QUANTUM INTERNET ALLIANCE

D1.5 Comparison report on next-generation devices

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1. Abstract

Task 1.4 within the Quantum Internet Alliance (QIA) project was to develop enabling technologies for the next generation of end-node devices. The end-node devices that were used to generate remote entanglement and teleportation within QIA are at the forefront of the field; however, we are lacking a clear route to scale up these devices to more complex network settings. Thus, from the start of the project, we undertook multiple efforts to advance high-risk, high-gain technologies that could open up new paths to scalable networks. We focused on three technologies: diamond device engineering, semiconductor-based mirrors, and fiber-based cavities. In the present report, we summarize and compare the progress that was made along these three paths.

2. Keyword list

Quantum end nodes, scalable quantum networks, diamond-device engineering, semiconductor-based mirrors, fiber-based cavities

3. Acronyms & Abbreviations

DoA	Description of Action
EC	European Commission
NV	Nitrogen Vacancy
QIA	Quantum Internet Alliance
WP	Work Package
ZPL	Zero Phonon Line

4. Introduction

The QIA project focused on three leading platforms for end nodes of quantum networks: atoms, ions, and nitrogen-vacancy (NV) centers. Within QIA, entanglement between two remote cavity-coupled atoms [1,2], two remote cavity-coupled ions [3], and three remote NV centers [4] was demonstrated. It is expected that these three platforms will continue to be at the forefront of quantum network demonstrations in the coming years. However, in order to extend these results to more complex network settings, it will not be sufficient simply to build more copies of our existing hardware. Instead, significant technological innovation is needed to develop next-generation devices.

The first route that we pursued was based on *diamond device engineering* in order to develop next-generation NV end nodes. Here, we focused on defect clusters of strongly coupled pairs of NVs in diamond. Our vision was that one NV of the pair would serve as a spin-photon interface and the other as a quantum memory in which remote entanglement could be stored, boosting the bandwidth available for quantum network protocols. The specific engineering challenge was to improve the production yield and coherence times of NV clusters as well as the charge state stability of individual NV centers.

Our second route targeted next-generation trapped-ion end nodes through the development of high-finesse *semiconductor-based mirrors* for optical cavities. This was a promising approach to address the charging effects in standard dielectric mirror coatings that are known to limit current experiments. Unfortunately, the project partner in this effort, Crystalline Mirror Solutions (CMS), was forced to withdraw from the project as of March 31, 2020 due to its acquisition by the American optics group Thorlabs.

Our third route was also based on cavities, and specifically, *fiber-based cavities*, which are a promising route to scale up all three end-node platforms. Fiber cavities were thus pursued for neutral atoms, as part of a dual-cavity approach; for trapped ions, as a means of increasing the coherent coupling rate between single ions and single photons; and for NV centers, as a means to enhance the zero-phonon-line (ZPL) photon rate and thus the remote entanglement rates.

5. Diamond device engineering

5.1. Methods and results

Efforts on diamond device engineering within QIA were led by the University of Stuttgart, in collaboration with TU Delft and Element Six. These efforts are also discussed in Section 2.4.1. of the Comparative Analysis Report produced for Deliverable 5.2.

Our aim was to produce pairs of NV centers, coupled via dipolar interactions, as a means to achive direct optical readout of spin qubits. These pairs were produced via ion implantation, which was successful but had a low conversion yield: only about one out of every 600 nitrogen atom implantation spots resulted in coupled NV center pairs. The low yield was due to the low implantation energy, which was necessary to avoid excessive ion straggle. In a subsequent effort, the conversion yield was improved by an order of magnitude by using a diamond sample in which NV centers had been created through the implantation of nitrogen-rich molecules [5].

Spin-spin entanglement within the coupled NV center pairs was demonstrated at room temperature.

A second engineering effort was based on single NV centers in phosphorus-doped diamond samples; the overabundance of electrons from phosphorus can effectively stabilize the charge environment. Within QIA, a dramatic improvement was demonstrated in the charge-state stability of shallow NV centers, without negative consequences for the spin coherence. An optical linewidth narrowing was also observed, but lifetime-limited linewidths — required for quantum network experiments — have not yet been achieved.

5.2. Outlook

Building on the improved conversion yield that has been obtained for NV-center clusters, the next step will be to demonstrate tripartite entanglement between opticallly active spins. With regards to phosphorus-doped samples, further studies are required to find an optimal doping concentration, which we expect will allow lifetime-limited linewidths to be achieved.

6. Semiconductor-based mirrors

6.1. Methods and results

Semiconductor “supermirrors” based on substrate-transferred single-crystal GaAs/AlGaAs multilayers offer a solution to the surface charging problems that arise when trapped ions are placed in the vicinity of dielectric mirrors. Until recently, dielectric mirrors were the only available means to achieve low enough scattering and absorption losses for cavity-based quantum network experiments. However, in recent years, CMS pioneered a novel approach based on substrate-transferred crystalline coatings. At the start of the project, these semiconductor mirrors were only available at wavelengths too far in the infrared to be of use for QIA’s three experimental platforms. Furthermore, it was unknown whether it would be possible to transfer the coatings (grown via molecular beam epitaxy) onto the mirror substrates used in quantum network experiments, which have tight radii of curvature (between 1 cm and 10 cm) in order to boost spin-photon coupling rates.

To address the first question, on wavelength compatibility, CMS started to develop a Bragg mirror structure for a target wavelength of 850 nm. After several discussions with epitaxial wafer suppliers, it was decided to select the material combination InGaP/AlGaAs instead of an AlGaAs-only semiconductor heterostructure. For testing the ultra-low optical absorption of such a structure with the photo-thermal common-path interferometry (PCI) method, CMS preselected possible laser sources around the target wavelength of 850 nm.

To address the second question, on compatibility with substrates with tight radii of curvature, CMS revisited and optimized every step in the process chain. A mechanical bonding chuck was redesigned to perform a controlled bonding process of the semiconductor mirror dies with the highly curved surface of the optical substrate. It was thus possible to perform temperature annealing under mechanical pressure to prevent a delamination of the semiconductor die after the initial contact (due to lower initial bond strength). For testing the mechanical stability of the bonded semiconductor die after annealing, wet chemical etch tests were performed. This etch process is necessary for the final mirror production and serves as the ultimate test for the adhesion strength.

Work on both questions ceased in December 2019, when CMS was acquired by Thorlabs, as discussed in Section 4.

6.2. Outlook

As of 2022, semiconductor crystalline mirrors are still considered a potentially transformative approach for cavity-coupled ion-trap end nodes of a quantum network. However, the expertise no longer exists in Europe to investigate this question within a European research project.

7. Fiber-based cavities

7.1. Methods and results

Device engineering of fiber-based cavities was carried out in parallel on all three experimental end-node platforms. These efforts benefited substantially from discussions and exchange of technical information between the teams throughout the project.

A quantum network node based on a pair of crossed optical-fiber cavities was constructed for the first time by QIA researchers at the Max Planck Institute of Quantum Optics [6]. It was shown that this pair of cavities provides two quantum channels, each coupled to a single trapped atom. One quantum channel can be used, for example, to write information into the atom, which serves as a quantum memory, while the other is used to read out the memory [6]. More recently, the two channels have been used to achieve nondestructive detection of photonic qubits, in which the qubit information is preserved with a fidelity of 96.2(3)% [7].

For trapped ions, a fiber-based cavity was constructed within the QIA at the University of Innsbruck [8]. This cavity is based on a novel design that allows the fiber-cavity axis to be oriented along the ion-trap axis, thus enabling the coupling of long ion strings to the cavity. In an initial experiment with the new setup [9], the fiber mirrors were used to probe the contribution of dielectrics to the heating rate of trapped ions, a materials issue that will be important to understand for future quantum-network and quantum-computing experiments [10].

For NV centers, a fiber-based cavity consists of one fiber-based mirror and a second mirror on a fused silica substrate with an embedded diamond membrane. QIA researchers at TU Delft have recently achieved resonant addressing and Purcell enhancement of a nitrogen-vacancy center in such a cavity [11].

7.2. Outlook

The two cavities in the crossed-cavity setup currently operate at wavelengths of 780 nm and 795 nm, both corresponding to rubidium atom transitions. It is planned to rebuild the setup with one cavity at a telecommunications wavelength in order to facilitate long-distance quantum network protocols [12].

The next steps for the trapped-ion fiber cavity consist of demonstrating and characterizing the coherent coupling between a single ion and a single photon. It will also be important to adapt existing ion-photon entanglement protocols to take into account the inherent birefringence of fiber cavities.

Three improvements are planned for the NV-center fiber cavity: an implementation of microwave spin-state control, a reduction of vibrations in the experimental system, and an increase of the cavity finesse by suppressing diffraction losses. It is expected that these improvements will lead to near-unity excitation of the NV center, more than an order of magnitude gain in ZPL photon collection, and a cooperativity greater than one, demonstrating that coherent processes play a dominant role in the spin-photon interactions.

8. Conclusion

During the QIA project, significant progress has been made towards next-generation devices. Extensive engineering and analysis of NV-based devices led to the demonstration of spin-spin entanglement within coupled NV pairs and to improved charge-state stability based on phosphorus doping. However, more investigation is needed on both fronts. While efforts to develop semiconductor-based mirrors for quantum networks were halted due to the acquisition of CMS, novel fiber cavities were implemented at all three end-node platforms, profiting from synergies between our technical approaches.

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