





HIGHLIGHTS 2021



Director of publication Giancarlo Faini Director

Editors Arnaud Bournel Head of Nanoelectronics Department

Pierre-Yves Joubert Head of Microsystems and Nanobiofluidics Department

> Jean-Christophe Harmand Head of Materials Department

Laurent Vivien Head of Photonics Department

Production Communication Department Céline Lashermes

C2N - Février 2022

Cover photos Copyright Laurent Ardhuin

Summary







A BIOCOMPATIBLE MICROFLUIDIC AR-TIFICIAL LUNG THAT BREATHES

P. 7



NATIONAL STRATEGY ON QUANTUM P. 35 TECHNOLOGIES

THE C2N TECHNOLOGICAL FACILITIES P. 29

HIGHLIGHTS 2021

Editorial

This booklet presents some of the major scientific facts, and events results obtained in 2021 at **C2N**.

demonstrate the Once again, thev dynamism of оиг laboratory, which promotes research of the highest level. This year has once again been marked by major scientific successes for C2N, prizes and medals for some of its researchers and teacherresearchers, promotions and advancement for technical and general service staff. This recognition by our peers and by our supervisory bodies contributes to the visibility of our Unit and the actors who live and work there, on the local, national and international scene.

I would like to express my deep gratitude to all the contributors of this edition of «Highlights 2021», in particular to the researchers and engineers who contributed to the writing, editing and translation of each news item, as well as to the C2N communication team for its valuable contribution to this edition.

We wish you a pleasant reading,

Giancarlo Faini Head of C2N *February 2022*





Copyright Stephan Gladieu

The C2N Management Board from left to right

Arnaud Bournel, Head of the Nanoelectronics department Pierre-yves Joubert, Head of the Micro Systems and Nanobiofluidics department Cynthia Vallerand, Chief Executive Officer Jean-Christophe Harmand, Head of the Materials department Giancarlo Faini, Head of the Unit Laurent Vivien, Head of the Photonics department

PUBLICATIONS

INDIRECT TO DIRECT BAND GAP CROSSOVER IN TWO-DIMENSIONAL $WS_{2(1-X)}SE_{2X}$ ALLOYS

Using angle-resolved photoemission spectroscopy (ARPES) combined with DFT calculations, physicists from the Center for Nanosciences and Nanotechnologies (C2N, Université Paris-Saclay / CNRS), in collaboration with researchers from Hunan University (China) demonstrated that high PL intensity value observed in WS_{0.4}Se_{1.6} bilayers is due to the proximity of direct and indirect optical transitions.

Transition metal dichalcogenides (TMDs) are usually characterized by a crossover from indirect to direct band gap semiconductor as the material thickness drops from several to a single monolayer. This transition can be followed optically as a large increase of the room temperature photoluminescence (PL) signal of at least one order of magnitude. Numerous studies on TMDs have revealed similar PL variation when these materials are reduced to a single layer. We demonstrate that this standard trend may show an exception for WS_{2(1-x)} Se_{2x} alloys. For a particular ternary alloy (x = 0.8), we observe a high PL intensity for monolayer and bilayer domains, for which the PL only decreases by a factor 2 compared to monolayer. To better understand this phenomenon, the electronic properties of $WS_{2(1-x)}$ Se_{2x} (x = 0.8) have been studied using ARPES and density functional theory (DFT) calculations. Our results confirm the classic trend with a direct band gap for single ML alloys and indirect band gap for increasing number of layers. However the case of bilayer (x=0.8) is at the limit and presents both direct and indirect optical transitions. This robustness of PL intensity will ease material integration because it is more tolerant to thickness fluctuations.

The mat2D group at C2N is expert in the electronic properties of 2D materials (Graphene, MX and MX_2) Our activities focus on the design, manufacture and electronic properties of new hybrid heterostructures based on two-dimensional materials, toward the realization of a new generation of nanoelectronic devices. This publication is produced in collaboration with the Hunan University.





References

Indirect to direct band gap crossover in two-dimensional WS_{2(1-x)}Se_{2x} alloys

Cyrine Ernandes, Lama Khalil, Hela Almabrouk, Debora Pierucci, Biyuan Zheng, José Avila, Pavel Dudin, Julien Chaste, Fabrice Oehler, Marco Pala, Federico Bisti, Thibault Brulé, Emmanuel Lhuillier, Anlian Pan, and Abdelkarim Ouerghi

npj 2D Materials and Applications 5, 7 (2021) DOI : 10.1038/s41699-020-00187-9

> **CONTACT C2N** Abdelkarim Ouerghi abdelkarim.ouerghi@c2n.upsaclay.fr

A MECHANICAL FREQUENCY COMB WITH AN ATOMICALLY THIN MATERIAL

By efficiently coupling nanoresonators, made up of suspended 2D semiconductor membranes, with an optomechanical platform, physicists from the Center for Nanosciences and Nanotechnologies (C2N, Université Paris-Saclay / CNRS), in collaboration with researchers from Pennsylvania, produced a coherent mechanical frequency comb having a very large number of harmonics.

We study the mechanical vibrations of innovative materials such as atomically thin 2D materials that are only one nanometer thick. This ultra-thin sheet resonates like a drum, and its resonant frequency is exceptionally adjustable for a nano-object, as a nanoscale guitar string. Taking advantage of this property, we simultaneously measured and adjusted the vibration of 2D materials with electrical and optical excitation techniques. We have coupled the mechanical vibration ω 1, to an electrical signal of frequency ωp. We obtain an artistic figure in the form of a checkerboard (on the left), which represents the comb of frequency $\omega 1 \pm m$ ωp and which contains up to m=100 harmonics and corresponding to the theoretical model (figure on the right). Potential applications are guantum information processing and heat transport.

The technology used is an optomechanical measurement, the mechanical vibration is measured by the reflection of a laser on the sample and the mechanical movement is activated by an electronic signal and a capacitive coupling.

The mat2D group at C2N is expert in the electronic properties of 2D materials (Graphene, MX and MX_2) Our activities focus on the design, manufacture and electronic properties of new hybrid heterostructures based on two-dimensional materials, with a view to the realization of a new generation of nanoelectronic devices. This publication is produced in collaboration with the University of Pennsylvania.



Figure : (left) Frequency comb appearing during the measurement of mechanical resonance as a function of the frequencies fD of the drive and fP of the pump (right) Strong coupling model between the mechanical resonance and the harmonics of the electronic signal. (bottom) Schematic of the device.

References

Multi-order phononic frequency comb generation within a MoS, electromechanical resonator

Anis Chiout, Franck Correia, Meng-Qiang Zhao, A.T. Charlie Johnson, Debora Pierucci, Fabrice Oehler, Abdelkarim Ouerghi, Julien Chaste

Applied Review Letters, 119 (17), 173102 DOI : 10.1063/5.0059015



Contact C2N Julien Chaste julien.chaste@c2n.upsaclay.fr

ELECTRICAL AND ION BEAM ANALYSES OF YTTRIUM AND YTTRIUM-TITANIUM GETTER THIN FILMS OXIDATION

Yttrium, titanium, and yttrium-titanium getter thin films were elaborated on silicon by coevaporation in ultrahigh vacuum. Y-Ti films exhibit nanometric crystallites size (18–35 nm) leading to a very high grain boundary density, which is a favorable microstructure for activation at low temperature. The yttrium content in Y-Ti alloys influences grain size, resistance against room temperature oxidation, and gettering performance for oxygen. Y-Ti films with an yttrium content higher than 30% show strong oxygen sorption during annealing at low temperature (<300 °C). After 1 h of annealing at 250 °C, it was estimated that the yttrium-based getter films can trap between 0.2 and 0.5 µmol of oxygen per cm2, while no oxygen sorption was detected for a single metal titanium film. This makes Y-Ti getter alloys attractive candidates for the packaging of MEMS under vacuum with a low bonding temperature.

A getter film is a metallic thin film that sorbs gaseous species when it is heated. A getter is required to package under vacuum several kind of MEMS which need vacuum to operate properly. For an ANR project, we develop new getter thin films based on the element yttrium, a transition metal which is also a rare earth. In this work, researchers from C2N, CEMHTI and IM2NP have developed new getter films based on the element yttrium, which is a transition metal and also a rare earth. In this work. the getter properties for oxygen-containing gases of thin films made by ultra-high vacuum co-evaporation of yttrium and titanium-yttrium at temperatures ranging from 200 °C to 400 °C were evaluated. They were compared with those of titanium film, the best known and most known used getter.



Figure : Oxygen content in Y-Ti getter thin films after 1 h annealing activation

References

Electrical and ion beam analyses of Yttrium and Yttrium-Titanium getter thin films oxidation

Clément Bessouet, Sylvain Lemettre, Charlotte Kutyla, Alain Bosseboeuf, Philippe Coste, Thierry Sauvage, Hélène Lecoq, Olivier Wendling, Aurélien Bellamy, Piyush Jagtap, Stéphanie Escoubas, Christophe Guichet, Olivier Thomas, Johan Moulin

Journal of Vacuum Science & Technology B 39, 054202 (2021) DOI : 10.1116/6.0001084

> Contact C2N Johan Moulin johan.moulin@c2n.upsaclay.fr

A BIOCOMPATIBLE MICROFLUIDIC ARTIFICIAL LUNG THAT BREATHES

End-stage lung diseases may result in death either by oxygenation and carbon dioxide exchange insufficency or by right heart failure. The macroscopic blood oxygenator ECMO (ExtraCorporeal Membrane Oxygenation) is a therapeutic option, currently used in intensive care units, which aims to temporarily alleviate respiratory failure. Since this oxygenator need to be exchanged within 20 days because of clotting, waiting for a transplant can be critical.

The main objective of the BioArtLung project financed by the French National Research Agency (ANR -RHU) is to develop a sustainable method of respiratory assistance based on microfabrication technologies. The development of a portable, miniaturized microfluidic oxygenator that can be used for several months would add a new therapeutic solution for patients awaiting lung transplantation.

In the field of microfluidic oxygenators, maximizing gas exchange efficiency while increasing blood flow remains a major challenge, as its use on humans requires the ability to process large volumes of blood. C2N microfluidic scientists (J. Lachaux, G. Hwang et A-M. Haghiri-Gosnet) have designed a 10-centimeter diameter microfluidic oxygenator, which maximizes the gas exchange area and allows multiple levels to be stacked to improve the maximum blood flowrate. This microfluidic oxygenator is manufactured layer-by-layer in assembly based on a patented wet bonding method [hal-03318568v1]. The stacking of several trilayers allows to reach very high blood flow rates. The high performance of the stacked device in terms of blood oxygenation and decarbonation comes from the architecture designed to facilitate gas exchange, but also from the thinness of the PDMS membrane (15 microns thick), which can withstand high blood flows thanks to the optimized bonding. The geometry of the vascular network also respects the natural laws of

blood vessels, allowing for reduced shear stress, promoting durable endothelialization with progenitor cells kept alive for up to 2 weeks after initial seeding.

This project, coordinated by Pr. Olaf Mercier, director of the clinical research laboratory and thoracic surgeon (lung transplantation) at the Marie Lannelongue Hospital (HML), is supported by a collaboration of 5 research laboratories, including C2N, 2 INSERM laboratories (unit 1197 and 1176), 2 CEA laboratories (LITEN and LEMM) and the hydrodynamics laboratory (LadHyX). Thanks to its experience in microfluidics, C2N is a major player in the consortium for the design and study of an oxygenator adapted to medical constraints.

These state-of-the-art results in terms of gas exchange efficiency and reduced priming volume have just been published in « Lab-on-a-Chip ».



References

A compact integrated microfluidic oxygenator with high gas exchange efficiency and compatibility for long-lasting endothelialization

Julie Lachaux, Gilgueng Hwang, Nassim Arouche, Sina Naserian, Abdelmounaim Harouri, Valeria Lotito, Caterina Casari, Thevy Lok,Jean Baptiste Menager, Justin Issard, Julien Guihaire, Cécile V. Denis, Peter J. Lenting, Abdul I. Barakat, Georges Uzan, Olaf Mercier and Anne-Marie Haghiri-Gosnet

Lab Chip, 2021, 21, 4791 DOI: 10.1039/d1lc00356a

Figure : 10 cm diameter microfluidic oxygenator with blood circulating in the vascular network

Contacts C2N Julie Lachaux and Anne-Marie Haghiri anne-marie.haghiri@c2n.upsaclay.fr

MANUFACTURING OF 3D HELICAL MICROSWIMMER BY AFM MICROMANIPULATION FOR MICROFLUIDIC APPLICATIONS

Manufacturing of microsystems based on complex three-dimensional microstructures requires critical steps such as mass calibrations and integration process. However, such steps involve several manipulation steps which are not well controlled thus the fragile 3D microstructures could be damaged or destroyed. In this work, we have demonstrated an AFM based direct mass measurement and manufacturing of 3D helical microswimmer. The proposed method shows to be rapid, repeatable and minimally-destructive thanks to the precise force control and manipulation by AFM. The proposed micromanipulation steps consist of the pick-measure-integrate manipulation steps using van der Waals force-based attachment and the mass measurement by resonant frequency shift. For the testing structures, we fabricated the 6 different types of 3D helical microswimmers vertically fabricated on the conical shape microneedle supports for uniform surface metallization and facile detachment. With the mass measurement sensitivity of 25 Hz/ pg and the direct integration to microfluidics, we successfully demonstrated the 3D propulsion and non-contact micromanipulation by 3D helical microswimmer in microfluidics. **This work is the result of the multidisciplinary and international collaboration of two different laboratories, including the LIMMS-CNRS laboratory, Institute of Industrial Science, The University of Tokyo and the C2N-CNRS, Université Paris-Saclay.**



Figure : Manufacturing process of 3D helical microswimmers by AFM micromanipulation for the microfluidic integrations and propulsion tests

References

Manufacturing of 3D Helical Microswimmer by AFM Micromanipulation for Microfluidic Application

G. Hwang, C. David, A. Paris, D. Decanini, A. Mizushima and Y. Mita.

IEEE Trans. Semiconductor Manufacturing, PP(99):1-1, may 2021 DOI : 10.1109/TSM.2021.3082902

> **Contact C2N** Gilgueng Hwang gilgueng.hwang@c2n.upsaclay.fr

EXPLOITING THE NON-IDEALITY OF MEMRISTOR DEVICES CAN ALLOW AI AT THE EDGE

Artificial Intelligence (AI) is currently offering incredible applications, but at the cost of a very high energy consumption. For these reasons, embedded objects like medical devices need to connect to the cloud to access AI, raising issues in terms of privacy and security. Memristors are a new technology, which due to its similarity with synapses in the brain, offers the possibility to reduce the energy consumption of AI dramatically, and to bring AI directly to embedded devices, an approach known as "edge" computing. However, it is a considerable challenge for AI systems based on memristors to learn new information: they need to be preprogrammed. This is because the way AI learns is fundamentally incompatible with the variability of memristors.

In this work, researchers from CEA LETI and from the Centre de Nanosciences et de Nanotechnologies used 16,384 hafnium oxide memristors cointegrated with standard transistors to show that the variability of memristors can be turned into a feature to enable learning at the edge. This variability can directly implement the sampling step of Markov Chain Monte Carlo, an AI learning technique particularly adapted for the edge. The researchers used this technique to train the memristors to recognize malignant tissue and detect heart arrhythmia. The accuracy of the memristor-based systems matches software implementation, with an energy consumption reduced by a factor 100,000.

These results open the way for multiple applications of edge learning, in particular for implantable medical systems, and also highlight that drawbacks of electron devices can sometimes be turned into powerful features.



Figure : Cross-section electron microscopy image the systems used in this study. It cointegrates CMOS transistors and memristors (credits: CEA LETI)

References

In situ learning using intrinsic memristor variability via Markov chain Monte Carlo sampling

Thomas Dalgaty, Niccolo Castellani-Clément Turck, Kamel-Eddine Harabi, Damien Querlioz & Elisa Vianello

Nature Electronics volume 4, pages 151–161 (2021) DOI: 10.1038/s41928-020-00523-3

> **Contact C2N** Damien Querlioz damien.querlioz@c2n.upsaclay.fr

HELIUM IONS PUT MAGNETIC SKYRMIONS ON THE TRACK

Magnetic skyrmions are deemed to be the forerunners of novel spintronic applications. Due to their nanometric size and predicted efficient current-induced manipulation, magnetic skyrmions hold great promise as future information carriers in ultra-fast, high-density non-volatile memory and logic devices. While their observation and their current-driven motion at room temperature have been demonstrated, certain issues regarding their nucleation, stability, pinning, and the skyrmion Hall effect still need to be overcome to realise functional devices. Here, we demonstrate that focused He+ irradiation can be used to create and guide skyrmions in magnetic racetracks. We show that the reduction of the perpendicular magnetic anisotropyand the Dzyaloshinskii–Moriya interaction in the track defined by ion-irradiationleads to the formation of stable isolated skyrmions. Current-driven, skyrmion motion experiments and simulations reveal that the skyrmions move along the irradiated track, resulting in the suppression of the skyrmion Hall effect, and that the maximum skyrmion velocity can be enhanced by tuning themagnetic properties. **These results open up a new path to nucleate and guide magnetic skyrmions in racetrack devices, bringing them one step closer to applications.**



Figure : On the left, a magnetic microscopy image showing trains of skyrmions 100 nm in size (white) in magnetic tracks defined by a focused He+ionbeam. These tracks are separated by a uniformly magnetised region (black) which acts as a barrier, creating channels for the skyrmions to move in a straight line. This is shown in the diagram onthe right, which shows two irradiated tracks (in red) separated by a uniformly magnetised region (in white).

References

Helium Ions Put Magnetic Skyrmions on the Track

Roméo Juge, Kaushik Bairagi, Kumari Gaurav Rana, Jan Vogel, Mamour Sall, Dominique Mailly, Van Tuong Pham, Qiang Zhang, Naveen Sisodia, Michael Foerster, Lucia Aballe, Mohamed Belmeguenai, Yves Roussigné, Stéphane Auffret, Liliana D. Buda-Prejbeanu, Gilles Gaudin, Dafiné Ravelosona, and Olivier Boulle

Nano Lett. 2021, 21, 7, 2989–2996 DOI : 10.1021/acs.nanolett.1c00136

> **Contact C2N** Dafiné Ravelosona dafine.ravelosona@c2n.upsaclay.fr

TAKING INSPIRATION FROM THE BRAIN TO ALLEVIATE CATASTROPHIC FORGETTING IN ARTIFICIAL INTELLIGENCE

For several years now, artificial intelligence has made considerable progress thanks to the implementation of deep learning: computer programs called deep artificial neural networks are now capable of learning very complex tasks. However, these programs suffer from a considerable limitation: they are subject to "catastrophic forgetting." When an artificial neural network has been trained to perform a task, using that same network to learn a new task largely erases what has been learned previously. Our brain does not have this problem: we are able to learn new tasks continuously.

C2N researchers have just discovered a solution to this problem, by using "binarized" neural networks, a type of neural network developed since 2016. These neural networks, in which most of the variables are binary, are studied intensely to create circuits dedicated to artificial intelligence with low energy consumption. C2N researchers have just proven that there is an unexpected link between binarized artificial neural networks and neuroscientific models of synaptic "metaplasticity", and that this link can be used to considerably reduce the problem of catastrophic forgetting. While synaptic plasticity is the brain's ability to alter the connections between its neurons, metaplasticity is its ability to alter its level of plasticity.

The researchers used this new technique in various tasks where an artificial neural network continuously learns new information. Unlike other approaches proposed in the literature to reduce catastrophic forgetting, the researchers' approach, like our brains, does not require a formal separation of the tasks to be remembered. This work illustrates the great interest of making links between research in neuroscience and artificial intelligence.

This work also resonates with the new magnetic nano-components developed at C2N because they could intrinsically implement this metaplastic behavior directly thanks to the rich physics of the components. The next work of C2N will therefore consist in demonstrating metaplastic systems using nano-components.



Figure : Neural networks implemented in artificial intelligence (top) are subject to catastrophic forgetting. If they are taught to recognize numbers (MNIST) and then clothes (FMNIST), these networks lose the ability to recognize numbers (bottom, left). Thanks to the metaplastic approach proposed by C2N researchers, these networks can successively learn the two tasks (bottom, right).

References

Synaptic metaplasticity in binarized neural networks

Axel Laborieux, Maxence Ernoult, Tifenn Hirtzlin and Damien Querlioz

Nature Communications volume 12, 2549 (2021) DOI : 10.1038/s41467-021-22768-y

> **Contact C2N** Damien Querlioz damien.querlioz@c2n.upsaclay.fr

ELECTRICALLY INJECTED PARITY-TIME SYMMETRIC DISTRIBUTED-FEEDBACK (DFB) LASER DIODES FOR TELECOM APPLICATIONS

Researchers at the Centre de Nanosciences et de Nanotechnologies (C2N), in collaboration with Laboratoire Charles Fabry (LCF) have reported single-frequency electrically-injected DFB laser diodes based on Parity-Time symmetric dual gratings in a standard ridge waveguide configuration, thus amenable to mass production. They demonstrated enhanced modal discrimination for these lasers as compared with index or gain-coupled devices from the same technology run.

Controlling the electric permittivity along with the magnetic permeability in photonic designs has long been a major field of research. Photonic crystals and metamaterials represent the best known examples of the tailoring of these quantities. In practice, the design and engineering of active photonic devices usually rely on the tailoring of not only the refractive index but also the amount of gain or losses inside the cavity. In particular, the presence of losses in too large amounts has long been considered to solely cause degraded performance of optical systems. A remarked trend in the photonics of the past decade, consisting in the engineering of structured losses balanced with gain and refractive index manipulation, is receiving growing attention from the community. This topic, originating from the so called Parity-Time

Symmetry (PT-symmetry) [1,2], was found to be of great interest in several compartments of optics for the implementation of optical devices with intriguing behaviors.

In a work published in January 2021 in the Nanophotonics journal, a team of researchers at the Photonics Department of the Centre de Nanosciences et de Nanotechnologies – C2N (CNRS/Univ. Paris-Saclay) in collaboration with the Laboratoire Charles Fabry– LCF (CNRS/Univ. Paris-Saclay), reports an implementation of the concept of PT-symmetry to a practical mature complex

device, specifically to the design and fabrication of an electrically-injected single-frequency distributed-feedback (DFB) laser diode, the workhorse of monochromatic transmitters in optical communication networks. The main interest of applying the concept of PT-symmetry to DFB lasers is to improve the single frequency behavior through the simultaneous presence of index and loss modulation.

Figure 1(a) presents the principle of complex index modulation with physically separated gratings, sensed as a whole by the waveguide mode supported by the production-compatible ridge waveguide implementation carefully selected in thus study.

The fabrication and characterization of the expe-

rimental structure (see Figure 1b) were performed at C2N while the design and modeling were carried out jointly by C2N and LCF partners. The laser performances in terms of single frequency behavior are at the state-of-the art, with routinely achieved SMSRs (a measure of spectral purity) greater than 50 dB and output laser beam power exceeding a decent 14 mW. The non-reciprocal reflection behavior in the DFB laser cavity was investigated using a dedicated setup and displays clear signatures of directional amplification, a feature directly associated to the staggered grating arrangement (Fig.1a, dashed lines), key to parity-time symmetry. Finally, in a first attempt to take advantage of non-reciprocity effects to increase robustness to optical feedback, encouraging preliminary data show a strong asymmetry in the immunity to optical feedback.



Figure : (a) Schematic of PT symmetric gratings, with symmetry planes of gratings (dashed lines) shifted by a quarter-period, (b) SEM pictures of fabricated DFB lasers with 3rd order complex-coupled DFB Bragg grating.

References

Electrically injected parity-time symmetric distributed feedback laser diodes (DFB) for telecom applications

V. Brac de la Perrière, Q. Gaimard, H. Benisty, A. Ramdane, A. Lupu **Nanophotonics** <u>DOI : 10.1515/nanoph-2020-0587</u>

> Contact C2N Anatole Lupu anatole.lupu@c2n.upsaclay.fr

SCIENTISTS DEVELOP AN ULTRA-FAST LASER MODULATOR FOR THE MID-IR

Applications based on mid-infrared radiation have grown at a very rapid pace, with clear links to environmental applications. Mid-IR cameras have propelled the field of thermal imaging, that permits to optimize and reduce thermal dissipation. In addition, the invention of the quantum cascade laser (QCL) has made compact mid-IR laser sources available, for trace gas spectroscopy for instance of dangerous/polluting gases.

All recent advances have resulted from the development of revolutionary optical components. A crucial functionality for most photonic systems is the ability to electrically modulate the amplitude of a beam at ultra-fast speeds of the order of GHz or more. While this technology exists for shorter wavelengths in the telecom range, the ultra-fast modulation of a mid-IR beam is a problem that does not have a well identified practical solution yet.

In a paper recently published in the journal Nature Communications, a team of researchers from C2N, in collaboration with an Italian team from CNR-IOM, has demonstrated a free-space amplitude modulator for mid-IR radiation ($\neq =10 \neq m$) that can operate up to at least 1.5 GHz at room-temperature [1].

First, a judiciously designed semiconductor structure has been implemented for operation in the proper wavelength range. Subsequently, this active region has been sandwiched into a metallic cavity that permits to dramatically increase the interaction between light and matter and achieve the so-called strong coupling regime.

The device then exploits an electric field to drive the system in and out of this strong coupling regime at ultra-fast rates. When a laser shines on the devices, the reflected beam is modulated in the same fashion.

Beyond the clear applicative possibilities that open up, this invention makes an elegant link between a fundamental physical phenomenon and a useful application.



Figure a) Sketch of the modulator geometry: the active gion is embedded in a metal–metal structure. By applying an external bias, the amplitude of the reflected beam is modulated. Intuitive view of the modulator operating principle: with no applied bias *(b)* the system is designed to be in strong coupling. Two polaritonic branches are visible in the reflectance spectrum. By applying a specific bias, we deplete an arbitrary number of quantum wells and bring the system in the weak coupling regime: the bare cavity mode is visible on the reflectance spectrum. (c) Normalized beat-note spectra obtained when the sample undergoes modulation frequencies at 100 MHz, 500 MHz, 1 GHz, and 1.5 GHz from top left. The modulator performs up to at least 1.5 GHz.

References

[1] «Fast amplitude modulation up to 1.5 GHz of mid-IR free-space beams at room- temperature»,

S. Pirotta, N.-L. Tran, A. Jollivet, G. Biasol, P. Crozat, J.-M. Manceau, A. Bousseksou and R. Colombelli

Nat. Communications, in press (2021) DOI : https://doi.org/10.1038/s41467-020-20710-2

> **Contact C2N** Raffaele Colombelli Stefano Pirotta raffaele.colombelli@c2n.upsaclay.fr

MEASURING TOPOLOGICAL PROPERTIES OF GRAPHENE

The discovery of topological phases of matter, which was awarded the 2016 Nobel Prize in physics, has profoundly impacted our understanding of condensed matter. The hallmark of these topological phases is the existence of surface states whose properties can be completely insensitive to local perturbations. One of the most famous example of such topological states are the electrical conductivity plateaus measured in two-dimensional materials subject to strong magnetic field, a well-known phenomenon called the integer quantum Hall effect. The extreme robustness of these plateaus, which is harnessed in several metrology protocols, is directly linked to a fundamental quantity in topological physics called a "topological invariant".

These topological invariants, which are a global property of a material, can be seen as the DNA of a topological phase, its mathematical signature. However, they are usually infer indirectly through local measurements at the edges of a sample, e.g. by probing the existence (or not) of topological states. This is a major drawback in many cases where the surfaces of a sample are dirty or difficult to probe. **Researchers from the Centre for Nanosciences and Nanotechnologies, in collaboration with colleagues from PHLAM in Lille and from ICFO in** Barcelona, have demonstrated a novel scheme allowing to directly measure these topological invariants from the bulk of a sample. Their results have been published in *Physical Review Letters*.

To do this, they used a photonic platform that emulates the physics of graphene, a material whose topological properties are well-known. In this platform, built by coupling semiconductor-based micropillars (see Figure a)), photons propagate similarly as electrons do in solid-state graphene. The technique developed by the researchers consists in generating a localized wave-packet and probing its propagation by collecting photons that escape the micropillars. Then, by doing a simple mathematical operation on the measured spatial profile, they were able to extract with a high accuracy the value of topological invariants that characterize the energy bands of this analog graphene lattice, which are related to the existence of edge states (see Figure b).

These results offer a new path for measuring fundamental topological properties of matter, directly from the bulk of a material. This technique could thus be extended to more exotic systems in order to identify and characterize the emergence of new topological phases.



Figure : Electron microscopy image of an artificial graphene lattice formed from the coupling of semiconductor-based micropillars; Extracted values of the topological invariant for a zigzag and a bearded termination. For regions of the reciprocal space where this value approaches 1, graphene exhibits an edge state.

References

Measuring Topological Invariants in a Polaritonic Analog of Graphene

P. St-Jean, A. Dauphin, P. Massignan, B. Real, O. Jamadi, M. Milicevic, A. Lemaître, A. Harouri, L. Le Gratiet, I. Sagnes, S. Ravets, J. Bloch, and A. Amo

Phys. Rev. Lett. 126, 127403 DOI 10.1103/PhysRevLett.126.127403

> **Contacts C2N** Jacqueline Bloch Sylvain Ravets jacqueline.bloch@c2n.upsaclay.fr

TOPOLOGICAL OPTO-MECHANICAL RESONATOR FOR ROBUST COLOCALIZATION OF LIGHT AND SOUND

Researchers have proposed a way to robustly co-localize light and sound at the nanoscale with enhanced optomechanical interactions.

It is phenomenal to observe the identical twin behavior of light and sound in the GaAs/AlAs heterostructures. This inherent property allows us to simultaneously control the propagation of the above two excitations in a single structure. Profiting from this remarkable coincidence one can simultaneously confine light and sound in a multilayer, and control their interaction. The optical and acoustical interactions in these structures are reinforced by adding the notion of topology wherein these confined modes are protected against disorder or deformations that can occur in realistic conditions.

Researchers from the Centre de Nanosciences et de Nanotechnologies - C2N (CNRS/ Université Paris-Saclay) have demonstrated the formation of a topological interface mode for the colocalization of light and sound. They can create an interface mode by concatenating two periodic lattices with inverted bands for both light and sound. The research shows the dynamical interaction of optical and acoustical modes in the structure experimentally and demonstrates a robust photoelastic interaction in theory.

Their work is published in the journal Optica.

Taking advantage of the topological characteristics of GaAs/AlAs superlattices, the researchers create a simultaneous topological micro-resonator for both light and sound. The topologically confined modes are engineered at the interface formed between two distributed Bragg reflectors. The interface modes are created due to band inversion in DBRs, which is related to topological invariants of their different bands based on the Su-Schrieffer-Heeger (SSH) model. The GaAs/AlAs heterostructures exhibit a simultaneous band inversion for light and phonons, leading to colocalization of optical and acoustical fields. The time-domain Brillouin scattering experiments display a dynamical interaction of the two topological modes in the structure. The rigorous calculations reveal the robustness of this interaction between the two fields with respect to disorder.

The reported structures are recognized as a potential candidate for devising robust opto-mechanical micro-resonator embedded with active media such as quantum wells and quantum dots for novel cavity-quantum-optomechanics experiments.



Figure : Schematic representation of the colocation of sound and light in a topological multilayer structure

References

Topological optical and phononic interface mode by simultaneous band inversion

O. Ortiz, P. Priya, A. Rodriguez, A. Lemaitre, M. Esmann, and N. D. Lanzillotti-Kimura

Optica 8, pp. 598-605 (2021) DOI 10.1364/OPTICA.411945

Contact C2N Daniel Lanzilloti-Kimura daniel.kimura@c2n.upsaclay.fr

VIBRATIONAL RESONANCE AMPLIFICATION IN A THERMO-OPTIC OPTOMECHANICAL NANOCAVITY

The enhancement mechanism of a weak (undetectable) signal, known as vibrational resonance, is activated by modulating an input field at high frequency and submitting it to a bistable system. Such general and wide spread concept has been theoretically investigated on various type of systems e.g. neural networks, excitable systems and even biological networks. Meanwhile, few experimental works have also been published but with devices whose works of principle rely on different physics (electronic circuits, VCSELS, electromechanical resonators...). In all these demonstrations, there are as many nonlinearities involved as there are systems. However, up to now, no demonstration of vibrational resonance has been performed using an integrated optical nanocavity with the well-known and largely used thermo-optical nonlinearity. Such nonlinearity manifests itself and strongly impacts optical and nanophotonic devices to the point of allowing tunability and elementary computational all-optical components.

In this context, we present a first experimental demonstration of weak optical signal amplification in a thermo-optically bistable optomechanical nanocavity, a fortiori operating in the telecom domain. We make use of a fully integrated hybrid platform including a suspended InP photonic crystal whose mechanical vibrations can interestingly be exploited to access the thermal properties of the system. Using thermo-optical nonlinearity, amplification of a weak optical signal of up to 16 dB have been achieved. These results have been published in NanoLetters.

Yet, the study of weak signal enhancement is of immediate interest for current nanophotonic technologies, in which the amplification of low-power signal remains a necessity. Beyond the optical domain, interaction between optical and mechanical degree of freedom, present in suspended photonic crystal, could open avenues of amplification of optical signal thanks to mechanics or vice versa. Furthermore, the optomechanical dimension of this system makes it also particularly well suited for sensing application like e.g. thermometry.



Figure : Schematic diagram of vibrational resonance with an optomechanical resonator exhibiting thermo-optic non-linearity. A weak signal as well as a control signal are sent to the system allowing the amplification of the first mentioned signal.

References

Vibrational Resonance Amplification in a Thermo-Optic Optomechanical Nanocavity

Guilhem Madiot, Sylvain Barbay, and Rémy Braive

Nano Lett. 2021, 21, 19, 8311–8316 DOI : 10.1021/acs.nanolett.1c02879

> Contact C2N Rémy Braive remy.braive@c2n.upsaclay.fr

METAMATERIAL ENGINEERED SILICON PHOTONIC COUPLER FOR WHISPERING GALLERY MODE MICROSPHERE AND DISK RESONATORS

Optical microresonators with high quality factors are key in photonic circuits requiring fine spectral filtering or resonant storage of optical power. Silicon (Si) photonics provides high-performance optoelectronic circuits but yields planar Si microresonators with rather low quality factors (Q < 105). On the other hand, bulk resonators achieve exceptionally high quality factors, Q > 107. Si photonic waveguides and bulk resonators have very different sizes and refractive indices that preclude efficient coupling.Here, we show an efficient method to couple bulk resonators and Si waveguides based on subwavelength metamaterial engineering. We demonstrate up to 99% light coupling efficiency for microspheres and microdisks made of silica, lithium niobate, and calcium fluoride, with 0.3-3.6mm diameter. This achievement could enable the heterogeneous integration of bulk resonators and silicon photonic circuits, with potential applications in sensing, communications, and quantum information.

Optical microresonators provide key functionalities like ultra-fine spectral filtering, lasers with high spectral purity, high-efficiency frequency comb generation, and high optomechanical coupling. The performance of the resonators is typically assessed by their quality factor, Q, defined as the energy stored in the resonator divided by the energy dissipated per radian. Since Q is inversely proportional to the fractional power loss per optical cycle, key performance metrics improve with increasing Q. For example, power consumption and phase and intensity noise in resonator-based optical sources scale inversely with the square of Q. At the same time, high Q improves precision in resolving the resonance wavelength, which is important for applications in sensing and frequency stabilization.

Silicon (SI) photonics provides a unique potential for large volume production of optoelectronic circuits and is considered a key technology for the development of emerging applications in sensing and communications. However, the performance of Si photonic circuits is often limited by the comparatively low quality factors of Si-based ring resonators, typically in the 104 -106 range. In addition, Si has some intrinsic physical limits that hamper the implementation of advanced nonlinear and optoelectronic functionalities. Strong two-photon absorption in the near-infrared compromises nonlinear applications, and the centro-symmetry of the Si lattice compromises the efficiency of optoelectronic circuits exploiting the Pockels effect. On the other hand, bulk whispering gallery mode (WGM) optical resonators like spheres and disks in diffe-



Figure : Schematic view showing the proposed subwavelength-engineered structure to efficiently couple nanophotonic silicon waveguides and bulk whispering gallery mode resonators

References

Metamaterial engineered silicon photonic coupler for whispering gallery mode microsphere and disk resonators

D. Farnesi, S. Pelli, S. Soria, G. Nunzi Conti, X. Le Roux, M. Montesinos Ballester, L. Vivien, P. Cheben and C. Alonso-Ramos

Optica Vol. 8, Issue 12, pp. 1511-1514 (2021) DOI 10.1364/OPTICA.438395

> **Contact C2N** Carlos Alonso-Ramos carlos.ramos@c2n.upsaclay.fr

rent materials provide a wide range of remarkable optical properties and ultra-high Q-factors of up to 1011. However, robust coupling between planar Si waveguides and low-index bulk resonators, e.g., silica, is not possible because of index mismatch.

Here, we propose and demonstrate a new type of highly versatile coupling approach, which enables coupling between integrated Si waveguides and a wide range of bulk WGM resonators with largely disparate sizes (300 µm–3.6mmdiameter) and refractive indices (1.42–2.21). The proposed coupler, see Fig. 1, is monolithically integrated on a silicon-on-insulator (SOI) wafer. This universal coupling approach leverages the subwavelength grating (SWG) metamaterial waveguides to shape the optical field distribution and wave vector of guided modes.

We have shown that SWG metamaterial engineered couplers provide unique flexibility to combine a wide range of bulk WGM microresonators with Si waveguides, achieving very high coupling efficiencies close to 100% and measured quality factors exceeding 107. The SWG couplers studied in this work demonstrate a proof-of-concept validation of a universal integrated photonic coupling approach that can be implemented using Si photonic technology, opening a new route to exploit a wide range of optical properties enhanced by ultra-high Q resonances. The presented approach can be readily exploited to implement robust devices combining high-performance bulk resonators and complex Si photonic circuits, with promising prospects for a wide range of applications, including sensing, nonlinear optics, microwave photonics, and quantum photonics.

AWARDS

AWARDS



copyright Simon Cassanas



copyright Stefan Gladieu









Jacqueline Bloch

CNRS Research Director at C2N, CNRS silver medal, elected member of the Académie des sciences, physics section

^{d)} **Pascale Senellart-Mardon** CNRS Research Director at C2N, laureate of the Grand Prix Mergier-Bourdeix of the Académie des Sciences b) **Laurent Vivien** C2N Deputy Director, Head of the photonics dpt, elected Fellow of SPIE

Rebeca Ribeiro-Palau CNRS Researcher Laureate of the Ernest Déchelle Prize of the Académie des Sciences Sylvia Matzen Teacher-researcher Univ. Paris-Saclay Bronze Medal CNRS 2021

Rémy Braive Teacher- researcher Univ. Paris finalist for the Jean Jerphagnon Prize 2020

AWARDS









Nicola Carlon Zambon Recipient of the C'NANO IDF 2020 Thesis Prize - EDOM Thesis Prize

د) Laëtitia Baringthon

Awarded the «L'Oréal-UNESCO Jeunes Talents France 2021» Prize for Women in Science

Hélène Ollivier

Laureate of the Physics of Waves and Matter (PhOM) 2021 thesis prize of the Graduate School of Physics of the Paris-Saclay University

d) Lucas Blanc

Former CIFRE doctoral student in the MicroSystems and NanoBioFluidics dpt, MNOEMS team, received the Innovation Awards» from the missile manufacturer MBDA.

EVENTS

NATIONAL STRATEGY ON QUANTUM TECHNOLOGIES -ANNOUNCEMENT BY THE PRESIDENT OF THE REPUBLIC, EMMANUEL MACRON, AT C2N, 21 JANUARY 2021



On 21 January, President Emmanuel Macron unveiled the national strategy on quantum technologies at the C2N.

This plan, with an investment of €1.8 billion over five years, which includes funding from the State, European credits and private sector funding, aims to position France among the leading countries in this technology and thus achieve "technological sovereignty" in the quantum field.



Its implementation is based on two pillars :

- A global and integrated technological development programme from fundamental research to industrialisation
- "A strengthening of the French ecosystem in its European environment"

SCIENTIFIC VISIT BY ANTOINE PETIT - CEO OF THE CNRS

Antoine Petit's scientific visit to C2N during which our various research activities carried out in our cleanroom and in our different laboratories were presented.



Mai. 2021



The visit continued with a discussion with our staff. Alongside Antoine Petit, we also had the honour of receiving Jean-Yves Marzin, Director of the Institute of Engineering Sciences and Systems - INSIS and Frédéric Petroff, Deputy Scientific Director of the National Institute of Physics - INP.



EVENTS

WHEN SCIENCE AND INDUSTRY MEET

Visit to the technical direction of the CNES one of our partners, for a visit prior to a working meeting with the startup ION-X Propulsion, which recently emerged from research work carried out at C2N.



Oct. 2021

FIRST WOMEN IN BUSINESS BECOME A LEADER PROGRAMME

We welcomed the participants of the first Women in Business BeCome a leader programme, launched by Paris Saclay University in partnership with Women Initiative Foundation. sept. 2021



KEY FIGURES

RESEARCH

212 PUBLICATIONS

26 THESIS DEFENDED

4 HABILITATION TO DIRECT RESEARCH (HDR)

20 SEMINARIES













STAFF 1st January 2022

346 STAFF MEMBERS 181 PERMANENTS STAFF 66 RESEARCHERS **43** TEACHER-RESEARCHERS **72** ENGINEERS TECHNICIANS **155 NON-PERMANENT STAFF** (INCLUDING) **41** POST-DOCS **103 PHD STUDENTS**

INTERNATIONAL CONTEXT



38 NATIONALITIES 221 FRENCH PEOPLE 39 EUROPEANS OUTSIDE FRANCE 86 OUTSIDE EUROPE

HIGHLIGHTS 2021 - CENTRE DE NANOSCIENCES ET DE NANOTECHNOLOGIES - C2N

THE C2N TECHNOLOGICAL FACILITIES

The C2N Technological Facilities are hosted in a clean room of 2 900 sqm, dedicated to micro and nanofabrication processes, epitaxy and characterization of materials. Some areas are also devoted to education and continuous training in micro-nanotechnologies, and 250sqm are dedicated to start-up or SME activities. More than 50 M€ are invested in state-of-the-art equipments for micro-nanotechnologies and 40 engineers and technicians work in 3 platforms : PIMENT, POEM and PANAM.



Copyright Laurent Ardhuir

The C2N cleanroom is an essential tool for research carried out in the laboratory. It is also part of the French network (RENATECH) coordinated by the CNRS to support research and innovation in the field of micro-nanotechnologies at the national level. Today, more than two hundred academic and industrial projects are supported by our facilities. Among these projects, 25% are from external laboratories.

To access our facilities : send a request via the RENATECH website* or contact directly the Technological Facility staff by e-mail at renatech@c2n.upsaclay.fr

* https://projets.renatech.org



Copyright Laurent Ardhuin





C2N - Centre de Nanosciences et de Nanotechnologies 10 Boulevard Thomas Gobert 91120 Palaiseau - France Tel : 01 70 27 01 00

