Market Research Study in Nanoscale Quantum Optics - Executive Summary

Motivation

This market Research Study (MRS) has been commissioned by the COST Action MP1403 Nanoscale Quantum Optics (NQO) to present the innovation potential of the field in terms of application opportunities and markets (report available at: www.cost-nqo.eu/support/documents/).

Aim of the COST Action MP1403 NQO has been to support and coordinate research activities in nanoscale quantum optics (NQO), explore innovative approaches by identifying, establishing and exploiting cross-links between quantum science & technology, nanoscale optics & photonics and materials science, and facilitate the early-involvement of end-users. The Action has also recently released a NQO Research and Innovation Roadmap, disseminated in Europe to various decision makers (available at: www.cost-nqo.eu/support/documents/).

Approach & Methodology

An initial analysis has been done to identify the technologies and the positioning in terms of functions and characteristics that can be of interest for companies. The following step has been to collect information through discussions with players along the value chain (workshops, interviews …). Next, online surveys have been used for the validation of potential applications and market information. Finally, all technology and market analysis, as well as the relevant data, have been gathered in a report and summarized in the present document.

About this MRS, the focus in terms of applications is on the following two topics:

- **Quantum Communication** with Quantum Key Distribution (QKD) and Quantum Random Number Generators (QRNG),
- **Quantum Sensing** with atomic sensors and Nitrogen Vacancy (NV) centres based sensors.

Quantum Communication

Communication systems can use quantum effects to securely transmit data. The near-term technologies are QRNG for secure key or token generation and point-to-point QKD for secure key exchange. Examples of mid/long-term technologies are QKD networks and quantum repeaters.

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Quantum Random Number Generator (QRNG)

The fundamentals of quantum mechanics (state superposition and quantum measurement) allow for generation of real random numbers in a relatively simple way.

Competing technologies (named “True RNG”) exploit Physical Unclonable Functions (PUF) and noise in complex physical systems. “True RNG” from electronic manufacturers (phase noise, electronic noise) are sold as ASICs and FPGA chips at 1-2$ for 1000 units.

Added value for QRNG is not yet clear against current True RNG whereas extra-cost is clearly perceived. Internet of Things will require QRNG for few cents, automotive sensors for no more than 1$. About telecommunication market for QRNG, end-price should be less than 20$ for markets around 10k to 100k units. There will be potentially an opportunity for QRNG in QKD systems as a complement manufacturer’s portfolio in the whole system.

Quantum Key Distribution (QKD)

QKD is a secure communication method, which implements a cryptographic protocol involving quantum mechanics. It enables two parties to produce a shared random secret key, which can then be used to encrypt and decrypt messages. An important and unique property of QKD is the ability to detect the presence of any third party trying to gain knowledge of the key.

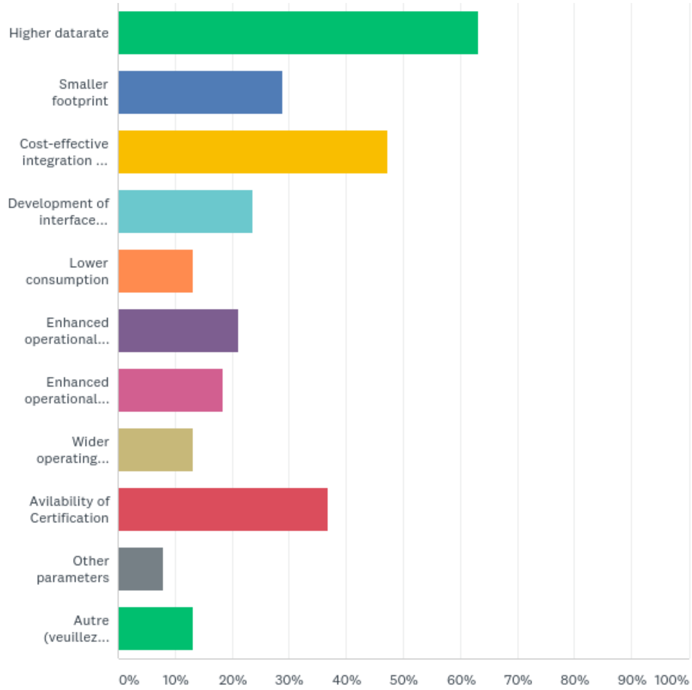
QKD systems deliver digital keys for cryptographic applications on fibre-optic based networks. They allow key distribution over standard telecom fibre links with distance sufficiently long for metropolitan coverage. There is a variety of cryptographic applications for QKD systems, e.g., encryption or authentication of sensitive documents, messages or transactions. They can be used by many different sectors, for example: public administration, financial services, chemical industry, public health, safety, emergency and defense, etc.

For QKD systems, there is a clear need for co-integration of integrated components with compatibility with optical communication infrastructures and multiplexing protocols.

The online survey on QKD gave useful answers about performances, costs and market:

- Three key parameters must be improved before QKD field deployment: higher data rate, certification, cost-effective integration.

- The willingness to pay for a high security link is about 15-50% of extra cost, compared to existing technology.
- Today's unit price of about +50 k€ must decrease to 8-10 k€ in market widespread regime.
- The market is expected to reach maturity at few tens of thousands units per year.



QKD Survey: requirements for QKD systems (scale in % of respondents)

Quantum Sensing

Quantum sensing describes the use of a quantum system, quantum properties, or quantum phenomena to perform a measurement of a physical quantity. Historical examples of quantum sensors include magnetometers based on Superconducting QUantum Interference Devices (SQUID), atomic vapors magnetometers, or atomic clocks. More recently, quantum sensing is expected to provide new opportunities especially with regard to high sensitivity and precision in various areas of science, e.g. applied physics. Quantum sensors capitalize on the central weakness of quantum systems: their strong sensitivity to external disturbances. The study about nanoscale quantum sensing has been focused on NV centres and atomic sensors.

Atomic Sensors

Atomic sensors are based on the optical properties of laser-cooled atoms or ions. They are used for Optical Atomic Clocks (OAC). Many innovations in OAC have led to orders-of-magnitude improvements over the last four decades with current relative precision of up to 2.5×10^{-19}. Their main applications are in fundamental

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physics, earth observation, Global Navigation Systems (GNSS) and satellite telecommunications.

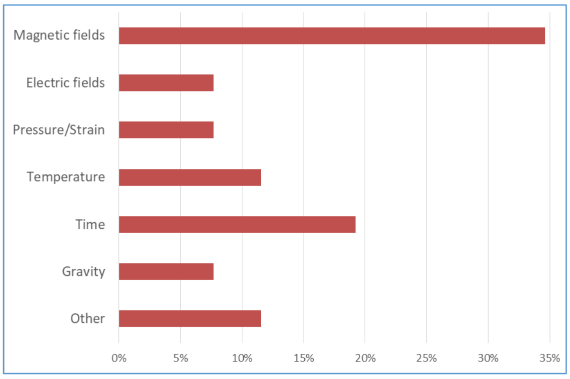
Atomic sensors are also used as Matter-Wave Interferometers (MWI), which offer unique properties for high performance inertial measurements as gravity sensors, accelerometers, gyroscopes. Their main applications are in sustainable management of underground resources (geothermic & hydrology, oil & gas, and mining industry), environmental security (volcanology and seismology), subsurface imaging (void, tunnel and cavity detection).

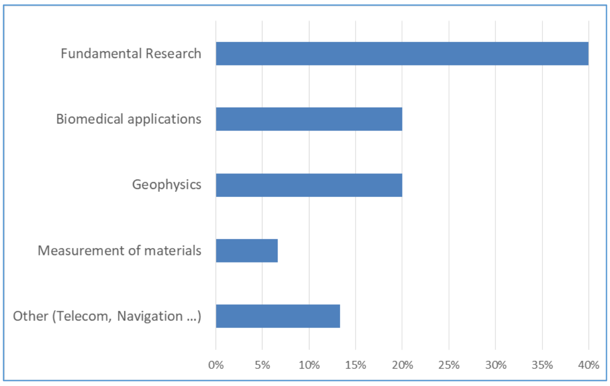
The technical feasibility to integrate atomic-clocks on-chip has been demonstrated, but the market linked to this level of performance is still quite low.

Nitrogen Vacancy (NV) Centres

NV centres allow electron spin readout by fluorescence, hence high sensitivity to magnetic fields with nanoscale spatial resolution. The performances reached by NV centres are: single electron spin detection (~20 nT/Hz$^{1/2}$), single proton spin detection, and a spatial resolution of about 1 to 20 nm. Their main applications are: solid-state physics, life sciences (magnetic cell labelling, nanoscale NMR or MRI) and very small current measurement (in IC, batteries ...). Some improvements are required from NV centres: better performance and integration are necessary to overcome today's market barriers.

The survey shows the user priorities for nanoscale quantum sensing in terms of quantity to measure and applications. The results are shown below.





Quantum Sensing Survey: quantities to be measured and applications of quantum sensing (scale in % of respondents)

Market Analysis

About **QKD**, interviews and online survey allows us to establish the market progression:

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- 1st step in about 5 years (space and airborne deployment): ~ 1000 units/year at 50000 €, i.e. 50 M€.
- 2nd step in about 7-8 years (ground professional segment): ~ 10000 units/year at 15000 €, i.e. 150 M€.
- 3rd step in about 10 years (ground telecom network): ~ 30000 units @ 10000 €, i.e. 300 M€.

However, some key parameters must be improve before QKD field deployment, these are: higher data-rate, cost-effective integration and establishment of standards and procedures for certification. Moreover, at the beginning, QKD will not replace conventional cryptography, but rather be a complement of current systems.

Quantum Sensing will reach multiple niche markets, with a market in 5 years expected by manufacturers to be:

- For NV centres-based sensors: 1000 to 3000 units/year at a price of 5000 - 20000 € and with high/rocket growth, i.e. 5 M€ to 60 M€.
- For atomic-chip sensors: around 500 units/year at a price of 10000 - 30000 € and with a steady growth, i.e. 5 M€ to 15 M€.

Note that the market for systems using these sensors will be much bigger: for example the market for MEG (Magnetoencephalography) is around 100 M€, while the SQUIDs used in these systems account for about 10 M€.

The table below summarizes the main applications of Quantum Sensing as well as the time-to-market.

Quantity to measure	Applications	Term
Time	Atomic clocks for time measurement & certification Synchronization for networks, GPS …	Now
Rotation & acceleration	Quantum gyrometers Quantum accelerometers	> 5 years
Gravity	Natural resources exploitation and monitoring	Now
Magnetic fields	Current Measurement in IC, batteries … Molecular analysis (NMR in vitro) NMR imaging Magnetoencephalography (MEG)	< 5 years
Electric fields	Measurement of IC and semiconductors Measurement of neuron signal (EEG)	< 5 years
Pressure	Constraints in materials (esp. for high pressure)	~ 5 years
Temperature	Nanoscale temperature measurement	~ 5 years

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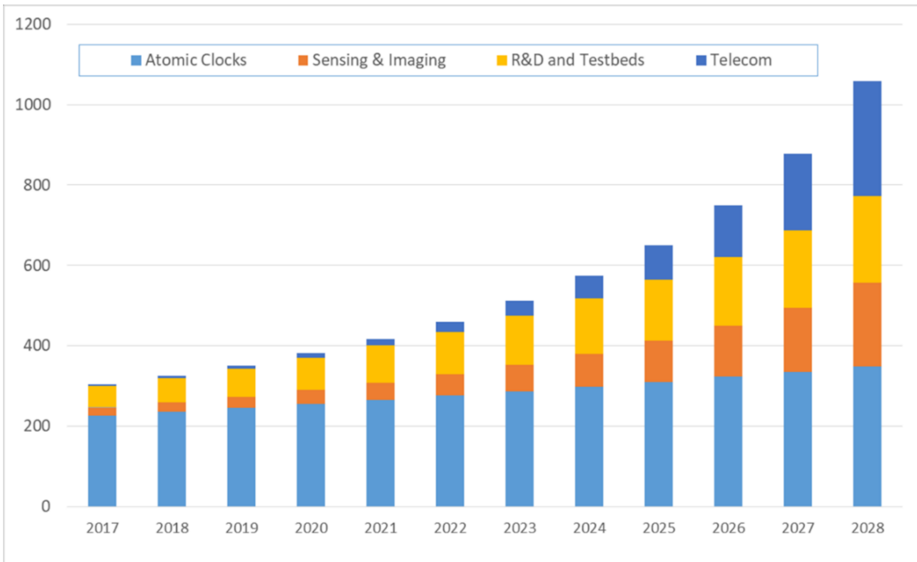
Total Market for Nanoscale Quantum Optics

Atomic clocks is by far the biggest market for Nanoscale Quantum Optics today. Another major part of Nanoscale Quantum Optics market consists of enabling technologies: stabilized laser systems, optical frequency combs, single-photon sources and detectors, etc. The most part of the market for enabling technologies is for R&D and testbeds.

In the figure below, we give an estimation of the current and future (10 years) market of Nanoscale Quantum Optics.



Total market for Nanoscale Quantum Optics (M€)

Conclusions

For the market in 5 years (2023), the main trends are the following:

- Atomic clocks will still represent the biggest market share.
- Sensing and imaging will account for about 60 M€ with the most part coming from Nanoscale Quantum Optics (NV centres and atom chips).
- Telecom market will be < 50 M€.

It is possible to give some insights for the market in 10 years (2028):

- Sensing and imaging will account for around 200 M€ with the most part for magnetometers.
- Telecom market will be around 300 M€.

The total accumulated market will account for about 7 B€ for the next 10 years. The associated systems and services will represent around 10 times this amount.

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