Optomechanical Technologies Newsletter

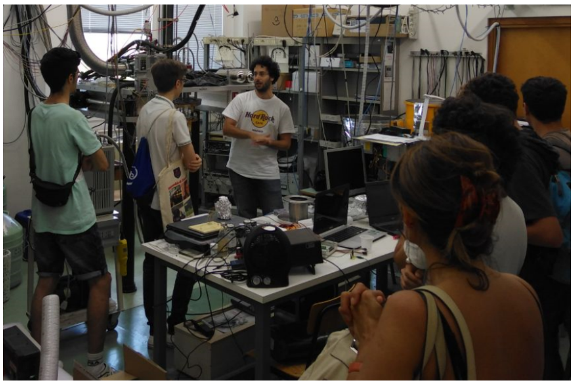
Editor: Simon Hönl, ESR IBM

Highlights

This edition of our newsletter features reports from our public outreach activities as well research news from our fellows. Two students have completed their secondment in the last half year since the last newsletter and for many of us, experiments are finally on the way. Some of us can also finally harvest the fruit of our labor and a number of publications have come out of this project, among which one was published in Science journal on ultra-coherent nano-mechanical resonators. Besides everyday lab work we have also had three workshops and one consortium meeting on which I will also report below.

Fellows updates

by Paolo Piergentili (ESR UNICAM)



Highschool students visiting the laboratory at University of Camerino, courtesy of OMT fellow Paolo, UNICAM.

Work is in progress in the laboratory of quantum optics, optomechanics and cryogenics of the University of Camerino. The main experiment I have carried out in this period was the characterization of a system where two Si_3N_4 high stress membranes are placed in the middle of an optical cavity. The advantage of this new setup is a gain in the optomechanical coupling strength of the membrane relative motion with respect to the single membrane case. A paper about this new setup was published on the Arxiv (http://arxiv.org/abs/1805.09699). In addition to this project, RLC circuits are under test for an electro-optomechanical experiment.
The University of Camerino also organized Open Days: high school students visited the University and the scientific laboratories to have an idea of the research that is carried on and to experience what it means to be a bachelor student for one day.

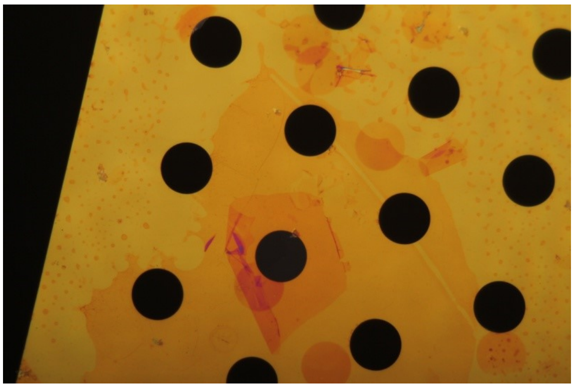
by Edouard Ivanov (ESR UPMC)

The last few months since the first newsletter were mostly spent in the cleanroom, working on the fine-tuning of the SiN membrane fabrication parameters. This has been a challenging and painstaking process, but thanks to the spirit of dissemination of the OMT consortium, I am confident these hurdles will be overcome shortly. When that will have been achieved, reaching the beautiful field of quantum electromechanics wil "just" be a matter of mastering superconducting circuitry...
A couple nice papers I would suggest reading are the ones on the exiting progress made in the emergent field of circuit quantum acousto-dynamics: the superposi-

toin of two phononic Fock states! (arXiv:1804.07308, arXiv:1804.07426)

by Irene Sanchez (ESR UKON)

These past six months have been very intense and involved a lot of travelling - I have not only participated in the four OMT workshops organized during this time, but also the annual meeting, a winter school on new materials and applications (IWEPMN 2018) and a secondment to TU Delft hosted by Prof. Gary Steele's lab.

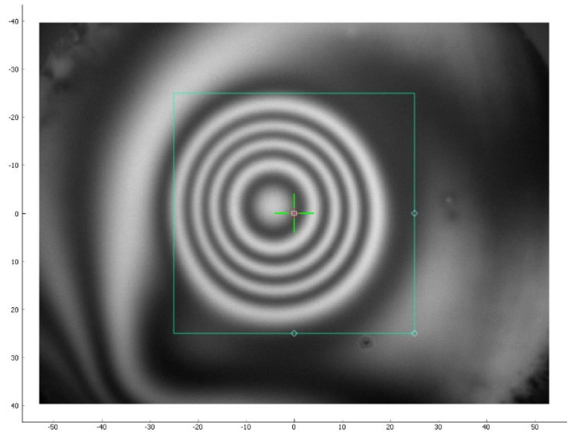


Bright field microscope image of a $10\,\mathrm{nm}$ *- thick hexagonal boron nitride flake transferred into a* $20\,\mu\mathrm{m}$ *diameter hole. The hole is patterned in a* $200\,\mathrm{nm}$ *thick SiN membrane. Courtesy of OMT fellow Irene, UKON.*

Khannan (ESR UGENT) and I spent almost one month for my secondment at TU Delft where we had the chance to learn a technique to deterministically transfer 2D materials. This technique, that will be implemented in the Nanomechanics lab in Konstanz, will allow us to fabricate our mechanical resonators. In my case, I have to transfer 2D materials with a bandgap larger than $0.8\,\mathrm{eV}$ into holes to create 2D drums. In the figure below one you can see an example of a successful transfer into holes patterned on SiN membranes. Once fabricated, they will be inserted in our optical cavity to perform optomechanical experiments. The second part of my project implies the fabrication of a two fiber-based optical cavity. For this, the fibers tips need to be concavely shaped and coated to create stable high reflecting mirrors. I performed the first part, together with Sampo (ESR UCPH) in the group of Prof. David Hunger as part of a collaborative visit at KIT (Karlsruhe Institute of Technology).

We used their CO_2 laser ablation setup to shoot the fibers and create the desire surface profile at the fiber tips - in my case concave shapes with radius of curvature between 100 and $300\,\mu\mathrm{m}$. In the next figure you can see the interferometric image of the surface profile of a fiber after shooting.

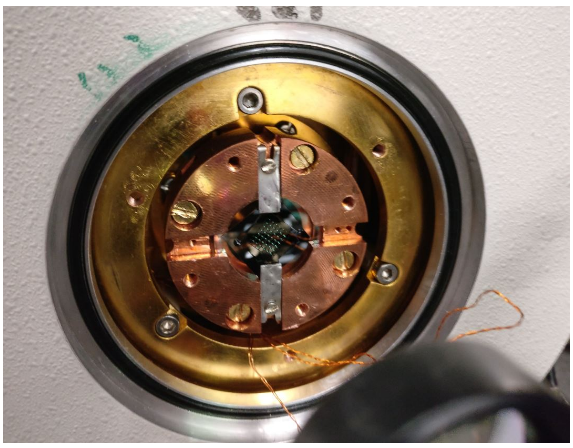
In the next months, we will build our own stamping set up in UKON, coat the fibers and start building a new cavity and optomechanical experiment operating at a wavelength of $1550\,\mathrm{nm}$.



Interferometric image of a fiber tip profile after shooting with the CO_2 *laser. Courtesy of OMT fellow Irene, UKON.*

by Corentin Gut (ESR UNIVIE)

The quest for optomechnical entanglement continues. In the last chapter the challenges were seemingly correlated shotnoise in our experimental data. At this stage I had a poster at the GRC in California, and please trust that it feels uncomfortable to present unfinished work in a place where la crème de la crème de la community gathers and shows truly remarkable and beautiful results (I hope I'll never have to do it again). Nevertheless, I received useful input and by now we solved this issue: shotnoise behaves as expected (Niedersachsen-flat) but no entanglement is in our data. Latest simulations show that we need larger cooperativity and that low frequency noise chmilblique in the experiment limits us. I attended a quantum control project kick-off meeting in Lisbon. My current understanding is that optomechanics enables the exploration of classical to quantum regimes' border, along parameters like noise properties or mass. Having a tool to dive some more in the quantum regime in a precise and controlled way will certainly help probing the quantum effects' emergence: this tool could be tunable non-linear potentials landscapes.



Illuminated hard-clamped phononicalyshielded membrane in its place holder. Courtesy of OMT fellow Corentin, UNIVIE.

by Mohammad Bereyhi (ESR EPFL)

In the past months, I was working on the design and fabrication of ultra-coherent mechanical resonators from silicon nitride which allowed us to achieve exceptional quality factor values exceeding 800 million at room temperature. This led to the publication of the article, "Elastic-strain engineering for ultralow mechanical dissipation", that got published in Science journal (Ghadimi, Amir H., et al. "Elastic strain engineering for ultralow mechanical dissipation." Science (2018): eaar6939.). In this article, we elaborate upon the mechanical dissipation in nanomechanical devices and apply our method to enhance the mechanical quality of nanobeam resonators. This introduced a new approach in mechanical system engineering for optomechanical applications which I am currently pursuing in my PhD project.

Mohammad presents the video game "save the astronaut" at the public outreach "La Nuit de la Science" in Geneva, Switzerland. Courtesy of OMT fellow Mohammad, EPFL.

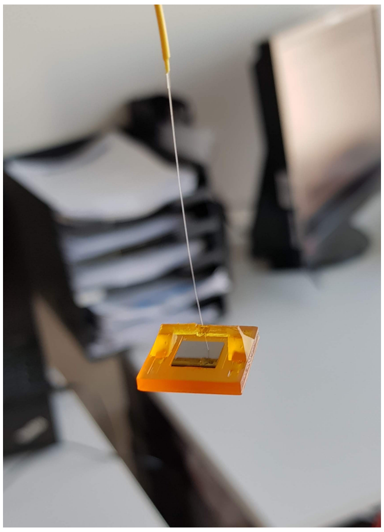
At the moment I am trying to utilize the expertise gained from this project in order to integrate our exceptional mechanical oscillators with an optical cavity to develop a monolithic optomechanical system. I am currently developing and processing a hybrid optomechanical system by integrating ultra-coherent mechanical oscillators with high Q microdisk cavities. Furthermore, we are also working on a fundamental phenomenon in nanomechanics - the clamping loss - that has been widely referred to but never studied in details for nanobeam resonators. We are verifying the effect of clamping geometry on the mechanical coherence of beam resonators.

Meanwhile, I have been participating in OMT workshops on "Art of presenting science" in Delft and "Electronics for mechanical sensing" in Vienna that provided us with many great skills on ways to present our research and electronic designs for optical detection. I have also participated in "La Nuit de la Science". An outreach event in which we showed our experiments to the public who are interested to know more about research in Optomechanics. We presented the "Save the Astronaut" game that is the traveling exposition of the OMT program and it was very well received and appreciated by families and their children.

by Simon Hönl (ESR IBM)

During the last half year, I have worked extensively on improving our GaP-on-insulator platform. Specifically, I have been working on the epitaxial growth of GaP layers by MOCVD (metal-organic chemical vapor deposition). Optimization of such recipes is often difficult as most of the processes that happen in the MOCVD reactor are inaccessible to the observer and only a few parameters such as temperature and reflectivity of the sample as well as the precursor flows can be directly measured. In practice that means that optimization often occurs purely empirically by evaluating the roughness and other surface properties of the grown film. This makes the improvement of such a recipe quite tedious and time consuming. However, now I feel we have reached a point from which we can move forward with our optomechanical devices. The end-goal of course is still a 'quantum link' of sorts, i.e. a coherent converter of microwave photons into optical photons that does not destroy the quantum nature of the signal during the process. The next step for us, since we already have a proven optomechanical platform, is to integrate electrodes for electro-mechanical actuation, allowing us to couple a microwave circuit to the optomechanical system. In addition to the design for the electromechanical implementation, I am also working on optomechanical measurements at cryogenic temperatures, which brings a whole new set of challenges, as we are working with integrated waveguide structures as opposed to free-space optics. We have to think carefully about coupling to waveguide structures in the limited space of a cryostat without using bulky alignment stages. We are collaborating with our project partners at EPFL for the first set of measurements with a tapered fiber setup at 3K but I'm also working on an implementation at IBM that does not involve active alignment. For that part of my project, I learned the value of a 3D printer for rapid prototyping! The image below shows the optical fiber connected to a grating coupler on the chip via a UV resin. The 3D printed sample holder provides enough stability for the sample to be picked up at the end of the optical fiber.

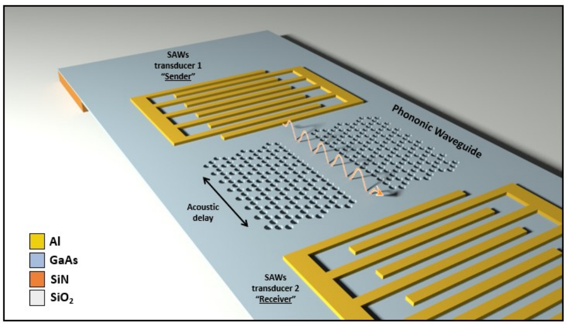
Another upcoming project that I'm looking forward to is the collaboration with ESR Alberto from EPFL who is going to work with me on an implementation of a direct electro-optic converter. Last year already in summer we have published some of our work in a conference paper for the *Optics + Photonics* SPIE conference ("*Optomechanics with one-dimensional gallium phosphide photonic crystal cavities*" Quantum Nanophotonics. Vol. 10359.). I also finally published an article about some processing work that I did in the beginning of my work at IBM on GaP in the *Journal of Physics D, Applied Physics* back in January and we have published a pre-print on arXiv (arXiv:1808.03554) of our most recent endeavors in GaP-on-insulator integrated nonlinear photonics.



Sample holder prototype for cryogenic measurements of photonic integrated circuits. Courtesy of OMT fellow Simon, IBM

by Giuseppe Modica (ESR CNRS)

During the second half of my first year of PhD studies, I have mainly focused on the optimization and fabrication of the excitation part of my system. Specifically, this building block, that will be integrated in the future with the optical part to complete the final scheme, exploits the mechanical excitation given by Surface Acoustic Waves (SAWs) transducers and phononic crystals (see artistic view below). In particular, the main goal of this period was to perform the design, fabrication and preliminary measurements of such a system. After the first half year spent mostly in bibliographic research and simulations, this last period allowed me to gain experience especially from a practical point of view, including a better understanding of the experimental setup.
On the other hand, an outreach event was organized by CNRS in my lab lab where I was involved in showing and explaining to high school students the fundamental principles of a laser and its optomechanical interaction with different nano-structures.



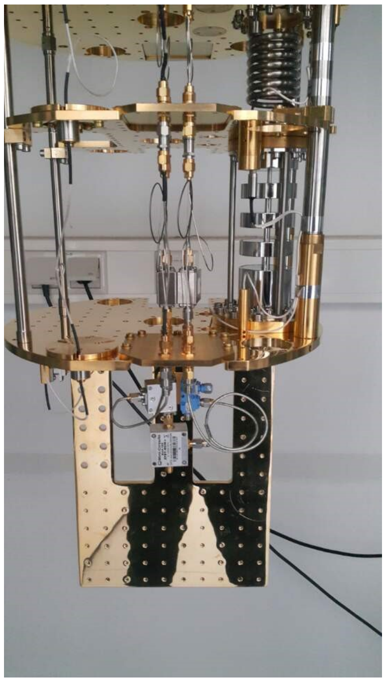
Artistic view of two SAWs transducers with a phononic crystal waveguide in the middle for transmission measurement. Courtesy of OMT fellow Giuseppe, CNRS.

by Sampo Saarinen (ESR UCPH)

The halfway of my PhD is drawing near - assuming normal length of graduate studies. Looking back, I'm happy to see progress on both experiments and personal knowledge.
On the research front, I have on a good authority, that an interesting article about an integrated RF to optical transduction scheme will soon hit the press (or at least the preprint server). In short, the transducer project I've spent most of the last months on has hit a significant milestone and we have results to report. This also frees bandwidth to be filled with other experiments: fiber cavities and microwave transduction. In fact, we have just fabricated a set of fiber mirrors during my secondment at UKON. The mount and characterization of the mirrors was then carried out during a collaborative visit to KIT (Karlsruhe Institute of Technology).
OMT workshops continue to be interesting and horizon expanding in a sense that they often point to directions which I might not have considered beforehand. For example, I had very little background in electronics so the Vienna workshop was a very nice introduction to the subject.

by Byoung-Moo Ann (ESR TU Delf)

As an interface between qubit and mechanical resonator attracts more and more attentions for quantum optomechanics, we are also building up our 'quantum tool box'.



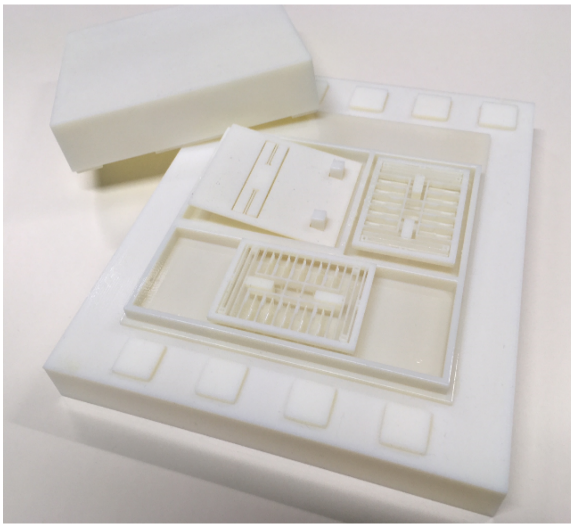
Cold stage of dilution refrigerator. Courtesy of OMT fellow Byoung-Moo, TU Delft.

I am currently taking part in designing and controlling

high coherence superconducting transmon qubit. I recently finished test qubit measurements in a frequency domain, which clearly shows a signature of transmon and the result is consistent with the simulation.
I also have checked its frequency tunability by sweeping magnetic flux through squid loop of qubit. Toward a full quantum control of qubit and a quantum interface with mechanics, we are developing time domain measurement and the main workhorse is arbitrary waveform generator. Since the quantum coherence of qubit is extremely fragile, we should place it cryogenic temperature with many shields and filters to block any disturbing source. The above picture shows our newly built dilution fridge, the stage where our quantum experiment will be performed. More shields and filters will be installed and protect from noise. We are looking forward to completing a full setup.

by Mohammad Ashour (ESR Bosch)

During the last 9 months, I have worked on exploring two major topics: 1) Opto-Mechanical Phase Shifters (OMPS) and 2) Electro-Optic Phase Shifters. After an extensive literature review, the opto-mechanical system and physics was modelled. Using these simulation models a number of layouts were derived for possible shifters. Our fabrication partner is now fabricating the shifters and we expect the chips back at the end of the year.

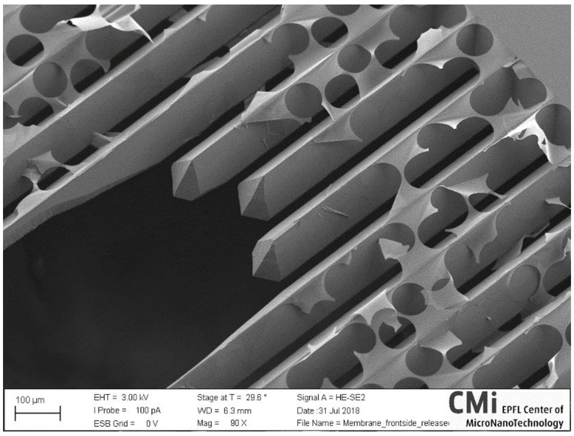


3D printed mock-up of a Bosch accelerometer as part of the OMT public outreach traveling exposition, 'Save the Astronaut'. Courtesy of OMT fellow Mohamed, BOSCH

Preparation for further technology post processing on the expected chips is to start within a few months. Until then, Current work is focusing on studying variations in different Electro-Optic Modulators, and optimizing of operating parameters like losses, dimensions, etc. I also received a comprehensive training on design, and characterization of Photonic Integrated Chips, during my stay for secondment at the University of Ghent, and IMEC in Belgium. The training concluded by fully characterizing a custom-made chip containing different types of Electro-Optic phase shifters.
I hope that these models and the corresponding experiments will result in a useful comparative study between the two fore-mentioned phase shifter designs. The study would then assess suitability of both methods for on-chip beam steering applications.
On the other hand, a public outreach activity in collaboration with the University of Hamburg is in the works. The activity involves 3D printing of a sensor mock that can help non-scientists understand the concepts of smart integrated sensors.

by Alberto Beccari (ESR EPFL-IBM)

During the past half year I have devoted most of my efforts on establishing a fabrication process for Si_3N_4 tensiley-stressed membranes in our lab, aiming to integrate a highly coherent mechanical element into a short Fabry-Perot resonator, striving to observe enhanced interaction with a light field trapped at the resonance condition. This experience let me appreciate both the technicalities of microfabrication (I am now convinced that almost any material and geometry can be patterned at the micro- and nanoscale, if one is creative and cautious enough) and the field of micromechanical sensing, fascinatingly intertwined with precision frequency metrology and with a remarkable range of applications so varied that one can think of measuring both stray electromagnetic fields and the stiffness of cell walls.

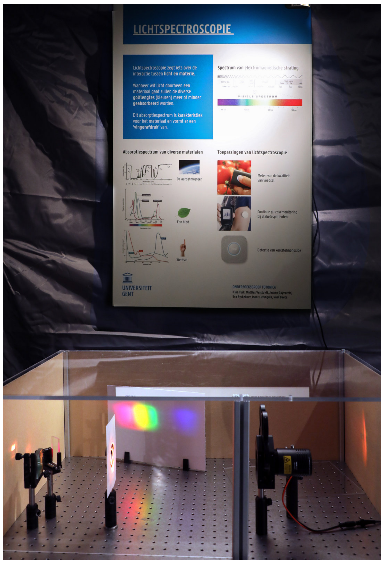


A failed Si_3N_4 membrane peeling away from it silicon growth substrate. The patterned membrane, used as a mask for KOH etch, drapes off to reveal the fascinatingly regular structure of the features left behind by the anisotropic KOH attack. Courtesy of OMT fellow Alberto, EPFL

In the coming months I will begin working on a different project on electro-optical direct transduction, collaborating with IBM and its distinguished champion, ESR Simon Hönl. This new direction will involve integrated photonics design, a subject which is more familiar to me, as well as integration with a superconducting microwave cavity, which is absolutely terra incognita.

by Khannan Rajendran (ESR UGENT)

The goal of my PhD is to realize optomechanics using 2-dimensional materials on CMOS compatible silicon photonics. To achieve this, low dimensional materials are suspended onto the air cavities of photonic crystals and slot waveguides. The first step towards this is to model and optimize the mechanical and optical resonators. In this regard, the workshop on FEM has been immensely valuable. My biggest challenge arises in the fabrication of the 2D-materials mechanical resonators on suspended Si nanobeams. To tackle this, I carried out my secondment at Prof. Gary Steele's lab in TU Delft on transfer printing and will try to implement a similar all-dry transfer technique using viscoelastic stamps at UGent. I also participated in the Silicon photonics summer school and the specialist design school organized by ePIXfab at UGent. The school offers an overview of the current research and progress in silicon photonics from the perspective of both industry and academia. While the design school following this, provided a training on integrated photonic circuit design using the ipkiss framework. A Nano-Bio photonics exhibition was held as a part of the 5-day Ghent light festival.



Light festival at the University of Ghent, Courstesy of OMT fellow Khannan (Copyright: @UGhent, Hilde Christiaens).

The exhibits were visited by more than 500 high school students. I was among the presenters for the spectroscopy booth where we elucidate IR spectroscopy using pulse oximetry and Raman spectroscopy by identifying different Belgian beers.

by Tirth Shah (ESR FAU)

It has been three months since I joined as a fellow of the OMT - the experience has been very stimulating. The primary objective of my PhD project is to optimize the design of photonic/phononic crystals for the purpose of topologically protected transport of photons and phonons at the nanoscale. In order to attain this objective, I learned about the theory of cavity optomechanics and using COMSOL software for simulating the optical and mechanical modes of nanoscale structures. After getting familiar with the prerequisites, I am designing a multiscale optomechanical crystal - which involves embedded optical cavities within a phononic unit cell. This design allows using the light for localized excitation and readout of vibrations at any point in a large lattice. Apart from my work at FAU, I have also participated in two OMT workshops: the art of presenting science at TU Delft and school on electronics for sensing of mechanical motion at UNIVIE. The workshop at TU Delft enabled me to include the elements of theater plays and movies in my scientific talks to make them more interesting. Coming from a theoretical background, the second workshop at UNIVIE helped me to appreciate the challenges and obstacles faced by experimentalists to implement a theoretical proposal.

by Mohammad Haque (ESR AALTO)

For my PhD project, I have been working on optomechanics with superconducting Josephson junctions of carbon materials: graphene and carbon nanotube (CNT). The project requires a combination of skills and expertise such as physics knowledge on quantum optomechanics and superconductivity, experimental skills on microwave measurement technique and high vacuum systems, and fabrication skills for preparing graphene and CNT samples. So far, sample preparation seems to be the most challenging part to learn. Right now, we are trying to prepare suspended graphene and CNT samples and then transfer them onto a Molybdenum-Rhenium superconducting microwave cavity. Josephson junction formed this way will act as a nonlinear inductor which is tunable by gate voltage and this, in turn, will tune the cavity resonance frequency. The optomechanical coupling strength can be enhanced by several orders of magnitude by embedding a qubit with the josephson junction. This josephson junction based optomechanical systems have applications for single phonon and photon detection.
Last year before Christmas, I also finished my three months long training secondment at University of Camerino, Italy. There I learned about the theoretical aspects of quantum optomechanics as well as interaction between two-level atoms and optical cavity from Prof. David Vitali. I also had the opportunity to attend two OMT workshops, one in Delft and the other in Vienna. The Delft workshop was quite unique and taught us some valuable techniques on communicating science more effectively. The Vienna workshop also had very important messages to teach us about electronics knowledge required for experiments.
Recently I have read a paper which I would like to mention: "Absence of quantum features in sideband asymmetry" by Ya.M. Blanter et al. This paper discusses the origin of sideband asymmetry, a phenomenon usually observed

in quantum optomechanical systems. Usually this effect is attributed to zero point motion and hence is regarded as a signature of quantum system. However, the authors in this paper argues that the effect comes from backaction and can be explained classically. I found this paper interesting as this provides a somewhat different approach and I recommend this paper to interested people.

by HOSSEIN MASALEHDAN (ESR UHAM)

I was the last OMT fellow who joined OMT, the Non-linear Quantum Optics lab at the Institute of Laser Physics and Quantum Optics at the University of Hamburg (UHAM), led by Prof. Dr. Roman Schnabel, at the end of March 2018. In my projects, I will try to investigate the quantum state tomography from a motion of membrane in few kelvins at the vacuum chamber. The main tool for my experiments is the squeezed light to realize how it affects the quantum state of motion. Since my academic and research background was more in applied optics, to compensate the incoherency and due to my interest to perform experiments at the foundations of quantum optics, I am involved in some of the ongoing experiments in our group and simultaneously establishing my setups. With respect to the OMT program, during the past few months, I participated in two workshops. The first entitled "Art of presenting science", was more general and covered techniques of how to increase self confidence, presentation logics, and how to communicate with audiences in scientific communities. In addition, visiting Kavli Nanolab cleanroom with Prof. Gary Steele describing the majority of the facilities was a valuable experience. The second was at the University of Vienna organized by UHAM/UNIVIE was about the electronics for sensing of mechanical motions, and I found it very useful.

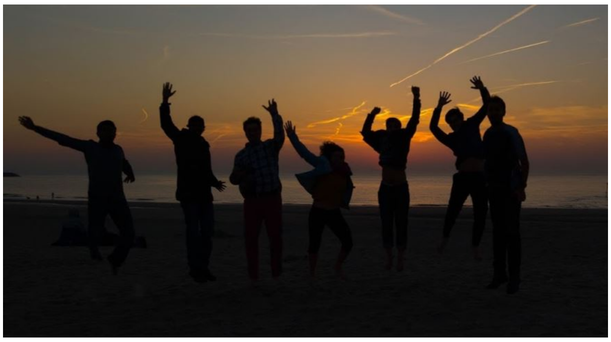
Workshops

by SIMON HÖNL

Since the last newsletter, the OMT fellows participated in a series of workshops focused on different aspects of being a researcher in industry and academia. In December 2017, we learned about intellectual property and how an idea becomes a product at my home institution IBM here in Zurich organized by my supervisor Dr. Paul Seidler. In January, we had the chance to meet face to face with all the supervisors and students of the OMT project at the annual meeting in collaboration with the HOT project, an H2020 FET Proactive project on Hybrid Optomechanical Technologies (`http://hot-fetpro.eu/`) which this year was held in beautiful Gstaad, Switzerland. Here we had the time to learn about one anothers research in a poster session presented by OMT fellows with feedback from the OMT and HOT PIs and expert talks by PhD students, PIs and senior experts. The meeting was organized in scientific sessions and a break for skiing or hiking, allowing to get to know each other better.

Group photo at the OMT/HOT annual meeting in Gstaad - Switzerland in the hotel lounge while a blizzard is raging outside.

After a few months break we met back at TU Delft for the workshop "The Art of Presenting Science" organized by Prof. Gary Steele. The workshop was held by *Artesc*, a group of actors that specialize in using acting skills to improve technical presentations. The workshop comprised exercises to improve the appearance before an audience and writing a presentation in the way of a coherent story with a red thread that the audience can follow. The grand finale of the workshop was a seven minute presentation where we demonstrated what we learned during the workshop.
During this week we also had the chance to meet students of Prof. Gary Steeles' and Prof. Simon Gröblacher's groups who showed us their work and facilities. Gary also showed us the downtown of Rotterdam on a tour with Kangaroo shoes!



OMT "jump!!" group photo at the beach in the Hague.

In June, we all met again for the "School on Electronics for Sensing of Mechanical Motion" in Vienna where we learned about circuit design for electrical filters, photo diode amplifiers and much more. The practical part of this workshop involved soldering a small PCB and it turned out that most of us could use some more practice handling the soldering iron. We certainly learned a lot during this week and we had a chance to see Vienna from a different side during the "street art" city tour.

OMT group photo after the "street art" tour in Vienna.

Now is summertime and we have a little time to go on vacation and work in the lab until our next workshop in Aalto in September.
As a little personal note in the end I think we have all learned a tremendous amount during the past year since we started and we have not only gotten to know one another a little better on a personal level but we also established a platform across Europe to collaborate and help each other out. To me this is an incredibly valuable asset as we don't have to sit in our small chamber solving the identical problem over and over again but instead can profit of each others expertise. Personally, I am extremely curious what we can achieve together during the years to come and how each project will develop.