National Science Foundation - University of Padova

Quantum Information on a Chip
Roadmap 2016

based on the outcome of a Workshop held at the University of Padua, Italy
12-14 October 2015
Organized by
Mario Dagenais (U Maryland), Shaya Fainman (UCSD), Paolo Villoresi (U Padova)

Quantum Computation on a Chip

Moderator: Prof. **Fabio Sciarrino**
Quantum Information Lab - Quantum Optics Group
Dipartimento di Fisica, Sapienza Università di Roma
Junior Fellow SSAS - Scuola Superiore di Studi Avanzati Sapienza
Roma, Italy

Introduction

The future for Quantum Information (QI) is enormously promising, both as an engine of fundamental discoveries and as a generator of transformative technologies that foster progress in many disciplines and industry sectors. Implementing QI on a chip may eventually replicate the enormous success of modern electronics technology. The advances in Atomic, Molecular, and Optical physics in seeding and progressing QI are indisputable. However, implementing QI on a chip can take advantage of the outstanding, continuous advances in material science and nanotechnology. If the platform would result CMOS compatible the chip integration becomes even more appealing because of the availability of foundries developed for conventional electronics.

The most challenging goal is certainly to carry out quantum computing and quantum simulation with an integrated technology. Quantum computation represents the ultimate goal: it requires however to address all the requirements for a scalable implementation. The applications range from quantum chemistry, factorization of large numbers to the recent algorithms proposed for quantum machine learning with an exponential speed up with respect to their classical counterpart. Simulation is a fundamental computational tool for modern science with applications ranging from drug design to materials science. Quantum simulators have the potential to revolutionize the way we perform simulations by accessing system sizes that are intractable in classical machines. As a result, they will become a suite of powerful and precise instruments enabling the investigation of relevant phenomena in the dynamics of complex quantum systems, such as quantum transport and energy transfer, as well as implementing quantum improved computation - tasks hard to simulate classically. Operating according to the laws of quantum mechanics, quantum simulators (QS) are machines that possess an intrinsic capability to simulate a broad array of quantum phenomena that are forever beyond that capabilities of the best classical computers. Without the daunting resource overhead required for a universal quantum computer, QS can deliver a fundamental leap forward for applications and research tools in science and engineering.

The Padova NSF meeting has assembled together the world's leading integrated quantum photonic science and engineering groups.
During the meeting, three fundamental steps have been identified for the construction of a realistic quantum computer/simulator:
(i) Scale – how to achieve a quantum machine of sufficient size and complexity?
(ii) Control – how can we optimize the performance of an integrated quantum processor?
(iii) Application – what new quantum applications become accessible with an integrated photonics system?

Technological objectives and challenge

The discussion has been first focused on the more technological aspects, which address both the scale and control issues. As a general criteria chip-integration should be pursued when new functionalizes are added and when the integrated devices achieve performance equal or higher than conventional implementation. However, it could be wise to even sacrifice the performance of some components, to a certain extent, to reach an overall improved system performance. Moreover, a compromise on a specific performance today could be a full gain tomorrow as fabrication technology progresses driven by industry.

It has been observed hat the level of sophistication in material/fabrication/packaging requires always more specialized expertise and laboratories. There is no university that alone is able to encompass all the necessary tasks for Quantum Information on a chip at the appropriate level. Thus, it is important to explore synergic approaches: a modular collaboration (MURI-like) between groups or more engaged interaction with foundries. In the second case a community interface could be a key player to achieve a critical mass with respect to the industrial partners.

The integration should successfully involve all the components: single photon sources, optical circuits and detectors. Ultimately, a modular scheme could be the most successful one by taking the best performance from each platform.

SINGLE PHOTON SOURCES

- Linear quantum photonics could benefit by having chip-integrated single photon sources based on quantum emitters (artificial atoms, point defects). For the single photon sources a clear goal to fulfill is the generation of 6-8 indistinguishable photons on demand with high indistinguishability. This target could be reached via the scaling of quantum dot sources by introducing tuning knobs, which could be adopted to ensure a high degree of indistinguishability. In this framework the engineering of new materials, such as ultrapure quantum dots heterostructures, can play a key contribution.
- An alternative approach exploits spontaneous parametric down-conversion and single photon multiplexing on a chip.

OPTICAL CIRCUITS

For the manipulation different platforms have been successfully developed within the last few years ranging from femtosecond laser writing to Silica on Silicon and purely Silicon integrated circuits.

- Future on-chip photonic optical circuits require a larger control of variability in components to obtain a large architecture. Moreover an active feed-forward on chip is needed within different schemes.

NON-LINEAR OPTICAL CIRCUITS

- The platform can exploit quantum dot, nitrogen vacancy in diamond. This research field is still in its infancy however it can a have very strong implications on quantum computing. Embedding a long-lived quantum memory on a chip can be a key tool as a source, as a non-linear gate and also a quantum repeater for quantum communication.

SINGLE PHOTON DETECTORS

- A high-efficiency high-yield detector is a key tool: very strong advances have been made in this direction in the last few years. On-chip detectors with efficiency >99% are within the reach.

Moreover other components can be developed for a hybrid approach to quantum information processing: the interest ranges from quantum memory to medium/high efficiency quantum converter between optical and microwave.

Two key challenges concern all these components: to minimize losses on chip and to achieve a high standard for the packaging of the devices. In this framework nanophotonics can be a viable approach.

Theoretical objectives and challenge

Several theoretical required input have been identified to take the maximum benefit from integrated quantum photonics.

Quantum computing

It is still an open question whether a quantum computer could be successfully implement with linear optics due to the detrimental role of losses. A recent article published after the Padova’s meeting has provided a key contribution in this direction:

“We find that photon-based devices must have approximately 100,000 more physical components than matter-based systems using trapped atoms or superconducting circuits. Our results do not rule out all-optical quantum computers, but they do reveal how demanding the requirements are for achieving these “ultimate machines.” We anticipate that our work will invigorate the linear optical quantum computing community to address the fidelity targets or derive better protocols.”
[Ying Li, Peter C. Humphreys, Gabriel J. Mendoza, and Simon C. Benjamin, Phys. Rev. X 5, 041007 (2015).]

As commented above the following theoretical challenges must be addressed:
- to develop new protocols (cluster states,)
- to develop more efficient error correction algorithms
- to identify advanced fault tolerant architectures for linear optic cluster states
- to identify possible no-go boundaries for experimentalists

Alternative approaches could also be investigated: dissipation driven computing and topological quantum computing, which has been to be resilient to noise in different platforms.

Boson sampling

Particular emphasis has been given to the Boson Sampling problem. Boson sampling is a computational task strongly believed to be hard for classical computers, but efficiently solvable by orchestrated bosonic interference in a specialized quantum computer. The boson sampling problem consists of sampling from the output distribution of n indistinguishable photons entering different input modes of a given m-mode random interferometer. The complex multiphoton interference within the device was shown, under mild computational assumptions, to yield an output distribution that is hard to sample using classical computers. The difficulty has been traced back to the known intractability of calculating the permanent function of a matrix. Because a photonic boson sampling computer does not use adaptive measurements, it falls short of the requirements for a universal quantum computer capable, for example, of factoring integers efficiently. First estimates have shown that 30 photons evolving in an interferometer with about 100 modes would already be extremely demanding to simulate classically, providing strong experimental evidence for the quantum computational supremacy. Moreover, boson sampling is an experimental platform suitable for addressing important intermediate challenges for the field of quantum computation, such as benchmarking and certification of medium-scale devices. A key objective is to identify how to use Boson Sampling approach for other applications.

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Finally the key challenges which have been identified in the long-term range are
- 20/30 indistinguishable photons on demand
- Circuits with quantum repeaters beating direct transmission rates

- Full tunability of integrated devices
- To demonstrate fault-tolerant quantum computing (if possible)

Discussion Table on **Computation on a Chip**

Questions to stimulate the discussion	· Linear Optics quantum computing: advantages, disadvantages, how to deal with losses, overhead, Boson sampling · Non-linear optics quantum computing: advantages, disadvantages: QDs, nitrogen vacancies in diamond, ions, atoms · High efficiency generation of single photons · High efficiency detection of single photons · Low loss nanophotonic structures · Efficient insertion and extraction of photons from a chip · Embedding long-lived quantum memory on a chip: how do you store and retrieve info on a chip · Long coherence times · Indistinguishable emission properties · Regulated site positioning: tuning · Number of Q-bits that can be controlled · Systems integration issues
Key motivation	The future for QI is enormously promising, both as an engine of fundamental discoveries and as a generator of transformative technologies that foster progress in many disciplines and industry sectors. Implementing QI on a chip may eventually replicate the enormous success of modern electronics technology. The advances in Atomic, Molecular, and Optical physics in seeding and progressing QI are indisputable. However, implementing QI on a chip can take advantage of the outstanding, continuous advances in material science and nanotechnology. If the platform would result CMOS compatible the chip integration becomes even more appealing because of the availability of foundries developed for conventional electronics.
Key challenges	· Minimize losses on chip. · Packaging of the devices. The level of sophistication in material/fabrication/packaging requires always more specialized expertise and labs. There is no university that alone is able to encompass all necessary tasks of QI on a chip at the apt level. Thus, it is important to explore - a modular collaboration (MURI-like) between groups. - interaction with foundries.
What is to transfer from the optical table to the Chip?	· Chip-integration should be pursued when new functionalizes are added and when the devices achieve performance equal or higher than conventional implementation. However, it could be wise to even sacrifice the performance of some component, to a certain extent, to reach an overall improved system performance. Moreover, a compromise on a specific performance today could be a full gain tomorrow as fab-technology progresses driven by industry. · Ultimately, a modular scheme could be the most successful approach. Chip-integration should be able to implement · single photon multiplexing (creation and storage),

	· few qubit applications for specialized applications (e.g. …), · fault tolerant architectures, · efficient quantum repeaters. It should also explore integration with trapped ions. Linear quantum photonics could benefit by having chip-integrated single photon sources based on quantum emitters (artificial atoms, point defects), · Demonstration of single photon multiplexing could be very beneficial. · Manipulation: different platforms · Detectors
What is now emerging from different areas that may have an impact for Q.I. on a Chip?	Platforms: · Quantum supremacy via boson sampling. · Quantum repeaters – memories. · Multiparty computation. · Topological states. · Quantum fluids of light. Materials Science: · Better and new materials such as ultrapure quantum dots heterostructures, defect free SiC, 2D transition metal chalcogenides. Instruments/devices: · Chip integrated, narrow linewidth lasers and frequency combs. · On demand efficient photon sources on chip. · Detectors with efficiency up to 99%. · Cheaper, smaller, and more user friendly closed-cycle cryostats. · Femtosecond laser machining. · Isotopes purification. Infrastructures: Increased access to Si foundry fabrication.
Where to go in 3 years - on a chip	
Desired/Required input from Theory	- better error correction algorithms - how to characterize large entangled systems - new protocols (cluster states,) - protocols for Quantum Machine Learning - what can useful we do with 10 qubits - how to use Boson Sampling approach for other applications - dissipation driven computing - no-go boundaries for experimentalists - system perspective to overcome components limitations - topological quantum computing: resilience to noise for different platforms - to identify advanced fault tolerant architectures for linear optic cluster states
Desired/Required input from Quantum Optical Devices	- configurability of the integrated devices: a better control of variability in components is requested to obtain a large architecture. Future on-chip photonic devices (quantum dots, circuits) need knobs to tune them. - 6-8 indistinguishable photons on demand with high indistinguishability scaling quantum dot sources by introducing tuning knobs

	- shipping around single photon sources - Implementation of active feed-forward on chip - high-efficiency high-yield detectors - integrate sources with low-loss circuits - good quantum memory - decrease losses - medium/high efficiency quantum converter between optical and microwave
Desired/Required input from Devices and technologies from outside Quantum Optics	- Circuitry (wires, cryogenic systems) to operate properly a quantum device - Virtual fabrication facility with uniform design and fabrication tools
Where to go in 10 years - on a chip	
Desired/Required input from Theory	- What can we do with 30 qubits
Desired/Required input from Quantum Optical Devices	- 20-30 indistinguishable photons on demand? - Circuits with quantum repeaters beating direct transmission rates - Full tunability of integrated devices - To demonstrate that fault-tolerant quantum computing is possible
Desired/Required input from Devices and technologies from outside Quantum Optics	
Lessons learned in the past	- Moving to a chip has always been a winning strategy for many applications. - Benchmark old roadmaps. - To define quantitative ranges for the technological goals.
Directions that will push Science forward	
Directions that will push Applications/products forward	
What aspects are more promising for international collaboration? Existing success cases?	

Communication and QKD on chip

Moderator: Dr. **Eleni Diamanti**
Laboratoire Traitement et Communication de l'Information
CNRS - Télécom ParisTech
23 avenue d'Italie
Paris, France

In the setting of quantum communications, photons are the ideal information carriers due to their long coherence time, their low interaction with the environment and their high speed. Photons also provide a viable pathway to integration, which is necessary to overcome the difficulties inherent in bulk systems to maintain mechanical stability in apparatuses of increasing size and complexity. Indeed, integrated photonics brings together many desirable characteristics in terms of efficiency, cost, scalability, flexibility and performance required for quantum communications.

The suitability of the available integration platforms for quantum communications is in general evaluated by various important features, including for example the necessity to use foundry services and compatibility with mass manufacturing processes, the ability to support nonlinear and electro-optic effects for routing, switching, and non classical state generation, single-photon detection and photon counting, the compatibility with specific encodings of quantum information, such as polarization, path, time bins, and the adaptivity to a practical communication network infrastructure.

The prevailing integration platforms for quantum communications are the following:
- Silicon-based platforms, which include silicon (Si) as well as silicon nitride (SiN) and silicon carbide (SiC), provide popular solutions as they combine several appealing characteristics, e.g. CMOS compatibility, compact structures, and strong nonlinear effects. These come at the expense of poor mode- matching with fibers and increased propagation losses.
- Platforms based on III-V compound semiconductors including indium phosphide (InP), gallium arsenide (GaAs), and gallium nitride (GaN), are widely used in optoelectronics. They allow for laser emission, lead to higher speed components, and several compounds (AlGaAs, InGaAs, etc) are suitable for telecommunication wavelengths. Foundry services are also required, and have the losses and mode- matching issues of Si.
- Nonlinear optical dielectric materials, in particular lithium niobate ($LiNbO_3$) and potassium titanyl phosphate (commonly known as KTP), form a particularly versatile integration platform. They present strong second-order nonlinearities and electro-optic properties, which makes them ideal for parametric down-conversion, frequency conversion and modulation processes. They have been historically used in quantum communications with immense success but are in general less scalable because of their size.
- Platforms producing glass waveguides, such as silica-on-silicon (where silica is the common name of silicon dioxide, SiO_2), femtosecond laser writing or UV writing, lead to reduced propagation losses and excellent mode-matching with standard optical fibers. Their fabrication does not need foundry services; hence they are ideal for rapid device and system tests. They do not support functionalities requiring nonlinear or electro-optic effects, but they enable the manipulation of

polarization and provide the possibility for 3D engineering. They also allow designing waveguide in rare-earth materials with optimized properties for quantum storage.
- Nitrogen vacancy centers in diamond are mostly used for quantum computing but were used recently for loophole-free Bell tests, which are relevant for device-independent QKD.

In general, no single integration platform can gather all the desired characteristics for a specific application. Indeed, it is generally understood that the next generation of quantum communication devices and systems will adopt hybrid integration technologies with the goal of bringing together the best elements of each platform.

The main optical quantum communication devices aim at generating, manipulating, storing and detecting quantum states of light. Integration efforts for all these devices were discussed in other discussion panels. In view of future large-scale quantum networks incorporating such devices, it is also crucial to take a system design approach including the components themselves but also the surrounding network environment and the additional constraints imposed by the implemented quantum communication protocols.

There is a wide range of protocols and applications pertaining to quantum communications. By far the most developed is QKD, while other important quantum cryptographic primitives include bit commitment, coin flipping, oblivious transfer, secret sharing, digital signatures, anonymous communication, secure identification, etc. Quantum communication complexity protocols, such as quantum fingerprinting, as well as random number generation are also essential elements of quantum commu- nications networks. Intrinsic losses in photonic communication channels eventually make it impractical to perform communication tasks over point-to-point links, and impose a network structure. Quantum networks are indeed crucial for increasing the range of quantum communication systems. This task is enabled by entanglement distribution, the fundamental building block of quantum teleportation and quantum repeaters.

Proof-of-principle on-chip demonstrations of QKD, entanglement distribution and quantum teleportation exist and are very promising. It is important to emphasize that in addition to developing the integrated quantum communication systems themselves, several other elements come into play in a practical network environment. In particular, the synchronization of the devices typically requires very fast electronics, hence integration of electronic components operating at GHz rates have to be devised. Furthermore, the packaging of the systems, whose operation requires the tuning and routing of a number of interconnected components, needs to satisfy stringent practical constraints. Finally, multiplexing techniques routinely used to increase the bandwidth in data communications and successfully tested in quantum communications, need to be adapted to on-chip systems.

Several advances can be expected in the following years. In particular, in a 3-year horizon, results could include:
- Optimization of losses due for instance to coupling to fibers. This will allow increasing the distance, which is extremely challenging but also crucial for applications.

- Integration of state preparation stage and of multiplexing techniques.
- The above will lead to high rate QKD systems (both for discrete and continuous variables) on chip.
- Implementation of advanced QKD protocols, in particular measurement-device-independent QKD on chip (and possibly device-independent QKD off chip).
- Implementation of active quantum teleportation on chip over some distance.
- Proof-of-principle 3-node quantum repeater link.
- Reduced payload components suitable for mobile QKD and for satellite communications; crucial for overcoming the challenge of losses, inherent in fiber optic networks, hence bringing quantum communications to the global scale.
- Entanglement with ions.
- Several quantum communication protocols have a direct link with tests of fundamental physics. It becomes possible to envisage on-chip foundation tests, e.g. for nonlocality and contextuality.

In a 10-year horizon, we may target:
- Total losses less than 1 dB.
- Implementation of device-independent QKD on chip.
- Demonstration of link to space, including integrated elements.
- Demonstration of a 1000 km entanglement distribution link, most likely within a trusted node network.
- Demonstration of a quantum repeater link (with some on-chip elements) surpassing the performance of direct transmission links.

To achieve the above goals input both from theory and technology will be required. In particular, theoretical results of interest include the design of optimal models for networks (for different levels of security); distributed quantum computing and communication protocols; protocols for secure transmission of data using qubits, incorporating error correction algorithms to counter losses, teleportation techniques, etc; certification and authentication techniques; analysis for quantum repeater requirements to beat direct transmission; channel capacities and ultimate rate-distance trade-offs over noisy channels; post-quantum algorithms in the context of a quantum-safe infrastructure; hybrid classical/quantum security schemes with different levels of realistic constraints. From a technological point of view, in addition to the losses and multiplexing mentioned above, desired advances include improvement of quantum error correction implementations; improvement in heralding efficiency for single and multi-qubit states; high-performance frequency conversion in thin $LiNbO_3$ or in KTP; further $LiNbO_3$ integration; channel monitoring techniques.

From a science vision point of view, it is important to keep in mind two directions at the two ends of the application spectrum. First, the new opportunities offered by integration in terms of long-distance entanglement distribution and quantum communications in space enable testing the quantum/classical interface and foundational notions in previously inaccessible regimes. Second, at a practical level, targeting truly useful systems with potential for industrial development will require the further enhancement of available infrastructures, both on the chip fabrication side, by developing worldwide high capacity multiple-use foundry services and III-V growth facilities, and on the network side, by using deployed fibers and satellite devices for the purposes of quantum communication experiments. Furthermore, work towards standardization, which is important for the impact and validation of future applications and already actively pursued for QKD, has to take into account the specificities of chip-based systems as well.

In terms of international collaborations, we remark that security remains a sensitive issue; however, the development of foundry services and growth facilities like the ones required for the large-scale development of quantum communications, as well as planning experiments in space and advancing with standardization will certainly requite coordinated worldwide efforts.

Discussion Table on **Communication and QKD on a Chip**

Questions to stimulate the discussion	
What is to transfer from the optical table to the Chip?	Components include o Source o Memory o Quantum repeater Sources for useful quantum states Packaging (tuning, routing of many components) Photonic and electronic integration (several GHz) Wavelength multiplexing
What is now emerging from different areas that may have an impact for Q.I. on a Chip?	Foundry facilities (both silicon photonics and III_V) can be beneficial Platforms for integration: o Silicon, SiN/SiO2, SiC o Diamond o Silica femto-second laser written, UV written (no foundry, 3D capabilities, no foundry) ° Femto-second laser written waveguide memories in rare-earth doped crystals o InP (III-V in general) o LiNBO3 o GaN o KTP Physical mechanisms o Polarization encoding (troubles in silicon photonics) o Cluster states o Frequency conversion interface o Single photon detection o Heralding with photon number detection o Routing and switching (electro-optics) o Quantum repeaters o Synchronization (fast electronics, standardization) Applications o QKD o Bit commitment o Relativistic protocol o Coin flipping o Secret sharing o Anonymous communication o Digital signature o Fingerprinting o Distributed entanglement o Secure identification

	o QRNG System level design (chip+network) Increasing distance is difficult
Where to go in 3 years - on a chip	Loophole free test outside chip Fully device independent Integrate state preparation (sources, multiplexing) Increase secure key rate by multiplexing Optimize coupling to fibers (Losses <1 dB) Space applications o Reduce payload by integration Entanglement with ions On chip teleportation Quantum contextuality
Desired/Required input from Theory	Design of optimal models for networks (for different levels of security) Find quantum ways to certification and authentication. Protocols for secure transmission of data using qbits (error correction to counter losses, teleportation) Analysis for quantum repeaters better than direct transmission
Desired/Required input from Quantum Optical Devices	Improve quantum error correction Improve heralding Frequency conversion in thin LiNbO3 or in KTP (filter, switches, detector on chip) Quantum repeaters 3 nodes link proof of principle
Desired/Required input from Devices and technologies from outside Quantum Optics	Define standards Channel monitoring
Where to go in 10 years - on a chip	Loophole free test using on-chip devices Total Losses <1 db Demonstration of link to space, possibly with on chip elements 1000 km link (entanglement distribution)
Desired/Required input from Theory	post quantum algorithms quantum safe infrastructure Hybrid schemes
Desired/Required input from Quantum Optical Devices	Quantum repeaters better than direct transmission LiNBO3 integration
Desired/Required input from Devices and technologies from outside Quantum Optics	

Lessons learned in the past	Do not overpromise Point out international competition
Directions that will push Science forward	Keep in mind products/industrial application Long distance entanglement for tests of fundamental physics (gravitation, quantum/classic interface…)
Directions that will push Applications/products forward	Infrastructure (fibers, clocks, satellite devices)
What aspects are more promising for international collaboration? Existing success cases?	Tests of fundamental physics in space Multiuse foundry services III-V growth facilities

Quantum Metrology and Sensing on a Chip

Moderator: Dr. **Alan Migdall**
Physical Measurement Laboratory - NIST
University of Maryland
Gaithersburg, MD, USA

A discussion was held on the potential applications and benefits of quantum metrology and quantum-enabled or quantum-enhanced sensing on a photonic-chip platform, as well as the critical issues that must be faced to allow that enable that potential. What follows is a summary of views expressed (although not necessarily consensus views) during that discussion. First, it was felt useful to define what is meant by a photonic-based quantum-enabled or quantum-enhanced application. Most broadly it involves some nonclassicality in the source or detection or processing of the light. And the applications must provide a benefit that cannot be achieved with only classical systems. The benefit could range from a measurement that is not possible at all classically or it could be a level of measurement uncertainty that cannot be reached classically. We broaden the definition to include measurement applications that enable measurements that could be done classically, but nonclassicality offers enough advantage to make the effort worthwhile, such as allowing an end user to achieve accuracy better than typically available to them, even if it is not at the level achieved by a metrology lab. An important point raised was that because of the overhead and other difficulties involved in quantum applications and also in designing a chip for a specific purpose, there must be a strong reason pushing the implementation. It will not be done "just because it can." Another point that is considered of high importance is the extreme sensitivity of nonclassical states to loss, that is while with some difficulty it is possible to generate states that are highly nonclassical, it is all to easy to degrade that nonclassicality with loss. So one must always keep in mind efficiency of the complete system, not just the source or the detector.

Discussion of applications that could potentially benefit from nonclassical light tools and particularly those amenable to implementation on a chip-based platform, yielded a number of areas. These included:

1) sensors based on single isolated quantum systems, such as using the spin of a single NV diamond to measure magnetic fields with unprecedented nanometer spatial resolution. Clearly an application meeting the requirements of exceeding what can be achieved with a classical measurement, which necessarily averages over much larger areas and it is particularly suitable to a chip deployment. Other measurements might be gravitational fields.
2) Bio applications, where samples cannot tolerate or survive large incident light fields and also applications where dynamics at the single molecule level is important.
3) Clinical applications would require that the sensor be small enough to take to the patient, so chip-based schemes offer a strong advantage in that direction.
4) Clock synchronization is an interesting application that has emerged as clock accuracy has improved beyond the accuracy capability of GPS-based synchronization. Potential solutions to this are frequency combs implemented on a chip and entire atomic clocks on a chip all linked and synchronized via fiber networks.
5) While it is a broad area, single- and number-resolved-photon detectors fall under the nonclassical measurement umbrella so any chip-based photon-counting system is of interest, particularly because any advance that makes such measurements more convenient and lower cost could have a significant impact in many areas. Single-pixel imaging is just one example of an application that could benefit from an inexpensive single photon detector.

Discussion of what could be implemented in a 3-year time frame included a chip-based frequency translator, which would be important for a number of quantum information applications, as it is likely that systems most suitable for the generation or storage of a single photon will not be most suitable sending that photon to a distant link. It was felt that this application is advanced enough and suited to a chip implementation that a chip-based implementation is foreseeable in the near future and most importantly has enough applications that there would be a strong argument for its implementation. Another near-term application would be some chip-based sensor application perhaps in a bio application where nanoscale spatial resolution is required. It was also felt that a chip-based radiometric standard might be implemented for use in national metrology labs, and perhaps ultimately more widely. Yet another chip-based application would be to allow photon-number-resolved detection to be more accessible which should have a broad range of measurement impacts.

What was seen as areas that need work on the theory side are a better understanding of fundamental physical processes involved in detection and what are the fundamental limits of a range of detection parameters like efficiency, timing jitter, dark rate, etc. More effort is needed on a theoretical understanding of applications in terms of which applications can best take advantage of quantum features. Examples of interest needing this theoretical understanding are bio-measurements and boson sampling. On the technology side there is a general need for more convenient/accessible detectors. Efforts to both make cryocoolers with small spatial and power footprints and to make detectors with higher operating temperatures. Specifically an example of the later would be developing new materials for superconducting nanowire detectors that allow operation at temperatures compatible with a Sterling cooler, both reasonable areas to expect progress in the next 3-5 years. More generally other detector materials such as graphene might enable new types of detectors with new performance combinations. Other desires are more and larger photon counting array detectors or for the compressive sensing application a faster spatial light modulator perhaps with 1000x1000 pixels with a 10 ns switch time.

What is possible on a 10 year time frame is of course highly speculative, but possibilities include commercial products capable of nanoscale field imaging using single quantum systems like an NV center. Another possibility would be commercial photon pair sources and standards. Also upconversion or direct IR photon counting cameras are conceivable on this time frame. Another desired outcome would be optomechanical inertial sensors developed into a readily available component perhaps where an optical beam is entangled with the system. Desired input from theory includes development of macro-entanglement applications and techniques. As with the 3-year time frame, developing the theory of fundamental detection physics is very important. Applications that might push the field are bio measurements, security applications, and automotive applications.

With a view for collaborations, it is expected that metrology and standards labs are natural collaborators. On a broader front having some system or market in place to allow freer access to knowledge of and exchange of quantum components might be helpful.

Discussion Table on **Quantum Metrology and Sensing on a Chip**	
Questions to stimulate the discussion	Loss Loss Loss Loss Squeezing is generally lost. What is quantum enabled app? What is quantum **advantage**? Lesson learned in quantum sensing program? Type I, II, III What applications would benefit from Quantum on a chip?- systems that cannot handle high light levels,example: Bio-samples Quantum illumination requires holding one entangled photon protected from loss. Unique applications. Or outperforming in terms of Resolution, Sensitivity? Source coding? Improvement in fieldability. “Electrosuiticles”? Optical or electrical trigger of biofunctions.
What is to transfer from the optical table to the Chip?	Dissemination of standards: single photon, radiometric source and detector standards. Force standards Sensors to measure B Field via NV centers at nanoscale. (Brain injury?) **Noninvasive** clinical sensing!!! Brain imaging. Implant sensors. Needs to be small enough to take to patient. Clocks on a chip Magnetometer on a chip Bio signature at single photon or molecule level. Time resolved measurements of single quantum system sample. Killer apps?.- imaging(single pixel, array) coherent control, quantum control(feedback loop is quantum). Clock sync via optical links via freq combs on chip? Big efforts on this. Entanglement distribution. Bfield mapping for navigation (underwater) requires small and sensitive system. Gavimeters, gyros. Apps that may win in terms of resources. Electronics close to system has advantages in itself. General advantage of integration. (Heterogeneous integration). Automotive app: single photon camera. Frequency translator from IR or far IR to visible. PNR mode analysis one a chip.
What is now emerging from different areas that may have an impact for	

Q.I. on a Chip?	
Where to go in 3 years - on a chip	Frequency translator from IR or far IR to visible. Some sensor/transducer chip application implemented. Some standard prototype in development at NMIs
Desired/Required input from Theory	Fundamental detection limits Fundamental mechanism for SNSPD Fundamental limits for bio applications and what bio apps are most promising. Better understanding of boson sampling. Is it possible to use this knowledge to make a workable experiment.
Desired/Required input from Quantum Optical Devices	Detectors compatible with Stirling coolers, eg. SNSPD at higher temps. Better substrate for nanowires. Graphene detectors. Timing jitter ~ ps.
Desired/Required input from Devices and technologies from outside Quantum Optics	Cryocooler with smaller footprint.
	Spatial light modulator Faster than mems. 1k x 1k x 10 ns Or laser source array.
Where to go in 10 years - on a chip	NV center nano imaging as commercial product Commercial chip pair sources/standards
Desired/Required input from Theory	Macro entanglement apps or techniques
Desired/Required input from Quantum Optical Devices	Upconversion camera or direct IR photon counting camera. Single pixel imager. Timing jitter ~100fs Optomechanic inertial sensors readily available (entangles reflected beam)
Desired/Required input from Devices and technologies from outside Quantum Optics	Better cryo coolers Better materials Single atom control of nanocomponents Packaging- quantum connector?
Lessons learned in the past	
Directions that will push Science forward	Fundamental detection physics theory
Directions that will push Applications/products forward	Bio apps Security apps

What aspects are more promising for international collaboration? Existing success cases?	Metrology labs/ standards. Quantum Ebay for widgets, measurements to facility collaborations

Generation and detection of single photons

Moderator: Prof. **Daniele Bajoni**
Dipartimento di Ingegneria Industriale e dell'Informazione
Università degli Studi di Pavia
Pavia, Italy

The discussion started with a loose classification of possible sources of quantum states of light in deterministic and probabilistic sources. Among deterministic sources the most discussed have been III-V quantum dots and lattice defects in diamond. It has been pointed out that the main present disadvantages for quantum dots are the need of cryogenics and their spectral inhomogeneity. For this last point solutions are however already available via electrical tuning of the quantum dot's energy levels.

The need to put together all recent results has been discussed, as well as the need to clearly define performance criteria for the sources, in particular to set a desirable value for the $g^{(2)}(t=0)$; this value should be different depending on the application in mind. A very promising line of investigation for the near future would be to easily obtain electrical injection of quantum dots, either directly or by monolithical integration of existing III-W tunable lasers.

Prospects for integration on photonics chips where later examined, either by using III-V or diamond photonics or by wafer bonding on silicon photonics chips. The possibility to modify silicon to induce a $c^{(2)}$ nonlinearity was also considered along with high band gap III-V dots operating at room temperature.

Regardless of the photonic platform the capability of fast optical switching, by either electrical or optical means, was identified as a key feature.

A very interesting emerging trend for deterministic sources is the possibility of having quantum dots emitting in the telecom band. Another very interesting emerging research is that of molecular single photon emitters. Although difficult to integrate, molecular emitters can be as stable as quantum dots when operated at very low temperatures.

For what concerns probabilistic sources of light, it was noted that spontaneous parametric down-conversion in BBO crystals is the process which yielded the record number of 8 entangled photons.

Views were exchanged on the opportunity of using high brightness external sources coupled to a chip instead of integrated sources. It was noted that integration of the source brings about a huge enhancement in efficiency, in particular in view of coupling losses for external sources. Problems with coupling efficiency are particularly severe when the chip needs to work at low temperature, as coupling methods are generally developed for room temperature.

Views were exchanged in particular on the importance of spontaneous four wave mixing to develop sources integrated in a silicon chip. It was suggested to design the samples in a way to limit the optical nonlinear response in the source region only, in order to manage losses from two photon absorption.

Details of heralding efficiency were discussed in the case of integrated probabilistic sources. A clear theoretical lower bound for the heralding efficiency to achieve linear optics quantum computation is still missing, and is needed.

On the side of detection integration was discussed. On-chip realization of Superconducting Single Photon Detectors (SSPDs) based on NbN is well underway, but a further increase in efficiency is needed. Improving the timing jitter is also necessary for efficient multiplexing of probabilistic sources. The relevance of fast electronic feedforward was also pointed out in the framework of quantum teleportation on chip.

The importance of photon number resolving capability in boson sampling applications was examined. Number resolution would result in a desirable reduction of the number of interacting waveguides.

Ongoing research on material science was reviewed. WSi detectors offer larger detection efficiency then NbN detectors, MoSi single photon counters have recently been demonstrated with high yield and negligible dark count rates.

Silicon APDs have also been discussed as a valid alternative in the visible and near infrared range, especially for their ability to operate close to room temperature. Commercial modules have up to about 80% efficiency, and can get to 90%. There are no physical limitations to improve it even more, and possibly reach 99%. Room temperature operation has still however some fundamental limiting factors, in particular the trade off between quantum efficiency and dark counts.

Fabrication and integration of superconducting nanowires is also easier than in the case of semiconductor detectors, especially when considering infrared single photon counters. On the other hand, semiconductor detectors can be easily operated with CMOS electronics and have excellent timing resolution and jitter.

In the case of infrared photons, up-conversion solutions can be envisaged. Up-conversion schemes have a very high timing resolution and could greatly benefit from on chip integration.

Another route to detection would be to use continuous variable quantum states of light in conjunction with homodyne detection schemes. In this case timing resolution is traded off for extremely high detection efficiency and the noise is lower that in the case of single photon counters.

Possible goals for the next 3 years were then considered. On the side of sources it was proposed to achieve deterministic emission of photons from probabilistic sources using multiplexing. For this applications detectors are needed with an efficiency of at least 90%, possibly more. In order to achieve multiplexing, high speed on chip modulators are also needed. The switching rate should at least be of the order of several GHz, and noise should be carefully managed, especially in the case of all-optical switches.

Other desirable goals include the emission of a large number of identical photons (possibly 10, for application in quantum simulation and computing), and the heralding of Bell pairs with good efficiency.

Regarding detectors, a research effort should be devoted to develop on chip SSPDs based on high T_C superconducting materials.

Several inputs will be required from theory. The development of quantum computing protocols tolerant to noise and losses would be beneficial to LOQC. Theoretical investigation of noise effects on entanglement generation is also desirable

An improved understanding of the physical mechanisms involved in semiconducting and superconducting avalanche photodiodes could also lead to a further improvement in their performances.

Concerning quantum optical devices, advances in quantum memories have been found to be of fundamental importance, as well as improved stability.

Improvements in on-chip photonic devices are also required. Fast on-chip switching, efficient connections to the driving electronics are needed.

Goals and requirements for the next 10 years were also debated.

An important goal would be the harvesting of entanglement from a system of ions to the optical domain. This would be pivotal for application in in quantum communications. The on-demand emission of Bell pairs, the heralding of three qubit entangled states, and possibly the achievement of an all-optical quantum repeater were discussed as possible research targets.

Frequency combs have been proposed as a way to obtain entangled states with a large number of qubits.

Other important goals were found to be the realization of on-demand emission of single photons using multiplexing, in order to achieve performances exceeding those of quantum dots. This goal requires a lot of research effort on the reduction of losses, and on the improvement of the interface with quantum memories.

On the side of detection three lines of research were mainly discussed: the reduction of dead time to a few nanoseconds, the use of SSPDs to achieve photon number resolution, and the use of high T_C superconductors.

Improvements in cooling hardware, and further studies in material physics have been found to be necessary. In particular research in material physics could lead to much better detectors.

The need to carefully balance promises have been discussed as a lesson learned from the past. In particular project objectives should be clear and consist in measurable predictions and deliverables.
Strategies to move from laboratory research to actual products were debated. Some of the abovementioned goals, in particular efficient detectors, could be used for several diverse applications, including biomedical devices, improving market interest in the fruits of quantum information research. The availability of foundries was found to be a fundamental key to drive down costs and develop devices for realistic applications.

Past and future collaborations were examined. Research in quantum information is a very successful field in these regards, with ongoing European collaborative projects (including for instance the NQO COST action) and global research efforts in the field of Metrology.
Future collaboration could include shared access to fabrication facilities (e.g. the facility at Sandia labs) or even the institution of foundries devoted to fundamental research topics.
Funding to overseas collaboration would greatly help EU-U.S.A. partnerships, for instance in the form of joint post-docs.

Discussion Table on **Generation and detection of single photons**	
Questions to stimulate the discussion	
What is to transfer from the optical table to the Chip?	probabilistic sources: III-V, diamond, quantum dots disadvantages: cryogenics, spectral inhomogeneity -> solutions available, need to put things together depends on application need to define performance criteria, trade offs applicable to all platforms AlGaAs allows for electrical injection, problems? Integrated tunable lasers exist g2 criterion for single-photon sources consider new materials (silicon defects) in parallel with optimization of present materials convert silicon to have chi2 integration of III-Vs: not define material platform fully, heterogeneous integration but leave open quantum dots in III-V integrated on silicon defects in diamond: room temperature? integration on Si? need to do active structures single-photon emission better with defects other than NV centres nonlinear crystals: record 8 qubit states (China) integrate or optimize coupling to chip leaving the source outside? integration huge enhancement in efficiency coupling methods work at RT, detectors usually at low T, difficult to optimize integration on Si well underway: SFWM absorption, get rid of nonlinearity after generation, how to build heralded sources? fidelity after heralding event has to be sufficiently high, theoretical proposals missing for reaching fidelities for LOQC with heralding emphasize other platforms trade off application, wavelength foundries (Si electronic infrastructure possible) deterministic sources: integration of single atoms using optical trapping: Rd (Harvard), more difficult than for ions trapped ions ok Achieve high beta for systems with QDs Spin photon interface with QDs on-chip detectors: SNSPDs: increase efficiency even more? timing jitter? multiplexing necessary fast feedforward eg for quantum teleportation on chip, electronics on chip photon number resolving detectors: necessary for boson sampling? reduces number of WGs (other types of modes can be exploited, need fast switching for time modes), useful for LOQC niobium nitride detectors, better materials? alternatives: WSi slower but high QE, moSi high yield

	dark counts: less important for multi-photon detection table in Alan's book with SPS and SPD characteristics applications for using detectors without cooling: QKD commercial APDs efficiency 80% (visible), 90% possible, 99%? cavity for specific wavelengths? trigger efficiency limiting factor for noise, trade off between dark counts and efficiency, fundamental issues for RT operation of semiconductor detectors fabrication of SNSPDs much simpler than semiconductor figure of merit dark count/efficiency: nanowires are better, but semiconductors can improve, easier to deploy, operate CMOS electronics is easier, more compact trade off between time resolution and efficiency homodyne detectors for CV applications: low noise, high efficiency upconversion solutions frequency conversion: benefits from integration, higher time resolution, higher efficiency, lower noise continuous variables sources: NOON states, loss issue, other states?
What is now emerging from different areas that may have an impact for Q.I. on a Chip?	telecom band QDs: InP polymer sources, integration? stability? for low temperatures as stable as QDs
Where to go in 3 years - on a chip	multiplexed probabilistic sources, faster than non-multiplexed needs detector efficiency at least 90%, affects fidelity directly concatenation of nanowire detectors on WGs? high speed (GHz), low loss (1% or less), low noise switching on a chip (no pollution from the pump in the case of optical switching) 10 identical Photonics heralded Bell pair with good efficiency on chip High TC devices investigated
Desired/Required input from Theory	study necessary sources for LOQC loss and noise tolerant protocols noise generating entanglement? tasks for which we can do better with SPS than with SPDC better modeling of hardware, benchmarking of devices mechanisms for superconducting detectors and APDs
Desired/Required input from Quantum Optical Devices	stability, wavelength division multiplexing quantum memories
Desired/Required input from Devices and technologies from outside Quantum Optics	fast switches fast electronics improve semiconductor detectors

Where to go in 10 years - on a chip	harvesting entanglement from an ion/atom systems to the optical domain: motivation? applications in quantum communications, all-optical repeaters, on demand Bell pairs useful large entangled states generated from frequency comb systems on-demand multiplexed source, interface with quantum memories better than with QDs -> need to fight losses, switching heralded 3-qubit entangled state on chip few ns dead time, photon number resolving SNSPDs high temperature devices
Desired/Required input from Theory	
Desired/Required input from Quantum Optical Devices	
Desired/Required input from Devices and technologies from outside Quantum Optics	more compact coolers materials for detectors good nonlinear optical materials (nonlinear phase shift/linear and nonlinear loss)
Lessons learned in the past	do not overpromise Set goals that are measurable, precise and verifiable progress is possible!!
Directions that will push Science forward	
Directions that will push Applications/products forward	increase operating temperature, improve efficiency at RT find biomedical and other applications availability of foundries
What aspects are more promising for international collaboration? Existing success cases?	COST action EU collaborative projects on QI Need for access to facilities: Sandia, aggregate effort in big centres, manufacturing facilities devoted to fundamental research? Not many available funding tools for overseas collaborations NSF funded post-doc scientific visits in Europe Metrology (global community oveseas collaborations)

Integration technologies; Nonlinear effects

Moderator: Prof. **Antonio Badolato**
Department of Physics and Astronomy,
University of Rochester,
Rochester - USA

Key Motivation

Implementing QI on a chip may eventually replicate the enormous success of current electronics technology. In modern optoelectronics the integration of several devices (such as lasers, waveguides, modulators, detectors, and amplifiers) on a chip is becoming a major scientific and industrial trend. Integration is pursued to resolve bottlenecks present in dense circuits, for example at high operation frequencies to mitigate problems such as power dissipation and cross-talk. In the next years, it is expected that advances in chip-integrated optoelectronics will enable unprecedented capability for optical systems, much in the same way that electronics have evolved using integrated circuits.
Quantum devises may largely benefit from the same framework and infrastructures driven by industry, and some of the advantages due to integration may even be a key for the implementation of QI systems. Quantum coherence is typically quite fragile, if we exclude the macroscopic quantum phases such as the superconducting phase, which can be a robust state under certain extreme conditions. To preserve quantum coherence between interacting functionalities the reduced latency obtained by chip-integration may be indispensable.

Today, QI tasks are implemented by photons, atoms/ions, spins, and mesoscopic superconducting circuits. Their physical properties make some of these systems better suited than others for specific tasks. A central goal for QI on a chip would be to integrate devices that can simultaneously perform several of these tasks, namely, reliably store, process, and transmit quantum information. The general consensus of the panel was that a modular (hybrid) scheme that integrates complementary functionalities could be the most successful approach, while the realization of all QI key operations in a single-crystal monolithically integrated circuit is not feasible in the next 10 years. A downside of the modular approach could be the communication times, which may require additional memories/low-loss delay lines, and the potential challenges associated with developing interfaces between the different modular sub-systems. Though promising results have been already obtained in this direction such as the realization of efficient spin-photon interfaces.

What complementary functionalities do we want to integrate?

The effective coupling strength between different systems could be too weak because of spatial (or impedance) or spectral (both center frequency and bandwidth) mismatching between the different systems. Even in presence of a strong interaction the resonant frequencies of two subsystems can be very different. This is an issue of particular importance for the integration of superconducting circuits with other platforms.

Nonlinearities are essential for QI schemes. Key components to be integrated are thus quantum emitters and devices that harvest the native $\chi^{(2)}$ and $\chi^{(3)}$ of materials by enhanced light-matter interaction. Current quantum emitters of interest are

- Defects in semiconductors (e.g., NV centers in SIC and Diamond),
- Quantum dots in III-V semiconductors (e.g., $In_xGa_{1-x}As/GaAs$)
- Neutral atoms (e.g., vapor cells),
- Organic molecules (e.g., DBT, dibenzoterrylene, in anthracene),
- Cooper-pair box in superconducting circuits.

One distinguishing aspect could be the inhomogeneous broadening (e.g., NV center inhomogeneous broadening is ~100 GHz; QD inhomogeneous broadening is several THz).

Native $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities (also called Kerr-type nonlinearities) in nanophotonic structures can be essential for frequency conversion and switches, and at the single photon-level when coupled to ultrahigh Q/V resonators.

What is to transfer from the optical table to the chip?

The general consensus of the panel was that chip-integration should be pursued when new functionalizes are added and when the devices achieve performance equal or higher than conventional implementation. However, it could be wise to even sacrifice the performance of some components, to a certain extent, to reach an overall improved system performance. Moreover, a compromise on a specific performance today could be a full gain tomorrow as fab-technology progresses driven by industry.

Chip-integration should aim to implement

- Single photon multiplexing,
- Fault tolerant architectures,
- Efficient quantum repeaters,
- Few qubit applications for specialized applications,

It should also try to explore integration with trapped ions.

Linear quantum photonics could especially benefit by having chip-integrated single photon sources based on quantum emitters (quantum dots, point defects in semiconductors). In this subfield we should aim to demonstrate

- Single photon multiplexing,
- Reconfiguration of the platform
- Integration with detectors.

What facilities can be used to pursue QI on a chip?

It was clear to the panel that there will be limitations due to fabrication facilities. For examples:

- Foundries have set processes that cannot be modified.
- Research facilities are more flexible but may impose segregation of material systems (III-V and Si cannot be process on the same instruments).

Dedicated facilities would be ideal but production of many units would be needed to justify large fixed costs.

What type of integration is best for QI on a chip?

CMOS compatibility for QI on a chip would be desirable because of the availability of foundries developed for conventional electronics. However, at this stage CMOS compatibility in a strict sense may be overly restrictive. Certain applications may already require complex fabrication schemes (e.g. Si switching), though might not be CMOS-compatible (e.g. silicon photonics with certain non-CMOS metals). On the other hand, need to think about whether all non-CMOS steps really need to be non-CMOS.

Integration may require specific tools such as

- Site-specific ion implantation (e.g., Si in SiC and diamond).
- Control at the atomic level (e.g., P in Si through STM positioning and overgrowth).
- Isotopic purification of materials to minimize dephasing fluctuations from the nuclei.

Relevance of collaborative work and interaction with other communities.

Pursuing integration of QI on a chip following a modular approach requires strong collaborations among several research groups with diverse expertise. The level of sophistication in material/fabrication/packaging/device requires many expert skills and lab instrumentations. There is no group that alone is able to encompass all necessary tasks of QI on a chip at the apt level. Thus, a sort of International Multidisciplinary University Research Initiative would be necessary.
QI could be one of those cases in the history of science where teamwork could result critical. Team science has led to scientific breakthroughs that would not otherwise have been possible, such as the discovery of the transistor effect and the Higgs boson. The scientific community has been pursuing QI goals for many year now, and as reported during this discussion session a certain "quantum fatigue" has emerged, namely, frustration from single research groups that despite the hard work are not able to produce real disruptive quantum technology. Team science could mitigate this issue.
At the same time, conducting research collaboratively can introduce challenges; for example, while the increasing size of team-based research projects brings greater scientific expertise and more advanced instrumentation to a research question, it also increases the time required for communication and coordination of work.

The advances in Atomic, Molecular, and Optical physics in seeding and progressing QI are indisputable. However, it was pointed out that a stronger involvement of the semiconductor community and materials science community would be necessary. The QI community could also benefit from contributions of industrial community that may be focused on a related problem, though information needs to be shared. There have been targeted efforts in the past in the context of certain problems (e.g. optical computing; integration of electro-optic materials).

EU programs are organized based on the above considerations.

Discussion Table on **Integration technologies, Nonlinear effects**

Questions to stimulate the discussion

- QI tasks are implemented by photons, atoms/ions, spins, and mesoscopic superconducting circuits. Their physical properties make some of these systems better suited than others for specific tasks. A central goal for QI on a chip would be to integrate devices that can simultaneously perform several of these tasks, namely, reliably store, process, and transmit quantum information.
    - What complementary functionalities do we want to integrate and actually can integrate?
      Can be limitations due to fabrication facilities (e.g., set foundry processes; segregation of material systems within research fabs). Dedicated facilities would be ideal; maybe discussion with related communities (on the engineering/materials side) could help.
    - e.g. can we interface superconducting circuits with other platforms [NV centers, cold atoms (hybrid though not necessarily chip-integrated), optomechanics, electro-optic modulators?]; what are the benefits – communication into and out of the cryostat? Is scaling to very large numbers of qubits difficult due to the size of the circuits?
    - Hybrid/modular approach: The effective coupling strength between different systems could be too weak due to spatial (or impedance) or spectral (both center frequency and bandwidth) mismatching between the systems. Even in presence of a strong interaction the resonant frequencies of two subsystems can be very different. Integrate when needed (e.g., better functionality). Production of many units is needed to justify large fixed costs. At this stage, modular components might make sense; downside is the communication times (might require memories/low-loss delay lines).

  Interfacing hybrid systems with each other will also require mitigating the decoherence that occurs when one brings quantum systems near surfaces, other quantum elements, etc. Surface, for instance, become inevitable when you speak of controlling single atoms/solid-state defects/SC qubits and coupling them to photons, phonons, or each other in any scalable way. Hence, the broad issue of "quantum interfaces" - coupling strategies, coherence preservation, etc is an important one.
- Quantum nonlinearities on a chip (maybe needs to be defined better; e.g., nonlinear for a single excitation; or defined for specific application): Monolithic (QD), hybrid (NV on ..), macroscopic quantum states. Defects in group IV materials (e.g. SiC), 2D materials (transition metal dichalcogenides); neutral atoms (e.g., vapor cells).

One distinguishing aspect could be the inhomogeneous broadening (e.g., NV center inhomogeneous broadening is 100 GHz; QD inhomogeneous broadening is several THz). Organic molecules in certain materials (e.g., DBT in anthracene).

Chi(2) and chi(3) nonlinearities for sources, frequency conversion, switches. Single photon-level nonlinearities in high-Q structures (improvement in Q by a factor of 10-100)

- Relevance of (i) CMOS compatibility, (ii) silicon photonics, and (III) interaction with foundries.

  CMOS compatibility in a strict sense may be overly restrictive. Certain applications may already require complex fabrication schemes (e.g. Si switching), though might not be CMOS-compatible (e.g. silicon photonics with certain non-CMOS metals). On the other hand, need to think about whether all non-CMOS steps really need to be non-CMOS.

  CMOS for electronics might make sense.

  Research fabs might be able to build upon what a foundry can provide.

- Synthesis at the nanoscale can proceed in two directions: starting on a larger scale and working down in size (top-down) or starting at the atomic scale and building up (bottom-up), e.g., crystal growth self assembly.

  Other fabrication tools – site-specific ion implantation (e.g., Si in diamond, atomistic control in other contexts, e.g., P in Si through STM positioning and overgrowth)

- What significant contributions can come from materials science?

  Could benefit from contributions of industrial community that may be focused on a related problem, though information needs to be shared. There have been targeted efforts in the past in the context of certain problems (e.g. optical computing; integration of electro-optic materials).

- Team science has led to scientific breakthroughs that would not otherwise have been possible, such as the discovery of the transistor effect and the Higgs boson. At the same time, conducting research collaboratively can introduce challenges; for example, while the increasing size of team-based research projects brings greater scientific expertise and more advanced instrumentation to a research question, it also increases the time required for communication and coordination of work. If these challenges are not recognized and addressed, projects may fail to achieve their scientific goals.

  The level of sophistication in material/fabrication/packaging/device of QI on a chip requires many expert skills and lab instrumentations.

	There is no group that alone is able to encompass all necessary tasks of QI on a chip at the apt level. Thus, a sort of International Multidisciplinary University Research Initiative could be necessary. EU programs are organized based on the above considerations MURI programs in the US can now include the UK (each country funds its own research towards a common goal) Materials World Network from NSF has a similar goal Maybe QI can do this more flexibly than technologies that are further along
Key motivation	The future for QI is enormously promising, both as an engine of fundamental discoveries and as a generator of transformative technologies that foster progress in many disciplines and industry sectors. Implementing QI on a chip may eventually replicate the enormous success of modern electronics technology. The advances in Atomic, Molecular, and Optical physics in seeding and progressing QI are indisputable. However, implementing QI on a chip can take advantage of the outstanding, continuous advances in material science and nanotechnology. If the platform would result CMOS compatible the chip integration becomes even more appealing because of the availability of foundries developed for conventional electronics.
Key challenges	· Minimize losses on chip. · Packaging of the devices.
What is to transfer from the optical table to the Chip?	· Chip-integration should be pursued when new functionalizes are added and when the devices achieve performance equal or higher than conventional implementation. However, it could be wise to even sacrifice the performance of some component, to a certain extent, to reach an overall improved system performance. Moreover, a compromise on a specific performance today could be a full gain tomorrow as fab-technology progresses driven by industry. · Ultimately, a modular scheme could be the most successful approach. Chip-integration should be able to implement · single photon multiplexing, · few qubit applications for specialized applications (e.g. …), · fault tolerant architectures, · efficient quantum repeaters. It should also explore integration with trapped ions. Linear quantum photonics could benefit by having chip-integrated single photon sources based on quantum emitters (artificial atoms, point defects), · Demonstration of single photon multiplexing could be very beneficial. · Manipulation: different platforms

	- Detectors
What is now emerging from different areas that may have an impact for Q.I. on a Chip?	Platforms: - Quantum supremacy via boson sampling. - Quantum repeaters – memories. - Multiparty computation. - Topological states. - Quantum fluids of light. Materials Science: - Better and new materials such us ultrapure quantum dots heterostructures, defect free SiC, 2D transition metal chalcogenides. Instruments/devices: - Chip integrated, narrow linewidth lasers and frequency combs. - On demand efficient photon sources on chip. - Detectors with efficiency up to 99%. - Cheaper, smaller, and more user friendly closed-cycle cryostats. - Femtosecond laser machining. - Isotopes purification. Infrastructures: - Increased access to Si foundry fabrication.
Where to go in 3-5 years - on a chip	
Desired/Required input from Theory	- better error correction algorithms - how to characterize large entangled systems - new protocols (cluster states,) - protocols for Quantum Machine Learning - what can useful we do with 10 qubits - how to use Boson Sampling approach for other applications - dissipation driven computing - no-go boundaries for experimentalists - system perspective to overcome components limitations - topological quantum computing: resilience to noise for different platforms
Desired/Required input from Quantum Optical Devices	- configurability of the integrated devices: a better control of variability in components is requested to obtain a large architecture. Future on-chip photonic devices need knobs to tune them Quantum dots have knobs with small electric fields - 6-8 indistinguishable photons on demand with high indistinguishability scaling quantum dot sources by introducing tuning knobs - shipping around single photon sources - Implementation of active feed-forward on chip

	- high-efficiency high-yield detectors - integrate sources with low-loss circuits - good quantum memory - decrease losses - medium/high efficiency quantum converter between optical and microwave
Desired/Required input from Devices and technologies from outside Quantum Optics	- Circuitry (wires, cryogenic systems) to operate properly a quantum device - Virtual fabrication facility with uniform design and fabrication tools
Where to go in 10 years - on a chip	
Desired/Required input from Theory	- What can we do with 30 qubits.
Desired/Required input from Quantum Optical Devices	- 20-30 indistinguishable photons on demand? - Circuits with quantum repeaters beating direct transmission rates - Full tunability of integrated devices - To demonstrate that fault-tolerant quantum computing is possible
Desired/Required input from Devices and technologies from outside Quantum Optics	
Lessons learned in the past	· Moving to a chip has always been a winning strategy for many applications. · Benchmark old roadmaps. · To define quantitative ranges for the technological goals. · The best material in terms of performance might not end up being the winning option (e.g., if the latter is more feasible to implement scale-up, etc)
Directions that will push Science forward	
Directions that will push Applications/products forward	
What aspects are more promising for international collaboration?	

Existing success cases?	

Applications Avenues and Imaging

Moderator: Dr. **Davide Calonico**
Istituto Nazionale di Ricerca Metrologica (INRIM)
Divisione di Metrologia Fisica
Torino - Italy

The Table "Applications Avenues and Imaging" focused on **two main issues, imaging and cold atoms on a chip.** Some overlap exists with the Table "Quantum Metrology and Sensors", but the remarkable difference has been that in this Table the participants, for their own professional experience, targeted more excellence science concepts rather than standardization and calibrated tools for science.

The report is divided into two separate sessions, one devoted to Imaging and the other one to Cold Atoms on a Chip, each section addressing the required inputs and possibilities in short term (3 years) and medium term (10 years).

General requirements from Quantum Optical Devices have been addressed:

- Calibration technique and protocols for chip devices /using chip devices
- Effective chip scale lasers (single frequency, narrow linewidth, different wavelength)

A third Application Avenue is the interferometry enhanced by quantum light, yet less discussed because of time issues. This is believed to be a key technology to beat quantum limits countering the sensitivity reduction by reduced (chip scale) sizes, envisaging in particular Sagnac interferometers on a chip. The straightforward application is an enhanced spectroscopy by quantum light, but not only. Here the main requirements are the development of different measurement strategies and adaptive protocols to exploit non-classical light.

The target in 10 years is an ubiquitous chip scale Sagnac/quantum light interferometers for sensing.

Quantum Imaging

The first issue about imaging addressed by the participants have was how to define the "quantumness" of this topic, in particular concerning the mainstream argumentations of the workshop. Imaging is an hard field where claiming "quantum"; in analogy with Quantum Information the Table also wondered a so called "killer application" of quantum imaging.

An interesting contribution could come from the transfer of new approaches from quantum to classical imaging and vice versa (hyper-dimensions, hyper-spectral imaging)

At the end, the Table focused on the main interesting topics in this field:

- sub-shot noise

- sub-diffraction with single photon
- quantum illumination,
- ghost imaging

And the applied issues (some overlap with Quantum Metrology):

- Calibration of CCD camera with quantum light
- Readiness for industrial exploitation, both for lowering costs and increasing interest of companies

General consensus was present about the main tools to be transferred from the optical table to the Chip, identified mainly in the kind of light sources: integrated sources, and in particular *Squeezing on the chip*; detectors and in general the capacity to correlate different light source for calibration.

Further inputs in the field are required, i.e. improved sampling/compression protocols using quantum correlations, 0.5 to 5 mm sources for quantum imaging (to fundamental and fast sensitivity), then to be extended up to 15 mm. In a more general scenario, the community is looking for an effective managing of multi-pixel devices, for inputs from LIDAR/LSR area, and for a better frame rate for the devices.

Atoms on a Chip

On this topic, first there was a sort of adamant claim that atoms are quantum, and that atoms and in particular cold atoms on a chip are the photon counterparts of the quantum technologies to be translated from the optical tables to the chips. Apart of this initial argumentation, the discussion split into an Application Avenues more devoted to magnetometers and clocks, overlapping a bit with Quantum Metrology and Sensing, and the general topic of Cold Atoms on a chip, yet less developed, but with a proper declination in the mainstream of Quantum Technologies on a Chip for Excellence Science.

General consensus was present about the main tools to be transferred from the optical table to the Chip, identified mainly in Neutral Atomic manipulation tools and in Adaptive Receivers beyond the standard quantum level on a chip. Requirements from base research addressed in particular the development of better methods to evaluate frequency shift due to magnetic fields, and for clocks the implementation of: sub-shot detection. Particular care must be required from effective vacuum technologies for chip scale atoms on a chip

Short Term Targets (3 years)

Imaging applications target the development of the general tools (sources and detector) that could get a breakthrough with industrial interests, in terms of costs and production processes. In particular, sources for quantum imaging ranging from 0.5 to 5 mm (to fundamental and fast sensitivity) will be present.

Atoms on a Chip address in 3 years two issues: one concerning hardware, the second related to performances. First, in 3 years the target is to have real chip scale atomic magnetometer and to reduce the size of chip scale clocks. Moreover, it is foreseen an improvement by a factor 10-100 in the stability performances, and for clocks also a factor 10 in clock accuracy.

Medium Term Targets (10 years)

In 10 years from now, imaging must demonstrate real benefits of squeezing in imaging devices, together with a commercial exploitation given by the availability of quantum cameras costing less than 1000 $.

From the hardware point of view, the source range extension will be pursued further up to 15 mm, and

quantum correlation will be exploited also in hyper-spectral imaging.

Chip scale atomic magnetometers are expected to be ubiquitous in 10 years, whilst cold atom clocks on a chip will attain the 10^{-15} accuracy level .

A network application of those devices is expected in 10 years, yet requiring inputs from outside the community; in general the Table expects a network exploitation of distributed quantum sensors.

Discussion Table on **Applications Avenues, Imaging**

Questions to stimulate the discussion	**Quantum Imaging** on a chip: sub-shot noise, sub-diffraction with single photon…quantum illumination, Ghost imaging Imaging is an hard topic where claiming "quantum" Calibration of CCD camera with quantum light Calibration unit Range of use Application field Advantages of quantum imaging? Analogy with QI: which are killer application of qantum imaging? Avenues: **enhanced interferometers by quantum light**; enhanced spectroscopy by quantum light New methods: detectors calibration…? Materials characterization Quantum Random Number Generators (10 years) **Cold-atom Magnetometry sensing** **Chipscale Cold-Atomic clocks** **Adaptive Receivers beyond the standard quantum level on a chip**
What is to transfer from the optical table to the Chip?	Squeezing on the chip; integrated sources, detectors Capacity to correlate different light source for calibration Neutral Atomic manipulation tools
What is now emerging from different areas that may have an impact for Imaging/AA on a Chip?	Now possibility to capture industry involvement. Addressing the development of low cost components.
Where to go in 3 years - on a chip	XXX (imaging) Real chipscale atomic magnetometer Reduce sizes of chipscale clocks – Improve by a factor 10-100 stability performances Improve by a factor 10 clock accuracy. **enhanced interferometers by quantum light** to beat quantum limits countering the sensitivity reduction by reduced (chipscale) sizes

	Sagnac on a chip
Desired/Required input from Theory	Improved sampling/compression protocols using quantum correlations Clock: Better methods to evaluate magnetic field shifts Clocks: sub-shot detection Interferometers: different measurement strategies, adaptive protocols, how to exploit non-classical light
Desired/Required input from Quantum Optical Devices	0.5 to 5 um sources for quantum imaging (to fundamental and fast sensitivity) Calibration technique and protocols for chip devices /using chip devices Effective chipscale lasers (single frequency, narrow linewidth, different wavelength) Interferometers: general devices advancement
Desired/Required input from Devices and technologies from outside Quantum Optics	Effective managing of multi-pixel devices Inputs from LIDAR/LSR community Better frame rate for the devices Transfer New approaches of imaging in quantum imaging (hyper-dimensions, hyper-spectral iimaging)
Where to go in 10 years - on a chip	Demonstrated benefits of squeezing in imaging devices Quantum cameras under 1000 $ Extending single photon imaging in a wider range, up to 15 um Quantum correlation in hyper-pectral imaging Ubiquitous chipscale atomic magnetometers Cold atom Clock on a chip at 1e-15 accuracy level Ubiquitous chipscale Sagnac/quantum light interferometers for sensing
Desired/Required input from Theory	Magnetomers/interferometers: Network application of the devices Network of Distributed quantum sensors
Desired/Required input from Quantum Optical Devices	Up to 15 um sources for quantum imaging (to fundamental and fast sensitivity)
Desired/Required input from Devices and technologies from outside Quantum Optics	Effective managing of multi-pixel devices Better frame rate for the devices Effective vacuum technologies for chipscale atomic magnetometers

Lessons learned in the past	
Directions that will push Science forward	
Directions that will push Applications/products forward	
What aspects are more promising for international collaboration? Existing success cases?	

The financial support from AFOSR-EOARD to EC participants is kindly acknowledged

Local Organization: **QuantumFuture** *Research Group, University of Padova*
quantumfuture.dei.unipd.it - paolo.villoresi@dei.unipd.it