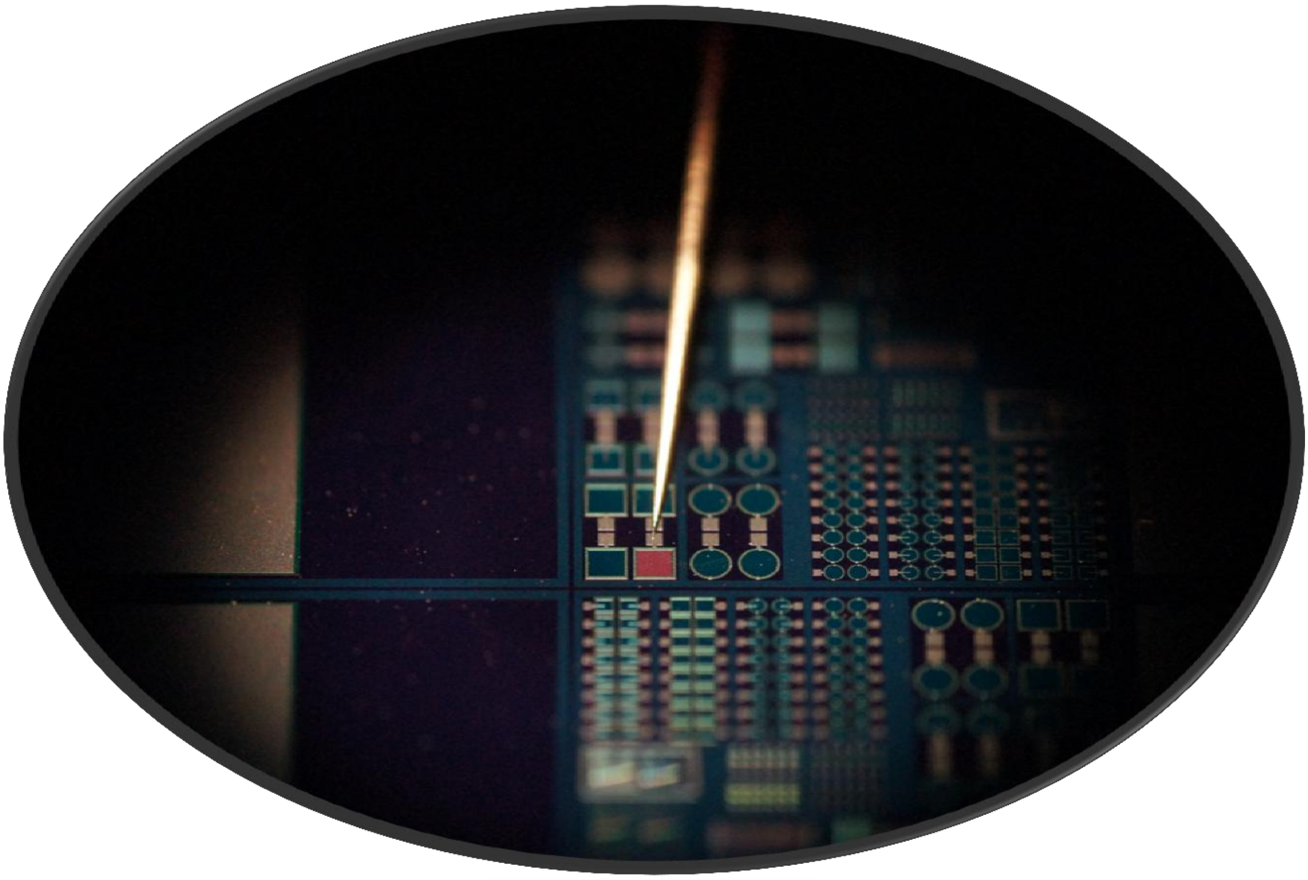
UNIVERSITY
OF TRENTO - Italy
Department of Physics

NANOSCIENCE LABORATORY



HIGHLIGHTS 2013

NANOSCIENCE LABORATORY
HIGHLIGHTS 2013

MEMBERS (2013)

Faculty and research staff

Lorenzo Pavesi (full professor, head)
Marina Scarpa (full professor)
Zeno Gaburro (assistant professor)
Paolo Bettotti (researcher)
Fernando Ramiro Manzano (researcher)

Technical staff

Massimo Cazzanelli (EP2 level)
Enrico Moser
Giorgio Fontana (EP5 level)

Administrative staff

Tatsiana Yatskevich
Dina Shakirova

Post-doctoral fellows

Oleksiy Anopchenko (left March 2013)
Elena Froner (left February 2013)
Nikola Prtljaga (left February 2013)
Mattia Mancinelli (from April 2013)
Andrea Tengattini (from December 2013)
Romain Guider (from July 2013)

Doctoral students

Mattia Mancinelli (graduated in March 2013)
Federica Bianco (graduated in March 2013)
Fabrizio Sgrignuoli (graduated in March 2013)
Andrea Tengattini (graduated in November 2013)
Neeraj Kumar (graduated in December 2013)
Davide Gandolfi
Massimo Borghi
Fabio Turri
Zahra Bisadi

Master students

Marta Guarisco
Stefano Tondini
Stefano Vidotto
Martino Bernard
Andrea Zanzi

SCIENTIFIC MISSION

Introduction to the Nanoscience Laboratory

The Nanoscience Laboratory (NL) is one of the laboratories of the Department of Physics of the University of Trento. Its main area of research is nanophotonics, silicon-based photonics and nanobiotechnologies. The mission of NL is to generate new knowledge, new applications and new devices by understanding the physical phenomena which occurs at the nanoscale. In particular, NL works on applying the nanoscience paradigm to silicon or silicon compatible materials to enable new uses of these key materials, and to develop nanosystems compatible with the main driving silicon technologies. However, silicon is not the only material studied. Other field of interest concerns the use of polymers to tailor the properties of nanostructure atom-by-atom or the use of metals to investigate new properties which rise from plasmonics.
The research projects of NL span from fundamental research work on the interaction between biomolecules and silicon nanostructures or on the control of photons by dynamically structuring the dielectric environment, to more applied research work on the development of integrated optical circuits, optical switches, light emitting devices and amplifiers, novel MIR sources, third generation photovoltaic and biosensors.
NL research group consists of more than 15 people with different scientific background. Such, researchers from physics, bio-chemistry, materials science and electrical engineering are gathered together to form a group of interdisciplinary nature.
It is worth mentioning that NL collaborates closely with the Center of Materials and Microsystems, Fondazione Bruno Kessler (FBK), in particular with its Advance Photonics and Photovoltaic and Biofunctional Surfaces and Interfaces units. This collaboration spans over the last twenty years and covers such topics as fabrication, testing and application of biomaterials and silicon based devices. There are many common projects: current initiatives are the project “On silicon chip quantum optics for quantum computing and secure communications – SiQuro” (financed by the Province of Trento (PAT)) and the project “Integrated SYsteM based on PHOtonic Microresonators and Microfluidic Components for rapid detectioN of tox-

ins in milk and diarY products – SYMPHONY" (sponsored by the European Commission).

Moreover, with the support of FBK and CNR-INO, other principal partner for NL, every two years NL organizes the winter school on optoelectronics and photonics. In 2013 it was organized a school on the Physics and Applications of optical resonators, while the next edition will be on Quantum Optics and is already scheduled for March 2015. Furthermore, the members of NL are invited to participate in the organizing committees of international conferences or workshops.

The research activity of NL is mainly funded by the local government (PAT), by the European Commission within the research frameworks, by the Italian Ministry of Education, University and Research (MIUR) and by companies. During the period covered by these Highlights, NL has been and is involved in the following projects: Project FIRB NEMATIC "Nanoporous matErials: self asseMbled blAckboard to study sTructure and InteraCtions of DNA, project SiQuro (supported by PAT within the call Grandi Progetti 2012), Project Fond. CARITRO "Colorectal cancer associated macrophages as potential prognostic biomarker and therapeutic target, project NANO@AT (supported by PAT within the collaboration between Adelaide & Trento), projects on the mid-wave infrared supercontinuum from silicon waveguides (supported by the CARIPLO foundation), collaborative project Italy-India (ITPAR) supported by MIUR, some European projects within the 7th Framework: POSITIVE (FP7-ICT-257401), APPCOPTOR (FP7-PEOPLE-275150), SYMPHONY (FP7-ICT-2013-10). Starting from January 1, 2014 NL will be involved in one more collaborative project within the 7th Framework titled "Integrated Reconfigurable sIlicon phonic Switch – IRIS" (FP7-ICT-2013-11).

Silicon Nanophotonics

Silicon photonics is the technology where photonic devices are produced by standard microelectronic processes using the same paradigm of electronics: integration of a large number of devices to yield a high circuit complexity which allows for high performances and low costs. Here, the real truth is to develop photonic devices that can be easily integrated to improve the single device performance and to allow high volume production.

We are involved in researching new optical scheme for implementing optical network on a chip by using concepts of nanophotonics. We use the concept of whispering gallery modes which develops in micro-disks or micro-rings to further tune the photon mode density. These disks or rings are coupled directly with narrow mode SOI (Silicon-on-Insulator) waveguides. High quality factor cavities allow studying fundamental quantum optics concept such as optical forces. Series of coupled micro-rings are studied to implement novel scheme of phase controlled optical networks where EIT (electromagnetic induced transparency) is manifested and exploited to route optical signals.

To develop silicon photonics, one further add-on is making silicon do something which it is not able to do in its standard (bulk) form. Low dimensional silicon, where small silicon nanocrystals or nanoclusters (Si-nc) are developed, is one way to compel silicon to act as an active optical material. The key ingredient that makes Si-nc appealing for photonics are: quantum size effects which makes new phenomena appear in silicon, such as room temperature visible photoluminescence, optical gain, coulomb blockade and multiexciton generation. Our research interests are to exploit quantum confinement and reduced dimensionality to produce effective light sources, lasers, and optical amplifiers. In addition, we use quantum confinement to increase the nonlinear optical properties of silicon and to achieve optical switching. Finally, the use of strain to tune the non-linear optical properties of silicon waveguides paves the wave to the development of new MIR sources.

Nanobiotechnologies, antioxidants and human health

All the aspects related to the nano-bio interfaces (which are the structures where the co-existence of physical principles and biological molecules is clearly evident) are a challenging field of research. Though the leading research concerns the design, synthesis and dynamic behavior of nano-structured bio-interfaces, more specifically we are working on three research topics: silicon- and titanium based nanosystems, single molecule detection, and antioxidant behavior in micelle systems.

To develop silicon based bio-sensors, we are currently focused on silicon based hybrid nanostructures. In particular silicon or silicon nitride flat or porous films are the starting inorganic support into which bio active layers are designed. Biological recognition elements are introduced on this hybrid layer. Molecular surface density, active layer thickness and integration of the bio-active interface with photonic devices will be the future challenges to develop the sensor system. In addition, we are developing nanostructured hybrid interfaces to capture bio-analytes and enhance their Raman signals. Gold and silver nanoparticles are used as enhancers.

Beyond traditional sensor applications, silicon nanostructures can be used as "nanosensors", which monitor the intracellular events without introducing irreversible perturbations. To this regard light emitting silicon quantum dots appear very promising. We are studying the nanoparticle coating to increase optical stability and decrease toxicity, moreover conjugation to biological molecules and strategies to increase cell uptake and control intracellular localization are future steps of this research. Titanium nanotubes showing hydroxyl-rich interfaces have been synthesized. These nanosystems are easily dispersed and stable in aqueous solutions and show a high photocatalytic activity.

Antioxidant compounds are able to control reactive and damaging forms of oxygen, referred to as free radicals. Though antioxidants have been largely studied, much remains unknown about the human body adsorption and use of these compounds. We are investigating the synergistic effect of plasma antioxidants at the interface of micelle systems. Beyond the basic biophysical investigation, the crucial point is the development of devices and methodologies to monitor the antioxidant action. Being these processes free-radical mediated, very high detection sensitivity is required. Moreover, to have physiological significance, the experiments should be performed in heterogeneous systems mimicking an un-perturbed biological environment. Thus we are proposing a new theoretically based methodology to compute antioxidant capacity and efficiency starting from oxygen concentration measurement, as well as, we are designing a nanostructured electrode to monitor molecular oxygen in real time.

Experimental facilities

The NL facilities allow for detailed experimental studies in nanoscience, photonics and biotechnologies. Since the effective collaboration with FBK, most material processing and device productions are performed within their premises.

For photonics, we have facilities to cover the light spectrum from the THz to UV ranges with whatever time resolution is needed. Laser sources comprehends: Ti-sapphire fs-ps laser (1 W average over 1000-700 nm, 2 ps or 70 fs pulses, 82 MHz repetition rate) interfaced with a second harmonic generator and pulse picker; Nd-Yag laser interfaced with an optical parametric oscillator which allows scanning the 400-3000 nm wavelength region (pulse 50 mJ, 10 ns, 10 Hz); Katana fiber laser at 1.55 mm (20 ps, kHz-MHz, 7W); TOPAS pumped with an amplified Ti:Sa laser which covers the 1-2.6 μm range with 35 fs, 10 kHz, 3 mJ; one CW, UV extended, Ar laser; four tunable CW lasers (850-870 nm, 1200 - 1700 nm and 1500 - 1600nm) fiber pig-tailed; 4W EDFA and 2W semiconductors amplifiers, several pig-tailed diode lasers, ASE source at 1550 nm and a broad band SLD at 800 nm. Three high-power true-CW DPSS single-line laser operating at 532 , 473 and 355 nm. Detectors comprehend: visible and infrared photomultipliers and CCDs, a streak camera with ps resolution, 4K cooled bolometers which cover THz region, avalanche photodiodes for vis and IR ranges plus one capable of photon-counting in the third telecom window, NIR and MIR and thermal camera for imaging and detection. Oscilloscopes at 3 and 16 GHz. To perform spectral analysis several set-ups are available: FTIR and dispersive spectrophotometers, a micro-Raman setup, a micro-FTIR and a UV-vis-IR spectrophotometer (shared with other laboratories), UV-Vis and fluorescence spectrophotometer dedicated to biochemical experiments. Six dedicated apparata for WG characterization equipped with nanopositioning systems and polarization controllers are available, each one specified on a given functions: visible, infrared, biosensing with microfluidics, grating coupling and non-linear measurements. Other apparata are: - visible and infrared photoconductivity set-up; - a solar simulator for cell sizes up to 5 inches; - two nanoprobe stations (AFM and SNOM) - two semiconductor probe stations (4 and 8 inches) and many different electrical characterization set-ups (I-V, Z-ω, EL-I, etc.). Two VIS to NIR optical spectrum analyzers are available to NL-Lab. A probe station is fiber-bunch interfaced with a spectrometer interfaced with IR and visible liquid nitrogen cooled CCDs. For sample treatment and high sensitivity analytical detection, an electrochemical laboratory equipped with several chemical hots, spinners, galvanostates and voltammeters is available. An electron beam lithography set-up (SEM attachment) is also owned. For optical, electrical and molecular dynamic simulations, the laboratory uses free and commercial software, a dedicated cluster with 16 nodes and work-stations. Two laboratories, one dedicated to chemical synthesis and the second to biological sample preparation, are also available.

2013 PhD Thesis

Mattia Mancinelli *"Linear and nonlinear coupling effects in sequence of microresonator"* (25 March, 2013)

Federica Bianco *"Second order nonlinear optical phenomena in strained silicon waveguides"* (25 March, 2013)

Fabrizio Sgrignuoli *"Silicon nanocrystals downshifting for photovoltaic applications"* (26 March, 2013)

Andrea Tengattini "*Erbium and silicon nanocrystals based light emitting devices for lightwave circuits*" (11 November 2013)

Neeraj Kumar *"Fabrication of n-type porous silicon membranes for sensing applications"* (17 December, 2013)

2013 publications:

1. "Toward a 1.54 μm electrically driven erbium-doped silicon slot waveguide and optical amplifier", A. Tengattini, D. Gandolfi, N. Prtljaga, A. Anopchenko, J. M. Ramirez, F. Ferrarese Lupi, Y. Berencen, D. Navarro-Urrios, P. Rivallin, K. Surana, B. Garrido, J.-M. Fedeli, L. Pavesi, Journal of Lightwave Technology, 31, 391 (2013).
2. "Quantum effects in silicon for photovoltaic applications", P.Ingenhoven, A.Anopchenko, A. Tengattini, D. Gandolfi, F. Sgrignuoli, G. Pucker, Y. Jestin, L. Pavesi, R. Balboni, Phys. Status Solidi (a) 210, 1071-1075 (2013).
3. "Er-doped light emitting slot waveguides monolithically integrated in a silicon photonic chip", J. M. Ramìrez, F. Ferrarese Lupi, Y. Berencen, A. Anopchenko, O. Jambois, J. M. Fedeli, L. Pavesi, N. Prtljaga, J. P. Colonna, P. Rivallin, A. Tengattini, D. Navarro-Urrios, B. Garrido, Nanotechnology, 24, 115202 (2013).
4. "Electroluminescent devices based on nanosilicon multilayer structures", A. Anopchenko, A. Marconi, F. Sgrignuoli, L. Cattoni, A. Tengattini, G. Pucker, Y. Jestin, L. Pavesi, Phys. Status Solidi (a) 210, 1525-1531 (2013).
5. "Infrared photoconductivity of Er-doped Si nanoclusters embedded in a slot waveguide", A. Anopchenko, N. Prtljaga, A. Tengattini, J.M. Fedeli, L. Pavesi, Applied Physics Letters, 103, 061105 (2013).
6. "Role of electron and hole transport processes in conductivity and light emission of silicon nanocrystals field effect transistors", L. Cattoni, A. Tengattini, A. Anopchenko, J. M. Ramìrez, F. Ferrarese Lupi,

Y. Berencen, B. Garrido, J. M. Fedeli, L. Pavesi, Proc. SPIE 8629, Silicon Photonics VIII, 862914 (2013).

7. "Electrically pumped Er-doped light emitting slot waveguides for on-chip optical routing at 1.54 μm," J. M. Ramírez, Y. Berencén, D. Navarro-Urrios, F. Ferrarese Lupi, A. Anopchenko, N. Prtljaga, P. Rivallin, A. Tengattini, J. P. Colonna, J. M. Fedeli, L. Pavesi, and B. Garrido, Proc. SPIE 8767, Integrated Photonics: Materials, Devices and Applications II, 87670I (2013).
8. "Super-Hydrophilic PDMS and PET Surfaces for Microfluidic Devices", R. Bartali, L. Lorenzelli, M. Scarpa, E. Morganti, C. Collini, V. Micheli, G. Gottardi, A. Gambetti, G. Gambetti, G. Coser, R. Pandiyan, I. Luciu, N. Laidani, Advances in Science and Technology (Volume 81), 96-100.
9. "Stable Aqueous Solutions of Naked Titanate Nanotubes", L. Zennaro, M. Magro, F. Vianello, A. Rigo, G. Mariotto, M. Giarola, E. Froner, M. Scarpa, ChemPhysChem 12, 2786-2792.
10. "Thermo-optical bistability with Si nanocrystals in a whispering gallery resonator", F. Ramiro-Manzano, N. Prtljaga, L. Pavesi, G. Pucker, M. Ghulinyan, Opt. Lett., 38, 3562 (2013).
11. "An all optical method for fabrication error measurements in integrated photonic circuits", M. Mancinelli, M. Borghi, P. Bettotti, J.-M. Fedeli, L. Pavesi, J. Lightware Technol., 31, 2340 (2013).
12. "Oscillatory vertical whispering-gallery resonator and a bus waveguide", M. Ghulinyan, F. Ramiro-Manzano, N. Prtljaga, R. Guider, I. Carusotto, A. Pitanti, L. Pavesi, Phys. Rev. Lett., 110, 163901 (2013).
13. "Dry adhesive bonding of nanoporous inorganic membranes to microfluidic devices using the OSTE(+) dual-cure polymer", F. Saharil, F. Forsberg, Y. Liu, P. Bettotti, N. Kumar, F. Niklaus, T. Haraldsson, W. van der Wijngaart, K.B. Gylfason, J. Micromech. Microeng, 23, 025021 (2013).
14. "Interferometric switching in coupled resonator optical waveguides-based reconfigurable optical device", M. Mancinelli, P. Bettotti, J.M. Fedeli, L. Pavesi. Opt. Lett., 38, 217 (2013).
15. Fernando Ramiro-Manzano ; Mher Ghulinyan ; Nikola Prtljaga ; Georg Pucker and Lorenzo Pavesi " Silicon-based monolithically integrated whispering-gallery mode resonators", Proc. SPIE 8600, Laser Resonators, Microresonators, and Beam Control XV, 86001G (2013).
16. " Interferometric switching in CROW based reconfigurable optical device for routing application ", M. Mancinelli ; P. Bettotti ; J.-M. Fedeli and L. Pavesi. Proc. SPIE 8629, Silicon Photonics VIII, 86290T (2013).
17. "Monolithic integration of high-Q wedge resonators with vertically coupled waveguides" Fernando Ramiro-Manzano, Nikola Prtljaga, Lorenzo Pavesi, Georg Pucker, and Mher Ghulinyan. Proc. SPIE 8767, Integrated Photonics: Materials, Devices, and Applications II, 876704 (May 22, 2013).

2013 book:

Handbook of Silicon Photonics, Laurent Vivien and Lorenzo Pavesi editors, CRC Press (Taylor and Francis group, April 2013) 849 pp. ISBN:978-1-4398-3610-1

1. Nanoporous materials for sensing and analytical applications (Paolo Bettotti)

The study of nanoporous materials structure and properties is of fundamental importance to develop reliable devices for sensing and analytical applications. The improvements in Porous Silicon (PSi) free standing membranes technology has led to the demonstration of their compatibility with the realization of microfluidic devices [1]. Free standing membranes were successfully transferred to foreign substrates and integrated into microfluidic devices. Furthermore, the large pore size tunability obtained with the optimized etching receipt allowed the fabrication of thin membranes (down to a couple of microns) having area of the order of square centimeter while, at the same time, keep the full tunability of the pore size [2].
The role of mass transport in the reduction of non-specific signal in optical bioassay was investigated using PSi membranes. We demonstrated a systematic overestimation of the sensitivity for porous devices made of closed-ended pores compared with open-ended pore ones. Our analysis shows that such an effect is due to the nonspecific signal induced by either unbound analytes or contaminants that remain trapped within the pores and are not removed by rinsing of the sample [3].
In March 2013, the FIRB project NEMATIC (www.science.unitn.it/~members/bettotti/nematic) started with the aim of exploring the possibility of using PSi membrane for DNA analysis and separation. To perform the initial characterization of the diffusion properties of the porous membranes, a dedicated setup for time resolved micro-photoluminescence, compatible with microfluidic devices, has been installed.

References:

1. F. Saharil et al., "Dry adhesive bonding od nanoporous inorganic membranes to microfluidic device using OSTE (+) dual cure polymer, J. Micromech. Microeng., 23,25021 (2013)
2. N. Kumar et al., "Self detachment of free-standing porous silicon membranes in moderately doped n-type silicon", Appl. Phys. A, DOI: 10.1007/s00339-013-8104-6
3. N. Kumar et al., "Investigation of non-specific signal in nanoporous flow through and flow over sensors", Analyst, 139, 1345 (2014)

2. Integrated system based on photonic microresonators and microfluidic components for rapid detection of toxins in milk and dairy products (Romain Guider)

Since November 2013, the Nanoscience Laboratory is involved in the European Project SYMPHONY. The objective of this project is the creation of a novel analytical platform to detect aflatoxin in milk and prevent infection of dairy products [1]. In order to achieve such a goal, our group will design and test a photonic sensing device based on photonic resonators integrated in microsystem technologies, for highly sensitive detection. With the use of this technology, we aim to achieve the characterization of miniaturized smart system that will perform low cost label free detection.
To realize this goal, we will develop a photonic circuit with laser source(s) (VCSEL) and photodetectors integrated on a single chip capable of measuring relative refractive index variations as small as $1x10^{-6}$ RIU, which can be easily integrated in the microfluidics cartridge and the analysis chamber [2].
Our main activity during these first three months was to establish a general design of the photonic sensor, according to the various project's requirements, like microfluidic or VCSEL integration. In agreement with the other partners, the complete sensing device will have an overall geometry of 1cm x 1cm. As a sensor, the material chosen for the design will be silicon oxynitride (SiON) on top of a SiO_2 layer, and covered by TEOS (that has similar refractive index to SiO_2). The parameters of the waveguide have been chosen in order to be single mode. As sensing elements, microrings resonators will be used and directional coupler will be in charge of the routing of the signal inside the photonic chip (Figure 1). Preliminary simulations concerning all building blocks of the photonic sensor have been performed in order to confirm the feasibility of such design.

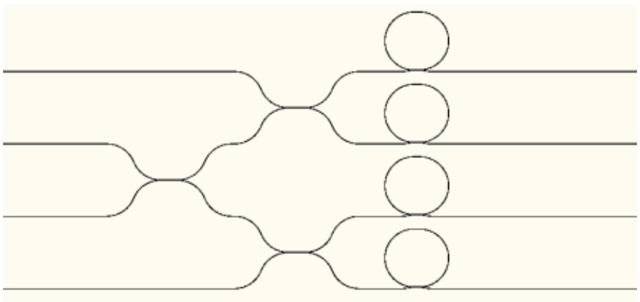


Figure 1. Scheme of a 1x2/1x4 splitter based sensor

References:

1. Eaton, D.L. and Groopman, J.D., “The Toxicology of Aflatoxins,” Academic Press New York., 383-426 (1994).
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3. Optofluidic setup for real-time immunoassays (Davide Gandolfi)

In the field of biological analysis, the immunoassay is a firm technique which is applied in many commercial devices. Nowadays, however, a cheap, portable and fast immunoassay-based detector is still not available. In our laboratory, we try to conjugate the paradigm of silicon photonics with that of label-free immunoassay biosensing. The advantages are the miniaturization of the sensing elements and the possibility of mass-production by means of photolithography [1].
In the past years, we acquired the experience necessary to fabricate high-Q whispering-gallery-mode resonators [2] and successfully demonstrate the specific recognition of target analytes in liquid phase. However, the sensor's performances were still limited by the poor reproducibility

and sample purity during the handling of the liquids. For this reason, we designed and developed an optofluidic set-up (Figure 2.) which permits a fast real-time monitoring of the sensor’s signal.

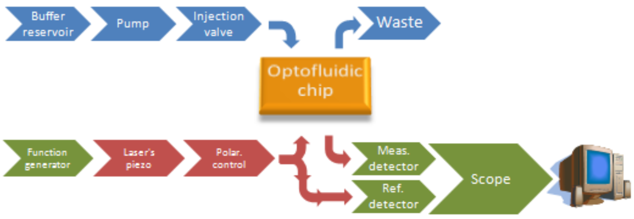

Figure 2. Schematic of the experimental set-up. Fluid paths are in blue, electrical signal in green and laser light in red.

For the optical part, we used an external-cavity tunable laser, modulated by a piezoelectric actuator driven by a function generator. The laser polarization is controlled and the light is split in two fibers. One is used as power reference and the other for the in-coupling to the photonic chip. At the output of the chip, the light is then measured with two photodetectors that are acquired by an oscilloscope. In order to get the spectral position of the sensor’s resonance, the signal is analyzed twice per second with a PC software.

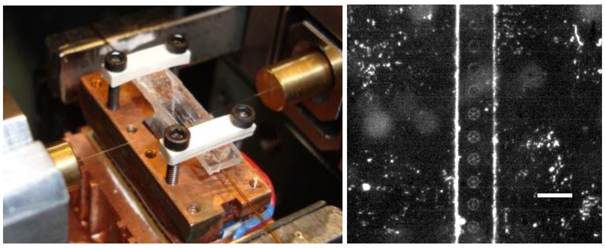

Figure 3. Close-up and microscope picture of the mounted optofluidic chip

For the fluidic part, we used a soft elastomer (PDMS) to cast a microchannel. The width and height of the channels are only 200µm and 100µm, respectively. Precision alignment of the channel with respect to the photonic structures is obtained with micrometric screws, while a leak-tight sealing is achieved by pressing the microfluidic chamber on top of the chip. The liquid sample is inserted in a continuous flow of buffer solution thanks to an injection valve. Flow rates can be as low as 0.01µl/min, and the minimum sample volume can be 0.1µl. The liquid is delivered towards the microchannel via capillaries.

With this setup we managed to monitor refractive index variations in real time with a detection limit of 10^{-5} RIU.

References:

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4. Charge Injection, Transport and Recombination in Silicon Nanocrystals Light Emitting Devices (Andrea Tengattini)

Current-Voltage (I-V) and Capacitance-Voltage (C-V) characteristics of the silicon nanocrystals based light emitting devices (LEDs) have been performed and tell us the different qualities of the oxide for different fabrication processes. Moreover, the C-V measurements give us a hint on the role of the thick barrier oxide in permitting the formation of the inversion layer, and, therefore, of the injection of hot electrons through the active layer.

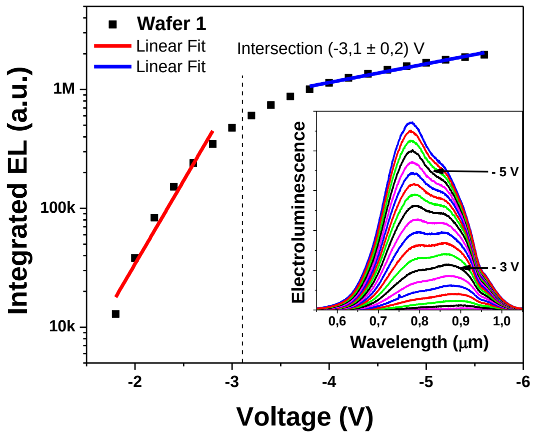

Figure 4. Integrated EL as a function of the applied voltage to a LED of W1. The EL spectra recorded for different applied voltages are represented as inset.

A spectral analysis of EL was performed on the studied samples (Figure 4). Starting from the obtained results the different emission mechanisms that can occur under appropriate gate bias condition have been discussed. The spectra revealed a peak around 900 nm, evident below 3V in forward bias, and the onset of a peak at about 800 nm, at higher voltages. The origin of this behavior lies in the different mechanisms that generate luminescence in the silicon nanocrystals. The most probable path for EL involves both exciton recombination in the Si-NCs, at longer wavelengths, and defect-assisted recombination, where luminescence is the result of the recombination of carriers trapped at radiative recombination centers that form at the interface between Si-NCs and the dielectric or even in the dielectric itself. The light emission at low voltages is due to the bipolar (electrons and holes) injection via direct tunneling mechanism. In fact, EL occurs at voltages lower than 3.1 or 4.7 V, which are the values corresponding to the height of the energy barriers at the silicon oxide interface for electrons or holes, respectively. At higher voltages, Fowler–Nordheim tunneling of hot electrons into the oxide conduction band occurs: EL is then produced by recombination of electron-hole pairs in the Si-NCs or through trapped carriers on radiative interface states, which have been excited by the current of hot electrons via an impact excitation mechanism. By applying square wave voltages at varying frequencies, integrated EL peaks at a frequency between 10 kHz and 100 kHz, depending on the root mean square value. Beyond these values the pulse duration will

be shorter than the radiative lifetime of the Si-NCs and some of the excitons will not recombine due to the statistical nature of spontaneous emission.
Time-resolved EL measurements yield more direct information of the carrier dynamics of the devices operation. Using pulsed pumping scheme there is the possibility of sequentially injecting opposite carriers into the Si-NCs material, which subsequently recombine radiatively. This is pointed out by the presence of EL overshoots when the supply voltage is swept abruptly from positive-to-negative value and vice versa.

References:

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5. Chaotic dynamics in coupled resonator sequences (Massimo Borghi, Mattia Mancinelli)

Thermal and free carrier induced refractive index changes in silicon microresonators have been widely investigated in the last few years due to their implementation in bistable switching or electro optic signal modulation. When carrier injection and material heating are internally induced by Two Photon Absorption in the 3rd Telecom band (1.55 μm), new phenomena emerges. The periodic self pulsing of the transmitted intensity of a single silicon microdisk at continuos wave (CW) input has been the most investigated one as it promises to be the fundamental building block of neuromorphic networks [1,2]. Only few theoretical works exist on sequences of coupled resonators, and they are mainly focused on Kerr-like nonlinearities, neglecting thermal and free carrier ones. In our work, we studied these effects in a coupled resonator sequence organized in the SCISSOR geometry [3,4]. The SCISSOR is composed by 8 ring resonators and has been fabricated using 193 nm Deep Ultraviolet Lithography in a Silicon On Insulator substrate. The sample has been probed using a CW tunable infrared laser. By monitoring the output intensity in time, we observed a new turbulent regime showing unambiguously the character of chaos. Chaotic instabilities have been only theoretically predicted under Kerr nonlinearities, but the extremely small ratio between the Kerr and the thermo optic coefficient have precluded any direct experimental observation. Here, the intra cavity optical feedback coupling is shown to overcome this limitation, enabling the instauration of chaos even in presence of thermal effects. To stress the chaotic nature of the oscillations, we proved that aperiodic intensity fluctuations possess a strong sensitivity to slightly changes in initial conditions, such as temperature and power, and that the output intensity never folds on itself as the time is running. Chaotic outputs have been observed in different ranges of input power and wavelength. Using the tools of Lyapunov exponents and phase space trajectories, we were able to relate the regions of chaotic instabilities to the input exciting conditions and to the device geometry.
The generated chaotic signals can be used to generate random bit sequences. Bitrates up to 1Gbps have been demonstrated in a single device. Being naturally compatible with silicon photonics, the device can be straightforwardly implemented in more complex networks which further manipulate the signals to raise the bitrate.

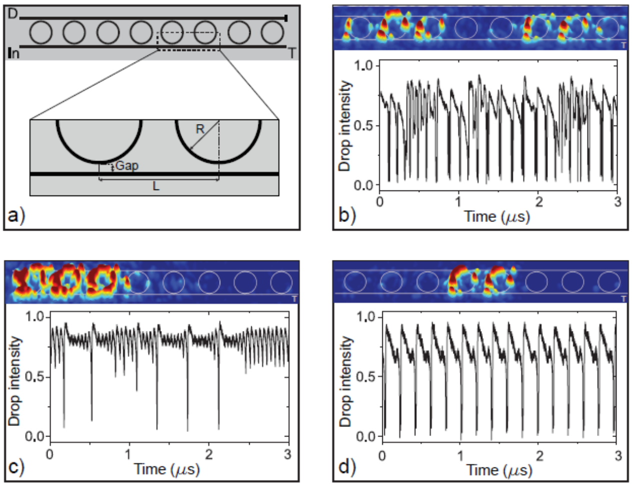

Figure 5. (a) Sketch of the device geometry. It has three ports, named Input (In), Drop (D) and Through (T). The rings, of radius R = 6.75 μm and separation L = 22 μm, are side coupled to the straight waveguides by a 300 nm gap. (b-d) Some of the observed drop signal waveforms at various condition of input power and wavelength. Insets on the top reveal the top scattered radiation patterns, showing the internal energy distribution among the resonators.

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6. Thermo-optical bistability with Si nanocrystals in a whispering gallery mode resonator (Fernando Ramiro-Manzano)

The phenomenon of optical bistability (OB) has attracted a large interest in photonics since it enables the full optical implementation of switches, logical gates, and memories. The functionality of a bistable device, which provides two stable states for the same input, relies on nonlinear modulation of the material properties. Optical bistable devices based on resonators exploit the nonlinear modulation of the resonant modes' spectral position relying on the light-intensity-dependent refractive index, n(I).

The refractive index changes required for the observation of OB can be achieved through several mechanisms such as χ(3) (Kerr) nonlinearities. This effect, also known as the quadratic electro-optic effect, has attracted particular attention because of its instantaneous nature. In most materials, the Kerr-associated nonlinear coefficient, n2, is extremely small; therefore the n(I)-modulation requires high pumping powers. Often, other nonlinear mechanisms related to the material absorption, such as the thermo-optical effect, can dominate the n(I) modulation and mask out the nonlinear Kerr contribution. One alternative to overcome the thermal effects is to employ highly transparent materials such as silica. Although the nonlinear Kerr coefficient of this material is very low (n2 ≈ 2.2×10−20 m2⁄W), ultra- high-quality factor (UHQ) resonators allow to reach GW⁄cm2 intracavity intensities in order to achieve efficient nonlinear generation schemes. On the other hand, crystalline silicon shows two orders of magnitude larger n2 with respect to silica; however, it suffers a large thermo-optical coefficient (TOC). A promising non-linear material composed of Silicon nanocrystals (Si-ncs) embedded in a dielectric host such as silica, has shown an order of magnitude larger Kerr coefficient n2 than the bulk Si and low TOC [1].

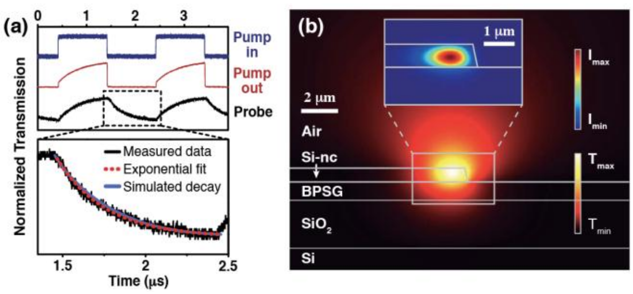

Figure 6. (a) Top panel: the modulated pump transmission measurements of the input pump beam, the output pump signal, and the probe signal. Bottom panel: a magnification of the probe signal decay, the fit curve, and the FEM model result. (b) The calculated temperature map profile of the resonator. The inset shows the optical energy density distribution employed in the FEM simulations for the heat dissipation.

In our work [2], we have demonstrated thermo-OB in a fully integrated Si-nc-based microresonator. We employed a vertical coupling scheme between the resonator and the waveguide to access the thermal nonlinearities of Si-ncs present in the resonator only. The estimated thermo-optical coefficient of the Si nanocrystalline material, dn⁄dT ≈ 2.92×10^{-5} K^{-1}, is an order of magnitude lower than that of bulk silicon. Both time-resolved pump-and-probe experiments and numerical simulations confirm that the silica host is responsible for the heat dissipation from the resonator (Figure 6). These results, combined with previous reports on large Kerr nonlinearities of Si-ncs, suggest that efficient nonlinear optical devices might be realized by proper engineering of Si-nc-based ultrahigh Q resonator devices.

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7. Oscillatory Vertical Coupling between a Whispering-Gallery Resonator and a Bus Waveguide (Fernando Ramiro-Manzano)

A typical strategy to study the physics of planar whispering-gallery mode (WGM) resonators consists of exciting the cavity modes from an adjacent waveguide and collecting the transmitted light. The resonator-waveguide coupling (RWC) takes place via an overlap of the evanescent fields of the waveguide and the resonator optical modes. In an in-plane geometry, where the waveguide and the resonator lay on the same plane, the mode coupling is known to grow exponentially when the gap between these two is decreased. This behaviour has important implications in the amplitude and the linewidth of resonant dips that appear in the waveguide transmission spectrum at cavity mode frequencies. As the gap x is reduced (Figure 6), the cavity mode linewidth increases monotonically. The transmission T_{dip} at resonance, in turn, vanishes at a single critical coupling gap when the field propagating in the waveguide and the secondary emission by the resonator interfere destructively on exact resonance.

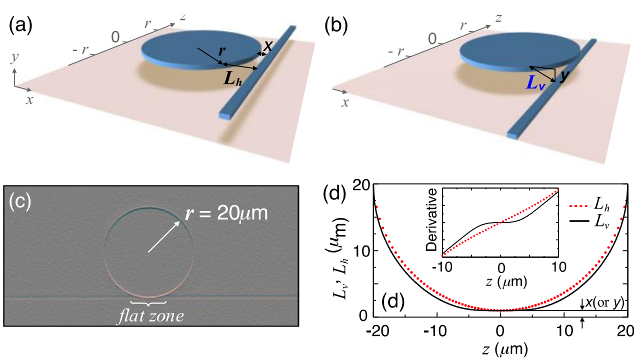

Figure 7. (a-b) Sketches of the coplanar (a) and vertical (b) resonator-waveguide coupling geometries. (c) The digitally processed optical image of the vertically coupled resonator and the waveguide (d) Plot of the effective gap between a 40 µm resonator and a waveguide as a function of the z coordinate along the waveguide axis in the in-plane (Lh, red dotted line) and vertical geometries (Lv, solid line). The presence of the flat zone in Lv is highlighted in the inset, where the first derivative of Lv and Lh are plotted.

Besides, in a vertical coupling strategy, the resonator and the waveguide lay on different planes. So far, it has been assumed that this standard model should be able to predict accurately the RWC coupling behaviour also in the vertical coupling geometry but no specific theoretical study had explicitly validated this assumption.

In our work [1] we show both theoretically and experimentally that this common belief is actually wrong. In fact, in a vertical geometry, the effective gap L_v between the resonator and the waveguide remains almost constant over a sizable distance Λ along the waveguide axis z (Figure 7).

Within this flat zone, the waveguide and the resonator can be modeled as a directional coupler for which the coupled mode theory predicts a periodic exchange of optical power as a function of the propagation distance. In contrast to the monotonic exponential dependence of the effective RWC in the in-plane geometry, the vertical one is characterized by an oscillating effective coupling as a function of vertical gap y, with alternating under- and over-coupling regions, separated by several critical coupling points (Figure 8). Correspondingly, both the cavity mode linewidth Γ and the dip transmission T_{dip} show oscillating dependencies. An excellent qualitative agreement is found between the analytical model based on coupled mode theory and the experimental observations.

The dramatic differences between the vertical and the in-plane coupling geometries have significant consequences. For instance, the use of vertical coupling geometry in second-harmonic generation experiments will allow to freely tune the Q factor of the second-harmonic mode at 2ω while keeping the pump at the fundamental frequency ω in critical coupling.

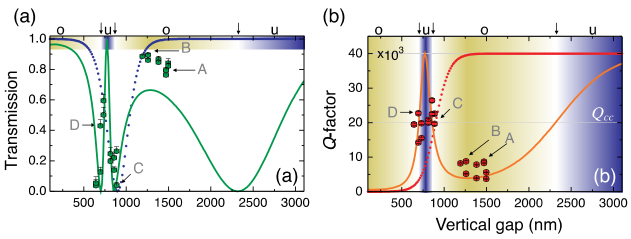

Figure 8. Vertical gap dependence of the resonant transmission T_{dip} (a) and the resonance Q factor (b) for the mode of the wavelength closest to 1:58 μm. Experimental points are compared to the theoretical predictions. For comparison, the T and Q trends for the point coupling model are reported as dotted lines. The background colors underline the regions where undercoupling (blue, u), critical coupling (white, ↓), and overcoupling (yellow, o) are expected.

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8. Optical excitation of thermo-mechanical effect in WGM resonator vertically coupled to a bus waveguide (Fabio Turri)

Optomechanics is becoming a wide field in photonics. In particular, the presence of coupled optical and mechanical degrees of freedom, the low mass and the high quality factors of WGM free-standing resonators offer the possibility to investigate fundamental physics phenomena [1] and to take advantage of optomechanical coupling in on-chip devices [2]. The innovative approach exploited in NL is to use the vertical coupling geometry [3] to investigate optomechanical features of an all-integrated optomechanical device. In this sense we have recently characterized the thermo-mechanical properties of a SiN free-standing WGM resonator fully integrated on a silicon chip. The system consists of a 100 μm diameter SiN ring resonator vertically coupled to a buried SiON bus waveguide.

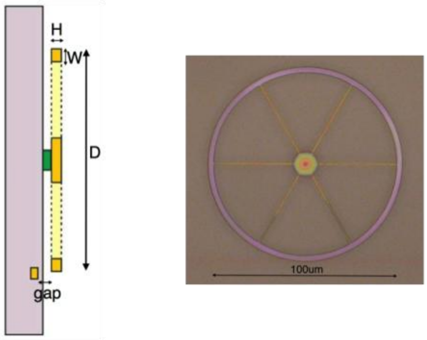

Figure 9. Cross-section sketch and top view of the characterized ring with a 100μm diameter; the buried waveguide is visible in red right at the bottom of the resonator (optical image).

We have characterized the device in high power regime, where temperature dependent processes become evident. An upper threshold for the power has been found, above which mechanical oscillation of the ring is observed. In this regime the system moves between two different configurations without any external modulation applied and it can be well described as a self-vibrating system.

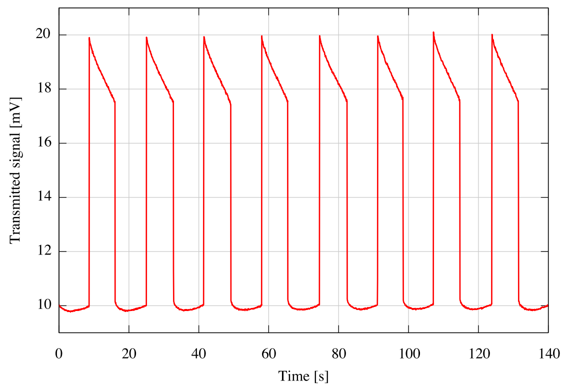

Figure 10. Periodic oscillation with period of 16.5(5) s. Slow variations during the high and low states are also visible.

This oscillation results from a complex thermo-mechanical excitation of the ring and presents interesting features. If power is set near the threshold value it shows a chaotic like nature and it turns into a more periodic pattern if power is further increased. The main parameters of this vibration can be tuned: period depends on the coupled power and duty cycle depends on the laser/ring resonance detuning. This particular behavior of the system at high powers is associated to the mechanical properties of the device, and to a complex interplay between the heating of the ring material and the mechanical deformation of the substrate due to the high optical power stored in the cavity. Future investigations should consider instantaneous temperature monitoring and control, as well as modeling of the thermal and mechanical properties of the device.

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9. Purcell effect and luminescent downshifting in Silicon nanocrystals coated back-contact solar cells (Fabrizio Sgrignuoli)

The high-energy photons (280-400nm) are not used efficiently by conventional silicon solar cell. An effective harvesting of ultraviolet photons is a necessary condition to improve the efficiency of solar cells reducing the cost per watt of electricity produced. Several methods have been proposed to address these spectral losses, and all these concepts concentrate on a better exploitation of the incident solar spectrum such as the luminescent downshifting effect (LDS). The basic idea of LDS is to move short-wavelength photons to long wavelength photons: a range where silicon solar cell has almost 100% internal quantum efficiency (IQE). We investigate this innovative effect using silicon quantum dots (Si-QDs) dispersed in a silicon dioxide (SiO2) matrix [1-3].

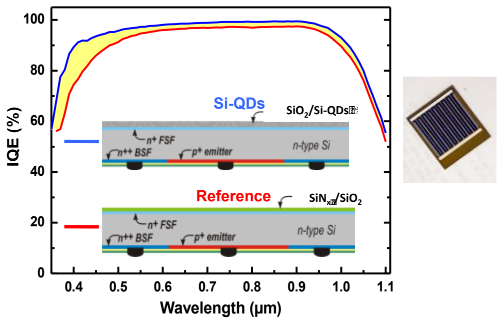

Figure 11. Measured internal quantum efficiency (IQE) enhancement of an interdigitated back contact (IBC) silicon solar cell with Si-QDs as active layer with respect to a reference device coated with an optimized SiNx layer. A photo of the backside of the produced IBC cell is also shown.

In more details, we fabricated, inside the European project LIMA, high quality interdigitated back-contact crystalline silicon solar cells in an industrial pilot line and coated them with optimized Si-QDs layers in a cost effective way. This nanostructured back contact silicon solar cell shows an enhancement of 0.8% in the cell efficiency with respect to standard photovoltaic devices. In addition, we proved that this increase is due to a combination of a better surface passivation, of a better optical matching, and of the LDS effect. Moreover, we demonstrated that the engineering of the local density of photon states, thanks to Purcell effect, is instrumental in order to exploit this effect [4].

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