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Quantum Technologies with Photons: Trends, Opportunities and Challenges

Klea Dhimitri
Applications Engineer
Marketing Department
Hamamatsu Corporation (HC)

Contents

The 4 Quantum Technology Pillars

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Quantum Technologies

- Quantum Computation & Simulation
- Quantum Communication
- Quantum Metrology & Sensing
- Fundamental Research

The 4 Quantum Technology Pillars

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Quantum Computation & Simulation

- Quantum Annealers
- Quantum Simulators
  - Neutral Atoms
- Quantum Computers
  - Silicon Quantum Dots
  - Superconducting*
  - Trapped Ions
  - Neutral Atoms
  - Photonic
  - Nitrogen Vacancy (NV)
  - Topological

Quantum Communication

- Post Quantum Cryptography
- Quantum Random Number Generators
- Quantum Key Distribution (QKD)
  - Continuous variable
  - Discrete variable, no entanglement
  - Discrete variable, entanglement
  - High-Dimensional
- Quantum Networks
  - Quantum Repeaters
  - Quantum Memories/Buffers

Quantum Metrology & Sensing

- Physical (pressure, magnetic fields, electric fields)
- Precise Timing
- Inertial (gyroscope, accelerometer, gravimeter)

Fundamental Research

- Quantum Optics & Imaging
- Quantum Biology
- Single Photon Sources/ Entangled Photon Sources

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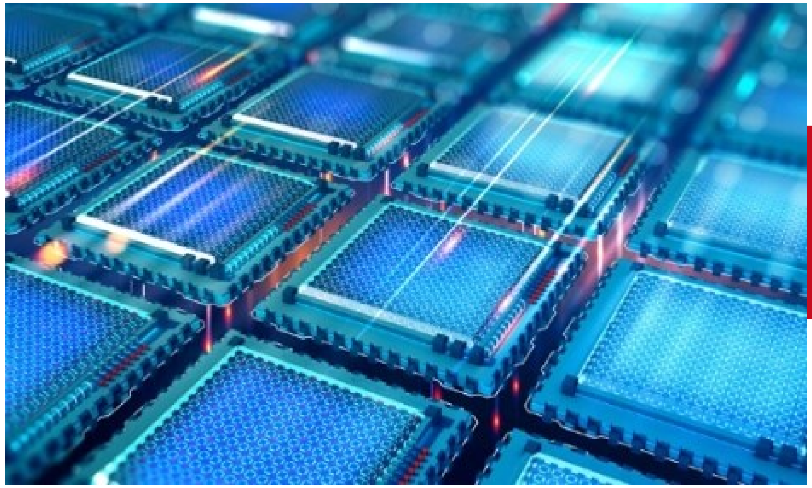
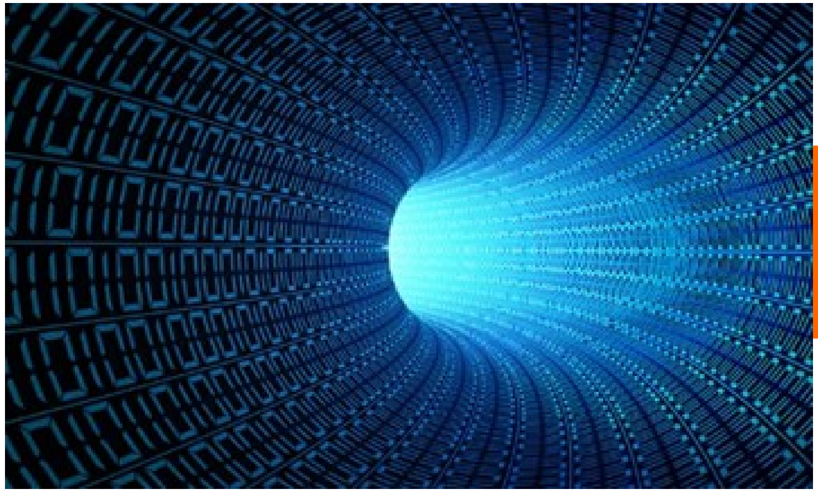
*To scale superconducting qubits some photonic link ideas have been demonstrated.

Quantum Technology Pillars & Role of Photonics



Quantum Computation & Simulation

Photonics enable the ability to confine qubits (ex: atoms) in arrays and detect qubit state (0 or 1) through low light fluorescence from ions and atoms.



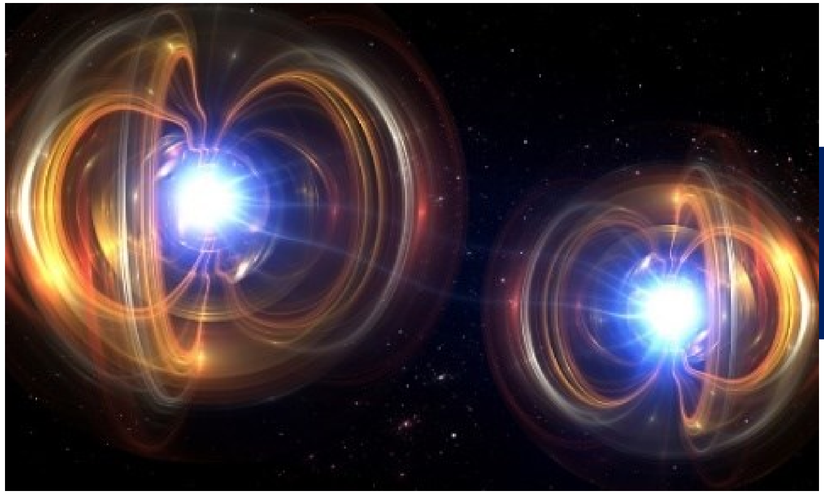
Quantum Communication

Photon acts as a secure carrier of information especially over long distances and has the ability to notify immediately when an eavesdropper is listening.

Quantum Technology Pillars & Role of Photonics

Quantum Metrology & Sensing

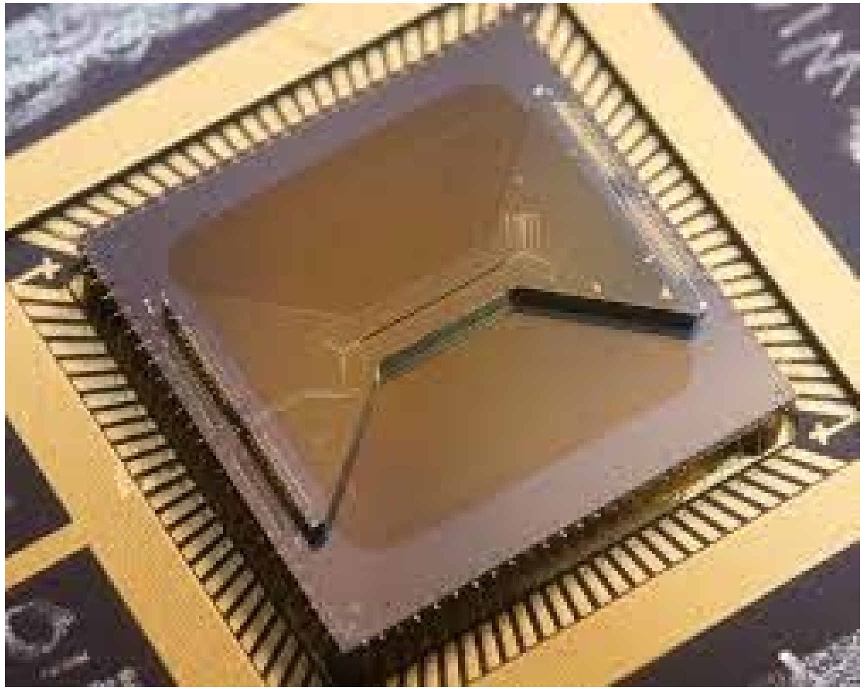
Accurate probing of environment in terms of measurement (ex: electric, magnetic, gravitational), timing and positioning. Information can be communicated via fluorescence (ex: NV, atoms or ions).



Fundamental Research

Photons can characterize quantum phenomenon such as entanglement through detection and imaging.

Quantum Computing with Photons – Trapped Ions



Sandia High Optical Access (HOA)Trap

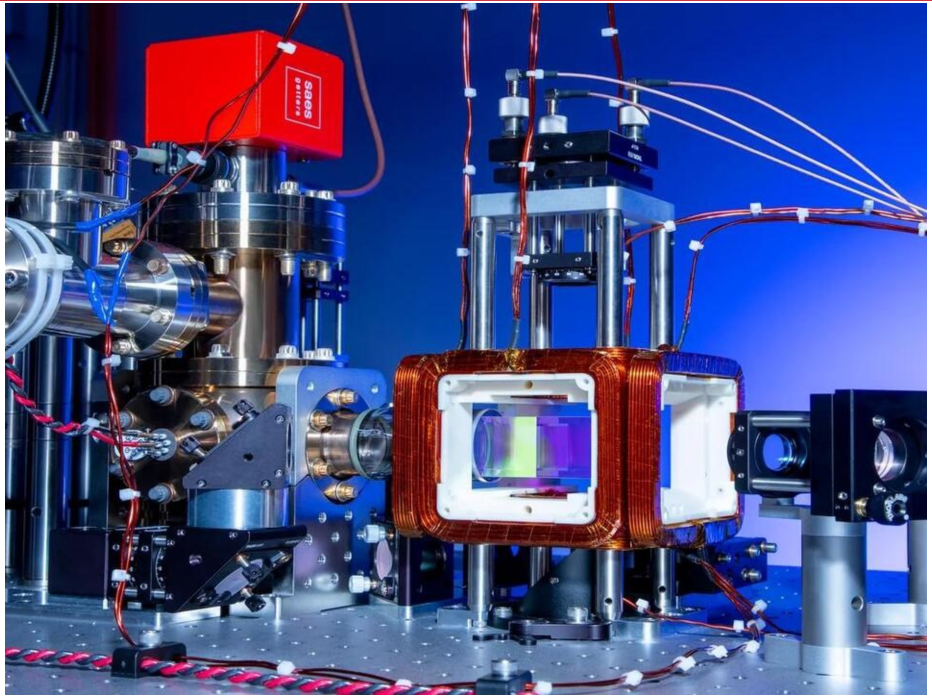
Trapped Ions Setup: Ions operate in an ultra high vacuum and cryogenic environment inside traps like Penning traps or Paul traps where electric fields create potentials that confine ions.

Trapped Ions Photonics Components:

- Lasers: cooling, initialize & readout ion state
- Modulators: control & direct laser beams at ions
- Optics: magnify ions
- Single Photon Counting Detectors & Cameras: qubit state detection & imaging

Maunz, P. High Optical Access Trap 2.0.
https://doi.org/10.2172/1237003

Quantum Computing with Photons - Neutral Atoms



Atom quantum computer

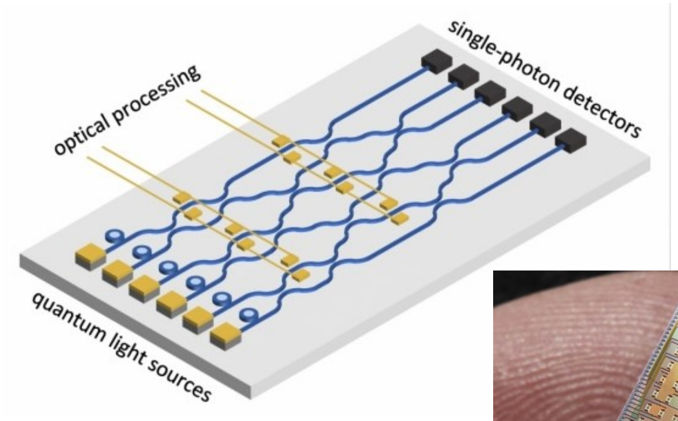
Neutral Atoms Setup: Operate in a magneto-optical trap (MOT) or ultra high vacuum cell and the atoms are confined in arrays with optical tweezers.

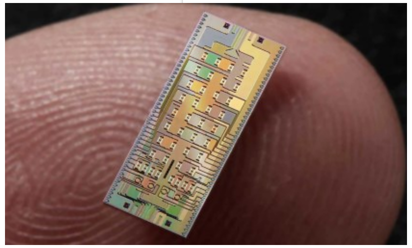
Neutral Atoms Photonics Components:

- Lasers: optical trapping, atom rearrangement, cooling, optical pumping and gate operations
- Modulators: generate optical trap sites, qubit addressing, sort atoms, adjusting laser pulse duration & intensity
- Cameras: qubit state detection & imaging

Hu, C. (2020,February). How neutral atoms could help power next-gen quantum. Popular Science.

Quantum Computing with Photons - Photonic Qubits





All-on-chip quantum photonic platform

Photonic Qubits Setup: sources, beam-splitters, waveguides and detector all on a tiny chip. Utilizing a certain property of the photon you could construct a qubit (ex: dual – rail, time bins, etc.)

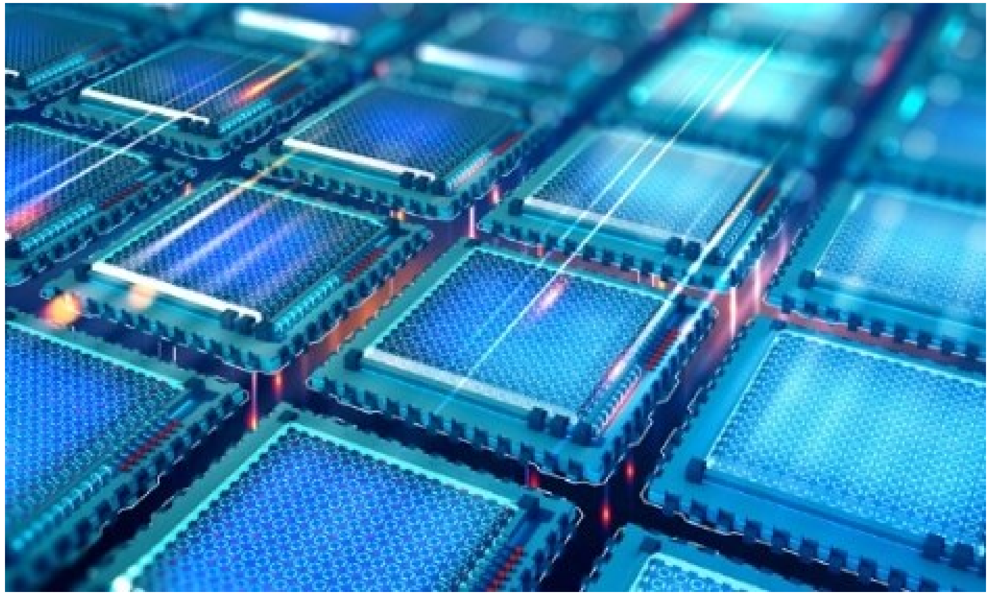
Qubit modalities such as nitrogen vacancy (NV) and superconducting qubits have utilized photonics.

Photonic Qubits Photonic Components:

- Photons Sources: generate photon states
  - Lasers: pumping probabilistic light sources or excitation laser for deterministic source
- Passive & Active Photonic Components: waveguides, couplers, phase shifters, etc. to manipulate your photon
- Single-photon detectors or Photon Number Resolving (PNR) Detector: qubit state detection

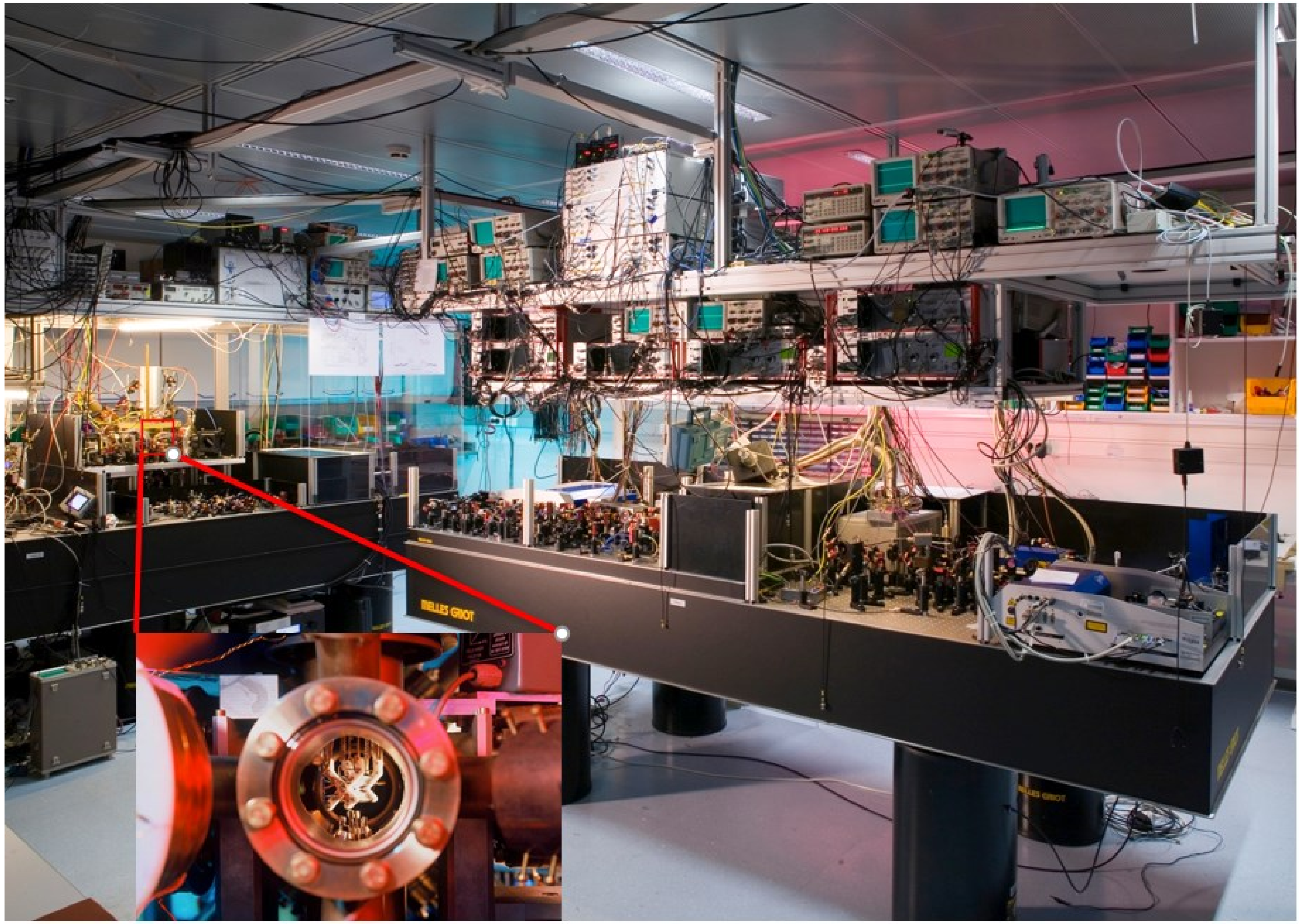
Masuda, A. (2019). https://www.news.ucsb.edu/2019/019679/pushing-quantum-photonics
Choi, C.Q. (2021). https://spectrum.ieee.org/race-to-hundreds-of-photonic-qubits-xanadu-scalable-photon
Lecocq, F. *et al*. Nature 591, 575–579 (2021).

What is driving photonic component development for **trapped ions, neutral atoms & photonic qubits**?



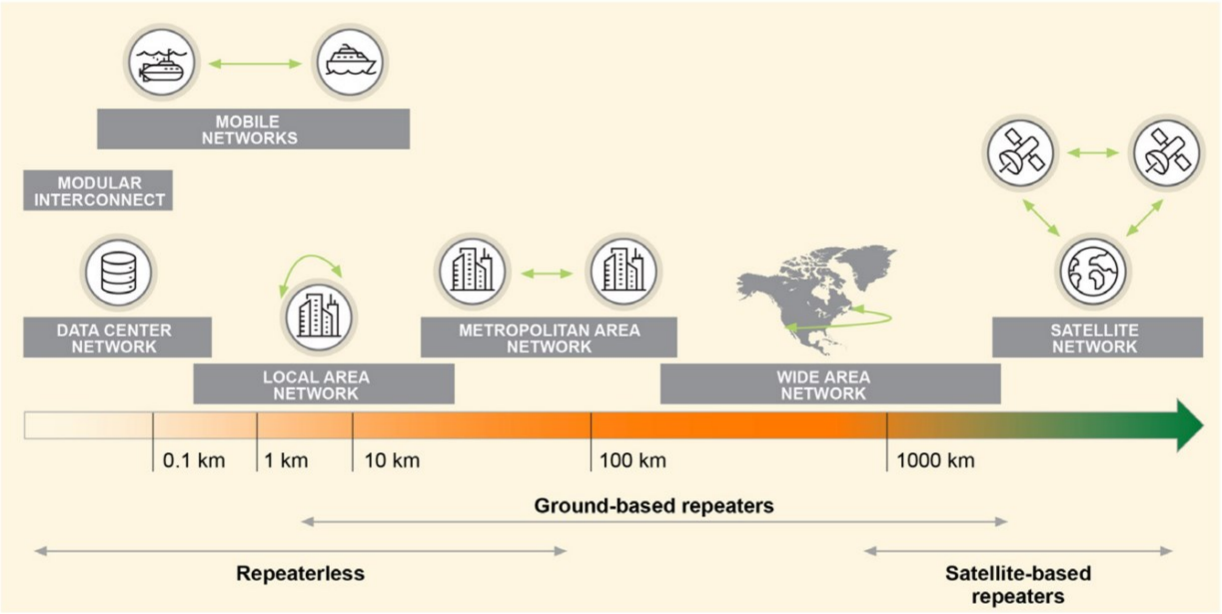
Scalability & Fidelity

Current Ion Trap Lab Demonstrates Issues with Scalability



Jurcevic,P.,Mandelbaum,R. (2021). Here's How Ion Trap Quantum Computers Work.
The Quantum Aviary. https://thequantumaviary.blogspot.com/2021/03/heres-how-ion-trap-quantum-computers.html

Quantum Communication with Photons



Different types of quantum networks

- **Quantum Random Number Generator**
  - Create truly random keys by leveraging randomness in quantum systems. Utilized in quantum key distribution.
  - **Photonics component examples:** LED and image sensors
- **Quantum Key Distribution:**
  - Land Quantum Networks: Distance limited on due to optical fiber losses and lack of quantum repeaters.
  - Space/Satellite Quantum Networks: aperture and diffraction loss limited.
  - **Photonics component examples:** lasers, photon sources, photodiodes, single photon detectors

Sanguinetti, B., et al, Phys. Rev. X 4, 031056 (2014).

Awschalom, D.D., et.al. https://doi.org/10.2172/1900586

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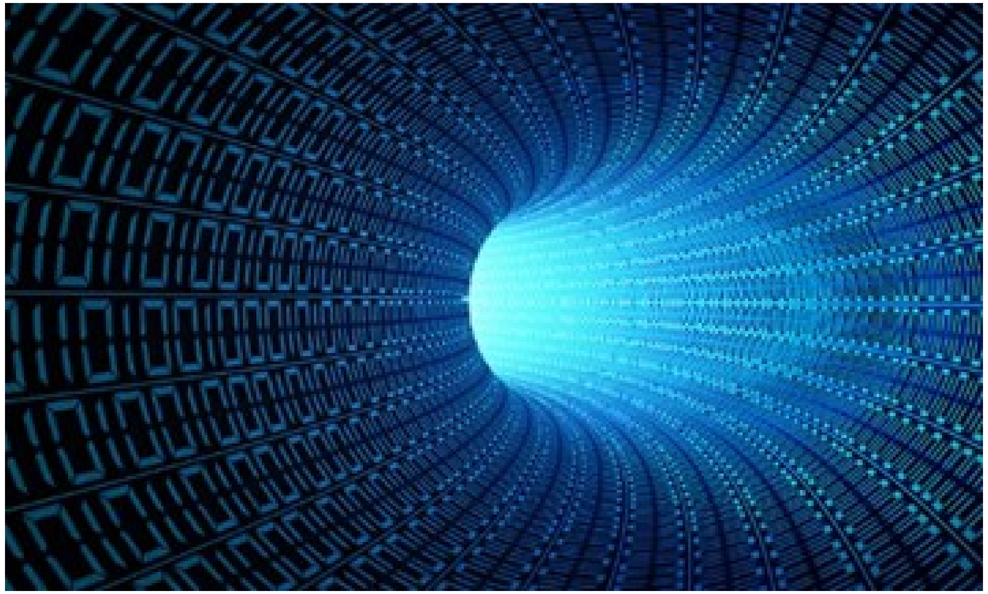
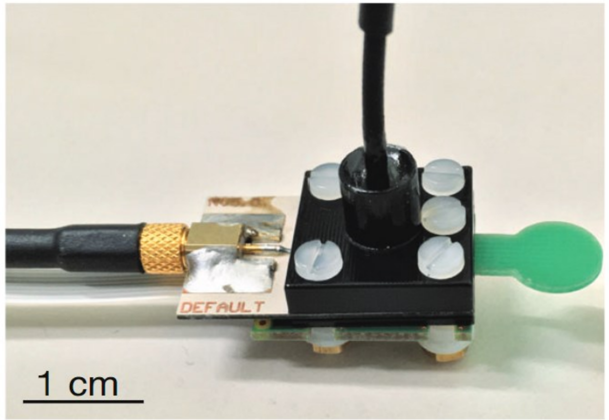
What is driving photonic component development for **quantum communication**?



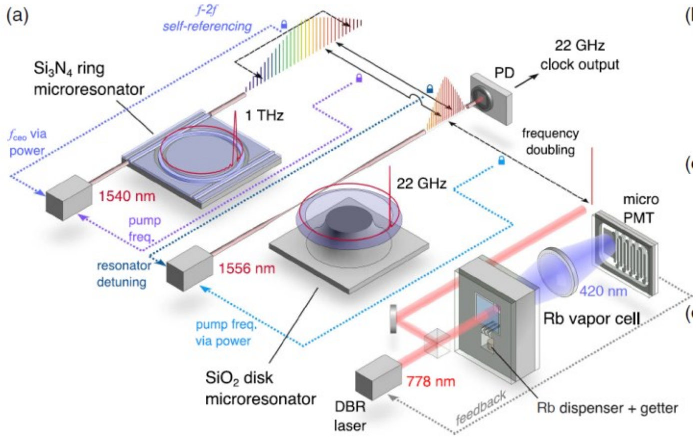
Preserving photons over long distances

Quantum Sensing with Photons

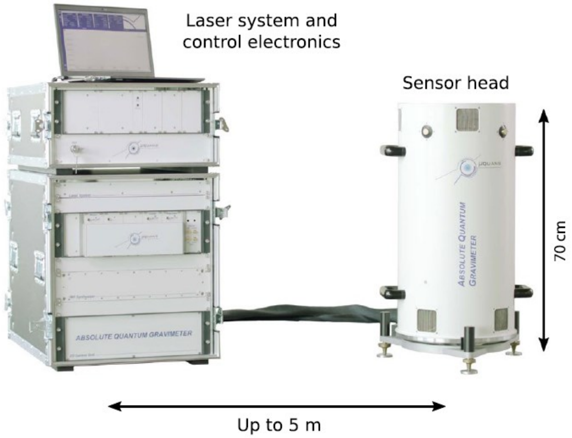
- **Magnetometer (NV or OPM):** Precise measurements of local magnetic fields in the case of NV different fluorescence intensities relate to strength of magnetic fields present. Uses: lasers, photodiodes, single photon detectors
- **Optical Atomic Clocks:** Certain transitions in atoms can be used as a time standard. Uses lasers, photodiodes, single photon detectors, frequency combs.
- **Gravimeter:** Precise measurements on gravitational field gradient by utilizing cloud of cold atoms and conducting measurements via fluorescence. Uses laser and photodiodes



Nitrogen Vacancy Sensor



Microfabricated photonic optical atomic clock



Absolute Quantum Gravimeter

Ménoret, V. et al. *Sci. Rep.* 8, 12300 (2018).
Z. L. Newman, et al., Optica 6, 680 (2019).
Stürner, FM, et al. Adv. Quantum Technol. 4(4), 2000111 (2021).

What is driving photonic component development for quantum sensing?

Size, weight, power & cost SWaP-C, for deployable applications

Business Trends & Growth for Photonics in Quantum

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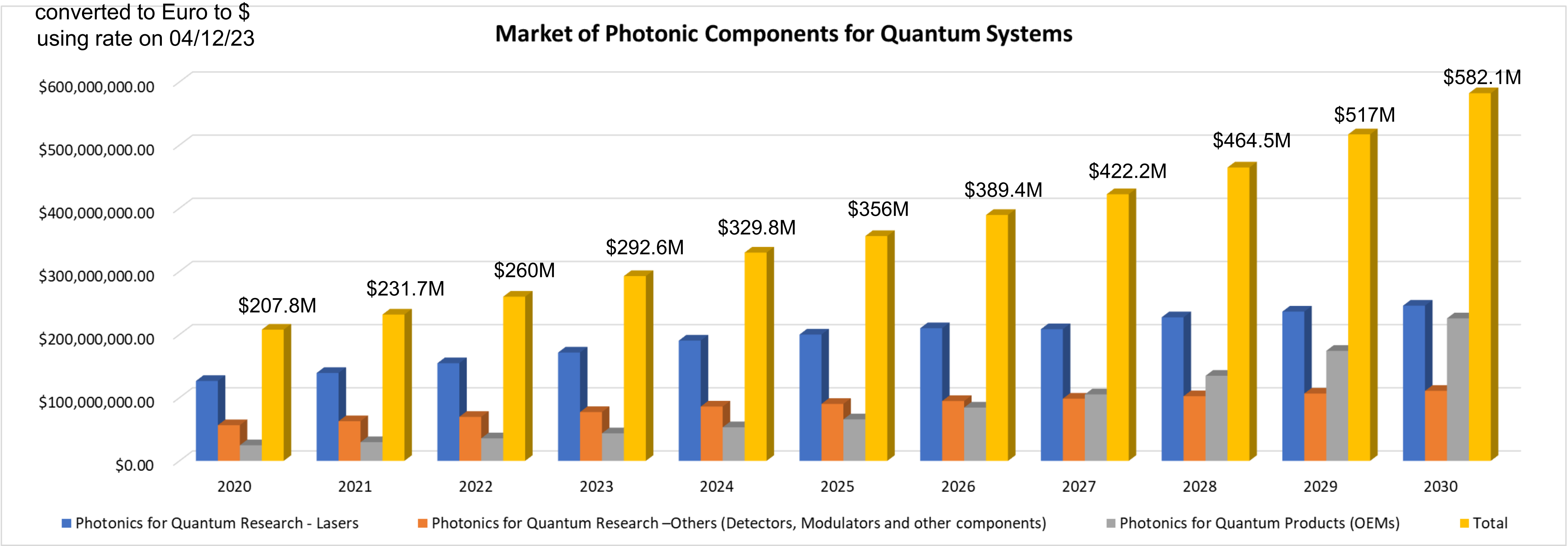

- Market for quantum systems is currently not high, but **market for photonic components is high and promising**.
- Over ½ of the bill of materials cost for quantum systems goes to lasers, the rest is split among detectors, modulators & other components.
- Currently largest market for photonic components is research. From 2025 photonic components for quantum products will take over.

Source:Tematys Photonics@Quantum: Technologies for Quantum Systems Report (April 2022)

Challenges of Photonics in Quantum Technologies

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- Single photon sources can be used for quantum key distribution and some forms of photonic quantum computing.
  - Need to build one source that contains ALL the features desired.
- Photonic integrated circuits (PICs) are the holy grail of quantum.
  - Challenge 1 is to bring EVERYTHING on chip
  - Challenge 2 is cost of PIC production line. Need high volume to keep costs manageable. Unclear if Quantum applications can sustain.
- Need improved NIR detectors (ex: InGaAs) for deployable quantum communication applications.

Davis.S et al. Piercing the Fog off Quantum-Enabling Laser Technology (QELT) A report based on a QED-C Enabling Technology Workshop. *QED-C.* (2018).

Free Reports on Photonics in Quantum Technology!

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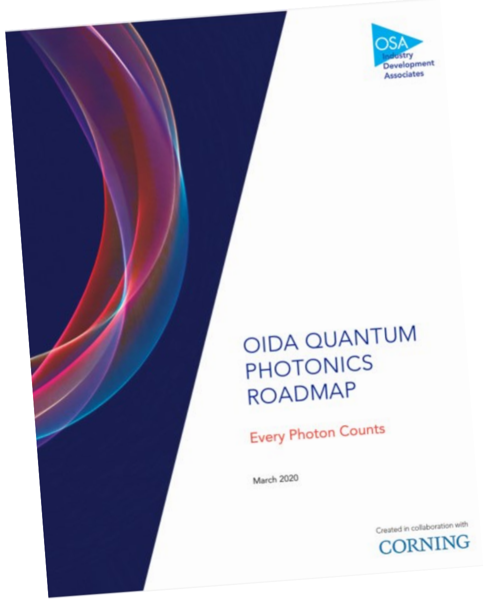

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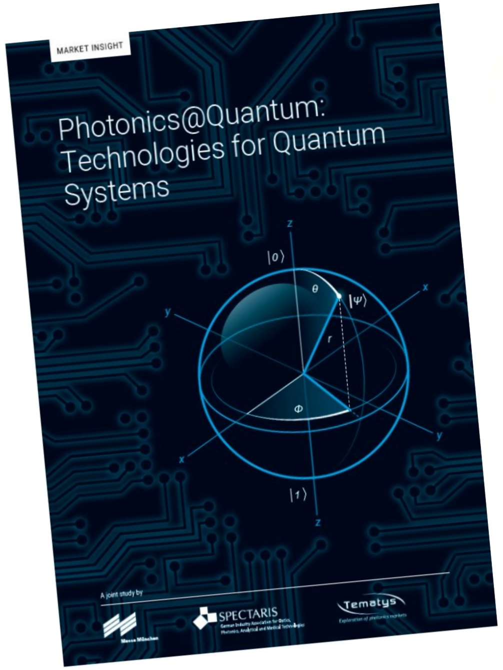


Tematys
Exploration of photonics markets

Single-photon measurement infrastructure for quantum applications (SPMIQA): Needs and priorities

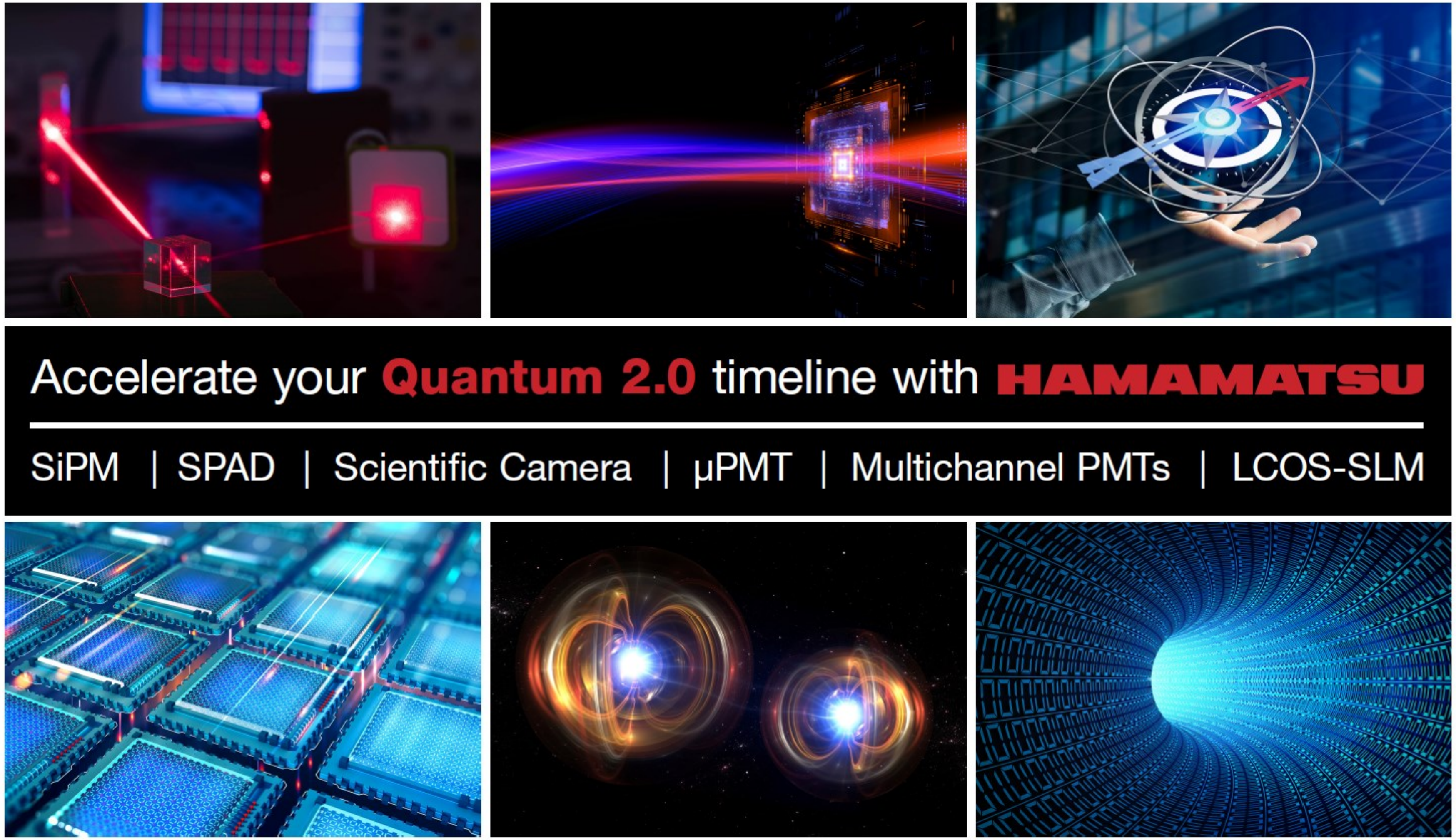
July 18, 2022

Executive summary

As the fields of quantum computing, quantum sensing, and quantum communication mature into engineering disciplines, a robust measurement infrastructure is needed that is available to all developers of quantum technology. This requirement for

QED-C

Hamamatsu for Quantum 2.0



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