WHITE PAPER ON QUANTUM METROLOGY & SENSING AND QUANTUM ENHANCED IMAGING

Based on the discussion during the respective workshop at the ZEISS Symposium "Optics in the Quantum World" on 18 April 2018 in Oberkochen, Germany

Executive summary

Quantum metrology & sensing (QMS) and quantum enhanced imaging (QEI) are very promising in terms of commercial applications. Presently, however, both technologies face several roadblocks that need to be tackled in order to enable a broader commercialization:

1. Need for advanced and cost intensive laboratory equipment makes it difficult to spread quantum technologies to a broader community – in contrast, e.g., to computer science.
2. Lack of a hardware platform "the missing Raspberry Pi for quantum technologies" as an easy development and prototyping platform.
3. A stronger collaboration and exchange between industry and academia is required.
4. The industry demands sensors that should be small, robust, have low power consumption, and all this of course at reasonable cost.
5. Sensor integration because a sensor is usually only a small part of a larger system.

Because of these roadblocks in many applications, feasibility demonstrations under real conditions are mostly lacking and the road to commercialization is not clearly visible yet.

The following actions are proposed:

1. Increased open access to both industrial and governmental facilities (manufacturing infrastructure).
2. Actions should be taken to facilitate the collaboration between industry and academia (e.g. quantum hubs in the UK).
3. Policies for the protection of knowledge are needed to combat the brain drain from Europe.
4. Guided by improved coordination between natural sciences and engineering faculties, university curricula should become more interdisciplinary to enable better collaboration between industry and academia.
5. Quantum engineering is needed to facilitate the transfer from science to commercial applications.
6. Simulation and emulation tools have to be created to help spread quantum technologies in this early stage.
7. Providing a hardware platform at a reasonable cost "Raspberry Pi for quantum technologies".
8. Pilot applications have to be identified to justify investments in the technology from industry. These pilot applications may accept fewer requirements but still benefit from the advantage of QMS.
9. Continued support of the enabling-technologies ecosystem and funding of fundamental research.

Preface and introduction

Today, quantum technologies (QT) form the basic technology for many branches of industry. These include the groundbreaking technologies of transistors in the semiconductor industry, lasers and light-emitting-diodes in telecommunication, image detectors in computer vision, and atomic clocks in global positioning systems.

A second wave of quantum technologies, based on the ability to control the quantum state of a single or a few coupled quantum systems, such as single atoms, single ions, or single photons, is about to transition from academic research to commercial applications.

Among others, this second wave provides new technologies for building sensor systems for very different modalities.

Quantum metrology & sensing (QMS) aims to reach and to go beyond the limits of classical metrology & sensing by harnessing the properties of suitable quantum states and their interactions with the environment.

Quantum enhanced imaging (QEI) exploits the properties of non-classical states of light to achieve unique imaging performance.

This white paper provides a summary of the discussion during the workshop on quantum metrology & sensing and quantum enhanced imaging at the ZEISS Symposium "Optics in the Quantum World" between representatives of industry and academia.

This white paper is divided into four parts:

1. Opportunities provided by QMS & QEI
2. Current status of QMS & QEI
3. Current challenges and potential obstacles on the road towards commercialization
4. Actions required to enable the commercialization of the technologies

Opportunities provided by QMS & QEI

Quantum metrology & sensing incorporates various technologies for measuring various physical quantities. An overview of the different technologies is provided in Table 1.

Quantum enhanced imaging encompasses several methods and techniques for providing enhanced imaging performance. An overview of the different technologies is given in Table 2.

Please note: The technology's full commercial potential remains largely unknown. Multiple special applications and niches have been suggested, however the list is not exhaustive and the full breadth of potential applications remains unknown today. This is no surprise given that a) the level of commercialization of QMS and QEI (see hype cycle for QMS, Figure 1) is at an early stage and b) sensor-based technology has a cross-applicational and cross-industry character, making it difficult to evaluate the potential of every highly specialized application.

Technology	Potential Benefits	Applications
NV centers	High-precision electric and magnetic field measurements	Medical applications (brain imaging …), semiconductor (failure analysis), …
Matter wave interferometry	High-precision, drift-free gravitometry, accelerometry, gyrometry	Natural resource exploitation, civil engineering, inertial navigation system,…
Optical atomic clocks/Lattice clocks	Improved time/frequency standards	Navigation systems (GPS), financial sector (time stamping), telecommunication (synchronization), …
Cavity optomechanics	High-precision force sensors	Inertial navigation systems, …
Phase discrimination/ Squeezed light	Enhanced signal-to-noise ratio for phase-encoded optical signals	Telecommunication (improved optical data transmission), industrial metrology (improved optical interferometers), …

Table 1: Overview of the different technologies within quantum metrology & sensing (including potential benefits and applications).

Technology	Potential Benefits	Applications
Ghost imaging	Better signal-to-noise ratio for imaging with low intensity, separation of light interaction with detector and object	Biomedical imaging, e.g. in developmental biology
Quantum multiphoton microscopy	Lower intensity, higher selectivity, higher resolution	Biomedical imaging, …
Quantum interferometry	High phase estimation sensitivity	PIC interferometric sensors for interference microscopy, …
Quantum lithography	Higher resolution	Beating the Rayleigh resolution limit in lithographic imaging, …
Quantum coherence tomography	Improved resolution (for same-source bandwidth), maximum axial resolution	Biological research, medical applications, functional imaging
NV microscopes	Replace SEM as an atomic resolution imaging tool	

Table 2: Overview of the different technologies within quantum enhanced imaging (including potential benefits and applications).

Current status of QMS & QEI

The participants of the workshop took part in a survey to estimate the time to first commercial products and the current position of the technologies on the Gartner hype cycle. The results for QMS are shown in Figure 1.

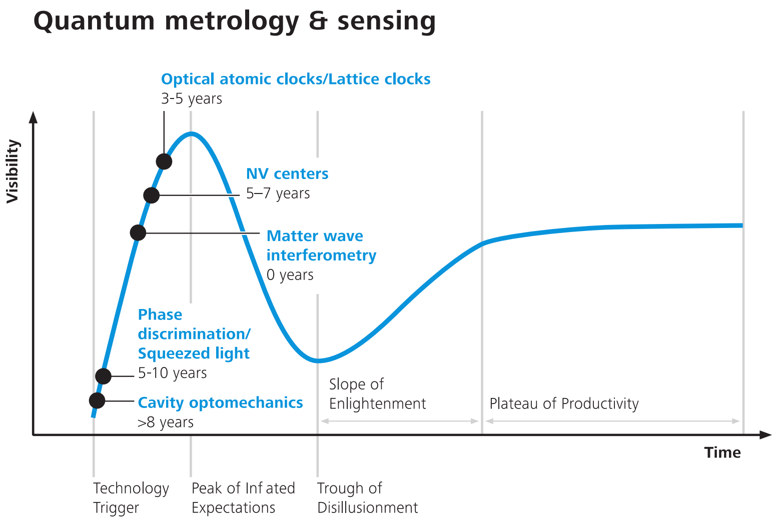

Figure 1: Hype cycle for quantum metrology & sensing. The times below the technologies indicate the expected time to the first commercial product (first commercial niche applications) for the different technologies. The estimates depicted above are based on a survey conducted among the participants of the quantum metrology & sensing and quantum enhanced imaging workshop.

For QMS the general assessment of its position on the Gartner hype cycle was between the "Technology Trigger" and the "Peak of Inflated Expectations", with atomics clocks already near to the "Peak of Inflated Expectations" and NV centers and electric/magnetic field sensors slightly before this peak. Phase discrimination, cavity optomechanics and squeezed light were all regarded to be still in the "Technology Trigger" phase. The potential for commercial applications was estimated between medium and high with a time to market above 5 years (except atomic clocks with 3–5 years)[1].

The technologies of QEI are located between the "Technology Trigger" and the "Peak of Inflated Expectations" with ghost imaging and quantum multiphoton microscopy being closer to first commercial application than quantum lithography and quantum coherence tomography being among the less-mature technologies. The estimated time to first commercial products for QEI is shown in Table 3.

[1] This refers to the 2nd wave of QT. Most of the 1st wave systems are commercially available and fully established.

Technology	Time to first commercial products
Ghost imaging	5–8 years
Quantum multiphoton microscopy	5–10 years
Quantum interferometry	5–10 years
Quantum lithography	>15 years
Quantum coherence tomography	>15 years
NV microscopes	5–10 years

Table 3: Estimated time to first commercial products (first commercial niche applications) for QEI.

Current challenges and potential obstacles on the road towards commercialization

QMS and QEI are both regarded as very promising in terms of commercial applications although it may take more than 5 years to achieve the first commercial products. Presently, however, both technologies face several roadblocks that need to be tackled in order to enable widespread commercialization. Some of these roadblocks are common to both technologies, while others are specific to either QMS or QEI. In general, for both technologies a lack of interdisciplinary education in physics and engineering makes it difficult to bridge the gap between basic research and real-world products for both technologies. Besides education, a stronger collaboration and exchange between industry and academia is required. The general necessity to use advanced and cost-intensive laboratory equipment makes it difficult to spread quantum technologies to a broader community – this is not true of areas like computer science.

For QMS the lack of a hardware platform – someone in the workshop expressed it as "the missing Raspberry Pi for QT" as an easy development and prototyping platform – makes it risky and expensive to develop industry-ready solutions. Limited access to industrial manufacturing facilities makes it difficult to try new sensor designs. The industry demands sensors that are small, robust, have low power consumption, and all this of course at a reasonable cost. Pilot applications have to be identified to justify investments in the technology from industry. These pilot applications may accept less requirements but still benefit from QMS. Another important aspect, especially for QMS, is the importance of sensor integration because a sensor is usually only a small part of a larger system. This comprises corresponding hardware components and software interfaces, which should be standardized as much as possible. Building committees to elaborate these preferably open standards is regarded an important part of the QT policy.

In general, there seems to be too little public awareness regarding the advantages and the scope of QMS and QEI. Finally, there are of course a number of technological challenges, e.g. the lack of a suitable quantum light source in a photonic system.

Actions required to enable the commercialization of the technologies

The participants of the workshop developed several action items during an open discussion. In view of its infrastructure issues, QMS and QEI would benefit from increased access to both industrial and government facilities (manufacturing infrastructure). Well-designed simulation and emulation tools could help to spread the QT technology at this early stage, when there is no general hardware platform available for creatively building new technical solutions. Providing a general hardware platform at a reasonable cost is regarded a key enabler to significantly speeding up development in the field of QMS and QEI. NV centers were identified as promising candidates for providing a building block of QMS solutions that a more complex system could rely on.

Having the government as an early adopter of quantum sensors would make it easier for startups to bridge long timespans between the initial prototype and the final product. Policies for the protection of knowledge are needed to combat the brain drain in Europe in order to capitalize on the investments in fundamental research as soon as quantum technologies become commercially viable. Solving the technological issues requires continued fundamental research funding. Guided by improved coordination between natural sciences and engineering faculties, university curricula should become more interdisciplinary. For QMS and QEI, interdisciplinary research initiatives are required to develop and to establish first and lighthouse-like applications. Continued support of the enabling-technologies ecosystem and fundamental research funding is needed in order to find a solution to the technological challenges.

Finally, actions should be taken to facilitate the collaboration between industry and academia (e.g. quantum hubs in the UK). More intense collaboration between industry and academia is required in order to demonstrate the benefits of QMS and QEI for practical application and to drive the adoption of the technologies – the Symposium “Optics in the Quantum World” was one step and a small contribution towards bringing both parties together.