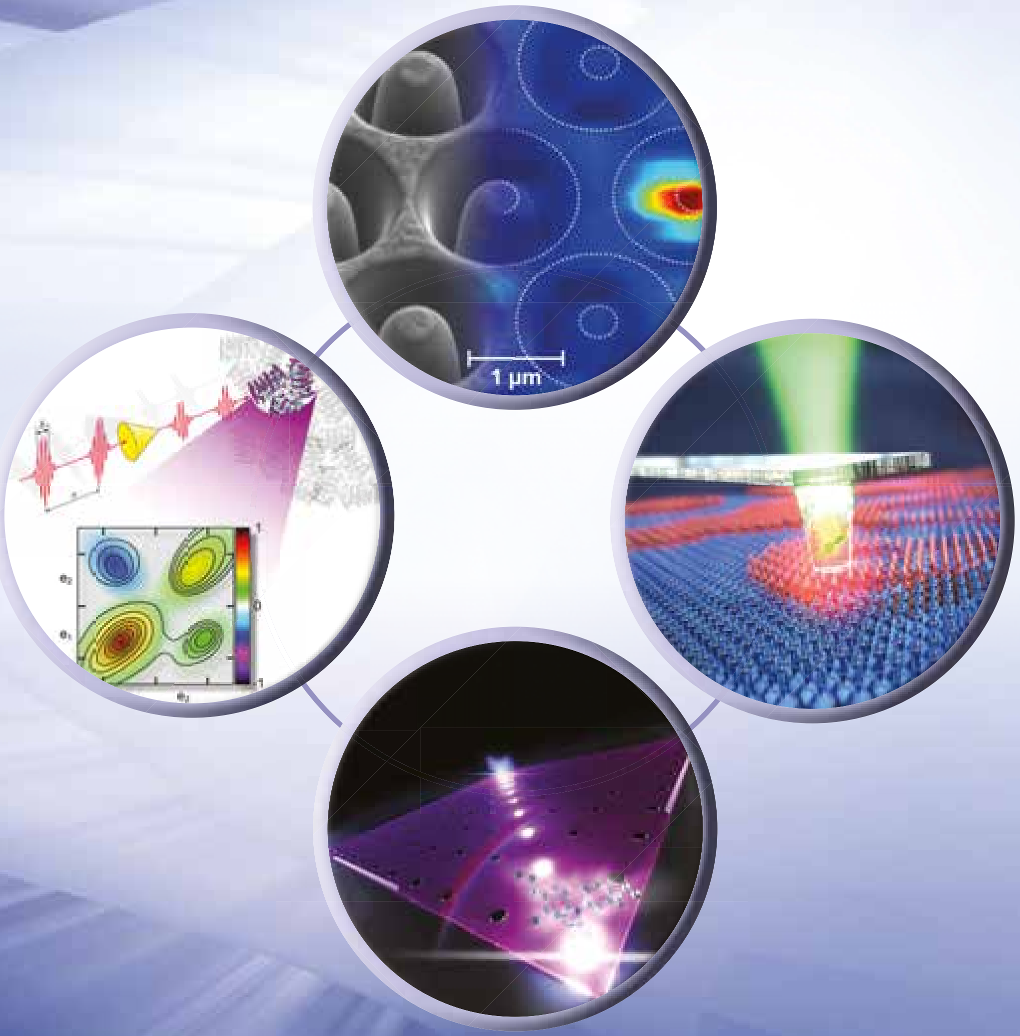
Research and Innovation in Nanoscale Quantum Optics



COST
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Research and Innovation in Nanoscale Quantum Optics

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Executive summary

This Research and Innovation Roadmap provides an outlook on the field of nanoscale quantum optics (NQO) including both basic science and applications, targeting researchers from academia and industry as well as decision makers in the public and private sectors. It has been prepared by the European Cooperation in Science and Technology (COST) Action MP1403 “Nanoscale Quantum Optics”, taking into account discussions at working-group meetings, the recent progress and feedback from all members. The Roadmap is organized into four focus areas:

- Generation, detection, manipulation and storage of quantum states of light at the nanoscale
- Nonlinearities and ultrafast processes in nanostructured media
- Nanoscale quantum coherence
- Cooperative effects, correlations and many-body physics tailored by strongly confined optical fields

In each area, the relevant topics are discussed emphasizing implications and challenges for basic science and applications, providing clear evidence that the combination of quantum optics with nanophotonics is valuable for information & communication technology (ICT), sensing & metrology, and energy efficiency.

Nanophotonics can highly concentrate optical fields and enhance light-matter interaction by orders of magnitude. Therefore typical applications are devices that rely on efficient light-matter interaction such as photovoltaic cells, photodetectors and sensors. The combination of these advantages with quantum

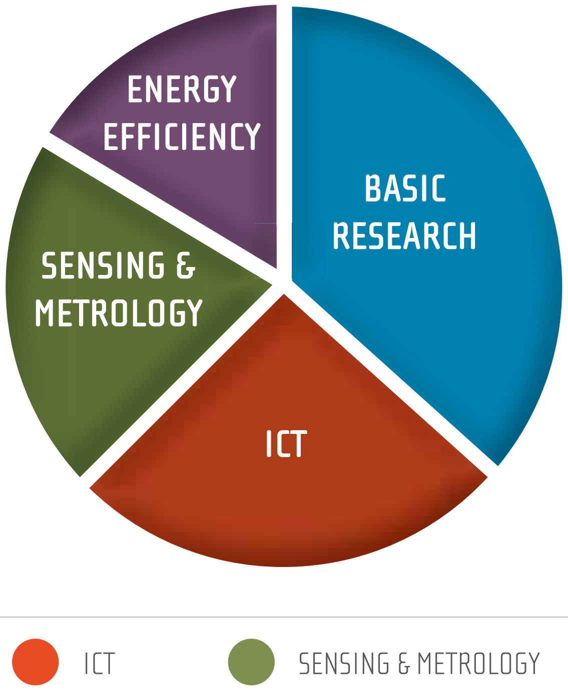

Figure 1. *Nanoscale quantum optics: basic research and applications. Relevance of the proposed topics for basic research (100%), ICT (71%), sensing & metrology (57%) and energy efficiency (51%). 100% means that all topics discussed in this roadmap are relevant.*

optics opens up even more potential for the development of new technologies. For instance, in the first focus area applications for single-photon sources are numerous. Even though ICT is historically the one put forward for quantum computation and communications, several other areas are now involved, like sensing for potential everyday applications (sensitive imaging) and more fundamental studies (single-photon interferometers), as well as metrology, e.g. for calibration. On the other hand, it is evident that the performances of single-photon sources would not be adequate for applications without the improvements made possible by nanophotonics. In the second area, nonlinear optical phenomena form the basis for coherent control, signal switching and entangled photon generation. Downscaling to the nanoscale is required to attain highly integrated quantum technologies (QT). Moreover, nanoscale spatial resolution expands significantly the applicability of nonlinear coherent spectroscopies. Considering the third area, the coherent manipulation and detection of individual spins in nanoscale solid-state systems plays an important role for quantum sensing and quantum computation. On the other hand, the investigation of coherent energy transport at the nanoscale contributes to the understanding of efficient energy harvesting. In the last and fourth focus area, the investigation of many-body physics in nanophotonic systems could open the pathway to novel platforms for quantum simulations. These and more examples on the wide implications of NQO are presented in the Roadmap.

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The COST Action MP1403 *Nanoscale Quantum Optics*

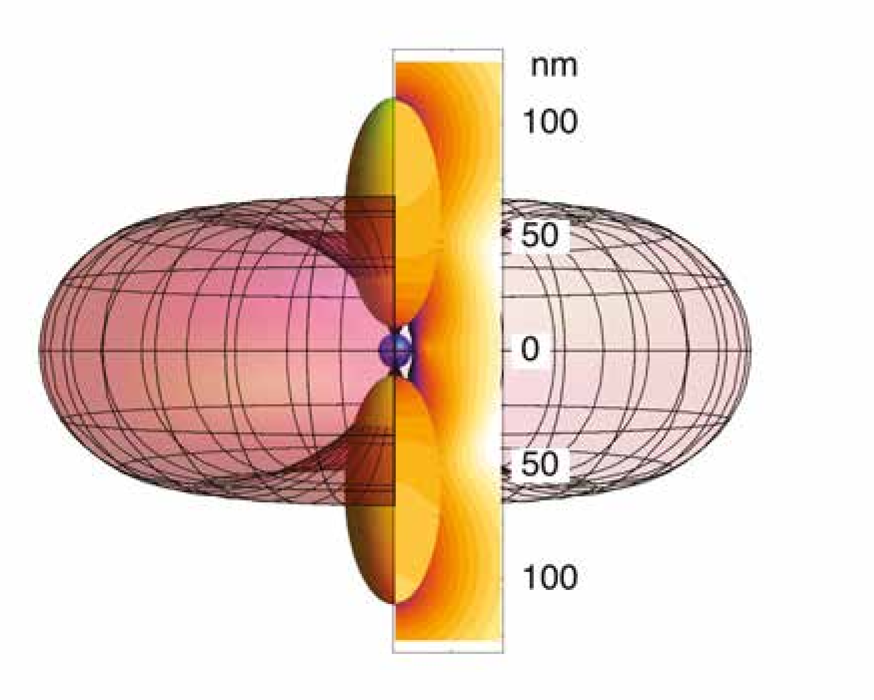

Figure 2. *Nanoscale quantum optics in a nutshell. Controlling light-matter interaction at the quantum level by coupling a quantum system with the near field of an optical nanostructure.*

The European Cooperation in Science and Technology (COST) Action MP1403 promotes and coordinates forefront research activities in nanoscale quantum optics (NQO). Since the Kickoff Workshop (Belgrade, 9–10 April 2015), it has connected about 500 scientists working on quantum physics, nanophotonics and spectroscopy. The dimensions of the Action have been growing also in terms of institutions, companies, and countries. With 28 COST Countries, 6 Institutions in 3 Near-Neighbour Countries and 13 Institutions in 9 International Partner Countries, the Action has reached a significant geographical coverage and has become a reference for scientists and engineers working at the interface between quantum physics and nanoscale optics. The goal is now to reach a more balanced participation from members in the different COST Countries and improve inclusiveness, for example by increasing the number of Short-Term Scientific Missions (STSMs) involving Inclusiveness Target Countries (ITCs). The scientific work plan, organized in four working groups corresponding to the four focus areas outlined in the Roadmap, has made much progress on topics of interest for quantum technologies (QT). For example, research on single-photon sources and superconductive-nanowire single-photon detectors has been very active. The Action has already made an impact in terms of topical events, high-quality publications, and involvement of industry, patents and startups. More challenging has been the acquisition of EU funding, which reflects the poor success rate of Horizon 2020 projects characterized by a substantial basic research effort (e.g. Future and Emerging Technologies [FET] Open and FET Proactive, European Research Council).

The Action will thus continue to work on an approach that privileges focused actions, quality and impact. Moreover, it will aim at further strengthening cooperation with industry, including startups, and at dissemination activities targeting decision makers. The Action has recently participated to public consultations, contributed to the shaping of the flagship initiative on QT, and has published a brochure that outlines its Memorandum of Understanding and the major objectives. Early stage researchers (ESRs) have been supported by STSMs and involved in the Action management. Moreover, they have been given the opportunity to organize workshops for ESRs. The Action is preparing a collection of lectures on NQO and will organize international PhD schools, with the possibility of hands-on-training activities. With regard to gender equality, the Action established focus sessions that involved male and female scientists at every meeting and carried out a survey that resulted in a public report. This effort was particularly useful to understand the pivotal role of unconscious bias and to establish a forum where people can discuss their issues and opinions. Notwithstanding this, much still has to be done in terms of increasing the number of female scientists in the Action and to give them more visibility in the networking events. Public documents and reports of the Action are freely available for download at *www.cost-nqo.eu/documents.*

List of abbreviations

- 1D – one dimension (one-dimensional)
- 2D – two dimensions (two-dimensional)
- 3D – three dimensions (three-dimensional)
- amu – atomic mass unit (1.66 x 10^{-27} Kg)
- COST – European Cooperation in Science and Technology
- CQED – cavity quantum electrodynamics
- ENZ – epsilon-near–zero
- ESR – early stage researcher
- ICT – information & communication technology
- KETs – Key Enabling Technologies
- NQO – nanoscale quantum optics
- NV – nitrogen vacancy
- OM – optomechanical
- PEEM – photoemission electron microscopy
- QD – quantum dot
- QED – quantum electrodynamics
- QT – quantum technologies
- SiV – silicon vacancy
- SNOM – scanning near-field optical microscopy
- SSPD – superconducting single-photon detector
- STSM – Short-Term Scientific Mission

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Introduction

Novel and more sophisticated technologies that exploit the laws of quantum physics form a cornerstone for the future wellbeing, economic growth and security of Europe. Among these technologies, photonic devices have gained a prominent position because the absorption, emission, propagation and storage of light are processes that can be harnessed at the quantum level. However, the interaction of photons with single-quantum systems under ambient conditions is typically very weak and difficult to control in the solid state. Furthermore, there are quantum phenomena occurring in matter at nanometre-length scales and femtosecond timescales that are currently not well understood. These deficiencies have a direct and severe impact on creating a bridge between quantum physics and photonic devices. Nano-optics and nanophotonics precisely address the issue of controlling the interaction between a few photons and tiny amounts of matter in a large bandwidth, and the ability to efficiently funnel light down to nanoscale volumes.

Several research efforts funded by numerous national and EU projects in the last decades have already resulted into enormous progress in quantum physics and quantum optics, and in nano-optics and nanophotonics as well. The COST Action “Nanoscale Quantum Optics” (NQO) is the instrument to proactively increase the interaction among the nanophotonics, quantum optics and materials science communities and to support them towards common objectives.

The grand vision is the development of new ideas, novel materials, and innovative techniques to control the interaction between light and matter at will, even down to the level of individual quanta. The potential breakthroughs will have profound implications in fields as diverse as classical and quantum information processing & communication, sensing & metrology, light sources, and energy harvesting.

Current state of knowledge

Research in NQO focuses on the development of novel materials (e.g. graphene, silicene, metamaterials) and optical devices (plasmonic structures, nanofibres, photonic crystals, optomechanical (OM) systems, superconducting detectors, photonic integrated circuits) that can facilitate and control strong quantum light-matter interactions, and the advancement of novel experimental methods that enable quantum degrees of freedom (colour centres in solids, quantum dots [QDs], ions, molecules, neutral atoms) to be interfaced with these systems. Prominent efforts include, but are not limited to:

- QD devices to generate single and entangled pairs of photons on demand
- Alternative materials for single-photon sources include organic molecules, 2D materials (e.g. hexagonal boron nitride) and thin transition-metal dichalcogenides
- Novel devices such as nanoscale resonant structures, plasmonic waveguides or nanofibres to achieve efficient coupling of single photons
- Novel fabrication techniques for diamond-based photonics, which can be used to enhance optical coupling to individual defect colour centres (such as the nitrogen vacancy [NV] and silicon vacancy [SiV])
- Methods to trap cold neutral atoms to nanophotonic systems, such as tapered optical fibres, thus enabling a coherent atom-nanophotonics quantum interface
- Active exploration of metamaterials and graphene plasmonics as new platforms to channel light and control their interactions with quantum systems

- Chip-based OM systems have recently been cooled to their quantum ground states: coherent interactions between light and phonons have been demonstrated, creating new opportunities to use mechanical systems to manipulate quantum light
- Superconducting devices for single-photon detection over a large wavelength range, with high time resolution, efficiency and photon number resolution
- Photonic integrated circuits to control the routing and interference of single photons in communications and metrology systems
- Strong light-matter coupling in high finesse semiconductor microcavities allows creation and manipulation of polariton condensates on a chip with controlled interactions

Theoretical developments and experimental implementations of novel protocols to use NQO systems to generate nonclassical states and utilize these states for diverse applications in information processing, metrology, sensing, etc., are extensively studied. NQO systems are expected to have a disruptive impact, not only because of performance advantage, but also because they can be fabricated and integrated in more flexible ways to access novel parameter spaces that are not possible with macroscopic systems. For instance:

- NV centres have been demonstrated to serve as sensors of electric and magnetic fields with nanoscale resolution and under ambient conditions, which will have significant applications in areas such as bio and environmental sensing
- Protocols to realize single-photon nonlinear optics and sources, quantum state transfer, and hybrid coupling of disparate quantum systems, also via quantum optomechanics, are being actively investigated
- Many promising techniques to realize quantum gates for computing, entangle quantum bits, and generate nonclassical optical fields are being pursued in NQO systems such as nanoscale cavities, graphene, plasmonic waveguides, photonic integrated circuits and nanofibres

There is also attention on the development of theoretical techniques to predict and quantitatively understand the rich quantum dynamics that emerges from strongly correlated quantum systems, and to understand and control the interaction of these quantum systems with complex electromagnetic environments. These efforts are critical both to position NQO systems as potentially groundbreaking quantum technologies (QT) and to leverage these systems as “simulators” of exotic quantum phenomena.

There has been increasing interest in the exploration of quantum phenomena in biological systems (e.g. energy transport in light-harvesting complexes), the development of advanced experimental techniques to investigate them with high spatial and temporal resolution, and the investigation of bio-inspired artificial systems that exhibit quantum effects (e.g. quantum simulators).

Furthermore, advances in these research areas may have immediate technological implications and be of interest to industry. For example:

- Highly efficient single-photon sources on demand, photon-number-resolved detectors, and photonic integrated systems including passive power splitters and wavelength filters would have impact in the field of secure quantum communication
- The development of switches that operate at few photon levels could drastically mitigate the high energy required for optical communication and computation in supercomputers, and it would also play a major role in the reduction of worldwide energy requirements in information & communication technology (ICT)
- Bio-inspired materials such as light-harvesting complexes could open new routes towards efficient photovoltaic cells
- New approaches to single-molecule detection and quantum-enhanced measurements will expand sensor capabilities, opening new scenarios particularly within the fields of metrology, security and safety

Scientific and technological focus

Three major application areas already exhibit clear evidence that the combination of quantum optics with nanophotonics is technologically valuable:

- ICT, e.g. to improve single-photon sources and photon-number-resolved detectors for secure communication as well as integrated nanoscale quantum-optical solutions for ICT
- Sensing & metrology, e.g. nanosensors and quantum-enhanced measurement devices
- Energy efficiency, e.g. development of new solutions for photovoltaics and energy saving

At present, several universities as well as public and private research laboratories worldwide are conducting research to introduce QT in these applications. However, the roadmap towards compact and efficient quantum devices still requires a substantial basic-research approach.

We have thus identified four research priorities that deal with problems and limitations in the operation of existing QT, and that may contribute to the discovery and understanding of novel quantum phenomena for future applications:

- Generation, detection, manipulation and storage of quantum states of light at the nanoscale
- Nonlinearities and ultrafast processes in nanostructured media
- Nanoscale quantum coherence
- Cooperative effects, correlations and many-body physics tailored by strongly confined optical fields

The first two priorities will also target technological aspects, such as performances and integrability of quantum photonics devices, whereas the other two include rather exploratory activities. It is worth noting that the topics involved are strongly related to three of the Key Enabling Technologies (KETs) recognized at the European level, i.e. nanotechnology, photonics and advanced materials, thus ensuring a synergic cross-KET approach to important application fields.

Moreover, to facilitate scientific exchange and to establish a common playground, the Roadmap encourages overlap between the four research priorities, which will occur through activities concerned with:

- Investigation of new materials and novel photonic structures (e.g. graphene, silicene, hybrid organic/inorganic, diamond nanostructures, plasmonics structures, semiconductor microcavities), and innovative techniques to combine them with quantum systems with a high and reproducible precision (e.g. scanning-probe techniques, two-step lithography, ion-beam milling and deposition, in-situ lithography techniques)
- High-throughput and low-cost fabrication methods for hybrid nanodevices and quantum photonic circuits (e.g. self-assembly, nanoimprinting, lithography)
- Optical methods for investigating quantum light-matter interfaces (e.g. single-molecule spectroscopy, stimulated-Raman adiabatic passage (STIRAP) and coherent population trapping), the development of novel approaches at the interface between quantum optics, nano-optics & nanophotonics and advanced spectroscopy (e.g. nanoantenna-based spectroscopy, coherent multidimensional nanoscopy) and also modern X-ray and neutron scattering techniques; this aims at leveraging state-of-the-art experimental capabilities for new QT
- Advancing theoretical techniques to quantitatively understand these phenomena (e.g. noncanonical quantization schemes, non-Markovian bath interaction models), including novel computational methods (e.g. hybrid electromagnetics/quantum mechanical algorithms or further advances in density functional theory methods)

In the following, we provide a structured list of topics on which we are currently working. We describe the various aspects concerned with each topic and offer our view on the progress that is expected/aimed at within the next 5 years.

Generation, detection, manipulation & storage of quantum states of light at the nanoscale

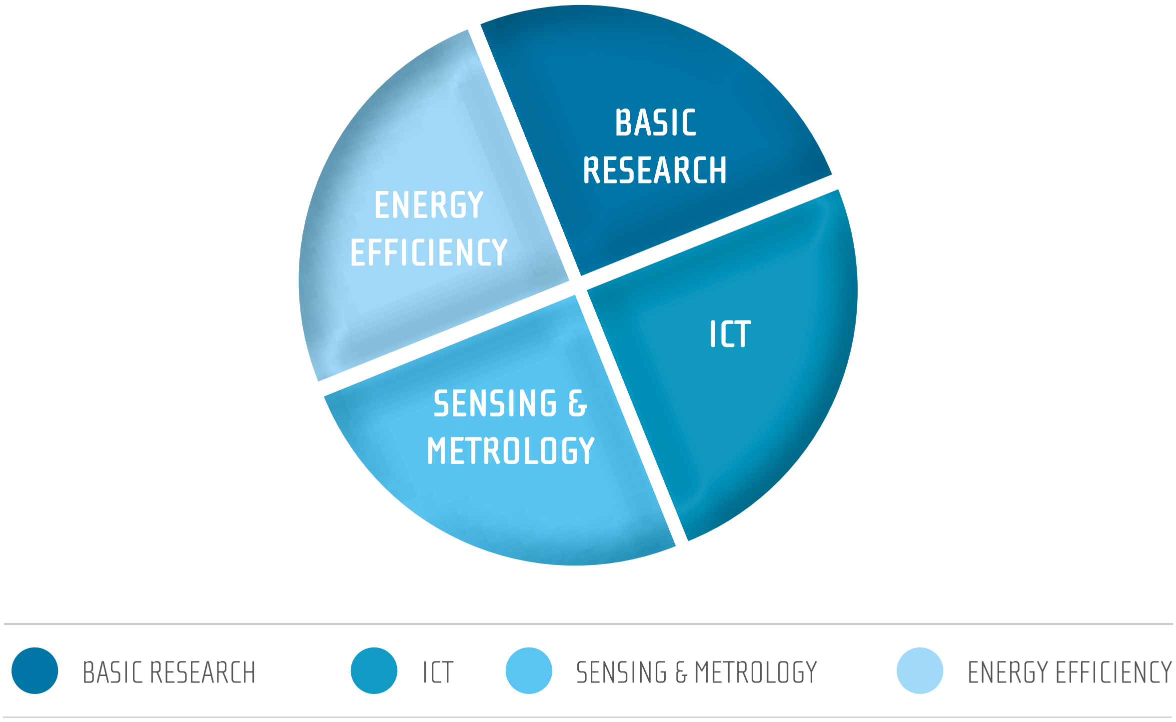

***Figure 3.** Generation, detection, manipulation and storage of quantum states of light at the nanoscale. Relevance of the proposed topics for basic research (100%), ICT (100%), sensing & metrology (100%) and energy efficiency (100%). 100% means that all topics discussed in this section are relevant.*

Single-photon sources

Single-photon sources are at the heart of many applications in QT. To this day, producing a scalable source of on-demand and efficient indistinguishable photons remains a challenge [1-3]. Nanosources of light seem the best potential option to meet this challenge but many key issues are still present.

CONCEPTS / THEORY / MODELS

As knowledge and means of controlling single-photon sources develop, more fundamental questions arise, in particular in terms of coherence, light-matter coupling and many-photon interaction. Therefore, novel experimental findings require progress in theoretical tools as well, such as:

- Finite difference time-domain simulation
- Optical Bloch and Maxwell-Bloch equations
- Density matrix approach for coupling with reservoir
- Modelling of light extraction and collection
- Density functional theory

MATERIALS / SYSTEMS / EXPERIMENTS

In the last few decades, a plethora of nanoscale single emitters have emerged, each with their pros and cons. The quest for the best host material and the best quantum emitter is still under way. Many materials are currently explored (semiconductors, diamond, 2D materials, etc.) as well as different geometries (rod, dots, pillars, wires, etc.), and even different dimensions (3D confinenement, defects in 2D

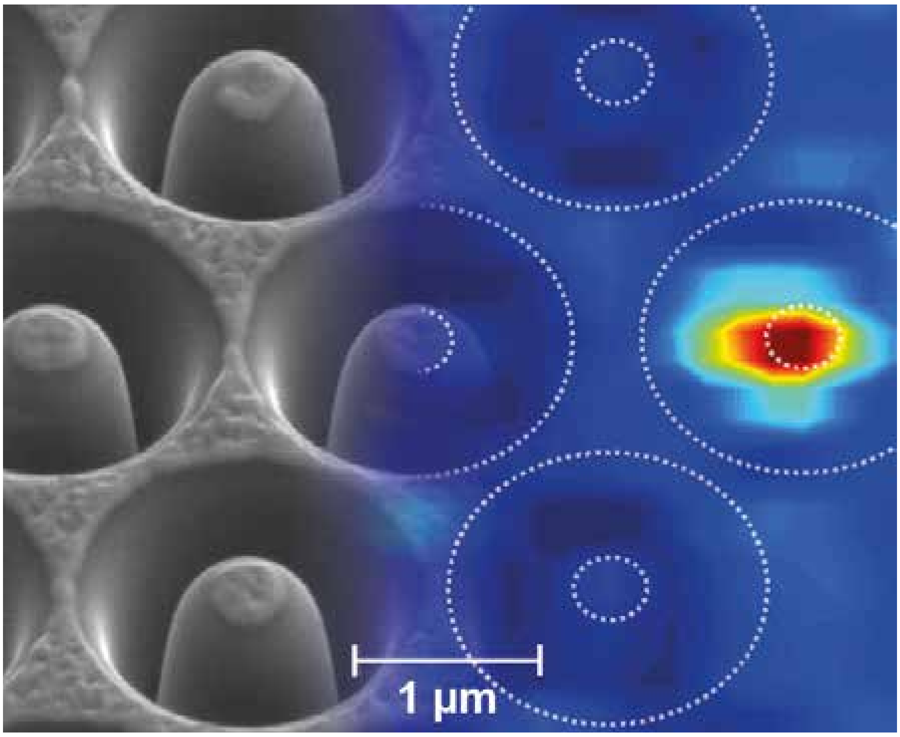

Figure 4. *Single SiVs implanted in high purity diamond with enhanced collection efficiency using solid immersion lenses. Courtesy of the Quantum Optics Group, Saarland University (www.uni saarland.de/fak7/becher). Figure adapted from B. Pingault, et al., All-optical formation of coherent dark states of silicon-vacancy spins in diamond, Phys. Rev. Lett. 113, 263601 (2014). (Copyright American Physical Society, 2014).*

materials, etc.). Moreover, efforts in material engineering are important to attain scalable and reproducible single-photon sources. Examples of these systems include:

- III-V semiconductor self-assembled QDs emitting at 900 nm, 1.3 µm and 1.55 µm
- Organic molecules
- Colour centres in diamond
- 1D materials, such as nanowires or carbon nanotubes
- 2D materials, such as hexagonal boron nitride or thin transition-metal dichalcogenides
- Spontaneous parametric down conversion and spontaneous four-wave mixing in micro- and nanostructures
- Rare earth ion doped crystals
- Electrically pumped systems (e.g. QDs, colour centres)

CHALLENGES / PERFORMANCES / GOALS

Electrically controlled single-photon sources, which work under ambient conditions and emit identical photons, remain the final goal. In the not-so-long run, single-photon sources serving different kinds of applications will be on the market (some already are, albeit not turnkey) and, as such, they will have to be ready for commercial challenges in terms of performances, cost and reliability. Many points will then have to be addressed, such as:

- Standardization and calibration of single-photon sources [4]
- Scalable fabrication of indistinguishable single-photon sources and sources of entangled photon pairs [5,6]
- Development of stand-alone and fibre-coupled single-photon sources
- Efficient electrical pumping schemes [7]

Application areas: Basic science, ICT, sensing & metrology, energy efficiency

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Superconducting single-photon detectors

Like single-photon sources, single-photon detectors are indispensable for applications in QT [1]. In the case of detectors, the challenge of detecting a single photon with close-to-unity efficiency over a wide wavelength range remains [2]. Moreover, these detectors should be able to resolve photon number and ideally work under relatively relaxed conditions (e.g. turnkey operations). Superconducting nanowire detectors seem the best potential option to meet this challenge, but there are still many associated problems to be solved [3,4].

CONCEPTS / THEORY / MODELS

Again, as knowledge and means of fabricating and engineering these single-photon detectors develop, fundamental questions arise, especially in terms of efficiency, speed or insertion into more complex photonic circuitry. Moreover, studying the detection mechanism allows us to determine the physical limits to the operation of these devices. It is at present not known how far away we are from these limits. Theoretical work is thus necessary for a better and more fundamental understanding of the systems, such as:

- Understanding superconductivity in nanostructures
- Numerical simulations of the detection mechanism
- Study of the superconducting single-photon detector (SSPD) mechanism in unconventional superconductors, to establish the feasibility of high-critical-temperature (Tc) SSPDs [5]
- Understanding non-Bardeen-Cooper-Schrieffer (BCS) electrodynamics (e.g. interplay of disorder, interaction and photon-driven out-of-equilibrium superconductivity)

MATERIALS / SYSTEMS / EXPERIMENTS

Material engineering is of prime importance for superior single-photon detectors. Many new materials have emerged recently as potential candidates. Meanwhile, progress in nanofabrication enables different paradigms for controlling detection at the nanoscale. Examples of topics being explored in this area include:

- Superconducting nanowire single-photon detectors (meanders, nanodetectors)
- Photon-number-resolving transition edge sensors (TES)
- Superconducting materials: NbN, NbTiN, WSi, NbSi, InO, MoSi, YBCO
- Waveguide detectors [6]
- Kinetic inductance detectors
- Alternative substrates
- Optical, electrical, temperature & magnetic field studies at < 1 K
- High-temperature operation
- Multilayer and novel geometries

CHALLENGES / PERFORMANCES / GOALS

An ideal single-photon detector has yet to be developed, where all the photons are sorted and detected, possibly over a large energy range (down to microwave region for some applications). Like single-photon sources, single-photon detectors are already on the market. However, there are still challenges in terms of performances, cost and reliability that need to be addressed, for instance:

- Standardization and calibration of single-photon detectors
- Specification sheets
- Development of affordable, small-footprint cryocoolers for commercial systems

Application areas: Basic science, ICT, sensing & metrology, energy efficiency

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Manipulation and storage of single photons

Besides generation and detection of single photons, the manipulation and/or storage of quantum states of light must also be implemented in integrated circuits [1]. Moreover, scaling quantum photonic technologies requires efficient and long-term single-photon storage [2]. A number of requirements are important, such as storage and retrieval efficiency, storage time and reduction of background noise to reach a high fidelity. These and other aspects have been actively studied for many years such that complex circuitry is now available and manipulation and/or storage are improving towards practical applications.

CONCEPTS / THEORY / MODELS

Manipulation of single photons has now reached a high degree of control and scalability compared to storage. The latter is more challenging, as it requires finer control over light-matter interaction. Therefore, it is in this area that a great deal of theoretical work is needed. Examples of key issues include:

- Semiclassical description of (arrays of) multilevel atoms with optical near fields
- Full quantum description of the interaction of multilevel atoms with resonator modes
- Schemes for the manipulation and storage of quantum states of light on a photonic chip
- Designs for coupling single photons to low-loss photonic integrated circuits

MATERIALS / SYSTEMS / EXPERIMENTS

Even though manipulation of multiple single photons has been achieved [3] and is scalable to some extent, there are still challenges for several schemes in quantum information processing. Likewise, quantum communication demands a stringent level of control that has yet to be achieved [4]. Quantum storage of single photons preserving coherence and other intrinsic properties is definitely very challenging [5], and different materials and systems are currently investigated, such as:

- Cavity quantum electrodynamics (CQED) with single emitters coupled to micro- and nanoresonators
- Quantum memories based on ion-doped crystals
- Nonlinear waveguides (e.g. periodically poled lithium niobate)
- Integration of solid-state single-photon source (e.g. QDs nanocrystals) in optical microresonators and in quantum photonic circuits
- Tapered optical fibres with a nanosize waist and >99% transmission [6]

CHALLENGES / PERFORMANCES / GOALS

The performance of single-photon manipulation has greatly increased recently, especially with the use of integrated optics components. Nevertheless, there is still need for improvement to turn devices into products. For the storage of single photons, it is even more challenging to achieve “commercial” performances (specific materials, low temperatures, etc.), e.g. for quantum repeaters, and efforts need to be focused in these areas:

- Developing strong light-matter interactions at room temperature
- Low-loss and low-cost coupling to optical fibres
- Low-loss optical channels down to 1 dB/km

Application areas: Basic science, ICT, sensing & metrology, energy efficiency

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Nonlinearities and ultrafast processes in nanostructured media

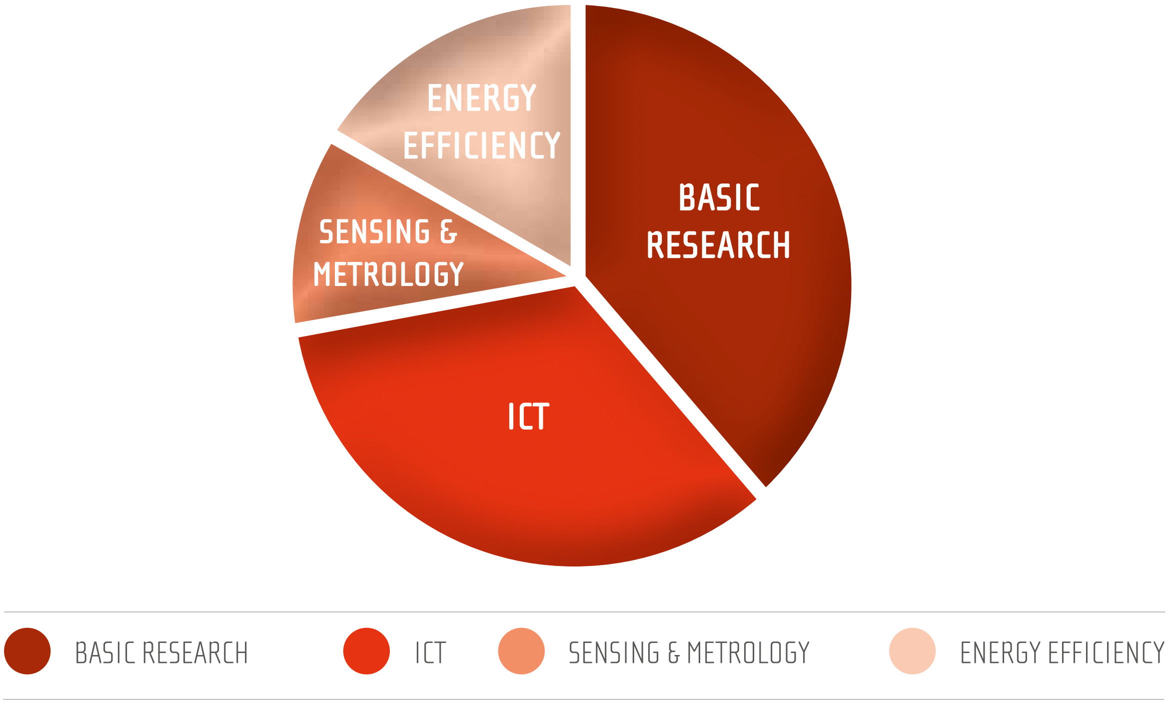


Figure 5. *Nonlinearities and ultrafast processes in nanostructured media. Relevance of the proposed topics for basic research (100%), ICT (86%), sensing & metrology (29%) and energy efficiency (43%). 100% means that all topics discussed in this section are relevant.*

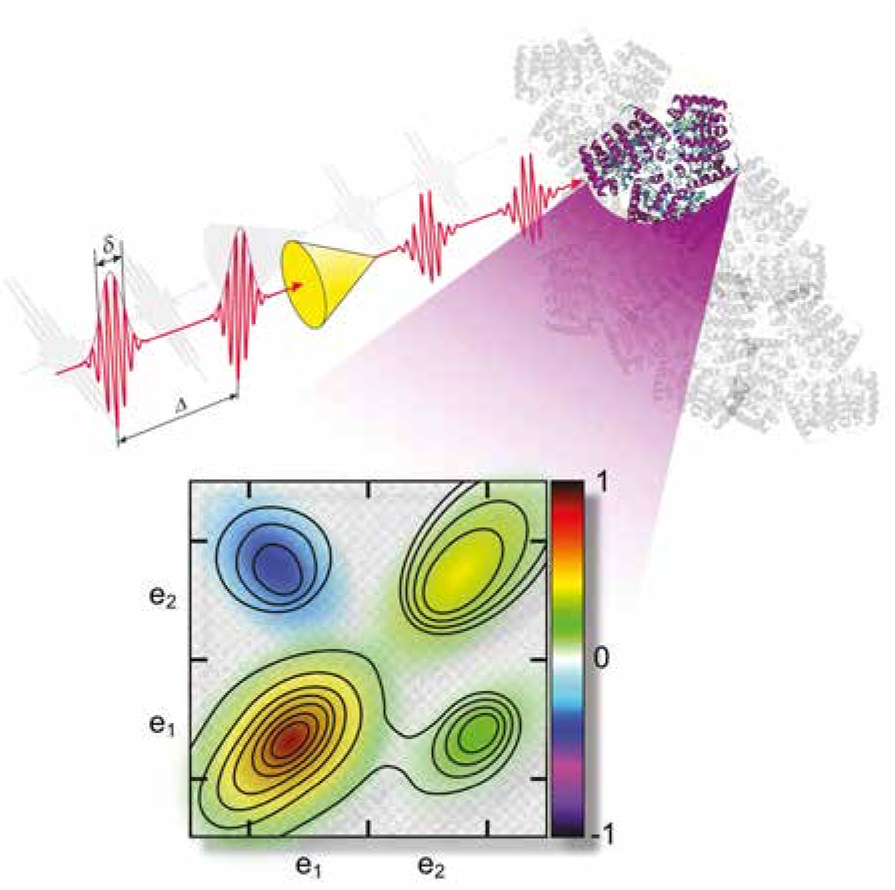
Coherent control at the nanoscale

Besides control of chemical reactions and nuclear spins, the field has significantly expanded to other realms. Particularly relevant in the context of future QT are applications of coherent control schemes in nanophotonics [1-3]. They allow for addressing and manipulating individual quantum systems and provide new insights about quantum coherences that are then no longer hidden in an inhomogeneous ensemble. The development of multidimensional coherent spectroscopy with nanometre spatial resolution [4], together with spatially selective addressing in optical near-fields, enables complex quantum protocols in individual nanoscale assemblies of interacting qubits. The rapid advances in nanotechnology complement this development. Precise fabrication of high quality nanostructures with deterministic coupling to single qubits allows investigating complex coherent phenomena. In the long-term, this field offers a promising route towards an alternative system platform for highly integrated QT.

CONCEPTS / THEORY / MODELS

The coherent control schemes developed in chemistry need adaptation for applications in nano-optical settings, where longitudinal fields become relevant, expanding the degrees of freedom for control. Theoretical efforts

Figure 6. Schematics of 2D coherent optical nanoscopy. Courtesy of the Laboratory of Nano-Optics, University of Siegen (nano-optics.physik.uni-siegen.de).



concern, for example:

- Optical near-field control
- Quantum control schemes
- Photon-photon interactions
- Adaptive versus open-loop control
- Nonlinear nanospectroscopy

MATERIALS / SYSTEMS / EXPERIMENTS

Nanoantennas serve as gateway to selective nanoscale quantum systems such as chromophores or QDs acting as qubits. The anisotropic response of such antennas enables selective spatiotemporal excitation schemes, based, for instance, on:

- Polarization pulse shaping assisted optical near-field control
- Time-resolved single- molecule spectroscopy
- QDs coupled to nanoantennas
- Hybridization and strong coupling between nanoantennas and quantum systems
- 2D materials and their heterostructures

CHALLENGES / PERFORMANCES / GOALS

Presently the nanoantennas used to selectively address individual quantum systems are conceived as classical entities. With increasing coupling strength, this picture fails and a fully quantum description of the combined system interacting with the environment is needed. In nanoscale quantum devices the effects of decoherence and dissipation must be minimized by developing robust control schemes [5] addressing:

- Minimizing dissipation and decoherence
- Realistic quantum description of system-environment interaction
- Development of robust coherent control schemes

Application areas: Basic science, ICT, sensing & metrology

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Nanoemitters and nanoantennas

Nanoemitters and nanoantennas link the nanoworld to the far-field transverse electromagnetic radiation [1] and thus play an essential role in nanoscale quantum optical phenomena. Broadband response and directionality [2] have been demonstrated and the interfacing to nanoscale transmission lines [3] and cavities is currently being investigated [4]. Strong coupling to single-quantum emitters is challenging [5] and even advanced nanofabrication methods may not always provide a satisfying level of control. Self-organized assembly of nanoantenna-quantum emitter structures may provide better control.

CONCEPTS / THEORY / MODELS

Not only the coupling of local excitations to the far field is of interest for quantum optical applications, dark modes or purely evanescent modes are also beneficial if efficient coupling between quantum emitters is desired. In adapting the properties of nanoantennas for particular applications, the mode hybridization concept is essential [6]. Combination of different modes allows tailoring the response, which has been described for Fano resonances, for example [7]. In this context, representative topics are:

- Mode hybridization
- Energy transfer efficiency
- Use of Fano resonances
- Subradiative and superradiative modes
- Strong coupling of antennas
- Coupling to cavities and transmission lines

MATERIALS / SYSTEMS / EXPERIMENTS

Up to now research has focused on metallic, i.e. plasmonic, nanostructures serving as nanoantennas and on nanoemitters. Although the losses induced by material imperfections can be minimized by employing single crystalline materials, intrinsic losses remain large. Dielectric and hybrid materials could serve to minimize these losses further. Hence, investigated systems include:

- Nanoplasmonics resonators
- Dielectric nanoresonators
- Hybrid nanoantennas

CHALLENGES / PERFORMANCES / GOALS

Dissipation and decoherence in nanophotonic systems is limiting the use of nanoantennas for quantum optical applications. If their coupling to the far field acts as an efficient dissipation channel, it can be minimized by employing dark modes. Moreover, successful implementation of NQO requires a precise manipulation and placement of individual quantum emitters in the vicinity of optical nanoantennas. The challenges to be addressed include:

- Minimization of dissipation
- Long-lived dark mode resonances
- Controlled coupling to single-quantum emitters
- Self-organized assembly of nanoantenna-quantum emitter structures
- Precise positioning/growth of quantum emitters

Application areas: Basic science, ICT, sensing & metrology, energy efficiency

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Nanoscale nonlinear response

The nonlinear response is typically only a weak effect in bulk materials or interfaces. However, the field concentration achieved in nanophotonics enhances the signal from nanoscale objects. Two aspects are of particular interest in NQO: (i) enhanced nonlinear response in optical near-fields and (ii) nonlinear CQED at the few- or single-quantum level. In contrast to bulk nonlinear materials, the field distribution can no longer be envisioned as homogeneous, which has generated renewed interest in the actual mechanisms of the nonlocal [1] and nonlinear [2] response on a microscopic scale. The investigated systems (metal or hybrid nanostructures) are still too large for a full ab-initio quantum theoretical treatment. Thus modelling relies on the combination of Maxwell solvers for complex geometries with implemented classical or quantum models yielding the local linear and nonlinear responses. In terms of experimental achievements, the capability to measure the response from individual nanostructures is essential. This avoids inhomogeneous line-broadening effects and dispersion in the spatial distribution of measured signals. The huge nonlinearities observed in conventional CQED occur at the few- or single-quantum level [3] and form a blueprint for the development of nanoscale quantum-optical devices [4]. Strong coupling with plasmons has been demonstrated for ensembles of quantum emitters [5] and between quantum emitters randomly placed in a nanophotonic cavity, for example [6]. Based on even higher field enhancements, strong coupling at room temperature has recently been achieved for a single dye molecule placed in a plasmonic gap resonance [7]. To increase the coupling strength the quality factor of nanophotonic cavities must be improved. This will also extend the time window for coherent manipulation of embedded quantum systems.

CONCEPTS / THEORY / MODELS

Investigation of the nonlinear response relies on the close interaction of experiment and theory. Experimentally determined nonlinear signals – preferentially from a single nanostructure – are quantitatively matched to theoretical simulations [8]. Highly nonlinear optical materials embedded in nanophotonic devices open a route to nanoscale all-optical switching and coherent photon-photon interactions. Adaptation of CQED for nanophotonics seems straightforward.

However, the presence of strong loss channels poses severe restrictions and robust, and ultrafast, coherent manipulation protocols need to be developed. The extension to the near-infrared part of the electromagnetic spectrum increases the number of loss-channels. Therefore a balance between ideal operation conditions has to be determined. There are thus many theoretical aspects that require consideration, especially:

- Integration of quantum mechanical response in Maxwell solvers
- Nonlinear response in nanostructures
- Ultrafast nanoscale all-optical switching
- Nanoscale CQED
- Jaynes-Cummings and Tavis-Cummings models
- Open quantum systems
- Rabi oscillations – strong coupling
- Ultrastrong coupling
- Maxwell solvers with local response kernel
- Developments of time-dependent density functional theory

MATERIALS / SYSTEMS / EXPERIMENTS

The concept of nonlinear response in nanostructures is currently investigated for plasmonic systems with rather simple hydrodynamic and jellium models. Application to anisotropic dielectrics and hybrid nanostructures and a more refined treatment of the quantum system response are needed. Nanoscale CQED relies on cavities with tiny mode volumes and thus requires a highly controlled embedding of quantum emitters. Improving the quality factor of nanoscale cavities would facilitate the reach of the CQED regime, but limit the bandwidth of the cavity on the other hand. Single-molecule spectroscopy methods are employed to study CQED effects. A list of materials, systems and experimental techniques would therefore include:

- Plasmonic and hybrid nanostructures
- Low-dimensional materials (e.g. nanowire, nanotubes, graphene) and their hybrid structures
- Nanophotonic wave guides and cavities, including nanocavities with improved quality factor
- Nonlinear metasurfaces
- Quantum emitters (defect centres in diamond, QDs, molecules, etc.)
- Single-molecule spectroscopy
- Second- and third-harmonic generation in individual nanostructures
- Tip-enhanced nonlinear spectroscopies

CHALLENGES / PERFORMANCES / GOALS

Improved understanding of optical nonlinearities could open routes to further enhanced nonlinear responses from nanoscale photonic devices. Hybrid nanostructures and tailored fields and responses could enable ultrafast all-optical switching. Reaching the strong coupling regime in nanoscale CQED requires cavities with huge local field enhancements and advanced methods for assembly that allow controlled embedding of quantum emitters. Further investigations and improvements are therefore needed, for example, in:

- Probing the nonlinear response with high spatial resolution
- Anisotropic nonlinear local response in nanostructures
- Strong nonlinear local response
- Nonlinear response in hybrid nanostructures
- Full quantum theory of linear and nonlinear response in complex geometries
- Ultrafast all-optical switching in nanophotonic devices
- Strong coupling regime for single emitters in nanocavities
- Ultrahigh local density of photon states
- QDs and molecules with stable spectral properties
- Single-quantum nonlinearity at the nanoscale
- Nonlocal quantum-emitter coupling schemes
- Ultrafast CQED

Application areas: Basic science, ICT

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Coherent spectroscopy on the nanoscale

Conventional coherent spectroscopy, especially time-resolved multidimensional coherent spectroscopy, already provides detailed information about nanoscale and even intramolecular energy transfer and coupling phenomena [1-4]. NQO benefits substantially from coherent spectroscopy with nanoscale spatial resolution, i.e. beyond the diffraction limit [5]. The probed linear and nonlinear responses contain more information than the integral responses measured in the far field. In addition, inhomogeneous line-broadening that might mask coherent dynamics in measurements performed on an ensemble is absent. Combination of methods adapted from conventional coherent spectroscopies with optical near-field probes (scanning near-field optical microscopy [SNOM], nanotips) [6,7] or photoemission electron microscopy (PEEM) [5] has significantly expanded the methodologies to probe nanoscale coherent dynamics [8].

CONCEPTS / THEORY / MODELS

The local nonlinear response contains information about coherent energy transfer in nanoscale systems. Combining multidimensional spectroscopy methods with nanoscale resolution avoids the effects of system inhomogeneity and yields access to local response functions. This entails combining various aspects of advanced spectroscopy, nano-optics and quantum optics, such as:

- Nanoscale energy transport
- Coupling mechanisms
- Multidimensional coherent spectroscopy
- Third-order nonlinear response and four-wave mixing
- Homogeneous linewidth
- Light confinement

MATERIALS / SYSTEMS / EXPERIMENTS

A broad range of nanophotonic systems is investigated using coherent spectroscopies. Both far-field methods and techniques that allow for nanoscale resolution are employed. Examples include:

- Exciton-plasmon coupling
- Disordered photonic materials
- Time-resolved far-field microspectroscopy (second harmonic generation [SHG] microscopy)
- Single-molecule spectroscopy
- Tip-enhanced spectroscopy
- Time-resolved PEEM

CHALLENGES / PERFORMANCES / GOALS

Spatiotemporal optical near-field control in combination with coherent spectroscopy allows probing the nonlocal response in complex nanostructures. Nonlocal coupling phenomena reaching over distances more than a few nanometres become accessible. Improved spatial resolution will provide access to coherent dynamics at the single-molecule level. This requires, among others:

- Spatiotemporally resolved coherent nanospectroscopy
- Nonlocal coupling
- Sub-10 nm resolution
- Single-molecule sensitivity

Application areas: Basic science, energy efficiency

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Active nanophotonics

Nanoplasmonic resonators embedded in an optically active medium allow for a nanoscale laser source known as spaser [1,2]. The localized surface plasmons are amplified using energy provided by the pumped active medium and photons are radiated to the far field via radiative damping. The demonstration of efficient subwavelength coherent light sources and amplifiers attracted great interest. However, the implementation of spasers in photonic nanocircuits requires novel electrical pumping schemes [3]. Beyond the spaser based on a single nanoantenna surrounded by an optical gain medium, interesting applications arise from combining metamaterials with optical gain [4].

CONCEPTS / THEORY / MODELS

Stimulated emission of radiation to the far field relies on near-field surface-plasmon amplification in a highly lossy nanocavity with optical gain. Controlling this process can be complex and requires a better understanding of:

- Spasers
- Nanoscale plasmonic resonators
- Optically pumped active media
- Lossy CQED
- Optical amplification beyond the effective medium gain model
- Master equations capturing many-body effects in emitter ensembles

MATERIALS / SYSTEMS / EXPERIMENTS

The first demonstration relied on dye molecules embedded in a polymer shell surrounding a gold nanoparticle. Optical pumping leads to fluorescence that narrows at some pumping levels, indicating amplification of localized surface plasmons in the nanoparticle mode. Developments beyond this proof-of-concept involve, for instance:

- Core-shell nanoparticles
- Nanowire lasers
- Optically pumped dye molecules as active medium
- Plasmonic nanoantennas as resonators
- Metamaterials with gain
- Single-QD lasers/thresholdless lasers (and their characterization)

CHALLENGES / PERFORMANCES / GOALS

The small mode volume of plasmonic nanoresonators requires high population inversion densities to allow nanolasing. Furthermore, for future applications electrical pumping schemes and nonradiative amplifiers are required. Some of the main challenges and goals are therefore:

- High population inversion densities
- Electrically pumped nanolasers
- Embedded nanoscale amplifiers
- Coherent light sources as nanocircuit components

Application areas: Basic science, ICT

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Nanoscale transport

Nanoscale electron, spin and energy transport occurs intrinsically on an ultrafast timescale. Excited electrons with typical Fermi velocities of about 10^6 m/s travel 10 nm within about 10 fs. Energy transfer relies on coupling and competes with other relaxation channels. Hence efficient energy transfer has to be fast [1]. Time-resolved nonlinear spectromicroscopy serves as a valuable tool to visualize coherent energy transport occurring in surface plasmon polaritons [2] and more complex electromagnetic modes. Ballistic charge transport is limited to the mean free path of the carriers. Typically it is restricted from a few nanometres to about 10 nm for excited carriers close to the Fermi level. Thus lateral transfer is difficult to directly measure. However, transient charging after photoexcitation [3], induced photocurrents in heterostructures [4], exciton microscopy [5], and photoemission of excited electrons provide access to nanoscale charge transport phenomena. Ultrafast electron transport is significant in the ultrafast demagnetization observed in ferromagnets after pulsed excitation [6].

CONCEPTS / THEORY / MODELS

The treatment of energy transfer in optical nanostructures is based on Maxwell's equations. Coupled localized plasmon polaritons, propagating plasmonic modes, and Förster energy transfer between quantum emitters are commonly applied concepts. Excited electron transport is limited by inelastic electron collisions treated phenomenologically using the Boltzmann equation. On short time and length scales ballistic transport dominates. Thus, the development of nano-optical tools for the investigation of energy transport in nanomaterials and quantum systems involves aspects as diverse as:

- Surface plasmon polaritons
- Propagating longitudinal modes
- Förster energy transfer
- Excited electron relaxation
- Nonequilibrium charge dynamics in nanostructures
- Boltzmann equation in complex geometries
- Ballistic transport

MATERIALS / SYSTEMS / EXPERIMENTS

Time-resolved imaging techniques are essential to directly investigate energy transport at the nanoscale. Examples are or have been applied to:

- Plasmonic waveguides and circuitry
- Plasmons on metal islands
- Time-resolved SNOM
- Time-resolved PEEM
- Heterostructures, metal insulator metal junctions

CHALLENGES / PERFORMANCES / GOALS

Monitoring the transport in complex nanostructures requires new approaches, such as:

- Spatially resolved coherent multidimensional spectroscopy
- Multiscale (time and space) techniques to simulate quantum nanoscale transport

Application areas: Basic science, ICT, energy efficiency

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Strong-field phenomena in nanosystems

Few-cycle laser pulses with stabilized carrier envelope phase allow investigating strong-field phenomena in nanosystems such as strong-field photoemission from metallic nanotips [1-4] and nanoparticles [5]. Acceleration of the emitted electrons in the optical near field and recollision of the emitted electrons with the nanostructure yield a broad electron kinetic energy spectrum. Similar to the generation of single-attosecond soft X-ray pulses, this offers the possibility for attosecond electron pulse generation. In addition to electron emission events in strong fields, an adiabatic ultrafast insulator-metal transition is induced in dielectrics [6] in sufficiently strong fields. This effect enables ultrafast switches operating at subcycle speed.

CONCEPTS / THEORY / MODELS

The basic concepts are adopted from atomic physics in intense laser fields. The optical near-field enhancements facilitate strong-field phenomena so that even for rather weak incident intensities strong-field effects become relevant. These involve:

- Above-threshold ionization
- Strong-field emission
- Keldysh parameter

- Carrier envelope phase-stabilized laser – few-cycle pulses
- Streaking
- Strong-field-driven insulator-metal transition

MATERIALS / SYSTEMS / EXPERIMENTS

Metallic nanotips serve as field concentrators and efficient electron emitters. Energy and momentum resolved electron spectroscopies are employed to obtain more complete information about the emission process. These approaches involve, for instance:

- Metal nanotips
- Dielectric nanoparticles
- Electron streaking in nano-optical fields
- Metal-insulator-metal junctions

CHALLENGES / PERFORMANCES / GOALS

Resonant excitation offers significantly enhanced local fields. However, longer coherence lifetimes mask few-cycle related strong-field effects. Nevertheless, the proper compromise between both phenomena could boost strong-field effects in nanophotonics. Based on wave packet dispersion control, the ultrashort electron pulses emitted in strong fields offer the chance to use attosecond electron pulses in time-resolved electron diffraction. The challenges involved therefore include:

- Resonant enhancement of nanoscale strong-field phenomena
- Generation of attosecond electron pulses
- Optical near-field enhanced insulator-metal transition

Application areas: Basic science, ICT

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Nanoscale quantum coherence

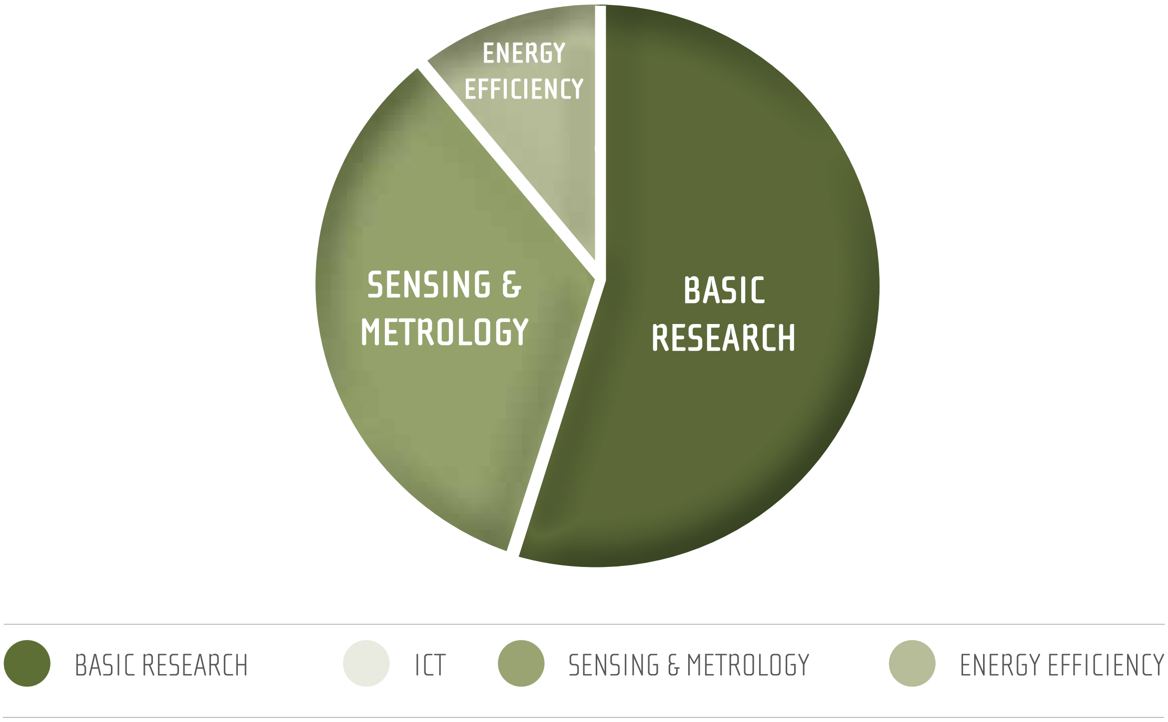

Figure 7. Nanoscale quantum coherence. Relevance of the proposed topics for basic research (100%), ICT (0%), sensing & metrology (60%) and energy efficiency (20%). 100% means that all topics discussed in this section are relevant.

Quantum coherence and dephasing as a sensing tool

Quantum systems are highly susceptible to external stimuli such as magnetic or electric fields, temperature changes or strain [1]. Consequently, they are amenable to precisely sensing these quantities, often with nanoscale spatial resolution, by virtue of the inherently miniature size that many solid-state quantum systems offer [2,3]. The sensitivity at which such measurements can be performed is limited by the quantum sensor's coherence time [1], i.e. the timescale over which it preserves its quantum phase. Quantum control and dynamical decoupling offer ways to protect coherence, while quantum logic can improve readout efficiency for quantum states. Both boost sensitivities significantly and in combination can yield, for example, quantum magnetometers that reach single-protein sensitivity [4].

CONCEPTS / THEORY / MODELS

While internal decoherence limits a quantum sensor's performance [1], decoherence caused by external sources, i.e. additional environmental fluctuations or entanglement with the environment, offers a valuable resource for sensing. Indeed, a quantum sensor in proximity to a sample may experience excess dephasing, which may carry relevant information. Such decoherence microscopy has been proposed in the context of life sciences [5] and fundamental solid-state physics [6]. One key strength of decoherence-based sensing is that it does not

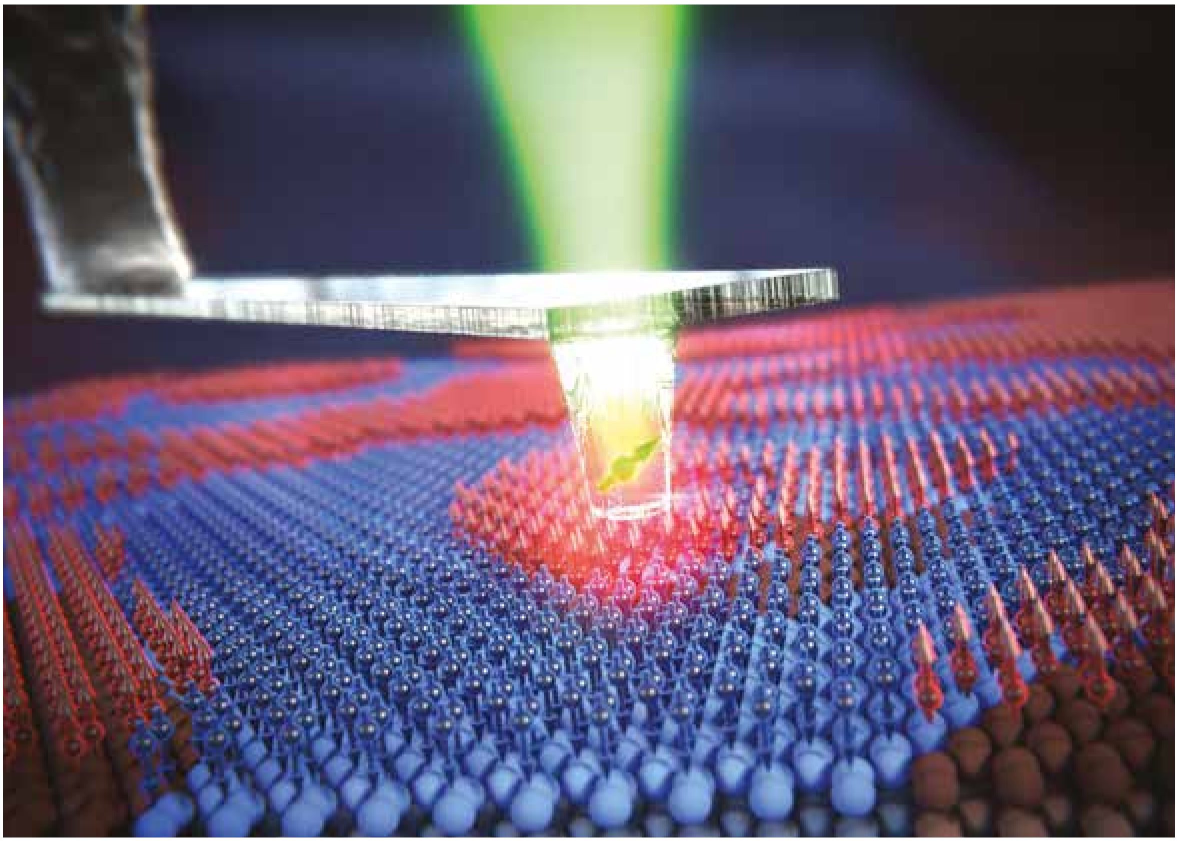

Figure 8. *Magnetic domains imaged with an NV centre on the tip of an atomic force microscope. Courtesy of the Quantum-Sensing Lab, University of Basel (www.quantum-sensing.ch).*

require phase-stable signal sources and that quantum control can be used to tailor the spectral response of the quantum sensor to either lock the sensor to a particular sensing frequency or perform noise spectroscopy of the environment [1]. In this context, research efforts are addressing:

- Quantum sensing
- Decoherence microscopy
- Decoherence models in nanostructures
- Realistic decoherence simulations in nanostructures
- Dynamical decoupling applied to nanostructures
- Many-body theory

MATERIALS / SYSTEMS / EXPERIMENTS

Initial experimental results have validated the potential of quantum decoherence microscopy and demonstrated its applicability to nanoscale sensing [7]. Promoting these concepts to real-life applications in life sciences [5] (where for instance ion channels in cell membranes could be investigated) or hard-to-address open problems in solid-state physics [6] (such as studying strongly correlated electron systems) remains an open challenge. However, recent advances in quantum sensing technologies, such as robust, coherent scanning quantum systems that employ innovative nanophotonic concepts, or the demonstration of nanoscale quantum sensing at cryogenic temperatures [8], render this a highly promising avenue in quantum engineering research. This involves, for instance:

- Single quantum systems (QDs, colour centres, etc.)
- Correlated electron systems
- Nanocrystals
- Photonic nanostructures
- Coherent spin manipulation
- Fluorescence steady-state and time-resolved spectroscopy at single-emitter level
- Medical imaging

CHALLENGES / PERFORMANCES / GOALS

The fact that startup companies have emerged that aim at marketing such technologies to a broader range of customers is a further indication of the attractiveness and broad applicability of coherence- or decoherence-based quantum sensing technologies. However, challenges related to reproducibility and robustness have arisen and include:

- Availability of highly coherent quantum probes at the nanoscale
- Development of highly efficient sensing protocols based on decoherence
- Understanding of decoherence mechanisms induced by and in relevant samples
- Developing new quantum sensing devices, robust enough to go beyond proof-of-concept, including upscaling of fabrication processes
- Identifying and demonstrating key applications outside the field of quantum sciences
- User-friendly fibre-coupled quantum sources and sensing devices

Application areas: Basic science, sensing & metrology

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Coherent quantum transport for energy harvesting

Nanoscale transport/bio-inspired materials such as light-harvesting complexes could open new routes towards efficient photovoltaic cells. There is theoretical and experimental evidence that coherent (quantum) transport is crucial for ultrafast energy transfer, which is in turn core to the efficiency of the photosynthesis processes of energy harvesting and energy transport [1-3]. A key role in this process is also played by the structural order/disorder interplay, which is conducive to a regime where population can be transferred between semilocalized and extended states, favouring coherent transport.

CONCEPTS / THEORY / MODELS

Coherence/decoherence interplay is fundamental for a step-change increase of excitation diffusion lengths, another important factor for energy harvesting and transport efficiency. Here coherence provides the memory necessary to ensure a degree of spatial directionality in an otherwise inefficient random walk of excitations [1]. The interplay between timescales, the importance of (quantum) correlations, the role of disorder, and the different coupling regimes between the components of these complex systems require the development of more accurate models to describe the natural energy-harvesting and transport processes, including going beyond Förster theory and Born-Oppenheimer approximation [1,4]. Concepts and methodologies of interest are:

- Energy harvesting
- Optimal energy transfer
- Master equation formalism
- Open quantum systems
- Computational chemistry
- Density functional theory (in its various flavours)
- Spin Hamiltonians
- Quantum transport in disordered systems

MATERIALS / SYSTEMS / EXPERIMENTS

Light-harvesting complexes [2,3,5] containing pigments and proteins are used by plants and photosynthetic bacteria to efficiently harvest solar energy. In recent years, synthetic light-harvesting arrays, e.g. using boron dipyrromethene dyes and pyrene [6] or artificially enhanced natural biological systems [7], have also been developed. Other systems and experimental methods to investigate them include:

- Light-harvesting complexes (natural, synthetic)
- Disordered photonic structures
- Nanoplasmonics
- Nanofabrication & synthesis
- Ultrafast and 2D spectroscopy
- Spectroscopy of single emitters
- Spectroscopy of nanoantennas
- Scanning probe techniques

CHALLENGES / PERFORMANCES / GOALS

Biological systems are very efficient light harvesters. This is due to the fact that the most efficient methods have been selected through evolution. Identifying and reproducing these mechanisms in photovoltaic devices may be crucial to reach a step-change in their performance. The main challenges and goals may be considered to be:

- Increase efficiency of artificial photosynthetic cells
- Development of accurate models to describe energy-harvesting and transport mechanisms
- Increase exciton diffusion lengths
- Reduce/prevent excitonic recombination
- Implementation of fully integrated photon-to-chemical conversion
- Self-organized, and self-sustained artificial photosynthetic cells

Application areas: Basic science, energy efficiency

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Fundamental aspects of quantum coherence at the nanoscale

Quantum coherence has been demonstrated in various interference experiments with electrons, neutrons, atoms, molecules and more recently aggregates counting up to 10000 amu [1]. It is extremely difficult to attain quantum interferences (Schrödinger-cat experiments) with larger objects [2] because (i) the de Broglie wavelength is inversely proportional to the mass of the object, while (ii) environmental decoherence increases exponentially with its size, which drastically reduces the coherence time during which it is possible to observe interferences. During the last decade, various mesoscopic systems (from 1 billion amu and beyond) have been developed, realized and studied in the laboratory in extreme vacuum conditions and at extremely low temperatures [3,4], aiming at realizing Schrödinger-cat experiments, and there is widespread hope in the community that it will be possible soon to let them operate in the quantum regime.

CONCEPTS / THEORY / MODELS

In order to investigate the mesoscopic transition it is imperative to take into account quantum decoherence and from a fundamental point of view to develop nonstandard models (gravitationally induced localization and/or decoherence [5-7], spontaneous localization [8]), which predict a quantum to classical transition in this regime. Models and techniques include, for example:

- Master equation
- Ab-initio methods
- Exact diagonalization techniques
- Spin-chain Hamiltonians

MATERIALS / SYSTEMS / EXPERIMENTS

Essentially all planned experiments in this field require OM devices at some level, but otherwise versatility is the rule. Therefore, the following broad range of nanoscale systems and techniques can be relevant for exploring the fundamental aspects of quantum coherence:

- Molecules, QDs and colour centres
- Spin chains
- Nanoresonators
- Beads
- 2D materials and graphene
- Quantum classical transition
- Spectroscopy of single emitters
- Nano-optical tweezers

CHALLENGES / PERFORMANCES / GOALS

Realizing quantum interferences in the mesoscopic regime would not only open new perspectives in sensing and metrology, but also open the door to fundamental experimental tests related to the nature of gravity [5-7] at the quantum level and/or to the measurement problem [8], by:

- Developing strong light-matter interactions at room temperature
- Developing a new generation of sensors
- Testing nonstandard formulations of quantum physics (e.g. spontaneous localization à la Ghirardi-Rimini-Weber, self-gravity à la Diosi-Penrose, etc.)

Application areas: Basic science, sensing & metrology

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Interaction of entangled light with nanostructures

A consequence of coherence in nanoscale objects is the possibility of achieving entanglement within such systems. However, directly generating entanglement in a controlled way would often require being able to fully control the interaction between such systems. On the other hand, entangled photons can be generated and therefore entanglement could be transferred from light to nanostructures, when the light-matter interaction preserves coherence.

CONCEPTS / THEORY / MODELS

Theoretical models aim at the application of quantum optical concepts to nanostructures, such as:

- Light-matter interaction with quantum light
- Entanglement in nanostructures
- Light-matter coherence transfer
- Photon-plasmon interaction

MATERIALS / SYSTEMS / EXPERIMENTS

Model experiments have studied the interaction of entangled photons with surface plasmons, demonstrating that the process of light conversion into plasmons and then back to photons preserves entanglement, both for polarization [1] and for time-energy [2] entangled photons. It would be interesting to study the dynamic of entanglement in those processes more closely by considering:

- Entangled photons sources
- Spectral manipulation of single photons
- Plasmonic structures
- Fluorescent molecules with high two-photon cross-section
- Self-assembled semiconductor QDs
- Multidimensional spectroscopy

CHALLENGES / PERFORMANCES / GOALS

Two-photon interactions with entangled light would also be relevant, for instance to probe a system. Recently, several schemes have been proposed demonstrating the advantage of performing spectroscopy beyond the classical paradigms by making use of such entangled states of light [4]. However, no experimental implementations of those theoretical ideas with energy-entangled photons have been realized up to now. Challenges and goals include:

- Low-signal/requirement of high two-photon cross-section
- Implementation of new spectroscopy schemes
- Demonstration of the transfer of entanglement from light to large collective structures, and atomic systems (quantum memories and quantum repeaters)

Application areas: Basic science

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Strong light-matter interaction at ambient conditions

The interaction between a quantum emitter and its local electromagnetic environment is typically weak, such that only the spontaneous decay rate is modified and the emission frequency remains unaltered [1]. However, in the case of strong light-matter interaction, the coupling creates a light-matter hybrid (dressed state, plexciton) that can have significantly different energy levels from those of the emitter or the optical system individually [1,2]. Moreover, strong light-matter coupling can be achieved even without the need for incident photons, as it simply relies on the vacuum field.

CONCEPTS / THEORY / MODELS

Only recently it has been discovered that strong coupling can have significant effects at a material and molecular level that were thought to be independent of the electromagnetic environment (phase transitions, conductivity, chemical reactions, etc.) [4-6]. Additionally, controlling and engineering the potential plethora of dressed states creates the prospect of studying and designing new quantum-optical systems and of controlling quantum coherence at the mesoscopic/macroscopic scale. This requires the advancement of theoretical models and techniques such as:

- Ab-initio/density functional theory methods
- Computational electromagnetics
- Dressed states

MATERIALS / SYSTEMS / EXPERIMENTS

Different photonic, plasmonic or hybrid plasmonic-photonic structures [3] with unique resonance patterns can be used to create an environment in which strong coupling with a nanosystem occurs that is controlled and harvested at ambient conditions. Examples of such systems and of experimental techniques to investigate strong coupling are:

- Molecules/organic dyes, QDs, nanocrystals and colour centres
- Proteins/DNA and other biological molecules
- 2D materials
- Photonic/plasmonic & hybrid plasmonic-photonic arrays
- Metallic nanoparticles
- Raman microscopy/surface-enhanced Raman scattering
- Nonlinear spectroscopy of single emitters and at the bulk level
- Fluorescence steady-state and time-resolved spectroscopy of single emitters and at the bulk level
- Quantum spectroscopy with entangled photons

CHALLENGES / PERFORMANCES / GOALS

Developing a nanophotonic environment that could efficiently control and mould strong light-matter interactions at room temperature is the major goal as this will enable:

- New hybrid light-matter structures with unique features
- Control molecular and material properties by strong light-matter interaction for chemical reactivity, catalysis, phase transitions, and wetting
- Encoding entangled photons into dressed states for quantum information science

Application areas: Basic science, sensing & metrology

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Cooperative effects, correlations and many-body physics tailored by strongly confined optical fields

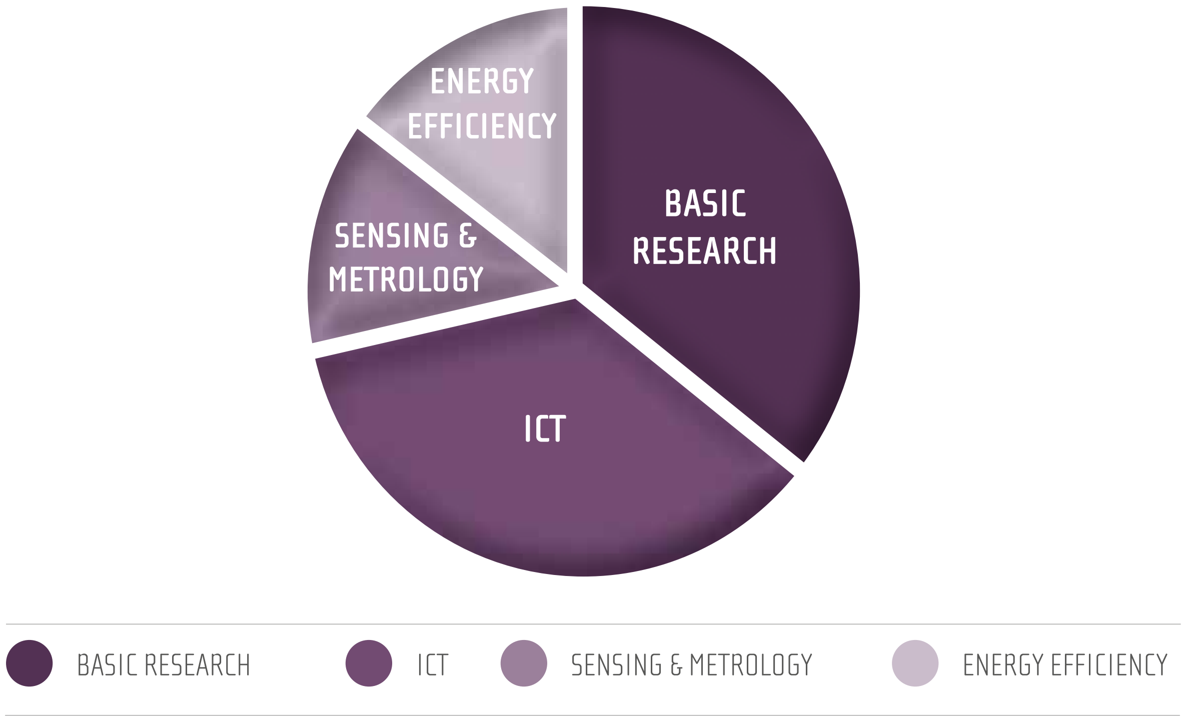


Figure 9. *Cooperative effects, correlations and many-body physics tailored by strongly confined optical fields. Relevance of the proposed topics for basic research (100%), ICT (100%), sensing & metrology (40%) and energy efficiency (40%). 100% means that all topics discussed in this section are relevant.*

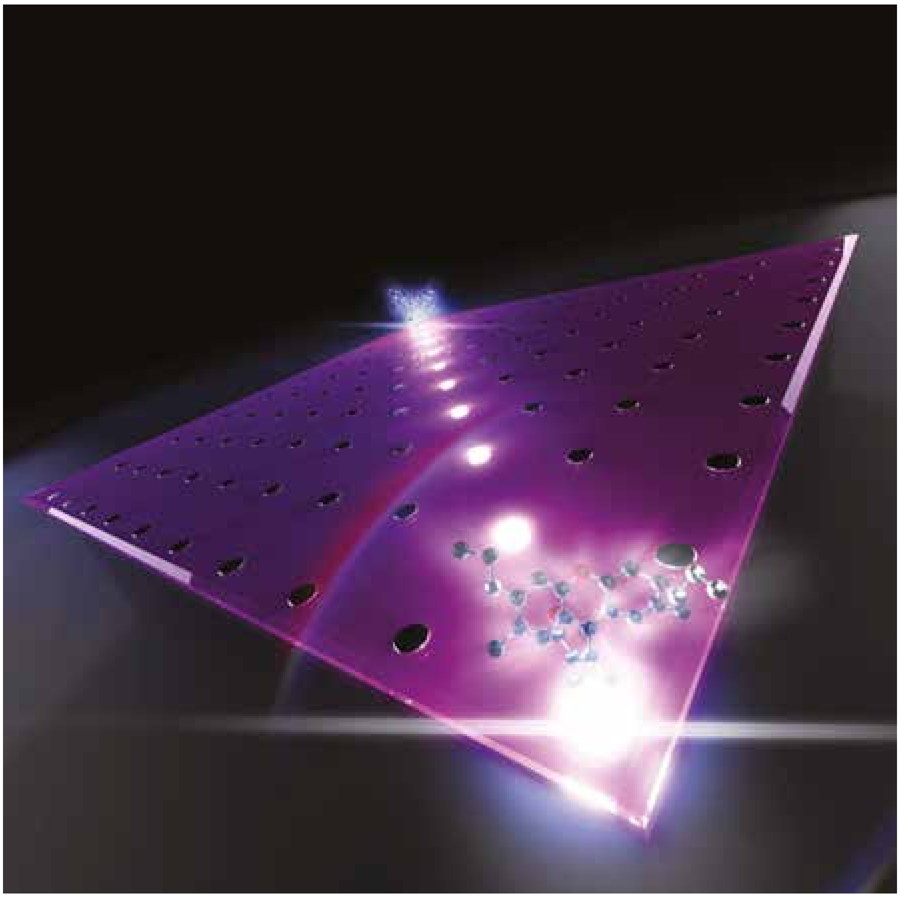
Photonic quantum simulators

The confinement of light to periodic nanophotonic lattices drastically reduces the photonic group velocities while nonlinear optical effects are enhanced. Under such extraordinary conditions, the optical field turns into a strongly correlated fluid of photons [1,2], which behaves in many ways similar to systems of interacting spins or electrons studied in condensed matter physics. The development of improved nanophotonic lattices with strong nonlinearities in different platforms ranging from semiconductor cavities to circuit QED lattices for microwave photons [3,4] will offer unprecedented possibilities to simulate and explore the dynamics of strongly correlated quantum many-body systems under nonequilibrium conditions, where coherent interactions compete with external driving fields and dissipation in a fully controlled way.

CONCEPTS / THEORY / MODELS

Photonic quantum simulators require new schemes for designing strong effective interactions for photons. For the theoretical modelling of photonic many-body systems, new numerical [5] and analytical tools to study many-body effects in the presence of driving

__Figure 10.__ Strong coupling in plasmonic nanoarrays. Courtesy of the Quantum Dynamics Group, Aalto University (physics.aalto.fi/en/groups/qd). Figure adapted from A. I. Väkeväinen, et al., Plasmonic surface lattice resonances at the strong coupling regime, Nano Lett. 14, 1721 (2014). (Copyright American Chemical Society, 2014).



and dissipation must be developed, such as:

- Engineering of strong photon-photon interactions and effective gauge fields in nanophotonic crystals with nontrivial topologies
- Floquet dynamics and nonequilibrium phases of driven dissipative photonic lattices
- Topological physics with driven many-body photonic systems, including edge states, Hall effect and robust optical delay lines [6]
- New numerical methods for driven-dissipative many-body systems in 1D/2D
- Atom-photon interactions in the ultrastrong coupling regime
- Nonequilibrium theory of condensation of photons, polaritons and plasmons
- Many-body theory of open quantum lattice systems in the presence of disorder

MATERIALS / SYSTEMS / EXPERIMENTS

The experimental implementation of strongly interacting many-body systems with photons relies on the fabrication of high-quality and low-bandwidth photonic lattice systems with integrated quantum emitters for generating strong effective optical nonlinearities. Current efforts are focusing on:

- 1D and 2D photonic lattices and coupled resonator arrays with low losses and strongly reduced frequency disorder
- Arrays of tunnel-coupled optical cavities with embedded two-level emitters
- Semiconductor polariton lattices
- Coupled circuit QED resonators
- Plasmonic lattice systems with low losses and high nonlinearities
- Spin-based polariton condensate lattices

CHALLENGES / PERFORMANCES / GOALS

Strong effective photon-photon interactions are already routinely achieved with single-mode CQED systems in the optical and the microwave regime. For the study of many-body effects, the key challenge is to fabricate large CQED lattices with sufficiently low disorder to observe a competition between kinetic and interaction-related energy terms. On the theoretical side, the overall goal is to develop generally applicable analytic and numerical methods for describing dissipative many-body systems. Other challenges and goals are:

- Optimized/flexible numerical methods for open quantum many-body systems
- Large-scale circuit QED resonator arrays in 1D and 2D
- Optical/plasmonic lattice systems with single-photon nonlinearities exceeding losses
- Simulating and realizing exotic out of equilibrium phases in driven dissipative photonic lattices

Application areas: Basic science, ICT

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Atom-light interactions in one dimension

Waveguide QED refers to a scenario where single- or multiple-quantum emitters are coupled to a 1D nanophotonic waveguide. The strong transverse confinement of light enables individual photons to be efficiently absorbed by even a single-quantum emitter, while photons emitted into the waveguide can be efficiently detected or used to mediate long-range interactions. This new regime of light-matter interactions is currently investigated with atoms [1,2], QDs [3], molecules and colour centres coupled to nanophotonic waveguides and offers many new opportunities for realizing single-photon switches and directional couplers [4], and for the implementation of long-range entanglement and quantum gate operations between travelling photons.

CONCEPTS / THEORY / MODELS

The efficient coupling of photons to single emitters requires new theoretical tools to describe the propagation of photons with strong nonlinearities on the level of individual photons. An additional complexity arises from infinite-range interaction mediated by photons in 1D. Theoretical work mainly concerns:

- Theory of few-photon transport in waveguide QED system based on scattering theory and quantum optical techniques
- Optical forces and self-ordering of atoms in driven 1D atom-waveguide systems
- Superradiance and collective phenomena in extended 1D systems
- Non-Markovian effects and atom-photon bounds states in slow-light waveguides
- Single-photon switches and quantum gates for propagating photons in 1D

MATERIALS / SYSTEMS / EXPERIMENTS

For the experimental realization of waveguide QED systems, the coupling of individual emitters to a photonic waveguide must exceed the decay into free space. This can be obtained with nanophotonic structures coupled to atoms or solid-state emitters, such as:

- QD-pillar systems and free-space lensing for efficient emitter-photon coupling
- Chiral photonic crystal waveguides with unidirectional coupling
- Epsilon-near-zero (ENZ) medium for position-independent dipole-dipole interactions
- Bright single-molecule emitters and natural colour centres coupled to 1D waveguides
- Long-distance coupling of separated QDs in 2D photonic crystal structures
- Atomic waveguide QED systems with large optical depth based on tapered optical fibres

CHALLENGES / PERFORMANCES / GOALS

Waveguide QED systems have been implemented with cold atoms or QDs coupled to tapered fibres and photonic crystal waveguides.

A main challenge is to achieve the simultaneous coupling of a large number of atom-like emitters to a 1D waveguide with a coupling efficiency of ~99%, which has so far only been reached with single QDs. Related challenges and goals are:

- Multiple identical emitters coupled to a single waveguide with ~99% efficiency
- Trapping of atoms close to nanophotonic waveguides
- Combining chiral or ENZ waveguides with QDs or other emitters
- Coupling of molecules to hybrid (plasmonic-dielectric) waveguides

Application areas: Basic science, ICT, energy efficiency

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Quantum plasmonics

Compared to optical photons, plasmonic excitations can be confined to a much smaller region in space, which increases substantially the coupling to emitters as well as all nonlinear interactions [1-3]. At the quantum level this strong confinement can be exploited for boosting plasmon-emitter interactions and for realizing strongly-correlated plasmonic systems [4]. Beyond new quantum simulation schemes, the resulting strong coupling effects can be relevant for controlling plasmon-mediated energy transport and chemical reactions.

CONCEPTS / THEORY / MODELS

The description of strongly coupled plasmonic systems requires new techniques for modelling dissipative few- and many-body systems, where plasmon-matter and plasmon-plasmon interactions must be treated on an equal footing. Current theoretical efforts include, for example:

- Nonlinear effects in organic “plasmonics”
- Exciton compensation of Coulomb blockade of the current through nanojunctions
- Modelling of 2D plasmons in graphene and nanographene sheets
- Pseudo-particle nonequilibrium Green function formalism for plasmon-exciton interactions

MATERIALS / SYSTEMS / EXPERIMENTS

Strongly interacting plasmonic systems can be implemented with nanostructured metals as well as unconventional materials like graphene. The coupling to molecules and emitters requires optimal designs, where strong confinement of plasmons without substantial increase of losses is achieved. Typical systems and experimental settings include:

- Plasmon-induced nonlinearities in nanostructured graphene
- Plasmonic lattices and metamaterials
- Experimental tests of the quantum properties of plasmons
- Strong coupling between plasmons and molecules – plasmon chemistry
- Plasmon-assisted energy transfer

CHALLENGES / PERFORMANCES / GOALS

Quantum plasmonics is a relatively new field of research, within which the efficient coupling of plasmons to single emitters as well as basic quantum optical effects have been demonstrated. However, compared to optical photons, plasmons suffer from large losses and a major challenge for further progress is the identification of optimized materials and structures to minimize such losses. Additional challenges and goals include:

- Increase plasmon lifetimes and propagation lengths
- Enhanced plasmonic nonlinearity using near-field effects
- Tailored plasmonic waveguides for coupling

to emitters and out-coupling to photons
- Many-body modelling with plasmon-matter and plasmon-plasmon interactions treated on an equal footing

Application areas: Basic science, ICT, sensing & metrology, energy efficiency

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Collective effects and phase transitions

The coupling of a collection of emitters to a single radiation mode results in many nontrivial phenomena associated with the existence of super- and subradiant states, where the coupling is either coherently enhanced or strongly suppressed. In CQED systems with ensembles of atoms or solid-state emitters, collective effects like superradiance, nonequilibrium Dicke phase transitions [1,2] as well as long-lived collective states are experimentally investigated. Relaxation phenomena [3], phase transitions and ultrastrong coupling effects [4] can be explored at the crossover from the classical to the quantum regime with potential applications ranging from low-power signal processing to collectively protected quantum memories [5].

CONCEPTS / THEORY / MODELS

The modelling of collective radiation phenomena in nanophotonic systems requires theoretical tools to model the transient dynamics and steady states of multiple emitters coupled to a single radiation mode in the quantum and classical regime, in the presence of frequency and coupling disorder. Current theoretical efforts include, for example:

- Superradiance, self-organization, relaxation dynamics and prethermalization in CQED
- Quantum phase transitions and universal dynamics of Rabi and Dicke models
- Cavity protection effects and decoherence control of atomic and spin ensemble quantum memories
- Green's tensor approach to model superradiance of many random emitters coupled to plasmonic resonances
- Superradiance in metamaterials and in an ENZ medium
- Higher-order cumulant expansions methods for modelling collective effects
- Collective and near-field dipole-dipole interactions in dense ensembles

MATERIALS / SYSTEMS / EXPERIMENTS

Collective effects occur in a variety of CQED setups in atomic and solid-state systems, whenever many emitters are coupled to a single radiation mode. Currently investigated systems include:

- CQED systems with ensembles of laser-cooled atoms
- Plasmonic resonances coupled to ensembles of molecules or other emitters
- Spin-ensembles coupled to microwave resonators
- Quantum well intersubband transitions in microcavities and metamaterials
- Superradiation and control of coherence with ENZ mediums
- Ultracold atoms in optical lattices with photon-mediated long-range interactions

CHALLENGES / PERFORMANCES / GOALS

Collective interaction phenomena have been explored for many years, but only recently it has become possible to study the steady-state and excitation spectra of such systems deep in the quantum regime and at ultrastrong coupling strengths using cold atoms and solid-state CQED systems. Open challenges lie in:

- Dynamical control of ultrastrong coupling effects for potential applications in interfaces, quantum memories and low-power switches

- Modelling of the quantum dynamics of ultrastrongly coupled CQED systems
- Control of collective coupling effects in nanophotonic and plasmonic structures for efficient light-matter interfaces

Application areas: Basic science, ICT

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Nano-optomechanics

Photons can couple to the motion of isolated micro- and nanomechanical resonators via radiation pressure [1]. In nanophotonic structures this interaction can be substantially enhanced by confining light and sound within a small region of space [2] while minimizing mechanical and optical losses. The resulting parametric coupling between light and mechanical motion offers many new possibilities for OM ground-state cooling of vibrational modes, for the sensing and readout of minute displacement forces and fields [3,4] even beyond the standard quantum limit, for a coherent conversion between optical and microwave signals [5], and for the implementation of mechanically induced nonreciprocal elements [6] and switches at the level of individual photons.

CONCEPTS / THEORY / MODELS

Applications of OM effects require the development of efficient quantum control and quantum information-processing protocols based on linearized OM couplings in single- and multimode OM systems as well as new theoretical tools for the modelling of nonlinear radiation pressure effects on the few-photon level. Current theoretical efforts include, for example:

- Conditional preparation of nonclassical mechanical states and entanglement for weakly coupled OM systems
- Theory of OM systems in the single-photon strong-coupling regime
- Theory of multimode OM systems and OM lattices
- Defect-phonon interactions in nanobeams for enhanced phonon nonlinearities
- Modelling of mechanical properties of carbon nanotubes, graphene and 2D materials

MATERIALS / SYSTEMS / EXPERIMENTS

OM interactions can be studied in a large variety of (nano)photonic and microwave systems but this requires the optimization of both photonic and mechanical properties. The coupling to individual emitters [7] can further introduce optical or phononic nonlinearities at the quantum level. Materials and systems currently of interest include:

- Nanoscale OM systems with strong couplings and low optical absorption
- Phononic shields and optimized materials for ultrahigh mechanical quality factors
- Arrays and low-disorder lattices of OM elements
- Integrated nanophotonic and microwave OM systems for optics-to-microwave conversion
- Near-field coupling of carbon nanotubes and graphene resonators to optical resonators and single emitters
- Diamond OM systems coupled to NV and SiV defect centres

CHALLENGES / PERFORMANCES / GOALS

Mesoscopic mechanical elements also tend to vibrate in the MHz to few-GHz regime, which makes them very susceptible to thermal noise and decoherence processes. Quantum control of individual mechanical modes has already been demonstrated in cryostats, but real-world technologies based on OM devices must be able to operate at, or close to, room temperature. Additional open challenges are the mass manufacturing of OM devices with low disorder and reaching the single-photon strong coupling regime for implementing efficient OM nonlinearities on the few-photon level. The main challenges and goals therefore include:

- OM systems in the single-photon strong-coupling regime
- Quantum control of OM systems at room temperature
- Scalability of OM systems beyond one or very few OM elements
- Complementary metal-oxide-semiconductor (CMOS)-compatible manufacture of OM devices

Application areas: Basic science, ICT, sensing & metrology

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Technological outlook

In recent years, several companies have emerged or have expanded their activities in the field of NQO, see for example the COST Action MP1403 industry partners at www.cost-nqo.eu/industry. Many companies have strong ties with academic research laboratories, highlighting the importance of academia/industry collaboration. This also emphasizes the potential of NQO for creating viable and sustainable companies by training highly skilled personnel and by developing risky technologies in an academic environment. Here we discuss several aspects of NQO that have already made an impact in industry.

Single-photon sources

The deterministic generation of pure single photons is a now highly sought-after technology for many research laboratories. The probabilistic generation of single photons from spontaneous parametric processes is currently severely hindering the progress of optical quantum information processing and quantum communication, and NQO offers several approaches based on compact and integrated sources such as QDs, colour centres, quantum light-emitting diodes (LEDs) and organic molecules that have the potential to yield high-rate, high-quality and, importantly, deterministic single-photon emission. Some emerging companies active in NQO are now offering single-photon sources that can be integrated in research laboratories. This is a first step that will lead to the generation of turnkey and user-friendly systems that will further facilitate dissemination by the academic and industrial communities. In terms of performance, the immediate needs are:

- Self-contained turnkey system (in a cryostat if necessary)
- Large coupling efficiency into an optical fibre to reach deterministic generation inside an optical fibre
- High-rate and deterministic emission to demonstrate a gain over spontaneous generation
- Electrical pumping
- Telecom wavelengths
- Deterministic and high-quality sources of entangled photon pairs
- Reproducible and scalable nanofabrication technologies (in-situ optical and electron-beam lithography)

The industry is now in a position to address these different aspects, which will lead to the development of performance standardization procedures.

Single-photon detectors

Superconducting nanowire single-photon detection, which offers unrivalled efficiency and detection rate, low noise and broadband operation, is currently a very active area of NQO in industry, with several companies offering systems and solutions. Turnkey operation has been reached, and users can now acquire fully operation systems that can be easily integrated in academic and industrial environments. While academic laboratories remain a strong acquirer of this technology, one challenge is now to disseminate the technology further in industrial applications and gain large acceptance. Some aspects that require further development are:

- Larger collection areas for free-space coupling or multimode fibre coupling
- Higher detection speed (towards GHz counting rate) in a cost-effective way
- Mid-infrared sensitivity (up to 5 μm)

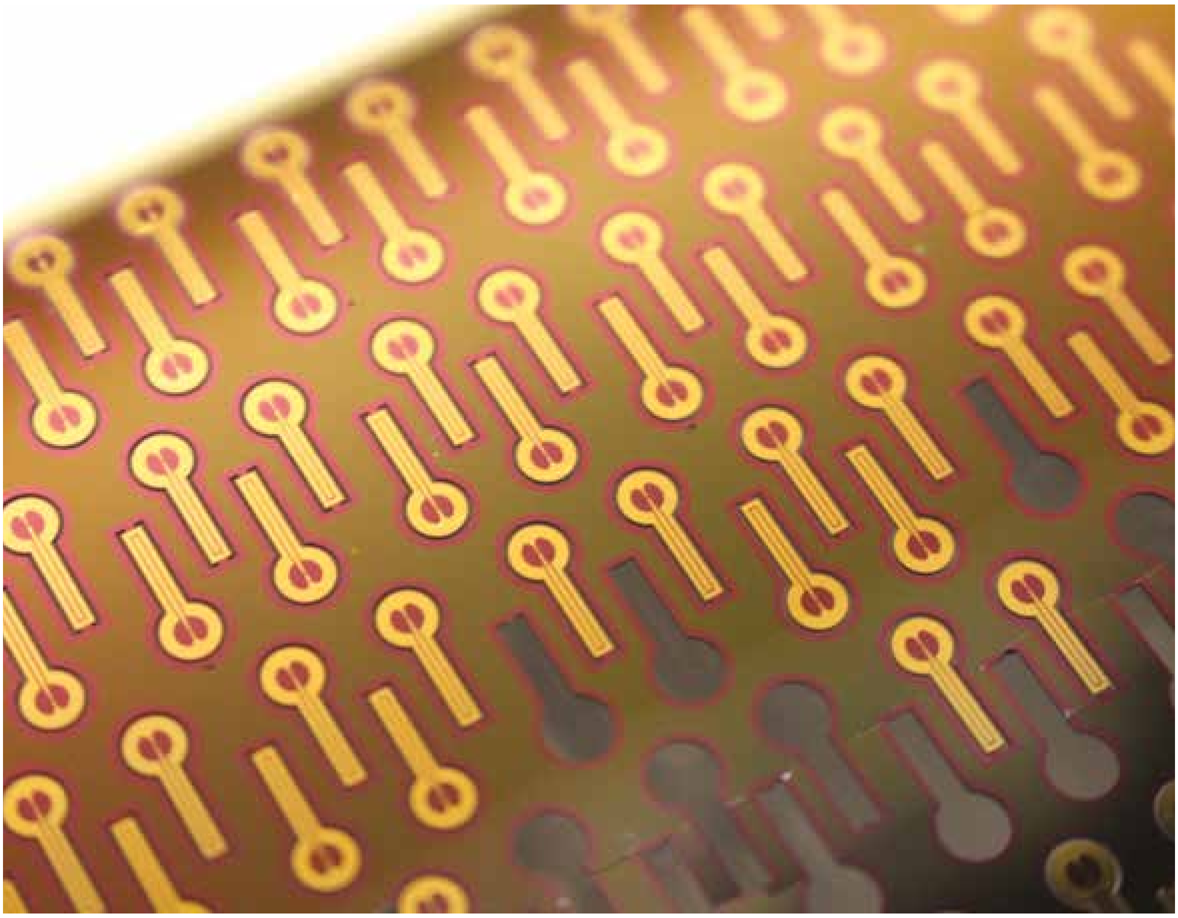

Figure 11. *Superconducting nanowire single-photon detectors. Courtesy of the Group of Applied Physics – Quantum Technologies, University of Geneva (www.unige.ch/gap/qtech).*

- Integration of high-performance detectors in quantum photonics platforms

Standardization of the performances will also play an important role in widening the acceptance of this technology in industry.

Photonic integration

Integration of NQO technologies in optical circuits is an important and timely objective for several industrial companies active in integrated optics. Indeed, companies and research laboratories now aim to leverage from the developments in the "optics-on-a-chip" field to start integrating single-photon sources, detectors and processing capabilities on the quantum photonics platform. Several materials are being pursued, such as GaAs, SOI, lithium niobate, silica and diamond. A unified approach involving both academics and industry is essential to converge rapidly.

Targeting specific applications such as quantum key distribution on a chip using deterministic and high-rate single-photon sources could achieve this. Another important application is computation tasks, such as Boson sampling on a chip, in which the combination of multiphoton generation, processing and detection could lead to the demonstration of quantum supremacy. The role of industry in this line of work is to find ways to develop rapid, performing and cost-effective ways to create integrated circuits. Fortunately, this progress will go together with that in integrated optics, which will be highly beneficial.

Single-spin sensing

Single-spin sensing has rapidly evolved in the last few years, and several companies have emerged in the area. These companies leverage from nanofabrication techniques and established diamond providers to explore the possibility of sensing with nanometre-scale precision and unprecedented sensitivity. Applications range from failure analysis of electronic systems (through magnetic or electric field sensing) to life sciences, where an understanding of the intracell mechanisms is key to understanding subcellular processes and to early diagnosis. One important challenge is therefore to disseminate the technology in areas outside of the quantum physics/nanotechnology sector.

This inevitably requires a consolidation of the technology in a rugged and turnkey system that can be adopted by many end users with diverse backgrounds. This will be combined with academic innovation, and the synergy between companies and laboratories will allow rapid development cycles.

Numerical modelling

Numerical modelling has played a crucial part in the development of nano-optics in research laboratories. Several companies are active in this field and are pursuing the development of software that will be useful for NQO as well. This could require adapting the numerical methods to take quantum effects into account, which would lead to a unique tool for developing NQO processes. Possible application areas cover fundamental quantum many-body physics, multidimensional coherent spectroscopy modelling tools, etc.

Enabling technologies

The core technology in NQO relies on more generic technologies such as lasers, high-speed electronics and cryogenics. The development of user-friendly tools exploiting NQO technologies will greatly benefit from partnerships with the generic technology companies. Such partnerships will be essential to disseminate NQO technologies, and will allow both sides to expand their market.

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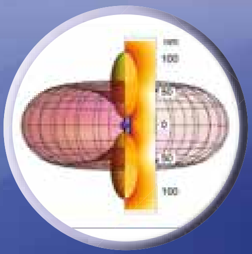

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