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

Intermediate Report on Recent Achievements

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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 presents the NAVOLCHI consortium achievements for the first 18 months of the project. Emphasis is given to lab results and developments.

Change Records

Version	Date	Changes	Author
0.1 (draft)	2013-02-15	Start	Emmanouil P. Fitrakis
99 (subm.)	2013-04-30	Contributions	Emmanouil P. Fitrakis Eleni Tsalera Ioannis Tomkos Juerg Leuthold Martin Sommer Manfred Kohl Argishti Melikyan Dries Van Thourhout Victor Calzadilla Meint Smit Isaac Suarez Pedro Rodriguez-Canto Juan Martinez-Pastor Alberto Scandurra Zeger Hens

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1. Introduction

Electronics has been dominating the interconnect industry for several decades now, but electrical interconnects are getting harder to design as needs develop (especially for data rates approaching or exceeding 10-25 Gbit/s). In the near future, very thick or multiple electrical wires may be able to cater for very short distances. However, these methods increase cost and also do not scale indefinitely.

Photonic systems utilize the superior bandwidth of light to transmit data much faster than electronics. But, while electronics is limited in operating speed, photonics is limited in miniaturization capability; photonic components are much bulkier than electronics, thus making hybrid electronic-photonic chips complex and costly.

The emerging field of plasmonics combines the speed of photonic systems with sizes much closer to the sizes of integrated electronics. By utilizing plasmonics, the NAVOLCHI project aims to bridge the gap between electronics and photonics, thus paving the way for the faster and smaller chip technology of the future. NAVOLCHI aims to explore, develop and demonstrate a novel chip-to-chip and System-in-Package interconnect with plasmonic transceivers. The main devices to be developed are a metallo-dielectric laser and a plasmonic modulator for the transmitter, and a plasmonic photodetector with a plasmonic pre-amplifier for the receiver. NAVOLCHI utilizes a CMOS-compatible approach that will ensure the cost-effectiveness of the future product.

This document lists the achievements of the first 18 months of the project towards the realization of the plasmonic chip-to-chip interconnect system. For more information on NAVOLCHI technology, see the References section.

2. Recent Achievements

The per-partner listing of the achievements in the first half of the project (18 months) is as follows.

2.1 Karlsruhe Institute of Technology (KIT)

- **Ultra-compact, low loss, high extinction ratio polarization beam splitter is designed integrated on SOI platform.** The device is 3.5 μm in length and provides 11dB extinction ratio with less than 1dB plasmonic losses. The polarization beam splitter is designed on silicon dioxide substrate, see Fig. 1.

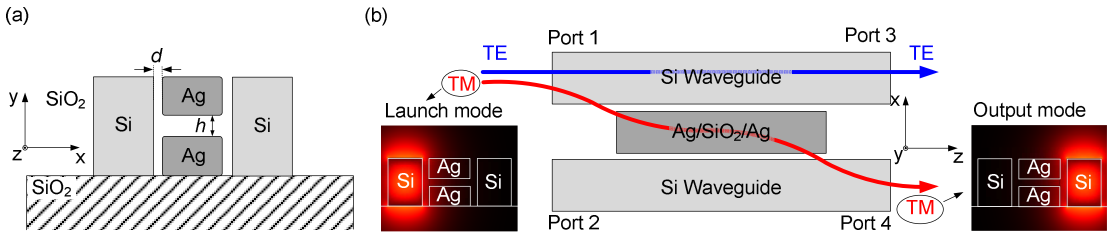

Figure 1. Supermodes at the PBS. Supermodes having high coupling efficiency for the TM excitation from the SWG are quasi-TM. The phase of the dominating electric field component (E_y or E_x depending if the mode is quasi-TE or quasi-TM) in the cross section is represented with (+) and (−) signs. Propagation of the second, the third and the sixth supermodes in the PBS results in coupling of TM mode of right SWG to the left SWG.

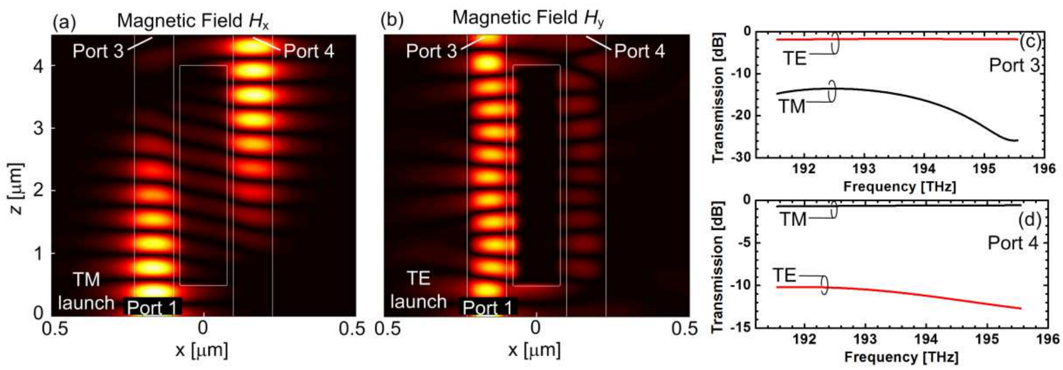

Figure 2. Field distribution in the PBS and transmission at the Port 4 and Port 3 for both TM and TE excitations. Magnetic field distribution in the PBS for the case of TE (a) and TM (b) excitation. Transmission spectrum at Port 3 (c) and Port 4 (d) for both TE (red) and TM (black) excitations from Port 1. TM polarized light tunnels through the PWG and couples to the neighboring SWG, while TE mode transmits through the PBS staying in the left arm. More than 11dB extinction ratio is feasibility at 3.5 µm.

- **Co-chairing of NAVOLCHI workshops.** KIT co-chaired (with partner AIT) a NAVOLCHI workshop at ICTON 2012 (Warwick, UK), and is also co-chairing the related workshop at ICTON 2013 (Cartagena, Spain).

2.2 IMEC

- **Steerable grating couplers:** IMEC developed a platform combining its standard grating couplers – for coupling light out of the chip –with MEMS based techniques to demonstrate dynamic beam steering (when tilting the platform) or optimizing fiber chip coupling (when combining with in-plane movement of the platform).

- **Compact wavelength filters:** IMEC designed and demonstrated several types of wavelength filters, which can be used to suppress noise of the receiver optical pre-amplifier. Filters with different bandwidth and different crosstalk values were realized. The final filter structure to be integrated in the demonstrator will be selected from these based on the input from the systems workpackages.

- **Optical amplifier based on colloidal quantum dots:** IMEC designed and simulated the structure for the pre-amplifier to be integrated in the optical receiver. With UGent, IMEC characterized the integration of colloidal quantum dots on silicon waveguides and developed a model for characterizing their properties. These results will be used in the coming months for developing the optical pre-amplifier.

2.3 Technical University of Eindhoven (TU/e)

- **Modelling of a Fabry-Perot plasmonic laser coupled to an InP waveguide**.

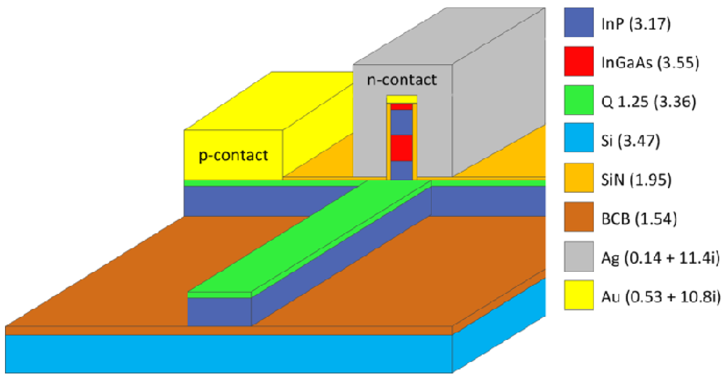

Figure 3: Scheme of the plasmonic laser coupled to an InP waveguide. In view of its high threshold gain required to achieve lasing, alternative solutions were investigated as shown below. Detailed modeling results can be found in Deliverable 3-1.

- **Optical simulations of a metallo-dielectric nanolaser**. Optical and electrical simulations predict a threshold current below 100 µA, and output power up to 100 µW seem feasible if the optical gain does not clamp at high injection currents due to self-heating.

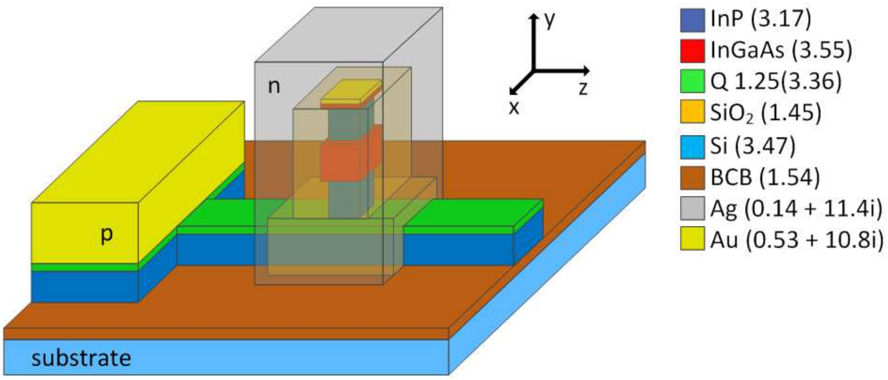

Figure 4: Scheme of the metallo-dielectric laser coupled to an InP-membrane waveguide. The fabrication of this laser is on-going.

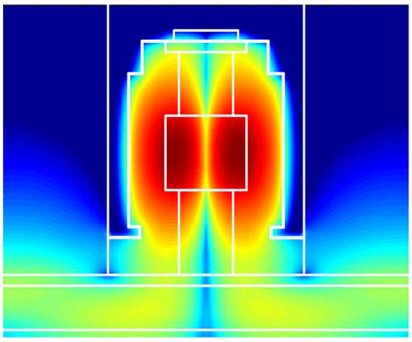

Figure 5: Device cross section showing evanescent coupling between the nanolaser pillar and the waveguide at the bottom.

- **Electrical simulations of the metallo-dielectric nanolaser** to investigate threshold conditions (e.g. threshold current).

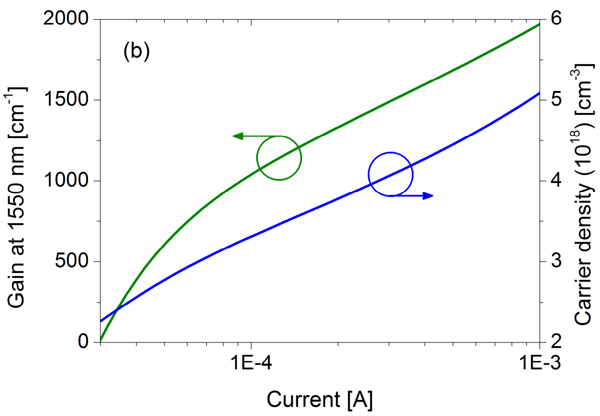

Figure 6: Gain-current curve. Optical simulations of the metallo-dielectric laser show a threshold gain below 1000 cm^{-1}, therefore a threshold current below 100 µA is expected.

- **A III-V wafer** for the fabrication of the metallo-dielectric nanolaser has been grown. The wafer enables us to start the fabrication of the nanolaser. Its growth has been carried out with metalorganic vapour phase epitaxy.

Material	Thickness [nm]	Doping
InP	50	N > $5x10^{18}$
InGaAs	50	N > $1x10^{19}$
InP	100	N > $5x10^{18}$
InP	100	N = $5x10^{18}$
InP	100	N = $1x10^{18}$
InGaAs	350	n.i.d.
InP	100	P = $3x10^{17}$
InP	100	P = $5x10^{17}$
InP	50	P = $1x10^{18}$
Q 1.25	50	P = $2.4x10^{19}$
InP	100	P = $1x10^{18}$
InP	100	n.i.d.
InP	Substrate	n.i.d.

Table 1: Layer stack of the wafer indicating materials, thicknesses and doping levels.

- **The etching of first nanopillars on InP wafers** has been done. Similar nanopillars etched on the real wafer will form the laser cavities.

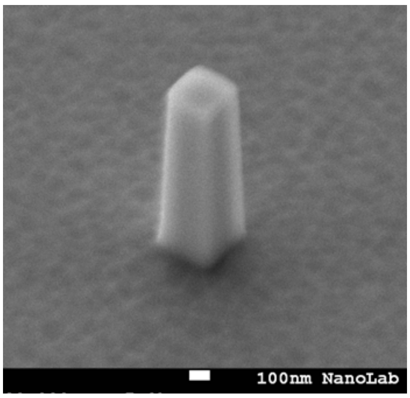

Figure 7: InP pillar etched with inductively-coupled-plasma reactive ion etching using a methane/hydrogen chemistry.

- **The rapid thermal annealing of silver** has been investigated. Its annealing is important to increase the grain size, since a non-homogeneous metal (i.e. small grain size) will increase the optical loss.

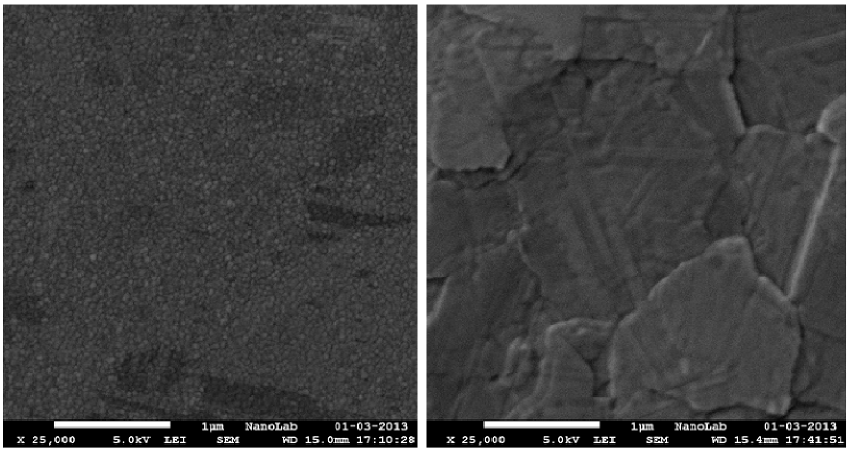

Figure 8: Silver depositions on flat samples by electron-beam evaporation. Left: sample without annealing. Grains of about 30 nm are formed during Ag deposition. Right: sample annealed with optimized recipe to form grains larger than 1 µm.

2.4 Athens Information Technology (AIT)

- **Simulation tools development.** AIT developed various numerical tools that simulate plasmonic devices for design and evaluation purposes. In particular, the following tools have been developed:
    - Muller's method.
    - Effective index method (modified) for plasmonic waveguides.
    - Finite Difference Frequency Domain (FDFD) method.

- **Design and evaluation (by simulations) of plasmonic amplifier structures.** Various plasmonic waveguide structures have been evaluated through simulations with respect to their potential as amplification platforms. In particular, PMMA/Au/PMMA and PMMA/Au/SiO_2 structures, as well as 2D structures have been designed and evaluated. The potential of such structures for other functionalities (e.g., nonlinear processing) has also been studied. This work is in close collaboration with consortium-partner UVEG.

- **System specifications and device definitions.** AIT led (along with STi) the effort of setting the goals for the chip-to-chip interconnect system performance. On the basis of these goals, AIT contributed to the definition of the plasmonic devices developed by other consortium partners. This is an ongoing effort, as devices development is in progress.

- **Dissemination and promotion of NAVOLCHI technology.** AIT is the leader of the dissemination and exploitation effort, and has been very active through the following efforts:

  - Organization of workshops on NAVOLCHI technology at ICTON 2012 (Warwick, UK) and ICTON 2013 (Cartagena, Spain).
  - Issuing of a technical brochure and a press release.
  - An open seminar at the AIT premises.
  - A white paper on innovation potential.
  - …and various contributions to conferences and scientific magazines.

2.5 University of Valencia (UVEG)

- **PL coupling in dielectric waveguides.**
  Optimal conditions to waveguide QD photoluminescence (PL) in QD-PMMA and QD-SU8 were obtained. The result is applied to several QD families (and wavelengths) from the visible to the IR: CdS (400 nm), CdTe (540 nm), CdSe (600 nm) or PbS (1100 nm). Initial results were published in *Nanothecnology*, 435202, 2011 and recent results were published in *Journal of nanomaterials*, 960201 (2012). Waveguiding of several colours was also demonstrated.

- **Variable stripe length method to characterize gain and losses.**
  The Variable Stripe Length method was used to characterize the gain and losses of the dielectric waveguides. A thorough analysis as a function of the concentration and reabsorption effects was carried out (paper sent to *IEEE Photonics* about CdS, CdTe and CdSe). For this purpose, not only spherical QDs, but also quantum rods from Ghent University were analysed in order to decide on the best material for gain applications.

- **Bilayer structures in dielectric waveguides.**
  Bilayer structures composed by active and passive layers were demonstrated to improve the propagation of the pumping beam and to demonstrate the coupling from a QD-PMMA nanocomposite to a SU8 pattern (paper sent to *Journal of Lightwave Technology*).

- **Design and characterization of plasmonic amplifiers.**
  Planar PMMA/Au/SiO2 and PMMA/Au/PMMA waveguides were designed at 600 nm and 1550 nm for amplification purposes. Waveguides were also characterized using the variable stripe length method.

- **Bilayer structures for plasmonic waveguides**
  The use of bilayer structures in plasmonic waveguides was studied with the intention to improve the coupling of the pumping beam. As a result light can be end-fire coupled in the waveguides.

- **Synthesis and characterization of infrared colloidal QDs (PbS and PbSe).**
  PbS (900-1600 nm) and PbSe (1300-1900 nm) have been successfully synthesized with appropriate diameters and properly characterized by optical spectroscopy (absorbance and photoluminescence) and TEM.

- **Preparation and characterization of QD-solids based on these nanostructures.**
  Fabrication of multilayers based on QDs has been performed using a layer-by-layer method. Thus, we are able to prepare air-stables QD-solids in a reproducible way to obtain photoconductive QD-layers (base of nanogap photoconductors/photodetectors and LEDs).

- **Electrical Characterization of the fabricated devices.**
  Fabricated QD-based devices exhibited appropriate photo-electrical properties for using them in photodetector devices. To measure the spectral photoconductivy/ photocurrent/photovoltage of these devices we have mounted an in-house set-up and are currently designing a new photomask to produce patterns by UV photolithography for the deposition of electrodes separated in the range of 2 to 10 μm (next generation of devices).

- **In-situ synthesis of conducting polymer into a patternable host matrix.**
  Conducting polymers with patterning capability is one of the routes (or an element) for the fabrication of a plasmonic photodetector. The first step was the synthesis of a patternable conducting polymer (PCP) based on Polyterthiophene as conducting polymer and Novolak as host matrix. This Novolak-based nanocomposite has shown good electrical properties and patterning capability by means of UV-lithography.

- **In-situ synthesis of Au nanoparticles into a patternable conducting polymer (PCP).**
  PCP containing Au nanoparticles has been also obtained using a gold salt to polymerize the terthiophene. In this case, the multifunctional material consisted of Au nanoparticles, Polyterthiophene, and PMMA as the host matrix, which can be patterned by means of E-Beam lithography. Preliminary results on the patterning performance of this PMMA-based PCP has been obtained being necessary the optimization of the formulation of the nanocomposite as well as the lithographic process parameters.

- **Development of metallic microstructures by a chemical regrowth of metal NPs: towards prepatterned plasmonic nanostructures.**
  UVEG proposed an alternative method for the fabrication of metal micro/nanostructures from metal-polymer (the polymer in this case is dielectric) nanocomposite resists and

their subsequent metallization by a novel wet chemistry method. A patent application on this method has been already presented.

2.6 STMicroelectronics (STi)

- **DDCM (Dual Die Communication Module) with electrical PHY design and verification data base**. The DDCM specified during the first year of the project has been implemented in VHDL, synthesized and characterized in terms of area and timing. A flow for its characterization also in terms of power consumption has been developed. The DDCM has been implemented as parametric module (number of external interfaces, internal storage (FIFOs) size, Quality of Service (QoS) policy, operating frequencies) in order to be configured in different ways according to the requirements of the system that will use it. In its first version, it employs a classical physical layer consisting of 16 wires over which data flow at the speed of 450 MHz. The whole system is able to run at up to 400 MHz. Its area depends on the internal storage size as well as on the number of external modules supported.

- **VHDL model of a configurable serializer/deserializer**. Serializer and deserializer have been implemented as parametric building-blocks, with configurable input and output size, allowing getting, in a fast and easy way, a specific serializer/deserializer pair, already verified and characterized in terms of area occupancy and operation frequency. The parametric approach will allow carrying out architectural exploration simply by changing the values of the parameters, for example understanding, by means of simulation results, which is the optimum width of the off-chip data stream, which in turn determines the number of plasmonic emitter/modulator/detectors to be used in order to get specific performances.

- **Transaction Level Model (TLM) view of the platform that will be used for demonstrator design and validation**. This platform allows generating the stimuli for the system to be validated. In the first phase, the RTL VHDL view of the overall system will be stimulated and validated. In a second phase, the system will be mapped onto FPGA and will be stimulated and validated re-using the same platform. At first, the system will include classical electrical PHY (wires) implementing the chip-to-chip communication. Then, the electrical PHY will be replaced with the novel PHY exploiting plasmonic components, that will be available as discrete components mounted on small boards driven by the digital parts mapped onto FPGA.

- **Verilog-A training attended**: Verilog-A, a Hardware Description Language (HDL) with capabilities for modeling analog electronic devices, as well as photonic, mechanical and thermal systems, will be used for modeling the plasmonic devices in terms of both functionality and physical effects conditioning their behavior (such as temperature variation impact on performance, etc.), and the analog electronic components allowing the digital electronic system to interact with the plasmonic devices, such as emitter/modulator driver, Trans-Impedance Amplifier (TIA), voltage level adjusters, and so on.

2.7 Ghent University (UGent)

- **Synthesis of multiple dot-in-rod heteronanostructures.** Pb cations in PbS quantum rods made from CdS quantum rods by successive complete cationic exchange reactions are partially re-exchanged for Cd cations. Using STEM-HAADF, UGent showed that this leads to the formation of unique multiple dot-in-rod PbS/CdS heteronanostructures, with a photoluminescence quantum yield of 45−55%. We argue that the formation of multiple dot-in-rods is related to the initial polycrystallinity of the PbS quantum rods, where each PbS crystallite transforms in a separate PbS/CdS dot-in-dot. Effective mass modeling indicates that electronic coupling between the different PbS conduction band states is feasible for the multiple dot-in-rod geometries obtained, while the hole states remain largely uncoupled.

- **Demonstration of broadband, picosecond intraband absorption in lead chalcogenide quantum dots.** Using femtosecond transient absorption spectroscopy UGent demonstrated that lead chalcogenide nanocrystals show considerable, photoinduced absorption (PA) in a broad wavelength range just below the bandgap. The time-dependent decay of the PA signal correlates with the recovery of the band gap absorption, indicating that the same carriers are involved. Based on this, UGent assign this PA signal to intraband absorption, i.e., the excitation of photogenerated carriers from the bottom of the conduction band or the top of the valence band to higher energy levels in the conduction and valence band continuum. UGent confirmed experimental results with tight-binding calculations. This broadband response in the commercially interesting near to mid-infrared range is very relevant for ultra high speed all optical signal processing. UGent benchmarked the performance with bulk-Si and Si-nanocrystals.

- **Demonstration of giant absorption enhancement in close-packed quantum dot monolayers.** The absorption cross section of colloidal quantum dots in close-packed monolayers showed a 4 (CdSe) to 5-fold (PbS) enhancement compared to quantum dots in a dilute dispersion. Quantitative agreement was demonstrated between the value and the size dependence of the enhancement and theoretical model predictions based on dipolar coupling between neighboring quantum dots. This collective optical behaviour offers a new degree of freedom in the custom design of optical properties for electro-optical devices.

3. Important References

- NAVOLCHI website: www.navolchi.eu
- More on NAVOLCHI and plasmonics for communications: Juerg Leuthold *et al*, “Plasmonic Communications: Light on a Wire”, Optics & Photonics News, May 2013.