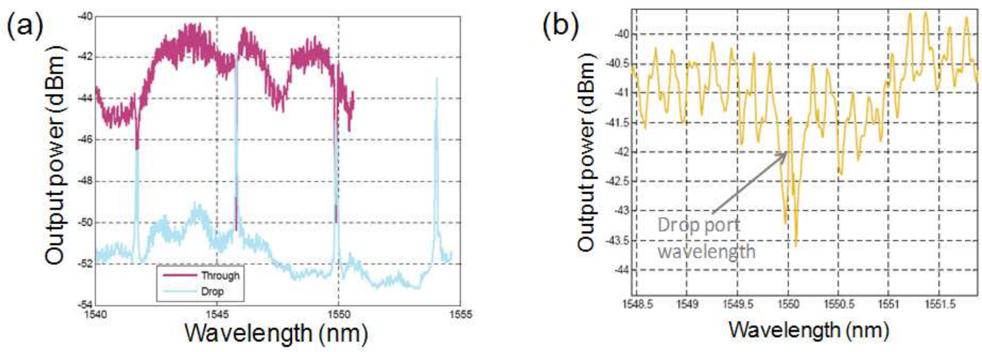

Figure 28 Transmission spectra of the (a) open and (b) closed IPHOBAC architecture (21.2 um RR, g_1=100nm and g_2=200 nm). It can be observed that the power difference between the dropped wavelength and the through port signal is less than 0.5 dB.

The final device we have fabricated is shown in Figure 29. Two different samples have been produced and tested (only amplitude measurements). One of them did not work properly owing to an over-etching of the RRs. The transmission spectra of the other sample are shown in Figure 29. The RR resonances are clearly appreciated, which can be used to properly tune the optical wavelengths. As mentioned below, this is a main requirement to measure the phase shift. The combined output has not a flat response as observed in previous samples, but we are confident that it should be enough to measure the addressed 90º phase shift.

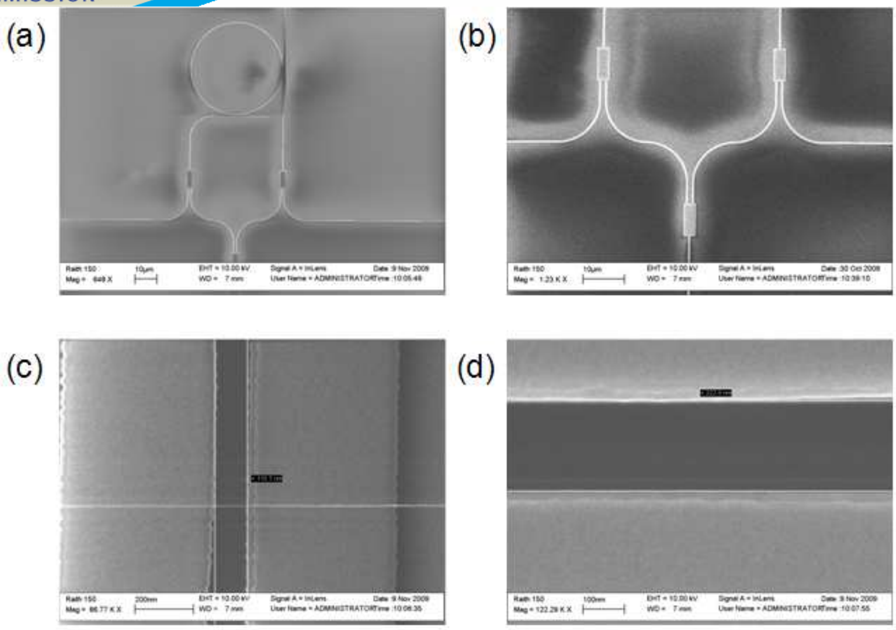

Figure 29 Scanning electron microscope (SEM) images of the last IPHOBAC RR-PS fabricated samples. (a) Complete structure with two MMIs to split up signals from the drop and through ports. (b) Detail of the three MMIs; (c) Through port gap; (d) Drop port gap.

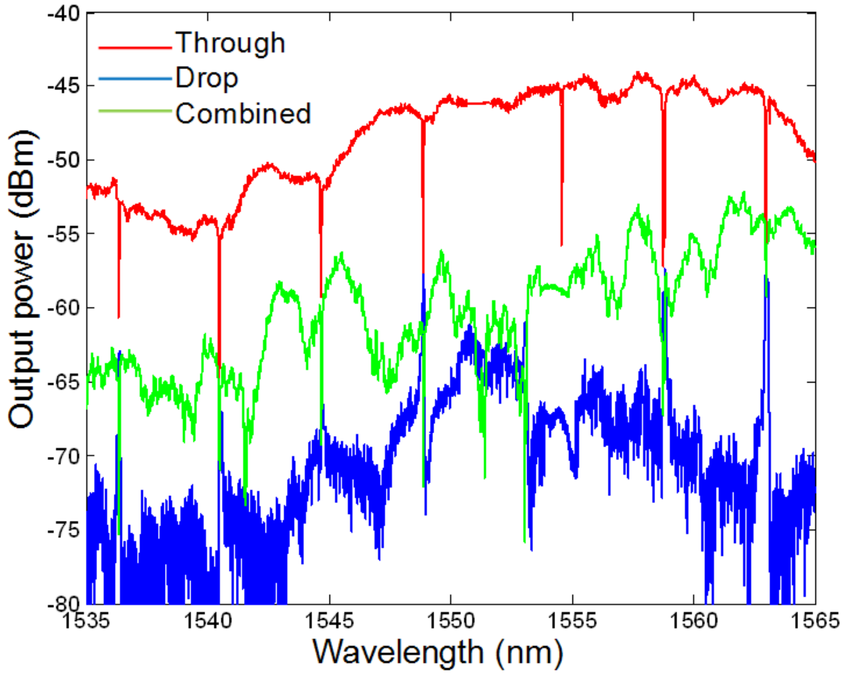

Figure 30 Last samples with three output ports: Transmission spectra showing RR resonances in the three ports.

The main achievements are summarized as follows [R1][R2]:

- Successful optimized design of the RR-PS using TMM, FDTD and BPM.

- Realization of a highly-compact RR-PS using silicon technology. The total size of the device shown in (a) is about 5000 μm^2. This means that more than 1 million RR-PS chips can be built on a 8" SOI wafer.
- RR-PS bandwidth: since the device is all-optical, there are no bandwidth restrictions. Moreover, the device is scalable and it can work at different optical carrier spacing.

Comparison to the State-of-the-Art

Only recently the fields silicon photonics and microwave photonics have converged. Some recent approaches make use of SOI photonics technology for applications related to those covered by IPHOBAC. For instance, in L. Zhang et al., Opt. Lett. **33**, 1428-1430 (2008), Silicon RRs are proposed to achieve ultrasmall differential quadrature phase-shift keying modulators and demodulators operated at 20 Gb/s, which may require a dramatically reduced chip size. This approach employs on-chip electro-optical modulators, so the device is quite different to that developed within IPHOBAC. Therefore, it is difficult to compare the SOI RR-PS circuit results with the current state of the art in silicon photonics since it is a completely novel device.

In comparison with current approaches in microwave photonics that make use of COTS components, it can be stated that the SOI RR-PS has two main advantages: no bandwidth restriction and extremely small footprint. These results, as well as the recent papers as that cited above, encourage us to continue working on the development of microwave photonics and radio-fiber applications using silicon technology.

1.4.2 Photonic and electronic integration

1.4.2.1 Hybrid integrated optical mm-wave source

Objectives

- The objective is to demonstrate a compact tunable, up to 300 GHz, integrated optical mm-wave source
- First hybrid integrated optical mm-wave source using the silica on silicon integration platform

Project work and achievements

For low phase noise photonic mm-wave generation, many approaches have been investigated during the IPHOBAC project and were reported in PAR2, D223, D614 as well as in the IPHOBAC publications [7], [8], [10], [23], [29], [30], [39], [42], [47], [48], [49]. The key IPHOBAC component used for all mm-wave generation schemes described in the following is the high-power and broadband photodetector developed in WP4. The photodetector converts the generated optical signal into the electrical domain. As regards the hybrid integrated optical mm-wave source using the silica on silicon integration platform also lasers developed in WP3 were employed.

Ultra-wideband photonic mm-wave generation (optical heterodyning)

Photonic mm-wave generation based upon optical heterodyning of a 1.55 µm dual-laser signal in the high-power and broadband photodetectors developed in WP4 is presented. UDE has constructed two different output port configurations, depending on the application field of the photonic mm-wave synthesizer. The first setup features a WR10 rectangular waveguide output comprising an additional amplifier exceeding W-band (75 to 110GHz) operation, whereas in the second configuration, a coaxial W1 output port is deployed covering a frequency range of DC to > 110GHz. Figure 31 shows the measured mm-wave output power versus mm-wave frequency for the WR10 output port configuration. As can be seen, the frequency response is extremely flat with a maximum power fluctuation below 3dB for a wide frequency range from 69GHz up to 112GHz.

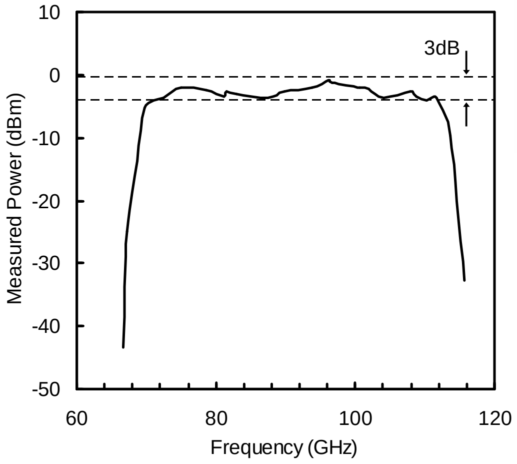

Figure 31 Output power of the photonic mm-wave synthesizer versus mm-wave frequency. For this experiment, the PD was operated at a reverse bias of 2V and a DC photocurrent of 2mA.

Using the coaxial W1 configuration, we also measured the frequency response of the synthesizer. Up to 50GHz, measurements were carried out with the internal mixers of the electrical spectrum analyzer (ESA). V-band (50-75GHz) and W-band (75-110GHz) measurements were carried out using external harmonic mixers. A flat and wideband frequency response (DC-110 GHz) was achieved with a total signal roll-off of about 6dB and output power levels of up to -3.23dBm. Considering a frequency range from 20GHz up to 110GHz, the total signal roll-off is below 3dB.

Low phase noise and tunable photonic mm-wave generation (external modulation)

Low-phase noise and tunable photonic mm-wave generation based upon external modulation was studied by UDE. For the optical mm-wave generation light from a laser (λ = 1.55 µm) was modulated using a single-drive Mach-Zehnder modulator (MZM) with a 3dB cutoff frequency of 40.7 GHz, which is biased at V_π to generate an optical double-sideband signal with suppressed carrier (DSB-SC). The modulator is driven by a tunable low phase-noise sinusoidal synthesizer with a frequency range of DC up to 60 GHz. An optical carrier suppression of approximately 26 dB is achieved. After photo-detection, the mm-wave is transmitted to a W1-coupled coaxial output port. Although the modulator was operated at a frequency much higher than its 3 dB cutoff frequency, the complete operational frequency range could be applied to the photodetector due to the optical amplification. We have performed phase noise measurements of the applied LO signal at 50 GHz as well as of the photonically generated 100 GHz mm-wave signal after detection by the photodetector. At an offset frequency of 10 kHz from the carrier, phase noise levels of -77.9 dBc/Hz and -69.8 dBc/Hz from the LO output and the photodetector output were measured, respectively.

Fixed frequency ultra-low phase noise photonic mm-wave generation (external modulation)

Here, we present low-phase noise photonic mm-wave generation based upon an optical quadrupling scheme. For the optical mm-wave generation, an electrical LO signal is applied to an Mach-Zehnder modulator, which is biased to completely suppress the even-order optical sidebands including the carrier. Thus two coherent carriers are obtained and then modulated by the same microwave signal, with a phase deviation of $\pi/2$ introduced by an electrical phase shifter in the next Mach-Zehnder modulator. After passing the modulator, each of them will generate many optical sidebands, where their interference will increase or decrease the intensity of the sidebands. This will result in optical sidebands having a difference frequency 4-times the frequency of the microwave LO source. After amplification using a low-noise EDFA, the photonic mm-wave signal was o/e converted by the high-power IPHOBAC photodetector. UDE has performed phase noise measurements of the quadrupled signal using a 24 GHz LO source. The 24 GHz LO source was provided by Mr. Erhard Salow from INWAVE GmbH. The 24 GHz LO signal was measured directly using the ESA whereas the measurement of the generated 96 GHz signal was carried out using the ESA with an external W-band harmonic mixer. Additionally, a measurement of a frequency doubling (48 GHz) as well as a measurement of the 24 GHz LO transferred into the optical domain was performed. The results are shown in Figure 32.

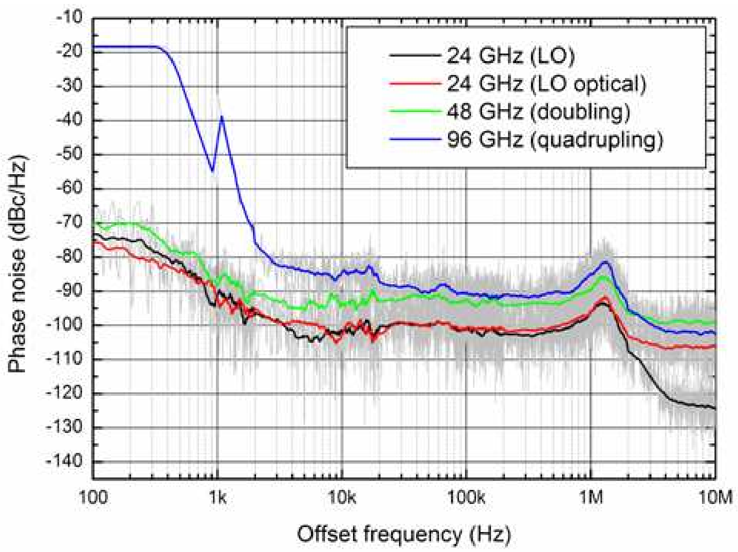

Figure 32 Phase noise measurements using a 24 GHz LO signal.

As can be seen from the 96 GHz measurement, at low offset frequencies there are very high phase noise values resulting from the harmonic mixer. Measurements at 48 GHz with and without using a harmonic mixer have been performed showing the same problem at low offset frequencies when using a mixer. Nevertheless, at an offset frequency of 10 kHz, the phase noise is around -85 dBc/Hz. Taking a deeper look at offset frequencies above ~2 MHz one can see that all measurements using an optical system saturate while the phase noise of the LO source itself further decreases. This can be attributed to noise sources coming from the optical system such as relative intensity noise (RIN) from the laser, amplifier noise from the EDFAs, shot noise from the PD as well as thermal noise. This means that the phase noise can not go below the limit which is determined by these noise sources. These results demonstrate that an efficient mm-wave generation is possible reducing the frequency requirements of the LO source for low-phase noise generation. Measurements were performed in Task 6.3 (special actions: demonstrations).

As regards the silica on silicon integration performed by CIP, a hybrid integrated tunable source comprising a twin amplified DBR laser and an antenna integrated photodiode connected by passive silica waveguides was assembled and packaged at CIP. The combined output power of the lasers after hybrid integration was 13 mW. The module was supplied to UCL for testing. It is described in D526.

In summary, We investigated several approaches for tunable and low phase noise photonic mm-wave generation. Ultra-wide tunability, a high-output power of up to 0 dBm and a low phase noise down to -85 dBc/Hz @ 10 kHz offset from a 96 GHz carrier were achieved.

Comparison to the State-of-the-Art

Several approaches concerning mm-wave generation have been investigated in the literature. Most of the approaches are based on either optical heterodyning in a high-frequency photodetector or external modulation which covers techniques such as double sideband with suppressed carrier mm-wave generation and optical multiplication techniques.

Approaches for **optical heterodyning** in a high-frequency photodetector are including several techniques like e.g. optical injection locking (OIL), optical phase lock loop (OPLL), mm-wave generation using a dual-wavelength laser signal (2λ-LD) and optical comb generation (OFCG) to name such a few. OIL of semiconductor lasers is rather challenging with respect to coupling the master into the slave laser especially for back side coupling and also the frequency resolution is rather limited given by the longitudinal mode spacing of the slave laser [R57]. Solid-state lasers (single or dual frequency) offer frequency stability that lead to an easier realization of OPLLs [R58], either directly or on harmonic lines from modulator/comb. Low-phase noise (-110 dBc/Hz @ 10 kHz) mm-wave generation has been demonstrated using a solid-state 2λ laser but only at frequencies up to 20 GHz [R59]. OFCG is also a very interesting approach for generating low-phase noise high frequency lines but so far, it seems not so easy to be implemented (optical frequency stabilization on a cavity) for instance in [R60]. Another drawback of the OFCG is that side-modes are selected by optical filtering, i.e. frequency resolution is rather limited.

Millimeter-wave generation using **external optical modulation** covers techniques such as double sideband with suppressed carrier generation and optical multiplication techniques. External modulation is a rather robust technique and components technology is mature. Without frequency multiplication mm-wave signals up to 110 GHz has been already demonstrated (IPHOBAC). With optical multiplication, external modulation has been demonstrated up to 337 GHz [R61] but the frequency resolution is rather poor (60 GHz steps). The phase noise depends on the RF synthesizer employed.

As regards the hybrid integrated silica on silicon optical mm-wave source, we are not aware of any prior work on such a device.

In conclusion, IPHOBAC has shown the capability of generating ultra-wideband (DC-110 GHz) and low phase noise broadband (W-band) mm-wave signals. Although the frequency tunability is much larger as compared to fixed frequency sources, in some cases it is even continuously tunable ([R60]), the achieved low-phase noise performance is almost as good as for fixed frequency sources, e.g. in [R59]. Furthermore, the approach using external modulation (W-band operation) can be easily extended by using the optical quadrupling scheme also presented in IPHOBAC.

1.4.2.2 10 Gb/s PRBS and data demultiplexers

Objectives

For the PVM experiments in task 5.3, several custom-made devices and (sub) systems were required. LUB was responsible to provide support to UPVLC, leader of the task 5.3, specifically to generate the needed high-datarate bitstreams of 10, 5 and 2.5 Gb/s. In addition, custom-made high-speed data demultiplexers were required to provide the decimated data streams for the various modulation formats within the PVM experiments. Lastly, custom-made laser-module-specific controllers were required for the maximal flexibility (changing various operating points and parameters of the devices used) of the PVM experiments.

- To design and implement a compact and low-cost 10Gb/s PRBS generator with pattern-synchronization output for a 10 Gb/s vectorial modulation experiment in the task 5.3
- To design and implement a 10 to 2x 5 Gb/s and 10 to 4x 2.5 Gb/s data demultiplexer for a 10 Gb/s vectorial modulation experiment in the task 5.3

- To develop and implement a laser controller with a direct-modulation capability for a 10 Gb/s vectorial modulation experiment in the task 5.3

Project work and achievements

Although commercial PRBS generators were available at relatively low-cost prices, LUB decided to design and implement its own 10 Gb/s PRBS generator for the broadband wireless experiments using optical QPSK modulation in task 5.3. The reason was that a novel PRBS-generation method was invented which provides several improvements over existing solutions and could provide a technological advancement and a commercial opportunity for its exploitation. The implemented PRBS generator features a low output-data jitter, 10 GHz and 2.5 GHz clock outputs and a pattern-length synchronization output. It consists of commercial components and none custom-made chips which makes it a cost-effective solution. The main advantage of its novel design would be in the form of an integrated device for the highest data rates (>100 Gb/s) due to a lower power consumption, simpler design and higher performance. During the test measurements it was found that the performance of the PRBS generator outperformed the commercial equipment (output-data jitter and eye width). This work is described in detail in the D535. Additionally, a patent on the novel PRBS generator was filed in. The manufactured 10 Gb/s PRBS generator satisfied the objectives fully and is shown in Figure 33.

Figure 33 Photograph of the manufactured 10 Gb/s PRBS generator.

Despite the fact some commercial data demultiplexers were available (Vitesse Corp., etc.), LUB decided to design and implement its own data demultiplexers to suit the demands and flexibility of the PVM experiments. The commercial products either require several additional circuits to adapt them to PVM sub-systems and experiments or severely limit the PVM-experiment flexibility. LUB designed and manufactured two data demultiplexers, each including the 10 GHz clock recovery, loss-of-signal and loss-of-lock indication. Additionally, the demultiplexers connected seamlessly within the PVM devices, sub-systems, equipment and finally the experiment. The manufactured data demultiplexers satisfied the objectives fully and are shown in Figure 34.

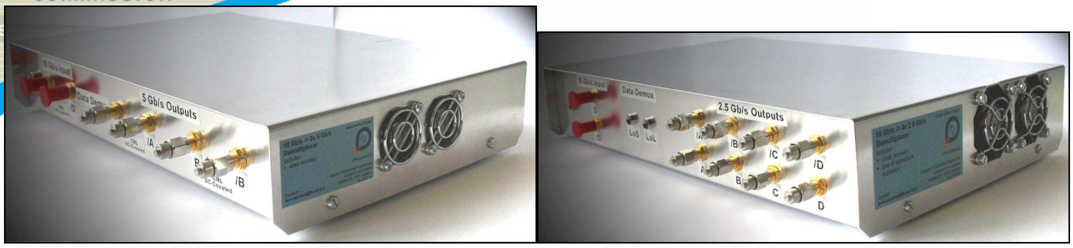

Figure 34 Photographs of the manufactured 10 to 2x 5 Gb/s (lefthand side) and 10 to 4x 2.5 Gb/s (righthand side) data demultiplexers.

For the first PVM experiments UPVLC used commercial (of the shelf) laser-modules. LUB designed and manufactured control units for these components to provide maximal flexibility for the PVM experiment. Beside the temperature control and readout, optical output-power and heating/cooling indication, laser-current and modulation-depth regulation, a data input with datarate capability of more than 5 Gb/s was provided. The optical eye diagram achieved more than 10 dB extinction ratio at 2.5 Gb/s and almost 10 dB at 5 Gb/s datarate, respectively. The laser-controller units seamlessly connected to the data demultiplexers and satisfied the objectives fully. Front panel of one laser-controller unit is shown in Figure 35

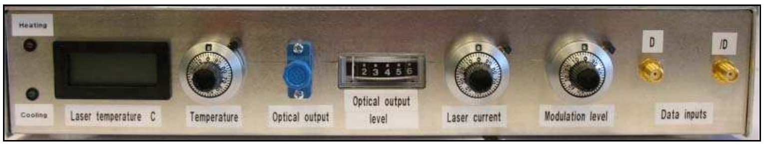

Figure 35 Photograph of the manufactured direct-modulation laser controller.

Comparison to the State-of-the-Art

Commercial PRBS generators are available at reasonably low-cost, but LUB invented a novel PRBS-generation method which provides several improvements over existing solutions and can provide a technological advancement and a commercial opportunity for its exploitation. In that regard, LUB has filed a Slovenian patent (SI200900158) to protect its knowledge and inventions on the novel and innovative high-performance and low-cost PRBS generation. The patent is entitled "Pseudo-random data-generation procedure and apparatus for the procedure realization". The novel design is especially important for the future highest bit-rate communication electronics.

1.4.2.3 OPLL with mm-wave photonic source & advanced phase detector

Objectives

The objective was to demonstrate a compact continuously tunable mm-wave source with phase noise better than -85 dBc/Hz at 10 kHz offset over a frequency range of 10 GHz to 300 GHz for targeting applications such as security, radar, high bit rate communications and instrumentation. This work was carried out in task 5.2.

Figure 36 shows the schematic of the mm-wave source based on optical heterodyning technique. In order to reduce the phase noise of the generated signal, each of the outputs of the monolithically integrated twin DBR laser (slave lasers: D342) is phase locked to two different lines of an optical frequency comb generator (OFCG) using two hybrid integrated OPLLs.

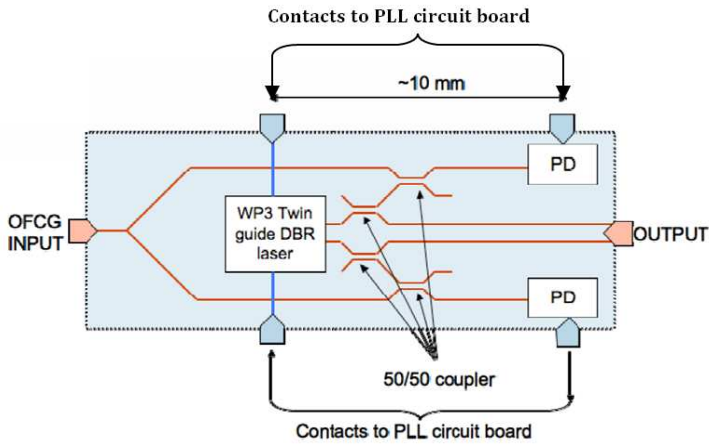

Figure 36 Implementation of hybrid integration of the twin OPLL.

The mm-wave source is based on the OPLL design developed at UCL, the hybrid integrated photonic circuit developed at CIP and the electronic loop circuit developed at LUB.

For the phase-noise reduction in the OPLL, custom-made OPLL electronics was required. It was the objective for LUB in task 5.3 to develop and implement digital phase detectors with extended input phase range for the phase noise reduction in the OPLL according to the specification provided by UCL and CIP.

Project work and achievements

Quantum dash mode-locked semiconductor laser fabricated (D333) at III-V labs generated comb lines with a spacing of 24.5GHz over a span of 1.6THz for the master source (Figure 37).

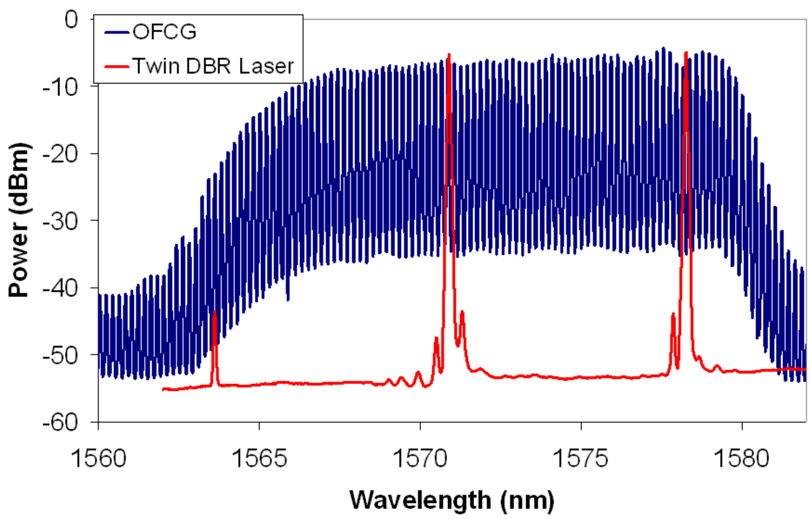

Figure 37 Optical spectrum of OFCG and the twin DBR lasers.

Monolithically integrated twin DBR laser (D342: slave lasers) had SMSR greater than 35dB and a tuning range of 8nm, giving heterodyne signal over 0 to 1.8THz (Figure 37).

The twin DBR laser and both the photodetectors were mounted on to daughter boards and subsequently flip-chip bonded on to the silicon motherboard.

High speed short delay electronics was provided by LUB consisting of a fast proportional loop and a slow integral loop (2nd order type 2 loop) built on a 4-layer printed circuit board (PCB). The total delay is estimated to be less than 1ns, sufficient to lock lasers with combined linewidth of 2MHz.

Figure 38 shows the completed mm-wave source including the temperature controlled motherboard, two PCBs and the support structure (D527).

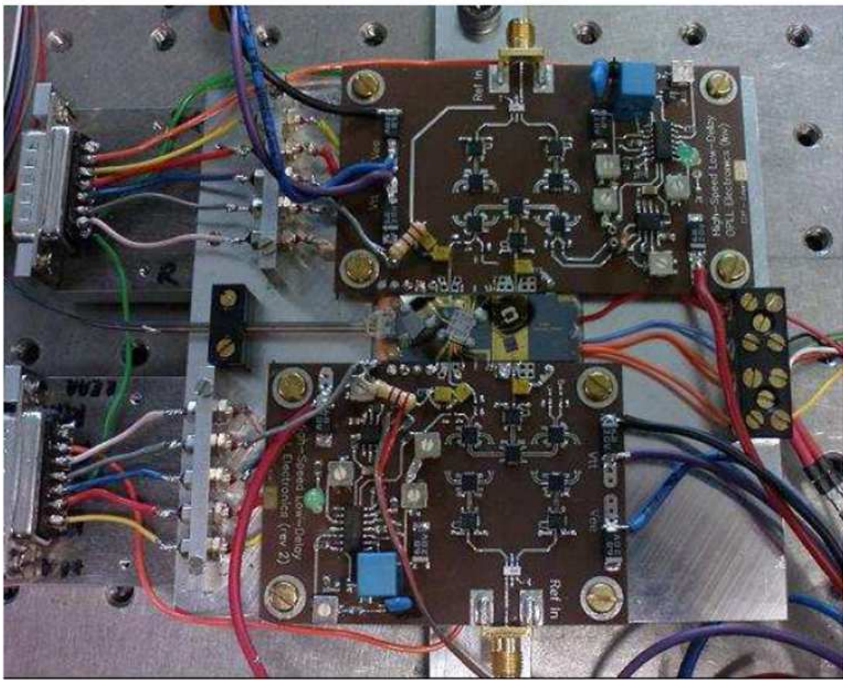

Figure 38 Photograph of the fully assembled OPLL.

The OPLL electronics, consisting of a phase detector with proportional and integral loops and some other circuitry, needed to satisfy special and demanding properties (ultra-low

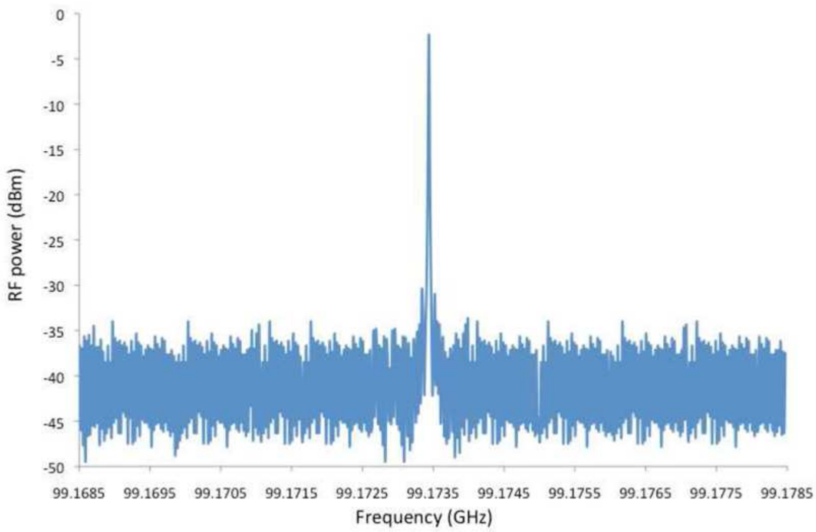

Figure 39 Spectrum of the heterodyne signal at 99 GHz (1kHz resolution)

loop delay, high bandwidth, etc) [R8]. During the project LUB designed, implemented and tested several phase detectors. At first, a scaled-down OPLL experiment using commercial DFB laser module was assembled and tested at LUB. Upon the encouraging results, the OPLL electronics for the UCL and CIP components was designed and manufactured. A revision of the OPLL electronics was required, since a modification of the electronics to optical-hybrid interface was necessary. Two final phase detectors (normal and inverted version) were manufactured, each for the appropriate side of the optical-hybrid module. In the mean time LUB designed a novel phase detector with an extended input phase range and reduced output noise and spurious. The innovative concept was proven again in the scaled-down experiment. A paper was submitted to Electronics Letters [R9]. Finally, an advanced phase detector with an extended input phase range and a lower output noise and spurious was designed and implemented for the UCL/CIP's optical hybrid module. Since currently OPLL experiments are being done with the original phase detectors, tests with the advanced phase detector will be done in the near future. Further phase-noise and spurious reduction are expected, achieving world-record phase noise figures for the broadband mm-wave generators. The work on the advanced phase detector is described in detail in the D524. The original phase detector satisfied the objectives fully (although with some operating limitations). The manufactured advanced phase detector surpassed the planned objectives and needs to be tested in an OPLL experiment with the hybrid module (up to now, it has been tested only with a microwave current-controlled oscillator).

The OPLL was tested for frequency offsets from 2 GHz to 7 GHz (limited by the electronics) and frequency generation of up to 300 GHz. The spectral performance was assessed using the IPHOBAC fast photodetectors (D422) for frequencies up to 110 GHz (Figure 40). The phase noise is less than -80 dBc/Hz at 100 kHz offset and is better than -75dBc/Hz at 10kHz offset. For frequencies between 110 GHz and 300 GHz only the generated power was measured using the IPHOBAC antenna integrated fast photodetector (D423) (Figure 41).

The measurement results (Figure 39, Figure 40, Figure 41) prove that the system meets the objective of the project by generating high purity signal (>-75dBc/Hz at 10kHz offset) with good long term tracking for frequencies ranging from 10GHz to 300GHz. As the OFCG developed within the project has a span of 1.6THz, the source will be able to generate high purity signals over the entire span, with the output power of ~ -20dBm at 300GHz.

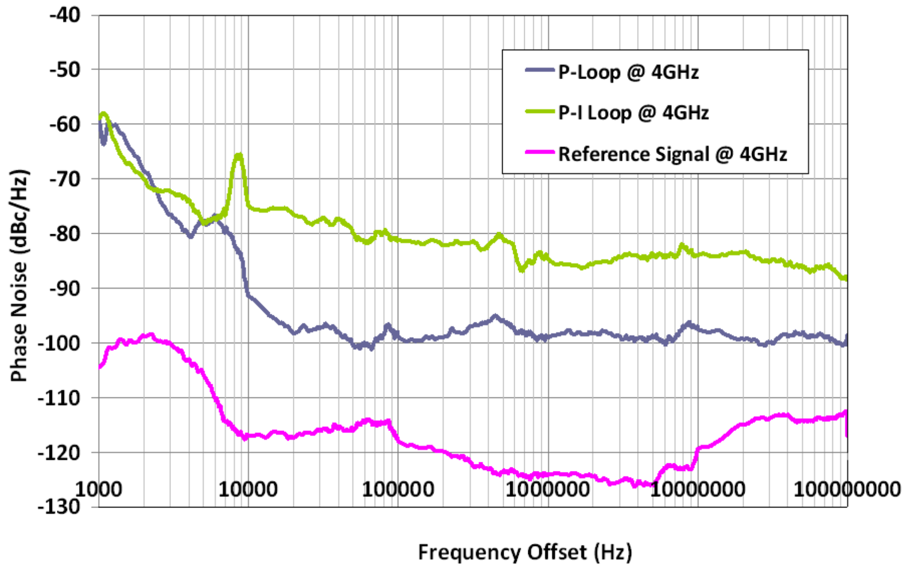

Figure 40 Phase noise spectrum of the locked signal at an offset frequency of 4GHz

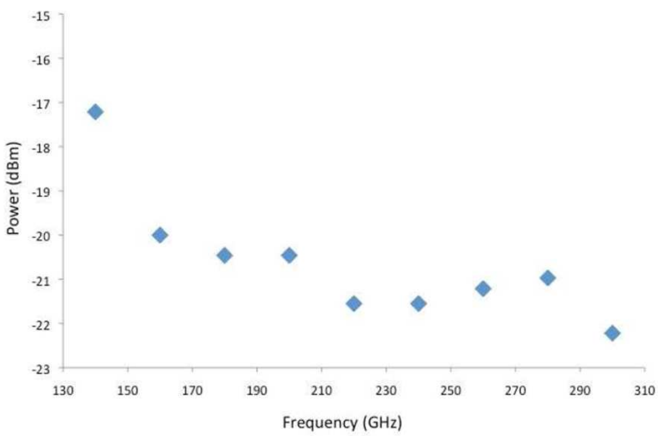

Figure 41 Measured power from the antenna integrated fast photodetector fed by the optical signal from the OPLL and the injection locked laser.

Comparison to the State-of-the-Art

Currently sources based on InP-based Gunn diodes are capable of emitting -14dBm at 422 GHz [R4]. Tunnel Injection Transit-Time (TUNNETT) diodes deliver more than -8.5dBm at 355 GHz [R5] and output power of -7dBm at 361 GHz has been reported from a room-temperature Impact Avalanche Transit-Time Diodes (IMPATT) [R6]. However, the output from a heterodyne source can offer better spectral purity with linewidths in the order of 1Hz and is easily modulated for data transmission. The source's frequency can be rapidly changed or swept. Such sources can also be compact and output powers of -8.3dBm have been measured at 457GHz [R7] with such sources combined with an uni-travelling carrier photodetector.

A monolithically integrated heterodyne source with optical phase locked loops has been reported recently [R8] where both the slave lasers are combined and modulated. Here the loop electronics locks one laser to the side band of the other modulated master laser, hence limiting the tuning range of the source to the modulator bandwidth. The reported maximum offset frequency is 15 GHz.

The innovative concept of the phase detector with extended input phase was proven in the scaled-down experiment. A paper was submitted to Electronics Letters [R9]. Although there were already some phase detectors with an extended input phase range published [R10][R11], none of the laters achieves such high operating frequencies and low output noise. The OPLL electronics designed by LUB to our knowledge outperforms any available (state-of-the-art) phase detectors due to its high performance: sub-ns loop delay, high bandwidth, separate proportional and integral loops and autolocking capability upon reset or power-up.

1.4.3 Photonic system developments and demonstrations

1.4.3.1 Broadband Radio-over-Fiber indoor system demonstrations

Ultra-Wide Band (UWB) over fiber has attracted a lot of interest, leading to numerous publications and technical demonstrations of the feasibility of remoting UWB over optical fiber at high data rate, high carrier frequencies and over large distances [R12]-[R17]. In the communications area, remoting UWB over fiber allows an UWB device to communicate with another one beyond the very limited reach of the UWB radio signal (less than 20 m). Indeed, UWB has been mainly designed to allow high data rate transmissions over short distances primarily in indoor environments where delay spread is potentially large. Such transmissions used for Wireless Personal Area Networks (WPAN) allow communications between devices in the users reach e.g. computers, personal organizers, camcorders, TV sets, DVD players, printers etc and have been designed in groups such as, for instance, ECMA-368 [R18], ECMA-387 [R19], IEEE802.15.3c [R20] as well as industry consortia such as WirelessHD [R21]. This is driven by ideas of in-home communication lifestyle that have been promoted by various groups such as DLNA [R22] or HGI [R23] which have performed many studies focusing on the requirement in the years to come regarding en-user services. These studies conclude that a data rate of 1 Gbps must be supported in home networks by 2010-2020 (also confirmed in [R24]). To accompany this trend, telecom operators are investing large amounts of money in the deployment of access solutions that are able to provide an ever increasing bandwidth (currently up to symmetric rates of around 100 Mbps via Fibre to the Home (FTTH), increasing to 1 Gbps and more in the coming years [R25]). However, it is impossible to market an access bandwidth greater than what the home network can handle. Finally, an implementation factor has to be taken into account: end-users are determined to continue using a wireless end-connectivity to preserve the flexibility and ease of use provided today by WiFi. UWB radios certainly can achieve the high data rate goal set-out in this study, especially the ones operating in mm-wave RF bands and in particular the 60 GHz band where no coexistence problems with WLAN and other radio mobile systems exist. But, such systems create typically small high speed radio cells (WPANs) limited to a single room. Associating several WPAN cells together will indeed create the required Ultra Broad-Band Wireless Home Area Network (UBB-WHAN). To link the different radio access points together, some kind of backbone network must be deployed (Figure 42). Such backbone must be able to transport large amounts of data (several Gbps) over only short distances (typically 50 m with a maximum of around 100 m [R26]). The cable must comply over a long period of time (10s of years) to a datarate evolution (several Gbps?) that is difficult to forecast today and as a result, it seems preferable to deploy Silica single mode optical fiber (SMF) as the UBB-WHAN backbone. In this section, we report our most recent results demonstrating the potential of some IPHOBAC components to apply radio-over-fibre techniques in the Home Network context in order to successfully transport and distribute a bidirectional 60 GHz radio interface.

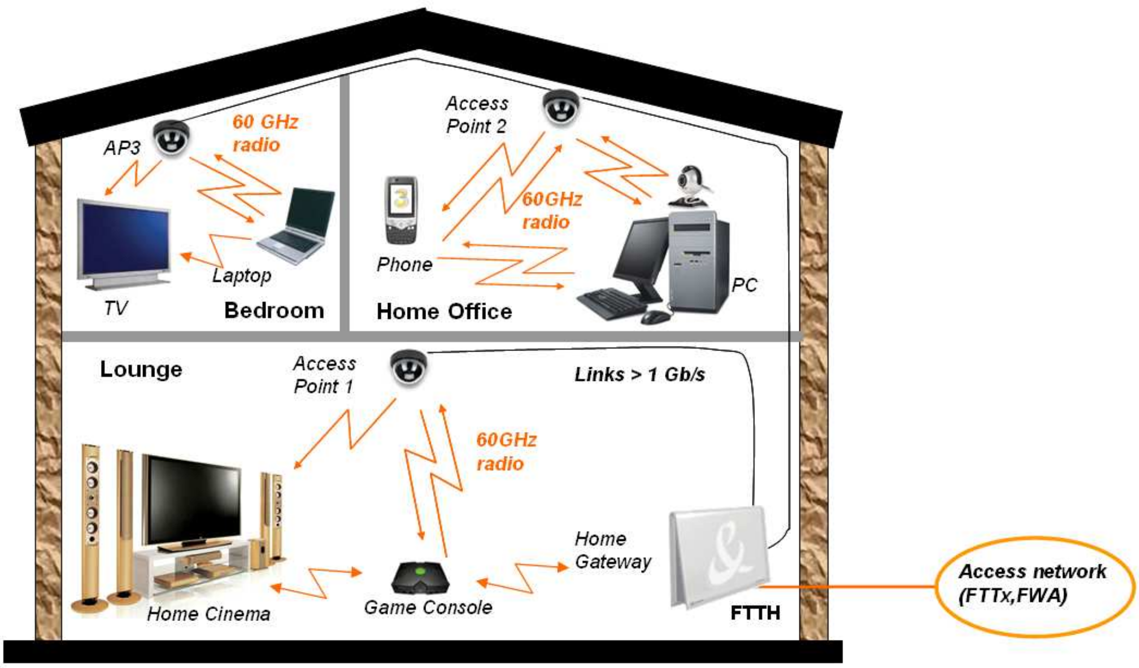

Figure 42 Proposed future multi-gigabit wireless home area network.

Project work and achievements

Several setups have been constructed in the course of the IPHOBAC project in order to demonstrate the feasibility of the concept described above and these are reported in different deliverable of the projects such as D221, D222, D223 and for the most recent results in D614. In the following paragraphs we will give some details about the most finalized setup whose proposed and experimented architecture is represented in Figure 43. We suppose that a radio transceiver is used in the central radio network management element generating and receiving an intermediate frequency (around 5 GHz) radio signal carrying several gigabits per second. The downlink radio signal (from the central element to the user), to be used and distributed in the different rooms of the house, must be converted to an optical signal as well as converted to the 60 GHz frequency window. This is achieved by means of the direct modulation of a 55 GHz self pulsating Fabry Perot Quantum Dot Laser (FPL) made specially by IPHOBAC partner Alcatel Thalès III-V labs. This modulation process creates intermixing products between the oscillation frequency of the laser and the intermediate frequency of the radio signal thus transposing it to 60 GHz (55 GHz + 5 GHz). At the remote radio head, a Reflective Electro-Absorption Modulator (REAM) made by IPHOBAC partner CIP is used as a photo-detector to transfer the signal back into the electrical domain and a series of filters (to remove the lower frequency side band and the 55 GHz carrier) plus amplifiers are used to prepare the signal for transmission into the air. On the uplink path (from the user to the central element), the 60 GHz radio signal is first amplified to modulate the REAM. The pulsed light from the FPL is again re-modulated thus creating intermixing products and transferring the incoming radio signal to around 5 GHz (corresponding to 60 GHz minus 55 GHz). In the central element, a conventional 10 GHz bandwidth photo-detector, transfers the down-converted signal back to the electrical domain for demodulation by the IF radio transceiver. In this setup the radio signal protocol relies on Time Domain Division (TDD), that is, the frequencies used in the uplink and downlink directions are the same and only one transmission direction is allowed at a time, so that, when the uplink signal modulates the FPL in the REAM, the FPL is un-modulated. This allows the bias of the REAM to be changed in order to optimize its performance when operating as a photo-detector (downlink) or modulator (uplink).

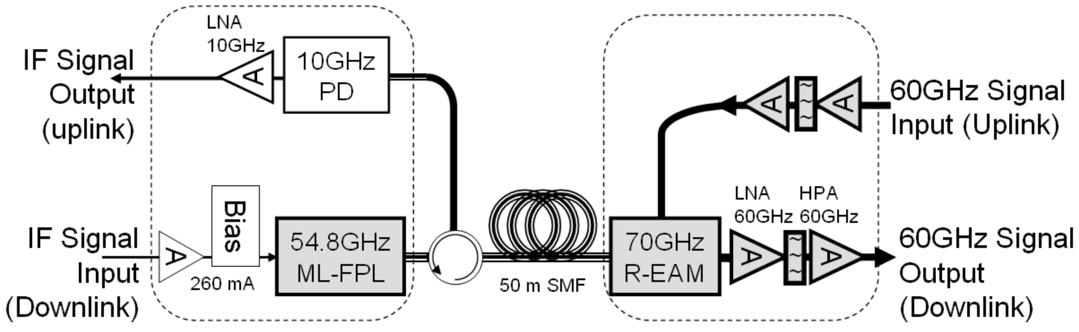

Figure 43 60GHz bi-directional UBB-WHAN building block. Wireless Network Controller interface (left), remote access point (right).

Among the different modulations recommended by the IEEE802.15.3c group, we chose to use OFDM as it has more stringent requirements in terms of linearity [R27]. The OFDM signal under test is created on a PC using Matlab® with a FFT block size of 512 with 336 data sub carriers. Each sub carrier is modulated in QPSK. The baseband is sampled at 2.59 GHz. A total raw data rate of 3.03 Gbps is achieved for a bandwidth of 1.87 GHz. The signal is generated by a 10 GS/s dual output Arbitrary Waveform Generator (AWG) and both outputs (representing both I and Q components) are sent to an RF mixer to generate the radio signal on a 4.5 GHz carrier. After amplification, the RF power is +12 dBm.

For the reference measurement, this signal is sent into a commercial mixer fed with a +16 dBm 54.5 GHz local oscillator to transfer it to a carrier frequency of 59 GHz. After filtering (to remove the lower modulation sideband) a power of +13 dBm is obtained. To measure the performance, the signal is first attenuated to the optimal power level (around -22 dBm) then down-converted using an electrical mixer fed with a 54.5 GHz Local Oscillator (LO) and finally, it is captured over 10 µs using a 40 GS/s Real-time oscilloscope (RTO). OFDM demodulation and Error Vector Magnitude (EVM) [R28] evaluation are then performed off-line using Matlab®. The spectrum of the received OFDM signal and the associated constellation diagram obtained after demodulation are shown on Figure 44 (top). The mean EVM is 9 % for a signal-to-noise ratio (SNR) of 25.2 dB. From the EVM, the Bit Error Rate is evaluated to be (theoretically) better than 10^{-21}.

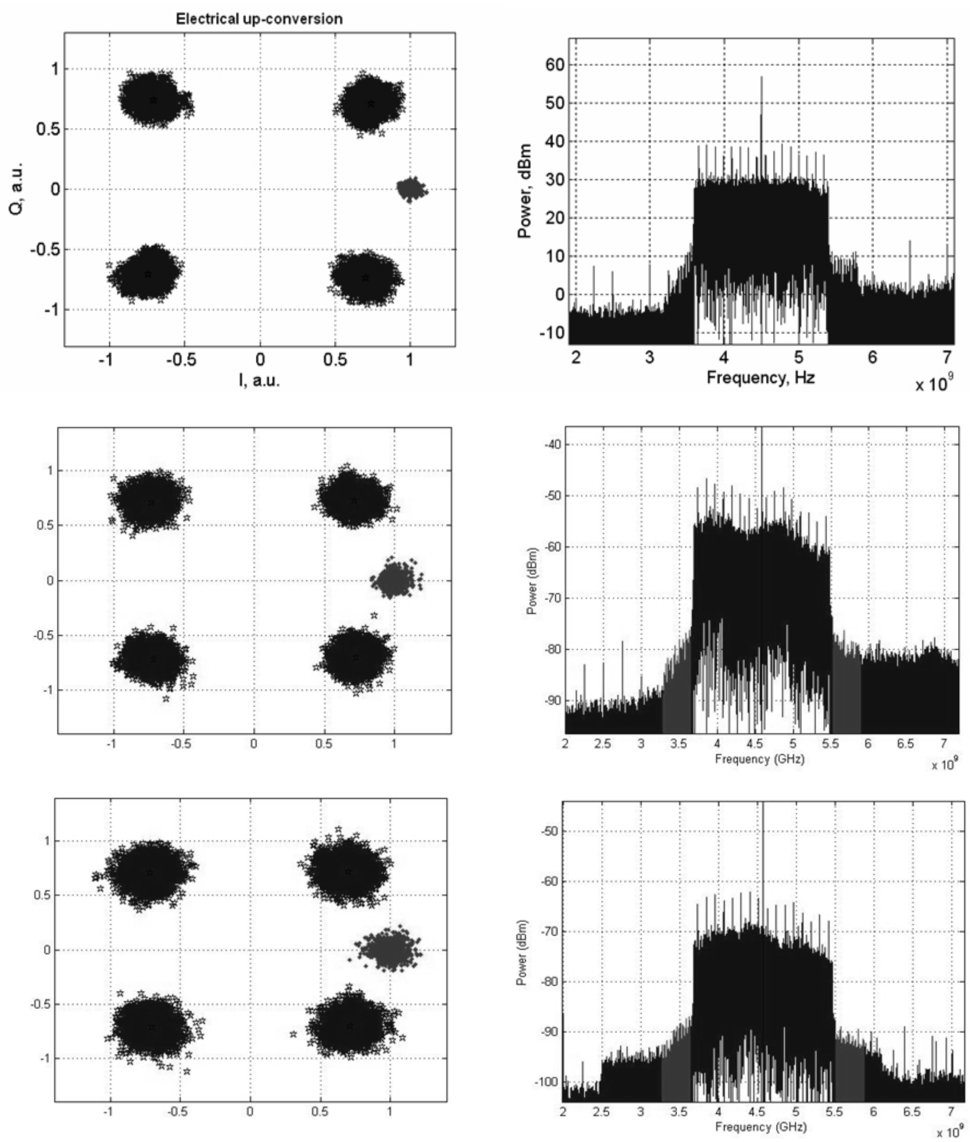

Figure 44 Constellation (left) and spectrum (right) obtained in our experimental setup. Top: reference all-electronic setup. Middle: IPHOBAC downlink setup. Bottom: IPHOBAC up-link setup.

To test the downlink transmission, the IF signal (4.5 GHz) is used to modulate the bias current of the FPL (average bias current set to 260 mA). The optical output power of the FPL is +6.5 dBm. The signal passes through an optical circulator before a 50 m Standard Single Mode Fiber (SMF) transmission. This fiber simulates the distribution of the radio signal within the home. At the end of the fiber, a 70 GHz REAM (bias reverse voltage set to -4.1 V) converts the 60 GHz signal into an electric signal, subsequently, two Low Noise Amplifiers (LNA, G=18 dBm from 55 to 65 GHz) and a band pass filter (58 to 64 GHz) were used to simulate the TX head. Performance analysis is made as described earlier. The computed EVM is 11.06% for a SNR of 23.5 dB (Figure 44 middle). From the EVM, BER can be estimated around 10^{-19}.

To test the uplink setup, the IF radio signal (4.5 GHz) is electrically up-converted to 59.8 GHz by a commercial mixer fed by a LO at 54.8 GHz. At this point, the RF power is adapted with a variable attenuator to pass through the two LNAs and the pass band filter. The signal modulates the REAM (-2.8 V bias voltage) with an input power of +11.6 dBm. The power of the laser at the input of REAM is +5.9 dBm. The reflected IF signal is then photo-detected, captured by the RTO and analyzed. The computed EVM is 12.79% and the SNR is 20.37 dB (Figure 44 bottom). From the calculated EVM, the BER can be estimated around 10^{-14}.

To conclude this work, we can underline the fact that the technical challenges created by the increasing wish to exchange/share multimedia content between friends and family is only partly answered by telecom operators deploying high bandwidth access networks. This effort has also to be extended to enabling Ultra-Broad Band Home Networks with wireless interfaces, allowing users to connect at high data rates (>1Gbps) with the same ease of use as what WiFi currently provides. 60 GHz UWB radio over fiber in this context can achieve the required function and performance. By using two photonic components developed in the frame of the IPHOBAC project, we have demonstrated the possibility of frequency conversion and distribution (bidirectional) of a multi-gigabit wireless radio interface (3 Gbps) over 50 m of SMF. The two key components used in this demonstration are a Mode Locked Fabry Perot Laser and a Reflective Electro-Absorption Modulator.

Our end-goal in this project was also to publicise among system vendors the upcoming need for very high speed wireless networking for the residential market. This was done successfully by way of many scientific publications on the results mentionned above [R29]-[R36] and also different meetings with various system vendors (reported in IPHOBAC D734).

Comparison to the State-of-the-Art

The use of optical fibre as a backbone for home networking is starting to gain momentum as the optical components prices are decreasing and the end-user needs are increasing. This situation is already much more developed for the more general framework of the "in-building" network where optical fibre is already widely used for enterprise networks for instance. Some of these solutions do use radio over fibre (for instance Zinwave and Andrew Wireless both offer radio-over-fibre based mobile telephony systems for indoor applications). On the scientific level, other groups are actively working and publishing on radio-over-optical solutions for residential users such as for instance [R37][R38] and also with mm-wave radio transport [R39]. We can also find a large number of publications regarding the transport of 60GHz high data rate radio signals over Passive Optical Networks such as for instance [R40]-[R42].

Compared to the general trend of studies, it is important to stress that the results obtained within IPHOBAC on this topic always targeted a bi-directional radio distribution system compatible with existing or upcoming radio standards that are forecasted to be used within the residential sphere [R18]-[R21]. It is our belief that an Optical Network targeting residential end-users and relying on radio-over-fiber shall comply with those standards. It is on this precise point that our contribution to the general scientific community shall be understood and judged.

1.4.3.2 Uncompressed HDTV transmission demonstration

Objectives

The transmission of uncompressed high-definition TV (HDTV) signals is seen as an upcoming major application as this would avoid encoding latencies and further allow preserving quality without any need for video compression and decompression. Such a system which transmits HDTV signals in real-time is especially interesting for live broadcasting without the need of a satellite link, the live transmission of video signals from a stadium to external screens or high-resolution video conferencing for business applications. In this case, the required data rates for 1080i and 1080p are 1.485 and 2.97 Gb/s, respectively.

Project work and achievements

Figure 45 shows the configuration of the 60 GHz RoF system. In general, it consists of an optical carrier generation solely using an IPHOBAC mode-locked laser diode (MLLD) and a subsequent broadband NRZ data modulation, a wireless 60 GHz RoF transmitter and a wireless receiver using incoherent detection.

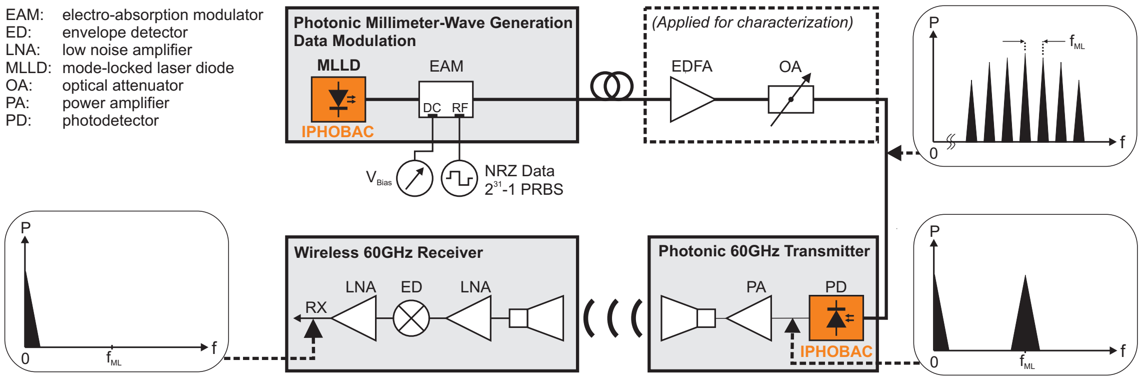

Figure 45 Schematic of the constructed 60 GHz RoF link consisting of an optical mm-wave carrier generator with subsequent broadband data modulation, a photonic 60 GHz transmitter and a wireless receiver.

According to the system setup shown in Figure 45, the three subsystems have been packaged to modules (see Figure 46), and further presented at ICT2008 in Lyon, France, demonstrating a live transmission of a real HDTV signal. IPHOBAC at ICT2008 is further discussed in section 2.4.

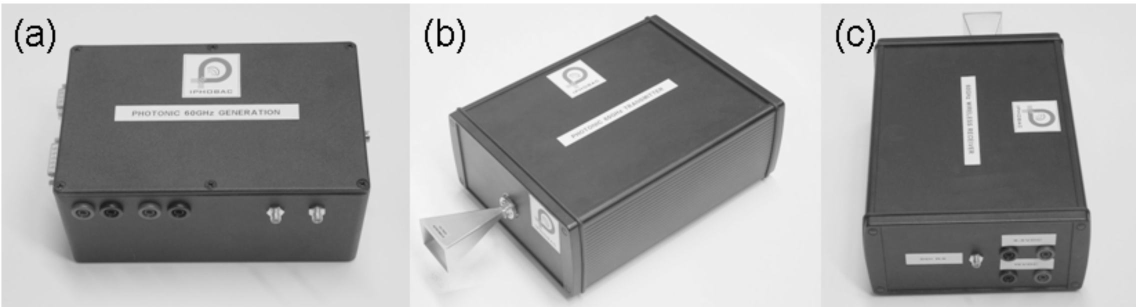

Figure 46 Photographs of the developed subsystems. (a) shows the photonic mm-wave unit with embedded MLLD, (b) the wireless 60 GHz transmitter and (c) the wireless receiver.

Different photonic-wireless transmission experiments have been accomplished to study the performance of the system; the key results are presented below. Outdoor experiments have been carried out, where the total fiber length between MLLD and PD was set to approximately 54 m whereas the wireless transmission span was set to 25 m. The receiver sensitivity has been investigated which is shown in Figure 47. The BER curves for 1.25, 1.5 and 3 Gb/s are nearly congruent, exhibiting sensitivities of -46, -45.5 and -45 dBm, respectively. The BER curve for 5 Gb/s-operation shows an error floor at about 10^{-7} mainly due to the applied envelope detector (reported in IPHOBAC D223). Corresponding eye diagrams for 3.0 and 5.0 Gb/s photonic-wireless transmission are further shown in the figure.

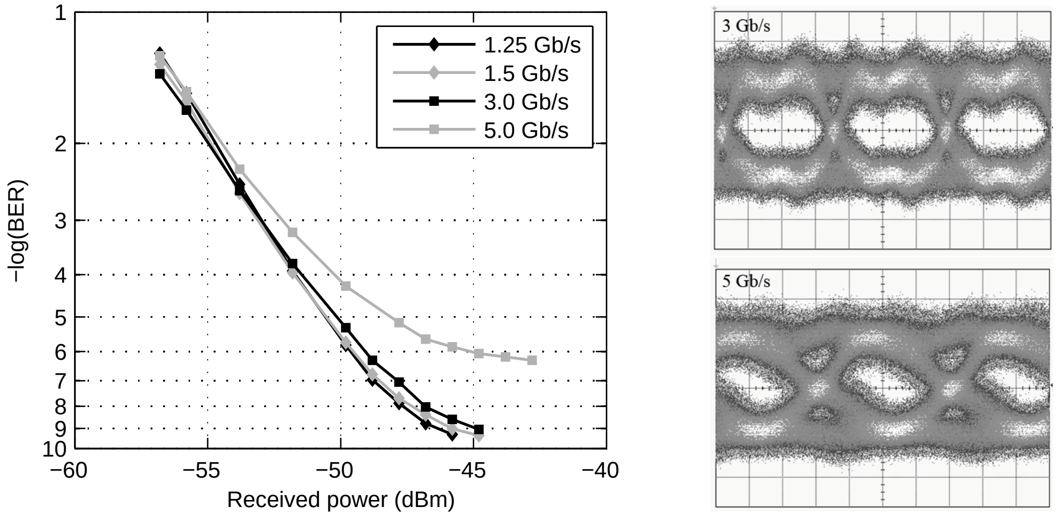

Figure 47 Measured BER as a function of received power after 54 m fiber-optic and 25 m wireless transmission. Eye diagrams at a received power of -45 dBm are further shown in the figure.

The goal of this demonstration was to exemplify the properties of IPHOBAC components within a more application-orientated scenario, i.e. uncompressed HDTV transmission with low latency. With a supported data rate of up to 5 Gb/s, the experimental results have clearly proven the applicability of the system for uncompressed 1080p transmission. Further on, low system complexity was achieved by utilizing an IPHOBAC MLLD for photonic mm-wave generation if compared to conventional approaches based upon external modulators. Results have been published in [45][47].

Comparison to the State-of-the-Art

As regards the state-of-the-art, there has been published one similar achievement by NTT, who demonstrate an RoF system also utilizing an MLLD at a carrier frequency and data rate of 240 GHz and 3 Gb/s, respectively [R43]. However, in this experiment the MLLD was not operated in passive mode but was actively mode-locked at a subharmonic requiring additional RF sources as compared to this work.

Various commercial products support/utilize uncompressed HDTV like cameras, video screens or projectors (HD serial data interface). In addition, rising interest in uncompressed wireless HDTV transmission can be observed and industry is working on standardized interfaces operating wirelessly at 60 GHz [R19][R21]. However, the transport problem may be challenging if an uncompressed HDTV should be transported by cable and the last meters wirelessly. This issue was successfully addressed in this demonstration; photonic-wireless 60 GHz transmission of an uncompressed HDTV signal was experimentally achieved for the first time.

1.4.3.3 Broadband Radio-over-Fiber system for wireless 10 Gb/s Ethernet

Objectives

The objective of this system is to demonstrate photonic-wireless connectivity at 10 Gb/s Ethernet compatible data rates. Perspectives and future demand are expected within the field of fixed wireless access (FWA) to bridge the last mile in combined FTTx / FWA scenarios and to develop broadband rural zones.

Project work and achievements

The architecture of the system is shown in Figure 48. Basic subsystems are a photonic 60 GHz generator with subsequent NRZ data modulation, a photonic-wireless transmitter and a coherent wireless receiver. An IPHOBAC photodetector was implemented in the photonic-wireless transmitter for performing o/e-conversion. Key properties of the system are a cascaded Mach-Zehnder modulator approach and a suppression of the optical carrier allowing high data transmission rates and an increased fiber-optic transmission range while maintaining a comparably low system complexity (see IPHOBAC D614).

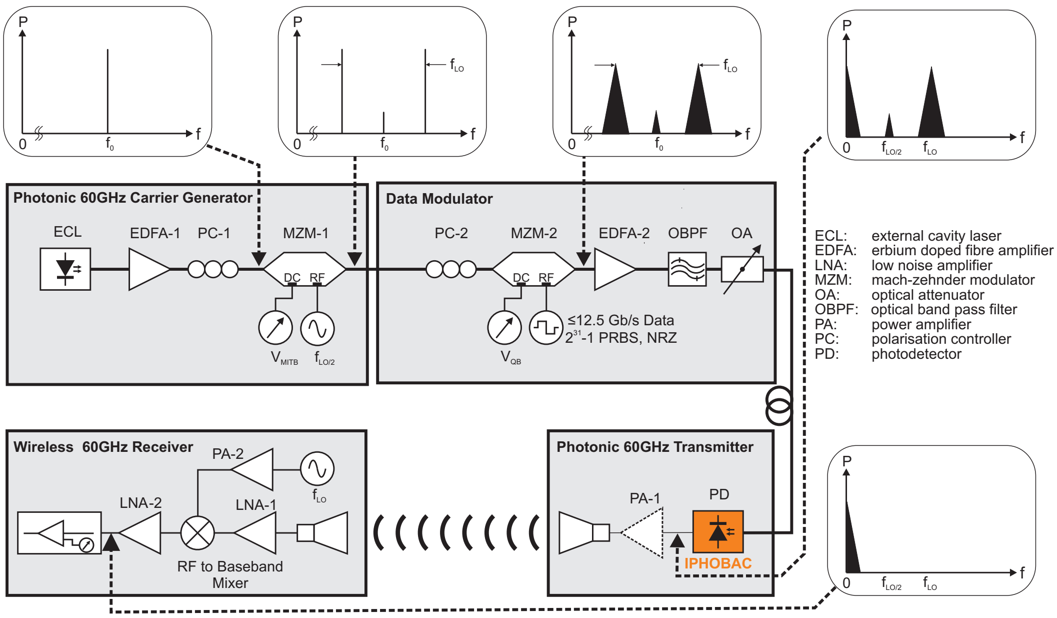

Figure 48 Technological demonstrator setup.

System simulations have been accomplished to identify the optimization potential with respect to fiber-optic and wireless path length. Based upon this expertise, electrical and optical components have been replaced and the operating conditions have been adapted as well within the project duration. The key results are indicated in Figure 49, showing BER measurements of up to 12.5 Gb/s for 50 m fiber-optic transmission and wireless path lengths of 50 m, respectively. Error free operation was limited to 7.5 Gb/s. For 10.3125 and 12.5 Gb/s-operation, the best bit error rates are about 10^{-7} and 10^{-3}, which is still below FEC limit. This is attributed to an insufficient bandwidth of the applied mm-wave amplifiers PA-1 and LNA-1. The achieved maximum wireless path length was as high as 50 m, limited by surrounding buildings and the remaining power budget. Extension potential is given by the replacement of the utilized medium-gain antennas with high-gain antennas. Further experiments have revealed, that the maximum fiber-optic transmission span at 10.3125 Gb/s is 6000 m at the minimum, which would be already sufficient for many applications within metro networks. Details on the accomplished experiments are reported in IPHOBAC D116 and D614. The overall goal, photonic-wireless transmission at 10 GbE-compatible data rates was clearly achieved. Results have further been published in [21][22][24][26][39][42][45][47][50][66].

A further system for 10 Gb/s wireless Ethernet was developed within IPHOBAC, utilizing an incoherent receiver architecture with simplified complexity. However, due to the applied envelope detector, photonic-wireless transmission was limited to 5 Gb/s (see IPHOBAC D614). A replacement of the detector would allow the transmission of 10 GbE-compatible data.

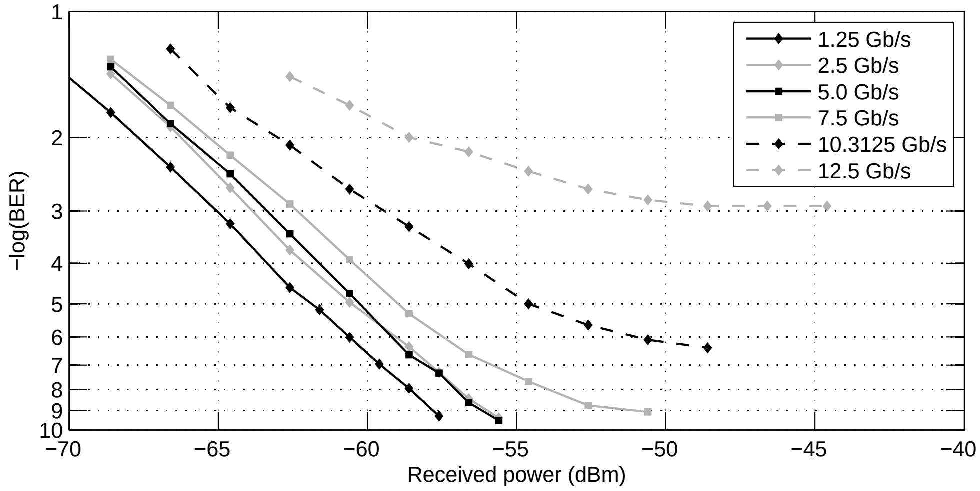

Figure 49 BER measurements after 50 m wireless and 50 m fiber-optic transmission.

Comparison to the State-of-the-Art

In conclusion, 12.5 Gb/s data transmission via fiber and via a 60 GHz wireless RF carrier has been demonstrated for the first time over technical relevant distances in [25]. This data transmission rate of 12.5 Gb/s has been achieved by utilizing the concept of cascaded Mach-Zehnder modulators and applying double sideband modulation with suppressed carrier. In addition, the fiber-optic transmission span was significantly extended if compared to conventional double-sideband systems as for instance reported in [R44][R45]. Further, compared to systems utilizing for instance single sideband modulation (e.g. reported in [R46]) or dispersion shifted fiber (e.g. reported in [R47]), the complexity of the system is comparably low. As regards the state-of-the-art, it should be noted that systems with higher data rates have been reported in [R48][R49][R50]. However, those RoF systems either operated at a lower RF carrier frequency and much shorter wireless distances (e.g. at 24 GHz with a wireless path length of only 6 m [R48]) or did not achieve any wireless transmission at all (e.g. in [R49][R50]).

A near-term demand for broadband wireless connectivity can be observed from the fact, that several companies are already offering broadband mm-wave links which are, however, limited to data rates of 1.25 Gb/s at the maximum to support 1 GbE [R51]-[R56]. In addition, these products do not support RoF but conventional baseband technology and exhibit therefore high complexity on the electrical component side with costly mm-wave products. The developed system offers a future perspective for FTTx/FWA application scenarios with increasing bandwidth demand on wireless connectivity.

1.4.3.4 27 Gb/s spectral efficient super-broadband transmission

Objectives

At the time of publication in 2008, the above presented achievements in section 1.4.3.3 represented world record figures in terms of data rate times wireless span for broadband mm-wave wireless systems. However, spectral efficiency is low due to the applied digital modulation scheme on-off keying. It is furthermore apparent, that the maximum capacity the OOK photonic wireless system shown above can offer is not sufficient for the development of a full duplex 10 Gb/s wireless system while considering for instance a 7 GHz unlicensed frequency band around 60 GHz. According to the IPHOBAC meetings with the network system providers Ericsson, Alcatel-Lucent and Nokia Siemens Networks, an RoF system has been developed which utilizes spectral efficient m-QAM OFDM modulation.

Project work and achievements

The configuration of the 60 GHz photonic wireless testbed is shown in Figure 50. In general, the system consists of an optical mm-wave carrier generator unit with a subsequent broadband data modulation, a photonic wireless transmitter and a wireless receiver.

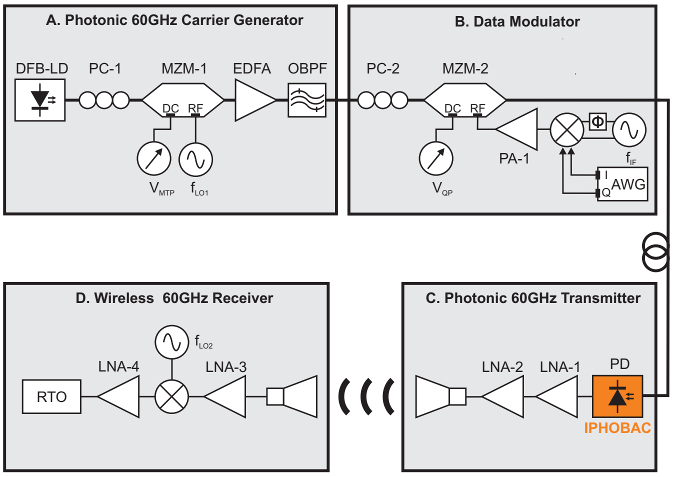

Figure 50 Schematic of the compact 60 GHz photonic wireless link consisting of an optical mm-wave carrier generator based upon external modulation, a subsequent broadband OFDM data modulation, a photonic wireless transmitter and a wireless receiver.

The applied OFDM signal under test is created on a computer using Matlab® with an FFT block size of 2048, utilizing a signal bandwidth of 7 GHz and applying m-QAM-modulation for each data subcarrier. Signal generation is performed by an arbitrary waveform generator (AWG). Later, after photonic-wireless transmission and reception by a real-time oscilloscope, OFDM demodulation and EVM evaluation are performed offline using Matlab®. For analyzing the system performance, we have performed experiments in a laboratory environment with a fiber-optic transmission span of 10 m and a wireless path length of 2.5 m. The data subcarriers of the 7 GHz bandwidth OFDM signal are modulated with either 8- or 16-QAM OFDM signals corresponding to transmitted data rates of 20.28 and 27.04 Gb/s, respectively. The received spectrum and constellation diagram using 8-QAM subcarrier modulation are shown in Figure 51. The measured mean EVM is 18.8% for a SNR of 18.9 dB. From the EVM, a BER of $2.20 \cdot 10^{-4}$ can be computed which is below the forward error correction (FEC) limit of $2.2 \cdot 10^{-3}$. We further demonstrated 16-QAM modulated OFDM transmission, which corresponds to a data rate of 27.04 Gb/s at a bandwidth of 7 GHz. The received spectrum and the constellation diagram are shown in Figure 52. The measured mean EVM is here 17.6 % for a SNR of 21.5 dB. From the EVM, a BER of $4.2 \cdot 10^{-3}$ can be computed, which is slightly above the FEC limit.

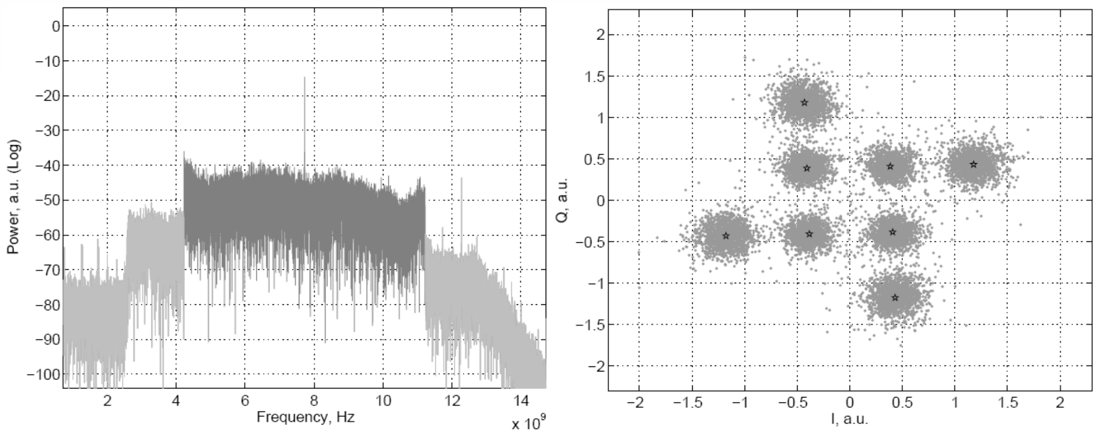

Figure 51 Received spectrum and constellation diagram obtained after photonic up-conversion, 10 m fiber-optic and 2.5 m wireless transmission. The 7 GHz bandwidth OFDM signal with 8-QAM subcarrier modulation gives a data transmission rate of 20.28 Gb/s.

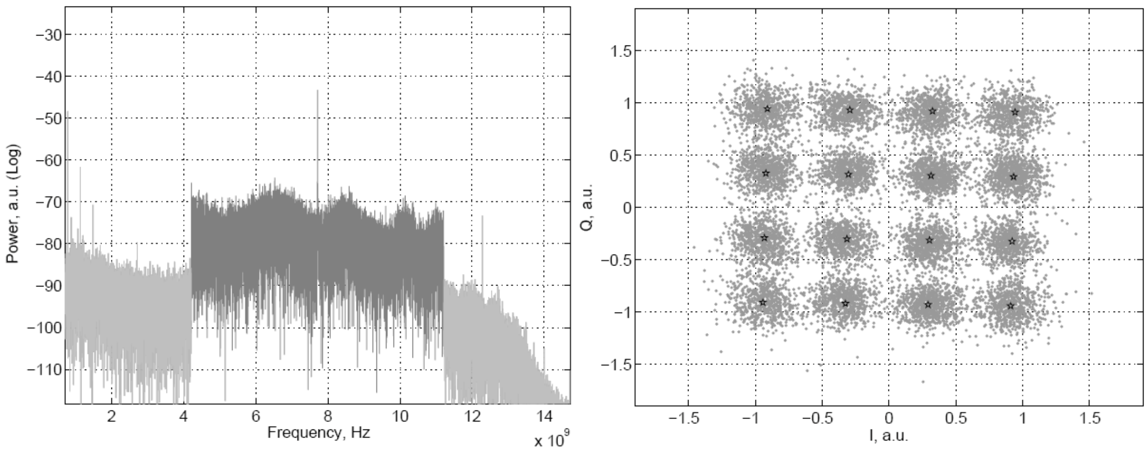

Figure 52 Received spectrum and constellation diagram obtained after photonic up-conversion, 10 m fiber-optic and 2.5 m wireless transmission. The 7 GHz bandwidth OFDM signal with 16-QAM subcarrier modulation gives a data transmission rate of 27.04 Gb/s

In summary, with the above presented broadband photonic wireless 60 GHz transmission system and by using an 8-QAM and 16-QAM OFDM modulation format, world record spectral efficiencies up to 3.86 bit/s/Hz have been achieved, allowing the bidirectional transmission of 10GbE signals. The transmit power and antenna gain used in the experiments were -1 dBm and 23 dBi, respectively. By increasing the transmit power and antenna gain, one can expect being able to extend the wireless span up to a few 100 m given the measured wireless receiver sensitivity. A detailed description on the results can be found in D614 and [55].

Comparison to the State-of-the-Art

Optimization potential of the system has been identified, giving the future perspective of a wireless OC-768 bridge. As regards the state-of-the-art, there has been published one similar achievement utilizing 16-QAM OFDM transmission and a signal bandwidth of 7 GHz, however without having achieved any wireless transmission [R50].

1.4.3.5 Sensor applications

Objectives

The aim of this objective was to study the perspectives of the developed IPHOBAC components in the area of transportation and security through experiments on mm-wave generation and distribution of signals toward a mm-wave sensor network and wide band EM sensing over the whole W-band.

Project work and achievements

First of all, in WP2, potential applications in transportation, security and sensor domains where IPHOBAC components could improve performances of existing systems or allow new possibilities were fixed (M211,D211). Indeed, we have looked more specifically into the impact of the insertion of the IPHOBAC photonic components in sensing and security (D221).

Then, the most relevant specifications to ensure their use in these fields were derived (main features being frequency sweep linearity and phase noise) (D222).

Within IPHOBAC, many photonic components under development covered not only mm-wave photonic generation but also mm-wave fiber link remoting.

Indeed, in comparison to waveguide techniques, the interest of this approach is linked to the fact that we can consider that the losses in optical links are independent of the distance. Using such links for our mm-wave applications would in terms decrease the number of local oscillators which would simplify architectures and by then decrease the costs of these systems.

In order to ensure future system use several test benches with increased complexity were proposed (see Figure 53):

- A first level demonstrator addressing the receiver remoter fiber optical link;
- A second level demonstrator dedicated to the mm-wave photonic generation;
- And finally a third level demonstrator covering the transmitter remote fiber link.

Furthermore, as some of the components could not be delivered to us (IPHOBAC tunable photonic mm-wave source and TWEAM) and some component with different potentialities was provided (III-V Lab DFL), we adapted our test bench to fit better the components we received. A chirped mm-wave source remoting was realized with the III-V Lab DFL and an optical distribution 1 to N was demonstrated using E/O and O/E converters (see Figure 54).

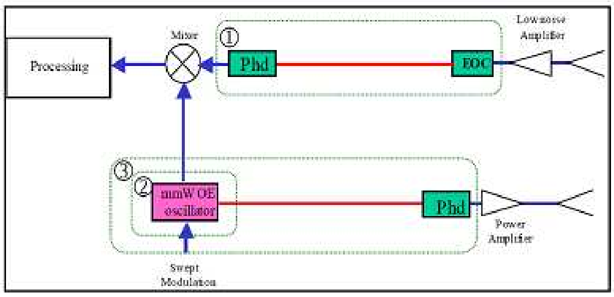

Figure 53 Test setup for TAS IPHOBAC demonstration (①, ② and ③).

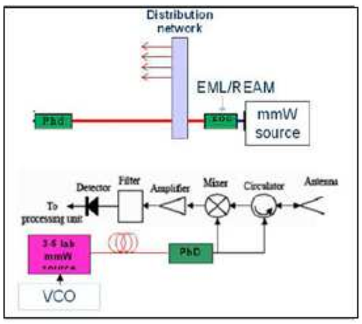

Figure 54 (top) Distribution 1 to N and (bottom) optical remoting of a mm-wave source with the III-V Lab

All these demonstrations were done in order to allow a comprehensive approach of the different photonic functions and their possible applications in real systems. An example of such a system for securing a sensitive area is displayed in Figure 55.

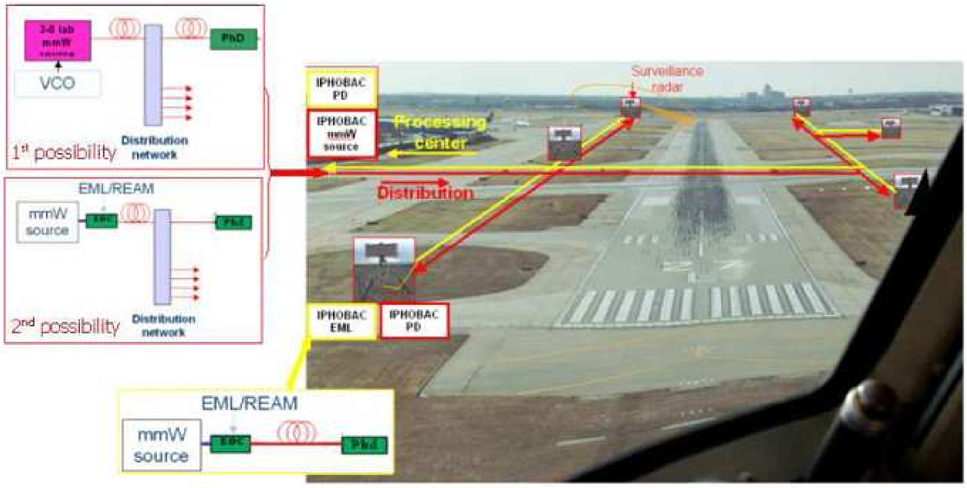

Figure 55 Example of possible application using IPHOBAC optical link for security application. Here two solutions are given for the source: the EML+PD link or the DFL+PD link.

Finally, the impact of the IPHOBAC components on system applications was analysed.

Transmitter remote fiber optical link: III-V Lab 77 GHz MLL CW source (M611)

The power (see Figure 56) and Doppler analysis performed on this source showed a good agreement between theoretical and experimental results which validated our setup (see Figure 57) but also validated that optical remoting of several km does not degrade the source signal and therefore the sensor measurement.

This is very interesting as, in comparison to waveguide techniques, losses in optical links are independent of the distance. Therefore, this technique would allow distributing local oscillators in a mm-wave sensor mounted for example on a transportation platform.

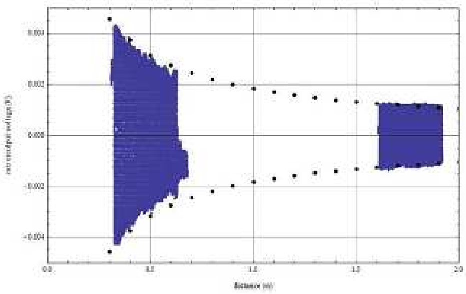

Figure 56 CW sensor power analysis measurements fitted with radar equation.

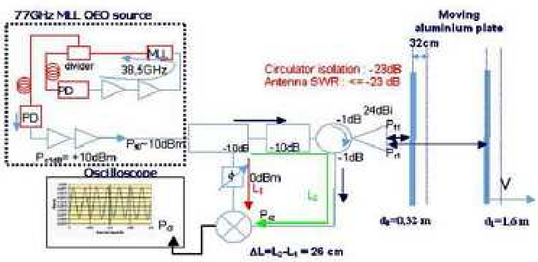

Figure 57 CW sensor setup.

Chirped mm-wave source remoting: 77 GHz/38 GHz dual wavelength laser source (D614)

The DFL was **locked at 38 GHz and 77 GHz**. A **chirp locking at 38 GHz** was realized **over 1,3 GHz** (see Figure 58) and a chirped source **remoting** at a **recurrence frequency**

of a few tens of Hz compatible to our sensor operation was demonstrated (see Figure 59). The laser additive phase noise was measured to be **~-95 dBc/Hz at 33 GHz** lower then the sensor phase noise requirement (-90 dBc/Hz@100 kHz offset of the carrier). However, as it was limited by the synthesizer noise level. The phase noise at 77 GHz was measured to be ~-80 dBc/Hz thanks to a 75 GHz harmonic mixer, however, we could not conclude as to the real phase noise level of the 77 GHz signal and the conversion losses associated to the additive noise brought by the mixer increased the noise floor of the synthesizer.

The injection locking of the DFL will require at least a medium RF input power level therefore it is legitimate to conclude that this component should be preferably used on the emitting end of the sensor. Also in theory, injection locking of a DFL should lead to better conversion losses than directly modulated lasers which would be another advantage of this component. However, there are still steps to be completed before an introduction in systems. Indeed, further work should be done on phase noise levels at mm-wave frequencies (such as 77 GHz) and the linearity conservation should be checked. Higher power output are needed as these components would be dedicated to the emitting ends of the sensors which need a power output of about 10-20 dBm.

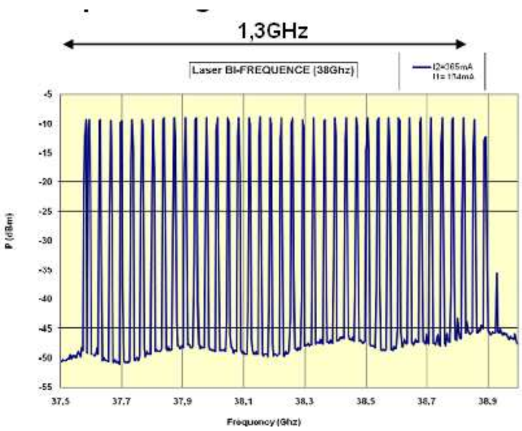

Figure 58 Chirp at 38 GHz locking over 1,3GHz.

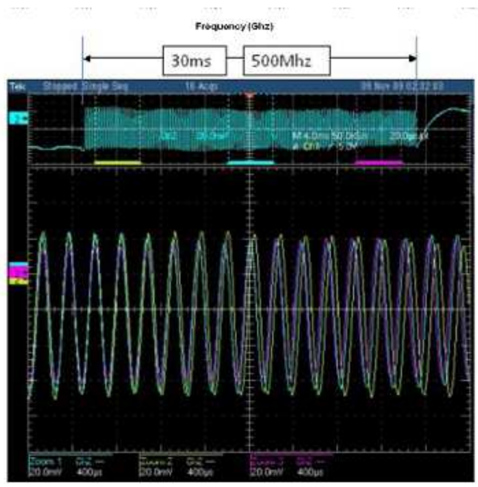

Figure 59 Chirp source remoting and sensor demonstration at ~30GHz beat frequency detection.

Receiver remote fiber optical link and optical distribution 1 to N

77 GHz EML IPHOBAC (D611 and D614)

The IPHOBAC link including the EML and the 110 GHz PD was demonstrated to display in its best configuration (I=50 mA; V=-3 V) conversion losses of the order of –55 dB at 77 GHz and a relatively flat mean value of –53 dB though it has a strong ripple of ± 2 dB. In this polarization configuration, the additive phase noise was measured at 10 GHz. The best result gave -124 dBc/Hz @ 100 kHz from the carrier for 0 dBm RF input power and -127 dBc/Hz @ 100 kHz from the carrier for +9 dBm input power which is quite a good result (see Figure 60). Assuming results could be applicable to higher frequencies (laser RIN dominant noise), these phase noise levels are compatible with typical sensor application (-90 dBc/Hz@100 kHz of the mm-wave carrier). For such low noise applications, it may therefore be necessary to pre-amplify in order to compensate the relatively high conversion losses of the link and to hide the IPHOBAC optical link noise figure. This could be achieved with the use of low noise amplifier.

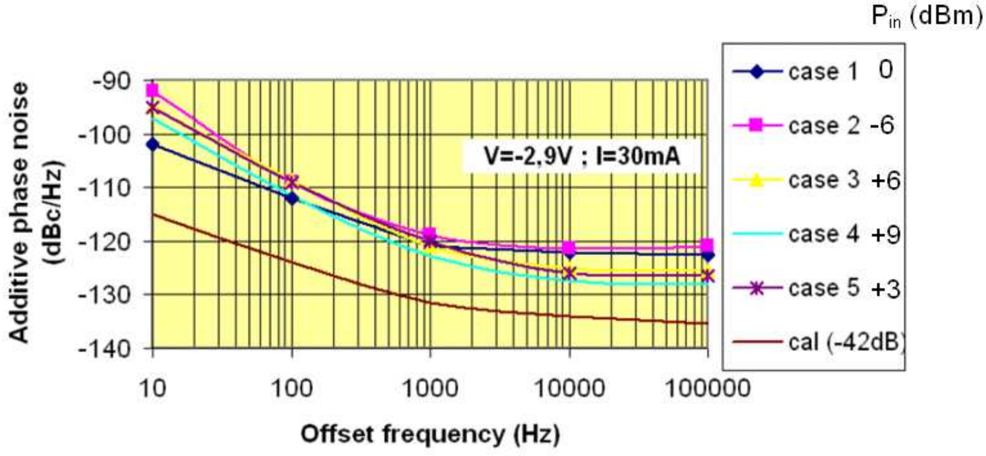

Figure 60 EML+PD link – additive phase noise.

Two demonstrators were realized:

- The **optical distribution 1 to 16 for a sensor application** was demonstrated and showed that it could transmit a mm-wave signal over the W band with no degradation of the transmission coefficient of the IPHOBAC optical link (EML + 110 GHz PD). For the additive phase noise, **no significant additive phase noise** is added the EML+10 GHz PD optical link **above a few kHz offset** of the 10 GHz carrier (see Figure 61). **Below the additive phase noise will be 10-15 dB higher** than the optical link with no distribution.
- A **FMCW sensor demonstration** was performed and showed that the IPHOBAC optical link (EML+110 GHz PD) can be inserted in the receiving end (see Figure 63). It was shown that the **degradation of linearity of the mm-wave frequency chirp** of the source by the IPHOBAC link is **<1%** (see Figure 61). The previous experiments have shown that the additive phase noise was compatible as long as enough low noise amplification could be added in front of the EML.

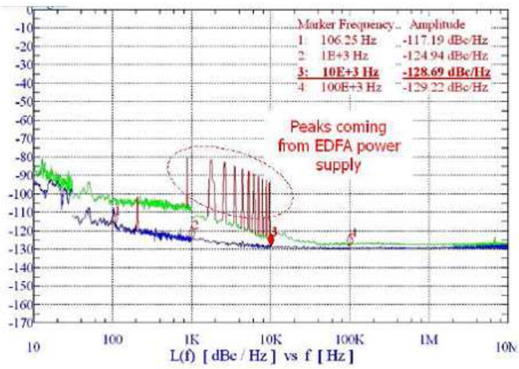

Figure 61 EML+PD link Optical distribution 1 to 16.

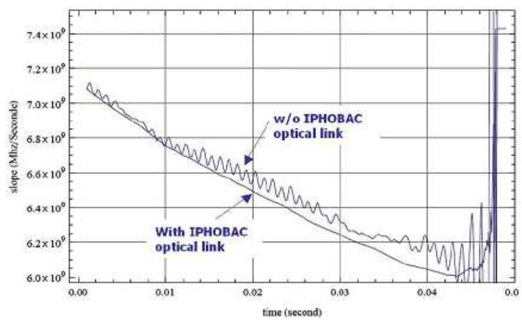

Figure 62 FMCW signal chirp slope.

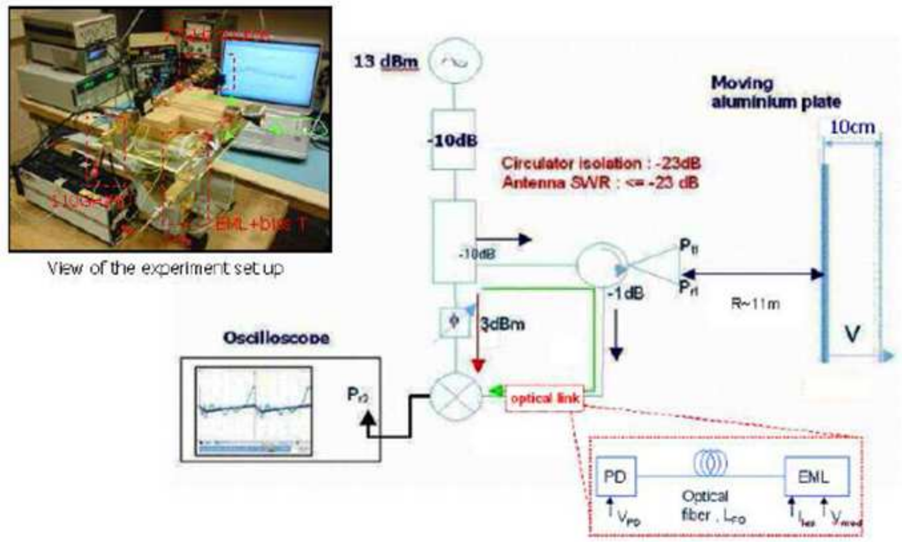

Figure 63 FMCW sensor setup.

TWEAM from HECTO (D611 and D614)

The optical link including the TWEAM from the HECTO project and the IPHOBAC 110 GHz PD displayed in its best polarization configuration (I=100 mA; V=1,6 V) **conversion losses of the order of –48 dB at 77 GHz** and **–50 dB at 90 GHz** and a **ripple of ~1 dB**. The **cut off frequency in the W band** was **105 GHz**. A better transmission was obtained with ~-40 dB losses but was not reproducible over the bandwidth. In the best polarization configuration given above the additive phase noise was measured at 10 GHz. The best result gave **-134 dBc/Hz@100 kHz from the carrier for 0 dBm RF input power** which is a very good result.

Assuming results could be applicable to higher frequencies (laser RIN dominant noise), these phase noise levels are compatible with typical sensor application (-90 dBc/Hz@100 kHz of the mm-wave carrier). For such low noise applications, it may be necessary, like for the IPHOBAC EML, to pre-amplify in order to compensate the relatively high conversion losses of the link and to hide the IPHOBAC optical link noise figure. This could be achieved with the use of low noise amplifier.

The **optical distribution 1 to 16 for a sensor application** was demonstrated and showed that it could transmit a mm-wave signal over the W band with no degradation of the transmission coefficient of the optical link (TWEAM from HECTO project + 110 GHz IPHOBAC PD).

These preliminary tests realized on the TWEAM sent by KPRC from the HECTO project give us an idea of the KPRC technology potential. It shows that conversion losses and additive phase noise characteristics are potentially good although some work needs to be done on the ripple, the cutoff frequency and the reliability of the component.

In summary, all demonstrations initially planed and presented in the WP2 progress report were performed except for the R-EAT that was not compatible to our demonstrator setups and the mm-wave tunable optical source that was delivered to us. Demonstrations included:

- CW mm-wave MLL optical source optical remoting in a radar set up
- mm-wave FMCW source locking on a DFL, optical remoting and FMCW radar sensor demonstration

- Demonstration of optical remoting of mm-wave signal over the whole W-band for EM sensor
- Optical distribution of mm-wave signal over the whole W-band (e.g. for local oscillator distribution in an EM sensor)
- Optical remoting of chirped mm-wave signal in a radar sensor configuration.

For all these demonstrations characterizations of conversion losses, parasitic reflection, phase noise and frequency chirp linearity when applicable were performed.

The components developed in this project, and tested within our multi level demonstrators can be considered in the future as building blocks to be used to realize more complex functions by mixing them together in a LEGO type approach.

Comparison to the State-of-the-Art

These demonstrations showed that many applications in the field of transportation, security, and sensors could be envisaged. Particularly, the use of IPHOBAC optical links are of great interest as in comparison to state of the art waveguide techniques, losses in optical links are independent of the distance. Therefore, IPHOBAC components could allow new possibilities such as the distribution of a local oscillator in a sensor architecture, or the deployment of a security sensing network over a large area with a central processing linked to each radar element by an optical link.

Although we could not test the IPHOBAC tunable mm-wave photonic source, we still believe that such a component would greatly benefit our applications as the source could be directly remoted and distributed as explained before but also only one source could be tuned in applications where different mm-wave frequencies are required. Finally the potentiality of realizing very large mm-wave frequency chirps thanks to the photonics technology would also be of great interest as the resolution of the sensor described bellow is directly proportional to the frequency chirp of the source. Indeed, as was demonstrated with the DFL locking over 1GHz chirped mm-wave source, the photonic technology intrinsically allows large bandwidth and could allow the synthesis of very large mm-wave frequency chirps.

Although the initial testing of the different components we received (III-V Lab CW MLL, IIIV Lab DFL, III-V Lab EML, UDE 110 GHz PD and KPRC TWEAM (from HECTO)) were very encouraging, some improvements would still need to be done to ensure further insertion of these components in systems. Improvements include particularly not only the performances of the components, but also their integration and selling cost, in order to go beyond the state of the art of electronic devices.

Technical improvements concern :

- Saturation power for photodiodes and CW MLL based mm-wave source;
- Conversion losses for modulators (EML and TWEAM);
- Operating bandwidth (modulators and CW MLL sources);
- Optical output power (modulators, CW MLL and tunable DL lasers)
- Phase noise (tunable DL and CW MLL lasers)
- Reliability of active components

No conclusions were made concerning the performances of the IPHOBAC tunable mm-wave source as it was not delivered to TAS.

1.4.3.6 Photonic wireless system using optical vector modulation

Objectives

In the IPHOBAC project, one of the system functionalities of the integrated photonic devices was the development of a photonic vector modulator/demodulator in task 5.3. Several devices were designed and fabricated to be used in a 10 Gb/s wireless link demonstrator. The main objective of using photonic vector modulation is to directly generate advanced spectral efficient modulation formats like QPSK 16-QAM, which can accomodate 10 Gb/s data in the limited available bandwidth in the frequency band of 60 GHz.

In this task, the involved partners were UPVLC and LUB. The task of UPVLC was the design and development of photonic vector modulator/demodulator, and the task of LUB is the design and development of electronic circuitry to support photonic vector modulation. The key objectives of this activity were:

- Frequency independent vector signal modulation up to 10 Gb/s employing photonic modulation schemes
- To validate experimentally 10 Gb/s QPSK vectorial modulation and demodulation using IPHOBAC components.
- Indoor wireless link of a 10 Gb/s QPSK signal at 60 GHz.

Project work and achievements

In the course of the project, various milestones were realized, which are listed below:

- Several architectures for photonic vector modulation and demodulation were proposed, numerically simulated and experimentally characterized. (M531: Choice of the PVM/PVdM architectures to be implemented, M533: Choice of two architectures for laboratory demonstration)
- Demonstration of a 10 Gb/s signal generation using 16-QAM modulation format
- M536: PVM/PVdM architecture employing IPHOBAC components characterized
- Indoor wireless link: 10 Gb/s 60 GHz with QPSK modulation (M612: 10 Gb/s wireless transmission achieved)
- More than 15 scientific publications in both international conferences and journals

In this architecture, shown in Figure 64, two optical carriers with wavelengths $\lambda 1$ and $\lambda 2$ are directly modulated using two independent baseband data streams I and Q respectively. The two optical carriers are combined, and a LO carrier at mm-wave frequency is externally modulated on the two optical carriers using a single MZ modulator biased at its Quadrature bias point. Later, the two optical carriers are transmitted through a dispersive element like an optical fibre prior to photodetection. Due to the chromatic dispersion of the fiber, a differential delay $\Delta\tau = D \cdot L \cdot \Delta\lambda$ among the optical carriers is introduced which depends on the wavelength spacing, $\Delta\lambda$ (nm), the fibre length, L (km), and the fiber dispersion parameter, (D ps/km·nm). A 90º phase shift is induced between the adjacent wavelengths by setting $\Delta\tau$=TLO/4, where TLO (s) is the period of the LO signal. At the PD output, as many replicas of the LO with differential phase shift of 90º as bits are obtained.

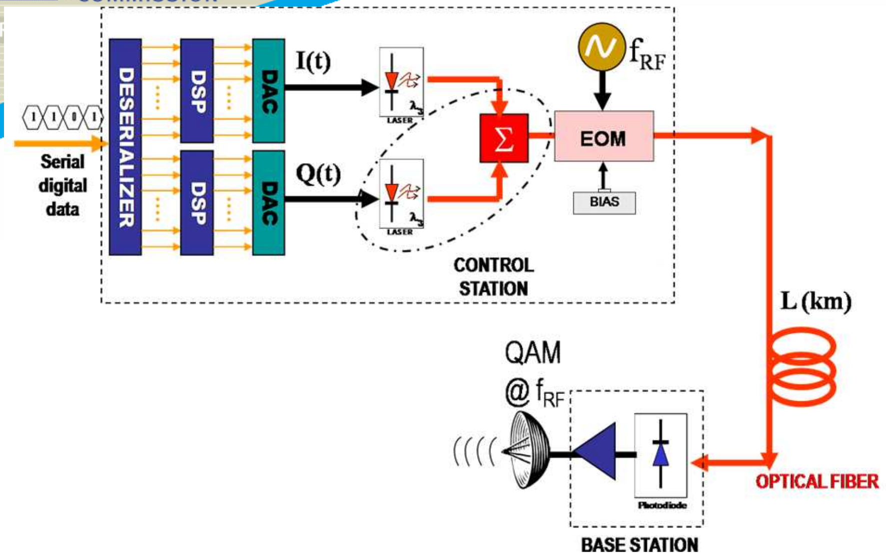

Figure 64 Schematic of the photonic vector modulator based wireless transmitter.

10 Gb/s 16-QAM Results:

A continuous wave DFB laser at 1555.4 nm with an output power of +15 dBm is externally modulated by a 42 GHz local oscillator carrier using a 50 GHz MZM biased at the QB point. The output of the MZM is amplified to +18 dBm using an EDFA to compensate the 6 dB insertion losses of the modulator, and the 3 dB losses due to QB. The output of the EDFA is divided into two arms using a 3 dB splitter: upper (I) and lower (Q). The Q-arm optical signal is delayed using an ODL to generate a 90º phase shift between the I and Q

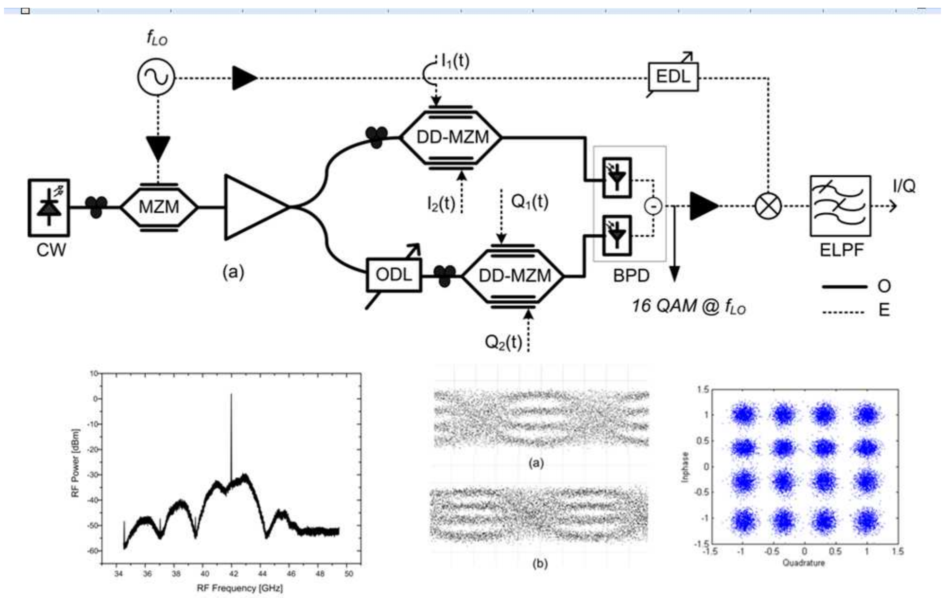

Figure 65 Experimental setup (above) and results (electrical spectrum, demodulated eye diagrms, and constellation diagram) of 10 Gb/s 16-QAM signal generator.

modulated LO carrier components. The I and Q optical components were corrected for polarization mismatch using a polarization controller. Two 40 GHz DD-MZMs biased at QB were used for generating the I and Q 4ASK signals. The two arms of the I-DD-MZM are driven with two 2.5 Gb/s independent data I1 and I2 where I1 was tuned to 1 V pp and I2 to 0.5 V pp, resulting in 5 Gb/s 4ASK modulation. Similarly the Q-arm DD-MZM was driven by 2.5 Gb/s Q1 and Q2 data resulting in another 5 Gb/s 4ASK. The I and Q optical signals with both the baseband data and RF signal modulated on them were photodetected and added in a 45 GHz BPD with 0.53 A/W responsivity. The output of the BPD is a 10 Gb/s 16QAM modulated 42 GHz carrier. Figure 65 shows the RF spectrum of the generated 16QAM 42 GHz carrier.

To analyze the quality of the generated signal, the 16QAM signal was demodulated using an electrical mixer. The 16QAM signal output at the balanced photodetector was amplified and input to a 42 GHz broadband electrical mixer, and mixed with the same LO used at the transmitter. The baseband output of the electrical mixer was filtered using an electrical low pass filter with a 3-dB cut-off frequency of 1.87 GHz. The I and Q components of the 16QAM signal were demodulated electrically by tuning the phase of the LO carrier input to the mixer using a tunable electrical delay. When the electrical delay was tuned to have 0º phase between the LO and the received 16QAM carriers, I signal was demodulated, and for 90º, the Q signal.

10 Gb/s 60 GHz Wireless Link with IPHOBAC Components

In the photonic vector modulator as shown in Fig. 10, a 10 Gb/s PRBS signal was de-multiplexed into two 5 Gb/s serial data using a 1:2 demux. Both these components were developed in the IPHOBAC project by the partner University of Lublijana. The duty cycle of the two 5 Gb/s PRBS data streams I, Q were measured to be around 360 mV peak-to-peak which was just sufficient to directly modulate two DFB lasers at emission wavelengths 1553.7 and 1557.8 nm respectively. The two optical signals with OOK data modulation were combined using a 3 dB coupler. The output power of the 3 dB coupler was measured to be around 4 dBm. Considering the optical budget of the system, an optical amplifier (EDFA) was needed in the system. The combined optical signals were amplified, and then fed into the port 1 of the optical circulator. The port 2 was connected to the R-EAM, and the port 3 outputs the reflected light from the R-EAM. Using the R-EAM a 60 GHz carrier was modulated on the two optical carriers. To generate a 60 GHz carrier, a 15 GHz local oscillator was multiplied by 4 times. The two optical carriers with the 60 GHz LO modulated are passed through a 62 m single mode fiber. The single mode fiber`s dispersion, induces an optical delay between the two optical carriers, which corresponds to a 90 degrees electrical phase shift between the 60 GHz carriers. A variable attenuator is used before a photo detector to vary the optical input power. The photo detected signal is a 10 Gb/s QPSK signal at a carrier frequency of 60 GHz.

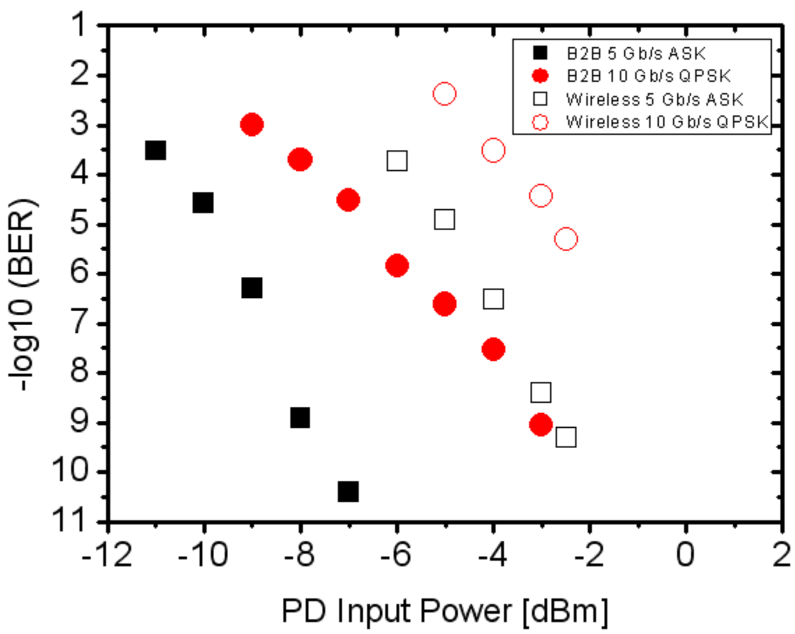

Figure 66 Bit error ratio curves of the 10 Gb/s QPSK, 5 Gb/s ASK signal in back-to-back scenario and a wireless link.

First the generated signal was demodulated in a back to back scenario. The photo detected signal was amplified using a low noise amplifier (G=17 dB) and later using a high power amplifier (G=27 dB). The amplified signal was mixed with a 60 GHz signal in a electrical broadband mixer. The 60 GHz carrier was generated using a 15 GHz LO, and multiplied by 4 times. By tuning the phase of the 15 GHz LO, the I and Q data were demodulated one at a time. By varying the optical input power to the PD, the average bit error ratio (of both I and Q data streams) was measured and the curves plotted in Figure 66. For the wireless transmission, the photodetected output was amplified using a low noise amplifier, and transmitted over air using a 20 dBi gain horn antenna. After 2 m of wireless transmission, the 10 Gb/s signals were received using another 20 dBi gain horn antenna, and amplified using a high power amplifier, before downconverting in the broadband mixer. No additional electrical amplification was used to make a comparison between the back-to-back and wireless transmission scenario. Similar to the back-to-back case, the data streams I and Q were demodulated one at a time by varying the phase of the LO at the receiver. Figure 67 shows the photos of the wireless link.

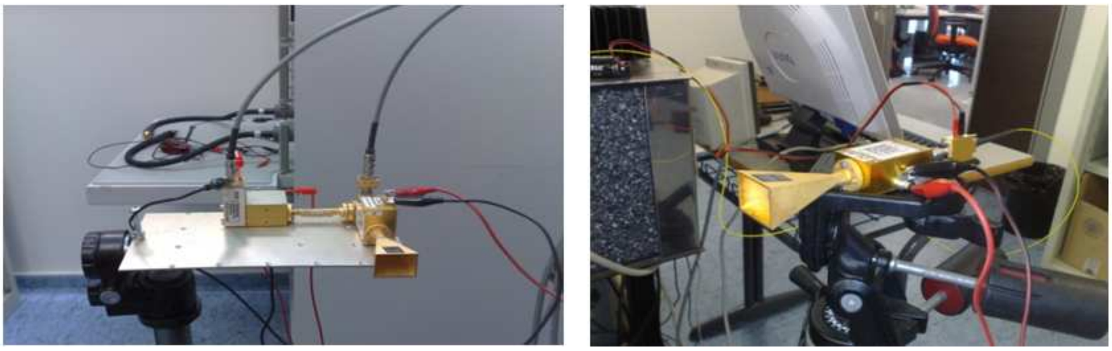

Figure 67 Photos of the wireless transmitter (L) and receiver (R).

Comparison to the State-of-the-Art

Until the beginning of the IPHOBAC project, most of the recent work on wireless links were based on direct upconversion of baseband data to mm-wave frequencies [1]. The disadvantage of such a scheme is the bandwidth inefficiency of the modulation format, and makes it impossible to transmit 10 Gb/s data in the 60 GHz band. Photonic vector modulation has enabled the direct photonic generation of advanced modulation formats and a spectral efficiency of 2.4 bit/s/Hz has been demonstrated. In photonic vector modulation, the most crucial component is the 60 GHz electro-optic modulator, and now several other initiatives are underway to develop e.g. 100 GHz electro-absorption modulators, and in IPHOBAC photodetectors upto 300 GHz have been demonstrated, which will make this technique independent of frequency.

Apart from photonic vector modulation, another technique of generating high spectral efficient wireless signals is incorporating complex electronics like arbitrary waveform generators, or FPGAs to generate IF signals with high spectral efficiency, and then upconvert it to high RF frequencies. The disadvantage of this technique is that it requires complicated electronics, and it is not easily scalable in bandwidth, whereas the PVM technique is only limited by the bandwidth of the electro-optic components like modulator and photodetectors.

Future Impact: The impact of this work in the future is that more and more efforts on direct generation and demodulation of gigabit wireless signals is underway. Also as more and more frequency bands are being allocated, frequencies above 100 GHz are more interesting, where photonics will play an important role in generation and transmission of these wireless signals. Also with the fast evolution of access and metro optical networks, a niche market will arise where 40 Gb/s or even 100 Gb/s wireless connectivity will be required, where techniques like photonic vector modulation, or photonic generation of these high capacity wireless signals will play a role.

1.5 Impact on the photonic industry and research field

IPHOBAC has had a significant impact on the photonic industry and research field.

All consortium partners are committed to use all their individual and joint efforts to ensure a solid exploitation of the IPHOBAC results. Depending on the nature of the results achieved, short or long term exploitation scenarios have been defined for the results of the project: A total of 22 exploitable results (see also next section) have been identified by the project partners and first steps to commercialize IPHOBAC components have already been taken.

More concrete, the small and medium size enterprises CIP and U2T participating in IPHOBAC were building upon the design and prototyping efforts of their own research and of the academic partners to prepare for the commercialization of new or advanced photonic components in the target markets. Although, the development of products was originally planned in continuation of the project work both companies already successfully launched new components.

For example, CIP's involvement in IPHOBAC allowed the company to commercialize 60 GHz reflective EAMs and W-band photodiodes. These products will encourage new and emerging applications in the field of mm-wave photonics. The research on the integrated OPLL may also be an enabling technology to open up new applications for CIP. The IPHOBAC project has also helped CIP to further develop its hybrid integration platform, a technology which will have applications in many industrial sectors.

As for U2T, their involvement in IPHOBAC has helped the company to also commercialize broadband DC-110 GHz photodiodes, which are to our knowledge the fastest photodiode modules that are commercially available today. Further impact is seen in launching further products in the targeted application fields. Concrete exploitation plans are currently being discussed with III-V Lab with respect to fast modulators and with UDE with respect to commercializing the developed mm-wave photonic transmitters as well as low-phase noise optical remote mm-wave links. As regards the photonic transmitters, several concrete buying interests were received; potential exploitation paths are currently looked at.

As regards the MLLD developed by III-V Lab, the potential of the different devices and systems that were developed in the frame of IPHOBAC has been presented in publications, conferences and exhibitions. IPHOBAC provided the opportunity to present, for example, performances of quantum dash mode-locked lasers for use in mm-wave wireless systems or for integration of opto-electronic oscillators ([39, 40, 45]). Thanks to these published data researchers or industry people can evaluate the potential of the proposed technical solutions. Also, the IPHOBAC system experiments were performed with the MLLD devices by industry partners like TAS and FT as well as academic partners including UDE that were an efficient way for them to evaluate the possibilities and the limits of the proposed solutions. For example, experiments performed at FT showed the potential of quantum dash mode-locked lasers as an integrated source for the generation and modulation of the mm-wave signal. These experiments were also a way to see the limits of the technical solutions that justifies device optimizations.

Overall, the results obtained with the quantum dash mode-locked lasers have raised a particular interest and the opportunity for III-V Lab to sell wafers with quantum dash structures ready for laser process to teams interested in processing and using these kinds of structures. Opportunity of collaboration with CIP has been studied during IPHOBAC through an evaluation of quantum dash material for DBR laser fabrication. At the end, due to compatibility problems with CIP standard fabrication process and with currently produced CIP device requirements, this option was not maintained. In the frame of the integrated 70 GHz DFB-EAM development, III-V Lab collaborated with U2T for the device packaging. This collaboration strengthens the contacts between III-V Lab and U2T that could potentially lead to collaboration where III-V Lab would deliver chips that U2T would package.

Furthermore, to ensure future direct exploitations e.g. by a spin-off, a patent on novel and innovative high-performance and low-cost PRBS generation was filed by LUB with the intention to establish a spin-off company focusing on low-cost and high-performance devices and (sub-) systems and specialized services (modeling and consultancy). A second patent on novel optical mm-wave source was filed by UDE with the intention to secure further exploitation of the respective developments in the field of optical low-phase noise mm-wave generation.

For LUB, the work on the OPLL electronics, specifically on the advanced phase detector within an electro-optical phase-locked loop (EO-PLL) and phase-noise reduction, will continue as an academic research. Given the fact that the IPHOBAC project and its current results produce world-record achievements already and there are still many improvements possible, a new EU-funded project or at least a cooperative work between the collaborating partners is strongly recommended. LUB foresees and expects the continuation of this work in the form of at least one doctorate thesis. Furthermore, the current participation and future cooperation will bring Slovenian mm-wave and THz research closer to the western developments in this field. The work on the low-cost electronics (PRBS, high-speed (de)mux, laser controllers, etc) will not have an immediate impact on the Slovenian industry, since there is hardly any present in this field. A major impact on the EU industry is possible if the knowhow (especially on the novel PRBS design) is transferred to an appropriate high-speed electronics industry, interested in the 40 Gb/s, 100 Gb/s and beyond electronic and communication devices. Currently, investigations of a possible spin-off company are being done at LUB for the exploitation and industrialization of the Task 5.3 results.

For UDE, the work on the low phase-noise optical mm-wave links has not ony led to a new contract with ESA for developing an earth observation W-band sensor together with TAS, UDE has also invented a novel technique for generating a microwave signal around 21 GHz with ultra-low phase noise performance and a wide frequency tunability. All frequencies inside the tuning range have shown similar phase noise levels around -105 dBc/Hz at 10 kHz offset from the carrier with a maximum deviation of only ±1.5 dB. Such a system is expected to have a high impact on the industry as well as on the research sector because high-spectral-purity and high-stability radio-frequency oscillators in the gigahertz range are important for many applications such as optical communications systems, clock recovery, radar systems, comb generation and analog-to-digital conversion systems to name only a few. Thus UDE has filed a patent application for such a system. In addition to that, there are concrete discussions with industrial partners in commercializing low-phase noise links.

Through its set of demonstrations, TSA has demonstrated that mm-wave signals could be optically generated, optically transmitted and received. This was experimented over the whole W-band. It was shown that even for a complex waveform, the quality of the mm-wave signal was preserved when converted to and from optics and that optical links could be used in more elaborated sensor demonstrations. This should greatly impact the development of applications where it is needed to transmit signals over meters, tens of meters up to a few hundreds of meters. Indeed, optical links have fixed losses directly linked to the EO and OE conversions but these are then virtually independent of length as opposed to waveguides that are very lossy and that are therefore very limited in terms of distance transmission. Moreover, the installation of fiber on structures is much simpler than that of waveguides. An example of application in the field of security was given where a network of surveillance radars is optically linked together to a remote processing unit.

Another major expected impact was concerning the mmW photonic source, a device that allows generating a widely tunable mm-wave signal by optical means. Indeed, as was demonstrated with the DFL locking over a 1GHz chirped mm-wave source, the photonic technology is intrinsically wide band and could allow the synthesis of very large mm-wave frequency chirps or the synthesis of signal linearly tunable between 30GHz up to more than 300GHz.

Following to the demonstrations, a technology roadmap of each IPHOBAC component versus potential applications in Thales was given in order to identify the time scale and the development necessary to ensure further insertion in our systems.

As already mentioned above, apart from providing a direct or indirect path to the end-user markets the industrial partners also benefited directly from the IPHOBAC results. An evidence for this is given by the fact, that UDE and TAS have been issued a development contract for a W-band optical mm-wave generation system for the European Space Agency (ESA) which was supported by the results on low-phase noise optical mm-wave generation achieved within IPHOBAC.

Apart from the wide field of system applications in instrumentation and sensing and as a result of the excellent dissemination of the IPHOBAC results some initial contacts with all European tier 1 system providers for the wireless communications network have been established, undertaking exploitation endeavors outside the consortium. In one case this has already led to joint research activities. These very promising efforts of exploiting the knowledge on broadband photonic wireless links developed within the IPHOBAC project for mobile backhauling applications will be continued between IPHOBAC partners and the world leading system suppliers. In addition to the field of potential applications in the mm-wave photonics area additional exploitation paths have been identified in the field of 100 Gigabit Ethernet optical systems.

2 Dissemination and Use

2.1 Market analysis

The operational frequency range of several potential applications, which include fixed services, broadband wireless access, short range nomadic services, indoor communication, radar and security as well as instrumentation and medical applications is already in the mm-wave region or is expected to be extended into in the mm-wave region within the next 5-10 years. IPHOBAC has developed new photonic based mature transmitter and receiver technology to support those applications.

In the exploitation plan reported in D621 and D623, it was under the responsibility of each industrial, academic, and research partner to use the scientific and technological results of the project. Joint efforts have been undertaken to identify and quantify potential markets, e.g. by launching a questionnaire for an industrial survey (D633 and D631). All partners have identified their options to exploit the results achieved in the project for the benefit of the European economy in a mid to long term perspective. These options are presented in the form of exploitation roadmaps in D623 and could include the licensing of intellectual property, the development of products or providing key enabling technologies for future system implementations. A total of 22 results with the potential for economical exploitation are summarized by each partner and the next steps towards commerciali-zation are identified.

2.1.1 Market description

The markets addressed by IPHOBAC were divided in five areas of applications: telecommunications, transport, instrumentation, security and medical. This segmentation was used to describe the current market size and projected growth in D623. In all of these segments there will be project partners participating at the different levels of the value chain. Component suppliers are going to develop and sell their products or subsystems to system integrators providing end customers with solutions for deployment. The participation of the project partners in these markets will then depend not only on their respective market share at their level of the value chain, but also on the contribution of their respective products to the full solutions at end customer level.

2.1.2 Survey on component requirements and market needs

To get a better knowledge on and stimulate the growth of the emerging European industry in the field of mm-wave components and functions, a questionnaire was launched. This action was part of task 6.3 (T6.3) and was carried out by UDE, OptechNet e.V. with the support from all partners Details on the questionnaires and the survey results are reported in D631 and D635. The following gives a summary report and over-all view on the survey results.

In summary, until October 2009 altogether 278 participants took part in the IPHOBAC survey. Even though the majority of respondents are from European companies and research organizations (two thirds of all participants), there was a fair amount of experts participating from non-European countries, predominately from the USA, representing worldwide trends in the mm-wave industry.

The survey revealed that in all addressed application fields, the general interest in utilizing photonic mm-wave technologies is very high. In all addressed application areas more than 2 out of 3 respondents indicated the need or whish for utilizing photonic mm-wave technologies as significant. The highest interest was found to be in the sector of *Telecommunications* closely followed by *Security / Radar*. In both areas more than 3 out of 4 respondents indicated the highest significance.

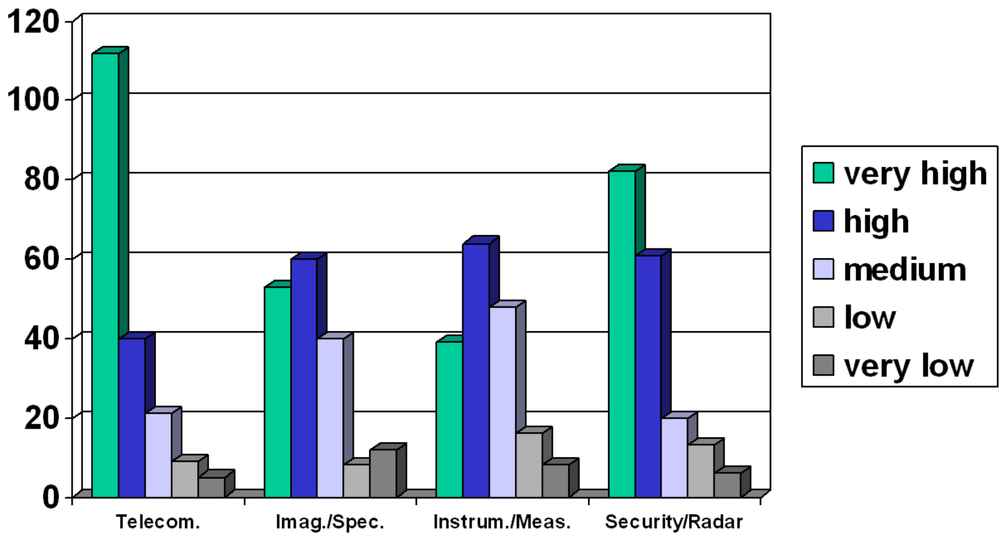

Figure 68 Results from the IPHOBAC survey. The need for mm-wave applications and systems is in telecommunications followed by security/radar according to the majority of the participants.

With respect to photonic mm-wave components/functions, it is interesting to note that generally more than 80% of the respondents are interested in a photonic solution. This indicates that the majority is not only interested in the mm-wave function itself but also interested in the underlying photonic technology. Only 19% indicated not to be interested in a photonic solution.

Generally, with respect to the technical requirements, we found out that with respect to the required power level almost half of the respondents would be satisfied with 0 dBm, more than 75% would be satisfied by power levels of up to 10 dBm. The most interesting frequency range is DC-110 GHz followed by a frequency range of 30-300 GHz. These general interests reflect that the objectives and achievements in IPHOBAC are well suited to the needs of the industry.

The survey reveals that the most required individual photonic mm-wave component is the broadband photodetector operating from DC-110 GHz. Here, a high output power level is seen as key for commercial success with a power level of up to 0 dBm satisfying 42% of all requirements, a power level of up to 10 dBm would even satisfy requirements of 77% of all respondents. With respect to the output connector the highest interest was in having a coaxial W1 output connector (45%) followed by rectangular waveguide output connectors (28%). This reflects that the broadband and high-output power photodetector modules using a fiber-optic package with w1-coaxial output connectors and integrated bias-tee developed in the IPHOBAC project are of high interest. As for the cost, those indicating an interest in a broadband W1 PD indicated cost of, 71% would accept cost in the order of up to 1000 € and only 24% indicated to be willing to pay up to 10.000 €. This is somewhat unrealistic, as even the current cost for 40 GHz PDs exceeds the 1000 € level. In summary, we expect that there is a reasonable market for 100G PDs – mainly for R&D applications and measurements. While the PDs developed in IPHOBAC with 0 dBm output power level and W1 coaxial connector fulfill the requirements of many respondents, it is also clear that 10 dBm output power and other connector types especially a rectangular waveguide would help addressing many more customers.

Another important component is the integrated photonic mm-wave transmitter operating in the 30-300 GHz frequency range. From responses gained by the questionnaire and from discussions and requests during the IPHOBAC exhibitions in Munich, Lyon and Rome, we notice interest for these devices mainly for THz wireless communications but also for THz measurements. For the time being we expect a market of a few tens 30-300 GHz emitter only with individual cost of about 12.-18 k€.

Summing up all survey results, mm-wave applications and systems will most likely be significantly needed in all stated fields, such as Telecommunications, Imaging / Spectroscopy, Instrumentation / Measurement Equipment and Security / Radar. A special emphasis certainly lies on Telecommunications, where 112 experts see a significant demand for mm-wave applications and systems, followed by the field of Security and Radar, where 82 specialists believe in a very high impact. Whereas mm-wave applications and systems are foreseen to play a stable role in Imaging and Spectroscopy (53), the lowest influence these services seem to have is in the area of Instrumentation and Measurement Equipment (39).

One specific photonic system of high interest is the integrated low-phase noise mm-wave source operating in a frequency range of DC-110 GHz whereas one third of all the respondents asked for such a fixed frequency source operating inside this range. Regarding the required phase noise levels, about three-fourth of the respondents would be satisfied with phase noise levels below -100 dBc/Hz at 10 kHz offset while 24% require a better phase noise level up to -140 dBc/Hz at 10 kHz offset. We expect that such a low phase noise (<-140 dBc/Hz) is only realistic for a fixed frequency source. Such a low phase noise photonic LO source is of high interest for several applications including radar applications, sensors to name a few.

On the more system level, a remarkable number of almost 86% of all the respondents expect the greatest need for photonic solutions in communications. This is manly driven by wireless communications; where the majority of the respondents of V1 tends to be satisfied with a small data rate or modulation-bandwidth, the participant of V2 prefer a higher one. The focus switched to components with modulation bandwidths of up to 10 Gbps. The tolerable costs, indicated e.g. for a broadband 60 GHz access link was more than 10.000 €. We expect photonic wireless systems with a CAPEX below 10€ per Mbit/s will be able to address a large portion e.g. of the annual mobile backhauling market. It should be noted that the annual market for broadband wireless backhauling systems was about 5.8 B$ in 2008.

2.1.3 Current market size and projected growth

2.1.3.1 Telecommunications

- Mobile telephony and broadband access

  Long Term Evolution (LTE) of the mobile telephony standard is expected to put pressure on the mobile backhaul network and infrastructure deployments with higher capacity and closer cell site requirements. In this context, radio over fiber can find a leading role to facilitate the deployment and access to new antenna sites. IDATE forecasts that by 2015 there could be up to 350 millions subscribers for LTE worldwide.

  Also important in this context is the potential created by radio-over-fiber to share the access between the central stations and remote base stations between operators (unbundling the fiber access to the different cell sites). There are many ways of sharing the Radio Access Network between different operators (RoF is just one potential candidate) but overall, the study in D623 indicated that the savings are enormous.

- Outdoor radio over fiber (RoF) systems (WLAN & WiMAX)

  In an outdoor context, WLAN could offer very high bit rate connections through hot spots. The bandwidth demands are continuously increasing and contention problems demand to manage the QoS (Quality of Service) by offering hierarchical services. High penetration of WLAN equipment induces a decrease in the spectral resources. In order to prevent QoS degradation, the idea is to develop wireless system with higher bit rate. A way is to increase carrier frequency up to mm-waves. At the same time, increasing the frequency offers a frequency band with less interference problems.

WiFi Hot spot are expected to increase by 128% from 2005 to 2006 for France Telecom. At the same time WiMAX is going to increase. WiMAX market opportunities include replacements to expensive T1based LAN hotspots, fixed wireless broadband access in rural areas, mobile computers and other connected devices.

Fixed Wireless, WiFi, and WiMAX markets are anticipated to reach $12.4 billion by 2010[1]. In the same time, WiMAX in Education market is forecast to be $1.8 billion by 2015[2]. Indeed, a school district can equip each student with a WiMAX enabled laptop extending the school intranet's content and application to the student at home for less than 10% of what a public school district receives in annual federal money per student alone (before state and local funding).

- RoF and UWB 100Mb/s and WPAN

For 2006, IDC[3] expects WiFi infrastructure to grow by 21.2% to $1.69 billion. As with the previous two years, the residential market will continue to be the main driver of WLAN equipment growth in 2006. Service providers will continue to promote additional broadband services and most broadband subscriptions will be bundled with a wireless router/gateway offering. More than 1.5 million France Telecom broadband subscribers used the home gateway "Livebox" with an 802.11 interface at end of 2005, the forecast for 2006 was more than 6 millions “liveboxes” (France Telecom). The bit rate is limited to 11 or 54 Mbps. Service scenarios not so optimistic (2 TV sets, with one HDTV for a family with 2 PC) lead to bit rate on the home network requiring 30 Mbps. The trend is to develop new wireless system UWB (Ultra Wide Band) with higher bit rate in the home network. SG Cowen and Co estimates the market for UWB enabled devices to grow at a rapid clip with meaningful market acceptance during 2006-2007. They estimate UWB becoming a billion dollar market by 2009. For instance, UWB based USB dongles market should grow to over 80 million units sales by 2013. Evolution of UWB technology from microwaves to mm-waves is leaded by regulation constraints of UWB to use upper band in order to prevent from electromagnetic perturbations. It addresses the components developed in IPHOBAC considering less than 1% of this market.

Recent studies suggest that 45m homes will possess a HDTV/HD-DVD system by 2009. Wireless in-house interconnects between different HD-video systems is under way to be standardized by IEEE and the 60 GHz band is widely accepted as a suitable solution apart from HDMI cables. France Telecom/ Orange estimated that by 2009 25% of these HDTV households will use UWB (ultra wide band) wireless HDMI interconnects at 3.1-10GHz, whereas 1.5% will use a 60 GHz system. In terms of market size this would amount to 700,000 homes or approx. 70 Mio€ (at 100 € per system).

- Nomadic broadband systems (Wireless 10 Gb/s)

Fourth generation mobile services are likely to be based on picocells with limited range of 10’s of meters. By analogy with WiFi, in order to cover hotspots in Europe, ultimately 20 million picocells may be required. If the cost of the mm-wave photonic components is reduced to €100 for each picocell, this yields €2,000M. If this massive program is rolled out over 10 years, starting from 2015, this could be worth approximately €200M/year. We estimate that 25% of this market (€50M/year) will be addressable as a result of IPHOBAC. In this regard it is also

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[1] Research and markets, “Fixed Wireless, WiMax, and WiFi Market Opportunities, Strategies, and Forecasts, 2005 to 2010”.

[2] “WiMAX Market and Business Assessment - Access, Affordability, and Applications for Education”, Published Date: 01/10/2007, http:/www.companiesandmarket.com

[3] Predictions for 2006 in the European Wireless and Mobile Communications Market, IDC, Jan 2006 by Rosie Secchi, Evelien Wiggers, Romolo Pusceddu, Lars Vestergaard

important to note the wireless GbE market which is expected to have a significant growth over the coming years with already available products reaching the market.

- Fixed service applications for On-board entertainment (Thales)

  Functions developed in IPHOBAC can be used to deliver very high data rates (multi gigabits) in a On-Board Entertainment system, to a sector of tens seats replacing some of the existing electrical cables, therefore allowing to simplify the cabling and reduce its overall weight.

  In-Flight Entertainment overall market size is more 600 000 units for 2005 and represents a market of more that 600M€. This market is addressed with standard copper wire technologies. Growth in this market is higher than 10% per year for the period 2005-2025 [4] [5] . Thales Systemes Aéroportés is already addressing 30% of this market [6], and it is expected that thanks to the development of advanced low-cost mm-wave photonic functions, new markets will be addressable thanks to IPHOBAC at the level of 0.5% to 2% of the overall market in 2010.

- RoF access systems

  The success of broadband services over the past few years and the strong demand for higher bandwidths, leads to a demand for new higher bandwidth services that cannot be offered by existing technology. If we assume that 10% of households in Europe (about 100M units) are technology leaders requiring this service by 2012, and that these technology leaders are prepared to spend €300 on the equipment for such a service. It is reasonable to expect that a percentage of this will be implemented via radio over fibre, say 5%. This yields a cumulative market size of €30,000M by 2012 of which €1,500M would be for mm-wave RoF. A reasonable estimate of the component part of this is 50%. The addressable part of this market is at least 10%, or €75M by 2012.

- MM-wave sources for wireless backhaul systems

  Different analysts expect 5 to 20 Billion Euros annual revenue for backhauling in the near future with a general growth expectation. In particular the Microwave Wireless segment of this market, globally representing around 50% of the overall market today, but with very different impact in different countries, a pronounced growth is expected.

  Microwave to mm-wave radio (MWR) is already introduced in modern wireless networks to provide the required high-bandwidth connectivity between the wireless access and the core network (aggregation). MWR offers communication service providers a flexible and cost-efficient transport solution from the first-mile to the backbone. If e.g. fiber is not available, MWR is sometimes the only viable option.

  As the P-P link capacities in the backhaul network will have to increase to 1.25 Gb/s in the very next future and to about 12 Gb/s longer term, high carrier frequencies have to be selected. Compliant with worldwide regulation, the 80 GHz-band (or E-band, i.e. 71-76 and 81-86 GHz) is most adequate for these applications. The high directivity of antennas, the huge spectrum available and the soft licensing make it a very promising solution. Microwave radio backhaul systems are currently still niche market but are expected to grow rapidly when LTE will require more backhauling capacity. The market is targeted to be mature in 2012. In the future, E-band radio could be combined with new mesh network concepts for more cost effective systems.

  The equipment for the E-band is still rather expensive mostly due to the limited number of suppliers holding high prices.

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[4] "Global Market Forecast 2004-2023", Airbus Industries, 2005.
[5] "Current Market Outlook 2005", Boeing, 2005.
[6] "Ramp-Up In-Flight Entertainment", Thales Aerospace internal communication, 2005.

This can be an entry point for mm-wave photonics to provide cost-effective and widely tunable sources covering all the frequency bands in use ranging from 7 – 38 GHz at present and up to 90 GHZ in the future with only one optical source.

The transparency of photonic technologies is another major advantage to address multiple system variants with only one source.

Cost analysis of an experimental optically sourced mm-wave point-to-point link (IPHOBAC-demonstrator) in comparison with commercially available RF-systems, even if they address the market early on, reveals that the photonic solution does not come at prohibitively high costs. The total cost for an electronic- and a photonic-based system are in the same ballpark area, even though high prices were still applicable for the R&D-oriented prototype optical components due to low market volumes.

If the cost is compared on a €/Mbit/s basis, the optical solution is in fact almost an order of magnitude less expensive, since the system could be operated at much higher bit rates than the commercial system.

- Optical 100 Gigabit Ethernet systems

  According to a current market analysis performed by the CIR [7], the fixed network Ethernet market is developing towards the next generation of Ethernet data rates to accommodate the drastically increasing demand for bandwidth. Driving factors are the virtualisation of servers and storage farms which require multiple 10 Gigabit Ethernet links between the different pieces of equipment. These networks will first be dominated by wavelength multiplexed 4 x 28 GBaud links using 4 wavelength channels with 5nm separation (LAN-WDM). Based on cost considerations and the availability of sufficiently fast transmitters serial 100 GBaud solutions are likely to occur in about 2012.

  CIR forecasts a sudden increase of the related market for 40 and 100 GbE components (including both, wavelength multiplexed and serial solutions) in 2012 reaching Billion Dollar markets (see figure below).

  IPHOBAC results targeting the 60 and 100 GHz frequency band will most likely be applicable for some of the 100 G serial transmission systems, both on the transmit and on the receive side.

2.1.3.2 Transport

- Enhanced Vision Systems (EVS) for transport vehicles (Thales):

  The basic motivation for EVS on transport is increased safety in particular during night and/or in low visibility conditions and also during approach, landing, takeoff and ground operations. In addition to existing infrared systems, mm-wave radar systems, in which components from IPHOBAC can be used, allow extending enhanced situation awareness to "all-weather" effectiveness. Moreover, in future systems, by determining the weight of potential obstacles in the approach path, this will allow autonomous approach and landing then opening a wide area of new applications.

  The overall market size addressed by classical infrared systems will be more than 800 units per year after 2007, this represents a market of more than 100M€. The world's airlines are forecast to take delivery of more than 17000 new passenger and freighter aircrafts over the next 20 years, equating to average annual deliveries of 866 aircraft [4] [5]. Thales Systemes Aéroportés plans addressing 5 to 20% of this market. It is expected that thanks to its "all-weather" effectiveness provided by mm-wave functions, new markets addressable will be at least 1% of

[7] "The Path to 100 Gbps Networks", CIR, market analysis, L. Gasman, 2008.

the total market in 2012. Later on, since these new systems will replace the classical already installed ones, this market share will continue to increase.

- High resolution automotive radars: (Autocruise or another partner)

  Strategy analysis predicts that short and long-range distance warning systems will become increasingly common features on passenger vehicles. Ultrasonic, camera and radar technologies will be used extensively, but only radar systems will find significant application in both short and long-range systems. It is expected market development of automotive radars to accelerate now; more safety-oriented features are reaching the market, along with lower-cost, short-range devices. Short-range system sales will reach around 12 million units/year by 2007. For long-range systems, a worldwide market of approximately 2.5 million system units is expected by 2007.

  IPHOBAC components have the potential implementing advanced functionalities that will enable mm-wave radar and sub-mm-wave radar based imagery thus leading to obstacle avoidance capabilities and autonomous transport. The size of high-resolution radars will reach 100000 units in 2012, and it is expected to address 10% of this market thanks to IPHOBAC.

2.1.3.3 Instrumentation

- Measurement equipments

  Thanks to their low phase noise performances, their modulation bandwidth and also their size, mm-wave generator functions developed in IPHOBAC are intended to be used in instrumentation equipments instead of replacement of existing devices. The equipments concerned are all the systems employing mm-wave generators.

  The worldwide market size is more than 180M€, for 4000-7000 units. Rhode & Schwarz addresses more than 25% of this market with the production of about 1500 units per year (37M€)8. Thanks to IPHOBAC, in 2010, 3% more can be addressed by Rohde & Schwarz, this represents 180 units, more that 5.4M€.

- Wireless Sensing Networks, Central Interrogating modules (Thales)

  Future electronic sensors will have to be very integrated, and able to communicate among each others. Wireless short distance communication will allow building-up an ad-hoc network between several sensors. Several key applications have already been identified such for instance distributed smart monitoring for transport applications, wireless sensor networks for health monitoring and distributed intelligent control. This approach called Smart Dust has been initiated at Berkeley in 1999. But, a lot of issues must be solved such for instance power consumption, size, weight, processing capabilities, communication links and cost. Consequently, the use of the technology directly developed in IPHOBAC into these modules will only be possible in medium term.

  An application can be foreseen into the “central interrogating modules” responsible for collecting data from all the sensors of the network. These modules are bigger and the constraints are less critical. Among the main functionalities required for these modules, there are very high operating frequencies, frequency diversity. This can be addressed by the approaches studied in IPHOBAC.

  In a rough analysis, that takes into account the mobile station market forecast, for the EU, a market of 100 000 interrogating units yearly could be expected by 2012. In a pessimist case, the market addressable thanks to IPHOBAC outputs can be in the range of 1% of the full market, and the expected cost must be less than 2k€.

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[8] Rhode & Schwarz internal communication, 2005.

2.1.3.4 Security

- Global security market (Thales)

  During the period 2000-2008, the global homeland security (HLS) market grew by 600% from $23 Billion by 2000 to $140 Billion by 2008.

  It is forecast that during the 2008-2018 period, the global HLS markets will grow by 81% - from a sum total of $140 billion in 2008, to about $254 billion in 2018. The global/HLS market will grow from 0.25% of the global Growth Domestic Product in 2008 to about 0.36%. Most of this growth will come at the cost of reducing traditional military outlays.

  While the notion of the global defense Industry is that they arrived at an all times high in orders backlog which will be followed by a market decliner. The global HLS market is robust and is forecasted to grow over the next 10 years at an impressive annual growth rate of 7-7.5%.

  Most significant HLS progress can be seen in countries such as Great Britain, Israel, Turkey, Saudi Arabia, and United Arab Emirate. (ISNR-2010)

  Amongst the Next Decade's Fastest Growing Market Sectors are the Information Technology systems, the Defending gas-oil energy facilities and the Border Security domains which could benefit. In the following we look at the possible market shares that can be expected in the related domains of high data rate short distance communications and fixed security radar for area surveillance.

- Point-to-point high rate short distance communications (Thales)

  The main application concerns crowd survey especially during peace keeping or light crisis periods. The goal is to detect troublemakers through video surveillance by cameras located on vehicles or on policemen close to the vehicles (several ten meters). The video quality has to be of an excellent level since the trouble leaders are usually hidden by the crowd and the image of them are available only during short periods of time. Therefore, face recognition becomes difficult and a sufficient quality of image is needed. Indeed, the video stream data rate cannot be reduced or limited by using compression algorithms, and can reach a couple of 100 Mb/s per channel. The use of mm-wave frequencies is of interest since it will allow delivering very high data rates over short distance, with frequency reallocation if necessary.

  Police forces responsible of such mission in France, concern roughly 20 thousand policemen. Extended to the European Union level, this represents roughly 500 thousand policemen. The overall yearly European market addressable can be estimated to be more than 10000 units – 50M€ in 2009, and it is expected to address 2% of this market with IPHOBAC components (1M€ in 2010).

  Thales provides network encryption solutions to be associated with mm-wave transmission (70/80 GHz) in order to provide a solution for securing data transmission including voice and video over wireless network. This is of interest for government entities as well as financial institutions that need to meet high level security standards. Licensed band 70/80GHz mm-wave radio technology is also ideal for government and security installations that demand rapid deployment of temporary high-bandwidth wireless links for quick restoration of communications in the event of a natural disaster or other emergency.

  The IT security market was estimated in 2007 at 32 billion Euros with an annual growth rate of 18% and the European market itself amounted to 12 billion Euros.9 We estimate the mm-wave wireless solutions to be of the order of 0.5% of this market and IPHOBAC components could address about 25% of this.

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[9] SERENITY project IST6, http://www.serenity-project.org/

- Fixed security radar for area surveillance (Thales)

  The market of the perimetric detection dedicated to the surveillance of industrial and sensitive areas (nuclear power station, embassies, ….) will represent a worldwide market of 1500 M€ in 2009. A third of this market is within Europe. The market addressed by Thales will be about 10% of the European market in 2009.

  It is forecast that the main boost in airport perimeter security will come from networking. A greater number of airports are switching to digital networks, making it essential to network all security solutions to the main command, control, and communications (C3) center('Airport security: A growing market offers opportunities for big and small companies', Homeland security newswire, Published 30 August 2009). This could therefore enhance the need for optical solutions that can be easily remoted to a central processing unit.

  The market that can be addressed with fixed mm-wave surveillance systems is in the order of 0.5% of the European market in a first step, in 2010.

2.1.3.5 Medical

Among the probable markets for IPHOBAC components, there are health-care and medical domains. Indeed, the European Union population which is close to 400 Million, has an average age nowadays close to 36 years that will be in 2025 45 years old [10] [8]. General ageing of the population will lead to an important number of senior citizens. Therefore, a significant increase of health expenses is expected and it is known that in average most of these expenses for seniors appear in the last two years of their lives. Therefore health expenses management is of importance, and to avoid a boom, it is crucial to implement at an earlier stage wearable diagnostic devices for providing a real time track of the health status of people concerned. As already indicated above, a more detailed study on medical applications was reported in M212 and will be reported also in the PAR for the third period. As for the "wireless sensor networks" area, the monitoring sensor in a short/near term approach will not take benefit of IPHOBAC. But, "central interrogating modules" responsible to collect data from all the monitoring sensor can probably take the benefit of IPHOBAC components and functions. In a rough estimation the targeted cost of an interrogating unit could be in the order of a k€ per unit, and it is expected that 100 000 citizen will require interrogating stations. The market that can be addressed with IPHOBAC components is in the order of 1%.

As regards market numbers, in 2005, medical techniques and life sciences represented 8% of the total photonic world market worth about 228 billion Euros. Therefore the photonics world market for medical techniques and life sciences represented about 18 billion euros in 2005. This number is expected to grow to about 30 billions in 2015. European production represents about 30% of this market that is to say about 2,3 billion euros in 2005 and an expected 9 billions in 2015.[11] In M212 possible applications in the biological/medical domain have been identified. This will be also reported in the final exploitation plan due at the end of the project. In the following, some medical applications in which IPHOBAC technologies could be potentially employed are listed:

- Photonic mm-wave endoscope

  The IPHOBAC technologies could potentially be used to construct an ultra-compact photonic mm-wave endoscope for intra-corporal, minimal invasive, local cell or tissue identification, thermal cancer treatment or cell activation. Absorption and reflection of mm-waves strongly depends on water and fat content and therefore on the composition of biological tissue. It has been reported that the use of mm-waves shows some advantages compared to classical infrared technology

[10] "La situation démographique dans l'union européenne", Direction Générale 5.
[11] 'Photonics in Europe, Economic impact', Arnold Mayer, Optech consulting, Published by European technology platform Photonic 21, dec. 2007

in terms of cancer detection [12] and treatment[13]. In that regard even the activation of natural killer cells seems to be possible[14].

- Photonic mm-wave radiator

  The IPHOBAC technologies could potentially be used to construct a low power mm-wave radiator for extra corporal, local tissue exposure for pain therapy. In addition to classical acupuncture and laser induced acupuncture there is some evidence that low power mm-wave radiation can be used to stimulate specific acupuncture points of the human body supporting pain therapy[15]. Additionally, studies[16] show the successful application of low power mm-waves to support the healing and pain relief of various forms of ulcer.

- Live surgery wireless video transmission system

  The IPHOBAC technologies could potentially be used to construct an mm-wave wireless system that enables real-time, high-definition video transmission. Such a system is crucially needed during surgery in an operating theatre inside a hospital (telemedicine). It is obvious, that for such an application high-definition video signals must be transmitted without compression as no latency is allowed. Given the fact, that there is currently no wireless system other than those developed in IPHOBAC that can provide the necessary data rate there is a good opportunity for addressing such a market. This will be investigated further.

- Broadband Indoor wireless system for mobile medical apparatuses

  The IPHOBAC technologies could potentially be used to construct a Multi-Gigabit Wireless LAN capable of bi-directionally transmitting medical data (high resolution X-Ray or MRT images, high definition videos from surgery or endoscopic analyses, histological data from tissues, patient records and life signs like long-term ECG, EEG, etc.) between different mobile medical apparatuses.

  The health care sector and small businesses will prosper the most from widespread implementation and use of wireless broadband, according to 'Broadband Wireless Information in Professional Markets 2009-2010,' the latest strategic market report released today from Simba Information, a leading media industry forecast and analysis firm. By 2012, the percentage of U.S. physicians using smartphones will increase to 81%. The current rate of penetration is 64%. Productivity improvements due to use of mobile broadband solutions across the U.S. health care industry are valued at almost $7 billion. That number is expected to triple by 2016 to $27.2 billion17.

- Wireless monitoring in home healthcare

  The market for wireless monitoring in home healthcare is still nascent, but rapidly evolving. Among the most common conditions to monitor at home are irregular heartbeats or cardiac arrhythmia, high blood pressure, the glucose levels in

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[12] J. Edrich et al., Imaging Thermograms at Centimeter and Millimeter Wavelengths, Annals New York Academy of Sciences, pp. 456-474, 1980

[13] I. Szabo et al., "Destruction of Cutaneous Melanoma With Millimeter Wave Hyperthermia in Mice", IEEE TRANSACTIONS ON PLASMA SCIENCE, vol. 32, no. 4, 2004

[14] V.R. Makar et al., "Effect of MillimeterWaves on Natural Killer Cell Activation", Bioelectromagnetics, vol. 26, pp. 10-19, 2005.

[15] T. I. Usichenko et al., " Low-Intensity Electromagnetic Millimeter Waves for Pain Therapy", Oxford Journals, eCAM, vol 3, no 2, pp. 201-207, 2006, doi:10.1093/ecam/nel012

[16] M.A. Rojavin et al., "Medical application of millimetre waves", Oxford Journals, QJM, vol. 91, pp. 57–66, 1998, doi:10.1093/qjmed/91.1.57

[17] ‘Health Professions to Benefit Exponentially as Broadband Wireless Adoption Proliferates’. Broadband wireless exchange magazine. 10/21/09

diabetes, and high levels of lipids or fats in the blood. In Europe and North America 40 million people have cardiac arrhythmia, 200 million people have high blood pressure, 60 million people are diabetic, and 180 million people have severe elevation of blood lipids. All these diseases are increasing as a result of people getting older and heavier, and all are major causes of high healthcare costs. Berg Insight estimates that 250 million people in the EU and the US suffer from one or several diseases that may require home monitoring. Although not everyone benefits from regular home monitoring, there will probably be 50 million people for whom wireless solutions available would be beneficial.

According to Berg Insight, the market for home health monitoring of welfare diseases was worth approximately 11 billion $ in 2008 and is growing about 10% annually[18].

As a next step in view of exploitation in the medical area, it is planned first to identify further applications in the medical area and second to contact potential partners for specifying the requirements of some specific applications in the medical area in order to potentially identify a commercialization path. The approach to be taken will also involve contacting some of the authors of the papers cited in T2.2 as well as some specific medical doctors active in the addressed application. From these contacts we should be able to get references also to companies, which can then be targeted to address for follow-up discussions and to identify applications, partnership and more quantitative market figures.

As discussed above it has been anticipated that the components and functions developed within IPHOBAC could find cross-market applications i.e. not only in telecommunications, but also in transport, instrumentation, security and probably also in other fields such as for instance health-care and medical domains.

The market size will be extracted from internal strategic market analysis of the participating industrial partners, from non-public internal communications as well as from global market forecasts from key industries (Airbus, Boeing, ATT, Rohde & Schwarz).

The current market share (CMS) figures will be derived by extrapolation from available information of the partners and targeted customers.

IPHOBAC is developing a new technology and as such it is expected that cost, performance and reliability benefits have to be proven during the project before IPHOBAC solutions will be able to heavily penetrate into existing markets. However, from our first analysis IPHOBAC will have a significant impact in these potential markets and will ensure a sufficient return on investment.

In an update of Sept. 2009 the industrial partners updated the market opportunities of the IPHOBAC project and confirmed the total potential market in the range of 170 M€, but with a slightly changed distribution amongst applications in favor of Telecom and medical applications (‘other’) as is illustrated in the figure below.

[18] ‘Wireless monitoring in home healthcare’, Berg Insight’s M2M Research Series , www.berginsight.com

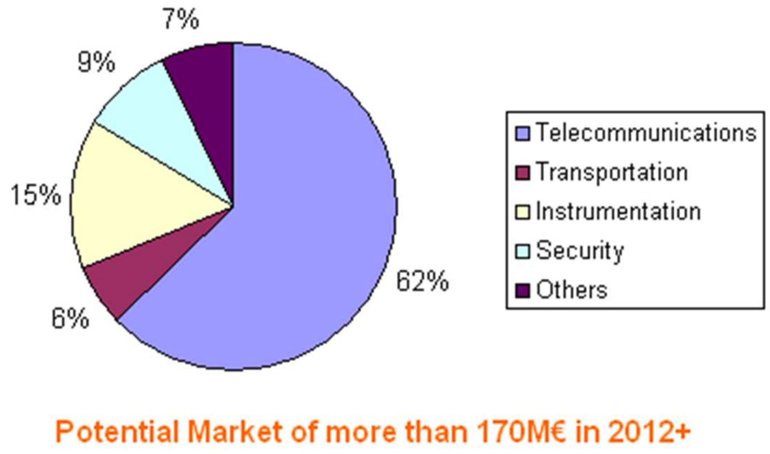


Figure 69 Potential market to be addressed by photonic technologies in 2012.

2.2 Exploitation strategies

2.2.1 General exploitation strategies of the consortium

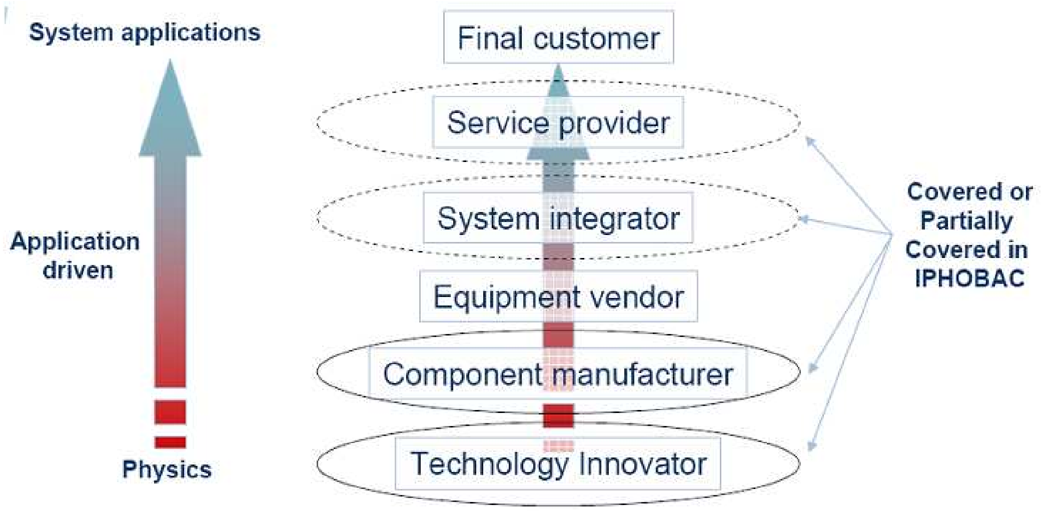


Figure 70 Schematic showing the vertically integrated project partners.

The IPHOBAC consortium integrated partners from academia, SMEs as well as industrial partners working on all levels of the value chain. This vertical integration of the consortium was considered most useful in defining applications and possible exploitation paths for products for all identified market segments within the partners of the consortium.

In general, the IPHOBAC academic partners seek at exploitation of their intellectual property by licensing agreements with SME and industrial partners, SMEs will be most active in supplying components and the industrial partners will use IPHOBAC results to explore new market segments with their systems.

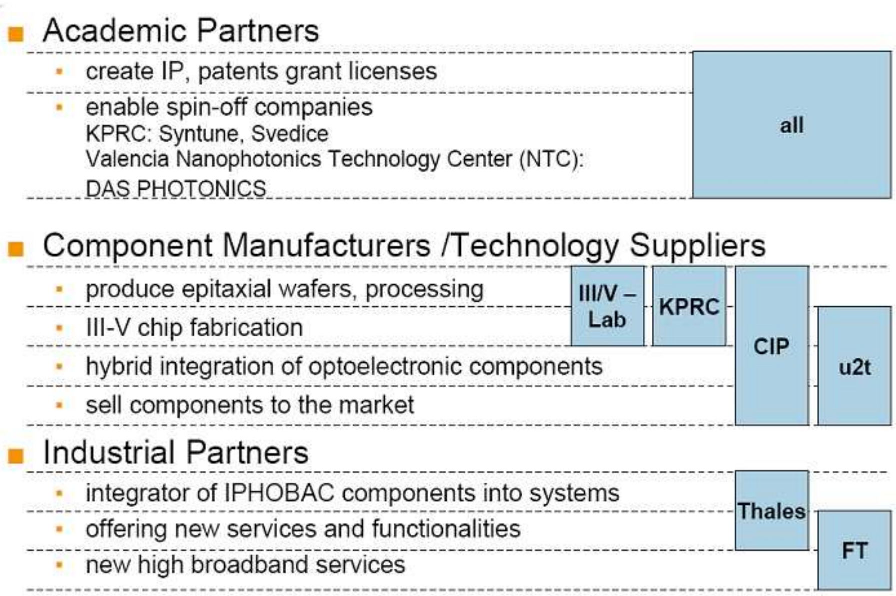


Figure 71 Overview on the exploitation strategies of the different IPHOBAC partners.

A very detailed report on the individual exploitation strategies of each project partner was reported in D621 and D623. The following extract lists the key exploitation interests of the individual partners.

2.2.2 Identification of exploitable results

The partners did regularly meet during the project meetings to update the exploitation plan. The Intellectual property committee identified and discussed results from the technical work packages to ensure their possible exploitation. Each of the partners used its most current market know-how to update possible exploitation paths and market information. The results are included in the first (D621) and final version (D623) of the exploitation plan.

The following list summarizes the exploitable results identified by the different partners. Actions taken to protect the result commercially and which partners participate in the exploitation of such results as well as the exploitation strategy for each result, technical and economical market considerations are reported in D623.

List of identified exploitable results:

- **Quantum dash Fabry-Perot mode-locked laser (III-V Lab, U2T)**

  A quantum dash mode-locked laser with a quantum dash gain medium that can be used to get sub-picosecond pulses with a repetition rate from 10 to 100 GHz with a limited phase noise (-75dBc/Hz at 100 kHz offset). This kind of device can be used as a comb generator with a -3dB optical spectrum width of more than 10 nm. Direct modulation of the device is possible either to lock the oscillation frequency or to super-impose data on the oscillation.

- **Continuously tunable dual wavelength laser over whole mm-wave range (III-V Lab)**

  A dual wavelength DFB laser used to generate simultaneously two wavelengths. The signal, after photodetection, will generate a tone at a frequency corresponding to the wavelength difference between the two optical modes. With this laser it is possible to tune the generated tone over the whole mm-wave range by tuning just one of the drive currents.

- **100 GHz externally modulated DFB laser (III-V Lab, U2T)**

  A DFB laser monolithically integrated with a large bandwidth electro-absorption modulator for modulation at up to 100 GHz. With this device it is possible to transmit signals at mm-wave frequencies over one wavelength. Depending on the signal that is applied to the device, data can also been applied to the device.

- **100 GHz externally modulated DFB laser and Integrated 60 GHz SOA-EAT (KPRC)**

  Optical transmitter for (up to) 100 GHz RF signals Integrated TW-EAM+DFB and resonant reflective EAT with integrated semiconductor laser for 60 GHz applications.

- **Dual wavelength tunable DBR lasers (CIP)**

  Narrow linewidth high output power dual wavelength lasers that can be used with a photomixer as a mm wave or THz source.

- **High frequency reflective EATs (CIP)**

  (1) Reflective EAM module with 60 GHz modulation bandwidth, ~ 4 dB optical insertion loss, low drive voltage, 43 GHz photodetection bandwidth with ~ 1.0 A/W responsivity. (2) Reflective EAM chips developed with bandwidths > 60 GHz and expected to be > 100 GHz although we have yet to prove that but with higher optical insertion losses of ~13 dB.

- **Packaged 300GHz Photodiodes with Antenna (UDE, U2T)**

  A fully packaged high-speed photodetector monolithically integrated with a planar antenna for tunable mm-wave generation and quasi-optic mm-wave emission in the frequency range from 30-300GHz.

- **100 GHz high speed photodiode (U2T, CIP)**

  Photodetector with 100 GHz electrical 3dB bandwidth, based on enhanced chips and rf-interconnect technology using W1-connectors as developed in IPHOBAC WP4.

- **Photonic 110GHz synthesizer instrument (UDE, TAS)**

  A compact photonic 110GHz synthesizer instrument offering low phase noise tunable mm-wave signal generation and signal remoting in the frequency range up to 110GHz.

- **Compact low phase-noise mm-wave Source (UCL, CIP, LUB)**

  Hybrid integrated continuously tunable mm-wave source with low phase noise based on optical phase locked loop techniques.

- **mm-wave low phase noise oscillator (III-V Lab)**

  A mm-wave, low phase noise signal generator that can generate simultaneously a low phase noise electrical signal and sub-picosecond optical pulses at a given frequency from 10 GHz up to 65 GHz.

- **Broadband photonic wireless mm-wave links (UDE, UPVLC, FT, UCL, DAS Photonics)**

  Broadband photonic wireless systems constructed with world record performances in terms of capacity and spectral efficiency. In the current mm-wave bands a limited bandwidth is available for example 7 GHz in the 60 GHz band, and a total of 10 GHz in the 70-80 GHz band. These bands have a potential for delivering 10 Gb/s data if the right modulation formats are incorporated. Using a photonic vector modulator, 10 Gb/s signal generation in a 7 GHz band has already been demonstrated using QPSK modulation, and also the use of advanced modulation like 16-QAM is also studied.

- **Reach extension of 60 GHz radio systems (FT)**

  The electro-optic converters (Mode Locked Fabry-Pérot laser, TW-EAM with integrated laser and R-EAT with integrated SOA) will be assessed as to their performances in providing reach extension capabilities as well as generation/detection for 60 GHz radio signals.

- **Low-cost 10Gb/s PRBS generator (LUB)**

  A pseudo-random binary generator exploiting a novel and innovative method which enables higher performance and requires lower power consumption and lower cost. The main advantage towards the existing commercial generators is foreseen at the highest data rates beyond 100 Gb/s, although the current design operates at 10 Gb/s.

- **Low-delay high-speed phase detector (LUB)**

  The mm-wave and THz signal generation using OPLL methods requires very small loop delay, therefore specialized phase detectors are required. Auto-locking low-delay and high-speed phase detector was designed and manufactured.

In summary, the IPHOBAC consortium comprises partners from academia, from SMEs and from industry, covering the full spectrum of the value chain for related markets. This and the excellence of all the partners in their specific fields will ensure a straightforward and seamless route to exploitation of the scientific achievements resulting from the project. The academic partners will concentrate on new designs and new solutions both on the component and the system level and will make their IP accessible for the partners in the consortium. The IP related issues such as exploitation and protection was governed by the Intellectual Property Rights Committee within the project. Two patent applications have been filed as result of IPHOBAC research:

A patent on novel and innovative high-performance and low-cost PRBS generation was filed by LUB with the intention to establish a spin-off company focusing on low-cost and high-performance devices and (sub-) systems and specialized services (modeling and consultancy).

The second patent on novel optical mm-wave source was filed by UDE with the intention to secure further exploitation of the respective developments.

The small and medium size enterprises are building upon the design and prototyping efforts of their own research and of the academic partners to prepare for the commercialisation of components in the target markets. The development of products is planned in continuation of the project work both on the level of semiconductors and on the level of packaged products and subsystems. A number of such co-operative exploitation scenarios are envisaged as described in D623 (“Identification of exploitable results”). For example, there is an ongoing discussion on commercializing QD-LDs for EML between U2T and III-V Lab.

First prototypes of targeted components have already been introduced to the market: High-power photodiodes with 100 GHz bandwidth are now commercially available from two partners: U2T and CIP. The 60 GHz reflective type electro-absorption (R-EAT) transceivers are also commercially available now from CIP.

The industrial partners did contribute their in depth knowledge on the markets of targeted applications. Their contributions to the project ensured from the very beginning, that the specifications and techno-economical requirements of the market are guiding the technological developments. A current update of the latest application trends and market information in the telecommunications, transport, security and instrumentation markets is included in this report as well as in detail in D623. One industrial partner (TAS) did also provide an assessment of the technological development status of the different results in terms of an industrial evaluation scheme.

Apart from providing a direct or indirect path to the end-user markets the industrial partners will also benefit directly from the IPHOBAC results. One evidence for this is given by the fact, that partners TAS and UDE have been enabled to apply for the development of a W-band optical mm-wave generation system for the European Space Agency (ESA) supported by the results on low-phase noise optical mm-wave generation achieved within IPHOBAC.

In addition to the field of potential applications in the mm-wave photonics area additional an exploitation path has been identified in the field of 100 Gigabit Ethernet optical systems.

The consortium partners are committed to use all their individual and joint efforts to ensure a solid exploitation of the IPHOBAC results. Depending on the nature of the results achieved, short or long term exploitation scenarios have been defined for the results of the project: A total of 22 exploitable results have been identified by the project partners (see also list above) and first steps to commercialize IPHOBAC components have already been taken.

A wide field of system applications was identified and as a result of the excellent dissemination of the IPHOBAC results some initial contacts with all European tier 1 system providers for the wireless communications network have been established, undertaking exploitation endeavors outside the consortium (cf. D.734). In one case this activity led to the joint proposal for a new FP7 – program to explore these solutions in more detail, an in one other case a commercial interaction was started to identify a potential commercial supply of IPHOBAC components in future products of the system provider. These very promising efforts of exploiting the knowledge on broadband photonic wireless links developed within the IPHOBAC project for mobile backhauling applications will be continued between IPHOBAC partners and the world leading system suppliers.

In conclusion, despite the forward looking nature of the program, the exploitation prospects of the IPHOBAC project are excellent, both by providing direct paths towards the commercialization of products based on IPHOBAC R&D and by enabling new application technologies to support the European industry to gain leadership in photonic-mm-wave systems.

2.2.3 Spin-off feasibility study

During the course of the IPHOBAC project, there were already discussions on commercializing some of the developed components by the participating partners. As an example, there are ongoing discussions on commercializing QD-LDs for EML between U^2T and III-V Lab and on using high-power PDs and fast modulators for low-phase noise mm-wave optical links. **On top of that**, **first prototypes of other targeted components have even already been introduced to the market:** As examples high-power photodiodes with 100 GHz bandwidth are now commercially available from two partners: U2T and CIP. The 60 GHz reflective type electroabsorption (R-EAT) transceivers are also commercially available now from CIP. A full list of the exploitable results/achievements can be found in section 2.2.2.

Further to a more direct exploitation by a participating partner, the consortium also investigated the possibility of founding or spinning-off a new company in the field. This activity was mainly carried out by UDE in task 6.3 (T6.3).

As regards the creation of a new spin-off company in the field, four possibilities focusing on different components / systems developed in the project we studied in more detail. The detailed feasibility study is reported in D632 and D634.

In summary, based upon the IPHOBAC technical survey and the IPHOBAC market analysis (D635), information gained during the meetings with external partners (D734) as well as based on other sources, the following components / systems appeared to be the most promising for short to medium term commercial exploitation by a spin-off company.

Those functions / systems are:

- Widely tunable low-phase noise photonic sources
- Broadband photonic wireless (RoF) systems for broadband mobile backhauling and access
- Packaged photonic THz and mm-wave transmitters
- Low-cost 10Gbps PRBS

Although the most promising applications are seen to be in the fields of instrumentation, radar, security and broadband communications (i.e. telecommunication), the discussion will be limited to those identified market segments. However, it should be pointed out that other market segments e.g. the medical area also offer a great potential for MWP technologies (see also M212 as well as section).

To ensure future exploitation actions after the project, two patent / patent applications have been filed. For the photonic mm-wave and THz sources, a component specification sheet was prepared and distributed at the IPHOBAC exhibitions. **Requests from industry and large research institutions located in Russia, France, South Korea, Australia, US and other countries asking for price information or purchasing the components were received**. Discussions on marketing the IPHOBAC transmitter are ongoing, also discussion on marketing some of the IPHOBAC developments in the US have been initiated during the EuMW 2009 exhibition in Rome. Furthermore, after proof-of-concept low-phase noise optical mm-wave links were demonstrated in IPHOBAC, partners currently work on the possible launch of a new low-phase noise photonic link system using some of the developed IPHOBAC components.

As regards broadband wireless, ongoing discussions with world leading system suppliers in the field on using the IPHOBAC technologies for mobile backhauling have already led to a new project proposal.

2.3 Standardization actions

Standardization activities were covered in task 7.4 of the project. The deliverables D741 and D742 give an update of the standardization landscape and actions carried out in the framework of the project. The standardization actions were mainly focusing on telecommunications and here especially on broadband wireless systems. In summary, worldwide issued 60 GHz regulations were studied including outdoor regulations at 60 GHz and safety aspects. The project has actively contributed to standardization issues in the Worldwide Wireless Research Forum (WWRF) and in connection with the WWRF activities an update of new research items was launched by Orange labs (FT). They integrate photonic components and mm-wave generation signal, providing new opportunities to promote IPHOBAC results and contribute to future mm-wave devices. RoF/IFOF and BBoF architectures are also envisioned as novel WPAN architectures.

Several contributions have been presented at the WWRF connected to IPHOBAC. A status of 60 GHz WPAN standardization is presented considering IEEE802.15.3c, ECMA-368 and IEEE802.11.vht.ad groups. Several workshops have been organized in order to promote mm-wave and THz MGWS wireless systems in the context of radio-communications. These systems are the baseline to advanced RoF architectures in the context of home networking.

2.4 Exhibitions

During the project three exhibitions at international fairs and one exhibition at the IPHOBAC workshop had been organized. Those are:

Laser-World of Photonics, 18-21 July 2007

During the second project year the consortium had organized an exhibition at the Laser-World of Photonics in July 2007 in Munich.

EuMW2007, Munich, 9-11 October 2007

During the second project year the consortium had also organized an exhibition at one of the largest fairs in the addressed field in Europe: the European Microwave Week in September 2007 in Munich, Germany. At that exhibition the project had displayed its first prototypes of 110 GHz photodiodes and 300 GHz photodiodes as well as first prototypes of motherboards and daughter-boards for integration. One further objective of the exhibition was to distribute the IPHOBAC questionnaire to other exhibitors and presenters that visited the IPHOBAC booth for identifying new or concretizing known RF applications mainly in radar and instrumentation. This way, almost 30 questionnaires were returned and evaluated in D631. From this preliminary analysis it was found that the performances of the IPHOBAC components could potentially address a quite large percentage of the overall market in that industrial field. Also a project meeting with Rohde & Schwarz was held at the IPHOBAC booth.

Figure 72 Photos taken during the IPHOBAC exhibitions at Laser-World of Photonics 2007 and EuMW 2007.

The IPHOBAC exhibition at EuMC2008 was very successful in terms of dissemination and gaining knowledge about applications in radar and instrumentation fields. Thus the consortium had decided to organize another more telecom oriented exhibition. The planning is to exhibit the projects 60 GHz Radio-over-Fiber Demonstrator during the ICT2008 exhibition in November 2008 in Lyon, France.

ICT 2008, Lyon, 25.-27. Nov.

Here we successfully demonstrated a Wireless Full HD Video Transmission operating 60 GHz. This demonstration was ranked as one of the Top10 demonstrations among about 200.

Figure 73 Photo showing the IPHOBAC booth at the ICT2008.

Workshop 2009, Duisburg, 18.-20. May

Within the “European workshop on photonic solutions for wireless, access, and in-house networks” the 12.5 Gb/s system was demonstrated to the more than 80 participants of the workshop.

EuMW 2009, Rome, 28. Sep. – 2. Oct. 2009

At the EuMW 2009, the consortium displayed the following components / systems:

- 100 GHz photodiode
- 60 GHz transceiver
- 60 GHz MLLD
- 300 GHz transmitters
- 100 GHz modulators
- 12.5 Gb/s Wireless System
- RoF modules for uncompressed HDTV transmission

Besides disseminating the IPHOBAC achievements, the exhibitions have significantly contributed to clarifying customers needs, giving the consortium a more clear impression on the requirements and interest in the IPHOBAC developments. This has guided direct and spin-off exploitation strategies of the IPHOBAC partners. It has also led to the fact, that in some cases, component and system characterizations were performed for demonstrating specific needs requested. The exhibitions have also helped to get new contacts in the addressed market fields.

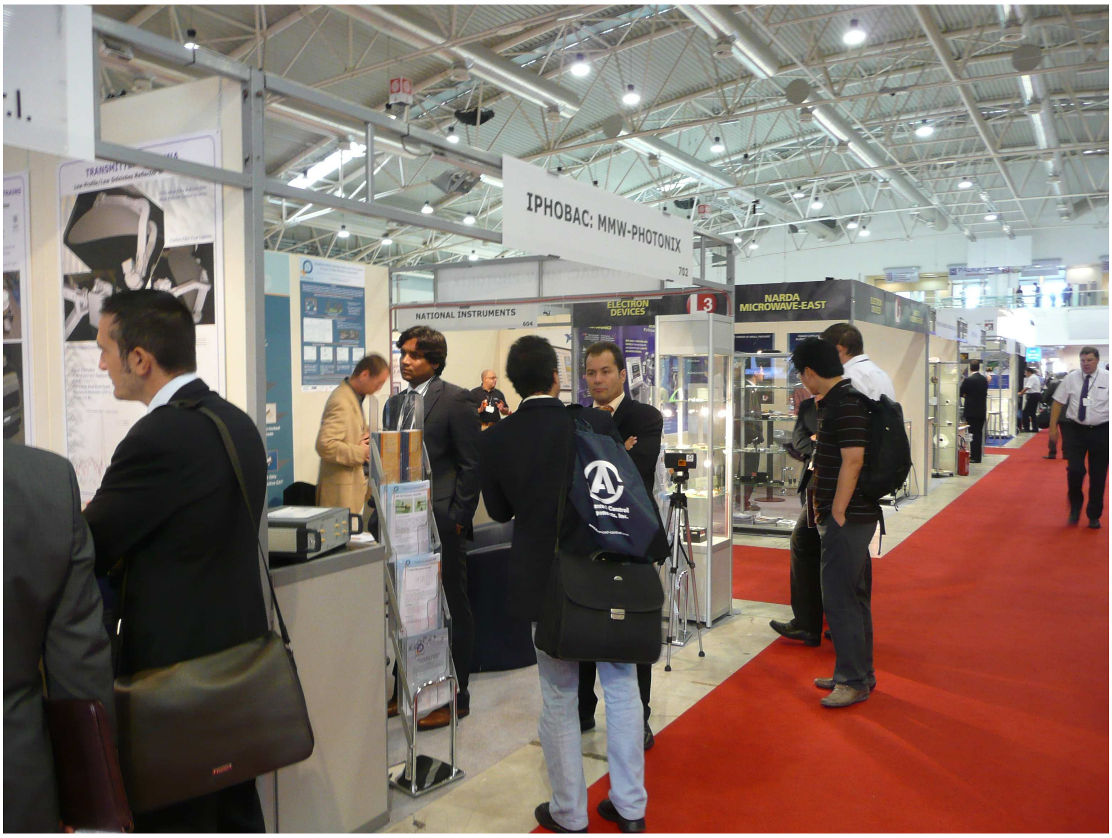


Figure 74 Photo showing the IPHOBAC booth at the European Microwave fair in Rome.

2.5 Demonstrations to external system vendors

The IPHOBAC consortium was build up mostly of partners developing photonic components as well as an operator (France Telecom, FT) and a large company active in the field of security and sensing (Thales Airborne Systems, TAS). Thus, in the telecom area, the consortium was "missing" the link between component-makers and large potential users such as FT. Therefore, to ensure an efficient take-over of the technology developed in the project, it was targeted to demonstrate the IPHOBAC achievements, especially in the telecom area to key European system vendors. The objective was to have at least three meetings with key European system vendors.

In total, the IPHOBAC achievements were discussed and presented to the following external industrial companies (in addition to demonstrations performed at exhibitions and during the IPHOBAC workshop):

- Rohde & Schwarz (October 2007)
- Ericsson (November 2007)
- Malaysia Telecom (February 2008)
- Virgina Diodes Inc. (April 2008)
- INWAVE GmbH (April 2008)
- SIEMENS (July 2008)

- Nokia Siemens Networks (May 2009)
- Alcatel-Lucent Wireless Business Unit (June 2009)
- Nokia Siemens Networks (November 2009)

Basically, it was the aim of these meetings with large infrastructure providers to improve the insight in the real market possibilities offered by the components developed in the project. How realistic were our expectations concerning the market and in particular the time schedule? Which steps are required for a deployment of systems using mm-wave frequencies? What are the views of these companies on the development of standards directly relevant for the use of mm-waves in communication systems? Do these companies have any substantial research on mm-wave based communication systems?

This section summarizes the discussions and the outcomes with these three Telecom infrastructure providers as well with the instrumentation vendor Rohde&Schwarz. Also additional meetings in other application areas are also briefly summarized. Details of these meetings were reported in D732 and D734.

In general, the meetings with European infrastructure provider in the telecom area can be considered as a success. A large amount of useful information had been exchanged and concrete common experiment were identified and carried out. The focus of the meetings with Ericsson (November 2007), Nokia Siemens Network (May 2009 and November 2009) and the Wireless Business Unit of Alcatel-Lucent (June 2009) were focusing on fixed wireless access using high frequencies in the 60 GHz band and in the E-band for multi-gigabit communications. In general, All system vendors expressed their interest in a broadband wireless link and confirmed the project's thesis that those systems will be operating in the mm-waves frequency range. Joint experiments have been planed and carried out, joint collaboration were agreed with some of the external system partners.

In the instrumentation area in the microwave and mm-wave range, one could probably not, strictly speaking, find a system vendor, but Rohde&Schwarz is anyway the leading company in the field. R&S (October 2007) has had an early interest in the IPHOBAC project and there have been a number of discussions for a closer collaboration. Their main interest was on photonic mm-wave generator to extend the frequency range of their product beyond 60 GHz up to 110 GHz without the necessity of electronic up-conversion. Another advantage expressed by R&S was the broadband modulation capabilities of the photonically generated mm-wave signals. R&S was especially interested in providing UWB compatible signals for test and measurement systems.

The key open question at the time of the meeting was in the phase-noise of the generated mm-wave signal. This led to contact INWAVE GmbH, a German based company.

Malaysia Telecom contacted UDE, after they had published the first results on the 12.5 Gb/s photonic wireless system, to discuss about mutual interests in 60 GHz photonic technologies and radio systems and a meeting took place at UDE in February 2008. TM had initiated a new program to develop 60 GHz wireless systems and were mainly interested in the IPHOBAC's 60 GHz photonic technologies for broadband wireless systems. TM was also planning to develop a 10 Gb/s wireless system operating in the 60 GHz range. However, it was unclear how IPHOBAC could benefit from the TM activities not only because TM is located outside Europe but also as developments at TM appeared to be in a rather early stage.

The aim of the meeting was to discuss with Virgina Diodes (VDI), USA on the delivery of special Shottky-detectors for mm-wave system applications, since these detectors exhibit a significantly higher responsivity than products from other competitors. At the time of the meeting (April 2008), there were no Schottky detectors available from any European source that could offer the requested bandwidths. UDE's idea was to setup a compact 60 GHz wireless system demonstrator which was then demonstrated at the ICT2008 exhibition in Lyon. VDI wished to have that meeting to verify that there were no conflicts of interest between IPHOBAC and VDI.

INWAVE (GmbH) is specialized on developing low phase noise and high performance electronic signal sources. Several phone and face-to-face meetings were organized between IPHOBAC and INWAVE, following the recommendation of R&S. Using the frequency doubling and quadrupling schemes with INWAVE's 24 GHz system, UDE achieved a phase noise of about -95 dBc/Hz at 10 kHz offset from the 48 GHz carrier and of about -85 dBc/Hz at 10 kHz offset from the 96 GHz carrier, respectively. Based on these experiments, UDE has developed a novel approach for ultra low-phase noise and tunable photonic mm-wave generation. As an example, a phase noise of -105 dBc/Hz was achieved at 10 kHz offset from a 21 GHz mm-wave signal. Tunability exceeds 1 GHz. An application for patent is being filed.

Siemens is a global powerhouse in electrical engineering and electronics. The meeting between IPHOBAC and Siemens (July 2008) was with the Siemens group on early technological product developments located in Munich. Siemens was especially interested in the 60 GHz photonic wireless experiments that had been carried out by UDE and France Telecom to potentially use it for their trains.

2.6 European workshop

Within the dissemination activities of Task 7.2, an international workshop was planned to be held during the last year of the project. The aim of this workshop was to disseminate the obtained results to an as wide as possible concerned audience. Since cross-project interaction was another target for the dissemination aspect, the idea of upgrading this almost internal workshop to a cross-dissemination event between several European projects was raised. Originally planned to be held jointly with the last project meeting, date and location were fixed to 18 to 20 May, 2009 and Duisburg, respectively. Consequently, IEMN (in charge of Task 7.2) and UDE (as coordinator and local representative) jointly manage the setting-up and progress phases of this event.

10 EU projects were then solicited participating to a joint organization. Not one declined and a steering committee was set involving representatives of these10 projects; these later covered sixth and seventh Framework Program as well as the different European tools: FP7 IP's as ALPHA, OMEGA, FUTON and IPHOBAC for FP6, FP7 NoE's as BONE, EUROFOS and ISIS for FP6, and FP6 STREP's as GIBON, HECTO and UROOF.

The workshop was fully supported by a specific part on IPHOBAC website (Task 7.1) for announcements, registration, paper submissions and all relevant information needed for the participants. This information was also relayed by the websites of the other co-organizing projects.

A two full day workshop program was so defined including 7 technical sessions, among those one was a poster session. One of these sessions was particularly dedicated to the presentations of the global technical achievements that were obtained in each of the 10 co-organizing projects. 52 papers were presented shared into 9 invited, 28 oral and 15 posters.

The workshop was attended by 84 participants of which 62 participants were not members of the IPHOBAC consortium. 21 participants were from industry and 23 were students or young researchers. Concerning the gender action, 14% were female participants.

A full description of this event is made in D722; a summary is given in D723.

IPHOBAC workshop: oral session

IPHOBAC workshop: poster session

We can conclude that this workshop clearly surpasses the original objective that was mainly dedicated to the dissemination of the sole results of IPHOBAC.

2.7 Patents

Two patents / patent applications were issued / filed during the final period.

One patent (SI200900158) was to protect LUB's knowledge and inventions on the novel and innovative high-performance and low-cost PRBS generation. The patent is entitled "Pseudo-random data-generation procedure and apparatus for the procedure realization". The novel design is especially important for the future highest bit-rate communication electronics. For now, we have just applied for the Slovenian patent, in the future we might also go for some EU countries.

A second patent application on a novel approach for an extremely low-phase noise microwave to mm-wave tunable optical source was filed. The patent application is entitled "Frequenzabstimmbarer optischer Mikrowellenoszillator". The aim is to apply for a Germany patent first; in the future we might also go for some other EU countries.

2.8 Press releases

The IPHOBAC consortium has undertaken strong efforts to have its achievements published in press releases. The total number of press releases can not be exactly stated because of the worldwide interest in the project, which has led to more than 100 press releases that can be found by google or other search engines. The project objective was to have three press releases published, thanks to the consortiums efforts, a significantly larger number than the targeted 3 press releases has been issued. Some press releases can be found on the IPHOBAC website, more details can be found in M717.

In the following a few press statements from press releases are listed:

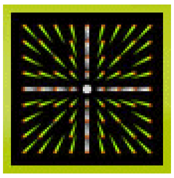
- **IPHOBAC listed among the 10 highlight projects out of the last five years among all disciplines**, European Commission, Research, Communications, Brussels
- **Breakthrough for Post-4G Communications – New Components from Europe**, Science Daily, USA
- **A new Class of InP Photonic Systems**, Compound Semiconductors
- **Commercial success for EU mm-wave research project,** EE Times France
- **EU sees High Speed Networking in Photonics, The Register,** United Kingdom
- **Europe demonstrates Photonic Wireless HDTV Transmission**, Pravda, Russia

- **EHF - a new frontier?**, IKSMEDIA, Russia
- **Fiber Optic Speeds Demonstrated over Wireless**, Policy Tracker, United Kingdom
- **12,5 Gbyte/s – The New Technology of Wireless Data Transmission,** Uzbektelecom International, Uzbek-Indonesian Joint Venture Company
- **While several companies in Japan and the USA have been working on merging optical and radio frequency technologies, IPHOBAC is the world's first fully integrated effort in the field,** The NextBigFuture, USA
- I**PHOBAC taking the Wireless World by Storm, feast,** The European-Australian Science and Technology Cooperation

The following lists a few of the IPHOBAC press releases issued, several press releases published worldwide but especially in Asian countries are not listed – partly due to translations difficulties.

[1] 

Optics & Laser Europe, March 2007

[2] 
Laser 2007 – World of Photonics, June 2007

[3] 

Microwave Journal, September 2007

[4] 
Alumni-Newsletter, December 2007

[5] 

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[9] Duisburg-Essen university Press Office, November 2008

[10] The spectrum management newsletter, January 2009

[11] The Register website, January 2009

[12] 

Ruhr Economic magazine, January 2009

[13] Forte website, January 2009

[14] IKS journal , January 2009

[15] European Research headlines, February 2009

[16] ICT results website, Mach 2009

[17] ORF Futurezone Website, March 2009

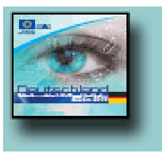
[18] Pravda website, March 2009-11-09

[19] Science Daily website, March 2009

[20] Global news for technology website, March2009

[21] Bild newspaper, July 2009

[22] The spectrum management newsletter, October 2009



[23] European Research center

More than 100 further press releases world wide were found by internet search which have not been listed above.

2.9 Publications and presentations

One major project objective was to achieve European leadership in Microwave Photonics and an effective way of doing so is of course to disseminate the IPHOBAC project results in prime journals and magazines and at prime conferences which are extensively diffused among the technical community. The below listed papers have all been published or are accepted for publication in key refereed journals and at prime conferences with an international evaluation procedure. Further conference, workshop and meeting papers are listed in the next section.

Among the listed publications there are several prime journal publications including invited papers in the IEEE/OSA Journal of Lightwave Technology, IEEE Microwave Techniques and Technology, Journal of Optical Networks, IEEE Microwave Magazin, Optics Letters, and others. With respect to conferences, the project managed to have at least one publication per year in each key conference including ECOC, OFC, MWP, EuMW, MTTS.

It should be further noted that the project has been invited for presenting its results at several key conferences which is also a clear indication about the international awareness of the project and its results.

[1] A. Stöhr and D. Jäger, Photonic mm-Wave and Terahertz Source Technologies, International Topical Meeting on Microwave Photonics 2006, Grenoble, France, 2006 (invited paper)

[2] F. van Dijk, J. Renaudier, F. Lelarge, R. Brenot, B. Rousseau, H. Sillard, O. Legouezigou, F. Poingt, F. Pommereau, G-H. Duan, Passively and Actively Mode-Locked DBR Laser for 34.5 GHz and 69 GHz Signal Generation, Australian Workshop on Microwave Photonics 2006, Melbourne, Australia, 2006

[3] A. Stöhr and D. Jäger, THz-Photomixers – An overview, Millimeter-wave and Terahertz Photonics 2006, Proceedings of the SPIE, vol. 6194, 2006, ISBN 0-8194-6250-0

[4] A. J. Seeds, K. J. Williams, Microwave Photonics, Journal of Lightwave Technology, 24, 12, 4628-4641, 2006 (invited paper)

[5] C. C. Renaud, M. Robertson, D. Rogers, R. Firth, P. J. Cannard, R. Moore, A. J. Seeds, A High Responsivity, Broadband waveguide Uni-Travelling Carrier Photodiode, Photonics Europe 2006, Strasbourg, 2006 (invited paper)

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[9] R. Sambaraju, V. Polo, M.A. Piqueras, J.L. Corral, J. Marti, Generation of 3.6 Gbps 16-QAM 39 GHz mm-wave carrier employing photonic vector modulation, European Conference and Exhibition on Optical Communication, ECOC 2007, Berlin, Germany, 2007

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[11] M. A. Piqueras, V. Polo, J. Marti, Simultaneous Base-band and mm-Wave Delivery of Gbps data Employing Photonic Vector Modulators, OFC 2007, Anaheim, CA, JThA60, 2007

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2.10 Training and education

This activity aimed mainly to support the integration of the young researchers within the scientific community and constituted the master concern of Task 7.2. All partners were involved in that activity either regarding to the young researcher(s) in their own institution or by participating to exchanges.

The young researcher community of IPHOBAC was constituted of 8 PhD and 4 post-doc students. From the beginning of the project an exchange policy was set up in order to foster and support exchanges between partners. As a consequence, 34 of them, almost equally shared on the 3 years of the project, have been recorded on the full project duration; one third of them being relative to young researchers. Longer exchange durations were also recorded for the exchanges involving young researchers. We can also report that there was a nice exchange level between academic and industrial partners since the relative exchange volume is close to 60%. Another indication of the good exchange and interaction level within the project can also be seen from the component/material transfers between partners. Altogether 58 components/material were exchanged.

A student cluster was created on the website grouping different information tools targeting the young researcher community. This student cluster had no restriction on access (open to everyone) but inscription was required. Moreover, it was also open to research staff in order to bring high level background knowledge. Three main tools were proposed:

- an open forum for technical discussions so that young researchers can address their technical problems or questions in order to get some valuable advice or solutions in return.
- a course and tutorial information based on national and European events that occur in the research domains of the project.
- a job opportunities section

A last action was to stimulate young researchers in acquiring new expertise as well as disseminating their results. Participation of young researchers in ISIS, EpixNET and TeraNova project events such as schools and workshops was so made. The young researcher community participated in the dissemination of project results by their major contribution (name in first author position) in 40 items:

- 13 communications in workshops or seminars,
- 27 conference or paper articles have been published.

This gives a mean value of dissemination activity for the young researcher community close to 1 publication or communication per year and per researcher.

The overall and detailed training and education activities of IPHOBAC are described in D723. No real objective on these activities was originally planned. Nevertheless, we can state on a mean value of 3 communications or publications per young researcher which is a rather good report. We also have a mean value of 1 exchange per young researcher; the average duration being somehow close to 1 week.

2.11 Milestones

In the following all project milestones are listed.

M111 First payment from the European Commission

M112 Kick-off meeting and 1st TMC meeting minutes

M113 2nd TMC and 1st GA meeting minutes

M114 Preparation of a competitive call

M115 3rd Technical Committee meeting

M116	Detailed implementation plan for the next 24 month
M117	4th Technical Committee and General Assembly Meeting
M118	5th Technical Committee & General Assembly meeting
M119	IPHOBAC NDA
M120	6th Technical Committee & General Assembly meeting
M121	7th Technical Committee & General Assembly meeting
M122	8th Technical Committee & General Assembly meeting
M123	9th Technical Committee & General Assembly meeting
M124	10th Technical Committee & General Assembly meeting
M211	Definition of End-Users Requirements
M212	Requirements for biomedical applications
M221	Component and system test beds definition
M311	Report on quantum-dot optimization for dual-mode DFB and DBR lasers
M321	Validation of vertical grating in the fabrication process coupling coefficient variation for 10 to 100 per cm
M322	Validation of SSC design and process vertical and horizontal divergence < 10°
M323	Report on SSC designs matched to device technology used within IPHOBAC
M331	Mode-locked DBR lasers with beating linewidth less than 50 kHz at 60 GHz
M332	Mode-locked DBR lasers with beating linewidth less than 10 kHz at 60 GHz, divergence < 10°, and a tuning range of 0.5 GHz
M333	Delivery of one comb generator module for dual-mode source injection locking (to UCL) and delivery of one mode-locked laser module for integration into opto-electronic oscillator (to III-V Lab)
M334	Delivery of two mode-locked laser modules for system demonstration (to FT, TAS and UDE)
M341	Dual-mode DBR laser with tuning range from 20 to 200 GHz
M342	Dual-mode DFB/DBR lasers with tuning range from 10 to 300 GHz, linewidth ~ 1 MHz and divergence < 10°
M343	Delivery of one dual-mode laser module for evaluation in opto-electronic oscillator (to III-V Lab) and for system evaluation (to TAS and UDE)
M411	First ultra-wideband photomixer without antenna fabricated and ready for chip level characterization
M412	Improved output power photomixer without antenna chips fabricated and ready for partners
M413	First antenna integrated photomixer fabricated and ready for chip level characterization
M414	Improved output power antenna integrated photomixer fabricated and ready for partners
M421	First UTC design for 110 GHz packaging fabricated and evaluated for output power capability at 50 GHz. Expected result > 1 mW output power
M422	First UTC design with integrated antenna for 300 GHz package fabricated and evaluated for output power capability at 300 GHz. Expected result >0.1 mW output power

M423	Evaluation of UTC design with spot-size converter. Expected result > 0.4 A/W responsivity
M431	Study of different architectural scenarios for RF distribution and needed specifications
M432	Study the needed specifications for using the TW-EAM as signal generator in an electro-optical network analyzer and simulation and measurements of existing TW-EAMs
M433	Design of an optimized TW-EAM integrated with a DFB laser
M434	Design of package for TW-EAM
M435	Characterization of first batch TW-EAM integrated with laser
M436	Design of second batch TW-EAM integrated with laser
M437	Mask layout completed for 100 GHz reflective-type EAM compatible to U2T w1 PD package
M438	Design of 70 GHz EML with sub-assembly compatible to U2T w1 EML package
M441	Study of different picocell architectural scenarios and needed specifications
M442	Simulation and measurements of existing TW-EAMs as transceiver
M443	Design of an optimized EAT integrated with a SOA
M444	Design of package and design of antenna
M445	Characterization of first batch EAT integrated with SOA
M446	Design of second batch EAT integrated with SOA
M451	First 110 GHz packages for photodetectors fabricated
M461	First packaged 10-300 GHz photomixers
M511	Conceptual Design of Hybrid Motherboards and Daughterboards
M512	Fabrication and assessment of motherboard and daughterboards
M513	Fabrication and assessment of optimized motherboard and daughterboards
M521	Optical microwave filter integrated and evaluated
M522	Evaluation of simultaneous low frequency and high frequency PLL on laser chip
M523	Report on hybrid integrated UTCs with dual-mode laser
M524	Report on full semi integrated tunable high spectral purity mm-wave source
M531	Choice of the PVM/PVdM architectures to be implemented
M532	SOI phase shifter performance optimized by simulations
M533	Choice of two architectures for laboratory demonstration
M534	Prospects towards integration identified
M535	First run of phase-shifter in SOI technology
M536	PVM/PVdM architecture employing IPHOBAC components characterized
M611	First set of demonstrations realized (III-V Lab). Includes setup for system level tests up to 300 GHz
M612	10 Gb/s wireless transmission achieved
M621	First draft of exploitation plan
M631	Inquiry questionnaire to European mm-wave industry filed
M632	More application-oriented inquiry to European mm-wave industry filed

M711	Website updated every month
M712	IPHOBAC Presentation updated every month
M713	10 scientific publications in journals and conferences
M714	1 Press release published
M715	Updated brochure presenting IPHOBAC
M716	30 scientific publications in journals / conferences
M717	3 Press releases published
M731	Action towards at least 2 infrastructure providers
M732	Action towards at least 4 infrastructure providers

2.12 Deliverables

In the following all project delivrables are listed. Those rated public can be received via the website located at www.ist-iphobac.org.

D110	Public IPHOBAC Presentation
D111	Report on 1st General Assembly meeting
D112	1st periodic activity report according to annex II.7.2 including an updated implementation plan for the next 24 months
D113	First periodic management report and first periodic partners according to annex II.7.2
D114	Second periodic activity report according to annex II.7.2 including an updated implementation plan for the next 18 months and an updated plan for using and dissemination of knowledge
D115	Second periodic management report and second periodic report on the distribution between partners according to annex II.7.2
D116	Third periodic activity report according to annex II.7.2 including an updated plan for using and dissemination of knowledge
D117	Final activity report according to annex II.7.2 including the final plan for using and dissemination of knowledge to be submitted after the end of the project
D118	Third periodic management report according to annex II.7.2
D119	Final management report and final report on the distribution between contractors according to annex II.7.2 to be submitted after the end of the project
D211	Definition of End-Users Requirements
D212	Technological component definitions
D221	Report on test method definition and system integration
D222	Report on the impact on the system applications
D223	Report on enhanced solutions and performances
D311	Report on quantum-dot optimization of mode-locked DBR lasers
D321	Report on the building blocks for the fabrication technology
D331	Report on mode-locked DBR lasers (III-V Lab) ready for integration in WP5
D332	Report on the optimization of mode-locked DBR lasers for mm-wave generation
D333	Report on comb generator module characteristics for dual mode injection locking source
D334	Report on mode-locked laser modules for OEO and system evaluation
D341	Report on dual-mode DFB (IEMN) and dual-mode DBR lasers ready for integration in WP5
D342	Report on the optimization of dual-mode DFB/DBR laser for mm-wave generation
D343	Report on dual-mode laser module characteristics for OEO and system evaluation
D411	Report on TW-photomixer design and fabrication process as well as on planar antenna design
D412	Report on the highest operating frequency and highest output power of TW photomixers characterized on chip level. Calibration report of TW-photomixer

D413	Report on simulation results of the planar antennas on a hemispherical lens
D414	Report on design and fabrication of antenna integrated TW-photomixer compliant with end-users requirements and package specifications provided in T4.6
D415	Calibration report of antenna integrated TW-photomixer
D421	UTC design compliant with the end-used requirements
D422	Report on on-chip characterization of first UTC design for 110 GHz package
D423	UTC devices with integrated antenna compliant with end-users and package specifications supplied for 10 GHz to 300 GHz package
D431	First generation TW-EAM integrated with a DFB laser
D432	Supply of characterized 70 GHz EML chips on submount compatible with the U2T w1 EML package
D433	Supply of preliminary characterized reflective type 100 GHz EAM chips compatible to the U2T w1 PD package
D434	Second generation packaged TW-EAM integrated with a DFB laser (KPRC) compatible to U2T w1 EML package
D441	First generation EAT integrated with a SOA
D442	Supply of 2 reflective-type 60 GHz EATs (to FT and UDE) and 1 transmissive EAM (to UPVLC) in V-connectorised modules tested up to 60GHz
D443	Second generation packaged EAT integrated with a SOA and antenna
D451	Report on the design, fabrication and characterization of coaxial 110 GHz package photodetectors
D452	Calibration report of packaged 110 GHz photodetectors
D461	Report on first packages for antenna-integrated photomixers
D462	Calibration report of packaged 300 GHz photomixers
D511	Report on the design of hybrid motherboard and daughterboards
D512	Hybrid integrated mm-wave source ready for assessment
D521	Report on PLL element evaluation (microwave optical laser on chip level) and PLL architecture to be integrated
D522	Report on design of hybrid OPLL
D523	Report on integrated lab trial with chip level devices (III-V Lab) and on low propagation delay OPLL down-converter and loop filter
D524	Report on the advanced digital phase detector with extended input phase range
D525	Provision of integrated low phase noise Opto-Electronic Oscillator for system measurements
D526	Demonstrator with hybrid integration of UTCs and dual-mode lasers (same performances as above) (CIP, UCL) and provision of mm-wave optical synthesizer electronics (LUB)
D527	Full hybrid integrated tunable high spectral purity (< -85 dBc/Hz, 10 kHz offset) locked mm-wave source, 10 GHz to 300 GHz
D531	Report on optimized PVM/PVdM architectures and GbE
D532	Report on optimized phase-shifter design

D533	Report on laboratory demonstration of PVM/PVdM architectures (UPVLC) including a report on the techno-economic comparison to commercially available assemblies
D534	Characterization of phase-shifter in SOI technology
D535	Report on standalone 10 Gb/s PRBS generator with pattern-synchronization output
D611	System experiment with the packaged TW-EAM integrated with a DFB laser
D612	System experiments with the packaged EAT integrated with a SOA and antenna
D613	Report on 10 Gb/s QPSK optically modulated and demodulated wireless transmission employing IPHOBAC photonic components
D614	Report on excellence of IPHOBAC components
D621	First version of exploitation plan as part of the periodic plan for use and dissemination of knowledge according to annex II.7.2
D622	Second version of exploitation plan as part of the periodic plan for use and dissemination of knowledge according to annex II.7.2
D623	Final version of exploitation plan as part of the periodic plan for use and dissemination of knowledge according to annex II.7.2
D631	First report on inquiry to European mm-wave industry
D632	First feasibility report on spin-off companies in the field of micro/mm-wave technology
D633	Final report on inquiry to European mm-wave industry
D634	Final report on feasibility of spin-off companies in the field of micro/mm-wave technology
D635	Final report on inquiry to European mm-wave industry
D711	Architecture and Functions of the IPHOBAC Website
D712	Report on scientific publications of IPHOBAC
D713	Report on the advanced website
D714	Summary report of the scientific publications of IPHOBAC
D721	Report on training activities for the first 18 months
D722	Workshop organized by IPHOBAC
D723	Report on training activities for the complete project
D731	First report on similar R&D programs
D732	First report concerning actions toward infrastructure providers
D733	Final report on similar R&D programs
D734	Final report concerning actions toward infrastructure providers
D741	First report concerning the standardization activities
D742	Final report concerning the standardization activities (FT) including standardization actions in IEEE 802.16

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