Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection

First Intermediate Progress Report

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List of Partners concerned

Partner number	Partner name	Partner short name	Country	Date enter project	Date exit project
1	Karlsruher Institut für Technologie	KIT	Germany	M1	M36
2	INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM VZW	IMEC	Belgium	M1	M36
3	TECHNISCHE UNIVERSITEIT EINDHOVEN	TU/e	Netherlands	M1	M36
4	RESEARCH AND EDUCATION LABORATORY IN INFORMATION TECHNOLOGIES	AIT	Greece	M1	M36
5	UNIVERSITAT DE VALENCIA	UVEG	Spain	M1	M36
6	STMICROELECTRONICS SRL	ST	Italy	M1	M36
7	UNIVERSITEIT GENT	UGent	Belgium	M1	M36

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Deliverable Responsible

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Executive Summary

This document shall incorporate (all) rules procedures concerning the technical and administrative management of the project and is therefore to be updated on a regular basis. Please look at www.navolchi.eu regularly for the latest version.

Change Records

Version	**Date**	**Changes**	**Author**
0.1 (draft)	06/05/2012	Start	Martin Sommer
1 (submission)	08/13/2012		Martin Sommer

INTERMEDIATE PROGRESS REPORT 1

Grant Agreement number: 288869

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Funding Scheme: Collaborative Project

Date of latest version of Annex I against which the assessment will be made:
2011-06-03

Intermediate report: 1st
Period covered: from 2011-11-01 to 2012-07-31

Name, title and organisation of the scientific representative of the project's coordinator[2]:

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Project website[3] address: www.navolchi.eu

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[2] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

[3] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Contents

1 Introduction

The report here present summarizes the results and achievements during the first 9 months of the NAVOLCHI project. It is the first intermediate report out of a list of four major reports during the project:

- First Intermediate Report after 9 months,
- First Periodic Activity Report after 18 months,
- Second Intermediate Report after 27 months and
- Second Periodic Activity Report after 36 months.

Additionally, a final report will follow in the end of the project.

Due to its ’intermediate’ character, this report focuses mainly on the technological and scientifical achievements along the report period. Although following the outline of a periodic report, some parts have been omitted or changed: Contrary to a periodic report, here the ‘Declaration by the scientific representative of the project coordinator’ is not needed and the ‘Publishable summary’ has changed to a simple ‘Summary’. Additionally, no FormCs are prepared, because this is necessary for the periodic and final reports only.

2 Summary

The Project

The NAVOLCHI project explores, develops and demonstrates a novel nano-scale plasmonic chip-to-chip and system-in-package interconnection platform to overcome the bandwidth, foot-print and power consumption limitations of todays electrical and optical interconnect solutions. The technology exploits the ultra-compact dimensions and fast electronic interaction times offered by surface plasmon polaritons to build plasmonic transceivers with a few square-micron footprints and speeds only limited by the RC constants. Key elements developed in this project are monolithically integrated plasmonic lasers, modulators, amplifiers and detectors on a CMOS platform. The transceivers will be interconnected by free space and fiber connect schemes. The plasmonic transceiver concept aims at overcoming the challenges posed by the need for massive parallel interchip communications. Yet, it is more fundamental as the availability of cheap miniaturized transmitters and detectors on a single chip will enable new applications in sensing, biomedical testing and many other fields where masses of lasers and detectors are needed to e.g. analyze samples. Economically, the suggested technology is a viable approach for a massive monolithic integration of optoelectronic functions on Si substrates as it relies to the most part on the standardized processes offered by the silicon industry. In addition, the design and production cost of plasmonic devices are extremely low and with the dimension 100 times smaller over conventional devices they will require much lower energy to transfer data over short ranges of multi-processor cluster systems. The project is disruptive and challenging, but it is clearly within the area of expertise of the consortium. It actually builds on the partners prior state of the art such as the demonstration of the first nano-scale plasmonic pillar laser. This project has the potential to create novel high-impact technologies by taking advantage of the manifold possibilities offered by plasmonic effects.

Project Status

During the first period up to month 9 of the NAVOLCHI project, the analysis of chip to chip interconnect requirements and needs as well as the modelling and beginning of fabrication of plasmonic devices has been of major concern. The plasmonic devices are divided into

- the transmitter and
- the receiver, subdivided into the amplifier and the QD-photodetector.

While the analysis part was handled in WP2, the WPs 3 and 4 deal with the devices. The realization of the optical and electrical interfaces for the plasmonic interconnection platform is focused in WP5. As core tasks in this project, these work packages 2-5 will be discussed in more detail.

Naturally and according to plan, minor activities have been carried out in WP6, which handles characterizing of the devices.

The project is accompanied by the management WP1 and by WP7, which cares for publication and dissemination work.

WP1 (Project Management) Summary

- WEB-Site www.navolchi.eu
- Objectives for this period achieved, no future problems expected

WP2 (Interconnect Specifications) Summary

In the context of WP2, the requirements and needs for chip-to-chip interconnects have been reviewed. Preliminary benchmarking has been performed. In view of the benchmarking review, industrial partner's ST input and all partner's contributions, targeted specifications have been set for the system in order for the plasmonic interconnect to be competitive and, eventually, outperform competing technologies. The future of multicore computing depends on the capability of interconnects to transmit great amounts of data from chip to chip, but electric interconnects are reaching their bandwidth limitations. The need for a chip-to-chip interconnect that can offer great bandwidth in combination with low latency and power consumption has surfaced, as expected. In this context, plasmonics technology appears to be very promising for overcoming the challenges at hand. Optical interconnects with plasmonic transceivers can be smaller than existing conventional photonic systems while retaining the bandwidth capabilities of photonic systems. In addition, initial definitions of the subsystem devices have been set.

WP3 (Plasmonic Transmitter) Summary

- The main objective of WP3 for the reporting period was to investigate via simulations the plasmonic transmitter, which consists of a plasmonic/metallic laser and a plasmonic modulator.
- The modelling of both, a Fabry Perot plasmonic laser and a metallic nanolaser has been carried out.
- A coupling scheme from a plasmonic laser to a dielectric waveguide has been proposed.
- Research on the modelling of the metallic nanolaser will continue in order to improve the performance.
- Fabrication of the metallic nanolaser is expected to be started within the next months.
- Modelling of both, a plasmonic phase modulator and a plasmonic absorption modulator has been performed.
- The fabrication of a plasmonic phase modulator has been started.
- Coupling schemes of plasmonics-Si photonics interfaces have been studied in WP5 between silicon nanowires and metal slot waveguides.
- Milestones 8 and 9 haven been reached in the reported period

WP4 (Plasmonic Receiver) Summary

A large database of Quantum Dot (QD) geometries and compositions (characterized optically) is available to be employed as the gain materials in plasmonic amplifiers. QDs of different types were dispersed in (lithographic) polymers like PMMA and SU8 (ligand exchange is necessary in this case), as the most promising host materials, and optical waveguiding with gain using optical pumping was demonstrated. Electrically pumped nanocrystal light sources based on electric-field excitation have been successfully demonstrated of both visible and near-infrared electroluminescence. This is due to AC electroluminescence by charge tunneling between neighbouring quantum dots. Polymer based symmetric and antisymmetric Insulator-Metal-Insulator (IMI) waveguides (planar geometry) were fabricated and modelled, and found a significant advantage of the first over the second design. Net gain is measured with gain limitations possibly due to Auger processes in QDs. Further advantages in propagation length are foreseen by using ridge IMI waveguides of finite width. We carried out also a modelling and first fabrication for the hybrid silicon-plasmonic amplifier. QDs interact with the optical mode of the waveguide, but losses were larger than expected from simulations. A Layer-by-Layer technology to deposit conducting QD layers for photo-detectors was developed successfully. The internal quantum efficiency can be controlled by the ligands used in this method. A nanocomposite based on conductive polymer in a photolithographic resist has been developed and optimized (maximum conductivity). Metal nanostructures can be dispersed and even in-situ synthesized in such nanocomposite that can be the base of plasmonic photoconductors.

WP5 (Optical and Electrical Interfaces) Summary

WP5 focuses on realizing the optical and electrical interfaces for the plasmonic interconnection platform. In this first period we mainly worked on completing a design for the different interfaces. KIT fully optimized the interface between a silicon wire waveguide and a plasmonic modulator while imec carried out a study for integrating beamshapers on a movable MEMS-platform. STM completed the DDCM (Dual Die Communication Protocol) specification document, starting from the existing STNoC protocol, which will form the electrical/optical interface. During this first period imec also already demonstrated compact filters which fulfil the specified requirements for noise suppression in the receiver.

WP6 (Integration, Characterising and Testing) Summary

Characterisation of active and passive plasmonic devices started at month 7.

WP7 (Exploitation and Dissemination) Summary

Dissemination of ideas and results is of high importance in the project. The partners of NAVOLCHI are top research organizations with proven track records in their field and are very active in disseminating their research results in a worldwide range to scientists, industry and the public. Although it is still early in the project, there is already substantial dissemination action concerning project activities and results. In particular, NAVOLCHI members have already produced 4 quality scientific journal and 17 conference publications. Importantly, a NAVOLCHI workshop has been organized at ICTON 2012 (Warwick, UK) where members presented their initial results and future plans; there was also a presentation from another EU-funded project related to plasmonics, the PLATON project, and there were communication channels established between the two projects. In addition, press releases concerning the start of the project and an advertising brochure have been issued. Finally, the project website (www.navolchi.eu) has been implemented and uploaded online, disseminating the NAVOLCHI activities further.

3 Core of the Report

3.1 Project Objectives for the Period

WP1 (Project Management) Objectives

- Performing common project management tasks
- WEB-site preparation and continuous update,
- Preparation of Project Reference Manual and,
- Project Quality Assurance Manual.

WP2 (Interconnect Specifications) Objectives

- To define optical interconnection system environment and parameters within which the plasmonic devices have to function and that will be used for evaluating its performance with respect to processor to processor communication in data centers;
- Preliminary benchmarking,
- Initial device definitions.

WP3 (Plasmonic Transmitter) Objectives

The main objective of WP3 for the reporting period was to investigate via simulations the plasmonic transmitter. This component consists basically of two devices, which are a plasmonic or metallic laser and a plasmonic modulator, both coupled to a Silicon waveguide. Therefore, the main objectives were to carry out theoretical studies to optimize the performance of the plasmonic/metallic laser and the plasmonic modulator. Concerning the plasmonic modulator, the numerical modelling of a plasmonic phase modulator and the plasmonic absorption modulator, as well as their comparison were performed. First attempts on the fabrication of the modulator are reported. The plasmonics – Si-photonics interface is studied in WP5, where efficient coupling schemes between a silicon nanowire and metal slot waveguides are studied.

The milestones corresponding to WP3 in the reported period are:

- Milestone 8: Decision on an optimized structure for metallic/plasmonic nanolaser and its coupling to Si waveguide,
- Milestone 9: Decision on an optimized structure for plasmonic modulator.

WP4 (Plasmonic Receiver) Objectives

- Synthesis of quantum dots with appropriate optical properties for plasmonic amplifiers,
- Characterisation of gain in QD solutions, waveguides based on polymers doped with QDs and plasmonic amplifier concepts,

- Study of electrical injection schemes,
- Design and first fabrication of plasmonic amplifiers and detectors.

WP5 (Optical and Electrical Interfaces) Objectives

- Design of and decision on optimized coupling scheme of Si waveguide to plasmonic waveguide,
- Design of optical filters for optical receiver,
- Design of beam shapers,
- Design of signal generation module.

WP6 (Integration, Characterising and Testing) Objectives

Characterization and testing of first active and passive plasmonic devices.

WP7 (Exploitation and Dissemination) Objectives

- Dissemination through paper submission to high quality and high impact scientific journals and conferences.
- Organizing workshops on NAVOLCHI technology.
- Supporting cluster and concerted activities in the EC framework program
- Dissemination through the website.
- Dissemination by issuing press releases and brochures.

3.2 Work Progress and Achievements

3.2.1 Work Package 1: Project Management

Please refer to chapter 3.3 for a detailed description of the activities concerning the project management.

3.2.2 Work Package 2: Inter Connect Specifications

This work package investigates the new plasmonic device technology for chip-to-chip interconnection.

General status

The progress of WP2 is on track. All deliverables (namely, D2.1) were completed in time. All milestones (MS 1 and 2) were reached. There are no delays expected in the foreseeable future.

Up to the 1st periodic report of NAVOLCHI, only Task 2.1 has been active (months 1-6) and has been completed successfully. Objectives have been met.

Task 2.1 work progress

(Analysis of chip to chip interconnect requirements and needs (bandwidth, latency, power consumption, noise immunity [M1-M6])

Task 2.1 has been completed successfully. The objective of this task was to define the interconnect system, as well as analyze and understand requirements and needs in terms of bandwidth, latency, and power consumption of chip to chip communication for systems split over more dice, implementing real applications. Initial device definitions were also performed, as did preliminary benchmarking to aid the definitions. The work on the system level was based on prior know-how of partners, review of the interconnect field, and direct input by industrial partner STMicroelectronics. The work on subsystem devices was based on the conclusions of the system report, as well as device leader expertise and research.

System Definition and Requirements

Definition and a detailed analysis of chip-to-chip interconnect requirements has been presented. In addition, an analysis has been presented on the future requirements of silicon devices that will host several processors and memory modules and will require high bandwidth and low latency interconnects. In D2.1, we analyzed the future requirements of high speed interconnects both in systems-on-chip (SoC) and systems-in-packages (SiP). Furthermore, we described the state-of-the-art solutions for these interconnects, such as electrical interconnects and silicon photonics and we discussed the limitations of these solutions.

In particular, it was shown that on-chip performance has been increasing much more rapidly than off-chip communication bandwidth because both on-chip transistor density and clock frequency are increasing faster than off-chip input/output density and frequency. This difference occurs because off-chip bonding and wiring are about two orders of magnitude larger than on-chip wiring: on-chip wiring pitch is on the order of 1 micron, while off-chip wiring and ball-bond pitches are on the order of 100 microns. The performance gap between on-chip and off-chip bandwidth makes off-chip bandwidth a performance bottleneck. Advanced high speed interfaces handle the transfer of large amounts of data between embedded processor cores and main off-chip memories in digital multimedia applications. These approaches support hundreds of Gigabits per second of aggregate I/O bandwidth but they require high power consumption and large chip area occupation.

The advantages of plasmonics for use in such systems have also been presented in D2.1. A communication technology based on plasmonics may allow overcoming the bandwidth, footprint and power consumption limitations of today's electrical and optical interconnect solutions. In terms of bandwidth, plasmonics is as promising as any optical technology by utilizing the properties of light (1000 greater bandwidth than electronics). In terms of footprint, plasmonics are more promising than other optical technology, because in plasmonic devices light can be manipulated in subwavelength scales beating the diffraction limit. Plasmonic devices can be 2 orders of magnitude smaller than conventional photonic devices; thus, plasmonics can bridge the size gap between electronics and photonics and allow for integration in hybrid electronic/plasmonic chips without significant size incompatibility. In addition, the presence of metallic parts in plasmonic geometries allows for the design of structures where both electric currents and optical waves can propagate as signals.

After review of the interconnect field and direct input by industrial partner ST, the targeted specs for the plasmonic interconnect system were set as follows:

- data rate 7.2 Gb/s
- latency < 8.8 ns at 450 MHz
- power consumption ~ tens of pJ/bit or lower

The targeted specs are such that the final product a) fits the systems of industrial partner ST for consumer applications such as Set Top Box, HDTV, etc., and b) is competitive with respect to competing technologies. The targeted system specs were summarized in the last section of Milestone 2.

Preliminary Benchmarking

In addition, some preliminary benchmarking was carried out and the basic operation targets were set for the system specifications. Although NAVOLCHI is a very ambitious project and it is still very early to predict safely whether all desired specifications will be achieved in its time frame, at this point the targeted specs are estimated by partners to be within realism. The preliminary benchmarking has been included in Milestone 2. It was used, along with system considerations, to set the initial desired targets for subsystem device specifications.

Note that the final benchmarking, along with the techno-economic evaluation, will take place in Task 2.4 in the last year of the project, as determined in Annex I of the proposal.

Subsystem considerations

In addition to the system concepts, Task 2.1 also included subsystem considerations, i.e., initial definitions of the devices that will eventually make up the chip-to-chip interconnect transceivers. In this context, partners discussed and then contributed the targeted specs for the devices they are responsible for, under the prerequisites of the system requirements that had been set previously. In addition, open issues were narrowed down and technological decisions were taken. Materials and architectures to be used were set (e.g., gold is going to be the metal material for the amplifier) and the operating wavelength of the devices was narrowed down to the spectral region 1.4-1.55 microns.

Parameter	**Targeted Value**
SOI device layer thickness	220 nm
Silicon waveguide width	500 nm
Plasmonic slot width	50 nm
Distance d	75 nm
Angle θ	36°
Efficiency of a single coupler	87%

Table 1: Example of targeted device specs from milestone 2. Shown are the targeted specs for the waveguide coupler.

The targeted specs for the devices were written down in Milestone 2. However, the work on device definitions is still a work in progress, as described in Annex I of the proposal. Deliverable 2.2 on Device Definitions (due in month 12, namely October 2012) will include the progress on technological decisions and choices on materials and device designs that will take place as research effort continues. Moreover, system simulations will take place in the second year of the project (under Task 2.2) so that the devices specs will converge to the desired system specs.

Task 2.2 Modelling of devices and system for communications applications

The goal of this task, led by AIT, is to give device specifications for the novel disruptive plasmonic Si-photonic devices and its application in the chip-to-chip interconnection environment. . This task starts in month 13.

Task 2.3 Value analysis in terms of cost and green aspects

This task, led by AIT, aims to evaluate the performance of the developed plasmonic devices and chip-to-chip interconnection platform with respect to the physical layer specifications that should be met within the proposed system scenarios from Task 2.1. This task starts in month 25.

Task 2.4 Techno-economical evaluation and benchmarking

This task, led by AIT, has the objective of evaluate and quantify the benefits of splitting a system over more dice (System in Package) with respect to the more traditional approach consisting of having the system in a unique die (System on Chip). This task starts in month 24.

having the system in a unique die (System on Chip). This task starts in month 24.

Task 2.5 VHDL modelling of plasmonic interconnect and CMOS interface circuits

The objective of this task, led by ST, is to model in VHDL both the plasmonic interconnect and the CMOS interface circuits (serializer/deserializer) for interfacing CMOS logic with the interconnect physical layer. This task starts in month 10.

Deliverables in first reporting period (month 1 – month 9)

D2.1 Definition of chip-to-chip interconnection system environment and specification (month 3) – Completed in time.

Upcoming deliverables

D2.2 Definition of plasmonic devices (month 12) – No delay expected

Milestones in first reporting period (month 1 – month 9)

MS 1 Definition of chip-to-chip interconnection system environment and specification (month 3) – Completed in time.

MS 2 Definition of plasmonic devices and material properties for chip-to-chip interconnection (month 6) – Completed with 1 month delay in order to reach consensus and converge to used technologies, as well as in order to include initial benchmarking. This minor delay does not translate to propagating delay for the progress of the project.

Upcoming Milestones

MS 3 Development of a system and device simulation platform (month 18) – No delay expected.

MS 4 Definition Derivation of the interconnection level specification (month 18) – No delay expected.

Use of resources

Use of resources has been according to plan. The table below gives a review of each partners contribution.

Partner	Person months	Main contribution
ST	3	Interconnect system review, contributions to initial device definitions and preliminary benchmarking.
AIT	3	Contribution to interconnect system review, contribution to initial device definitions, preliminary benchmarking.
KIT	1	Contribution to initial device definitions.

UVEG	0.4	Contribution to initial device definitions.

Table 2: Use of resources in work package 2.

3.2.3 Work Package 3: Plasmonic Transmitter

Task 3.1. Modelling of plasmonic laser and its coupling

It is one of the aims of WP3 to develop a plasmonic laser coupled to a silicon waveguide. During the reported period, the design and optimization of a plasmonic laser was carried out. For technological feasibility reasons, the laser was designed to be coupled as a first step to an InP waveguide on a silicon substrate. The coupling to a Si-waveguide will be done in a second stage, by tapering the InP-based waveguide to push the optical mode down to an underlying Si waveguide.

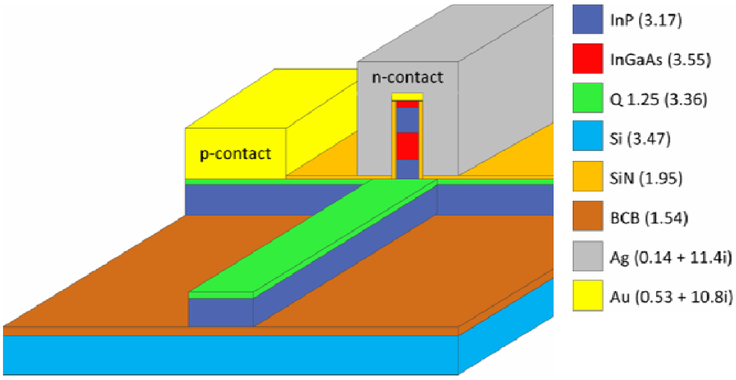


Figure WP3 - 1: Fabry Perot plasmonic laser coupled to a dielectric waveguide. The refractive index of each material at 1,55 µm is shown in parenthesis. Optical absorption in InGaAs has been neglected for the simulations.

Figure WP3 - 2 shows a longitudinal cross section of the laser structure and output waveguide to appreciate the coupling scheme proposed. As it can be seen, a standing wave is formed inside the laser due to the facet reflectivity, whereas part of the power couples into the output waveguide.

The threshold material gain and internal efficiency have been estimated based on rigorous simulations. For example, assuming a laser length of 50 µm and cavity width of 200 nm, a threshold gain of g_{th}=1769 cm^{-1} and internal efficiency of 11% can be obtained, which could be realizable at room temperature under a high injected carrier density above $6\cdot10^{18}$ cm^{-3}. Shorter structures could be more easily realizable at room temperature, however they would require to be wider in order to have a higher confinement factor and lower propagation loss.

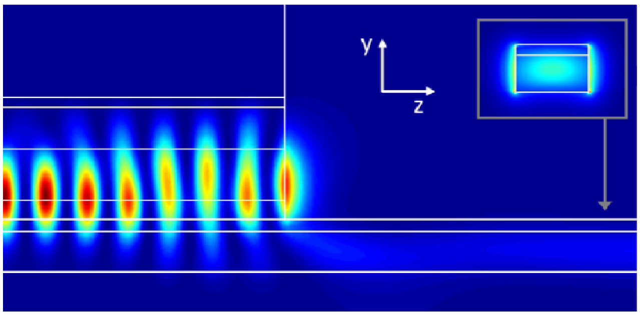


Figure WP3 - 2: Longitudinal cross section showing the coupling between the laser and the dielectric waveguide. The inset shows a transversal cross section of the waveguide. Blue: low intensity. Red: high intensity.

Despite the relatively large propagation loss and low confinement factor, the plasmonic laser structure studied is interesting in view of the high reflectivity at its open facet and coupling to a dielectric waveguide mode. The threshold gain can be compatible with room temperature operation, albeit with a poor efficiency and at high carrier densities. The device length determines the threshold gain required to achieve lasing as it is shown in Figure WP3 - 3, where the external efficiency is also estimated.

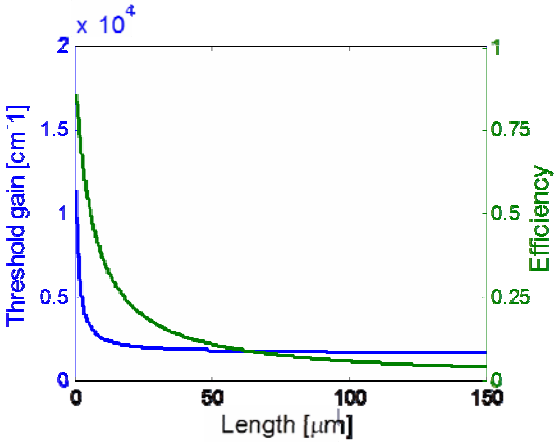


Figure WP3 - 3: Threshold gain and external efficiency of the Fabry Perot plasmonic laser.

At the moment, we are investigating a metallic laser structure that relies on a dielectric mode to achieve high confinement factor and low metal loss. Such a structure is coupled to the output waveguide by evanescent field and preliminary results show that it can be highly efficient compared to the plasmonic laser. For example, in order to achieve the same external efficiency in both, the plasmonic and metallic laser, the metallic laser requires a threshold gain around five times lower and will have a current density of about twenty times higher than the plasmonic laser for the same pumping current, due to its smaller active region. Such structure might offer an overall better performance compared to a plasmonic laser, however further investigations are required.

Task 3.2. Modelling of plasmonic modulator

To understand the performance of the plasmonic modulator as well as to make a decision on its design, detail theoretical and numerical investigations have been carried out on it.

The plasmonic phase modulator has been studied in vertically orientated slot configuration. KIT has developed Matlab code which combined with COMSOL Multiphysics (based on Finite Element Method) gives a possibility to compute important characteristics of the plasmonic modulator such as its propagation length L_θ and the length L_π necessary for having a phase shift of π for the unity applied voltage of 1 V. Simulations show that reducing the metal slot size significantly reduces the length L_π of the device, see Figure WP3 - 4. This is a consequence of both electrical and optical field enhancements in the slot. The plasmonic phase modulator is compared with the previously published Surface Plasmonic Polariton Absorption Modulator. Much lower driving voltage and overall losses have been estimated for the plasmonic phase modulator.

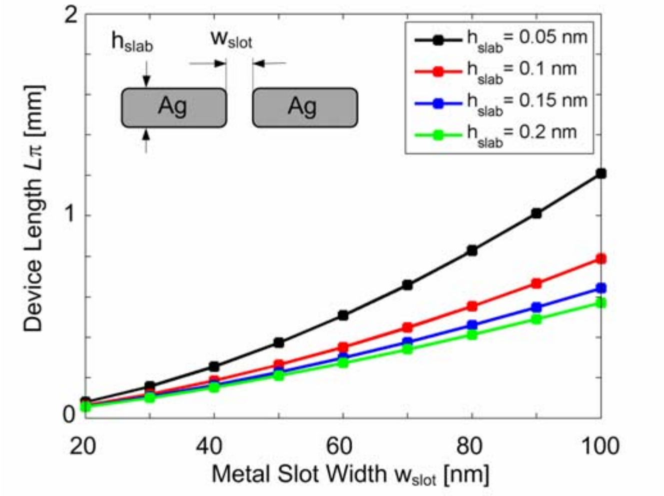


Figure WP3 - 4: Plasmonic modulator length for various metal slot widths w_{slot} and metal heights h_{slab}. The device length is defined as the length necessary for having a phase shift of π for the 1 V applied voltage.

The decision has been made to fabricate the phase modulator with slot widths in the range of 60-100 nm. Because Focused Ion Beam (FIB) milling technique shows less reliability for the fabrication of the plasmonic active devices, decision has been made to use lift-off or dry etching fabrication approaches to design the metal slot. This increases the risks of having difficulties in achieving metal slots width of down to 50nm.

Task 3.4. Fabrication of Si-plasmonic modulators

KIT has made the first attempts to fabricate the plasmonic phase modulator consisting of two metal taper couplers and middle active metal slot waveguide, see Figure WP3 - 5(a). The fabrication makes use of FIB milling technique. Modulators have fabricated with three different lengths of 5 µm, 10 µm, 15 µm and with a metal slot widths of approximately 50 nm, see Figure WP3 - 5(a-c). The fabricated slot widths are not the same because of the uncertainties in the milling process. Using cutback technique the optical losses in these metal slot waveguides has been measured to be approximately 2.6 dB/5 µm, see Figure WP3 - 5. While the FIB technique is good approach for fabrication of ultra-narrow metal slots, it shows less reliability for the fabrication of active devices because of the change in the electrical properties of the device during the milling process which is most likely caused by the Ga-ion implantation.

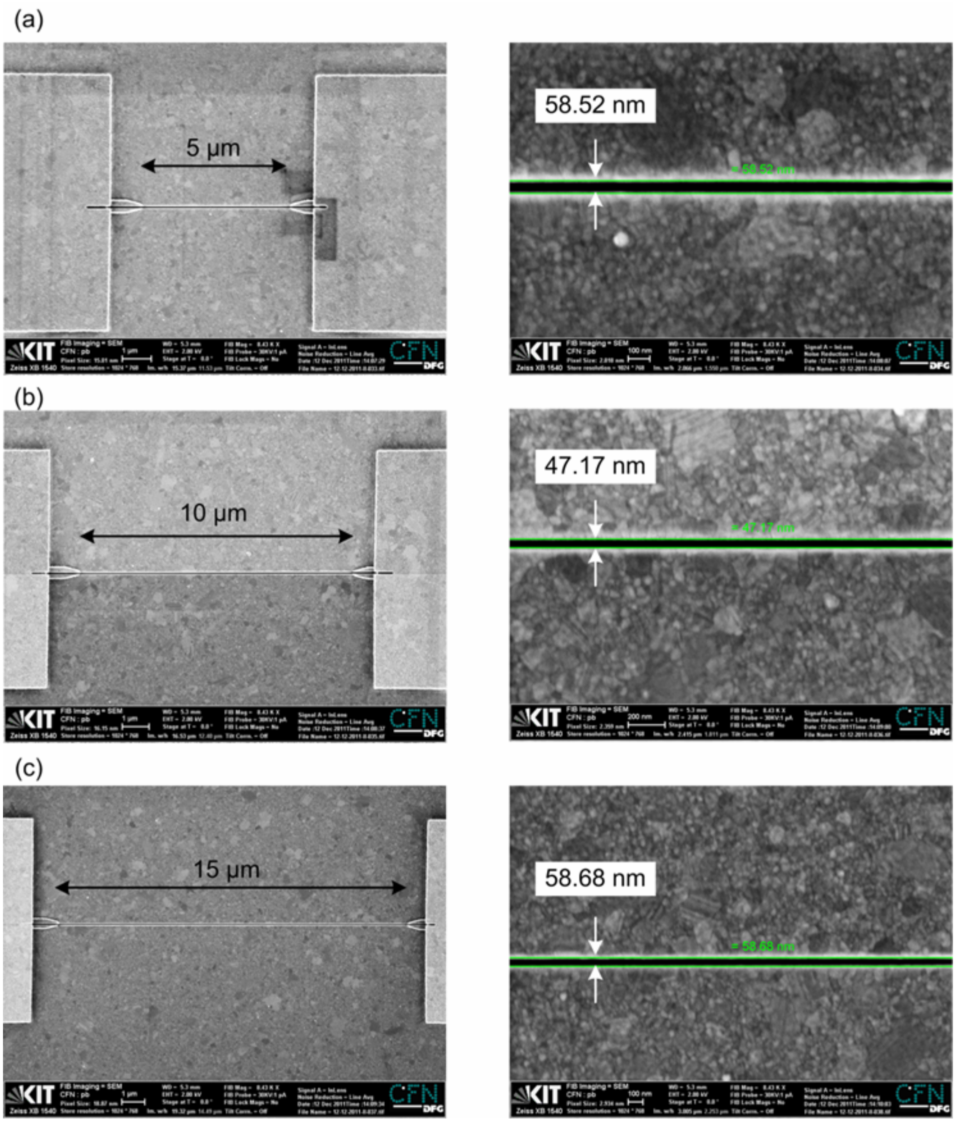


Figure WP3 - 5: SEM images of plasmonic modulators before lift-off. (a) 5 µm device with 58 nm slot width, (b) 10 µm device with 47 nm slot width, (c) 15 µm device with 58 nm slot .

KIT has designed a layout for the SOI chip which has already been fabricated with ePIXfab IMEC10 run. The chips have been successfully fabricated and currently are being post processed at KIT. Process flow has been constructed for the fabrication of plasmonic phase modulator and fabrication steps, such as e-beam lithography, dry etching, metal evaporation, are currently being optimized.

Use of resources

Use of resources has been according to plan. The table below gives a review of each partners contribution.

Partner	**Person months**	**Main contribution**
TU/e	5.6	Modelling, fabrication and characterisation of plasmonic laser.
KIT	4	Modelling of plasmonic modulator

Table 3: Use of resources in work package 3.

3.2.4 Work Package 4: Plasmonic Receiver

Task 4.1 Design and modeling of plasmonic pre-amplifier

a) Polymer based version

Various plasmonic waveguide designs have been modeled, such as:

- 1D asymmetric IMI waveguide (to simulate the PMMA-Au-SiO_2 structure).
- 1D symmetric IMI waveguide (to simulate the PMMA-Au-PMMA and the PMMA-Au-PMMA-SiO_2 structures, when the thickness of the PMMA that separates the metal film and SiO_2 is thick enough.
- 2D rectangular waveguide (to simulate IMI waveguide of finite width).

The above mentioned geometries have been modeled both for the cases when PMMA is doped with QD gain material and when there is no gain. The following methods were utilized for modeling:

- Müller's method for 1D structures,
- Graphical methods in order to ensure that Müller's method converges to the desired mode.
- Finite Difference Frequency Domain (FDFD) method for simulation of 2D structures.
- A modified Effective Index Method (EIM) for 2D geometries.

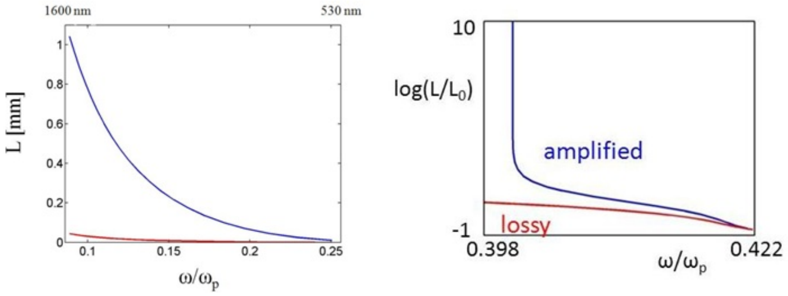


Figure WP4 - 1: (a) Propagation length for the long-range mode in PMMA-Au-PMMA (blue line) and PMMA-Au-SiO_2 (red line) waveguides without gain. (b) Propagation length in PMMA-Au-PMMA waveguide without gain materials (red line) and when gain materials are present (blue line).

Key findings:

- The symmetric IMI waveguide has a significant advantage over the asymmetric IMI waveguide with respect to propagation length (see Figure WP4 - 1 (a)), especially for longer wavelengths.

- The IMI waveguide of finite width presents even bigger advantages with respect to propagation length.
- The effect of gain materials on the propagation length of the SPP for each geometry is under study. For metal thicknesses of 30 nm, a few tens of cm^{-1} layer gain is enough to achieve net gain even for 1D structures, in the spectral regions of visible and telecom frequencies. For example, the PMMA-Au-PMMA waveguide is estimated to present net gain at 1072 nm and for longer wavelengths, when PMMA-layer gain is 20 cm^{-1} (see Figure WP4 - 1 (b)).

b) Hybrid silicon plasmonic amplifier

Figure WP4 - 2 (a) shows a schematic view of the second type of amplifier we proposed. It consists of a silicon waveguide covered with a stack of quantum dots, a low index dielectric layer and a metallic top contact Figure WP4 - 2 (b) shows the TM-like optical mode existing in this structure. A clear enhancement of the optical confinement in the active layer is noticed (e.g. compared to TE-like modes). This structure has been fully modeled and the influence of the geometric parameters on the level of material gain required for reaching a net modal gain has been determined. The structure has also been compared with alternatives such as a MIM structure (larger plasmonic losses but also larger confinement) or a dielectric slot structure (less confinement, lower modal loss). Initial results of this study have been presented at the IPC conference (Washington, 2011).

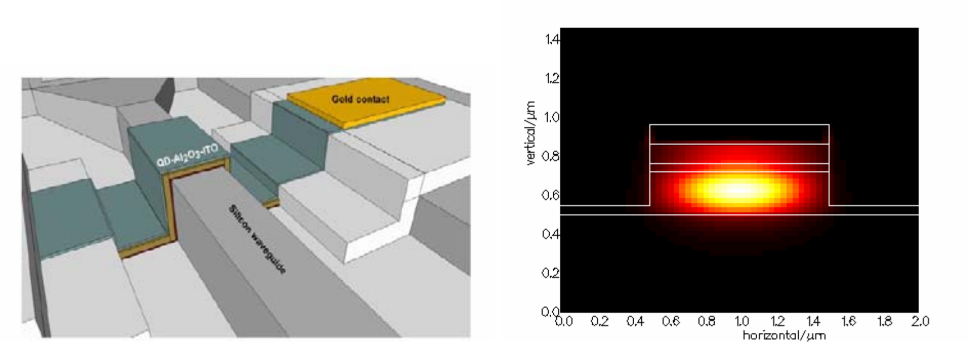


Figure WP4 - 2: a) Schematic of proposed hybrid silicon amplifier. b) Simulation of optical mode in proposed amplifier.

Task 4.2 Modelling of plasmonic QD polymer based photodetectors

No modelling has been undertaken until having basic data on materials: QD based photoconductors/photodetectors and plasmonic-polymer photoconductors. See activities on them below.

Task 4.3 Colloidal quantum dots with optimized gain and electrical injection scheme

a) Synthesis

Cationic exchange: from CdS QRs into PbS QRs:

The initial CdS rods are prepared by a seeded growth method based on Manna et al. procedure. The exchange into PbS rods is done in two steps based on the procedure of Luther et al.

In the first step, CdS rods are mixed with a Cu (I) salt dissolved in methanol. A Cu^{+}:Cd^{2+} excess of 20:1 is used. The reaction is performed inside a nitrogen-filled glovebox at room temperature. After washing the sample, the Cu_2S rods obtained are transformed into PbS rods by injecting a mixture of lead acetate and tri-n- butylphosphine. The final product is washed twice with methanol and stored in toluene under vacuum.

Core/shell PbS/CdS QRs synthesis:

PbS rods are transformed into their subsequent PbS/CdS core/shell by adding cadmium oleate. Cd:Pb 10:1. The reaction takes place at 65°C for 1 hour. The final core/shell is washed twice with methanol and stored in toluene under vacuum.

A similar procedure can be used for different dimensions of CdS rods and for different materials like CdSe rods obtaining PbSe/CdSe core/shell rods.

Figure WP4 - 3 gives an overview of the full procedure. Samples of prepared particles have been delivered to UVEG and imec.

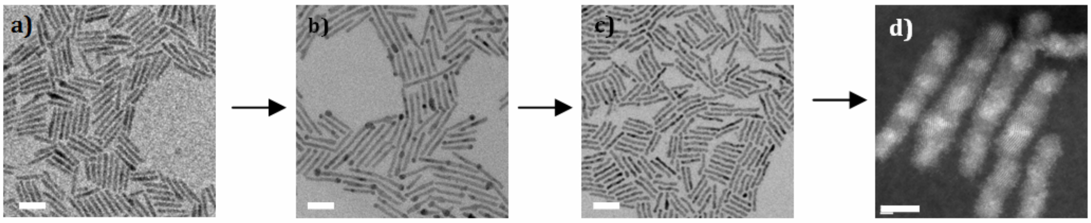


Figure WP4 - 3: TEM overview images of the different steps of the cationic exchange procedure. a) CdS initial rods. Scale bar 20 nm. b) Cu_2S rods. Scale bar 20 nm. c) PbS rods. Scale bar 20 nm. d) PbS/CdS rods. Scale bar 5 nm.

<u>*b) Light absorption by colloidal quantum dot monolayers*</u>

In a device context, nanocrystals will always be deposited in thin layers. However, colloidal nanocrystal properties (e.g. absorption cross sections, exciton lifetime, ...) are typically evaluated in solution using effective medium approaches such as the Maxwell-Garnett (MG) model. These models assume that the nanocrystals behave as uncoupled dipoles embedded in a host medium with a given permittivity. However, it is clear that this assumption no longer holds for a close packed film of nanocrystals where those dipoles tend to couple through electromagnetic multipolar interactions. Using properties measured in solution to evaluate the performance and physics of thin film devices is therefore incorrect, or at least a serious simplification.

An improved description starts from the idea that the internal field of a particle in close proximity to other dipoles will be a superposition of the influence of the external field and the induced dipolar fields of the neighbouring particles. We expect that this type of electromagnetic coupling will increase the absorption cross-section relative to that of the particles in solution. We therefore define an enhancement factor ‘E’, as the ratio between the absorption cross-section of the film and that in solution.

To access the enhancement E experimentally, we measure the absorption spectrum of single and multiple close packed monolayers of nanocrystals on glass substrates using a standard UV-VIS-NIR spectrophotometer. The layers are deposited using Langmuir-Blodgett deposition and are well defined (i.e. particle density and lattice symmetry are uniform over large areas). The enhancement predicted by our intuitive reasoning is substantial, leading to a size-dependent value of E up to 5 for

PbS monolayers. The effect is smaller in CdSe because of the smaller dielectric screening in these materials. The latter probably decreases the influence of a dipole on its neighbours (see Figure WP4 - 4).

Starting from the intuitive coupling idea, we can calculate E from theory as a function of particle size. To achieve this, we use the coupled dipole model (CD model), which was developed to understand the localised plasmonic response of coupled arrays of metallic nanoparticles[3]. We are able to predict the size-dependence of the measured enhancement, both for CdSe and PbS using a limited number of free fitting parameters.

We use monolayers since they are 2D structures that are easy to model in a scalar approach. In a device context (e.g. a solar cell) nanocrystals will be stacked in multiple layers to achieve a certain thickness (e.g. to absorb sunlight). Our model can be extended to predict the behaviour in these technologically very relevant multilayers. It turns out the enhancement is also present in these stacked systems.

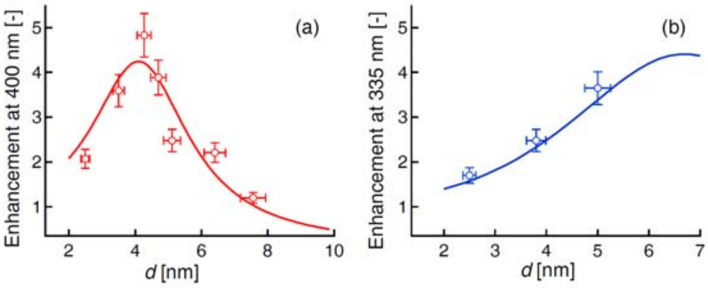


Figure WP4 - 4: Absorption enhancement *E* for (a) PbS quantum dots at 400 nm and (b) CdSe quantum dots at 335 nm as a function of QD diameter. The markers indicate experimental values, while the solid lines represents the enhancement predicted by the coupled dipole model. The horizontal error bars are based on the particle size dispersion, which is typically 5–10%.

c) Gain characterization in solution

In collaboration with the TU Delft (Delft, Netherlands, Prof. A. Houtepen) white-light transient absorption spectroscopy is used to characterize the ultrafast optical properties of the nanorods developed in task 4.3.a. Samples are prepared under nitrogen at band gap optical densities of 0.1. The samples are pumped at 700 nm under varying fluences. Due to the large absorption cross section of the nanorods typical excitation densities are higher than 1 exciton per particle.

A typical near-infrared difference spectrum is shown in Figure WP4 - 5 (a) below. We can distinguish a region of bleach (blue) and of photo-induced absorption (red). Typical picosecond time-scales are indicative of fast multi-exciton decay. Spectral cuts were taken at 3 ps (just after excitation from the pump) and 3 ns. We can see the initial broad bleach band decays to an absorptive background after all multi-excitons have decayed.

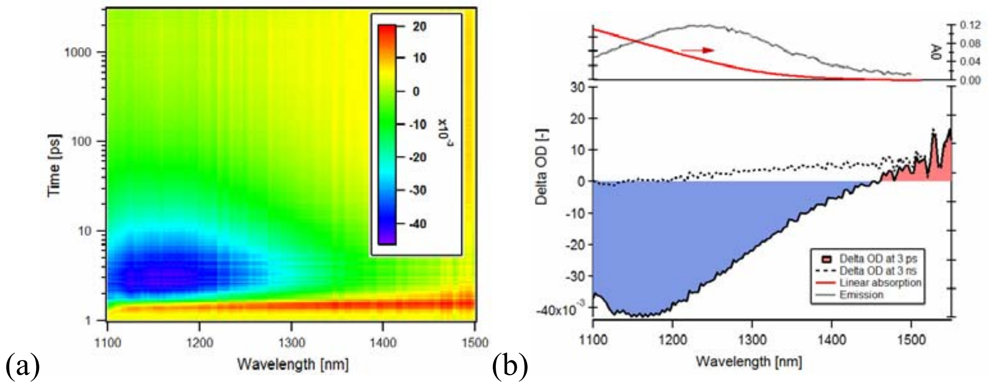


Figure WP4 - 5: (a) differential spectrum as a function of time for 4 x 12 nm nanorods. (b) spectral cuts at 3 ps and 3 ns compared to linear absorption and emission spectrum

Kinetic traces however show a component with a lifetime ~0.3 ns still decaying after the 3 ns time-window of the setup. We are unsure of the nature of this component, measurements are underway to eludicate this as it could be indicative of charging or surface trappig, both limiting the performance of the nanorods in applications.

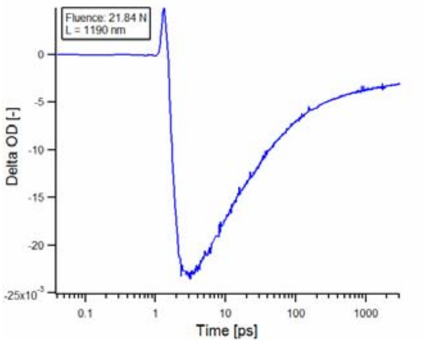


Figure WP4 - 6: Kinetic trace of the band-edge bleach at 1190 nm for an exciton fluence <N> = 21.84.

Pump dependent measurements were performed to estimate the potential for optical gain, i.e. normalized bleach > 1. Due to limitations in both sample stability and pump laser fluence, the exciton density <N> could not be ramped up to full saturation of the band-edge bleach. The maximum percentage obtained is 70%. Higher fluences can be obtained pumping directly with the fundamental light of the laser closer to the band edge absorption. We also hope to avoid any carrier cooling problems, possibly limiting the band edge population and thus the bleach performance.

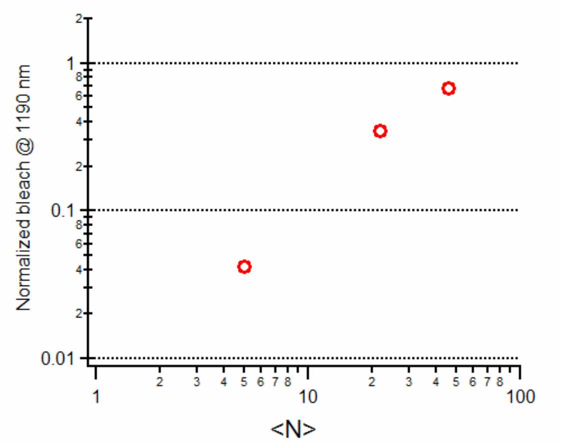


Figure WP4 - 7: Fluence dependent normalized bleach for 4 x 12 nm PbS rods.

Future measurements will focus on near-resonance pumping. Also the comparison with normal 0D PbS dots should be made to estimate any potential profit from the 1D rods.

A large database of sample geometries and compositions is available now (see previous sections) and will also be tested in terms of optical gain performance.

d) Gain characterization in dielectric films

Table 4 summarizes the effective refractive index deduced (Bruggeman's model) for (CdSe-QD)/PMMA nanocomposites with QD filling factors between 10^{-4} and 0.15. With these nancomposites thin films between 1 and 3 µm thick were deposited by spin coating on Si-SiO_2 substrates. Optical waveguiding of emitted light from QDs has been demonstrated for different QD materials (CdS, CdSe, CdTe and PbS). PbS-CdS quantum nanorods have been tested as a material with promising gain properties (see results on prior subtasks 4.3.a-b). Two PbS/PMMA nanocomposites with filling factors 0.008 and 0.04 have been prepared and studied. Absorption losses in planar waveguides are around 6 and 9-21 cm^{-1} for nanocomposites with ff = 0.008 and 0.04, respectively. For a similar nanocomposite using spherical CdSe QDs emitting at 600 nm and ff = 0.008 the absorption losses were close to one order of magnitude higher. However, for both materials (CdSe or PbS) the gain is of the order of the losses (net gain very low) because a gain saturation effect is observed (see Figure WP4 - 8). We have also demonstrated the fabrication of PbS/SU-8 and CdSe/SU-8 ridge waveguides (see basic results summarized in Figure WP4 - 9), as a way to increase the gain as compared to planar structures (still needing optimization of the waveguide parameters and QD filling factor). A ligand exchange of oleate-terminated QDs was necessary to enhance their solubility in γ–butyrolactone.

Filling factor	*n_{eff}'**	*n_{eff}''**	*PL peak (nm)*	*waveguiding*	
				404	*633 nm*
0.15	1.65022	0.02	610	no	no
0.017	1.50618	0.002	610	no	no
1.75e-3	1.49101	2e-4	610	no	yes
4.5e-4	1.48945	9e-5	600	yes	yes
0 (PMMA)	1.489	0	-	yes	yes

Table 4: Properties of a CdSe-PMMA nanocomposite: n' and n'' refer to the real and imaginary part of the effective refractive index (deduced at 600 nm).

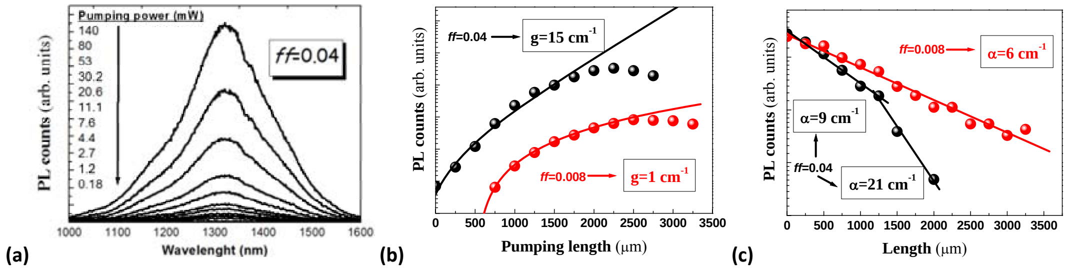


Figure WP4 - 8: Waveguided PL as a function of pumping power (a), gain (b) and losses (c) on PbS-PMMA thin films (as a function of the pumping stripe length).

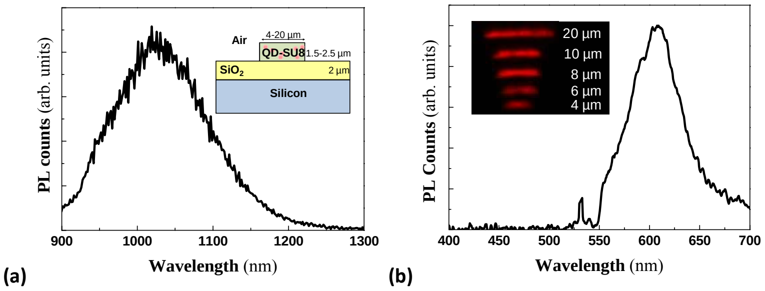


Figure WP4 - 9: Waveguided-PL in CdSe/SU-8 (a) and PbS/SU-8 (b) patterned ridge waveguides 4 to 20 µm wide and 2.5 µm high. The insets on (a) and (b) stand for fabricated structures and end-waveguided PL in several stripes, respectively.

e) Electrical injection

Electrically pumped nanocrystal light sources can be based on direct charge injection or electric-field excitation. The latter technique was explored during the previous months and led to successful demonstration of both visible and near-infrared electroluminescence. The concept of AC electroluminescence relies on charge tunneling between neighbouring quantum dots under internal fields comparable to the band gap of the material as is depicted in Figure WP4 - 10 (right).

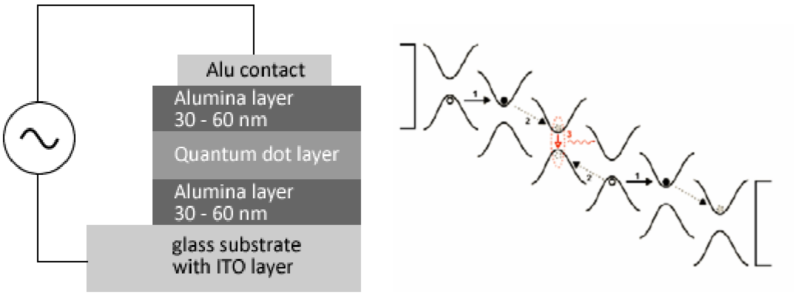


Figure WP4 - 10: (left) Schematic of AC stack with active quantum dot layer sandwiched between two insulating layers (aluminum oxide) deposited using atomic layer deposition and (right) depiction of working mechanism.

Comparing the solution photoluminescence to the electroluminescence under AC excitation, a good agreement is found for visible emitting quantum rods (CdSe/CdS). Plotting the output power as a function of driving frequency and peak-to-peak voltage also indicates the potential of these structures as efficient light sources. For the visible emission, efficiencies of 0.14 lumen/watt were achieved which is comparable to results in literature to state-of-the art direct charge injection based devices.

We believe further improvement of the oxide encapsulation and AC driving mechanism (waveform, frequency, …) can further improve these devices for efficient electroluminescence, both in the visible and the near-infrared.

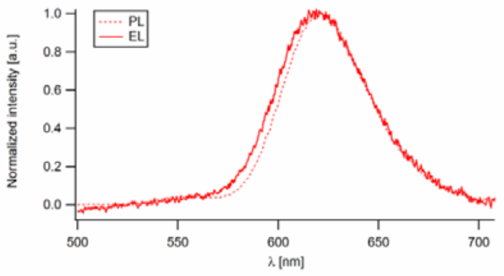


Figure WP4 - 11: PL spectrum of nanocrystals in solution (solid line), overlayed with the electroluminescence (dashed line) under 70 V (peak) AC excitation.

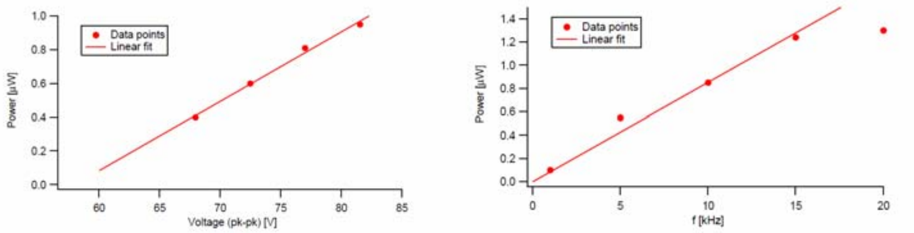


Figure WP4 - 12: Electroluminescent power output as a function of (left) peak-to-peak voltage and (right) AC driving frequency.

To model the structure, a simple RC circuit was put forward. Measuring the admittance of the individual layers allows us to calculate the capacitance of the quantum dot layer. This will allow for further optimization of the total stack to achieve higher power efficiencies. We believe this concept is a good direction to continue as it is compatible with both visible and near-infrared emitting quantum dots and with standard silicon processing technology (no high temperatures are used and oxide deposition is well characterized). Since the proposed mechanism requires no conductive host for the nanocrystals, also the polymer based systems (see Figure WP4 - 12) could be viable candidates for electroluminescent device fabrication.

Task 4.4 Fabrication and characterization of QD-based plasmonic amplifiers

a) Polymer based version

Figure WP4 - 13 shows the gain and losses measured in a plasmonic asymmetric structure design (see Task 4.1) using CdSe QDs as a gain medium. The results correspond to the TM propagating light at 600 nm (emitted light from CdSe QDs pumped at 405 nm). Measured losses in this plasmonic structure are significantly larger than those measured in a similar structure without the Au layer, from 19 cm^{-1} to 86 cm^{-1} (ff = 4·10^{-4} to ff = 0.017). This is may be due to hybrid nature (photonic/plasmonic) of the TM (and TE) propagating mode in this plasmonic structure, hence having the influence of the metal layer losses. A saturation of the gain is also observed (around 110 cm^{-1} for the highest ff), but a net gain is measured that increases with the concentration of CdSe QDs in PMMA, from 0.9 to 27 cm^{-1}. In the case of plasmonic structures using PMMA doped with PbS-CdS nanorods (see Task 4.3) we obtain qualitatively similar results, that is, higher losses than the corresponding dielectric case, but for this material the gain is similar to losses (no net gain is measured). Finally, it is also interesting to note that results obtained in the case of the symmetric structure (Figure WP4 - 14), where the net gain increases significantly from 6 to 30-40 cm^{-1} (for the same ff of the CdSe/PMMA nanocomposite). This is due to the index matching of the dielectric materials cladding the Au layer.

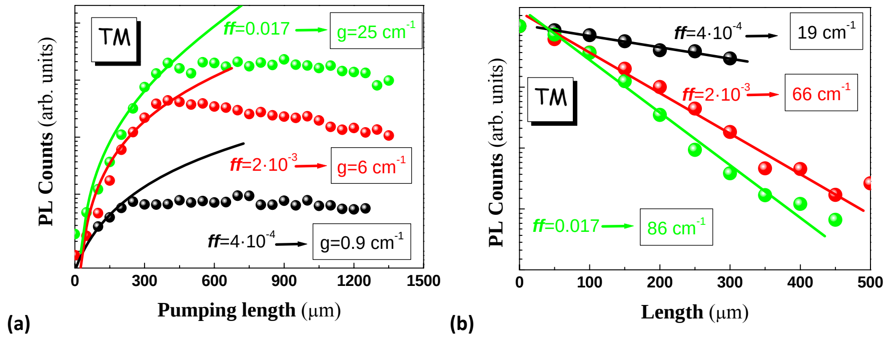


Figure WP4 - 13: Gain (a) and losses (b) on the TM propagation of waveguided PL in an asymmetric plasmonic structure (Au layer on Si-SiO$_2$ covered by a CdSe-QD/PMMA thin film).

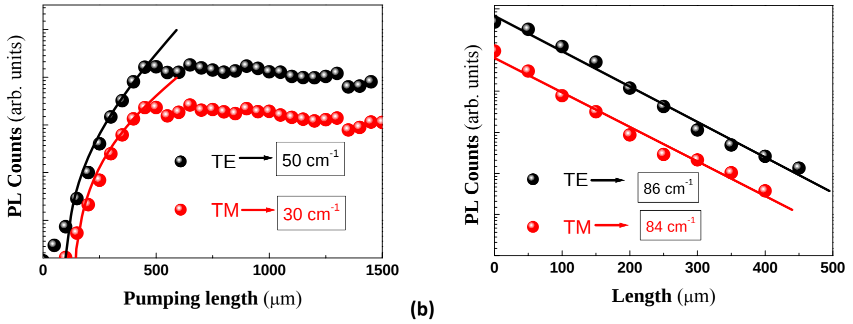


Figure WP4 - 14: Gain (a) and losses (b) on the TM propagation of waveguided PL in a symmetric plasmonic structure (Au layer cladded by CdSe-QD/PMMA thin films).

b) Hybrid silicon version

We carried out also a first fabrication run for the hybrid silicon-plasmonic amplifier (discussed in task 4.1b). Figure WP4 - 15 (a) shows a cross-section of a fabricated device. We deposited nanocrystals through spincoating on standard SOI waveguides. Alumina and ITO were used to complete the stack. Passive loss measurements were performed to confirm that the quantum dots have an influence on the optical properties of the stack. Figure WP4 - 15 (b) depicts the power transmission difference between waveguides with and without quantum dots (before deposition of the ITO film) . We clearly see an effect of the quantum dots which means that they interact with the optical mode of the waveguide. However after depositing the AlOx layer and ITO layer we see a much larger increase in loss than expected from the simulations. From the cross-section in Figure WP4 - 15 (a) we see that the AlO_x layer is much smaller (<5 nm) than anticipated (>50 nm). This is apparently due to a delayed onset in the ALD-deposition process, which is now being investigated further. The thin AlO_x layer can explain the higher than expected losses. New devices are in preparation now, where we will take the delayed onset into account. In the next step we will then aim at obtaining electroluminescence from integrated stacks.

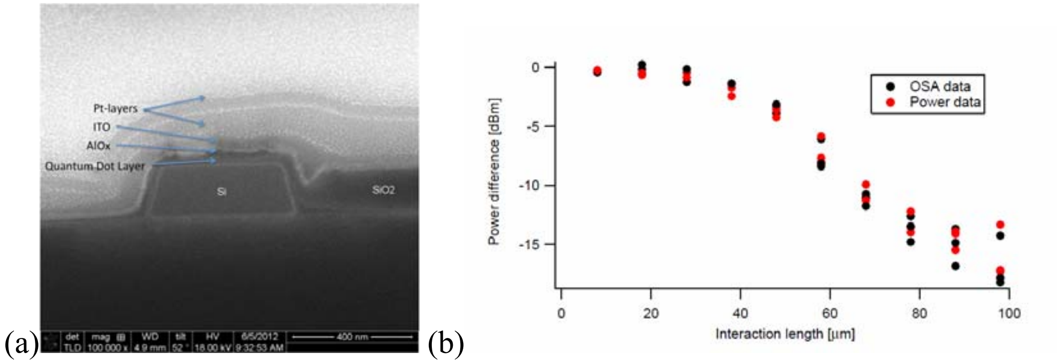
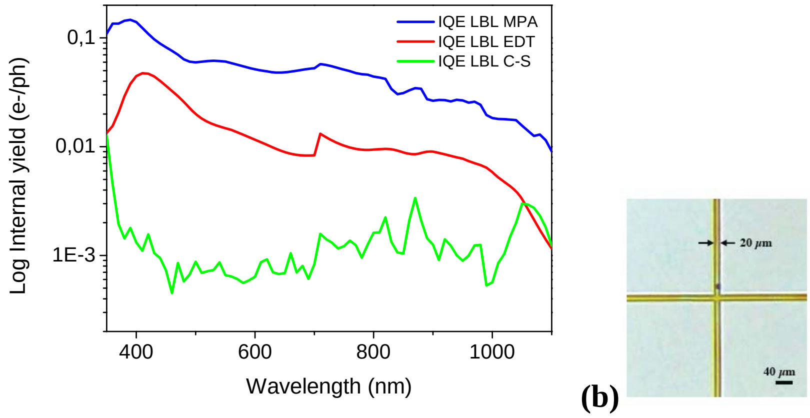


Figure WP4 - 15: (a) Cross-section of hybrid slicon-plasmonic amplifier and (b) passive loss measurements on integrated samples.

Task 4.5 Fabrication of plamsonic polymer QD based photodetectors

a) Layers of IV-VI QDs

The spacing between individual QDs is controlled by the length of the organic ligands used to passivate their surfaces and has been shown to be a determinant factor in the conductivity of QD films. We have developed the synthesis of PbS spherical QDs with two different sizes exhibiting excitonic peaks at around 900 and 1500 nm and exhibiting good air and light stability. The QD films are prepared by using the layer-by-layer (LBL) deposition technique of colloidal QD films, which has been recently proposed to be the base of photodetectors and solar cells. We have used new short ligands to displace the original long and insulating ligands (oleylamine in our case, 2 nm long), in order to enable improved electron and hole transport. Here, three different bidentate ligands have been investigated: ethanedithiol (EDT), 3-mercaptopropionic acid (MPA) and oxalic acid (OA). An important increase of the internal quantum efficiency (IQE) in the case of the MPA-capped PbS QD film is measured in comparison to EDT- and oxalic acid-capped PbS films as observed in Figure WP4 - 16 (a). This IQE difference is consistent with the measured dark conductivity of the layers: $5\cdot10^7$ and $8\cdot10^8$ Ωcm for MPA and EDT based layers, respectively.



(a) **(b)**

Figure WP4 - 16: (a) Quantum efficiency for various ligands used in the LbL method: MPA (blue curve), EDT (red curve) and OA (green curve); (b) Feature patterned by using a PCP.

b) Optimization of patternable conductive polymers (PCP)

We have optimized the in-situ polymerization of 3T with $Cu(ClO_4)_2$ inside several host polymers. Particularly, Novolak photoresist was properly formulated to preserve as far as possible its negative lithographic characteristics and generate conductive (10^{-2} S/cm) micropatterns by means of UV lithography, as shown in Figure WP4 - 16 (b).

c) Plasmonic PCP

In this case, we have developed the synthesis in-situ of the PCP and Au nanoparticles, simultaneously, even if they can be dispersed by using appropriate solvents (and ligand exchange if necessary, as was proved to disperse QDs in the SU-8 resist). Thus, we can combine the conductive and lithographic properties of the IPN composite with plasmonics. Similarly to the case of the PCP explained above, now the metal salt is able to reduce the monomer enabling the generation of polytertiophene. Simultaneously, the reduction of Au(III) to Au(0) produces metal NPs inside the IPN. The conductivity of the composite increases as a function of the Au concentration, since a higher polymerization degree is reached, and the molar ratio $3T/HAuCl_4$ determines conductivity values between $2\cdot10^{-3}$ to 0.5 S/cm.

Status deliverables and milestones

There were no deliverables and milestones in the current reporting period. There are a few upcoming milestones however:

MS16	Demonstration of decision on optimized structures for plasmonic amplifiers	4	UVEG	12	10/2012
MS17	Synthesis of nanoparticles with gain at 1550 nm	4	Ugent	12	10/2012
MS18	Demonstration of conductive QD layers with photoconductive properties	4	UVEG	15	01/2013
MS19	Demonstration of metal-(lithographic) polymer and QD metal-(lithographic) polymer nanocompo-sites	4	UVEG	15	01/2013

Comments on upcoming milestones:

MS16: Optimized structure is under design and will be reported in time.

MS17: This was considered as one of the most risky tasks of the project. Measurements at UVEG of UGent synthesized particles seem to provide optical gain. This has to be confirmed further.

MS18: Promising results have been obtained by using the LBL method in air and appropriate ligands.

MS19: We have optimized the synthesis of conductive polymers in other polymer matrices (IPN strategy), including commercial photolithographic resists. The electro-optical properties of such a nancomposite (PCP) after adding Au-nanoparticles are now under investigation.

Use of resources

Use of resources has been according to plan. The table below gives a review of each partners contribution.

Partner	**Person months**	**Main contribution**
UVEG	10.6	Fabrication and characterisation of polymer plasmonic amplifiers, study of quantum dot detectors
UGent	7	Synthesis of colloidal nanoparticles, fundamental particles properties characterization, study of electrical injection
IMEC	4	Fabrication and characterization of silicon hybrid plasmonic amplifier, study of electrical injection
KIT	1	Modelling of plasmonic photodetector
AIT	4.5	Modelling of polymer plasmonic waveguides

Table 5: Use of resources in work package 4.

3.2.5 Work Package 5: Optical and Electrical Interfaces

Task 5.1 Modelling and fabrication of coupling Si waveguide to plasmonic waveguide

KIT is theoretically investigating two coupling schemes between silicon (Si) nanowires and metal slot waveguides (MSW) with vertically and horizontally oriented slots, respectively, see Figure WP5 - 1. Depending on the polarization of photonic mode in Si-nanowire and MSW's slot orientation appropriate coupling scheme should be selected.

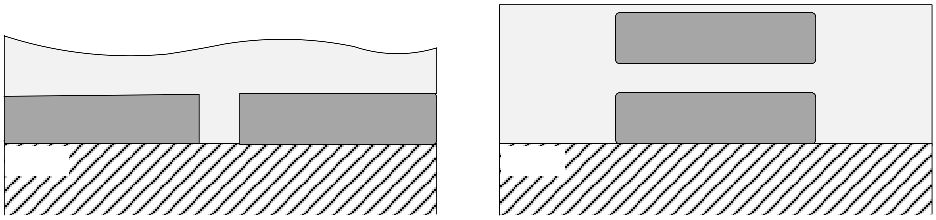


Figure WP5 - 1: Two configurations of metal slot waveguides. (a) Vertical slot and (b) horizontal slot

Tapered Coupler: Commercially available CST Microwave Studio (based on Finite Integration Technique (FIT)) electromagnetic simulator has been used for investigating metal tapered couplers for the excitation with the quasi-TE photonic mode of Si nanowires with 220 nm height. The optimum geometry has been found for various MSW slot widths as well as for various refractive indices of material within the slot. *3D FIT simulations show less than 1dB (equivalent to the 80% transmission on the graph) coupling loss for 50, 80 and 100 nm of metal slot widths, see* Figure WP5 - 2.

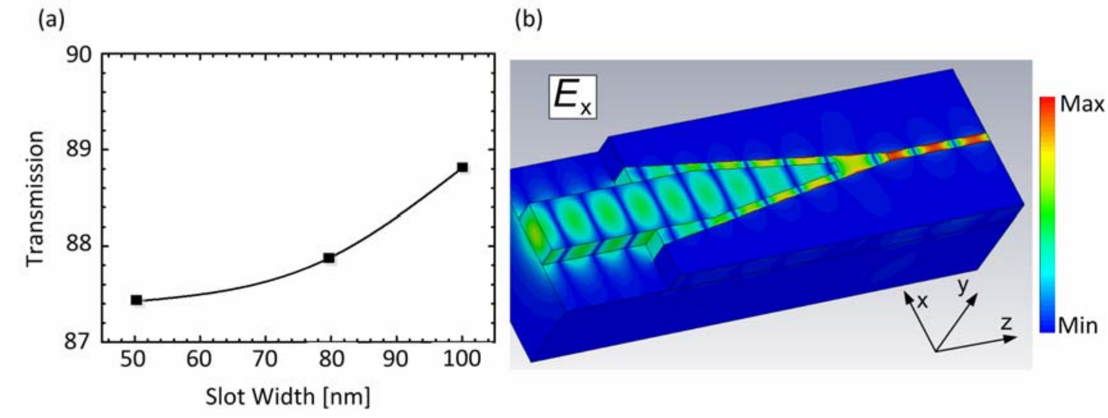


Figure WP5 - 2: Light transmission to the metal slot waveguide and the field distribution in the structure. (a) Optimized transmissions through the coupler for various metal slot widths of 50 nm, 80 nm and 100 nm. Transmission is defined as the ratio between transmitted to the metal slot and launch powers. (b) Electric field distribution in the structure. Light propagates from left to right.

First attempts have been carried out on the fabrication of the metal tapered coupler on 220 nm SOI photonic chip fabricated with an ePIXfab run. *The fabrication approach makes use of the focused ion beam (FIB) milling technique to fabricate couplers for MSWs with a slot width of ≈50 nm. The coupling coefficient of 12.5 dB* has been measured with the cutback technique. Large deviation from the theoretical values is because of the fabrication imperfections in FIB technique. FIT simulations show 5.3 dB coupling loss for the realistic couplers fabricated with FIB.

Side Coupler: Second coupling scheme is being currently investigated with an own developed Matlab code combined with COMSOL Multiphysics.

Task 5.2 Design and fabrication of Si beam shaper

The original goal of this task was to design focusing grating couplers that allow coupling of light between two distinct chip surfaces in a static way. In this first period however we evaluated the possibility of shifting the focus of this task to the realization of dynamic (steerable) grating couplers that will allow to build reconfigurable interconnections. The principle is illustrated in Figure WP5 - 3 (a). A standard silicon grating coupler (which allows to couple light from the waveguide upwards) is integrated on a movable platform. The latter is formed by underetching the grating coupler so that it hangs free on 3 S-shaped hinges. Electrodes on each side of the platform allow to tilt the grating coupler in 3 independent directions as illustrated in Figure WP5 - 3 (b) (for back electrode activiation). The first measurement results in Figure WP5 - 3 (c) do show that the grating coupler can be tilted. However, the tilt is smaller than expected and not entirely controllable in direction at this moment. Therefore a second design and fabrication cycle with optimized devices is currently being undertaken.

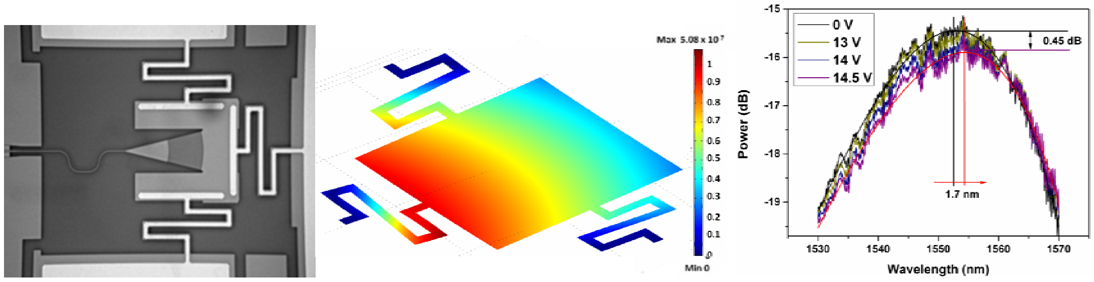


Figure WP5 - 3: a) SEM picture of reconfigurable beam steerer b) Electro-mechanical simulation of device. c) First characterisation results

Task 5.3 Design and fabrication of passive ultra-compact components as filters

The goal of this task is to develop a passive filter to suppress noise inserted by the receiver pre-amplifier. The targeted device performance is: <3 nm bandwidth – >30 nm FSR – >10 dB crosstalk suppression. According to the original work plan this device would be designed by month 12 and fabricated by month 18. However, we already completed a first design cycle within this first reporting period. The results are shown in Figure WP5 - 4. We focused on an AWG-type filter, which provides multiple channel filtering at once (in this case 10 channels). otal size was 370x330 µm^2, orders of magnitude smaller than currently commercially available devices. FSR (42 nm), crosstalk (-22 dB) and losses (0.9 dB) were all better than the targeted specs for this device. The 3 dB (10 dB)-bandwidth was 1.75 (3.19) nm. System simulations in WP6 have to show if this is a practical value.

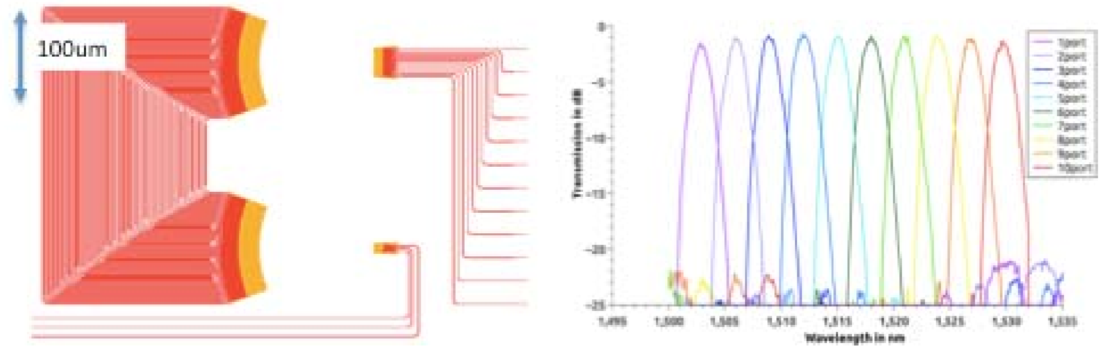


Figure WP5 - 4: a) Device layout and b) performance of receiver filter

Following completion of this first set of devices, we now also designed ring resonator based filters. These have the advantage of being much more compact than the AWG-filter. The challenge however is to reach a sufficiently large FSR and bandwidth, while keeping the losses acceptable. A range of designs with different parameters (e.g. : R = 2 µm, Lc = [0, 2, 5] µm, FSR = [47, 36, 26.6] nm, R = 3 µm, Lc = [0, 2, 5] µm, FSR = [31.8, 26.2, 20] nm). The expected 3 dB bandwidth for these devices varies from 0.1 nm to 1.5 nm (Lorentzian response). Figure WP5 - 5 shows an excerpt from the mask file. Devices are currently under fabrication.

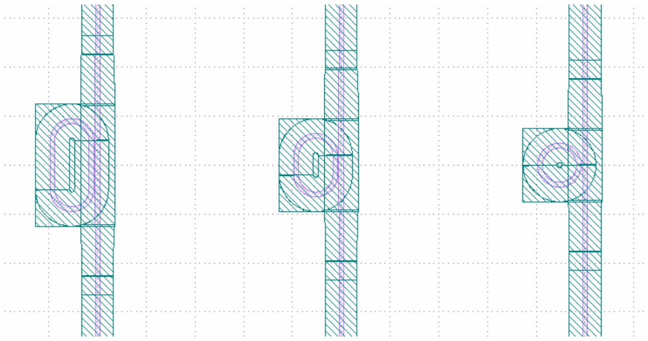


Figure WP5 - 5: Excerpt from mask file for compact optical filters (second generation – ring resonator based)

Task 5.4 Signal generation module design

The signal generation module, called **Dual Die Communication Module** (abbreviated **DDCM**) or alternatively **Inter Dice Network Plug** (**IDN Plug**) from a system point of view, is the building-block responsible for the interconnection of different dice within a so called Network in Package (NiP), the communication system enabling inter dice data transmission in the context of Systems in Package (SiP) technology.

According to a widely used approach, as shown in next figure the DDCM is considered composed of two main building blocks:

- the **DDCM controller**, responsible for managing incoming/outgoing STNoC traffic and IDN segments, generating them through STNoC flits encapsulation and preparing them to be sent to the PHY transmitter, as well as collecting them from the PHY receiver;
- the **DDCM PHY**, responsible for transmitting output phyts across the physical link and collecting inputs phyts from the physical link.

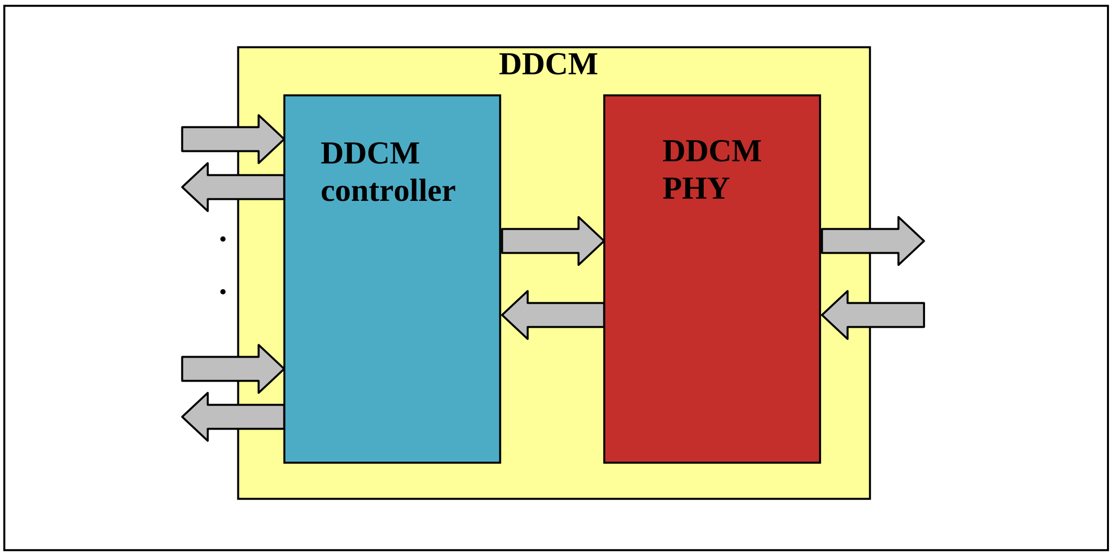


Figure WP5 - 6: DDCM top level structure

The DDCM is a parametric design that, depending on the SoC where it is used, can be configured properly in order to meet system requirements and needs in terms of interfaces, FIFOs sizes, clock domains synchronization and functionality.

The DDCM is also programmable in terms of some functionalities, in particular layer A (PHY adapter, PHY) operation and routing (virtual channels), trough a set of registers. QoS management is also planned to be configurable via registers.

From an architectural point of view the DDCM top level in each die consists of a transmitter (DDCM Tx) and a receiver (DDCM Rx).

In next figure it’s possible to see the two information flows supported by a complete DDCM architecture, i.e.

- requests from STNoC/STBus/AMBA-AXI initiators in chip 1 to STNoC/STBus/AMBA-AXI targets in chip 2, responses from STNoC/STBus/AMBA-AXI targets in chip 2 to STNoC/STBus/AMBA-AXI initiators in chip 1, virtual wires from chip 1 to chip 2 (continuous lines);
- requests from STNoC/STBus/AMBA-AXI initiators in chip 2 to STNoC/STBus/AMBA-AXI targets in chip 1, responses from STNoC/STBus/AMBA-AXI targets in chip 1 to STNoC/STBus/AMBA-AXI initiators in chip 2, virtual wires from chip 2 to chip 1 (dotted lines).

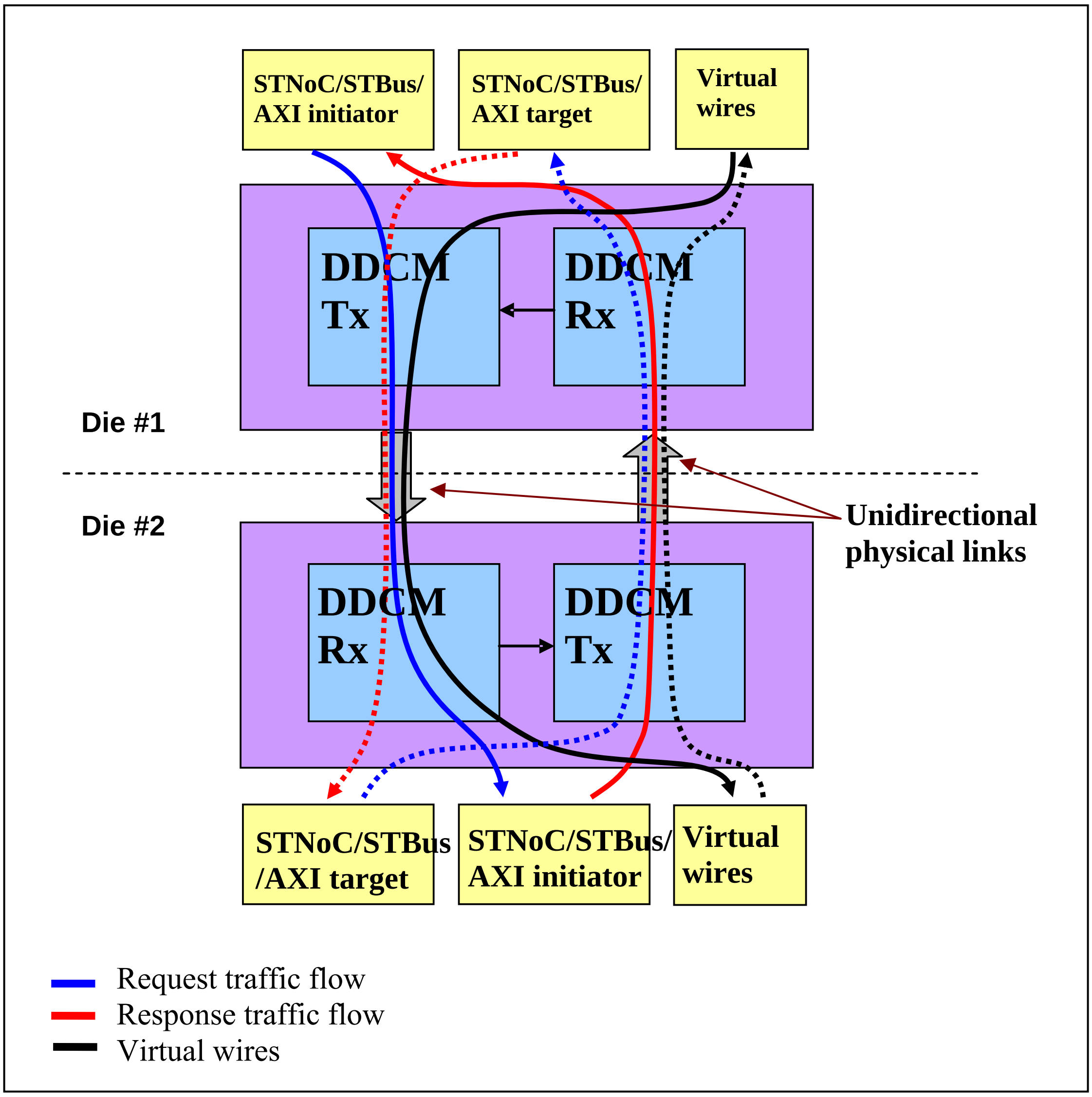


Figure WP5 - 7:

The DDCM transmitter (DDCM Tx) is responsible for

- receiving requests from STNoC/STBus/AMBA-AXI initiators in the same die and sending them to STNoC/STBus/AMBA-AXI targets in the other die;
- receiving responses from STNoC/STBus/AMBA-AXI targets in the same die and sending them to STNoC/STBus/AMBA-AXI initiators in the other die;
- sampling ancillary signals (virtual wires) generated in the same die at a specified rate and sending samples to the other die.

The DDCM receiver (DDCM Rx) is responsible for

- receiving requests from STNoC/STBus/AMBA-AXI initiators in the other die and sending them to STNoC/STBus/AMBA-AXI targets in the same die;
- receiving responses from STNoC/STBus/AMBA-AXI targets in the other die and sending them to STNoC/STBus/AMBA-AXI initiators in the same die;

- receiving ancillary signals samples generated in the other die and sending them to the proper destination in the same die.

Next figure shows a full architectural view of an DDCM, highlighting the separation between an DDCM transmitter and an DDCM receiver.

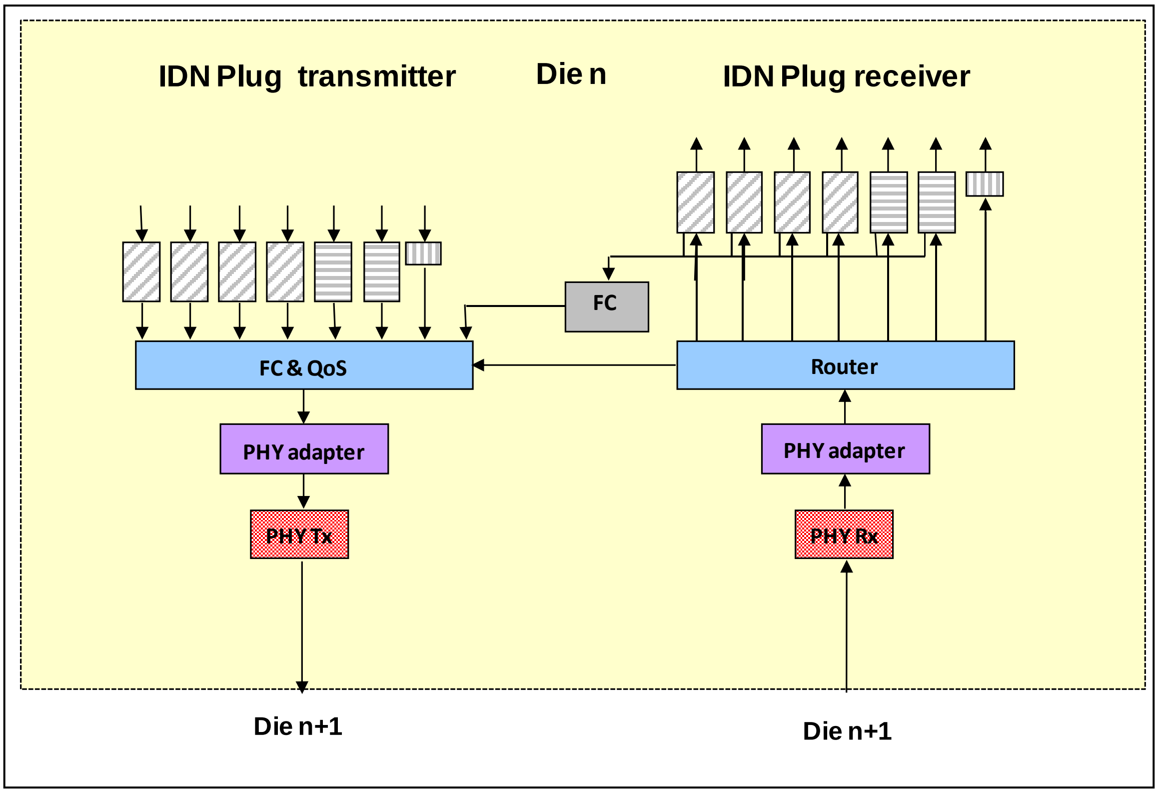


Figure WP5 - 8:

Next figure shows the architecture of the DDCM highlighting the connections with initiators and targets across an STNoC interconnect. In this picture it’s possible to see clearly how request and response traffic streams flow.

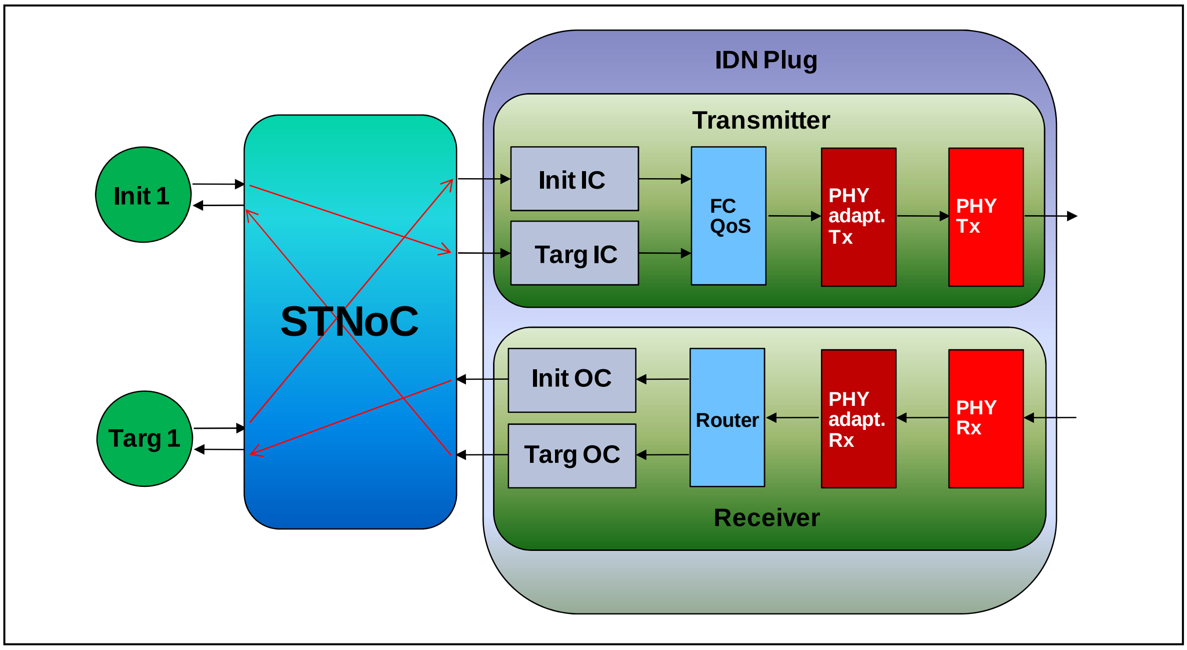


Figure WP5 - 9:

The figure below shows the connection and the traffic streams flows between two dice, highlighting the two DDCMs architectures and their crossing. Specifically, the orange line represents the request traffic stream flowing from initiator 1 in die #1 towards target 2 in die #2, while the yellow line represents the response traffic stream flowing from target 2 in die #2 towards initiator 1 in die #1.

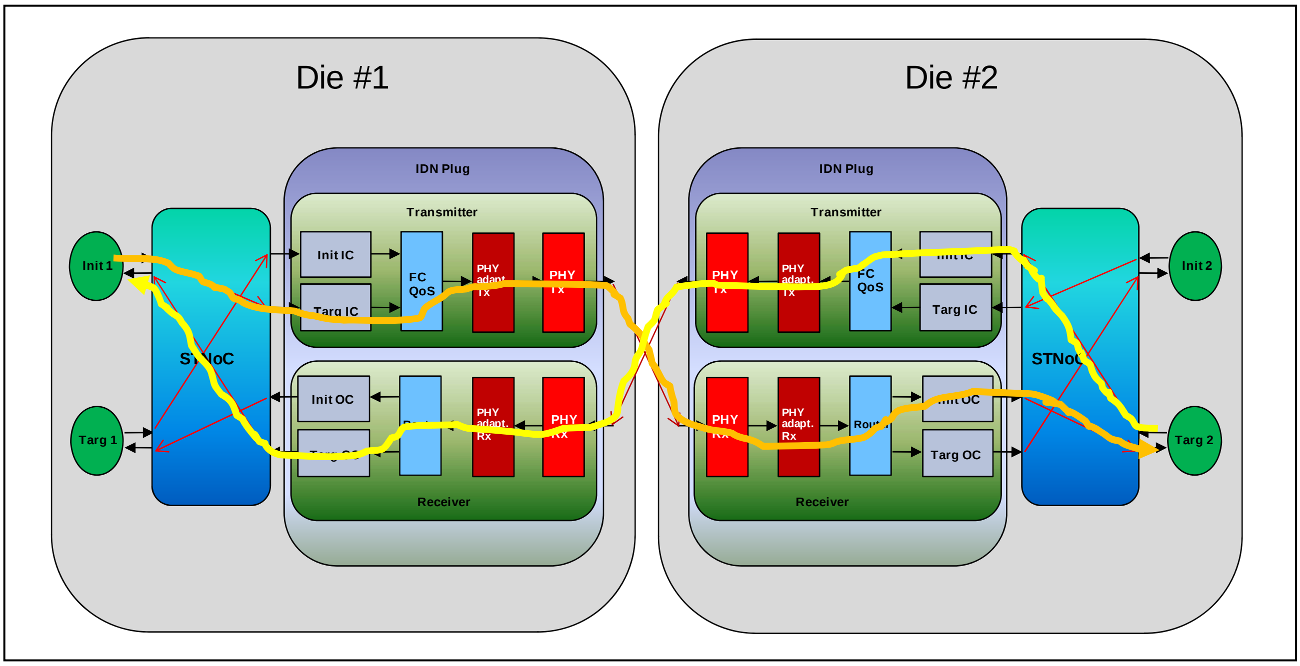


Figure WP5 - 10:

Deliverables in first reporting period (month 1 – month 9)

D5.1 – DDCM specification document (month 6) : Completed in time

Upcoming deliverables:

D5.2 – DDCM with electrical PHY design and verification data base (month 12)

→ No delay expected

D5.3 – Report on Compact optical filters and first generation beam shapers (month 21)

→ No delay expected

Milestones in first reporting period (month 1- month 9)

MS25 - Decision on optimized plasmonic waveguide couplers (month 6): Completd in time

Upcoming milestones

MS26 - Fabrication of plasmonic waveguide couplers with less than 3 dB coupling loss (month 12)

→ The SOI chips have already been fabricated with an ePIXfab IMEC10 run. Post processing with several steps of e-beam lithographies are currently carried out on the samples to fabricate the couplers. The scheduled date for the completion of the task is October 2012.

MS27 - Design of first generation beam shapers and compact optical filters (month 12)

→ Filter design near completion, beam shapers still under study

MS28- DDCM with electrical PHY design and verification (month 12)

→ DDCM VHDL design is almost complete, just some refinements are required in order to optimize performance and operation with some clock ratios in case of asynchronous mode. Logic synthesis has been done and some iterations are required. Once this phase is completed, netlist verification will be carried out.

MS29 - Data codecs for power consumption reduction (month 15)

→ A number of encoding algorithms have been studied and a set of circuits implementing them have been implemented and characterized in terms of area and timing; this activity has been carried out by a graduate student during his thesis activity in ST.

MS30 - Decision on plasmonic waveguide couplers with less than 3 dB coupling loss (month 15)

→ The Side Couplers are being currently investigated and the decision on the coupler design is planned to make on January 2013 (in line with original workplan)

MS31 - Fabrication of compact optical filters and first generation beam shapers (month 18)

→ These devices are scheduled to be fabricated together with an ePIXfab run with scheduled fabrication completed in Dec. 2012 (i.e. in time according to this milestone)

Use of Resources

Use of resources is according to plan

Partner	**Person months**	**Activity**
IMEC	4	WP-leader, design and fabrication of ultracompact filters and beam steerers
ST	16	DDCM Development
KIT	1	Modelling of Si-waveguides

Table 6: Use of resources in work package 5.

3.2.6 Work Package 6: Integration, Characterising and Testing

During the first period of the project, only task 6.1 has been started. Tasks 6.2-6.4 will start later.

Task 6.1 Modelling and fabrication of coupling Si waveguide to plasmonic waveguide

Objective of this task, led by AIT, is testing and characterization of all the passive and active plasmonic devices such as plasmonic laser, modulators, amplifiers and photodetectors. AIT will also define the testing procedures and the required characterization data that need to be collected and provide feedback to studies in WP2.

This task has been started recently (month 7). AIT is already in contact with all partners regarding the goals set for their devices, as this is work that has been started in WP2 (see the report on WP2, which is also led by AIT).

The list of the required characterization data is being compiled. To this end, AIT is developing trial simulation tools using Matlab, so that the required parameters are known in advance. Once the trial simulations finish, the final required data list will be given to partners.

AIT is involved also in the definition of the testing procedures, so that the required characterization data can be gathered. For example, the trip to Valencia happened in May was important in that the AIT researcher and the UVEG team could reach better understanding on their common goals.

Task 6.2 Design and fabrication of Si beam shaper

The goal of this task, led by KIT is to integrate plasmonic transmitter and receiver in a unique device, test and characterize it. This task starts at month 30.

Task 6.3 Design and fabrication of passive ultra-compact components as filters

This task, led by AIT, aims at integrating plasmonic devices and building a full plasmonic interconnect. This task starts at month 32.

Task 6.4 Signal generation module design

The objective of this task is to integrate a simple but complete SiP, exploiting the electronic parts developed by ST and the plasmonic devices developed by the other partners. This task starts at month 22.

Deliverables in first reporting period (month 1 – month 9)

No deliverables expected in this first reporting period.

Upcoming deliverables:

D6.1 – Report on characterization results of all plasmonic devices (month 27)

→ No delay expected

D6.2 – Report on characterization results of all optical interface plasmonic passive components (month 27)

→ No delay expected

D6.3 – DDCM Report on chip to chip interconnect characterization (month 36)

→ No delay expected

D6.4 – Report on plasmonic system-in-package interconnect prototype testing and evaluation (month 36)

→ No delay expected

Milestones in first reporting period (month 1- month 9)

No milestones expected in this first reporting period.

Upcoming milestones

M6.1 - Plasmonic active device characterization results allowing for decision on best combina-tion of devices (month 24)

→ No delay expected so far

M6.2 - Plasmonic passive components characterization results allowing for decision on best coupling and beam shapers (month 24)

→ No delay expected so far

M6.3- Concept for system integration developed (month 27)

→ No delay expected so far

M6.4 - Chip to chip interconnect characterization (month 36)

→ No delay expected so far

M6.5 - Individual plasmonic devices characterization, testing and evaluation (month 36)

→ No delay expected so far

M6.6 - Fabrication Plasmonic components integration to demonstrate chip-to-chip interconnect (month 36)

→ No delay expected so far

M6.7 - Plasmonic chip-to-chip interconnect prototype testing and evaluation (month 36)

→ No delay expected so far

Use of Resources

Use of resources is according to plan

Partner	**Person months**	**Activity**
AIT	0.44	Collection of required characterization data, implementation of a devices simulator using Matlab

Table 7: Use of resources in work package 6.

3.2.7 Work Package 7: Exploitation and Dissemination

General Status

During the first reporting period, only Task 7.1 (Dissemination) has been officially active. Although it is still early in the project, a major dissemination activity has already taken place in the form of a NAVOLCHI workshop at ICTON 2012 (Warwick, UK). In addition, NAVOLCHI partners have contributed several publications to high-quality scientific journals and conferences disseminating project technology. Communication has been established with another plasmonics-related EU-funded project (PLATON). All objectives for this period have been confronted successfully. These objectives were of the type of ongoing effort and the NAVOLCHI consortium is committed to the continuation of the effort.

In this period, there were two milestones to be reached and they were reached successfully; there were no deliverables to be completed.

Task 7.1 Dissemination

Dissemination of ideas and results is of high importance in the NAVOLCHI project. The partners of NAVOLCHI are top research organizations with proven track records in their field and are very active in disseminating research results in a worldwide range to scientists, industry, and the public.

Dissemination activities this far

Although it is still early in the project, there is already substantial dissemination action concerning NAVOLCHI activities and results. In particular:

- journal and 17 conference publications disseminating the project have been published by NAVOLCHI partners (see Objective 1),
- a white paper on the innovation potential of plasmonic interconnects is well under preparation (see Obj. 1),
- a NAVOLCHI workshop on plasmonics-based components has been organized at the ICTON 2012 conference at Warwick (UK) (see Obj. 2), attracting more than 50 attendees.
- communication has been established with plasmonics-related EU-funded project PLATON (http://www.ict-platon.eu) (see Obj. 3),
- the project website is up and running with useful information on the project (see Obj. 4),
- a brochure on NAVOLCHI activities and goals has been issued (see Obj. 5),
- a press-release on the start of the project has been issued and another one has been submitted to the Photonics Unit newsletter (see Obj. 5).

In particular, the dissemination activities that have taken place are analyzed below per partner:

AIT is the leader of WP7. As such, AIT has already performed several activities related to the dissemination of the project. In the context of Milestone 45, AIT issued an official press release announcing the start of the project to the public. In the same context, an announcement was also sent to the Photonics Unit newsletter and awaits confirmation of future publication. AIT designed and issued a brochure advertising NAVOLCHI. A white paper led by AIT is in progress on the innovation potential of plasmonic interconnects; the white paper is expected to be finished within the summer or early fall. AIT organized and chaired the NAVOLCHI workshop at the ICTON 2012 conference (Warwick, UK) which was a major dissemination activity in this period. The NAVOLCHI workshop featured 4 presentations from consortium partners as well as presentations from research groups outside the consortium. Specifically, there was a presentation from a group representing EU-funded project PLATON (a project that also involves plasmonic technology) and communication ties were established. Finally, AIT also contributed to two conference papers at ICTON on plasmonic amplifier design (led and presented by partner University of Valencia) and the NAVOLCHI plasmonic interconnect concept (led and presented by partner KIT).

KIT was engaged to implement the project website on which the ideas of the project are published as well as to establish a common platform for the partners where useful information is gathered. Therefore the WEB-site is separated into a public part containing

- basic project information,
- an introduction into the project partners,
- the list of publications, and
- offers of employment within the project,

as well as a part with limited access for project partners only. The latter covers the following subtopics:

- A collection of presentations given from the partners in meetings and phone conferences. Beneath archiving purposes, this collection is helpful during the phone conferences for distributing the presentations to all partners.
- Two lists containing deliverables and milestones including their actual state. Both lists can be ordered by deliverable/milestone respectively or by date.
- A page with a full contact list, e-mail lists and useful information how to join phone conferences.
- A page with documents important for internal use, mainly the 'Project Reference Manual' and the 'Quality Assurance Manual'. Templates for internal documents are also available on this site.
- A further site holds the documents for the Grant Agreement and the Consortium Agreement. Additionally, templates for progress reports can be found here.
- Finally, a page announces next meetings or other important target dates.

The website can be found on www.navolchi.eu. It was started immediately at the beginning of the project and is updated continuously.

In addition, KIT participated in two international conferences, disseminating NAVOLCHI information and results. In particular, this happened at OFC and ICTON with the following works:

- A. Melikyan, C. Gaertner, K. Köhnle, A. Muslija, M. Sommer, M. Kohl, C. Koos, W. Freude, and J. Leuthold, *Integrated Wire Grid Polarizer and Plasmonic Polarization Beam Splitter*, in Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America, 2012), paper OW1E.3.
- A. Melikyan, M. Sommer, A. Muslija, M. Kohl, S. Muehlbrandt, A. Mishra, V. Calzadilla, Y. Justo, J. P. Martínez-Pastor, I. Tomkos, A. Scandurra, D. Van Thourhout, Z. Hens, M. Smit, W. Freude1, C. Koos, J. Leuthold, *Chip-to-Chip Plasmonic Interconnects and the Activities of EU Project NAVOLCHI*, ICTON 2012, Th.A5.1.

In the OFC talk, an ultra-compact, low loss, high extinction ratio polarization beam splitter integrated on SOI platform was proposed. The device is 3.5 µm in length and provides more than 11dB extinction ratio with less than 1dB plasmonic losses.

At ICTON, the concept and goals of the NAVOLCHI project were presented.

TU/e is in the process of designing and building the plasmonic laser for the interconnect system, and there are still no major experimental results to announce on the matter –it is still early. Yet, TU/e contributed to the interconnect ICTON paper that was led by KIT (see section on KIT) and also presented early design work on the plasmonic laser at ICTON 2012:

- V. Dolores-Calzadilla, A. Fiore, M. K. Smit, *Towards Plasmonic Lasers for Optical Interconnects*, ICTON 2012, Th.A5.7.

UVEG has been very active disseminating the activities related to plasmonic amplifiers in 2 journal publications and 5 conference presentations. In particular, UVEG's dissemination activities in this period were:

- H. Gordillo, I. Suárez, R. Abargues, P. Rodríguez-Cantó, S. Albert and J.P. Martínez-Pastor, *Polymer/QDs nanocomposites for wave-guiding applications*, Journal of Nanomaterials, Vol. 2012, Article ID 960201 (doi:10.1155/2012/960201), 1-9 (2012).
- Bueno, I. Suárez, R. Abargues, S. Sales and J.P. Martínez Pastor, *Temperature sensor based on colloidal Quantum Dots-PMMA nanocomposite waveguides*, IEEE Sensors Journal, in press (2012).
- Suárez, H. Gordillo, P. Rodríguez-Cantó, R. Abargues, S. Albert and J. Martínez-Pastor, *Multicolor wave-guiding in polymer/quantum dot nanocomposite waveguides*, ECIO, Barcelona (Spain) 05/2012.
- Suárez, E. P. Fitrakis, P. Rodriguez-Cantó, R. Abargues, I. Tomkos and J. Martinez-Pastor, *Surface plasmon-polariton amplifiers*, ICTON 2012 (UK).
- Pedro J. Rodríguez-Cantó, Rafael Abargues, Raúl García-Calzada, and Juan P. Martínez-Pastor, *In-situ synthesis of conducting polymers into patternable polymer matrices*, ITC 2012, Lisboa, Portugal, 30/01/2012.
- R. García-Calzada, P. Rodríguez-Cantó, V. Chirvony, R. Abargues, J. Martínez-Pastor, *Gold nanoparticles obtained by pulsed laser ablation in liquids: formation of monolayers on chemically functionalized patterns/substrates*, ANGEL 2012 - 2nd Conference on Laser Ablation and Nanoparticle Generation in Liquids Taormina (Sicilia), Italy, 22/05/2012.
- H. Gordillo; I. Suárez; P. Rodríguez-Cantó; R. Abargues; R. García-Calzada; V. Chyrvony; S. Albert; J. Martínez-Pastor, *Colloidal QDs-polymer nanocomposites*, SPIE Photonics Europe Conference, Brussels, Belgium, 16 - 19 April 2012, Published as Proceedings in SPIE Vol. 8424, 30 April 2012, ISBN: 9780819491169.

STMicroelectronics is collaborating closely with AIT on the white paper that is under progress concerning the innovation potential of plasmonic interconnects. In addition, ST contributed to a conference paper at ICTON 2012 led by KIT. Lastly, a section on NAVOLCHI is soon to appear in the upcoming ST internal magazine. Major dissemination events by ST will take place as research continues and the industrial potential of the interconnect system becomes clearer.

IMEC and ***UGent*** have produced jointly several journal and conference publications. They are listed below (works where IMEC and UGent have acted independently follow later in the report).

Journal:

- B. De Geyter, Houtepen, Arjan J., Carrillo, Sergio, P. Geiregat, Gao, Yunan, Ten Cate, Sybren, Schins, Juleon M., D. Van Thourhout, Delerue, Cristophe, Siebbeles, Laurens D.A., Hens, Zeger, *Broadband and Picosecond Intraband Relaxation in Lead-Based Colloidal Quantum Dots*, accepted for ACS Nano, (2012).

Conference:

- P. Geiregat, B. De Geyter, S. Carillo, A. Houtepen, Y. Gao, S. Ten Cate, J. Schins, D. Van Thourhout, C. Delerue, L. Siebbeles, Z. Hens, *Broadband and Picosecond Intraband Relaxation in Lead Chalcogenide Nanocrystals*, International Quantum Dot Conference 2012, (2012).

- B. De Geyter, P. Geiregat, A. J. Houtepen, D. Van Thourhout, L. Siebbeles, Z. Hens, *Ultrafast Photoinduced Intraband Absorption in PbS, PbSe and PbSe/CdSe Core/Shell Nanocrystals for near-Infrared to Mid-Infrared All-Optical Signal Processing*, MRS Fall Meeting 2011, United States, (2011) .
- Q. Lu, P. Geiregat, D. Van Thourhout, Zeger Hens, *Design of Nanocrystal Light Source for Silicon Photonics*, IEEE Photonics Annual Meeting 2011, WP4, United States, p.527-528 (2011) .
- Pieter Geiregat, Floris Tallieu, Philippe Smet, Kilian Devloo – Casier, Sreeparvathi Warrier, Dries Van Thourhout and Zeger Hens, *Integrated light source for silicon photonics using colloidal nanocrystal light emitters under AC field excitation*, submitted for ELOPTO 2012.
- Contribution to KIT’s ICTON conference paper (see KIT’s section).

IMEC has also contributed to the following conference:

- Dries Van Thourhout, *Colloidal quantum dots for silicon photonics*, invited presentation at NANAX 5, 7-11 May 2012, Fuengirola (Spain).

IMEC has two master theses that are related to NAVOLCHI:

- Floris Taillieu, “Broadband colloidal quantum dot LED for active plasmonics”, Master Thesis UGent, June 2012
- Qi Lu, “Colloidal Nanocrystal Light Sources on Silicon”, Master Thesis UGent, June 2011.

UGent has also contributed the following journal and conference publications:

Journal:

- Yolanda Justo, Bart Goris, John Sundar Kamal, Pieter Geiregat, Sara Bals, and Zeger Hens, *Multiple Dot-in-Rod PbS/CdS Heterostructures with High Photoluminescence Quantum Yield in the Near-Infrared*, Journal of the American Chemical Society 2012, 134, 5484–5487.

Conference:

- P. Geiregat, Y. Justo, Z. Hens, *Giant Absorption Enhancement in Colloidal Quantum Dot Supercrystals*, International Quantum Dot Conference 2012, United States, (2012).
- Pieter Geiregat, Yolanda Justo and Zeger Hens; *Giant Absorption Enhancement in Close Packed Monolayers of Colloidal Quantum Dots through Dipolar Coupling Effects*, ICTON 2012 (UK).
- Yolanda Justo, Bart Goris, John Sundar Kamal, Pieter Geiregat, Sara Bals and Zeger Hens, *PbS/CdS core/shell nanorods, highly luminescent anisotropic near infrared nanomaterials by cationic exchange*, NaNaX 5, Fuengirola (Spain), 2012.
- Pieter Geiregat, Yolanda Justo, Zeger Hens, *Absorption enhancement in colloidal quantum dot monolayers through coherent dipolar coupling*, NaNaX 5, Fuengirola (Spain), 2012.

Dissemination plans for the future

NAVOLCHI members have made some further plans on their future dissemination activities.

In particular:

AIT plans to contribute at least 4 publications in scientific journals and magazines as well as at least another 3 conference papers and presentations. In addition, AIT will organize a public event in the form of an open seminar related to the NAVOLCHI technology to students and professionals in the 2nd or 3rd year of the project, within the context of the Open Seminars that AIT organizes every year. At least one more workshop (as the one at ICTON 2012) will be organized in the 3rd year, when the vision for the NAVOLCHI technology will be clearer and can be communicated in the form of results. Two more newsletter contributions are planned in the 3rd year concerning NAVOLCHI achievements and the end of the project, as well as at least two more press releases (months 18 and 36). AIT leads the dissemination workpackage, and therefore will interact with all partners on their dissemination activities and plans. In addition, AIT will organize or help organize the summer school (more on the summer school later in the report) and other future activities in collaboration with partners.

KIT expects to have 4-6 journal publications and 4-6 presentations at international conferences until the end of the project. One of the publications of the near future will be on the coupling between horizontal metal slot and silicon nanowire waveguides. KIT will continue to disseminate project activities through the NAVOLCHI website, as was described in the previous section. KIT is also one of the prime candidates for organizing the summer school in the 3rd year of the project.

TU/e has concrete plans on the content of at least 2 journal publications and 2 conference presentations. In particular, in the 2nd year of the project TU/e expects a conference paper on the optimization of the integrated plasmonic/dielectric laser. In the same year, a journal paper on the fabrication of said laser is expected. In the 3rd year of the project, TU/e expects a journal paper on the characterization of the laser and a conference paper with more details on the device.

UVEG will pursue plentiful journal and conference-related dissemination activities on the NAVOLCHI results in the next 30 months. In particular, UVEG estimates to contribute 6-8 journal publications on high-impact factor scientific journals and participation in at least 5 conferences. In addition, UVEG plans to issue press releases through their university service in the 3rd year of the project, when the amplifier and receiver platforms will be (or will be close to be) a reality. UVEG has also offered to organize one of the planned workshops, but there is no final decision taken by the consortium on this issue yet.

STMicroelectronics is planning a paper and a patent in the short term. ST also contributes decisively to the white paper on the innovation potential of plasmonic interconnects. Should research results permit, ST will lead the exhibition dissemination activities at prestigious conferences later, when there is a better picture on the NAVOLCHI product. Being the industrial partner in the project, ST will perform much of the dissemination to other industrial entities, and will play a key role in advertising the NAVOLCHI technology platform towards the end of the project.

The primary focus of ***IMEC*** with regard to disseminating NAVOLCHI results is on international journals and conferences. Next to the general activities in this sense, members of the IMEC team are (co)chairing several workshops at international conferences (ECOC 12, CLEO 13) focusing on the topic of “hybrid silicon photonics”, whereby the silicon PIC’s are “enhanced” through the addition of extra materials (III-V’s, polymers, or in this case plasmonics and quantum dots). Besides standard scientific dissemination, the photonics group of IMEC is also strongly involved in student education through the organization of an international Erasmus mundus master program in Photonics. Integrated photonics devices are an important part of the regular course program of that master and every year several master students are carrying out a master thesis related to the topics covered in this project. IMEC is also one from the prime candidates for organizing the summer school.

UGent will primarily focus on international journals and conferences. Next to the general activities in this sense, UGent members are (co)chairing a session at the E-MRS 2013 conference on ‘Semiconductor Nanostructures towards Electronic and Optoelectronic Device Applications – IV’, which will be an opportunity to present results from NAVOLCHI. The Physics and Chemistry of Nanostructures group of UGent is also strongly involved in student education in Chemistry, Physics and Applied Physics. Master thesis projects on colloidal nanomaterials for optical applications – topics in close connection with NAVOLCHI – will be proposed to students in their 1st master year; these projects typically attract 1-2 students.

In the context of dissemination plans, major events being planned include:

- A *summer school* for young researchers, PhD students and possibly industry professionals. The purpose of the school will be to convey expertise gained through the project and to extend the scientific skills of participants. At this point, the school is planned for the 3rd year of the project. KIT or IMEC are being strongly considered as hosts, in part because of the availability of specialized laboratories on their campuses. Organizational activities for the summer school will begin in fall 2012.
- At least one public event in the form of an *open seminar* to students and experts held at AIT.
- Appropriate results from the project will be fed into the *Jeppix Optical chip design course* which is held at the TU/e and has attendees from around the world.
- Exhibition activities in the form of *booths at major European and US conferences* in order to generate commercial interest for NAVOLCHI, provided that research results allow for it. More information on this plan will be available as NAVOLCHI progresses.
- One or two more NAVOLCHI *workshops*.

Deliverables in first reporting period (month 1 – month 9)

None

Upcoming deliverables:

D7.1 First report on NAVOLCHI dissemination and promotion activities (m18)–no delay expected.

D7.2 First report on NAVOLCHI exploitation activities (m18)–no delay expected.

D7.3 Mirror Deliverable of D7.1, which will be available to the public on the website (m18)–no delay expected.

D7.4 Intermediate report on recent achievements (m18)–no delay expected.

Milestones in first reporting period (month 1- month 9)

MS44 Dissemination of activities in the project's website and continuous update (m1)–completed in time (ongoing ever since).

MS45 Press release on start of project distributed to the public (m2)–completed in time.

Upcoming milestones

MS46 Identification of possible contributions to the industrial partners for commercialization (m15)–no delay expected.

Use of resources

Use of resources has been according to plan. The table below gives a review of each partners contribution.

Partner	Person months	Main contribution
AIT	1.29	NAVOLCHI workshop organization and chair at ICTON 2012, contribution to ICTON publication, brochure, 2 press releases, white paper preparation.
KIT	1.00	Project website, 2 conference publications.
IMEC	0.10	Journal and several conference publications, master theses.
TU/e	0.20	1 conference publication and contribution to 1 more.
UVEG	0.10	2 journal and several conference publications.
ST	1.00	NAVOLCHI section in internal ST magazine, contribution to white paper preparation and to 1 conference publication.
UGent	0.00	2 journal and several conference publications.

Table 8: Use of resources in work package 7.

3.3 Project Management (Work Package 1)

Beneath common management functions as

- Strategic management at project level,
- Control of work package activities, including technical quality control,
- Organisation of project reporting and meetings,
- Control of deliverable preparation,
- Conflict management,

the WP1 leader KIT is responsible for the quality management within the project during the complete projects run-time. The detailed list of management activities is given below.

3.3.1 Administrative Boards and Decisions

One of the first tasks for the coordinator was to implement the main administrative boards of the project, i.e. the General Assembly and the Project Management Committee. Additionally, a Technical Project Manager had to be appointed.

General Assembly:

The General Assembly as the prime board in this project is responsible for all major decisions within the project and consists of one representative of each party. It is chaired by the coordinator. The members are listed in Table 9.

Karlsruhe Institute of Technology, Germany	KIT	Manfred Kohl
Interuniversity Microelectronics Centre VZW-IMEC, Belgium	IMEC	Dries Van Thourhout
Eindhoven University of Technology, Netherlands	TU/e	Meint Smit
Research and education laboratory in information technologies, Greece	AIT	Ioannis Tomkos
University of Valencia, Institute of Materials Science, Spain	UVEG	Juan Martinez Pastor
ST-Microelectronics, Italy	ST	Alberto Scandurra
Ghent University, Belgium	Ugent	Zeger Hens

Table 9: General Assembly.

Technical Project Manager:

PD Manfred Kohl (KIT) was elected as the Technical Project Manager for NAVOLCHI at the Kick-Off meeting in Karlsruhe (see below). He chairs the Project Management Committee and coordinates all technical issues.

Project Management Committee:

Chair: Technical Project Manager: Manfred Kohl (KIT)

Coordinator: Juerg Leuthold (KIT)

WP 1 Leader	KIT	Manfred Kohl
WP 2 Leader	AIT	Emmanouil-Panagiotis Fitrakis
WP 3 Leader	TU/e	Meint Smit
WP 4 Leader	UVEG	Juan Martinez Pastor
WP 5 Leader	IMEC	Dries Van Thourhout
WP 6 Leader	ST	Alberto Scandurra
WP 7 Leader	AIT	Dimitrios Klonidis

Table 10: Project Management Commitee.

3.3.2 Management Deliverables

Deliverables covered by work package 1 with delivery dates are:

D1.1	Project web site with .eu domain (M01) and continuous update	11/2011
D1.2	Project reference online manual	01/2012
D1.3	Project quality assurance manual	04/2012

All have been prepared in time, for access to the WEB-site and the manuals please follow the links.

3.3.3 Communication: Meetings and Phone Conferences

Up to now, two meetings and six phone conferences have been held:

Meetings:

1) Kick-Off meeting in Karlsruhe, Germany, February 3rd 2012.

2) Intermediate Meeting in Warwick, Great Britain, July 6th 2012.

To provide a short reaction time on possible problems, it was decided that phone conferences will be held every month if applicable, typically on the first Monday of every month.

Phone Conferences:

1) November 16th, 2011
2) December 12th, 2011
3) March 12th, 2012
4) April 2nd, 2012
5) May 7th, 2012
6) June 4th, 2012

Detailed documentation of partner presentations, results obtained and decisions made during the meetings and phone conferences can be found in the minutes-files available on our WEB-site (please follow the link).

3.3.4 Legal Status

No changes.

3.3.5 WEB-site

Since project start in November 2011, the WEB-site is available under www.navolchi.eu and is updated periodically. A detailed description can be found in chapter 0.

During the first half of 2012, the WEB-site has been opened at least 340 times by 177 different visitors. (Including visits by the project partners itself.)

Broken down by country, Table 11 shows - beneath visits from project partners - also visits from China, US, Great Britain, Canada and others.

Additionally, and not listed in the table aside, about 300 accesses from automated 'robots' like Yandex (Russian), GoogleBot (US) and BaiDuSpider (Chinese) have been observed.

Country	Domain	Count
Germany	de	105
China	cn	35
Netherlands	nl	25
Greece	gr	23
United States	us	13
Spain	es	11
Belgium	be	11
Great Britain	gb	3
Canada	ca	1
Other / Unknown		113

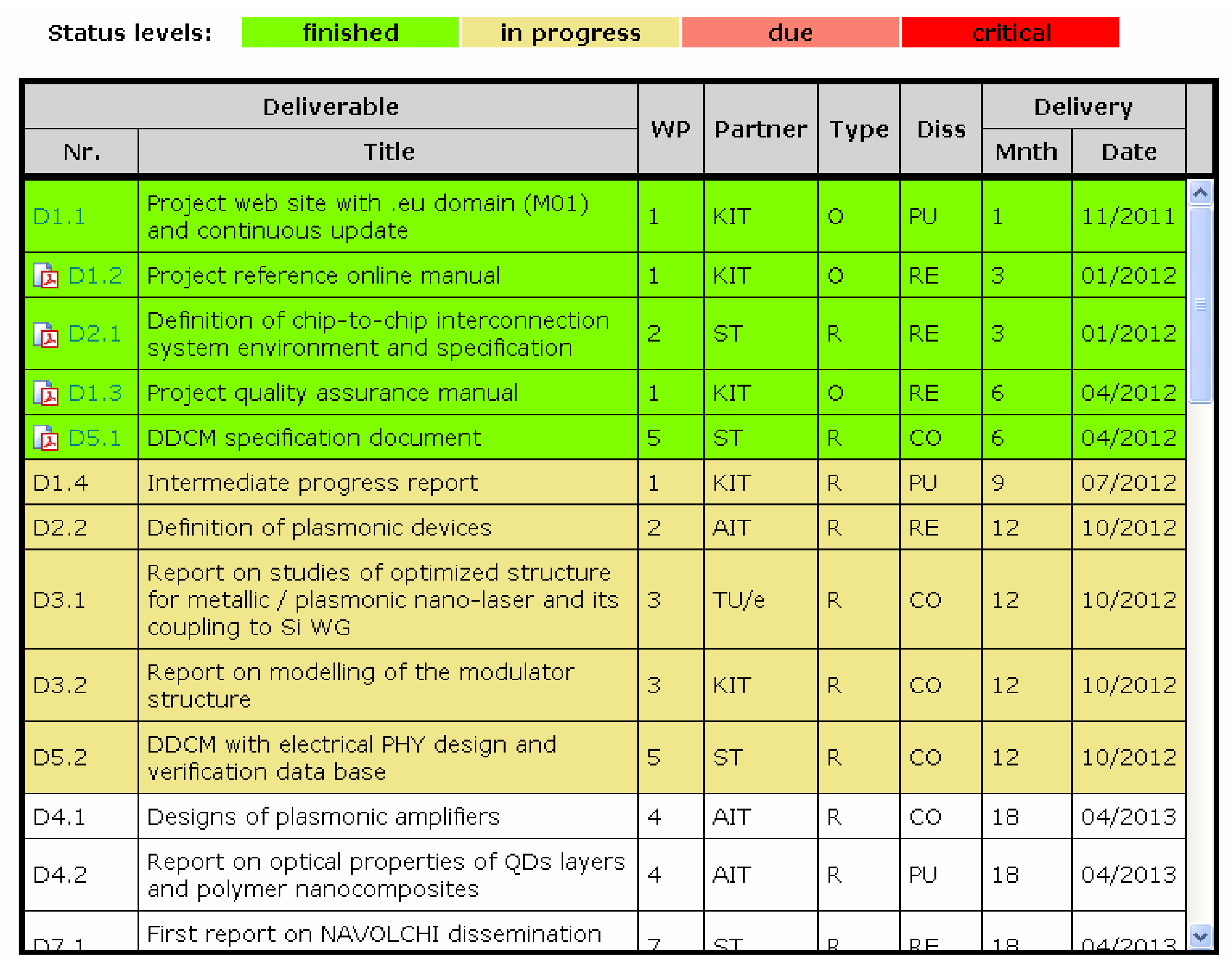
Table 11: Visits of www.navolchi.eu itemised by country.

3.3.6 In Total

As stated in the reports concerning the work packages 2-7, all deliverables and milestones of the first report period have been accomplished successfully. Problems for the next months are not expected. Therefore, changes in overall strategy are not necessary.

3.4 Deliverables and Milestones Tables

3.4.1 Deliverables



Status levels: finished in progress due critical

Deliverable		WP	Partner	Type	Diss	Delivery	
Nr.	Title					Mnth	Date
D1.1	Project web site with .eu domain (M01) and continuous update	1	KIT	O	PU	1	11/2011
D1.2	Project reference online manual	1	KIT	O	RE	3	01/2012
D2.1	Definition of chip-to-chip interconnection system environment and specification	2	ST	R	RE	3	01/2012
D1.3	Project quality assurance manual	1	KIT	O	RE	6	04/2012
D5.1	DDCM specification document	5	ST	R	CO	6	04/2012
D1.4	Intermediate progress report	1	KIT	R	PU	9	07/2012
D2.2	Definition of plasmonic devices	2	AIT	R	RE	12	10/2012
D3.1	Report on studies of optimized structure for metallic / plasmonic nano-laser and its coupling to Si WG	3	TU/e	R	CO	12	10/2012
D3.2	Report on modelling of the modulator structure	3	KIT	R	CO	12	10/2012
D5.2	DDCM with electrical PHY design and verification data base	5	ST	R	CO	12	10/2012
D4.1	Designs of plasmonic amplifiers	4	AIT	R	CO	18	04/2013
D4.2	Report on optical properties of QDs layers and polymer nanocomposites	4	AIT	R	PU	18	04/2013
D7.1	First report on NAVOLCHI dissemination	7	ST	R	RE	18	04/2013

Table 12: Deliverables of the NAVOLCHI project, ordered by delivery date.

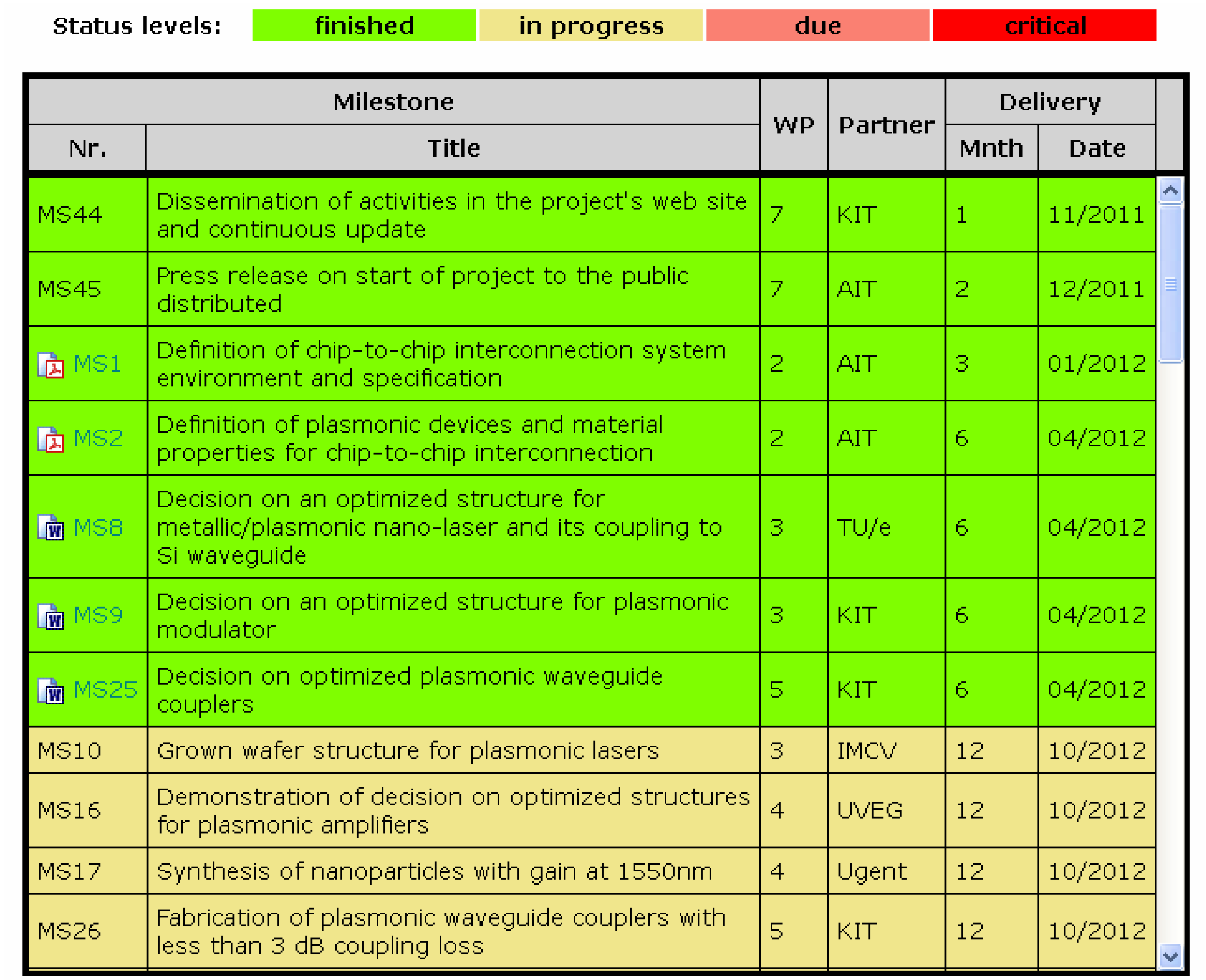
Diss: **PU** = Public

PP = Restricted to other programme participants (including the Commission Services).

RE = Restricted to a group specified by the consortium (including the Commission Services).

CO = Confidential, only for members of the consortium (including the Commission Services).

3.4.2 Milestones



Status levels: finished in progress due critical

Milestone		WP	Partner	Delivery	
Nr.	Title			Mnth	Date
MS44	Dissemination of activities in the project's web site and continuous update	7	KIT	1	11/2011
MS45	Press release on start of project to the public distributed	7	AIT	2	12/2011
MS1	Definition of chip-to-chip interconnection system environment and specification	2	AIT	3	01/2012
MS2	Definition of plasmonic devices and material properties for chip-to-chip interconnection	2	AIT	6	04/2012
MS8	Decision on an optimized structure for metallic/plasmonic nano-laser and its coupling to Si waveguide	3	TU/e	6	04/2012
MS9	Decision on an optimized structure for plasmonic modulator	3	KIT	6	04/2012
MS25	Decision on optimized plasmonic waveguide couplers	5	KIT	6	04/2012
MS10	Grown wafer structure for plasmonic lasers	3	IMCV	12	10/2012
MS16	Demonstration of decision on optimized structures for plasmonic amplifiers	4	UVEG	12	10/2012
MS17	Synthesis of nanoparticles with gain at 1550nm	4	Ugent	12	10/2012
MS26	Fabrication of plasmonic waveguide couplers with less than 3 dB coupling loss	5	KIT	12	10/2012

Table 13: Milestones of the NAVOLCHI project, ordered by delivery date.

Comment to MS8: A suitable structure based on a plasmonic laser was designed, however further investigations are being carried out to design a metallic laser, which might offer a better performance.

3.5 Explanation of the Use of the Resources and Financial Statements

	WP1		WP2		WP3		WP4		WP5		WP6		WP7		Total	
	Real	Plan	Real	Plan	Real	Plan	Real	Plan	Real	Plan	Real	Plan	Real	Plan	Real	Plan
KIT	2	16	1	2	4	26	1	3	1	12	0	4	1	3	10	66
IMEC	0	1	0	1	0	3	4	11	4	14	0	3	0.1	1	8.1	34
TU/e	0.2	1	0	6	5.6	29	0	0	0	0	0	3	0.2	1	6	40
AIT	0.6	2	3	18	0	0	4.5	9	0	0	0.4	10	1.3	8	9.8	47
UVEG	0.4	2	0.4	2	0	0	10.6	32	0	4	0	2	0.1	1	11.5	43
ST	0.5	2	3	12	0	1	0	1	16	30	0	22	1	10	20.5	78
UGent	0	0	0	0	0	0	7	24	0	0	0	0	0	0	7	24
Total	3.7	24	7.4	41	9.6	59	27.1	80	21	60	0.4	44	3.7	24	72.9	332

Table 14: Total Person-Month Status Table. Real: Actual state for months 1-9; Plan: Total for months 1-36.

	actual claimed costs **Reporting Period M1 – M9**	**planned costs** **Funding Period 1 M1 – M18**	**actual requested funding** **Funding Period 1 M1 – M18**	**planned requested funding** **Funding Period 1 M1 – M18**
KIT	63 588.97 €	287 807.50 €	290 000.00 €	287 807.50 €
IMEC	111 069.00 €	124 906.00 €	83 302.00 €	93 679.00 €
TU/e (a)	59 158.92 €	59 719.25 €	45 381.53 €	44 789.43 €
AIT	68 720.00 €	78 516.50 €	52 567.60 €	59 920.12 €
UVEG	108 947.14 €	215 000.00 €	155 770.00 €	161 250.00 €
ST				
UGent				

Table 15: Costs claimed in the reporting period versus the costs planned in the first funding period.

(a) **TU/e: Data for months 1-7.**

PERSONNEL, SUBCONTRACTING AND OTHER MAJOR COST ITEMS FOR BENEFICIARY 1 (KIT) FOR THE PERIOD 01/11/2011 – 31/07/2012			
Work Package	Item description	Amount in €	Explanations
1-5, 7	Personnel direct costs	19 616.00	Salaries
	Travels	1 869.30	
	Major costs	29 655.67	
	Indirect costs	12 448.00	Overhead
	TOTAL COSTS	63 588.97	

Table 16: Personnel, subcontracting and other major cost items of beneficiary 1 (KIT) for the period 01/11/2011 – 31/07/2012.

PERSONNEL, SUBCONTRACTING AND OTHER MAJOR COST ITEMS FOR BENEFICIARY 2 (IMEC) FOR THE PERIOD 01/11/2011 – 31/07/2012			
Work Package	Item description	Amount in €	Explanations
4,5,7	Personnel direct costs	50 600.00	Salaries of engineers design and technology (8.1 PM)
5	Consumables	6 340.00	SOI wafer cost
4, 5	Travel	559.00	Coventry project meeting
	Indirect costs	53 570.00	Overhead
	TOTAL COSTS	111 069.00	

Table 17: Personnel, subcontracting and other major cost items of beneficiary 2 (IMEC) for the period 01/11/2011 – 31/07/2012.

PERSONNEL, SUBCONTRACTING AND OTHER MAJOR COST ITEMS FOR BENEFICIARY 3 (TU/E) FOR THE PERIOD 01/11/2011 – 31/05/2012			
Work Package	Item description	Amount in €	Explanations
3	Personnel direct costs	26 608.44	Salaries of D. Calzadilla and M. Smit
3	Travels	2 262.46	Kick-off meeting in Karlsruhe (2x) and ECIO 2012 in Sitges
3	Hewlett Packard	1 140.66	Laptop
3	Hembach Photonik	2 608.20	Licenses of FDTD Solutions and MODE Solutions of Lumerical
3	Indirect costs	26 539.16	Overhead
TOTAL COSTS		59 158.92	

Table 18: Personnel, subcontracting and other major cost items of beneficiary 3 (TU/e) for the period 01/11/2011 – 31/05/2012.

PERSONNEL, SUBCONTRACTING AND OTHER MAJOR COST ITEMS FOR BENEFICIARY 4 (AIT) FOR THE PERIOD 01/11/2011 – 31/07/2012			
Work Package	Item description	Amount in €	Explanations
1,2,4,6,7	Personnel direct costs	38 395.00	Salaries of I. Tomkos, D. Klonidis, E.P. Fitrakis and C. Kachris
1,4,7	Travels	2 811.00	Kick-off meeting in Karlsruhe, experimental activity in Valencia, ICTON 2012 conference, and Warwick (Coventry, UK) plenary meeting,
7	Conference registration fee	638.00	ICTON 2012, for I. Tomkos
1,2,4,6,7	Indirect costs	26 876.00	Overhead
TOTAL COSTS		68 720.00	

Table 19: Personnel, subcontracting and other major items for Beneficiary 4 (AIT) for the period 01/11/2011 – 31/07/2012.

PERSONNEL, SUBCONTRACTING AND OTHER MAJOR COST ITEMS FOR BENEFICIARY 5 (UVEG) FOR THE PERIOD			
Work Package	Item description	Amount in €	Explanations
1, 2, 4	Personnel direct costs	51 750.00	11.5 Person Months (2 permanent staff and 2 posdocs: partial time)
1,4	Major cost “Meetings and Conferences”	3 652,40	Kick-off meeting (Karlsruhe) and 2 Conferences
4	Major cost “Optomechanics”	7 709.36	Optomechanical for waveguide light coupling, optomechanical for Nd:YAG doubling and “photonic fiber” pumping (supercontinuum generation), lenses and objectives, colour/neutral filters, ..
4	Major cost “Chemicals-gases-wafers”	4 549.53	Chemicals and gases for chemical lab: preparation of polymers doped with QDs, Layer-by-Layer deposition of QDs (including ligand exchange), Si-SiO2 wafers for preparation of samples (waveguides based on QD doped polymers and metal + waveguides)
4	Remaining direct costs	430.67	Electrical, electronic, informatics, DHL, …
	Indirect costs	40 855.18	
TOTAL COSTS		108 947.14	

Table 20: Personnel, subcontracting and other major cost items of beneficiary 5 (UVEG) for the period.

<table>
<tr><th colspan="4">PERSONNEL, SUBCONTRACTING AND OTHER MAJOR COST ITEMS FOR
BENEFICIARY 6 (ST) FOR THE PERIOD 01/11/2011 – 31/07/2012</th></tr>
<tr><td>Work Package</td><td>Item description</td><td>Amount in €</td><td>Explanations</td></tr>
<tr><td></td><td>Personnel direct costs</td><td></td><td></td></tr>
<tr><td></td><td>Consumables</td><td></td><td></td></tr>
<tr><td></td><td>Travel</td><td></td><td></td></tr>
<tr><td></td><td>Indirect costs</td><td></td><td></td></tr>
<tr><td colspan="2">TOTAL COSTS</td><td></td><td></td></tr>
</table>

Table 21: Personnel, subcontracting and other major cost items of beneficiary 6 (ST) for the period 01/11/2011 – 31/07/2012.

<table>
<tr><th colspan="4">PERSONNEL, SUBCONTRACTING AND OTHER MAJOR COST ITEMS FOR
BENEFICIARY 7 (UGENT) FOR THE PERIOD 01/11/2011 – 31/07/2012</th></tr>
<tr><td>Work Package</td><td>Item description</td><td>Amount in €</td><td>Explanations</td></tr>
<tr><td></td><td>Personnel direct costs</td><td></td><td></td></tr>
<tr><td></td><td>Consumables</td><td></td><td></td></tr>
<tr><td></td><td>Travel</td><td></td><td></td></tr>
<tr><td></td><td>Indirect costs</td><td></td><td></td></tr>
<tr><td colspan="2">TOTAL COSTS</td><td></td><td></td></tr>
</table>

Table 22: Personnel, subcontracting and other major cost items of beneficiary 7 (UGent) for the period 01/11/2011 – 31/07/2012.

Form Cs are not required for this intermediate report.

4 Attachments

As determined in the projects “Description of Work”, the milestones (refer to chapter 3.4.2) achieved so far are delivered with this report. To avoid redundant lengthening of this document, the milestones are delivered as separate files. Additionally, you can find them on our web site www.navolchi.eu .